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Vulnerability of Tropical Pacific Fisheries and Aquaculture to Climate Change

Edited by Johann D Bell, Johanna E Johnson and Alistair J Hobday

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Foreword

The bonds between the people of the Pacific and their fisheries are extraordinary. Fish and shellfish are common in Pacific folklore and nowhere else do so many countries and territories depend as heavily on fisheries for economic development, food security and livelihoods. These unique relationships underpin the directive of Pacific Island Forum Leaders to 'develop and implement national and regional conservation and management measures for the sustainable utilisation of fisheries resources' – a priority of the Pacific Plan.

Rapid population growth in many Pacific Island countries and territories demands new approaches to the sustainable use of natural resources for economic, human and social development. A recent study entitled 'The Future of Pacific Island Fisheries' by the Forum Fisheries Agency and Secretariat of the Pacific Community is a valuable guide to optimising the benefits from fisheries and aquaculture. However, achieving these benefits over the long term will depend on our ability to recognise and respond to the many drivers affecting the production and use of fish and shellfish.

There is now little doubt that the impact of climate – already an important driver of fisheries and aquaculture production – is likely to increase in the years ahead. To respond effectively, we need to know the vulnerability of the sector to the changing climate and how best to adapt. This book, written with generous support from the Australian Agency for International Development (AusAID), brings together valuable contributions from scientists and fisheries managers from 36 institutions around the world to provide this vital information.

The fact that the main findings are mixed – there are likely to be winners and losers – underscores the importance of this vulnerability assessment. Practical adaptations, policies and investments are now needed to reduce the threats of climate change to the many fisheries and aquaculture activities that are part of the economic and social fabric of the region. Adaptations, policies and investments are also needed to capitalise on the opportunities. These essential planning tools are described in the last chapter – I recommend them to all stakeholders and their development partners.

This book is much more than a comprehensive assessment of the vulnerability of tropical Pacific fisheries and aquaculture to climate change. It is also a valuable resource for anyone wanting to learn about the diverse oceanic, coastal and freshwater fisheries and aquaculture activities of the Pacific Islands region, and the environmental conditions and habitats that support them.

Dr Jimmie Rodgers
Director-General
Secretariat of the Pacific Community

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Preface

It is now clear that the global community must do more than plan how to reduce global warming – we must also learn to adapt to the inevitable increases in the temperature and acidification of the oceans while we rein in emissions of greenhouse gases. Adaptation has been a focus of recent international climate change negotiations and strong pledges have been made to help developing countries respond to the climate-related changes ahead.

Australia is well aware of the potential effects of climate change on yields from agriculture and fisheries and we are deeply committed to helping our Pacific Island neighbours understand the vulnerability of their resources to these changes, and how best to respond. Together we must find ways to maintain the quality of life for all people in the region as the impacts of climate change intensify.

The onus is on everyone involved to make the best use of the technical and financial support available for adaptation. The process should begin with thorough assessments of the vulnerability of the resources that underpin national economies, food security and livelihoods. Only then can sensible adaptation initiatives be identified and implemented in a timely and cost-effective way.

Australia is proud to be a partner in this comprehensive analysis of the vulnerability of Pacific Island fisheries and aquaculture to climate change – the result of impressive teamwork coordinated by the Secretariat of the Pacific Community with support from our International Climate Change Adaptation Initiative. This rigorous assessment by almost 90 scientists from the region and around the world is both authoritative and practical. It is a prime example of how to use the latest scientific knowledge to inform effective adaptation. I am confident that the peer-reviewed analyses presented here will be of great value to the Intergovernmental Panel on Climate Change during the preparation of its 5th Assessment Report.

Pacific Island countries now have the information they need to understand the potential effects of climate change on the many economic and social benefits they derive from fisheries and aquaculture. Australia looks forward to assisting the region to apply the priority actions described in this book, many of which address other pressing issues for the environment, such as rapid population growth.

For many people, particularly Australians, this book will usher in a new understanding of the significance of fisheries and aquaculture to the people of the Pacific. It will also heighten awareness of our responsibility to help Pacific Island countries maintain the benefits they receive from well-managed coastal ecosystems, and stocks of fish and shellfish – benefits that extend to everyone who visits their shores.

The Hon Kevin Rudd MP

Minister for Foreign Affairs
Australia

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This book is the product of remarkable teamwork – a partnership that started between the Australian Agency for International Development (AusAID) and the Secretariat of the Pacific Community (SPC), and then grew to embrace intellectual contributions from authors at 36 institutions. The late Gordon Anderson, in his role as the AusAID Pacific Fisheries Programme Development Adviser, was the first person to actively promote the need for a comprehensive assessment of the vulnerability of fisheries and aquaculture in the tropical Pacific. Generous support from AusAID's International Climate Change Adaptation Initiative and strong commitment from the executive team at SPC provided the opportunity to bring this important vision to fruition.

The Secretariat of the Pacific Community and the editors are grateful to the many authors who accepted the invitation to contribute their expertise to this assessment. We also thank the members of the technical working group, and the advisory committee, comprising representatives from French Polynesia, Solomon Islands and Vanuatu, who provided guidance throughout the project. Special thanks are due to the institutions that made the time of their senior staff available to lead the writing of several chapters (Australian Institute of Marine Science, Collecte Localisation Satellites, Institut de Recherche pour le Développement, James Cook University and Snowy Mountains Engineering Corporation). We also appreciate the valuable contribution made by the internationally recognised scientists and managers (listed at the end of the book) who provided the peer reviews of each chapter.

Many other people helped turn the text from the expert authors into a book. Catherine Collier and Aroon Edgar found effective ways to illustrate key points with attractive conceptual diagrams based on symbols from The Integration and Application Network. Carla Appel and Boris Colas did a masterful job with the layout to make the large volume of technical information easy to digest. Angela Templeton provided valuable editorial advice from the earliest stages and Astrid Baker carried out copy editing assisted by Julian Heinz. Céline Barré helped finesse the layout of all chapters, checked the references and meticulously corrected page proofs. Nathalie Wiegandt, Christophe Boe, Julie Vasello and Patricia Demmke helped with the great variety of tasks involved with the project, including organising meetings of the technical working group, corresponding with authors and word processing draft manuscripts. Trevor Viney and Ange Marelli Ballou made arrangements to acquire the many photographs and Fiona Paladini helped publicise the photo competition to select the cover image. Jeff Maynard did the final checking of the entire book, Sherrey Quinn compiled the index, Robert Le Borgne assisted with the glossary of terms and Lindsay Chapman reviewed the final wording of several chapters.

The people who kindly helped authors to produce or improve their contributions are listed here by book chapter. Chapter 1: Tim Lawson, Peter Terawasi, Apolosi Turaganiva and Peter Williams. Chapter 2: Julie Arblaster, Kevin Hennessy, Felicity McAllister, Alex Sen Gupta and Tim Simmonds. Chapter 3: Jérôme Lefèvre. Chapter 4: Christophe Menkes and Martine Rodier. Chapter 5: Sophie Dove. Chapter 6: Michael Batty, Tim Adams, Claire Garrigue, Jeff Kinch, Kelvin Passfield, Chris Roelfsema and Satja Sauni. Chapter 7: Patricia Demmke, Frank Pezold, Scott Pontifex and Jodie Thomas. Chapter 8: Don Bromhead, Jesus Jurado-Molina and Shelton Harley. Chapter 9: Aymeric Desurmont, Jeff Leis, Lyndon Llewellyn, Shilpa Kumar Roine and Colin Wen. Chapter 10: Frank Pezold and Jodie Thomas. Chapter 11: Robert Jimmy. Chapter 12: James Hemphill, Nicola Kingston, Tim Lawson, Colin Millar, Warwick Nash, Peter Terawasi, Nathalie Wiegandt and Peter Williams. Chapter 13: Sandra Bernklau, Michel Blanc, Tea Braun, Eric Clua, Patricia Demmke, Bob Gillett, Elise Huffer, Robert Jimmy, Brigitte Leduc, Seema Naidu, Jason Rubani, Hugh Walton, Arthur Webb, Meryl Williams and Stephen Yen Kai Sun.

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Finally, we acknowledge the modelling groups at the Program for Climate Model Diagnosis and Intercomparison (PCMDI) and the World Climate Research Programme's (WCRP) Working Group on Coupled Modelling (WGCM), for their roles in making available the WCRP CMIP3 multi-model dataset. Their work, and the support provided for these datasets by the Office of Science, US Department of Energy, enabled the authors of Chapters 2 and 3 to assess the projected effects of climate change on surface climate and the tropical Pacific Ocean.

Photo: Natalie Behring

Chapter 1

Pacific communities, fisheries, aquaculture and climate change: An introduction

Johann D Bell, Tim JH Adams, Johanna E Johnson, Alistair J Hobday and
Alex Sen Gupta

> *'[There is] an imperative need for us to take immediate and decisive collective action to ensure that we secure our peoples' future livelihoods, regional food security, and the environmental sustainability of our seas and their ecosystems.'*
> (Pacific Islands Forum, Vava'u Declaration 2007)[i]

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[i] Pacific Islands Forum, Vava'u Declaration (2007) *The Vava'u Declaration on Pacific Fisheries Resources: 'Our Fish, our Future'*. Forum Communiqué, Thirty-eighth Pacific Islands Forum, Nuku'alofa, Tonga, 16–17 October 2007.

Contents

1.1 Introduction

The 22 Pacific Island countries and territories[ii] span much of the tropical and subtropical Pacific Ocean. The area encompassed by the exclusive economic zones of these countries and territories, from the Commonwealth of the Northern Mariana Islands (CNMI) in the north (25°N) to New Caledonia in the south (25°S), and from Palau in the west (130°E) to Pitcairn Islands in the east (130°W), exceeds 27 million km^2 (**Figure 1.1**)[iii]. From a fisheries perspective, the ocean area bounded by these islands almost matches the tropical portion of the Western and Central Pacific Ocean (WCPO) defined in the Western and Central Pacific Fisheries Convention[iv]. From an oceanographic viewpoint, it includes the area known as the western tropical Pacific Ocean.

It comes as no surprise given this vast area that the region covered by the Pacific Island countries and territories (PICTs) is one of great geological, biological and social diversity. The region has historically been divided into three subregions in recognition of this diversity – Melanesia, Micronesia and Polynesia – based on the physical nature of the islands, biogeography, and ethnic and cultural factors (**Figure 1.1**).

This chapter sets the scene for this book by describing the physical, biological and social diversity of the tropical Pacific; the demography of the region; the nature of local economies and limitations to economic development; and the importance of oceanic, coastal and freshwater fisheries and aquaculture to economic development and government revenue, food security and livelihoods.

We briefly outline regional arrangements and plans to optimise benefits from fisheries and aquaculture, the ways in which climate change could derail these plans, and the need for a comprehensive assessment of the vulnerability of fisheries and aquaculture in the Pacific to climate change. We also describe the approach we have taken to deliver this vulnerability assessment and how the results can be used to help industry and communities adapt to maintain the benefits of fisheries and aquaculture.

1.1.1 Physical nature of the islands

In the west of the region high islands (**Figure 1.2**) dominate the land-scape of Melanesia, which includes Fiji Islands (Fiji), New Caledonia, Papua New Guinea (PNG), Solomon Islands and Vanuatu (**Figure 1.1**). The large size of these high islands,

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[ii] The 22 Pacific Island countries and territories are American Samoa, Cook Islands, Federated States of Micronesia, Fiji, French Polynesia, Guam, Kiribati, Marshall Islands, Nauru, New Caledonia, Niue, Commonwealth of the Northern Mariana Islands, Palau, Papua New Guinea, Pitcairn Islands, Samoa, Solomon Islands, Tokelau, Tonga, Tuvalu, Vanuatu and Wallis and Futuna.

[iii] This map is indicative only of agreed and potential maritime boundaries between Pacific Island countries and territories (PICTs). It does not reflect the claims of PICTs to offshore areas.

[iv] Convention for the Conservation and Management of Fisheries for Highly Migratory Species in the Western and Central Pacific Ocean. www.wcpfc.int/key-documents/convention-text

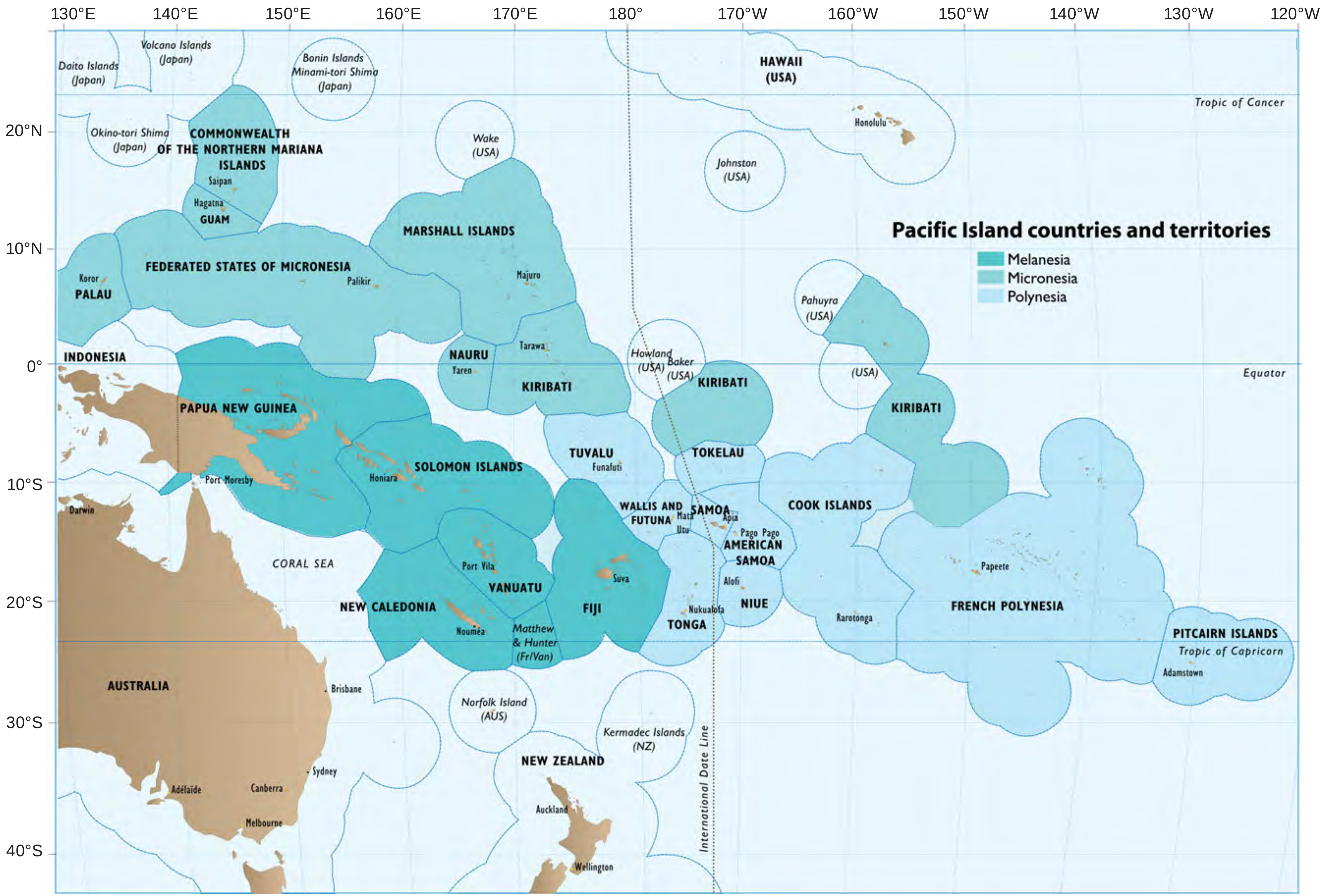

Figure 1.1 The exclusive economic zones of Pacific Island countries and territories. The subregions of Melanesia, Micronesia and Polynesia are also shown.

and the prevailing weather conditions (Chapter 2), have supported the expansion of human settlement by providing opportunities for agriculture, fisheries, forestry and mining. The coastal waters surrounding the islands of Melanesia are relatively productive due to (1) nutrients delivered from terrestrial runoff; and (2) the occurrence of small-scale, nutrient-rich upwellings created by deflection of large-scale ocean currents around the islands.

Local climate is also affected by the size of the islands in Melanesia – by intercepting the monsoons and trade winds, they generally receive much higher rainfall than the low-lying islands further to the east (see below). However, these high islands are generally subject to strong spatial variations in rainfall, with windward (usually eastern) slopes typically receiving more rain than the leeward (usually western) slopes.

Papua New Guinea is so large compared to the other countries and territories it could be considered a distinct biophysical area. Both its land area and population are greater than those of all the other PICTs combined (**Table 1.1** and **1.2**). Mainland PNG is also the only Pacific island situated on a continental shelf, which it shares with Australia and Indonesia. The geography of PNG has a significant influence on the surrounding ocean and on the nation's fisheries. The scale and value of PNG's tuna industry[1], the diversity of its coastal and freshwater fisheries, and the opportunities for aquaculture far exceed those of other PICTs.

Figure 1.2 Guadalcanal, Solomon Islands: a typical high island in Melanesia (photo: Michael McCoy).

Further eastwards and northwards of Melanesia are the countries and territories of Micronesia and Polynesia (**Figure 1.1**). The islands within these subregions are typically smaller than those in Melanesia (**Table 1.1**) and can be considered 'atolls' in various stages of evolution[2]. They range from geologically recent volcanic peaks surrounded by a narrow fringing reef, to partially subsided peaks surrounded by a lagoon, to fully evolved atolls, i.e. ring reefs formed around a completely submerged peak (**Figure 1.3**). Some islands have gone through more than one cycle of uplift and erosion (e.g. Nauru). Others are as large as some of the high islands of Melanesia (e.g. Pohnpei in the Federated States of Micronesia). Consequently, the islands of Micronesia and Polynesia vary greatly in the size and extent of their lagoons and their capacity to support a diverse range of habitats and resources for fisheries and aquaculture.

1.1.2 Biogeography

There is a general reduction in marine biodiversity from west to east across the region, proportional to the distance from the centre of Indo-Pacific diversity in insular southeast Asia[3,4]. For example, the number of fish species associated with coral reefs decreases from ~ 1600 in PNG to 600 in French Polynesia[5]. The number of coral reef fish species used for subsistence and livelihoods also decreases from west to east[6]. There is also lower diversity of hard and soft corals[7], seagrasses[8] and mangroves[9] in the eastern Pacific than in the western Pacific.

The great biodiversity of the western tropical Pacific is recognised internationally and has resulted in high-level marine conservation initiatives in many of the countries in this area. These include the Coral Triangle Initiative[v] involving Indonesia, Malaysia, Philippines, Timor Leste, PNG and Solomon Islands, and the Micronesia Challenge[vi] underway in the Federated States of Micronesia (FSM), Guam, Marshall Islands, CNMI and Palau.

1.1.3 Ethnic and cultural diversity

The broad ethnic and cultural distinctions among the people of the tropical Pacific coincide generally with the geomorphological differences between the islands. Melanesians inhabit the larger high islands in the southwest of the region, while Micronesians occupy the smaller islands to the north and Polynesians the islands to the east (**Figure 1.1**). However, there is some integration between regions, particularly in Fiji where Melanesia meets Polynesia. Somewhat unusual exceptions are the Polynesian communities on the small outlying islands of Melanesia. Many of these Polynesian communities were established relatively recently by secondary or tertiary migration from east to west, following a primary wave of migration from west to east that populated Polynesia[10].

[v] www.cti-secretariat.net

[vi] www.micronesiachallenge.org

Figure 1.3 'Atolls' in varying stages of evolution; (a) a geologically-recent volcanic peak surrounded by a narrow fringing reef (Rarotonga, Cook Islands) (Photo: Ewan Smith); (b) a partially subsided peak surrounded by a lagoon (Bora Bora, French Polynesia) (Photo: Jerry Lew); and (c) a ring reef around a completely submerged peak (Majuro, Marshall Islands) (Photo: Greg Vaughn).

The time since first settlement declines from west to east across the region[10]. In PNG, human habitation is measured in tens of thousands of years, and agriculture appears to have developed there at about the same time as in the Middle East[11]. Towards the east, settlement is more recent. Fiji has archaeological sites dating back thousands of years and still has oral legends about the 'first landing'. Some Polynesian island cultures record their history in terms of hundreds of years.

The migrations out of Polynesia were possibly due as much to the inability of small-island ecosystems to support large human populations as they were to social causes[12]. Indeed, there is sporadic evidence of depletions or local extinctions of species known to be vulnerable to exploitation, such as some species of giant clams in Fiji[13].

A consequence of the large differences in availability of land across the region (**Table 1.1**) is that Micronesians and Polynesians generally have a strong affinity with the sea and fishing, whereas most Melanesians have a stronger culture of using agricultural methods to produce food. This is reflected in the generally lower fish consumption per person in PNG, Vanuatu and New Caledonia[1,14,15].

Table 1.1 Land and exclusive economic zone (EEZ) areas for each of the 22 Pacific Island countries and territories (PICTs).

PICT	Land area (km²)	Area of EEZ* (km²)	Ratio land/sea (%)
Melanesia			
Fiji	18,272	1,229,728	1.464
New Caledonia	19,100	1,111,900	1.689
PNG	462,243	2,446,757	15.890
Solomon Islands	27,556	1,553,444	1.743
Vanuatu	11,880	668,220	1.747
Micronesia			
FSM	700	2,939,300	0.024
Guam	541	214,059	0.252
Kiribati	810	3,550,000	0.023
Marshall Islands	112	2,004,888	0.006
Nauru	21	293,079	0.007
CNMI	478	752,922	0.063
Palau	494	605,506	0.082
Polynesia			
American Samoa	197	434,503	0.045
Cook Islands	240	1,947,760	0.012
French Polynesia	3521	4,200,000	0.084
Niue	259	296,941	0.087
Pitcairn Islands	5	800,000	0.001
Samoa	2935	110,365	2.590
Tokelau	10	318,990	0.003
Tonga	699	676,401	0.103
Tuvalu	26	719,174	0.004
Wallis and Futuna	255	242,445	0.105
Total (average)	**550,354**	**27,116,382**	**(2.03)**

* The area between the territorial/archipelagic sea boundary and 200 nautical miles from the base points. This area denotes the 'Fisheries Zone' where a country does not have an EEZ.

1.2 Demography

Like most developing regions around the world, the populations of many Pacific Island countries and territories are increasing. In 2010, the total population of all PICTs combined was estimated to be 9.9 million people, and is projected to rise by ~ 50% to ~ 15 million in 2035 (**Table 1.2**).

Most of the region's population is concentrated in Melanesia, which also has higher population growth rates in general[16]. PNG alone accounted for 69% of the regional population in 2010 and is predicted to contribute 79% of the population growth by 2035 (**Table 1.2**). This overall outlook hides two important demographic trends. Firstly, some of the smallest countries and territories (Cook Islands, Nauru, Niue, Pitcairn Islands, Tokelau, Tuvalu) have experienced a population decline in recent years due to emigration. Secondly, there is rapid urbanisation throughout the region. This widespread urbanisation is a result of migration from outer islands and rural areas within larger countries to the main population centres. PNG provides a particularly potent example – urban populations there are predicted to increase by 180% by 2035, compared to a total population increase of 60%[16].

1.3 Nature of local economies and limitations to economic development

The economies of PICTs are diverse, but all are characterised by the advantages and constraints typical of oceanic islands, particularly the effect of geographic isolation[17]. Tourism plays the major role in some economies, including those of Cook Islands, Fiji, French Polynesia, Guam, CNMI and Palau. Other countries and territories in Melanesia and Nauru have derived economic benefits from forestry, agriculture and/or mineral resources. Several of the smaller island nations are heavily dependent on remittances from family members working overseas. But in almost all PICTs, fisheries play a much larger role in the economy than in most other countries[1,15].

Oceanic fisheries are the only natural resources that PICTs have which are not limited by the small sizes of their islands. Geographic isolation has also helped protect Pacific island fisheries from the overexploitation afflicting many stocks elsewhere in the world[18]. The potential to develop the tropical Pacific tuna fishery within the limits set by regional and international agreements is of great interest to several PICTs. In particular, the transfer of capacity from distant water fishing nations (DWFNs) to Pacific Island countries holds the promise of substantial, sustainable economic returns.

There are, however, constraints to the onshore development of the processing facilities needed to domesticate the benefits of oceanic fisheries in the smaller countries. These constraints include limited freshwater supplies, high freight charges, relatively high wage rates compared to Southeast Asia and the limited capacity of the environment and society to absorb such large-scale operations.

Table 1.2 Population estimates for the 22 Pacific Island countries and territories (PICTs) for 2010, with projections to 2020 and 2035[16], based on the 2010 assessments. See www.spc.int/sdp for ongoing adjustments to population estimates and projections for each PICT.

PICT	Mid-year population estimate		
	2010	2020	2035
Melanesia	**8,654,200**	**10,465,000**	**13,492,371**
Fiji	847,800	890,400	977,600
New Caledonia	252,300	291,200	322,538
PNG	6,752,700	8,267,400	10,822,300
Solomon Islands	549,600	703,500	969,900
Vanuatu	251,800	312,500	400,033
Micronesia	**538,800**	**607,700**	**676,300**
FSM	102,400	100,000	105,300
Guam	187,100	224,200	250,400
Kiribati	100,800	119,900	144,600
Marshall Islands	54,400	59,500	62,700
Nauru	10,000	12,000	14,400
CNMI	63,100	70,300	76,200
Palau	20,500	21,800	22,700
Polynesia	**663,800**	**710,800**	**780,800**
American Samoa	65,900	74,600	87,300
Cook Islands	15,700	16,400	16,900
French Polynesia	268,800	297,600	330,800
Niue	1500	1200	1200
Pitcairn Islands	*	*	*
Samoa	183,100	188,400	202,000
Tokelau	1200	1200	1200
Tonga	103,400	106,500	115,000
Tuvalu	11,100	11,800	12,800
Wallis and Futuna	13,100	13,100	13,600
Total	**9,856,300**	**11,783,500**	**14,949,471**

* Population for Pitcairn Islands not estimated (currently 66).

Forest resources in Melanesia do not have the same sustainable development potential – they have long renewal times relative to current exploitation rates. Indeed, the remaining lifetime of logging industries in Solomon Islands is estimated to be less than five years[19]. Terrestrial mineral deposits promise to generate wealth in the region but in Nauru primary phosphate reserves have already been exhausted. On the other hand, tourism has significant economic potential. However, this potential will depend largely on the way tourists perceive the health of the marine environment.

1.3.1 Exclusive economic zones

The United Nations Convention on the Law of the Sea (UNCLOS) increased the potential for economic development and government revenue for all PICTs by allowing them to declare national exclusive economic zones (EEZs) of up to 200 nautical miles from national territorial sea baselines (territorial seas extend 12 nautical miles from these baselines in most PICTs). UNCLOS provided international recognition of the vast areas over which Pacific Island states could exercise sovereign rights (**Table 1.1**) to exploit, manage and conserve resources found in the surrounding waters and on the ocean floor.

As well as providing opportunities, sovereign rights over EEZs also carry the responsibility for conservation and management of resources. In this regard, Pacific Island countries have a long history of regional cooperation, particularly in managing shared highly migratory stocks of tuna and associated species. The Pacific Islands Forum Fisheries Agency (FFA)[vii] was set up in 1978 for the specific purpose of allowing the members to cooperate in the management of these highly migratory fish stocks within their EEZs (Section 1.5). The establishment of the Western and Central Pacific Fisheries Commission (WCPFC)[viii] in 2004 enables PICTs to cooperate with other states for the conservation and management of tuna resources and associated species in tropical Pacific high seas. The WCPFC also allows PICTs to impose an overall limit on the fishing of tuna across the entire distribution of the stocks, not just in their EEZs.

UNCLOS also conveys other rights and responsibilities, including the assessment of resources. Regional cooperation in fisheries science is supported by the Fisheries, Aquaculture and Marine Environment Division (FAME) of the Secretariat of the Pacific Community (SPC), which provides PICTs with the scientific expertise and research required to understand the size and status of oceanic fisheries in the western and central Pacific. FAME also provides technical assistance for the development and management of coastal fisheries and aquaculture.

Surveys of seabed minerals and the delimitation of EEZs are coordinated through the Applied Geoscience and Technology Division of SPC (SOPAC), and regional cooperation in the protection and preservation of the marine environment is coordinated by the Secretariat of the Pacific Regional Environment Programme (SPREP).

[vii] Members of FFA are: Cook Islands, Federated States of Micronesia, Fiji, Kiribati, Marshall Islands, Nauru, Niue, Palau, Papua New Guinea, Samoa, Solomon Islands, Tokelau, Tonga, Tuvalu, Vanuatu, together with Australia and New Zealand.

[viii] Members of WCPFC and participating territories include Australia, Canada, China, Cook Islands, European Union, Federated States of Micronesia, Fiji, France, Japan, Kiribati, Korea, Marshall Islands, Nauru, New Zealand, Niue, Palau, Papua New Guinea, Philippines, Samoa, Solomon Islands, Taiwan/ROC, Tonga, Tuvalu, United States of America and Vanuatu.

1.4 Importance of fisheries to the people of the tropical Pacific

'Tuna fisheries are the wealth of small island nations in the Pacific; reef fisheries are their food'. These two phrases have been heard so many times over the past 20 years that they have lost their immediacy. Nevertheless, they still hold a great deal of truth even though the reality may be more complex. For example, in much of Melanesia, economic development and government revenue are based mostly on forestry or mining, and the people are more dependent on agriculture than fishing for their subsistence. This is particularly true for inland PNG[20]. In some small islands, tourism is the main source of income and tuna provide more local food than reef fish.

But whatever the details and exceptions, many PICTs are heavily dependent on their fisheries resources for economic development, government revenue, food security and livelihoods, and are vulnerable to any change in the status of these resources. For these reasons, three main questions frame national aspirations and plans for the sustainable use of fish (1) How can oceanic (tuna) fisheries best contribute to economic development and government revenue? (2) How much fish will be needed for future food security? and (3) How many livelihoods can be based on the sustainable use of fisheries resources?

1.4.1 Economic development and government revenue

The future potential for economic development and government revenue within the fisheries sector is dominated by the harvesting of oceanic fish, particularly tuna (**Figure 1.4**). For the purposes of this book, we use the usual broad definition of economic development as 'an increase in the production levels of goods and services, resulting in a greater real gross domestic product (GDP)'. However, we also highlight the contribution of fisheries to government revenue, given the high proportion of such revenue derived from tuna in several PICTs[1].

Photo: Bruno Leroy

Fishing for tuna in Solomon Islands

The annual production from oceanic fisheries in PICTs, based on data for industrial fleets that target four species of tuna (skipjack, yellowfin, bigeye and albacore), is ~ 10 times greater than production derived from coastal fisheries. An accurate comparison is difficult, however, because data on production from the region's coastal fisheries are still quite poor[1] and industrial tuna catches are normally aggregated for the whole WCPO Convention area, which is larger than the region under the jurisdiction of PICTs.

In 2009, the total landings of tuna in the WCPO Convention area were almost 2,468,000 tonnes (**Table 1.3**). The majority of the catch was skipjack tuna and most of the fish were caught by purse-seine vessels (**Table 1.3**). The 2009 catch from the WCPO represented 58% of total world tuna landings and, based on the average for 2005–2009, 48% of the catch in the WCPO was taken from the EEZs of PICTs.

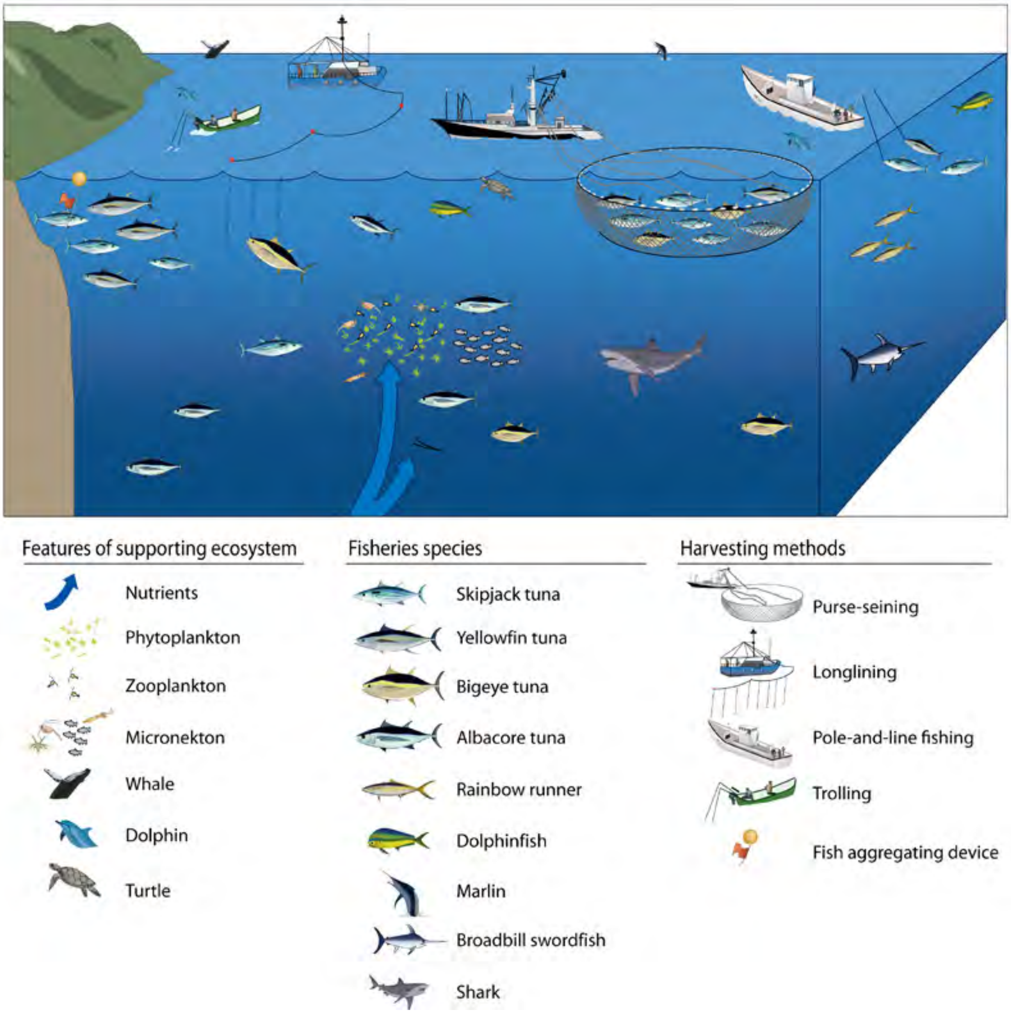

Figure 1.4 The basis of tuna production in the Western and Central Pacific Ocean, and the main methods used to harvest tuna.

The main contribution of tuna fisheries to government revenues within the region comes from a combination of access fees paid by vessels from DWFNs, transshipping fees, export duties and taxes. The broader contribution to economic development in a number of countries comes from Pacific island-owned or joint-venture industrial fishing operations, onshore processing plants, and the employment created. These enterprises also contribute to government revenue, although many benefit from tax concessions.

Access fees have historically provided the most stable of these benefits. Currently, they contribute ~ USD 80 million per year to the region[1]. In the case of FSM, Tuvalu, Tokelau, Nauru and Kiribati, these fees provide ~ 10–40% of annual government revenue[1]. Although access fees contribute less to national economies per tonne of catch than domestic fishing or processing operations, they avoid many of the risks of such investment. Nevertheless, access fees fluctuate due to market forces and the uncertainty associated with the way large-scale climate events influence the availability of tuna within different EEZs.

The best-known of these climate events is the influence of the El Niño-Southern Oscillation (ENSO) on purse-seine fisheries near the equator. Under La Niña conditions, the Western Pacific Warm Pool (Warm Pool), where 80% of purse-seined tuna are caught, becomes more confined towards the west of the basin (**Figure 1.5**), and these fishing operations are concentrated in PNG's waters. During El Niño episodes, the Warm Pool spreads eastwards and purse-seine catch rates in Kiribati's EEZ increase[21].

Table 1.3 Total catch and estimated landed value of the four species of tuna, and main fishing methods, for the Western and Central Pacific Ocean (WCPO) Convention area in 2009. Note that 48% of the catch is estimated to have come from the EEZs of Pacific Island countries and territories (source: SPC Oceanic Fisheries Programme).

Species	**Catch (tonnes)**	**Value (USD x 1000)**
Skipjack	1,789,979	2,193,000
Yellowfin	433,788	1,023,000
Bigeye	118,657	650,000
Albacore	125,479	320,000
Total	**2,467,903**	**4,186,000**
Fishing method		
Purse-seine	1,894,500	2,354,000
Longline	223,792	1,296,000
Pole-and-line	165,814	344,000
Other	183,797	192,000
Total	**2,467,903**	**4,186,000**

Pacific island-owned fishing operations have a history of variable success. Competition with more industrialised countries, or those with lower labour, transport and infrastructure costs, is intense. Also, many Pacific island enterprises have been unable to attract private investment and have had to be financed or managed by government. Nevertheless, local operations have produced substantial economic benefits in some island nations. For example, a large percentage of the tuna unloaded from vessels fishing in the region now passes through FSM, Kiribati, Marshall Islands and Solomon Islands. Successful tuna loining and canning operations have also been established in American Samoa, Fiji, Marshall Islands, PNG and Solomon Islands[1,15].

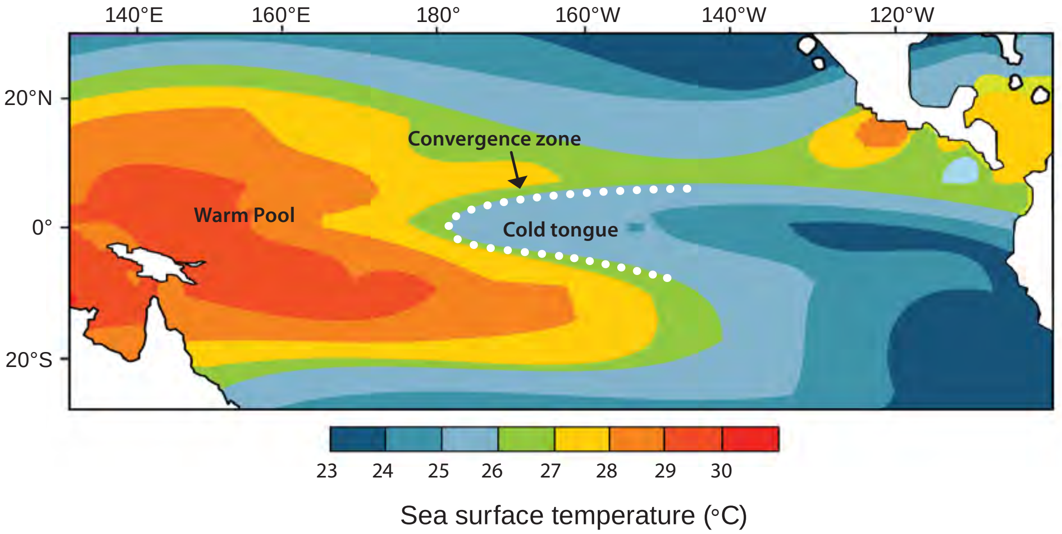

Figure 1.5 Position of the Warm Pool in the western Pacific under La Niña conditions, and the convergence zone where the Warm Pool meets nutrient-enriched waters of the eastern equatorial Pacific. Tuna and their prey are most abundant in this convergence zone[21,48] (source: HadISST)[109].

In 2009, the total value of all fish landed by locally-based offshore fleets in PICTs was more than USD 600 million[1], compared to the total value of ~ USD 4.2 billion from the entire WCPO (**Table 1.3**). Due to the relatively low percentage value added by industrial tuna operations (compared to small-scale coastal fisheries), the combined contribution of catches from locally-based fleets to the GDP of PICTs is estimated to be ~ USD 200 million per year[1]. A key challenge for the region is to develop the optimum mix of domestic and distant water fishing operations to increase these returns on a sustainable basis.

Aquaculture contributes to the economies of Cook Islands, French Polynesia and New Caledonia, and their governments receive revenue from income taxes of people employed in the sector and from other charges. For many years, French Polynesia imposed a tax on the export of pearls. Other governments, e.g. Solomon Islands, have also benefitted in a modest way from export duties on commodities such as bêche-de-mer, trochus, finfish, aquarium products and seaweed.

1.4.2 Food security

Food security means that all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food to meet their dietary needs and preferences for an active and healthy life[ix].

In the tropical Pacific, fish[x] is a cornerstone of food security[14,22,23]. The average annual consumption of fish (including shellfish) by coastal rural populations ranges from 30–118 kg per person in Melanesia, 62–115 kg in Micronesia, and 50–146 kg in Polynesia[14]. Even in urban centres, fish consumption usually greatly exceeds the global average of 16–18 kg per person per year[14,18,24].

Most of the fish used for food in the region comes from subsistence fishing in coastal waters (**Figure 1.6**, **Table 1.4**), particularly around coral reefs[12,14]. However, in some of the larger islands, particularly in inland PNG, freshwater fisheries (**Figure 1.7**) also contribute to food security.

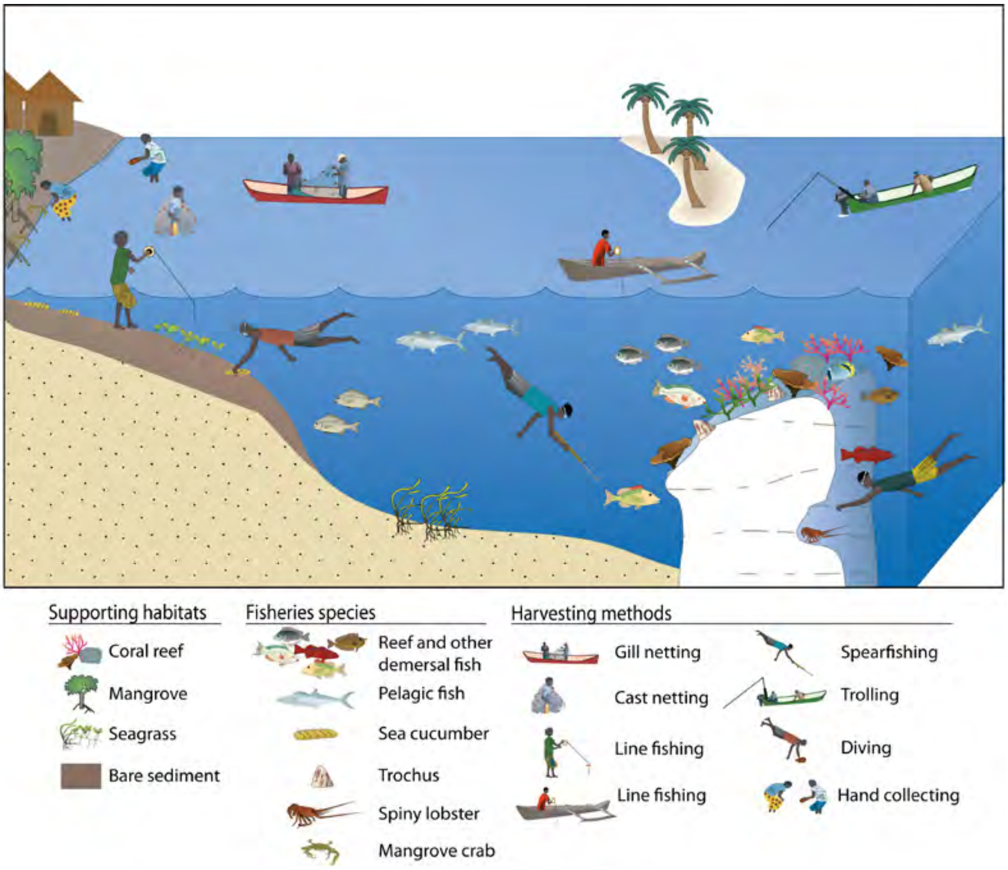

Figure 1.6 The range of coastal fisheries activities in the tropical Pacific, and the habitats that support them.

[ix] World Food Summit (1996) www.ipu.org/splz-e/food.htm

[x] Fish is used here in the broad sense to include fish and invertebrates.

Table 1.4 Estimates of catch, and landed value, for subsistence and commercial coastal fisheries in Melanesia, Micronesia and Polynesia in 2007[1].

Subregion	Type of coastal fishery			
	Subsistence		Commercial	
	Catch (tonnes)	Value (USD)	Catch (tonnes)	Value (USD)
Melanesia	68,730	101,776,365	20,338	74,950,795
Micronesia	28,290	52,636,474	12,090	33,775,731
Polynesia	12,913	45,954,124	12,361	56,964,478
Total	**109,933**	**200,366,963**	**44,789**	**165,691,004**

Serious concerns are now being raised about the capacity of coastal fisheries to supply the fish needed for food security by the region's rapidly growing populations. Another 115,000 tonnes of fish (a 47% increase) will be needed to help provide good nutrition for the expanding population of the region by 2030 (**Figure 1.8**).

These concerns arise because preliminary analysis indicates that by 2030 coastal fisheries will supply the nutritional demands for fish in only a minority of the 22 PICTs[14]. The main problems are that the reef area available to support fisheries in many countries and territories does not have the capacity to produce the fish required

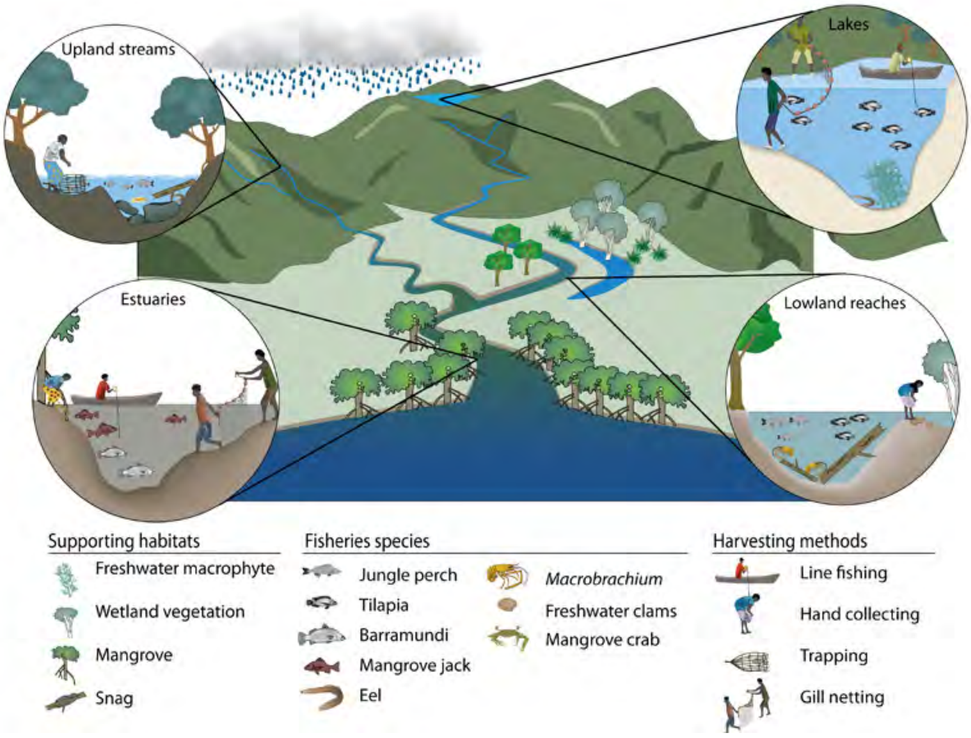

Figure 1.7 Range of freshwater and estuarine fisheries in the tropical Pacific, and the habitats that support these fisheries.

to maintain current levels of fish consumption into the future, and that other sources of protein for a healthy diet will not be readily available. In other places, there are fears that overexploitation has already reduced the productivity of coastal fisheries substantially, and that it may be difficult to restore stocks to more productive levels given the high dependence on reef fish for food and livelihoods.

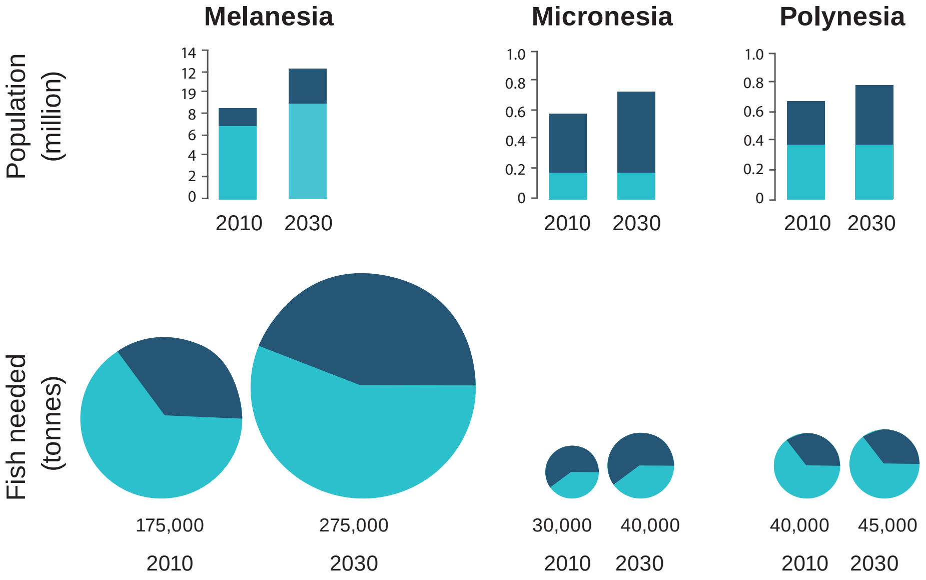

Figure 1.8 Forecasts of population growth, and the fish needed for food security in rural (■) and urban (■) areas of Melanesia, Micronesia and Polynesia in 2030 (source: SPC).

SPC's Coastal Fisheries Programme recently surveyed fish populations associated with coral reefs in 17 PICTs. Their findings showed great variation in the productivity of sites and the status of coral reef fisheries across the region[6]. The challenge is to improve the management of coastal fisheries in PICTs so that they fulfill their potential to contribute to future food security[14].

There can be no doubt, however, that additional sources of fish are required to meet the growing need for high-quality dietary protein in the majority of PICTs. The region is fortunate that there are at least two options for increasing the supply of fish in many places.

First, allocating a relatively small proportion of the rich tuna resources of the tropical Pacific for food would go a long way to filling the emerging gap between the amount of fish required for food security and the fish available from coastal fisheries. The challenge is how to distribute this proportion of the tuna resources among coastal communities and the urban poor, where it is needed most, and how to make it socio-economically feasible for these communities to access the fish[14,23,25].

A second option involves progressive development of small pond aquaculture[14,25], particularly in Melanesia, where the availability of fresh water and widespread acceptance of tilapia as a food fish provide the basis for such production systems. Although development of small pond aquaculture has yet to become economically sustainable in many areas, this option has longer-term potential to supply substantial quantities of fish for household nutrition. For example, culture of Nile tilapia in ponds of 450–500 m^2 in Fiji can yield up to 500 kg of fish every 4–5 months, equivalent to ~ 25 tonnes per ha per year[14].

Small pond aquaculture also promises to provide a hedge against times when it is too rough to fish at sea, as used to be the case in several Pacific island traditions before trade goods became available[26]. However, for small pond aquaculture to fulfill its potential as a well-integrated, economically viable and sustainable production system, several issues need to be overcome. These include identifying appropriate species and culture methods; reducing possible effects on freshwater biodiversity; developing cost-effective feeds based on locally available ingredients; providing incentives for investment to produce and distribute fry; and training farmers[14,27].

1.4.3 Livelihoods

Livelihood has been defined as 'the activities, assets and access that jointly determine the living gained by an individual or household'[28]. Although 'livelihood' is often used to embrace all the activities involved in making a living, including subsistence farming and fishing, we treat it more narrowly as the 'activities, assets and access needed to earn income' because the widespread involvement of people in subsistence fishing is covered under 'food security' above. Our definition also highlights the aspirations of many rural households to obtain cash where opportunities to do so are often limited but the need is increasing, driven by the 'westernisation' of the region.

Fisheries and aquaculture provide an important source of household income and part-time or full-time employment in the tropical Pacific. Throughout much of the region, people are involved in the chain supplying fish and aquaculture commodities to local and export markets. Full-time jobs have been created through development of domestic industrial tuna fleets and tuna processing operations within the region (**Figure 1.9**). For example, almost 12,000 people are employed in canneries or other tuna processing operations in American Samoa, Fiji, Marshall Islands, PNG and Solomon Islands[1]. Crewing on foreign vessels and transshipping operations at designated ports also provide employment opportunities based on tuna resources in some PICTs. Elsewhere in the region, shrimp farming (New Caledonia) and the culture of black pearls (French Polynesia, Cook Islands and Fiji) provide thousands of people with full-time or part-time work[1].

Although information on participation in coastal fisheries is generally poor throughout the region[1], artisanal and small-scale coastal fishing enterprises provide a source of income for hundreds of thousands of people. The recent socio-economic surveys by SPC's Coastal Fisheries Programme demonstrated that an average of 47% of coastal households, across 17 PICTs, earned their first or second income from selling the fish and shellfish they catch. These enterprises are based on (1) selling catch surplus to subsistence needs to local markets or urban centres; (2) exporting high-value invertebrates such as sea cucumber, trochus and spiny lobster, and high-value finfish such as deepwater snapper, to export markets; and (3) supplying a wide range of wild-caught fish and invertebrates to the tropical marine ornamental trade.

Figure 1.9 (a) Processing tuna for export in Fiji (photo: Peter Sharples); (b) crew on a tuna longline vessel in Cook Islands (photo: Steve Beverly).

Aquaculture of marine ornamental commodities (e.g. 'live rock', giant clams and corals) and seaweed farming (**Figure 1.10**) also provide opportunities to earn income in several countries. In most cases, the artisanal and small-scale fisheries and aquaculture operations do not provide full-time employment for many people. Instead, they help diversify the income earned by households.

Several PICTs, particularly in Melanesia[29], are looking to fisheries and aquaculture to provide more livelihoods for their rapidly growing populations. In many cases, this will be a challenge. Tuna processing plants face competition from operations in Asia, the productivity of coastal fisheries is naturally relatively low and already damaged due to overfishing in some places, and the remoteness of many PICTs limits the potential to develop competitive aquaculture operations for fresh seafood export commodities.

1.5 Arrangements to optimise the benefits of fisheries for the region

Pacific Island governments are well aware of the importance of their fisheries and have invested considerable effort in regional cooperation to maximise the sustainable benefits. Most of this cooperation is focused through (1) SPC, which provides scientific support for management of fisheries at both national and regional levels (Section 1.3.1); (2) FFA, which assists countries with national tuna fishery management and development, as well as administering various regional tuna fishery agreements; and (3) the Office of the Parties to the Nauru Agreement (PNA)[xi], established to provide of focal point for optimising the benefits from the purse-seine fishery for PNA members.

[xi] PNA members: Federated States of Micronesia, Kiribati, Marshall Islands, Nauru, Palau, Papua New Guinea, Solomon Islands and Tuvalu. www.pnatuna.com

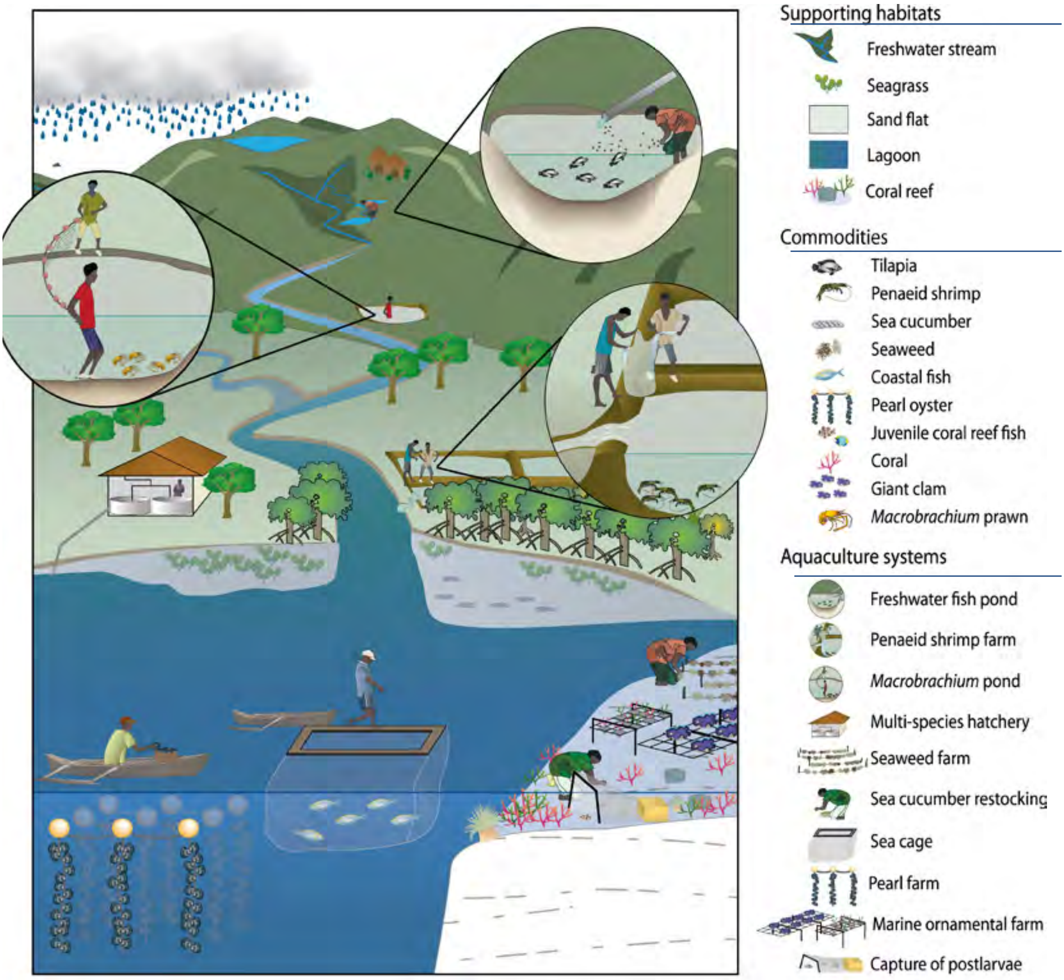

Figure 1.10 The range of aquaculture commodities in the tropical Pacific, and the habitats that support them.

Examples of the cooperative regional management arrangements are the recent measures by the PNA to limit and monitor catches of purse-seine vessels licensed to fish in their EEZs. These measures were introduced in response to scientific advice that fishing mortality for bigeye tuna in the WCPO needed to be reduced by 30%, and by 10% for yellowfin tuna, to avoid the possibility of these stocks becoming overfished. They include a ban on fishing around drifting fish aggregating devices (FADs) for several months each year and a fishing closure for the high seas pockets adjacent to their EEZs (**Figure 1.1**). PNA members also prohibited discarding of undersized tuna at sea, directed that all purse-seine vessels must have fishery observers on board, and established fishing effort schemes.

Pacific Island countries negotiate with DWFNs to identify suitable bilateral and multilateral licensing arrangements. The countries also engage with DWFNs and adjacent coastal states such as the Philippines and Indonesia through the Western and Central Pacific Fisheries Commission. This regional fisheries management organisation administers the Convention for the Conservation and Management of Highly Migratory Fish Stocks in the Western and Central Pacific Ocean.

In addition to these regional fisheries arrangements, various agencies and countries provide bilateral assistance to PICTs for the development of fisheries and aquaculture, management and capacity building. These agencies include the Food and Agriculture Organization of the United Nations (FAO), the University of the South Pacific and the WorldFish Center. The countries include Australia, China, members of the European Union, Japan, Korea, New Zealand, Taiwan/ROC and USA.

Although management of the tuna fishery is the most active expression of regional cooperation in fisheries, several other regional instruments have been developed to move the rest of the sector forward in an efficient and responsible way. The most important of these is the Pacific Plan[30], and the ensuing Vava'u Declaration on Sustainable Fisheries issued by the Pacific Islands Forum[31]. The Vava'u Declaration recognises the importance of well-managed fisheries to the countries of the region and includes commitments to:

- 'domesticate' tuna fisheries by increasing the involvement of Pacific Island countries in the catching, processing and trading subsectors, rather than focusing mainly on optimising access revenues;
- promote food security, sustainable livelihoods and economic growth through the development and management of coastal fisheries and aquaculture;
- strengthen solidarity among Pacific Island countries in applying a regionally harmonised approach to the management of tuna fisheries; and
- protect high seas biodiversity and develop conservation and management measures for fish stocks in the Pacific Ocean that are not highly migratory.

Relevant elements of the Vava'u Declaration were also welcomed by the 5th Conference of the Pacific Community in 2007[25]. Collectively, Pacific Community members called for a long-term strategic approach to fisheries in the region. FFA and SPC took up this challenge and commissioned 'The Future of Pacific Island Fisheries' study to identify the most appropriate range of fisheries interventions to optimise outcomes over the next 25 years. The study focused on:

- assessing trends in the sustainability of production from oceanic, coastal and freshwater fisheries, and aquaculture;
- identifying the key drivers of fisheries and aquaculture at local, national, regional and international levels, and possible scenarios for the status of fisheries and aquaculture in the region in 2035;

- harmonising the use of the various sources of fisheries production and aquaculture to optimise economic development and government revenue, food security and livelihoods; and
- informing national and regional agencies about the policies, management measures and collaborative arrangements needed to deliver sustainable supplies of fish.

Many of the national and regional scientific, managerial and monitoring activities needed to implement the Vava'u Declaration have already been developed (**Table 1.5**). However, there is a need to prioritise and integrate these activities to help fulfill the aspirations of Pacific leaders. The results of 'The Future of Pacific Island Fisheries'[xii] study now provide a roadmap for this process.

Table 1.5 Science, management and monitoring currently underway in the tropical Pacific region to help optimise benefits from fisheries resources.

Regional strategy/Management measure	Responsible agency
Science	
Regular scientific assessments of the status of tuna stocks and their supporting ecosystem[99], and occasional scientific assessments of non-tuna fisheries	SPC
Tuna tagging programme[99]	SPC
Management plans and action	
Regional Tuna Fisheries Management and Development Strategy – a regional agreement on a set of shared principles for the management and development of tuna fisheries by FFA member countries[100]	FFA
Implementation of effort quotas, and other subregionally agreed management measures for tuna, by Parties to the Nauru Agreement (PNA) on vessels fishing within their EEZs[101], and the Te Vaka Moana Arrangement (TVMA) for limits on longline fishing in the EEZs of Polynesian countries	PNA, TVMA
National tuna fishery development plans, incorporating regionally agreed standards, domestication of fisheries operating in their zones, and mechanisms to implement ecosystem approaches to fisheries[102]	FFA
Definition of a Western Tropical Pacific Insular Area (WTPIA) that could form part of the emerging South Pacific Regional Fisheries Management Convention area	FFA
The Apia Policy – regional agreement on best-practice strategies to improve the management of coastal fisheries[103]	SPC
Aquaculture Action Plan[27]	SPC
Monitoring	
Monitoring, Control, Surveillance (MCS) strategy for the tuna fishery[104]	FFA
Regional, subregional and national observer programme for industrial tuna fisheries[105]	FFA/SPC, WCPFC

[xii] www.spc.int/fame/doc/corporate_docs/Future_of_PI_fisheries_Report.pdf

1.6 Threats to fisheries benefits from climate change

The plans outlined above to optimise the benefits of fisheries for PICTs will not only have to contend with the various forces driving the sector, such as rapid population growth, market demand, fuel costs, and the need to develop an ecosystem approach, they will also have to be adapted to a changing climate. The effects of climate change on fisheries are already apparent elsewhere in the world. Here, we briefly summarise why and how the climate in the tropical Pacific is expected to change, and outline some of the likely effects on fisheries and aquaculture in the region.

1.6.1 The changing climate

The build-up of greenhouse gases in the atmosphere is acting in two major ways that are ultimately expected to affect fisheries and aquaculture in the tropical Pacific. First, the accumulation of greenhouse gases is trapping more of the heat that would normally escape from the Earth, leading to an overall increase in global surface temperature[32]. The oceans have absorbed almost 80% of the additional heat, acting as a buffer against more rapid atmospheric warming. However, the continued uptake of this extra heat has wide-ranging implications for marine resources[33] (**Figure 1.11**). Thermal expansion of the ocean, together with melting of land ice, is resulting in rising sea levels. Increases in ocean temperatures are also changing the strength and direction of currents, and making surface waters more stable, reducing vertical mixing and the availability of nutrients in the upper layer of the ocean. Reductions in the supply of nutrients usually limit the primary production at the base of the food chains that support fisheries.

Warmer oceans also cause changes in atmospheric circulation patterns, giving rise to regional changes in climate. In the tropical Pacific, greater evaporation and moisture availability are expected, leading to an intensification of the hydrological cycle, and a poleward expansion and possible slow down of the Hadley circulation[34,35]. As a result, rainfall is projected to increase in tropical areas of the Pacific and decrease in subtropical areas, although there is still considerable uncertainty about the regional pattern of projected changes. There is also the possibility that warmer conditions may result in more intense cyclones and storms, resulting in rougher seas, more powerful waves and greater physical disturbance of coastal environments[xiii].

The second way that increasing greenhouse gases are expected to affect fisheries and aquaculture is through changes to oceanic concentrations of CO_2 and the resulting effect on ocean acidity. The ocean has absorbed more than 30% of human CO_2 emissions since the beginning of the industrial revolution and it is now more acidic than at any time during the last 800,000 years[36,37]. This effect is largely independent of global warming but also has grave consequences for marine ecosystems. The

[xiii] Chapters 2 and 3 provide details on projected changes to surface climate and the physical and chemical nature of the ocean.

dissolved CO_2 reacts with sea water to form weak carbonic acid, which reduces the availability of dissolved carbonate required by many marine calcifying organisms to build their shells or skeletons[33,38,39].

There is serious concern that continued emissions of CO_2 will drive sufficient gas into the sea to cause under-saturation of carbonate in some areas of the ocean this century[40,41]. Where this happens, the environment will favour dissolution rather than formation of carbonate shells and skeletons[42,43].

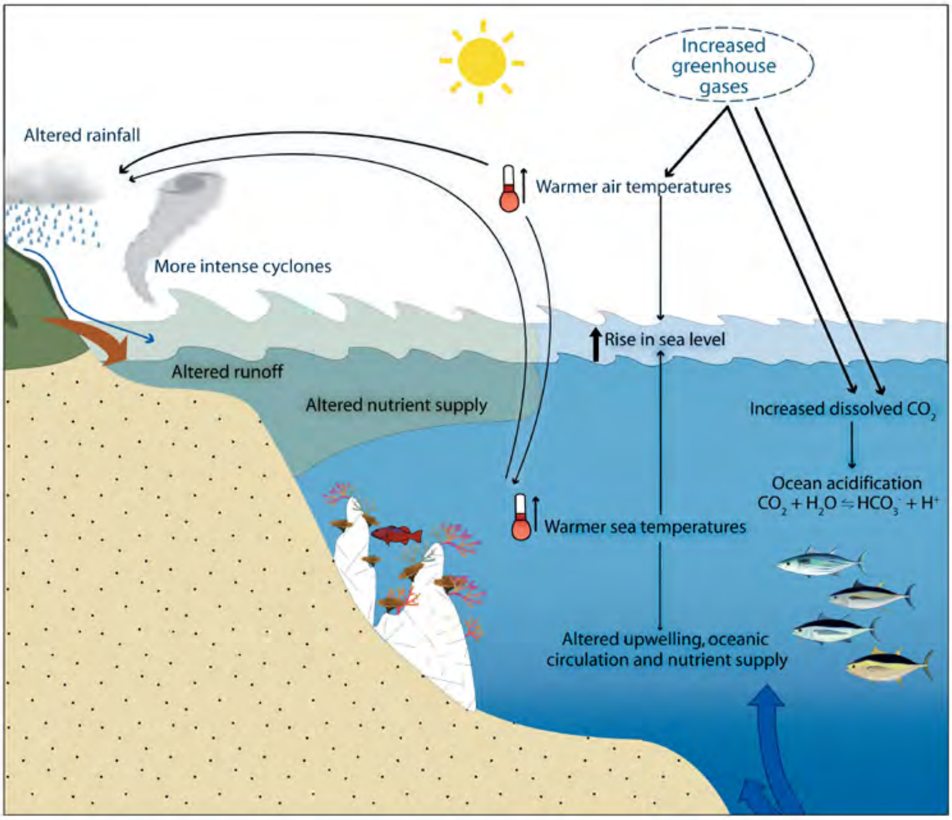

Figure 1.11 Generalised effects of increased greenhouse gases on oceanic and coastal ecosystems in the tropical Pacific.

1.6.2 Nature of effects of climate change on fisheries and aquaculture worldwide

Although investment in assessing the likely effects of climate change on the productivity of fisheries and aquaculture has been modest compared to that for agriculture, there is much concern worldwide about the effects of future climate changes on the sector[44,45]. We already know that variations in climate on time scales of years to decades can cause significant changes in fisheries production. For example, catches of Peruvian anchovies have varied between < 100,000 tonnes and > 13 million tonnes since 1970 as a result of changes in ENSO[46,47]. The different phases of the ENSO cycle also determine the distribution of skipjack tuna in the Western and Central Pacific Ocean – the fish move further east during El Niño events and further west during La Niña episodes[21,48] (Section 1.4.1).

Over and above normal year-to-year variations, longer-term changes in physical oceanography and biology, known as regime shifts, can have major consequences for the species composition and productivity of fisheries[46,49]. Some heavily fished stocks have collapsed due to the additive effects of environmental and fishing stresses[50,51]. However, the effects of such changes in climate have not always been negative. For example, a period of ocean warming around Greenland starting in 1925 resulted in a northern extension in the range of cod by > 1000 km and the creation of an international fishery of up to > 400,000 tonnes per year[46].

Questions abound for fisheries management. Will the species that currently support substantial harvests still be available as climate change continues? If not, which types of species are most likely to replace them? For those species that continue to support fisheries, will climate change reduce the capacity for replenishment and production, and increase the risk of overfishing? How should managers and policymakers respond to the projected changes to maintain sustainable benefits from fisheries? How will fishers perceive and react to the risks associated with projected changes? Will fishing at sea become more hazardous? How much will it cost to adapt?

In some parts of the world, a concerted effort is being made to answer such questions. Numerous studies have documented how the observed and projected changes to the atmosphere and oceans are directly and indirectly affecting, or likely to affect, the distribution and production of fish, and the fisheries that depend on them[33,45,46,52–58,xiv].

1.6.2.1 Effects on distribution of fish

Climate-induced changes to water temperature, currents and the depth of the surface mixed layer are having significant effects on the distribution of both oceanic and coastal fish. In particular, changes in water temperature have a direct effect on the distribution of fish because each species is adapted to complete its life cycle within a specific temperature range.

On the grounds of thermal tolerances and preferences alone, many studies have now documented or projected (1) expanded distributions of warm-water fish species towards the poles[53,59,60], (2) contracted distributions of species adapted to cooler waters[61,62], (3) latitudinal shifts in areas where species occur[53,55,56], (4) increased depth range of some species[63], and (5) increases in local diversity of species[64].

[xiv] See also papers in ICES Journal of Marine Science Volume 68(6) and www.pices.int/meetings/international_symposia/2010/cc_effects_fish

Other effects of climate change are also altering the patterns of fish distribution. These include (1) expansion of oceanic nutrient-poor zones[65], which fish avoid in their search for food; (2) occurrence of key species of phytoplankton and zooplankton at increasingly higher latitudes[66–68], which help support the food chain for oceanic fish in areas where it was previously inadequate; and (3) changes in the strength of currents, which affect the dispersal of fish larvae and consequently the areas of habitat that may or may not be replenished[56].

1.6.2.2 Effects on production of fish

Climate change can be expected to mediate fish production through effects on reproductive success, recruitment processes, survival and growth. These effects can occur both directly due to changes in the atmosphere and oceans and/or indirectly through the influence of climate change on the habitats that support fish[46].

Reproduction of fish is often highly sensitive to fluctuations in temperature[56]. Therefore, warming seas could have either a positive or negative effect on egg production and the timing and location of egg release, depending on whether the fish species is living where the temperature is close to its thermal optimum for reproduction. Total lifetime egg production could be enhanced if species reach maturity at a younger age and spawn over a longer period each year due to earlier onset of spawning. Egg production will be reduced where peak seasonal water temperatures inhibit species that normally reproduce year-round, and where higher temperatures cause mortality of eggs. Increases in ocean acidity can also reduce fertilisation success in some species[33,69,70].

The supply of juveniles available to replenish populations, varies greatly between years and locations for many species of fish and invertebrates. This variation occurs because the developing larvae have to survive a series of bottlenecks; in particular, they need to find sufficient planktonic food, encounter currents that help them reach suitable habitats, and avoid predators[71–73]. The great natural variation in abundance of juveniles resulting from the vagaries of larval life is projected to become even more extreme under climate change[56,58,74]. Interactions between the effects of higher water temperatures, ocean acidification, altered currents, changes to the depth of the mixed layer and disruptions to food webs on the production, dispersal and survival of larvae[33,74–78] are expected to result in new patterns of recruitment. As a result, the areas that have the potential to yield the most fish within the distribution of a species can be expected to change.

Collectively, these effects can alter the productivity of fisheries. For example, the dynamics of 12 important commercial Atlantic and Pacific fish stocks have mirrored long-term changes in air-sea temperatures and atmospheric circulation[49].

The direct effects on the distribution and abundance of fish, and the potential for replenishment, are not the only ways in which changes to the atmosphere and oceans will affect fisheries. Many components of climate change are expected to have strong indirect effects on the survival of coastal and freshwater fish species through modification to the habitats that they depend on for food and shelter. For example, the seagrasses and mangroves which provide nurseries for many coastal fish species would be vulnerable to increased rates of damage if storms and cyclones become more intense. Seagrasses and mangroves are also likely to be affected by changes in sedimentation from new patterns of rainfall, and rising sea levels[33,79]. The extent of these fish nursery areas has already been dramatically reduced worldwide through the impacts of development in the coastal zone[80–82]. The concern is that synergies between the effects of climate change and localised non-climate stressors will exacerbate loss of habitats[54,58].

Of particular concern to coastal fisheries in the tropical Pacific are the indirect effects of climate change on fisheries caused by degradation of coral reefs[38,83]. Survival of fish that depend on coral reefs and their associated communities for food and shelter is expected to decline as reefs become progressively degraded through the combined effects of (1) more frequent bleaching, (2) reduced capacity to grow or repair skeletons as a result of lower levels of carbonate ions in sea water, and (3) possible increased damage by more severe storms or cyclones[56,58,84,85]. Degraded coral reefs and populations of associated fish and invertebrates are also expected to provide fewer opportunities for aquaculture of wild-caught juveniles.

Rising sea temperatures are projected to increase the risk of marine pathogens[52,86,87], affecting the growth and survival of fish and invertebrates both directly and indirectly. For example, diseases are expected to have a greater impact on corals, and ultimately the coral reef habitats that support fish. The increased risk of pathogens may be particularly relevant to both small pond and marine aquaculture operations, where greater incidence of disease at high temperatures is already linked to mortality in some regions[88].

The effects of climate change on the growth of fish will be manifested largely through the way faster growth influences reproduction and dispersal, although production of adult fish may also improve where temperatures currently limit growth during much of the year[89]. However, the impact of this increased production may well be overshadowed by alterations to the species composition of catches, which are likely to occur as a result of changes to fish distribution and modification of supporting habitats.

1.6.3 Implications for fisheries

Climate-induced changes to the distribution and abundance of fish have numerous implications for fisheries. They may include, for example, the following changes:

- **Availability of target species:** Varying ocean temperatures or distributions of key habitats or prey species may affect the distance that fishers must travel to access commercially viable fish stocks, or the time of year that fish occupy preferred fishing grounds.
- **Catchability of target species:** Alterations to the depth distribution, abundance or behaviour of fish species can be expected to affect catch rates, even though the fish are still present in traditional fishing areas. Any variation in average fish size stemming from climate change will influence the selectivity of fishing gear, possibly causing changes in catchability as well.
- **Proportion of non-target species:** Lower-value fish species favoured by climate change may affect the productivity and profitability of industrial fishing operations through, for example, the increased time and effort needed to exclude them, and greater loss of bait. Increases in unwanted species may eventually trigger catch restrictions to limit bycatch.
- **Value of fishers' knowledge:** Changes to the distribution and abundance of target species will reduce the benefits of current knowledge about fish and increase variation in catches until information on new patterns of fish behaviour and movements can be obtained.

Where climate-induced changes in landings are strong and negative, economic benefits will be curtailed, food security will be diminished and livelihoods will be lost. Investment decisions are also likely to be postponed and the lower returns on labour may reduce willingness to engage in long-term stewardship of fisheries resources.

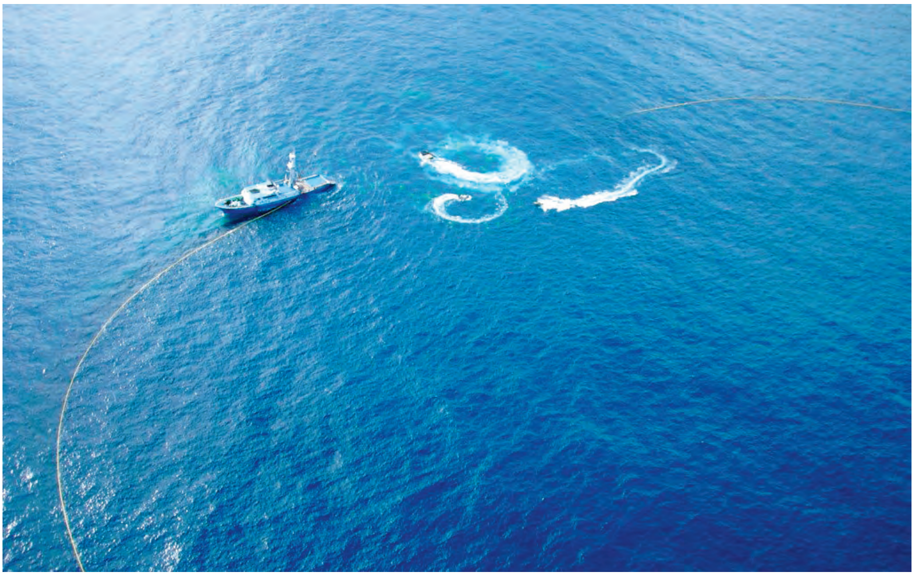

Photo: SPC collection

Purse-seining for skipjack tuna

1.7 Potential impact of climate change on fisheries and aquaculture in the tropical Pacific

All fisheries and aquaculture activities in the region are likely to be affected by climate change. The distribution and abundance of tuna, which dominate oceanic fisheries and are the mainstay of the economies of some smaller PICTs[1], are influenced largely by water temperature and the availability of nutrients.

The coastal fisheries that currently provide much of the animal protein for Pacific islanders[14], and the contribution of aquaculture to the economies of French Polynesia and Cook Islands, are based largely on coral reef habitats. These habitats are threatened by changes to water temperature, acidification of the ocean and sea-level rise, and possibly more severe cyclones and storms.

The freshwater fisheries of PNG have evolved in a climate of heavy rainfall and any major alterations in precipitation can be expected to change the nature of these resources, on which hundreds of thousands of people rely.

Preliminary analysis[90,91] has already identified the following possible effects of climate change on fisheries and aquaculture production in the tropical Pacific from climate change:

- **Changes to the distribution and abundance of tuna:** Alterations in ocean temperatures and currents and the food chains that support tuna, are projected to affect the location and abundance of tuna species[21,48]. In particular, the concentrations of skipjack and bigeye tuna are likely to be located further east than in the past. This has implications for the long-term management of the region's tuna resources, and for the development and profitability of national industrial fishing fleets and canneries in the western Pacific.
- **Decline in coral reefs and coastal fisheries:** Rising sea surface temperatures and more acidic oceans are projected to have direct impacts on coral reefs and the habitats and food webs they provide for reef fish and invertebrates[83]. Degraded coral reefs are likely to support different types of fish and lower yields of some species[56,85,92]. Reduced catches of reef-associated fish will widen the expected gap between the availability of fish and the protein needed for food security.
- **Freshwater fisheries:** The projected increases in rainfall for the tropics, and sea-level rise, are expected to increase the extent and duration of inundation that governs the life cycles and productivity of fish in the large rivers of PNG. These changes will also affect where and when people can catch fish. Increased flooding and warmer water are also likely to enhance the ability of some exotic species to colonise PNG from Irian Jaya. Freshwater fisheries in the tropical Pacific are based largely on species that migrate between the sea and fresh water. Changes in either rainfall or sea level may have impacts on these migration patterns with consequences for fisheries production.

- **Difficulties in developing aquaculture:** Changing patterns of rainfall and more intense storms could flood aquaculture ponds more regularly in some places, and make small pond farming for food security impractical in others due to more frequent droughts[18,45,90,93]. There could also be higher financial risks associated with coastal aquaculture as a result of (1) greater damage to infrastructure and equipment from rising sea levels and the possibility of more severe cyclones and storms; and (2) the effects of higher water temperatures, ocean acidification, reduced salinity and increased incidence of disease on the growth and survival of shrimp, pearl oysters, seaweed and ornamental specimens[90].
- **Increased operating costs:** Projections that cyclones and storms could possibly become progressively more intense would involve increased risk of damage to shore-based facilities and fleets for domestic tuna fishing, and processing operations. Fleets operating within the cyclone belt may need to be upgraded to provide improved safety at sea. Rising sea level may eventually make many existing wharfs and shore-based facilities unusable. Taken together, increased costs associated with repairing and relocating shore-based facilities, and addressing increased risks to occupational health and safety for fishers, may affect the profitability of domestic fishing operations. Such increased costs will need to be taken into account by PICTs when planning the optimum mix of developing local industries for tuna and providing continued access for DWFNs.

1.8 Assessing the vulnerability of fisheries and aquaculture in the tropical Pacific to climate change

1.8.1 General approach

The heavy dependence of PICTs on fisheries, and the wide range of ways that fishery resources may be affected, warrants a comprehensive analysis of the vulnerability of fisheries and aquaculture in the region to climate change. The purpose of this book is to provide this assessment. To do this, we have assembled the latest information available from the tropical Pacific to determine the degree to which access to oceanic, coastal and freshwater fisheries resources, and the productivity of aquaculture, is likely to be affected by the changing climate. Our approach involves six steps (**Figure 1.12**).

1. Describing the observed and projected changes to atmospheric (surface) climate in the region (Chapter 2).
2. Describing the observed and projected changes to the main features of the tropical Pacific Ocean (Chapter 3).
3. Assessing the way in which projected changes to the climate and ocean are likely to affect the ecosystems that support fisheries resources, i.e. the food webs in the open ocean (Chapter 4), coral reefs (Chapter 5), other important coastal habitats such as mangroves, seagrasses and intertidal flats (Chapter 6), and freshwater and estuarine habitats (Chapter 7).

4. Assessing the likely direct effects of projected changes to surface climate and oceanic conditions, and the indirect effects of projected changes to ecosystems on the abundance and distribution of species supporting oceanic fisheries (Chapter 8), coastal fisheries (Chapter 9), freshwater and estuarine fisheries (Chapter 10) and aquaculture (Chapter 11).
5. Identifying the economic and social implications of projected changes to the productivity of oceanic, coastal and freshwater fisheries, and aquaculture, for regional plans to use fisheries resources for economic development and government revenue, food security and livelihoods (Chapter 12).
6. Recommending management measures and policies to enable communities and fishing industries to adapt effectively, and to help maintain the benefits of fisheries in the face of climate change (Chapter 13). In making these recommendations, we have also identified key gaps in knowledge and the investments needed to fill them and to launch the recommended adaptations.

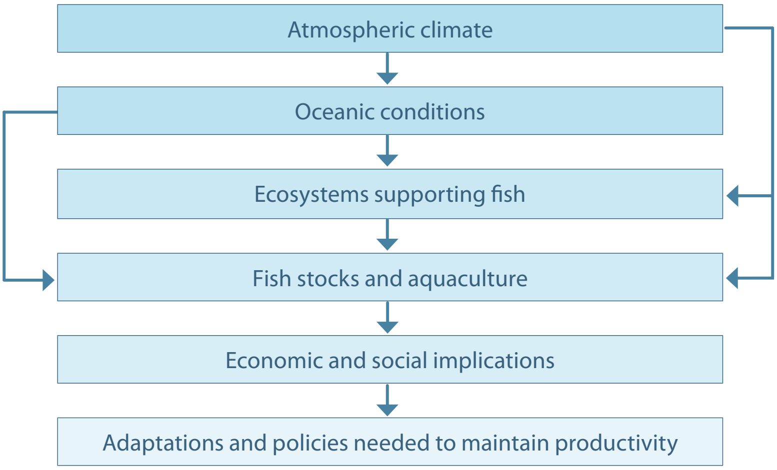

Figure 1.12 Summary of the approach used to assess the vulnerability of tropical Pacific fisheries and aquaculture to climate change. The approach is applied separately for oceanic, coastal and freshwater fisheries, and aquaculture.

1.8.2 Climate models

Global climate models were used to provide the projections involved in Steps 1 and 2 of the approach outlined above. A climate model is a numerical description of our understanding of the physics, and in some cases chemistry and biology, of the ocean, atmosphere, land surface and ice regions. Climate models with reasonable 'skill' in capturing present and past states of the climate system are the best tools we have to make projections of what the future might hold, based on current understanding.

At its most basic level, a climate model describes (1) Newton's law that the motion of a fluid (water or air) can be determined if the forces acting on it are known (e.g. the winds pushing the surface of the ocean, or the friction trying to oppose any motion), and (2) the laws of conservation of mass and energy (e.g. if water flows into an obstacle it will be deflected, or if solar energy penetrates the ocean surface, the water will warm). In principle, we should be able to use these mathematical formulas to give a near perfect description of the real world, but in practice compromises must be made due to computational limitations.

To implement these physical laws within the architecture of even the most powerful computers, our simulation of the climate system must be greatly simplified and broken down into a collection of grid 'boxes'. For the current generation of global climate models, these boxes have a resolution in the ocean that is typically 1–2° or 100–200 km on each side (atmospheric resolutions are generally even coarser). This means that all the currents (or variations in temperature or salinity, etc.) within the area of a particular box will be represented by a single average current (temperature or salinity, etc.). Consequently, many smaller-scale processes (e.g. finer-scale circulation in coastal zones) with widths of a few kilometres are not resolved by the models. Unfortunately, these smaller scales are often the ones we are most interested in and care must be taken in 'downscaling' the projections from models to ensure they are useful in assessing regional impacts. To help address this limitation, many of the unresolved processes are 'parameterised'. These parameterisations essentially translate the effect of small-scale processes to the larger scales on which the models operate.

Model results presented in various chapters of this book are primarily from the Coupled Model Intercomparison Project Phase 3 (CMIP3) multi-model data set, which was used by the Fourth Intergovernmental Panel on Climate Change (IPCC) Assessment Report (AR4). All models are state-of-the-art 'coupled' models, meaning that ocean, atmosphere, land and ice models are coupled together, with information continuously being exchanged between these components to produce an estimate of global climate that evolves with time.

These global climate models are generally run for hundreds of simulation-years subject to constant, pre-industrial (1870) forcing, i.e. constant solar energy and appropriate greenhouse gas levels (**Figure 1.13**). This gives the ocean time to 'settle down' into a near equilibrium. Using the 'pre-industrial run' as a baseline, the 20th century simulations incorporate increasing greenhouse gases[xv] in the atmosphere in line with historical emissions and take observed natural forcing (e.g. changes in solar radiation, volcanic eruptions) into account.

[xv] Some simulations also include sulphate aerosols and ozone.

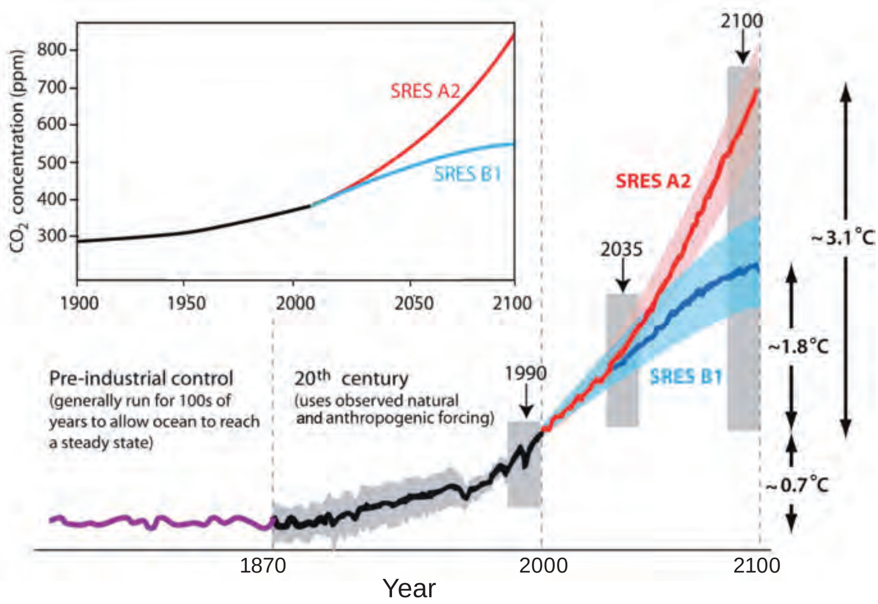

Figure 1.13 Globally averaged surface air temperature (SAT) simulated by a multi-model average of the CMIP3 coupled climate models (pre-industrial simulation – purple; 20th century simulation – black; 21st century SRES B1 scenario – blue, and SRES A2 scenario – red). The spread associated with output from different models is highlighted by the translucent shading. Also shown are observed and multi-model average changes in SAT relative to 1980–2000. Information after 1900 is based on IPCC-AR4 (Working Group 1, Figure 10.4). Inset shows the historical and future CO$_2$ concentrations used by the models.

At the end of the 20th century, projection simulations are carried out based on pre-defined 'plausible' future emission trajectories. In our case, we focus on two of these trajectories, corresponding to low (B1) and high (A2) emissions scenarios from the IPCC Special Report on Emissions Scenarios (SRES) (Section 1.8.4). Assessments are made of the ability of the models to simulate the atmosphere and ocean (for the end of the 20th century) and both near-term (2035) and long-term (2100) projections (**Figure 1.13**)[xvi]. These models are far from perfect, however, and represent only an approximation of the real world. Two different models will simulate two different climate trajectories, even when subject to the same carbon dioxide equivalent emissions, due to the use of different parameterisations and levels of approximation.

The difference between models is highlighted by the spread in the projections around each of the scenarios in **Figure 1.13**. In general, the projected changes tend to be more certain at large spatial scales (e.g. global average temperature) but become increasingly uncertain at more local scales (e.g. the strength of a particular ocean current). To overcome some of these uncertainties, average output from a suite of

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[xvi] Since this study was designed, the IPCC has decided to use a new generation of scenario simulations based on Representative Concentration Pathways (RCPs), i.e. prescribed greenhouse gas concentration pathways throughout the 21st century, corresponding to different radiative forcing stabilisation levels by the year 2100[107,108]. The highest priority global model simulations will be RCP4.5 and RCP8.5, corresponding roughly to SRES B1 and A2, respectively.

independent climate models is considered, rather than the outputs from individual climate models. For this book, we selected subsets of the possible 24 CMIP3 models, based on their ability to simulate present climate. By averaging across multiple models it is possible to reduce many of the biases inherent in individual models. However, systematic biases still persist in some cases, so it is important to interpret model results with an awareness of their shortcomings.

The CMIP3 models only provide projections of the physical climate (**Figure 1.14**) and do not explicitly simulate responses of habitats and fish stocks to climate change. Such responses must be inferred from our best understanding of how productivity and higher trophic levels react to observed climate variability. For some of the analyses in this book, a number of biological components have been coupled to one of the CMIP3 models (IPSL-CM4)[94] to make projections of (1) primary production and the extent of the different ecological provinces in the Pacific Ocean (Chapter 4), and (2) catches of skipjack and bigeye tuna (Chapter 8). Thus, any uncertainties associated with this model are transferred to the simulated biological responses.

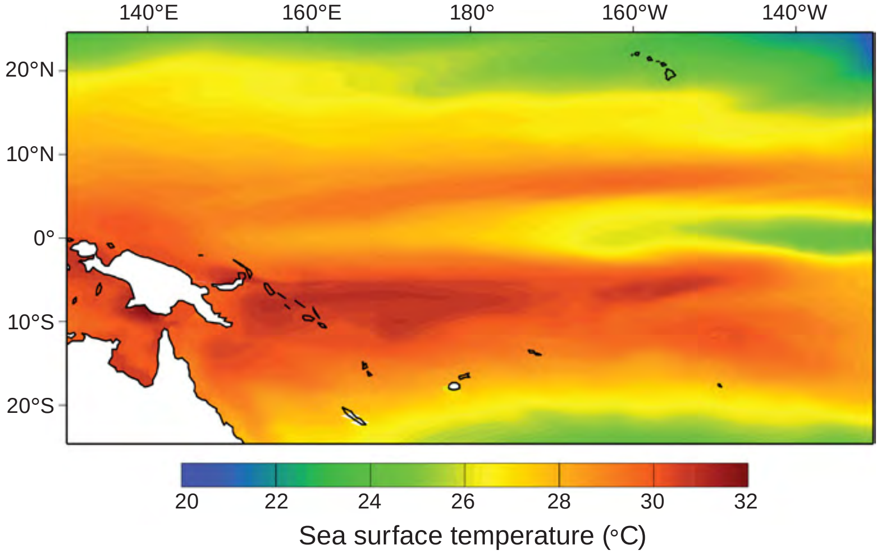

Figure 1.14 An example of a model output of physical climate from one of the CMIP3 models (CCSM3); in this case sea surface temperature for the A2 emissions scenario in 2035 (source: IPCC)[110].

1.8.3 Assessing vulnerability – a framework

Steps 3, 4 and 5 of our approach (Section 1.8.1) involve determining the vulnerability of ecosystems, fish stocks and fishing industries and communities to climate change. The IPCC has described vulnerability to climate change as 'the degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes'[32].

In this book, we have used the framework adopted by the IPCC, and several other initiatives in the fisheries sector[55,95,96], to assess the vulnerability of fisheries and aquaculture in the tropical Pacific to climate change. The framework assesses vulnerability as a function of the character, magnitude and rate of climate variation to which natural and social systems are exposed, their sensitivity and their adaptive capacity (**Figure 1.15**).

Exposure is the nature and degree to which a species, ecosystem or society is subjected to significant direct or indirect effects of a changing climate, including variations to natural extremes that exceed known stress thresholds. An example of a direct effect of climate change is the way that higher sea surface temperatures increase the frequency of coral bleaching[83]. An indirect effect is the way that coral reefs degraded by higher temperatures and ocean acidification provide a poorer habitat for fish[85].

Sensitivity is the degree to which a species, ecosystem or society is affected, either adversely or beneficially, by exposure to the direct and indirect effects of climate change. Sensitive species, ecosystems and societies are highly responsive to such effects and can be significantly affected by small changes in the magnitude and frequency of climate variables. Assessing sensitivity requires an understanding of the thresholds at which these responses begin to occur, and knowledge about whether these adjustments are likely to be gradual or 'step changes' and whether they are reversible.

Taken together, the consequences of exposure and sensitivity result in a potential impact due to the changing climate. However, this impact can be modified by the capacity of the species, ecosystem or society to adapt to the consequences. Adaptation may be autonomous (the only option for most species) or planned (where human interventions are feasible). A planned adaptation is a strategic change in anticipation of a variation in climate.

This approach to assessing vulnerability involves integrating scientific information, professional and community knowledge, and expert opinion across all the variables that affect species, ecosystems and societies directly and indirectly to highlight the risks and costs imposed by climate change. Expert opinion played an important role in the assessments presented in this book because quantitative scientific information and professional and community knowledge were often lacking. In such cases, expert judgments were used to (1) project the direction and degree of change, (2) suggest thresholds, and (3) gauge the likelihood of the projections occurring and confidence in the estimates (see Appendix 1.1 for definitions of these and other relevant terms).

As a result, there are uncertainties at a variety of levels in the vulnerability assessments. First, there is uncertainty about how human society will change to address greenhouse gas emissions, and what our future emissions trajectory will be.

Ultimately, this controls a large component of the differences in the model projections of surface climate and oceanic conditions that underpin the assessments in this book and inferences of the extent of the exposure of fisheries and aquaculture to climate change. Secondly, there is uncertainty in the global climate models themselves (Section 1.8.2). Thirdly, there is uncertainty due to incomplete knowledge of several of the ecosystems and biological processes that support fisheries and aquaculture – referred to as 'structural' uncertainty. Finally, there is still a lack of data on some important processes and relationships at appropriate spatial or temporal scales, contributing to difficulty in quantifying all parameters adequately in models – referred to as 'value' uncertainty[97]. Structural and value uncertainty affect all components of the vulnerability framework.

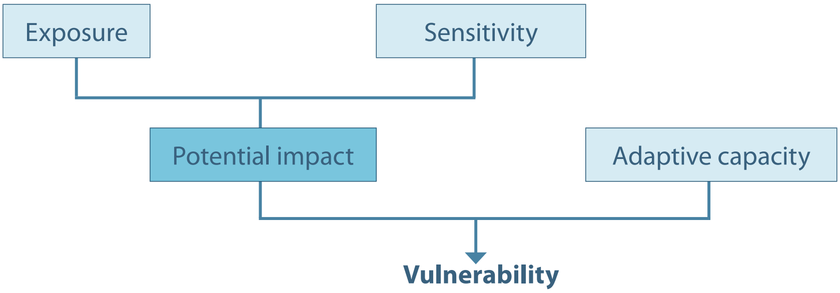

Figure 1.15 Framework used for assessing vulnerability of tropical Pacific fisheries and aquaculture to climate change. Adapted from Schroter and the ATEAM Consortium (2004)[106].

1.8.4 Scenarios for the tropical Pacific

We deal with the uncertainties described above by basing the vulnerability assessments on scenarios. Scenarios are plausible alternative pictures of how the future might unfold. The rationale for using scenarios is not only to encompass the range of possible outcomes stemming from the uncertainties but also to alert decision-makers to potential future situations. Ultimately, governments need to be ready to adapt to all scenarios. For any scenario, they need to be able to answer the question: 'How can we best respond if these circumstances eventuate?'

As noted above, the scenarios used in this book were based on the IPCC Special Report on Emissions Scenarios storylines B1 (low emissions) and A2 (high emissions)[98] for 2035 and 2100, outlined below.

B1 storyline – describes a convergent world with a global population that peaks in mid-century and declines thereafter, rapid changes in economic structures towards a service and information economy, reductions in material intensity, and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social and environmental sustainability, including improved equity, but without additional climate initiatives.

A2 storyline – describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in a continuously increasing global population. Economic development is primarily regionally orientated, and per capita economic growth and technological change are more fragmented and slow compared to other storylines.

It is important to note that the term 'low emissions' is used in a relative sense. Even following the B1 scenario, large changes to the climate system are projected. Indeed, the B1 trajectory is likely to result in average global surface air temperatures that exceed 2°C above pre-industrial levels in 2100, commonly defined as the boundary for 'dangerous' climate change.

The four scenarios we use in this book (i.e. the four combinations of the B1 and A2 storylines for 2035 and 2100) were chosen to portray (1) a near-term timeframe that people can relate to easily, and longer-term projections; and (2) an optimistic scenario for greenhouse gas emissions (B1 storyline) and one that foreshadows the extent of possible impacts if the world continues to emit high concentrations of greenhouse gases (A2 storyline). It should be noted, however, that the global community is presently following an emissions trajectory that is at least as damaging as the A2 scenario, if not worse – between 2005 and 2009 an average of 2 ppm of CO_2 was added to the atmosphere each year[xvii]. For those interested in mid-term projections, the B1 scenario in 2100 can be used as a proxy for A2 in 2050. Note, however, that although CO_2 emissions are similar, the multi-model means for some variables differ slightly in model simulations for B1 2100 and A2 2050. For example, sea surface temperature is 0.18°C (±0.23) higher under B1 2100 than under A2 2050.

All four scenarios were constructed first for surface climate (Chapter 2) and oceanic conditions (Chapter 3), and then cascaded throughout the book along two pathways (**Figure 1.16**). This process was carried out separately for oceanic, coastal and freshwater fisheries, and aquaculture. In one pathway, the scenarios developed for Chapters 2 and 3 were used to define the direct exposure of the species/stocks supporting fisheries and aquaculture. In a second pathway, the four scenarios that resulted from the vulnerability assessments for the ecosystems underpinning fisheries and aquaculture (Chapters 4–7) were used to determine the indirect exposure of the species/stocks. Estimates of direct and indirect exposure of the species/stocks were then integrated and used in the framework (**Figure 1.15**) to assess the vulnerability of oceanic, coastal and freshwater fisheries, and aquaculture, under each of the four scenarios (Chapters 8–11).

[xvii] See www.esrl.noaa.gov/gmd/ccgg/trends/#mlo_growth for the latest trends in the growth of CO_2 emissions.

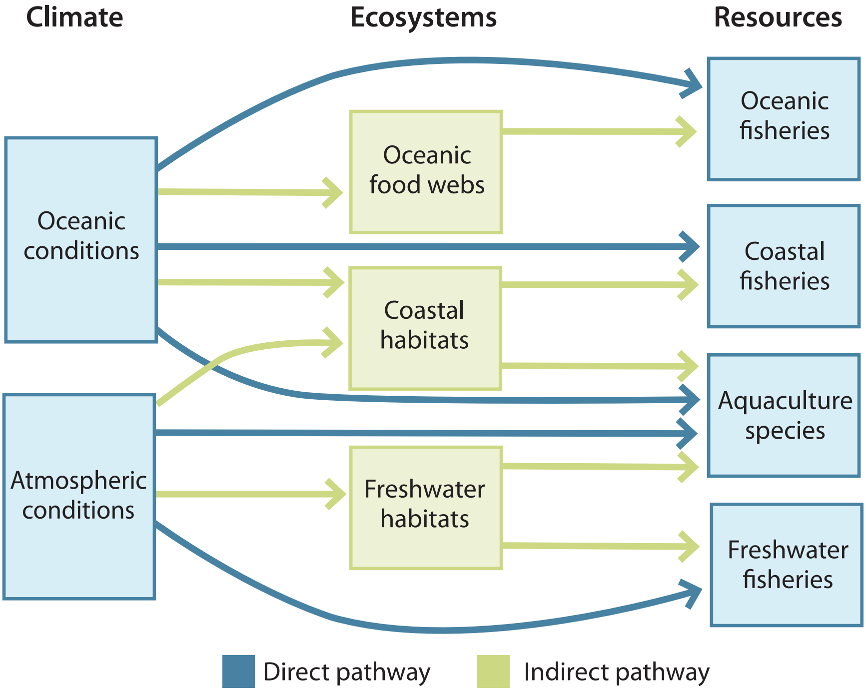

Figure 1.16 The two pathways used to develop scenarios of the exposure of the various fisheries resources and aquaculture species in the tropical Pacific to climate change.

The four scenarios that resulted from merging these two pathways for oceanic fisheries were used to assess the vulnerability of the tuna industry and identify the implications for economic development and government revenue in each PICT (Chapter 12). A similar integrated process was used to assess the vulnerability of rural and urban communities to the future availability of fish, and the implications for food security and livelihoods, based on the projected changes in production from oceanic, coastal and freshwater fisheries, and aquaculture (Chapter 12).

We conclude by describing the adaptive management measures, policies and investments that governments, enterprises and communities in PICTs can use to maintain the benefits of fisheries and aquaculture. These proposed interventions are designed to reduce the vulnerability of PICTs to the effects of climate change, and help them take advantage of opportunities created by the changing climate (Chapter 13).

But this book provides more than just a vulnerability assessment. Chapters 2–11 all begin with extensive descriptions of how the region's climate, ocean, fish habitats, fisheries resources and aquaculture have functioned recently. These summaries not only provide a yardstick against which the impacts of climate change can be evaluated, they should also be useful to anyone seeking information on the significance of fisheries and aquaculture to PICTs, and the ecosystems that support these important activities.

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Appendix 1.1 Definitions of terms

Adaptation, as broadly defined by the Intergovernmental Panel on Climate Change, is an adjustment in natural or human systems in response to actual or expected climatic changes or their effects, which moderates harm or exploits beneficial opportunities.

Adaptive capacity is the potential for a species, ecosystem or society to adapt to climate change (including changes in variability and extremes) to maximise their fitness, moderate potential damage, take advantage of opportunities or cope with consequences.

Attribution is the process of establishing cause and effect with some defined level of confidence, including the assessment of competing hypotheses.

Detection is the process of demonstrating that an observed change is significantly different (in a statistical sense) to one that can be explained by natural variability.

A **prediction** is a statement that something will happen in the future, based on known conditions at the time the prediction is made, and assumptions about the processes that will lead to change. Because present conditions are often not known precisely, and the processes affecting the future are not perfectly understood, such predictions are seldom certain and are often best expressed as probabilities. Daily weather forecasts are 'predictions' in this sense – they are predictions of what the weather will be like, but have uncertainties due to inexact observations and weather models. They are often expressed in probabilistic terms.

Projections are sets of future conditions, or consequences, derived from explicit assumptions, such as scenarios. Even for a given scenario or set of assumptions, projections introduce further uncertainties due to the use of inexact rules or 'models' connecting the scenario conditions to the projected outcomes.

Resilience is the amount of change a species, ecosystem or society can withstand without fundamental alteration or loss. For example, the resilience of an ecosystem is its capacity to absorb shocks and regenerate and re-organise to maintain key functions, without undergoing a 'phase shift' (moving into another state controlled by different processes). Both sensitivity and adaptive capacity are influenced by resilience.

Likelihood is the probability that a future projection or prediction will occur based on expert judgement. The categories of likelihood, expressed as a percentage, used in this book are:

Very likely	90–99% chance
Likely	66–90% chance
Somewhat likely	30–66% chance
Unlikely	29% chance or less

Confidence is a quantitative or qualitative evaluation of the level of scientific understanding in support of a conclusion. A quantitative assessment specifies the degree of belief among authors in the validity of a conclusion based on collective knowledge, evidence, modelling results and theory. A qualitative assessment is an evaluation based on the amount of supporting evidence, and the level of agreement between experts about the interpretation. The levels of confidence, expressed as a percentage, applied to assessments made in this book are:

Very High	95% or greater
High	67–95%
Medium	33–67%
Low	5–33%
Very Low	5% or less

Photo: Jurgen Freund

Chapter 2

Observed and projected changes in surface climate of the tropical Pacific

Janice M Lough, Gerry A Meehl and M Jim Salinger

> *'Warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level.*
>
> *Most of the observed increase in global average temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations.'* (IPCC 2007)[i]

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[i] IPCC (2007) Summary for Policymakers. In: S Solomon, D Qin, M Manning, Z Chen, M Marquis, KB Averyt, M Tignor and HL Miller (eds) *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom, and New York, United States of America.

Contents Page

2.1 Introduction

Weather is defined as the relatively instantaneous state of the atmosphere as described from day-to-day by measurable variables, such as air temperature, rainfall, wind speed and direction, cloud cover and humidity. Climate is the long-term average weather – what is expected at a particular time and place – and is based on observations over many years. Descriptions of climate can include both the average values and measures of variability from year-to-year. A climate change is then defined as a significant change in what we expect the weather to be like at a particular location and season[1]. Such a change could be in average values and/or in the variability around the average, i.e. the range of extremes. Determining the nature and significance of changes in climate globally or regionally is dependent on long, homogeneous weather observations from as many locations as possible[2].

Humans, and the natural and managed ecosystems that we rely on for the goods and services they provide, are adapted to prevailing climatic conditions. Global and regional climate has varied in the past on a range of time scales. For example, orbital forcing of the climate system over the past 450,000 years resulted in major swings in global climate between four cooler periods of widespread glaciation (ice ages), interspersed with warmer interglacial periods lasting from 10,000 to 30,000 years. Warming of the global climate by 4–7°C since the last glacial maximum about 21,000 years ago is estimated to have occurred at a rate 10 times slower than the observed warming during the 20th century[3]. Climate also varies on interannual to decadal time scales due to a range of forcings that are internal (such as El Niño-Southern Oscillation and North Atlantic Oscillation) or external (such as volcanic aerosols, amount of incoming solar radiation) to the climate system[4]. We have, however, entered a new era of rapidly changing global climate as a consequence of human activities.

'All these changes characterise a carbon cycle that is generating stronger climate forcing and sooner than expected.' (Global Carbon Project 2008)[5]

The evidence for increasing greenhouse gases due to human activities since the late 18th century is unequivocal[6–8]. The atmospheric concentration of the main greenhouse gas, carbon dioxide (CO_2), rose from 280 parts per million (ppm) in 1750 to 385 ppm in 2008[9], a 38% increase and the highest concentration of the last 800,000 years[10] and possibly the last 20 million years. The concentrations of other greenhouse gases such as methane and nitrous oxide have also risen over this period. Not only are atmospheric concentrations of greenhouse gases rising but the rate of increase is accelerating (**Figure 2.1a**). These concentrations are projected to continue to rise over the 21st century (**Figure 2.1b**). The annual mean growth rate of the main greenhouse gas (CO_2) was 2.0 ppm per year for 2000–2007 compared to an average annual growth rate of 1.5 ppm per year from 1990 to 1999[5,11,12].

This increase in atmospheric greenhouse gases is causing significant positive radiative forcing of the global climate system[8], i.e. global warming (**Figure 2.2**). The most recent assessment of the Intergovernmental Panel on Climate Change, the Fourth Assessment Report (IPCC-AR4), indicates that average global land and ocean surface temperatures (based on instrumental observations) have warmed by 0.74°C over the last 100 years (1906–2005) and that the rate of warming over the past 50 years (0.13°C per decade) is almost twice that of the past 100 years (0.07°C per decade)[13]. Assessments since IPCC-AR4 highlight that the pace of climate change is accelerating and is tracking the upper end of the more pessimistic scenarios for the 21st century[14,15].

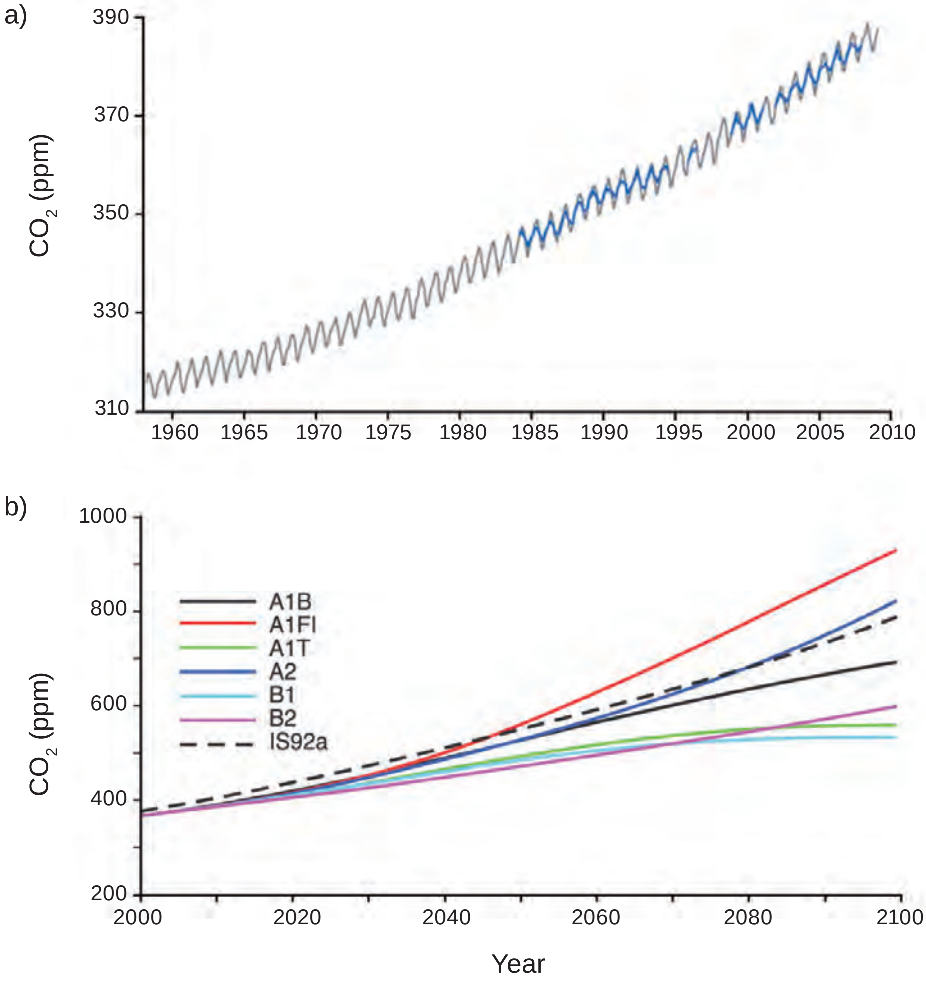


Figure 2.1 (a) Monthly atmospheric carbon dioxide (CO_2) concentration (ppm) for Mauna Loa, Hawaii (March 1958 – February 2009) (grey) and Christmas Island, Kiribati (March 1984 – December 2007) (blue), illustrating the increase, and accelerating rate of increase, of this greenhouse gas in the northern and equatorial central Pacific (source: World Data Centre for Greenhouse Gases)[93]; (b) Projected concentrations of atmospheric carbon dioxide (CO_2) concentrations to 2100 for six IPCC SRES scenarios (source: Meehl et al. 2007)[71].

The relatively modest global warming observed to date has already been associated with changes in the global climate system, such as more intense rainfall, more frequent droughts, sea-level rise, loss of Arctic sea ice, melting of land-based ice[13] and a widening of the tropical climate belt[16]. The rate of warming is also about twice as fast for land masses compared to oceans and, in the Northern Hemisphere, for high versus low latitude regions. Warming of the ocean varies between basins, with that of the Pacific being 'punctuated' by El Niño events and Pacific decadal variability compared to the steadier observed warming of, for example, the Indian Ocean[13]. Many of the instrumental observations of recent climate changes are, however, centred on temperate land areas with relatively little detail for tropical islands and ocean regions, which are the focus of this publication.

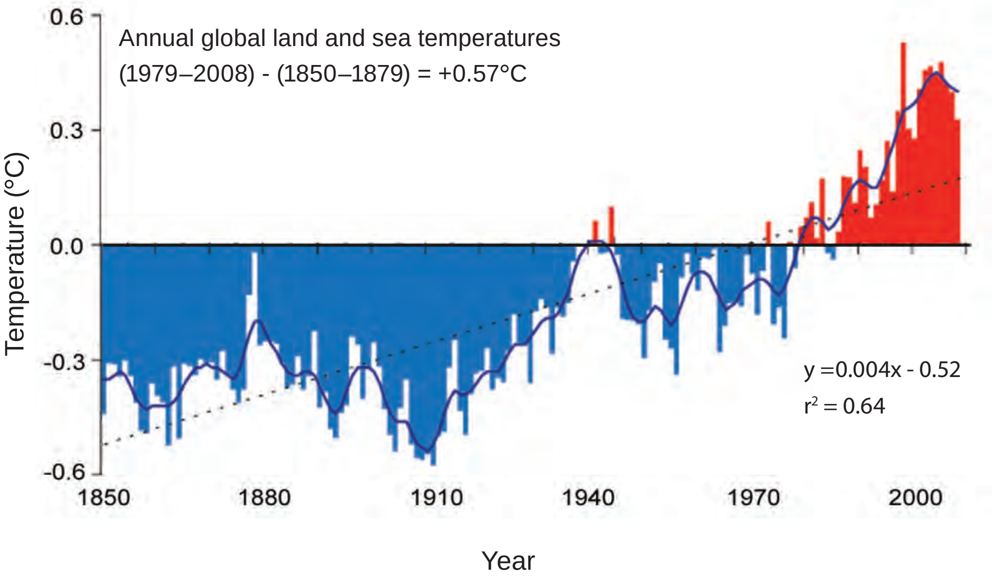


Figure 2.2 Annual global land and sea temperature anomalies (from 1961–1990 mean) for the period 1850–2008, illustrating the observed warming of global temperatures and the occurrence of the warmest years in the observational record in recent years. Thick line is 10-year Gaussian filter emphasising decadal variability, and dashed line is linear trend (source: HadCRUTV3, Jones et al. 1999, Brohan et al. 2006, Rayner et al. 2003, 2006)[94–98].

Assessing the nature, magnitude and significance of recent climate variations and trends relies on high-quality observational records from a range of locations. In particular, there is a paucity of reliable precipitation measurements for tropical oceanic regions, and discrepancies among observational and remotely sensed products make assessing changes in precipitation in these regions difficult. Despite some data limitations, the observed changes in climate are, however, driving changes in the world's biological and physical systems that are consistent with a rapidly warming climate[17,18].

The Pacific Island countries and territories (PICTs) are scattered across the large area of the tropical Pacific Ocean. These relatively small land areas encompass diverse environments, from high-elevation volcanic islands to low-lying coral atolls (Chapter 1). Although the magnitude of warming is, and is expected to be, greater over land areas than the oceans, and greater at higher compared to lower latitudes, significant changes are also occurring in the tropical Pacific Ocean[ii] (**Figure 2.3**). In this chapter, which builds on earlier assessments[19,20], we first review some of the uncertainties in accurately projecting future climate changes in the tropical Pacific, then provide a brief description of the current surface climate of the region and the major controls on seasonal and interannual climate variability. We then present examples of how some components of the recent surface climate are already changing with the global warming observed to date. Finally, we describe how surface climate is likely to change in coming decades for two scenarios – low emissions and high emissions. The specific focus of this chapter is to help provide the basis for assessing the vulnerability of fisheries and aquaculture in the Pacific to the regional consequences of global climate change.

2.2 Understanding how climate will change – uncertainties

'*Many aspects of tropical climatic responses remain uncertain.*' (Christensen et al. 2007)[21]

A number of factors must be taken into consideration to understand and document the potential consequences and impacts of a rapidly changing climate. First, we need high-quality observations of modern climate conditions that are sufficiently detailed to determine, for example, the climatic envelope of particular organisms. Such records need to be long, continuous and ongoing to also detect changes in current conditions. Unfortunately, such high-quality data for the vast area of the tropical Pacific and the scattered and isolated islands[2] are relatively scarce compared, for example, to records for temperate Northern Hemisphere land areas[iii].

Secondly, we need sufficient understanding of the complex physics of the global climate system, and the various interactions between the atmosphere, ocean, land, cryosphere and biota, to realistically model current climate conditions. Such global climate models then provide the basis for projecting future changes as a consequence of radiative forcing by greenhouse gases. The present generation of global climate models still has difficulties in correctly simulating certain components of the present day, tropical western Pacific climate[22,23]. Present climate models are also fairly coarse (~ 150 km grid size) in their spatial resolution, which makes projecting to the regional scales most relevant to human populations a challenge[21,24]. Current models, for example, do not differentiate the small PICTs from the ocean, and may not adequately incorporate some of the ocean-atmosphere interactions of importance to island climates. Although there are various dynamic or statistical methods to

[ii] Defined here as the area 25°N to 25°S and 130°E to 130°W.

[iii] The Pacific Climate Change Science Program has recently undertaken recovery and homogenisation of historical climate data for many Pacific Island countries and made them available at www.bom.gov.au/climate/pccsp

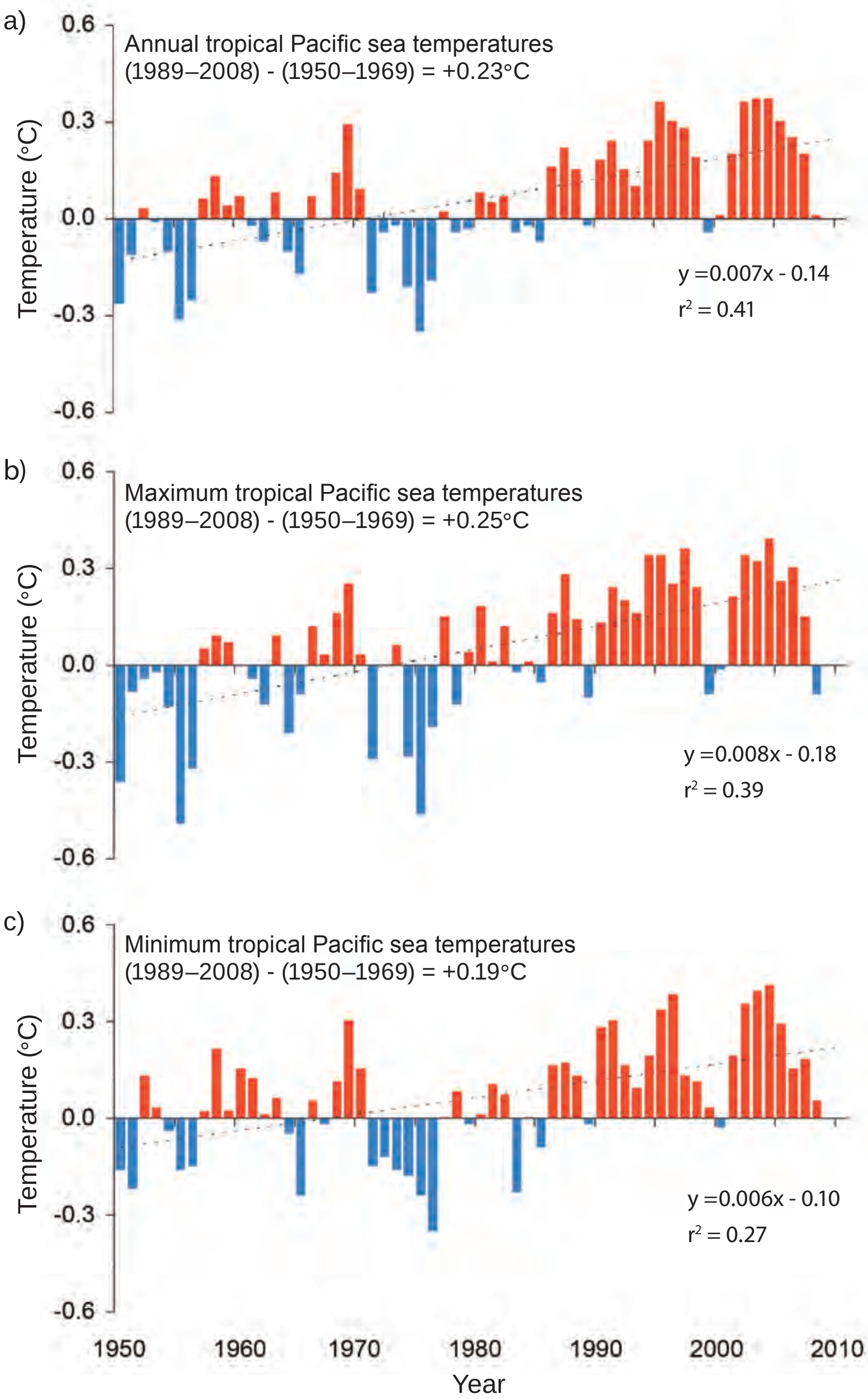


Figure 2.3 Anomalies for tropical Pacific sea surface temperatures, from the 1961–1990 mean, for the period 1950–2008 for (a) annual average temperatures, (b) annual maximum temperatures and (c) annual minimum temperatures, illustrating the recent acceleration in the rate of global warming, and that significant warming (~ 50% of global average) is already occurring in the tropical Pacific. Dashed line is linear trend (source: HadCRUTV3, Jones et al. 1999, Brohan et al. 2006, Rayner et al. 2003, 2006, Climate Research Unit)[94–99].

'downscale' coarse-resolution model outputs to finer spatial scales, these rely on a high degree of realism in the 'coarse' model and corrections for bias in SST. There is a need to produce more reliable models with higher spatial resolution, especially for the tropics[25].

Thirdly, although based on the same physical laws, different global climate models vary in the way in which they handle or 'parameterise' key small-scale processes that are unresolved by the models. This can lead to slightly different results for both present and future climate simulations. Such parameterisations (e.g. cloud formation or ocean eddy mixing) rely on a thorough understanding of the physical processes involved and are a vital component in climate modelling as they keep computational costs down to manageable levels. There is, therefore, no single 'perfect' global climate model and the most recent IPCC-AR4 often presents a multi-model average across a large number of relatively independent climate projections to account for the inter-model variability. This averaging tends to remove opposing biases in the models and is considered a suitable method for obtaining useful output, though it can also remove climate extremes that may be real[26] (Chapter 1).

Finally, projecting future climates also depends on projecting future greenhouse gas concentrations (i.e. the link to radiative forcing). The latter depends on a variety of socio-economic factors – basically the global response and level of commitment to reducing and stabilising greenhouse gas emissions in the atmosphere (mitigation), which in turn will affect the magnitude and timing of future climate changes. To take account of the uncertainty in future human emissions, the IPCC constructed a number of plausible scenarios, ranging from very carbon-intensive futures with high emission rates, to scenarios where emissions are 'reined in' very quickly. These scenarios specify the concentrations of greenhouse gases used as inputs for the climate models. Here, we use two scenarios from the Special Report on Emissions Scenarios (SRES)[27], which were used widely for the IPCC-AR4:

1. the relatively low emissions SRES B1 scenario (hereafter B1) which assumes that the concentration of the main greenhouse gas, CO_2, will be 500–600 ppm by the end of the 21st century, and
2. the most commonly modeled higher SRES A2 scenario (hereafter A2) with CO_2 concentrations reaching ~ 750–800 ppm by the end of the 21st century (**Table 2.1**).

Table 2.1 Projected global air and sea temperature changes, sea-level rise (relative to 1980–1999) and carbon dioxide (CO_2) concentrations for the low emissions B1 and high emissions A2 scenarios for 2100 (source: Bindoff et al. 2007, Meehl et al. 2007)[71,112]. In the shorter term, values for both scenarios are very similar, with projected warming by 2035 of ~ 0.9°C, sea-level rise of ~ 0.10 m and atmospheric CO_2 concentrations of ~ 400 ppm.

Scenario	Temperature (°C)	Sea-level rise (m)*	CO_2 (ppm)
B1	+1.8 (1.1–2.9)	0.18–0.38	500–600
A2	+3.4 (2.0–5.4)	0.23–0.51	750–800

* See Chapter 3 for updated estimates of sea-level rise.

Projections are presented for the near-term, 2026–2035 (hereafter 2035), and long-term, 2090–2099 (hereafter 2100)[iv]. Many scientists consider emissions reductions well below those of the B1 scenario are necessary to avoid dangerous climate change and significant ecosystem impacts[28,29]. Unfortunately, we are currently tracking above the high emissions A2 scenario[11,30].

There are, therefore, a range of uncertainties in projecting the nature, magnitude and consequences of how the surface climate of PICTs will change in the future. This 'explosion of uncertainty'[31] needs to be considered when attempting to delineate the range of potential impacts of a rapidly changing climate on marine ecosystems of the tropical Pacific. The planet, however, is already committed to ongoing, rapid, possibly intensifying climate changes for the foreseeable future. Climate will continue to change due to gases already in the atmosphere, even with drastic mitigation strategies[32,33], and there is the spectre of irreversible changes on the scale of thousands of years[34]. Our challenge in confronting a rapidly changing climate is to avoid the unmanageable, and manage and be prepared for the unavoidable[35].

2.3 Present-day surface climate

2.3.1 Atmospheric circulation

Surface climates of islands in the tropical Pacific are dominated by the vast surrounding ocean and the large-scale atmospheric and oceanic circulations[36–38]. The major atmospheric circulation features (**Figure 2.4**) include the northeast and southeast trade wind regimes, which originate in the subtropical high-pressure belts of each hemisphere where air sinks and dries. These tropical easterly flows are characterised by their constancy in speed and direction, although they tend to be strongest in the winter season of each hemisphere and to extend further polewards in the summer seasons.

The trade winds from the two hemispheres converge in the Intertropical and South Pacific convergence zones (ITCZ and SPCZ), where rising air forms the ascending branch of the Hadley circulation. The Hadley circulation represents the main north to south component of the Pacific atmospheric circulation. In addition, the Walker circulation operates in the east to west plane of the tropical Pacific with, normally, rising air over Indonesia and sinking air in the southeast tropical Pacific. This circulation is intimately linked to the major source of interannual tropical climate variability, El Niño-Southern Oscillation.

[iv] Examination of 10-year periods is based on multi-model averages (see Chapter 3, which uses 20-year averages but a smaller subset of models). The two approaches, which cancel out differences among models and use 10–20 year averages, are likely to produce relatively stable scenarios[26].

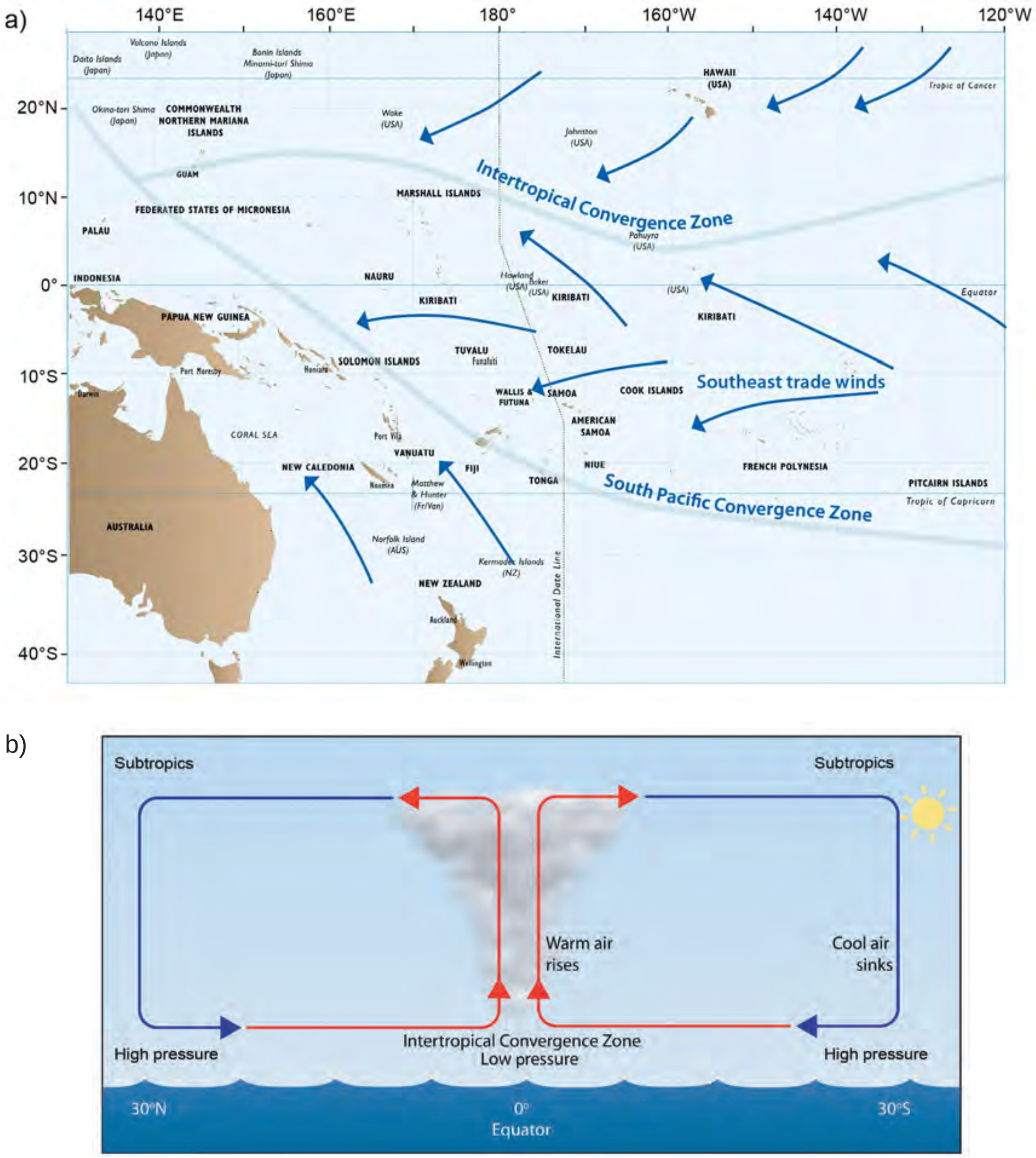


Figure 2.4 (a) Major atmospheric circulation features in the tropical Pacific; (b) cross-section illustrating the Hadley circulation of the region.

The SPCZ (**Figure 2.5**) is one of the most significant features of subtropical Southern Hemisphere climate[39,40]. It is characterised by low-level convergence of air flow leading to uplift and a band of cloudiness and rainfall stretching from the 'Warm Pool' in the western Pacific southeastwards towards French Polynesia[39–41]. The SPCZ shares some characteristics with the ITCZ, which lies just north of the equator, but is more subtropical in nature, especially east of the dateline[42]. To the west, it is linked to the ITCZ over the Warm Pool. To the east, it is maintained by the interaction of the trade winds and transient disturbances in the mid-latitude westerly winds emanating from the Australasian region. The SPCZ tends to lie over a region of large sea surface temperature (SST) gradient, rather than the maximum of SST, and is most active in the austral summer period, November–April. The location of the SPCZ convergence maximum varies considerably between seasons, by 10–15° of latitude (**Figure 2.6**). This causes large variability in rainfall throughout the southwest Pacific.

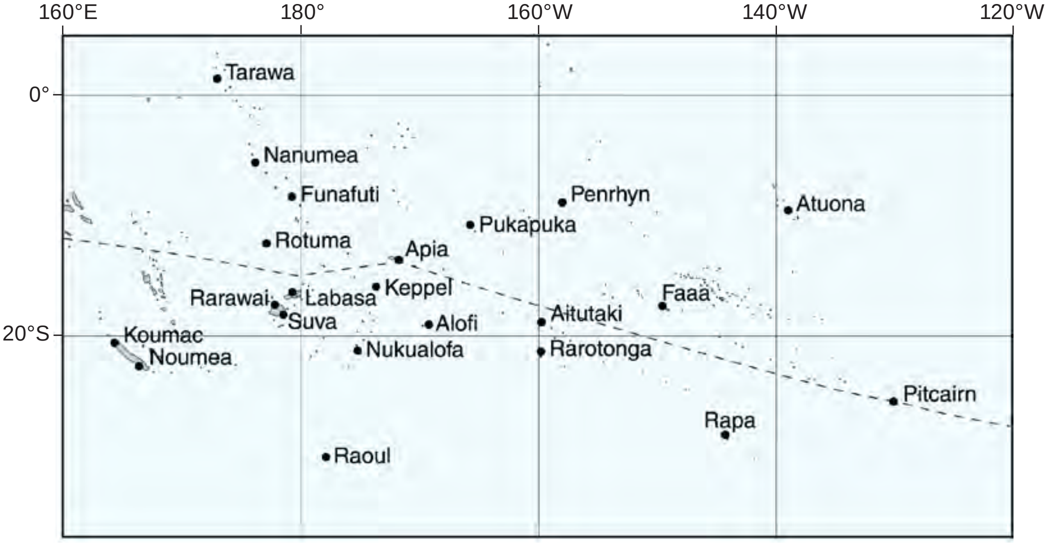


Figure 2.5 Mean position of the South Pacific Convergence Zone (SPCZ) (dashed line), defined as a maximum of low-level convergence (source: Folland et al. 2002)[53]. The zonal portion of the SPCZ lies west of 180°, and the diagonal section to the east. The locations of stations used in the analyses of instrumental temperature and rainfall records (Section 2.4) are also shown.

2.3.2 Temperature

The tropical Pacific consists primarily of ocean, with extremely small land areas (Chapter 1), and therefore the mean temperature climate is dominated by the average SSTs. The SSTs are similar to air temperatures for low-lying land areas and thus are a good proxy for surface temperatures. In general, average SSTs are warmer in the western Pacific compared to the eastern Pacific (**Figure 2.7a**). Annual maximum temperatures of around 30°C characterise the Warm Pool (**Figure 2.7b**) (Chapter 3) and annual minimum water temperatures (**Figure 2.7c**) exceed the threshold considered suitable for coral reef growth[43] throughout the region. The annual range of SSTs is < 2°C throughout much of the western tropical Pacific (**Figure 2.7d**). This is quite a narrow range to which marine organisms will be adapted, meaning small temperature changes may have relatively large impacts.

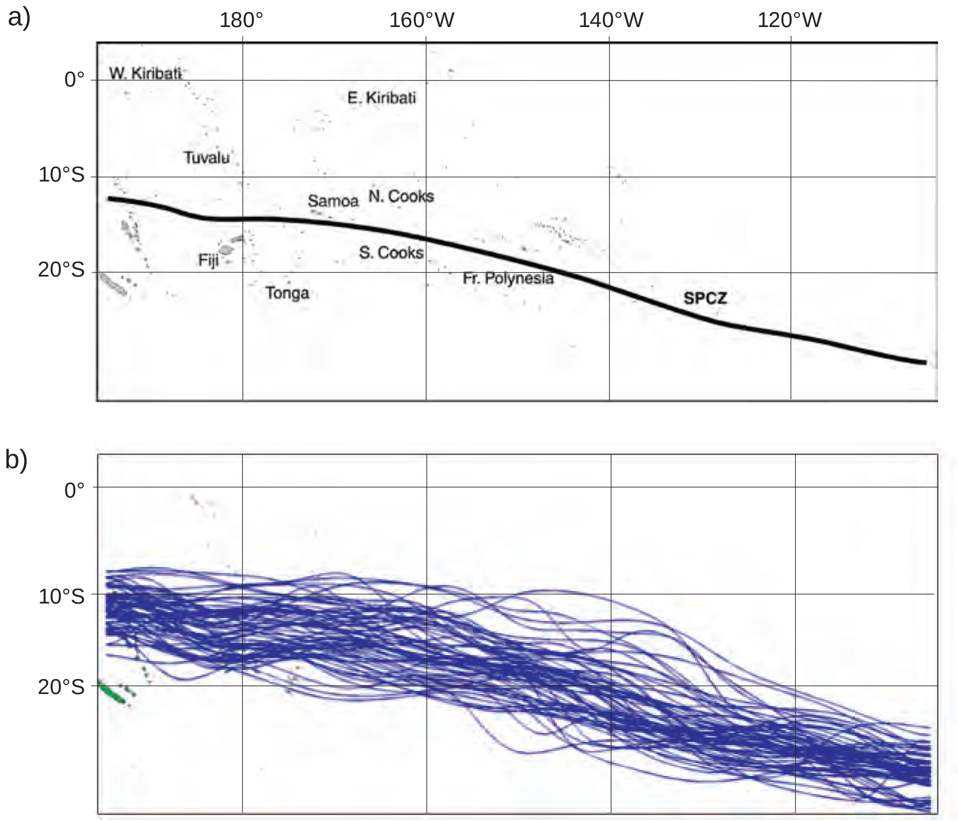


Figure 2.6 Average position of the South Pacific Convergence Zone (SPCZ), in (a) November–April, and (b) individual positions in all seasons, illustrating the considerable interannual variability in the SPCZ's mean position, which can give rise to substantial rainfall anomalies either side of its locations. The SPCZ is defined here as the maximum of convergence calculated from monthly mean reanalysis of wind speeds measured at 10 m elevation and direction with the mean SPCZ location at each longitude taken as the position of maximum convergence between the equator and 30°S.

2.3.3 Seasonal variation in winds, rainfall and temperatures

The average seasonal variation in the surface climate of the tropical Pacific is described here using monthly average wind fields, SSTs and rainfall (**Figure 2.8**). How this large-scale Pacific seasonality translates into average island climates is illustrated for five stations (**Figure 2.9**). These show the very small annual air and sea temperature variation of the near-equatorial sites of Tarawa and Funafuti, with an austral summer rainfall maximum; the greater annual air and sea temperature range of Nadi, with a more marked austral summer rainfall maximum; and the greater annual air and sea temperature and range for subtropical Rarotonga and Pitcairn, with little seasonality in monthly rainfall.

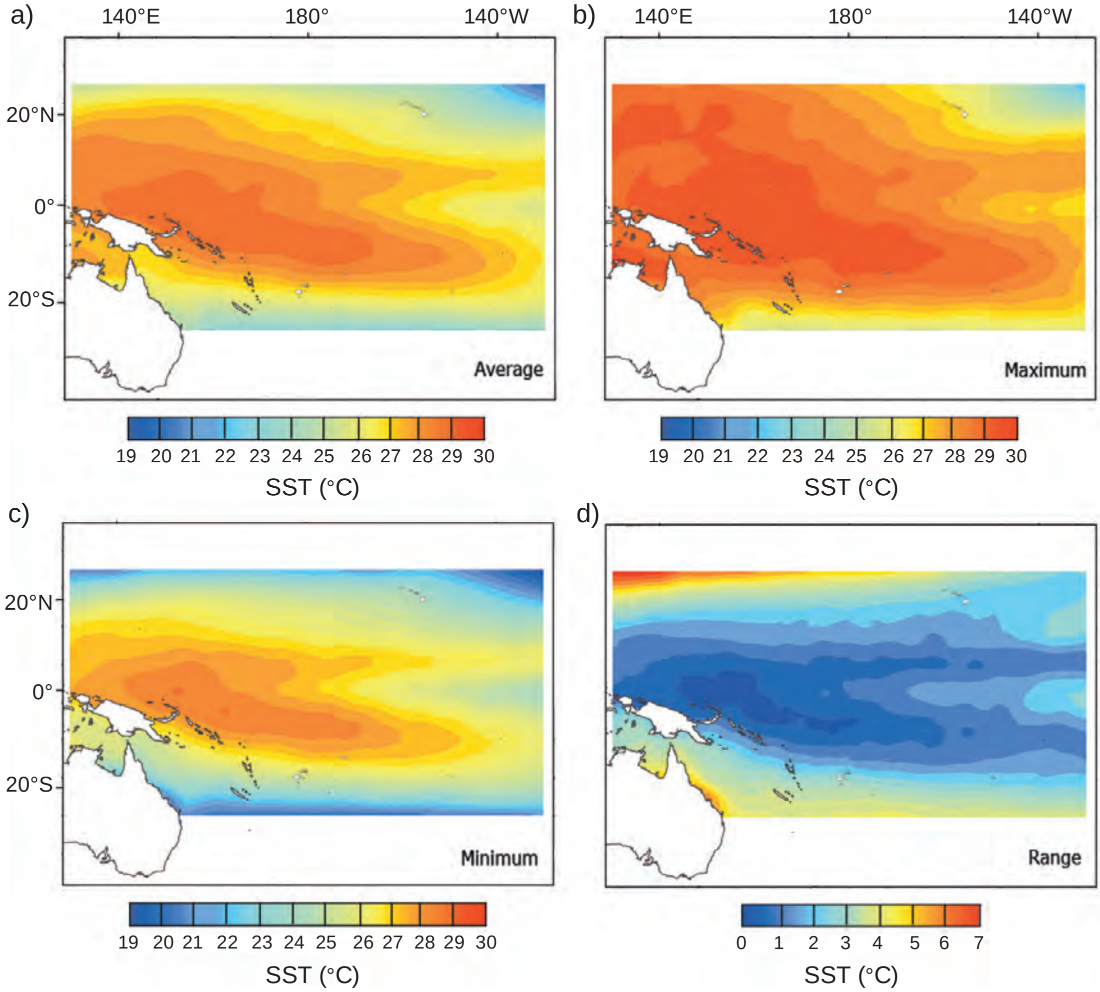


Figure 2.7 Average sea surface temperature (SST) in the tropical Pacific, 1950–2007, for (a) annual average, (b) annual maximum, (c) annual minimum and (d) annual temperature range (source: Rayner et al. 2003, 2006, HadISST)[97,98,100].

2.3.4 Tropical cyclones

Tropical cyclones are the most destructive weather disturbances that affect parts of the Pacific[44]. They are rarely observed within about 5–10° of the equator and, thus, their main impacts are on the islands of the southwest and northeast tropical Pacific (**Figure 2.10**) during the respective summer seasons. Tropical cyclones bring strong winds, high rainfall, storm waves and destructive storm surges to affected islands and are currently graded in the region from category 1 through to the most severe, category 5 (**Table 2.2**). In the southwest Pacific, tropical cyclones usually develop in the summer season, from November to April, but occasionally occur in May. Peak cyclone occurrence is usually from January to March.

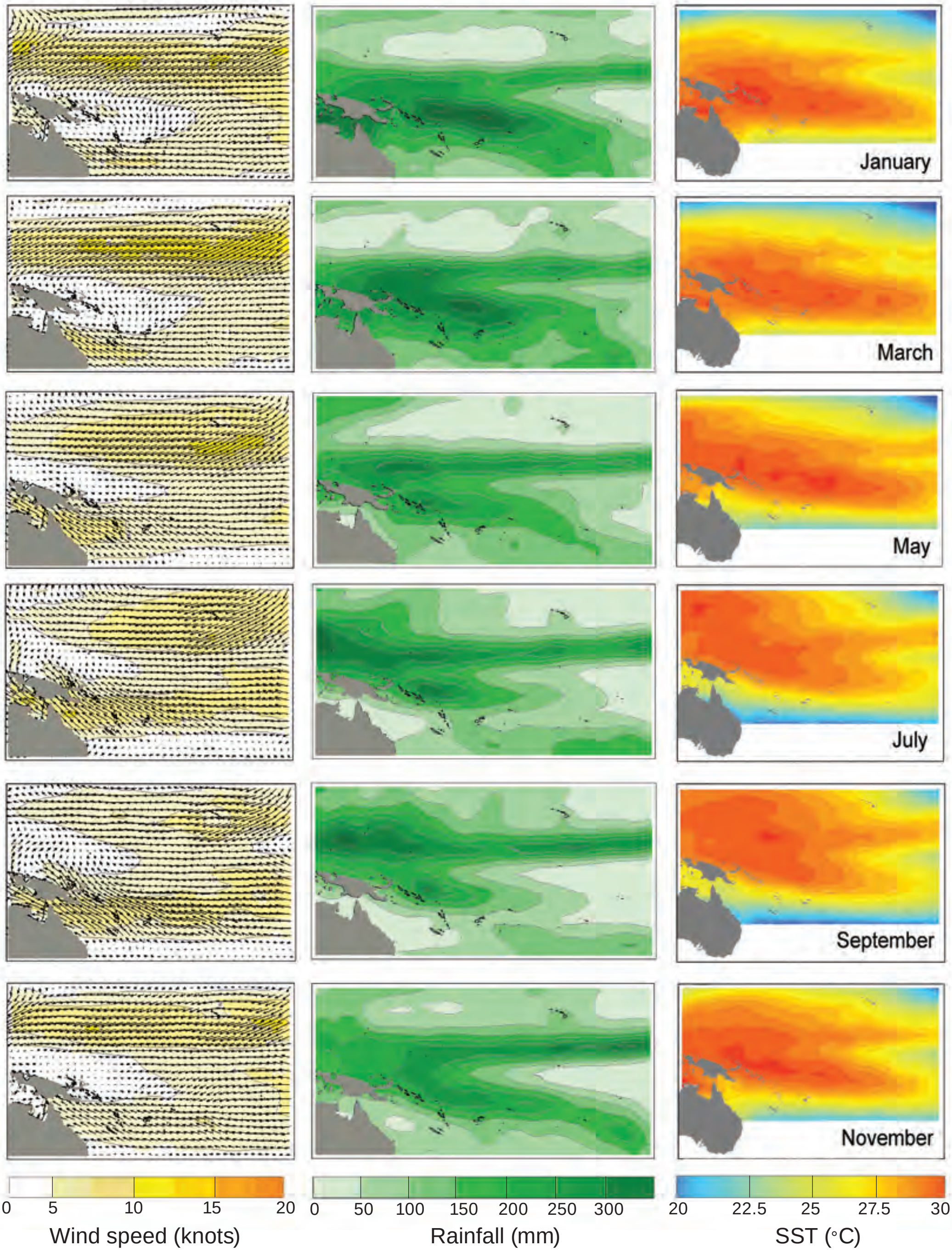


Figure 2.8 Surface climate averages, every two months throughout the year, for the tropical Pacific. Left: monthly average wind speed and direction (1971–2000) (NCEP Reanalysis). Centre: monthly rainfall, mm/month (1979–1995) (source: CAMS-OPI climatology, Janowiak and Xie 1999)[102,103]. Right: monthly average sea surface temperature (HadISST)[100].

Several tropical cyclones usually occur between Vanuatu and Niue each year with some affecting other areas. About half of the tropical storms that develop in the Pacific reach cyclone force with mean wind speeds of at least 118 km/h. Regionally, the highest frequencies of tropical cyclones occur between New Caledonia and Vanuatu in the Coral Sea, and towards Fiji (**Figure 2.11**).

Table 2.2 Tropical cyclone category and severity scale indicating typical magnitude of effects (source: Australian Bureau of Meteorology)[113].

Category	Strongest gust (km/h)	Average maximum wind (km/h)	Central pressure (hPa)	Typical effects
1	< 25	63–88	> 985	Negligible house damage. Damage to some crops, trees and caravans. Craft may drag moorings.
2	125–164	89–117	985–970	Minor house damage. Significant damage to signs, trees and caravans. Heavy damage to some crops. Risk of power failure. Small craft may break moorings.
3	165–224	118–159	970–955	Some roof and structural damage. Some temporary dwellings destroyed. Power failures likely.
4	225–279	160–199	955–930	Significant roofing loss and structural damage. Many caravans destroyed and blown away. Dangerous airborne debris. Widespread power failures.
5	> 279	> 200	< 930	Extremely dangerous with widespread destruction.

2.3.5 Intra-annual, interannual and decadal Pacific climate variability: ENSO, PDO and SAM

Superimposed on the average seasonal cycles of surface climate (Figure 2.8) and observed trends in surface climate (Section 2.4), are various sources of natural climate variability that modulate atmospheric and oceanic climate on time scales from weeks to decades.

The El Niño-Southern Oscillation (ENSO) phenomenon is the principle source of interannual global climate variability. This highly coupled ocean-atmosphere phenomenon is centred in the tropical Pacific. ENSO has significant impacts on climate and society, both within the region and, through teleconnections, in many distant parts of the world[13,45–48]. ENSO fluctuates between two phases, El Niño and La Niña, that disturb the normal atmospheric and oceanic circulations in the tropical Pacific (**Figure 2.12**). Both phases typically evolve over a period of 12–18 months and have some predictability once they have started to develop[49,50].

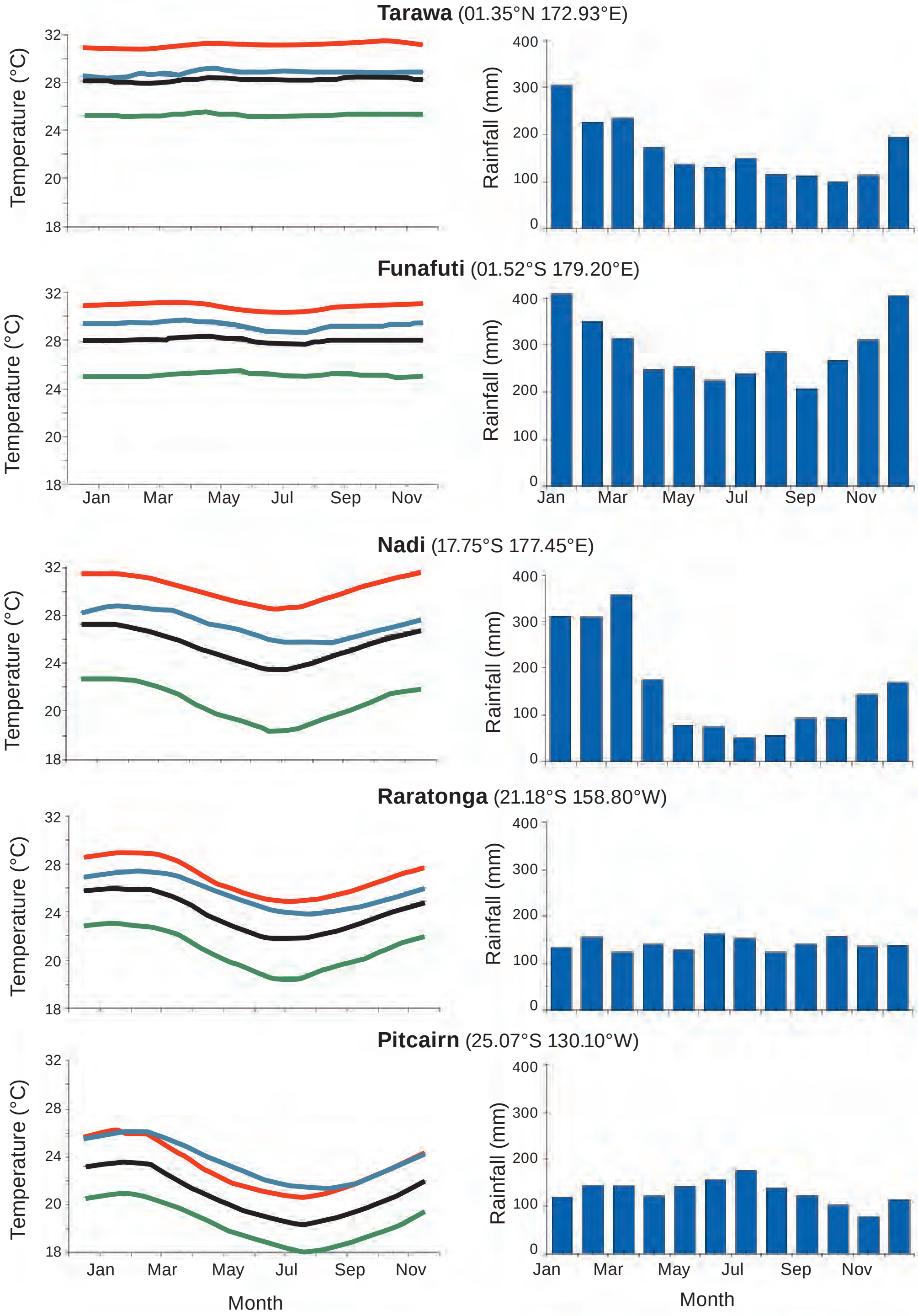


Figure 2.9 Average seasonal climate for five Pacific island stations, 1951–1980 (source: NIWA)[92]. Left: monthly average air temperature (black), monthly maximum air temperature (red), monthly minimum air temperature (green) and sea surface temperature (blue). Right: monthly total rainfall. The latitude and longitude of each station are also shown.

During El Niño events, the easterly trade winds weaken along the equator and a large part of the Pacific experiences unusually warm SSTs. This is associated with a weakening of the horizontal Walker circulation and strengthening of the meridional Hadley circulation. The centre of intense tropical convection shifts eastward towards the dateline and the ITCZ and SPCZ move closer to the equator. As a result, some regions experience drought conditions, while others receive much greater than average rainfall. There are also shifts in the dominant location of tropical cyclone activity. The slope of the thermocline (separating warmer surface and cooler deeper waters) flattens across the Pacific and the Warm Pool shifts eastwards (Chapter 3).

Climate anomalies during La Niña events are typically opposite to those of El Niño episodes, with stronger trade winds and large parts of the tropical Pacific experiencing cooler than normal SSTs. There are changes in the usual locations of tropical cyclones and a shift of the heaviest rainfall zone to the far western tropical Pacific. The depth of the thermocline increases from east to west across the Pacific during La Niña events.

The reliability of seasonal outlooks for ENSO conditions has improved significantly and is based on being able to successfully observe and model the development of SST anomalies in the tropical Pacific up to a year in advance of an event[47]. Two commonly used indices of ENSO activity are (1) the Southern Oscillation Index (SOI), which measures the atmospheric component and reflects anomalies in sea-level pressure between Tahiti in the southwest Pacific and Darwin in northern Australia (**Figure 2.13a**), and (2) the Niño 3.4 region (5°N–5°S, 170°W–120°W) average SST anomaly, which captures the oceanic component of ENSO (**Figure 2.13b**). These indices are very similar, indicating the highly coupled ocean-atmosphere nature of ENSO, but also show differences in the timing and magnitude of individual events that typically recur every 3 to 7 years.

Each ENSO event evolves slightly differently, and there have been suggestions that the major features of ENSO (termed 'ENSO-Modaki') have recently changed[51]. However, there are features common to these different ‘flavours’[52], and features typical of the two phases can be determined by averaging the surface climate anomalies across several events. Large parts of the tropical Pacific typically experience significantly warmer than normal SSTs during El Niño events and, conversely, significantly cooler than normal SSTs during La Niña events (**Figure 2.14**). Different patterns of rainfall are also associated with the two phases (**Figure 2.15**).

ENSO events also affect the spatial occurrence of tropical cyclone activity. During El Niño episodes, the overall number of tropical cyclones tends to be lower, with highest occurrences between Vanuatu and Fiji, and chances of occurrence higher further east in Samoa, southern Cook Islands and French Polynesia. During La Niña events, tropical cyclones are more frequent in the Coral Sea, with highest occurrence around New Caledonia, and higher occurrence between the coast of Queensland and Vanuatu in the Coral Sea. There is an absence of tropical cyclones from Cook Islands eastwards during La Niña episodes (**Figure 2.16**).

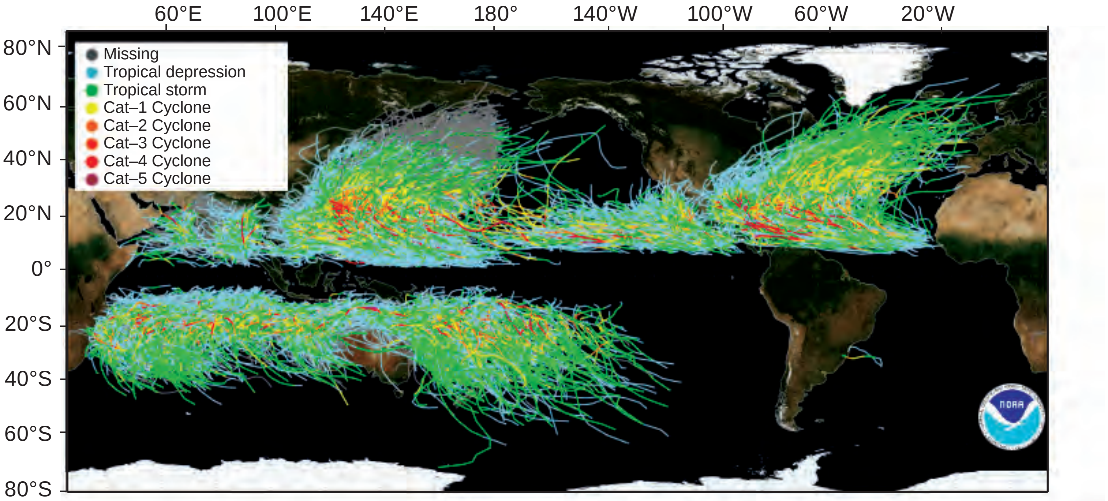


Figure 2.10 Tropical storm and cyclone tracks, 1947–2007, illustrating the areas of the tropical Pacific that are regularly affected by tropical storm activity and the near-equatorial region, which does not experience disturbances from these severe weather events (source: IBTrACbtracs)[104].

The location of the SPCZ also varies systematically with ENSO-related expansion and contraction of the Warm Pool[53]. Such movements can result in very large anomalies in precipitation on either side of the mean location of the SPCZ[54] as it moves northeast during El Niño events and southwest during La Niña episodes (**Figure 2.17**).

The interannual variability of ENSO and the strength of its climate teleconnections are modulated on decadal timescales by a long-lived pattern of Pacific climate variability known as the Pacific Decadal Oscillation (PDO)[55,56] or the Interdecadal Pacific Oscillation (IPO)[57]. The PDO is the North Pacific part of a Pacific basin-wide pattern encompassed by the IPO. It is described by an 'El Niño-like' pattern of Pacific SST anomalies and appears to persist in either a warm or cool phase for several decades (**Figure 2.13c**). Warm phases characterised the 1920s to 1940s and the period from the mid-1970s to at least the 1990s. In these periods, ENSO was a weaker source of interannual climate variability. They were preceded and separated by IPO and PDO cool phases from the 1900s to 1920s, and 1940s to 1970s, when ENSO was a major source of interannual climate variability[58]. Decadal variability in the SST field of the tropical Pacific is associated with decadal variability in atmospheric characteristics such as sea-level pressure, winds and precipitation[58,59].

The Southern Annular Mode (SAM) is the most important source of variability in the atmospheric circulation of the mid to high latitudes of the Southern Hemisphere, where it operates on time scales longer than ~ 50 days. It is characterised by a zonally symmetric pattern of atmospheric circulation with pressure anomalies of opposite sign in mid and high latitudes[60,61]. SAM fluctuates between two phases, which can be defined by the sea-level pressure difference between ~ 45°S and ~ 65°S. The strength of the westerly winds of the Southern Ocean is enhanced in the positive phase of SAM and weakened during the negative phase. The two phases influence surface climate patterns of rainfall and temperature over Antarctica and the mid-high latitudes of Southern Hemisphere land masses. Variations in the strength of the zonal westerly winds associated with SAM also influence sea level and ocean circulation patterns (Chapter 3). There is also observational evidence that SAM has become more positive in recent decades, enhancing westerly winds in the Southern Ocean[13].

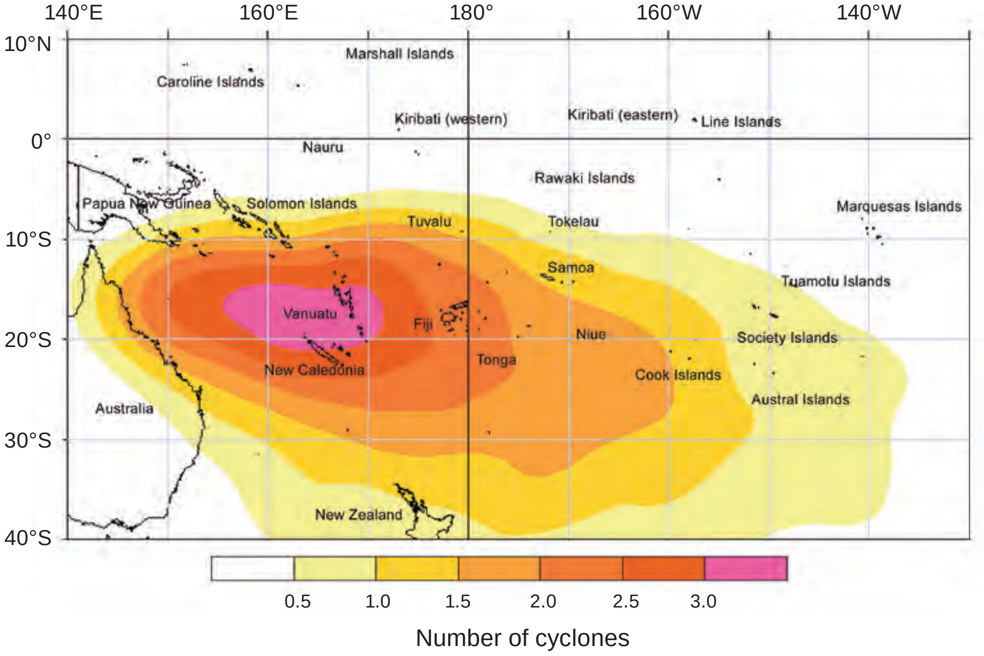


Figure 2.11 Average spatial occurrence of tropical cyclones in the southwest Pacific over the period 1970–1971 to 2001–2002, illustrating maximum numbers near Vanuatu (source: NIWA)[92].

2.4 Recently observed climate trends

Average global air and sea surface temperatures have already warmed significantly (**Figure 2.2**) and the rate of warming appears to be accelerating (0.12°C per decade for the period 1950–2008 compared to 0.04°C per decade from 1850 to 2008). Sea surface temperatures from 1950 to 2007 averaged over the tropical Pacific (25°N–25°S, 130°E–130°W) also show significant warming. For SST, however, the rate of change in the region is less than the global average, with values for the annual average of 0.07°C per decade, for the annual maximum of 0.08°C per decade and annual minimum of 0.06°C per decade (**Figure 2.3**). Linear trends can be distorted by the choice of the start and end year, but a comparison of temperature differences for two 20-year subperiods (1989–2008 and 1950–1969)[1] supports the linear trend analyses showing that there have been significant changes in temperature globally (+0.44°C), and in tropical Pacific SSTs (+0.23°C, +0.26°C and +0.19°C, for average annual, maximum and minimum temperatures, respectively). These large-scale averages, however, hide important spatial differences in the patterns of warming in the tropical Pacific (**Figure 2.18**), with some regions warming more than others, and some parts showing no significant trends as yet.

Here, we look in more detail at observed changes in various climate variables, mainly in the south Pacific where considerable effort has improved and homogenised the instrumental climate records[2,62]. The observational networks were still quite sparse in the first half of the 20th century but improved markedly after World War II.

2.4.1 Surface air temperature

Surface air temperatures, averaged over the southern tropical Pacific, have warmed significantly since the late 19th century (**Figure 2.19**). The rate of recent warming has accelerated (from 0.03°C per decade from 1850 to 0.11°C per decade since 1950) and 8 of the 10 warmest years between 1850 and 2007 have occurred in the last 10 years. As noted for SSTs, the changes are not uniform and the southern tropical Pacific can be divided into distinct areas on the basis of observed temperature trends: southeast trades (16°S to 27°S, 164°E to 144°W), central Pacific (2°N to 17°S, 172°W to 139°W) and convergence zones (1°N to 12°S, 169°E to 179°E). Temperature trends in the central Pacific and convergence zones are quite similar but differ from those in the area of the southeast trade winds[54,63,64].

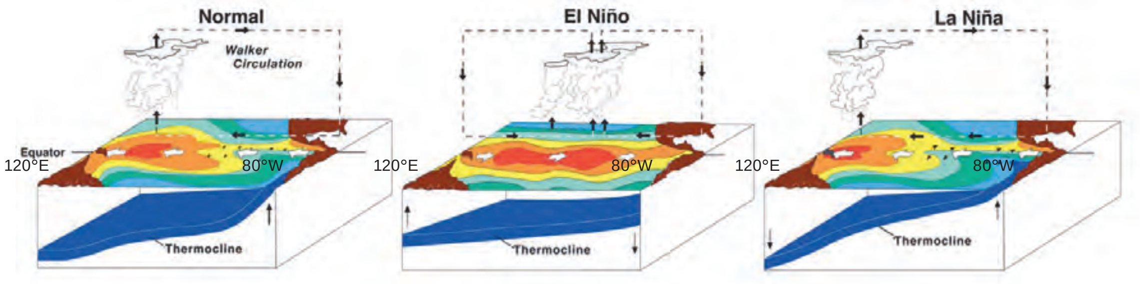


Figure 2.12 Pacific climate conditions during normal years (left), El Niño events (centre) and La Niña events (right) (source: McPhaden 2004)[47].

Average surface air temperatures in the area of the southeast trades have increased significantly but at a slightly lower rate than for the southern tropical Pacific as a whole (**Figure 2.20a**). The rate of warming since 1950 is 0.08°C per decade and 5 of the 10 warmest years on record have occurred in the last 10 years. There are, however, differences in the observed trends for daily maximum and minimum temperatures and between seasons over the period of high-quality observational data, 1941–1990 (**Table 2.3**). Significant warming occurred in annual and austral summer and autumn daily mean and daily minimum air temperatures by ~ 0.4–0.5°C. Warming of daily maximum air temperatures over this period was not significant and nor were the slight decreases observed in the daily temperature range.

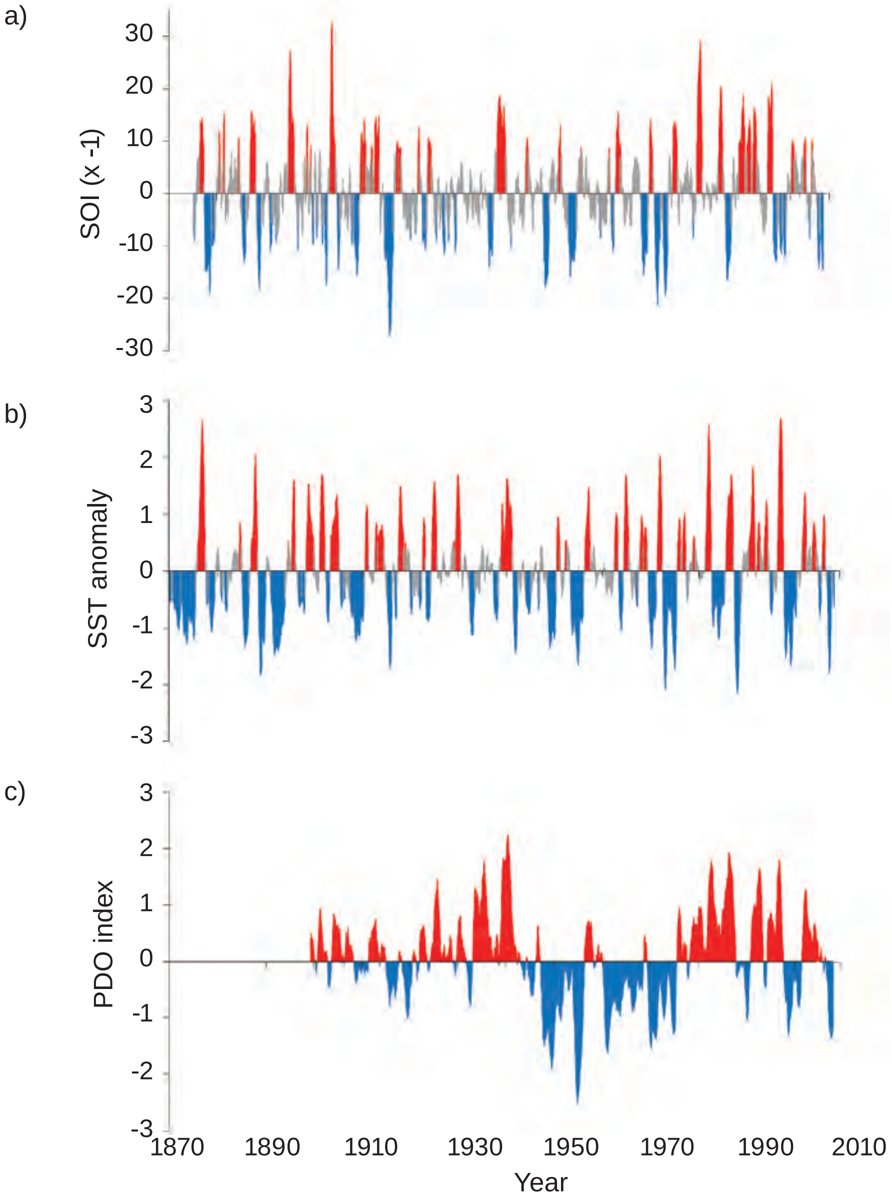


Figure 2.13 Indices of interannual and decadal climate variability in the tropical Pacific. (a) Southern Oscillation Index (SOI), standardised monthly anomaly of sea-level pressure difference between Tahiti and Darwin, values filtered with 5-month running mean and multiplied by -1; monthly values ±1 SD highlighted in red (positive El Niño) and blue (negative La Niña); for the period 1876–2008 (source: Troup 1965, Australian Bureau of Meteorology)[45,105]; (b) Niño 3.4 region (5°N–5°S, 170°W–120°W) sea surface temperature index, i.e. monthly sea surface temperature (SST) anomalies from 1971–2000 mean filtered with 5-month running mean and then standardised by 1971–2000 SD; monthly values ±1 SD highlighted in red (positive El Niño) and blue (negative La Niña); for the period 1871–2008 (source: Trenberth 1997, HadISST, Rayner et al. 2003, National Oceanic and Atmospheric Administration (NOAA))[97,100,106,107]; (c) Pacific Decadal Oscillation (PDO) Index based on Empirical Orthogonal Function (EOF) analyses of Pacific SSTs; monthly values filtered with 12-month running mean, for the period 1900–2008 (source: Mantua et al. 1997, Zhang et al. 1997)[55,56].

Warming of air temperatures in the central Pacific area is significant but is slightly less since 1850 than for the other regions (**Figure 2.20b**). The current rate of warming since 1950 is, however, similar at 0.10°C per decade and three of the 10 warmest years have occurred in the most recent 10-year period. Although daily mean, maximum and minimum temperatures have all warmed by ~ 0.3–0.4°C (**Table 2.3**) in all seasons, there have been no significant changes over the period 1941–1990.

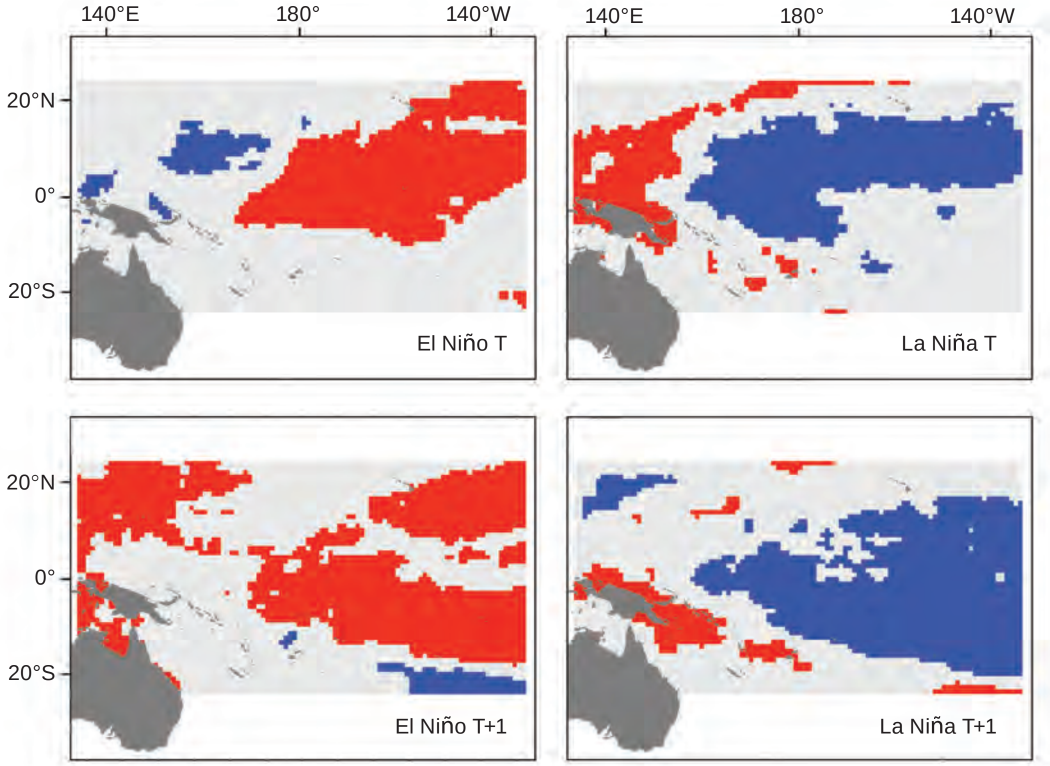


Figure 2.14 Areas with significantly warmer (red) or cooler (blue) maximum annual sea surface temperature (SST) during El Niño events (left) and La Niña events (right) for year T (top panels) and year T+1 (lower panels). SST anomalies were averaged for two years spanning 20 El Niño and 20 La Niña events and tested for significant difference from similar averages for 20 ENSO-neutral years within the period 1871–2002 (source: Rayner et al. 2003, 2006, HadISST)[97,98,100].

The area covered by the ITCZ and SPCZ also shows significant warming since 1850 (**Figure 2.20c**). The rate of warming since 1850 of 0.02°C per decade was slightly lower than for the other regions but has recently (since 1950) accelerated to 0.15°C per decade, and 5 of the 10 warmest years have occurred within the most recent 10-year period. Changes in daily temperature characteristics are not significant over the period 1941–1990, although in contrast to the other regions, a warming of maximum daily temperatures and slight cooling of daily minimum temperatures have resulted in an increase in the daily temperature range.

Table 2.3 Differences in seasonal and annual mean, maximum and minimum daily surface air temperatures (°C) determined from linear trend analyses from 1941 to 1990, for three areas in the Pacific (see Section 2.4 for the definition of these areas). Daily southern tropical temperature range is also shown.

Area	Surface air temperature (°C)			
	Mean	Maximum	Minimum	Daily range
Southeast trade winds				
DJF	0.46*	0.43	0.49*	-0.06
MAM	0.45*	0.36	0.52*	-0.16
JJA	0.36	0.33	0.35	0.02
SON	0.44	0.33	0.52	-0.19
Annual	0.45*	0.37	0.47*	-0.10
Central Pacific				
DJF	0.41	0.34	0.43	-0.09
MAM	0.43	0.26	0.52	-0.26
JJA	0.40	0.39	0.35	0.04
SON	0.49	0.37	0.53	-0.16
Annual	0.43	0.34	0.45	-0.11
ITCZ and SPCZ				
DJF	0.01	0.21	-0.08	0.29
MAM	-0.02	0.11	-0.09	0.20
JJA	0.05	0.24	-0.14	0.38
SON	0.01	0.06	-0.05	0.11
Annual	0.02	0.16	-0.09	0.25

* Indicates significance at the 5% level; ITCZ = Intertropical Convergence Zone, SPCZ = South Pacific Convergence Zone; DJF = December–February; MAM = March–May; JJA = June–August; SON = September–November (source: Salinger 1995)[64].

2.4.2 Rainfall

'At present, documenting interannual variations and trends in precipitation over the oceans remains a challenge.' (Trenberth et al. 2007)[13]

How much rain falls, when it falls, and the frequency and intensity of rainfall events all shape the 'climate envelope' of a given location. Detecting trends in rainfall, especially over tropical ocean regions, is hampered, however, by the relative lack of long-term observations, the inherently larger variability of rainfall in space and time compared to temperatures, and the high interannual variability of Pacific rainfall due to ENSO events[65,66].

Trends in rainfall and rainfall extremes have been examined for the period 1961–2000 for a number of stations with high-quality daily data (**Figure 2.5**) in the south Pacific[62]. Total annual rainfall (**Figure 2.21a**) shows a general decrease over the south Pacific southwest of the SPCZ and a general increase to the northeast of the SPCZ. The largest changes occurred east of 160°W.

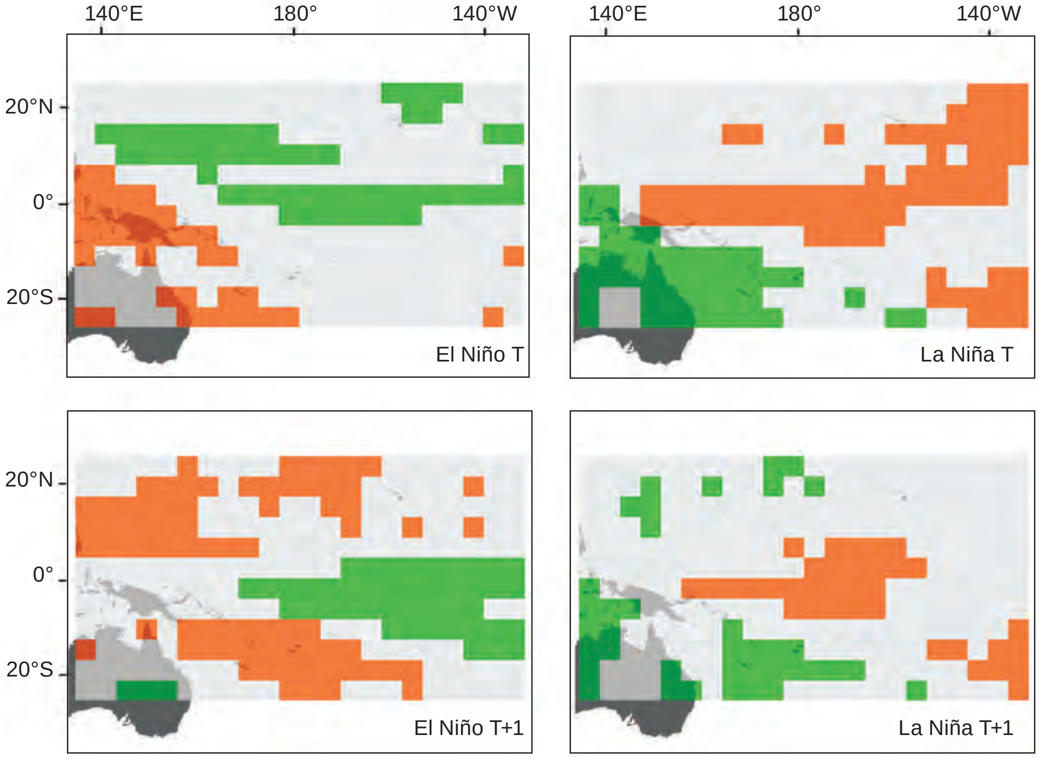


Figure 2.15 Areas with significantly wetter (green) or drier (orange) conditions during El Niño events (left) and La Niña events (right) for year T (top panels) and year T+1 (lower panels). Annual rainfall anomalies were averaged for two years spanning 16 El Niño and 14 La Niña events and tested for significant difference from similar averages for 15 ENSO-neutral years within the period 1900–2006 (source: Smith et al. 2008)[109].

Significant increases in total rainfall occurred only at Penrhyn (about 500 mm per decade) and at Atuona (about 250 mm per decade). Small but insignificant decreases in total rainfall occurred in southern Cook Islands, Rapa, Apia, Nuku'alofa, and Raoul Island, but there has been a significant decline of 180 mm per decade at Pitcairn. West of the dateline, trends in total rainfall are small and show no obvious spatial patterns within the island groups of Tonga, Fiji, New Caledonia and Tuvalu. Trends in total rainfall are spatially consistent east of the dateline, with a discontinuity across the diagonal portion of the SPCZ. These results are consistent with the diagonal SPCZ having moved northwards over the analysis period[53].

Trends in the number of days on which rain falls (rain day index ≥ 2 mm per day) are similar to those for total rain, with sites experiencing more rainfall typically having more rain days than sites with less total rainfall (**Figure 2.21b** cf. **Figure 2.21a**). East of 160°W, there was a significant increase in the number of rain days at Penrhyn (by 17 rain days per decade) and Atuona (by 13 days per decade), and a significant decrease at Pitcairn (by 8 days per decade). As for total rainfall, no significant trends or consistent patterns of change were found for the island groups of Tonga, Fiji, New Caledonia and Tuvalu. Again, these observed trends are consistent with the northward movement of the diagonal portion of the SPCZ.

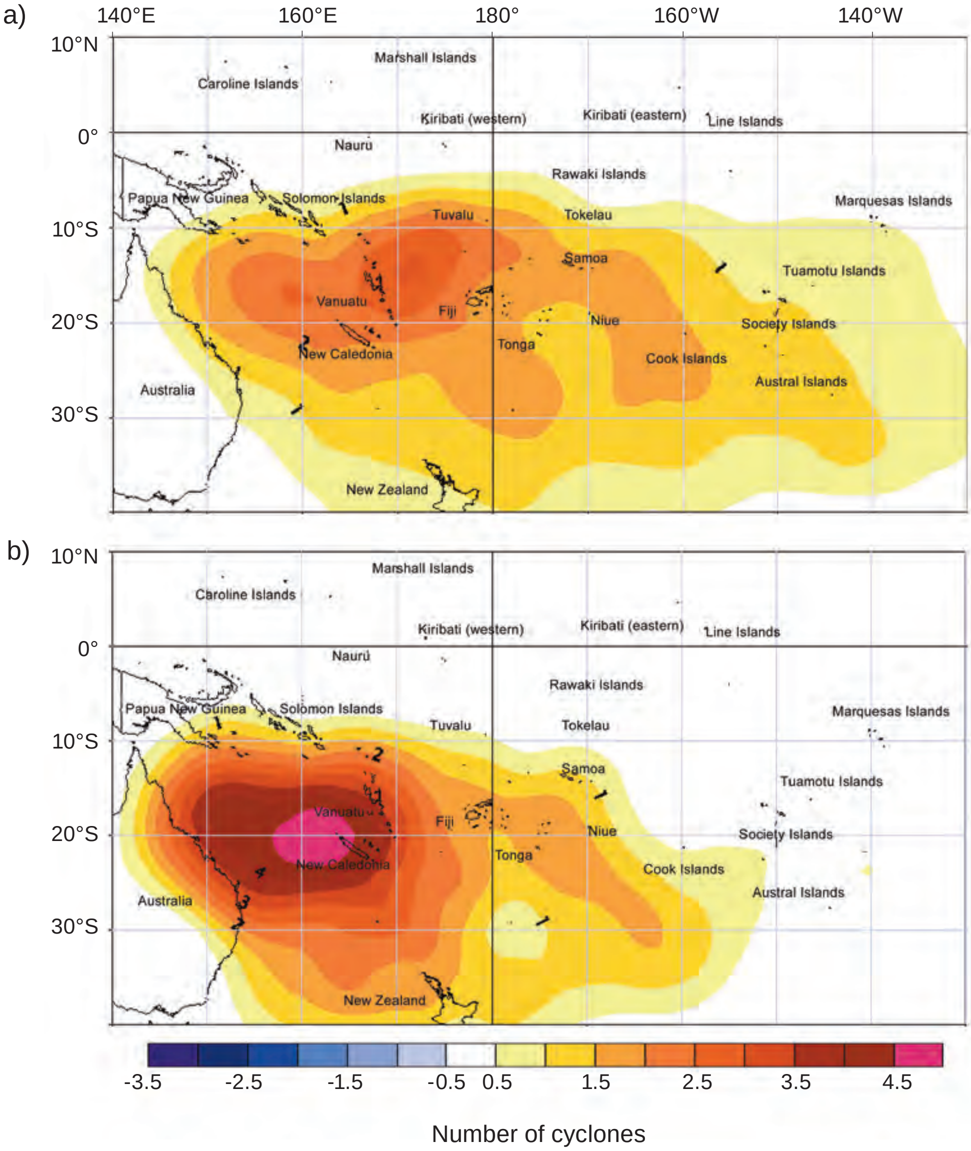


Figure 2.16 Typical spatial patterns of occurrence of tropical cyclones in the southwest Pacific for (a) El Niño and (b) La Niña seasons (source: NIWA)[92].

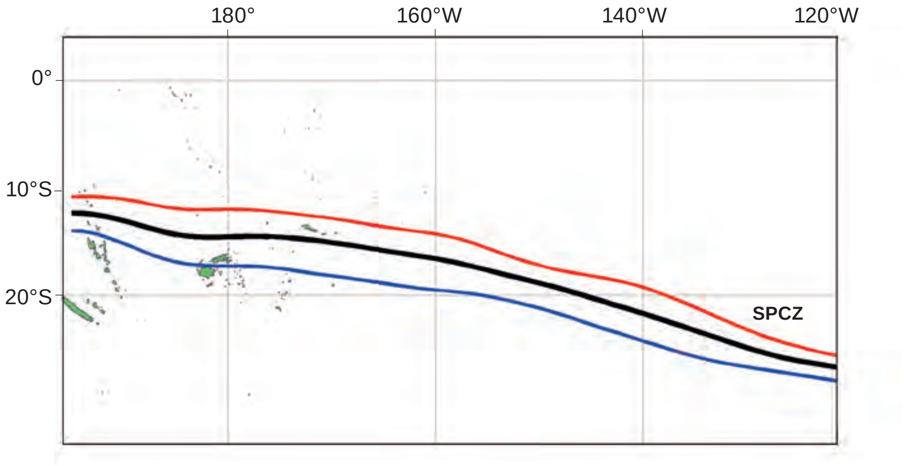


Figure 2.17 Average position of the South Pacific Convergence Zone (SPCZ) from November to April in El Niño (red), ENSO-neutral (black) and La Niña (blue) seasons.

The dry spell index is the maximum number of consecutive dry days each year (days < 1 mm of rain). Stations lying to the southwest of both the zonal and diagonal sections of the SPCZ, or near the SPCZ zone itself, showed an increase in dry spells, corresponding to a lengthening of the maximum dry period duration (**Figure 2.21c**). New Caledonia, Raoul Island, Tonga, Niue, Samoa, Pukapuka, Rarawai, Labasa and Pitcairn all show an increase in dry spells, with the greatest increase of 4.3 days per decade at Koumac. The only significant trend, however, occurs at Aitutaki, with an increase of 1.7 days per decade over the period 1961–2000. Unlike total rain and rain days, the dry spell indices for Tarawa, Penrhyn and Atuona show only small and insignificant decreases. The lengthening of the dry spell southwest of the entire SPCZ is consistent with the diagonal section of the SPCZ having moved northwards. Changes in the SPCZ are associated with an increase in mean sea-level pressure west of the dateline since 1977[67].

Three other indices of daily rainfall were examined: the 5-day rainfall index; the extreme intensity rainfall index (calculated as the average of the highest four rainfall events each year) as an indicator of the typical size of an extreme rainfall event; and the extreme frequency index, which is a count of high rainfall events per year (frequency of daily rainfall exceeding the 1961–1990 mean 99th percentile (days)).

The 5-day maximum rainfall index increased significantly at Penrhyn and decreased significantly at Nanumea (**Figure 2.22a**). Trends in extreme rainfall intensity are again incoherent west of the dateline, and in the island groups of Fiji and the southern Cook Islands (**Figure 2.22b**). More intense extreme rainfall events occur in the vicinity of the diagonal SPCZ near 170°W (e.g. Rotuma to Alofi), and to the north of the diagonal SPCZ east of 170°W. There have been no significant changes in these extreme intensity events in New Caledonia, Niue, Apia and Pukapuka. Significant increases in extreme rainfall intensity are exhibited at Penrhyn and Atuona, which both show an increase of 10 mm per decade. Significant decreases in extreme intensity events occurred at Nanumea, Rapa and Pitcairn (with decreases ranging between 6 and 10 mm). As with total rain, the largest trends in this index occur in the eastern Pacific Ocean, e.g. east of 160°W, with the exception of Nanumea.

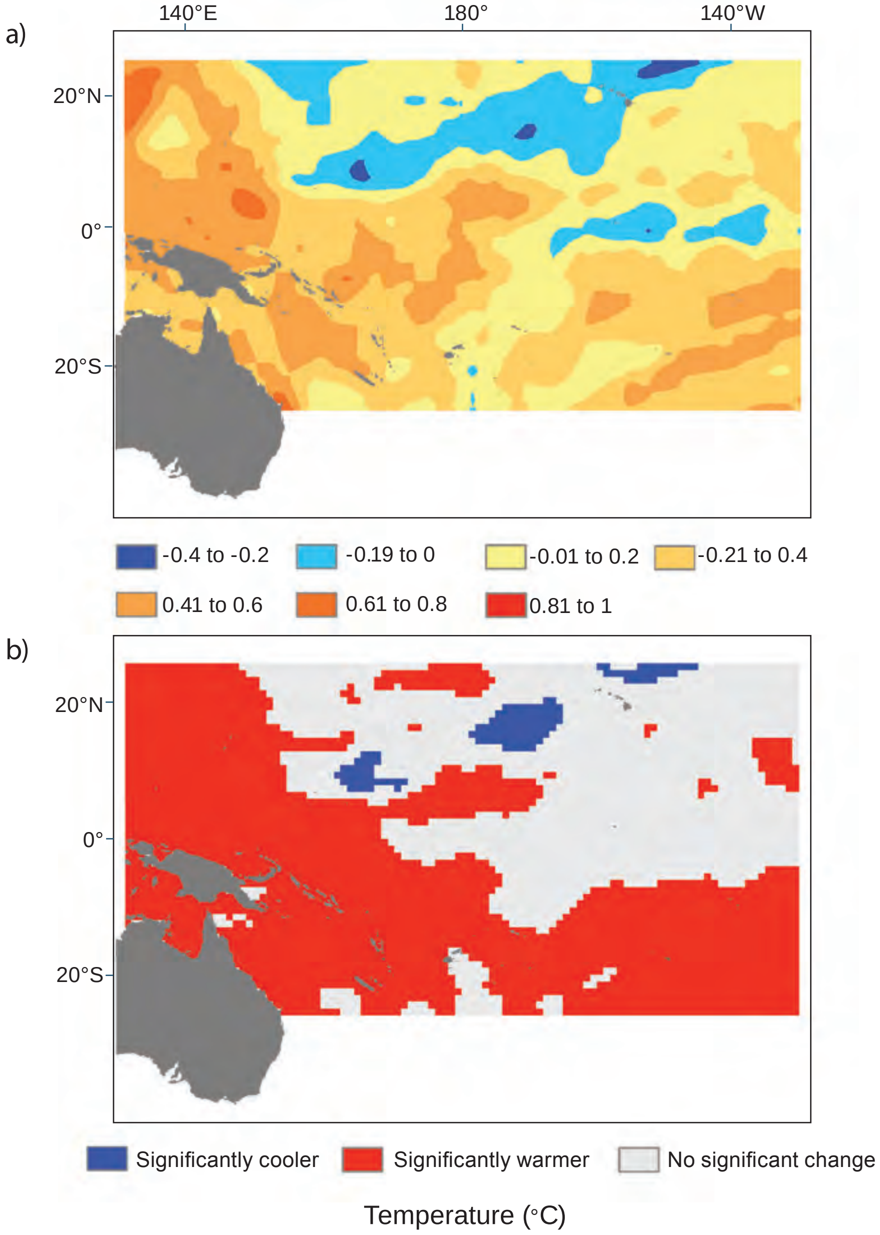


Figure 2.18 (a) Differences in average annual sea surface temperatures between the periods 1988–2007 and 1950–1969; and (b) the significance of differences between these periods (source: Rayner et al. 2003, 2006, HadISST)[97,98,100].

Trends in the extreme frequency index show the same sign and spatial pattern as the trends in extreme intensity. Generally, there has been a decrease in the frequency of extreme events south of the SPCZ (**Figure 2.22c**) and an increase to the north and in the vicinity of the SPCZ near 170°W. West of the dateline, trends are incoherent and small. As with total rain, significant increases in the extreme frequency occur only east of 160°W at Penrhyn and Atuona (1.5 and 1.2 days per decade, respectively). Significant decreases are seen at Rapa and Pitcairn (0.5 and 0.8 days per decade, respectively).

In summary, there have been some significant changes in the observed annual and daily rainfall climate of the southwest tropical Pacific, primarily on islands east of 160°W, with changes to the west tending to be small and incoherent. Generally, over the period 1961–2000, there has been more rainfall and more intense rainfall northeast of the SPCZ and less rainfall to the southwest of the SPCZ.

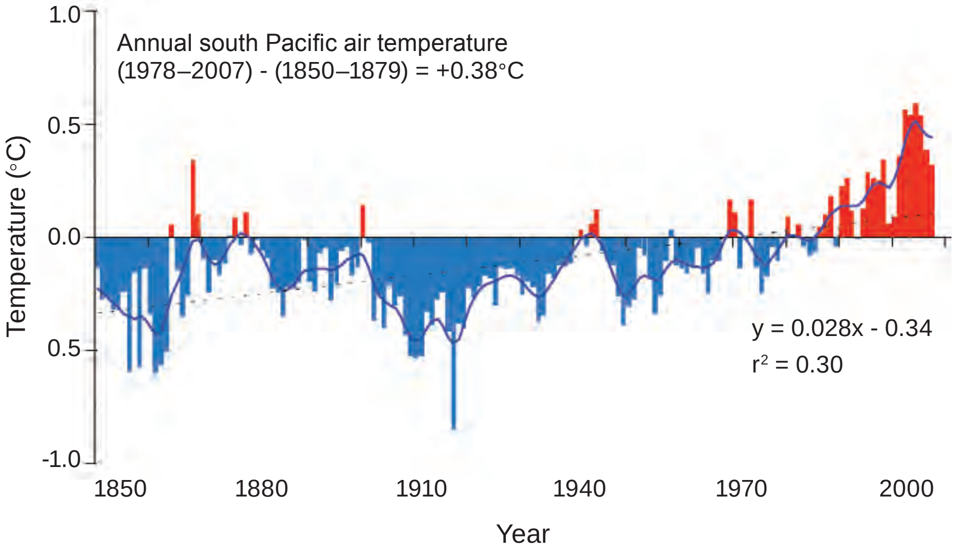


Figure 2.19 Annual average southern tropical Pacific surface air temperature anomalies (from 1971–2000 mean) for the period 1850–2007. Thick line is 10-year Gaussian filter emphasising decadal variability; dashed line is linear trend (source: HadCRUTv3)[94].

2.4.3 South Pacific Convergence Zone

The above analyses of observed changes in surface temperature and rainfall all highlight the significant role played by the SPCZ in the climate of the southwest Pacific. To assess whether there have been significant changes in the position of the SPCZ through time, high-quality, mean sea-level pressure data from stations in Suva (18°9'S, 178°26'E) and Apia (13°48'S, 171°47'W) were used to calculate a proxy index of SPCZ position. These two stations with long and reliable data often lie on opposite sides of the mean SPCZ location. Long-term variations (with positive values representing a displacement towards Apia, and negative values a displacement towards Suva) in the position of the SPCZ do not show any significant long-term change in the position over the period 1890–2005 (**Figure 2.23**). There are, however, decadal variations in the position that closely align with the warm and cool phases of the IPO/PDO (warm and cool refer to the relative sign of SST anomalies in the tropical Pacific) (**Figure 2.13c**).

During the cool phases of the IPO/PDO (e.g. mid-1940s to mid-1970s), the mean position of the SPCZ is displaced to the southwest. Conversely, during the warm phases of the IPO/PDO since the late 1970s, and during the 1920s–1930s, the SPCZ was northeast of its average position. The marked shift that occurred in the mid-1970s, when the IPO/PDO transitioned from relatively cool to warm, has been attributed to a combination of external anthropogenic forcing and internally generated decadal variability[68]. Since the late 1990s, the position of the SPCZ has been displaced southwest. Thus, the SPCZ, one of the most extensive features of the global atmospheric circulation, varies its location according to both the polarity of ENSO, and of the PDO. This significantly affects rainfall patterns throughout the south Pacific.

2.4.4 Tropical cyclones

There are, on average, nine tropical cyclones in the southwest Pacific per season over the period of reliable monitoring from 1969/70 to 2007/08 (**Figure 2.24**). About four tropical cyclones reach at least category 4 each season, with mean wind speeds of at least 118 km/h, and at least two will usually reach category 5, with mean speeds in excess of 167 km/h. There is no discernible trend in the frequency of tropical cyclones in the southwest Pacific over the 30-year period. There is also no evidence, as yet, for any significant change in the intensity of those tropical cyclones that do occur in the southern Pacific Ocean. This contrasts with evidence for stronger tropical cyclones in the Atlantic Ocean and, to a lesser extent, other regions of tropical cyclone activity[69].

2.5 Projected changes in surface climate

Many of the projections of future climate change for the tropical Pacific region continue trends that have been observed over the past several decades. With ongoing increases in anthropogenic greenhouse gases, and given that most of the global temperature increases over the last half century are very likely to have been due to those greenhouse gas increases[70], we can expect such changes to continue for at least the next several decades. This is because the future emissions scenarios do not diverge much over the short term[71]. There is still, however, an urgent recognised need to both improve current climate models for the tropical oceans[25] and to produce better regional-scale climate projections[72]. It is possible that the relatively coarse resolution and still imperfect generation of the global climate models used here do not adequately capture unanticipated changes in tropical Pacific climate. In addition, as a result of the inertia inherent in the ocean, even with an immediate cessation

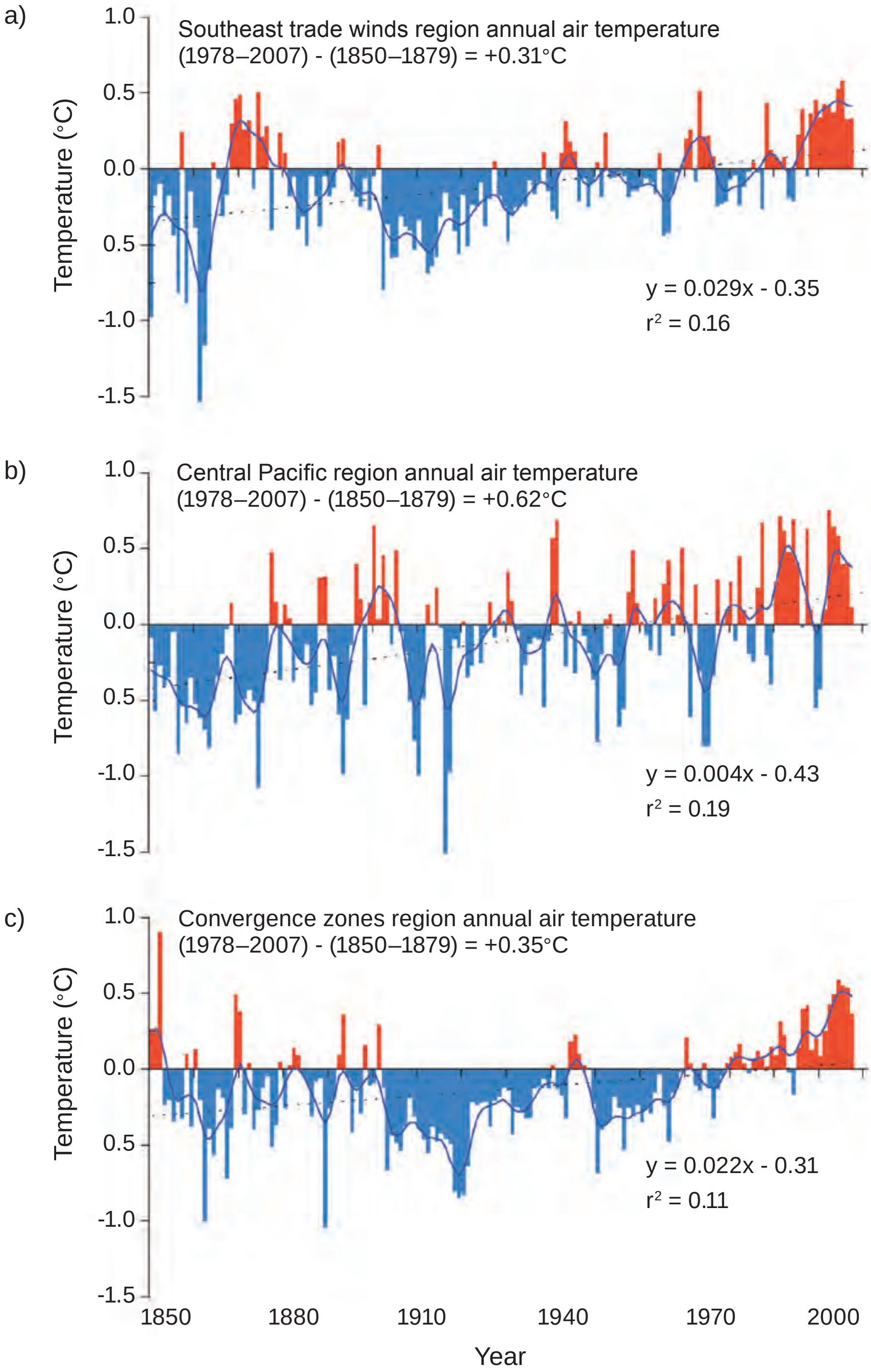


Figure 2.20 Annual average surface air temperature anomalies (from 1971–2000 mean) for the period 1850–2007 for (a) southeast trade winds, (b) central Pacific and (c) convergence zones regions of the tropical Pacific. Thick line is 10-year Gaussian filter emphasising decadal variability; dashed line is linear trend (source: HadCRUTv3)[94].

of greenhouse gas emissions, climate changes will still continue for many decades. Major differences in future climate outcomes due to different emissions scenarios do not become apparent until later in the 21st century.

In this section, we show projections for average temperature and precipitation change for the near-term (2035) and the longer term (2100) for the B1 low emissions scenario and the A2 high emissions scenario. Results from both these scenarios were extensively described in the IPCC-AR4[71]. Here we provide greater detail for the tropical Pacific region.

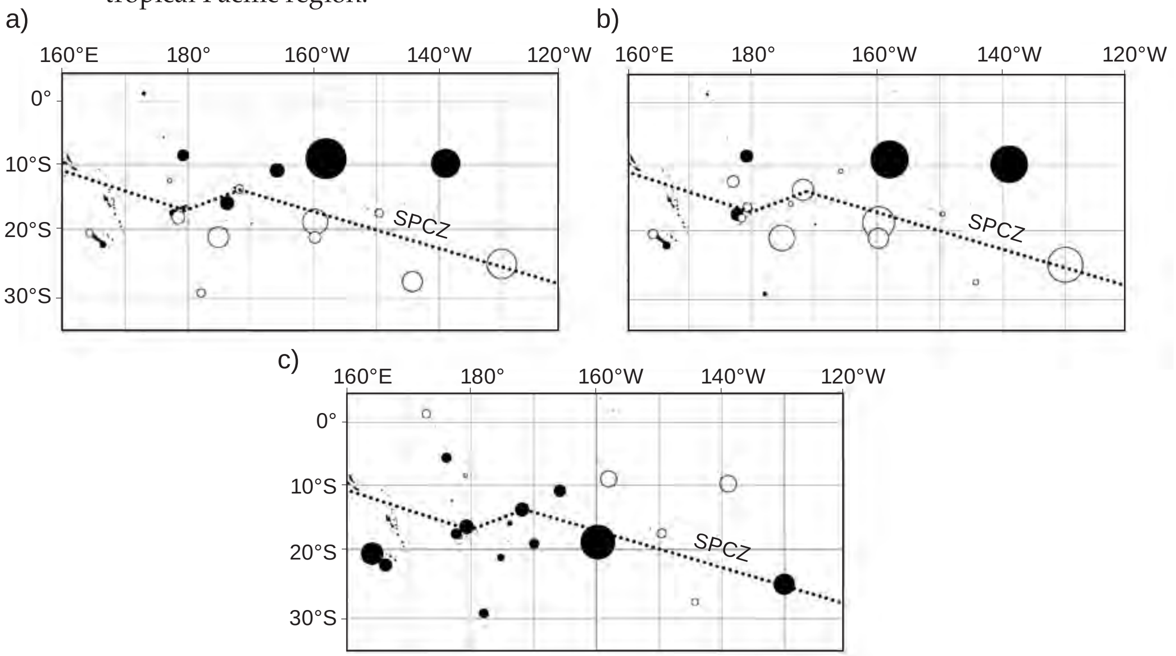


Figure 2.21 Trends in (a) total rainfall, (b) rain day index, and (c) dry spell index from 1961 to 2000, recorded at the meteorological stations shown in Figure 2.5. Black circles represent positive trends and white circles, negative trends. The size of the circle is proportional to the magnitude of the normalised linear trend per decade. SPCZ = mean position of the South Pacific Convergence Zone.

2.5.1 Air and sea surface temperatures

For the near-term (2035), both the low (B1) and high (A2) emissions scenarios show similar amounts of warming across the tropical Pacific, with values ranging from about +0.5°C to +1.0°C. Greater warming occurs in the equatorial regions compared to the subtropics[73], in particular in the eastern equatorial Pacific (**Figure 2.25a,c**).

Some of the warming is from climate change commitment; that is, the warming the climate system is committed to as a result of the additional greenhouse gases already in the system[32]. This is due to the fact that oceans warm more slowly than land and the thermal inertia of the oceans introduces a lag into the system. Averaged globally, climate change commitment amounts to about 0.10°C per decade for the next several decades[71]. Of course, the concentrations of greenhouse gases are also projected to increase in both the B1 and A2 scenarios over this time period. The globally-averaged temperature increase from that forcing, added to the commitment, is about 0.2°C per decade[71]. Therefore, over the next three decades, global warming would be about 0.6°C, close to the average projected for the tropical Pacific.

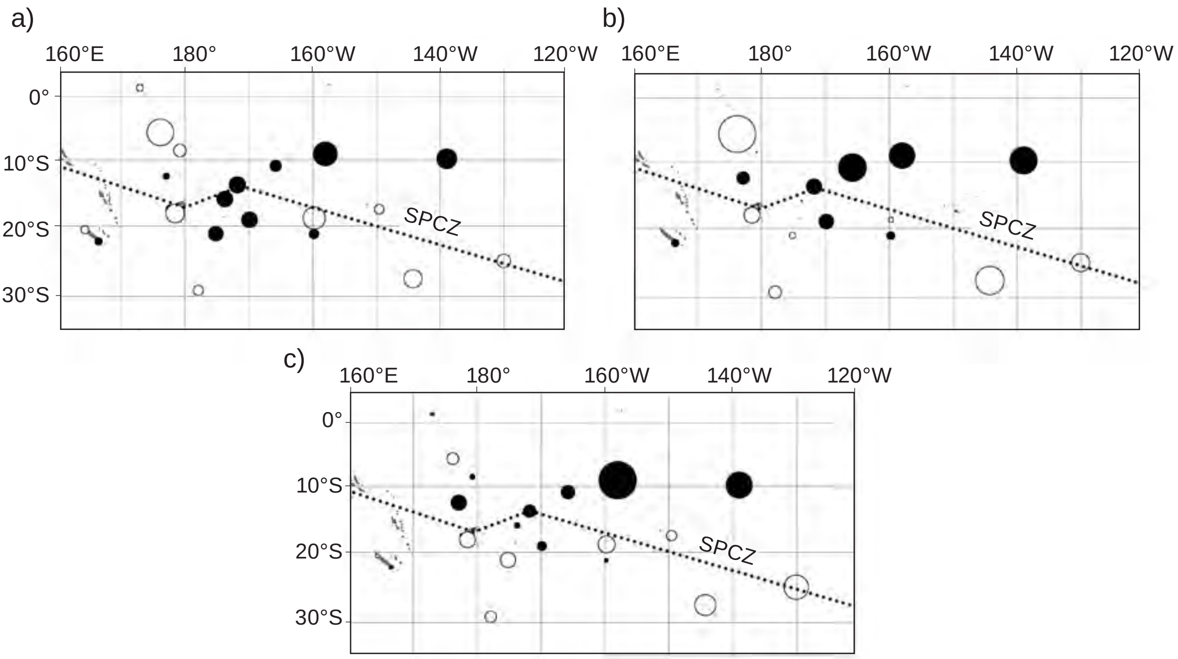


Figure 2.22 Trends in (a) 5-day rainfall, (b) extreme intensity rainfall, and (c) extreme frequency rainfall from 1961 to 2000, recorded at the meteorological stations shown in Figure 2.5. Black circles represent positive trends and white circles, negative trends. The size of the circle is proportional to the magnitude of the normalised linear trend per decade. SPCZ = mean position of the South Pacific Convergence Zone.

This additional warming over the next three decades is similar to the warming already observed (see previous section) and thus continues present-day trends. Future warming will also still be modulated by natural sources of climate variability[74]. These projections for 2035 assume, for example, that no large tropical volcanoes erupt. If a Pinatubo-type volcano were to erupt during this time period, the rate of warming would be reduced as was observed in the years after Pinatubo erupted in the early 1990s. However, after the volcanic aerosols clear from the atmosphere, the warming resumes and catches up (with some lag) in response to the forcing from the ever-increasing greenhouse gases that would continue during and after an eruption.

By the end of the century (**Figure 2.25b,d**), the emissions trajectory clearly makes a difference to projections. The warming of the tropical Pacific in the low B1 scenario (based on the multi-model averages) ranges from 1°C to 1.5°C, while in the high A2 scenario the warming is greater than 2.0°C over much of the tropical Pacific, with largest values in the eastern equatorial Pacific of 3.3°C. The annual mean values shown in **Figure 2.25** are also representative of seasonal mean values. **Table 2.4** illustrates what these short- and long-term temperature projections for the two scenarios might translate into in terms of average annual air temperatures at five Pacific island sites (**Figure 2.9**). Projections for SST are discussed in more detail in Chapter 3.

Table 2.4 Average observed annual air temperature (°C), 1951–1980, and projected ranges of estimated annual air temperatures (°C), for 2035 and 2100 under low emissions (B1) and high emissions (A2) scenarios (Figure 2.25) for five Pacific island stations (Figure 2.9).

Station	1951–1980 observed (°C)	2035		2100	
		B1	A2	B1	A2
Tarawa	28.2	29.0–29.2	28.7–29.0	29.7–30.0	31.2–31.5
Funafuti	28.0	28.5–28.8	28.5–28.8	29.3–29.5	30.8–31.0
Nadi	25.6	26.1–26.4	26.1–26.4	26.9–27.1	28.4–28.6
Raratonga	23.9	24.4–24.7	24.4–24.7	25.2–25.4	26.4–26.7
Pitcairn	20.9	21.4–21.7	21.4–21.7	21.9–22.2	22.6–22.9

* Note that the observed averages are for the period of good observational coverage, 1951–1980, whereas the projections are relative to the 1980–1999 average. Given the global warming observed already, the specific projections presented here may be underestimates.

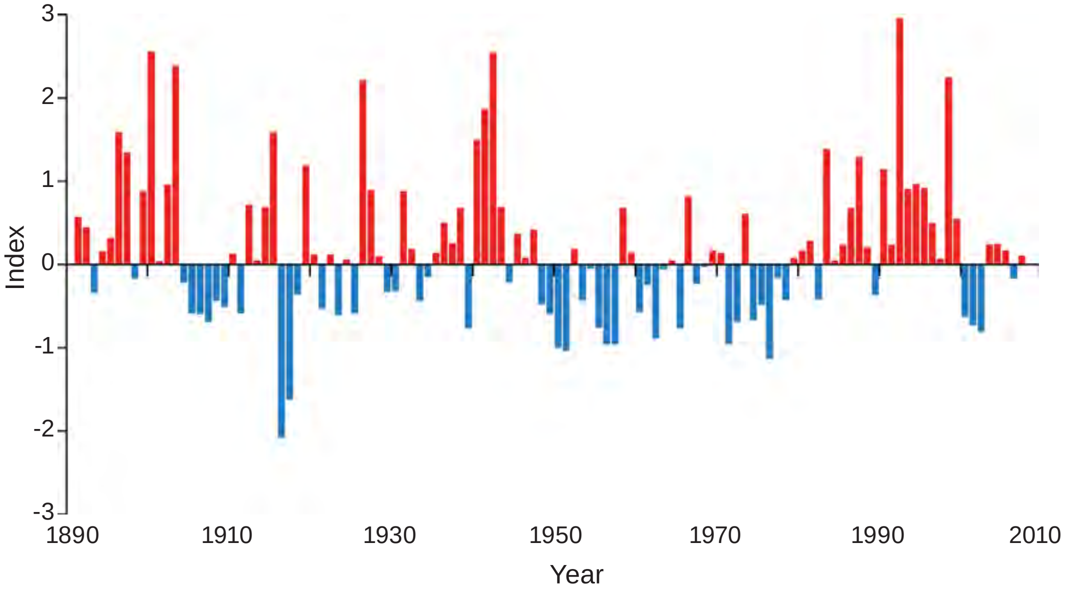


Figure 2.23 Annual index of the position of the South Pacific Convergence Zone (SPCZ) between 1891 and 2008. The index was calculated as the normalised November–April difference in mean sea-level pressure between Suva and Apia, based on the period 1961–1990. It defines the latitude of the SPCZ between longitudes 180° and 170°W.

2.5.2 Rainfall

In general, as tropical Pacific SSTs warm, rainfall increases in both the wet and dry seasons examined here (December–February and June–August) between about 10°N and 10°S, and decreases in the subtropics (**Figure 2.26**). As for temperature, the projected changes in rainfall are not significantly distinguishable between the two scenarios for the near term. However, by the end of the century, even though the pattern is similar, there are larger and more consistent increases of tropical precipitation between about 10°N and 10°S in the A2 scenario compared to the B1 scenario. As tropical SSTs warm, there is greater evaporation and moisture availability for precipitation, so rainfall increases as a consequence. With the increases in tropical precipitation, there is an intensification of the hydrological cycle, an expansion of the Hadley circulation (**Figure 2.4b**), and greater subsidence in the subtropics with reduced rainfall there.

These projected patterns show similarities to observed changes in tropical rainfall between 1991 and 2002, and 1979 and 1990, based on large-scale global precipitation data blended from satellite and surface rain gauge observations[66]. These observations show more total rainfall and more intense rainfall in the ITCZ and SPCZ regions of intense tropical convection, and small to negative changes in the southeastern Pacific. There are also some seasonal variations that could have implications for island water resources[75]. For example, in the A2 scenario, more consistently dry conditions are projected in the southwest Pacific for June–August. **Table 2.5** illustrates what these short- and long-term rainfall projections for the two scenarios might translate into in terms of December–February and June–August rainfall totals at five Pacific island sites.

Table 2.5 Average rainfall totals (mm) for December–February (DJF) and June–August (JJA), 1951–1980, and range of estimated rainfall totals for 2035 and 2100 for the B1 and A2 emissions scenarios (Figure 2.26) for five Pacific island stations (Figure 2.9). Grey shading indicates projected changes are within ± 5% of observed average; dark blue shading indicates wetter conditions, and orange drier conditions.

Station	Season	1951–1980 observed (mm)*	2035		2100	
			B1	A2	B1	A2
Tarawa	DJF	725	761–798	761–798	> 870	798–870
	JJA	397	> 476	437–476	> 476	> 476
Funafuti	DJF	1164	1106–1222	1106–1222	1222–1280	1280–1397
	JJA	748	785–823	785–823	823–898	> 898
Nadi	DJF	785	746–824	746–824	746–824	864–942
	JJA	182	173–191	173–191	173–191	191–200
Raratonga	DJF	426	405–447	405–447	447–469	469–511
	JJA	439	417–461	417–461	417–461	461–483
Pitcairn	DJF	377	358–396	339–358	339–358	302–339
	JJA	471	447–495	447–495	446–495	447–495

* Note that observed averages are for the period of good observational coverage, 1951–1980, whereas the projections are relative to the 1980–1999 average. Specific projections presented here may be underestimates.

2.5.3 El Niño-Southern Oscillation events

ENSO events (see Section 2.3.5) represent the largest interannual climate fluctuations in the tropical Pacific. These events have major effects on regional temperatures, tropical cyclone activity, SPCZ position and rainfall. Given the magnitude of climate anomalies associated with ENSO events and the disruption they can cause, it is of great interest to determine what the possible future changes in El Niño might be.

A number of factors combine to make such estimation difficult. The historical data show that there are multi-decadal changes of ENSO amplitude and frequency associated with the IPO/PDO (see Section 2.3.5). Such multi-decadal variations of ENSO have also been documented in long climate model simulations with no changes in greenhouse gases[76,77]. Given such large, natural multi-decadal variability, it is difficult to assess whether there have been any changes in ENSO frequency and intensity that can be attributed to human activities in the observed record.

A similar problem applies to future climate model simulations of ENSO. Models show a variety of ENSO changes in response to increasing greenhouse gases, but some could simply be sampling each model's inherent multi-decadal variability without any systematic change in ENSO amplitude or frequency. In fact, in an assessment of projected ENSO events from about 20 global coupled climate models there is no consistent change in ENSO behaviour in a future warmer climate (**Figure 2.27**).

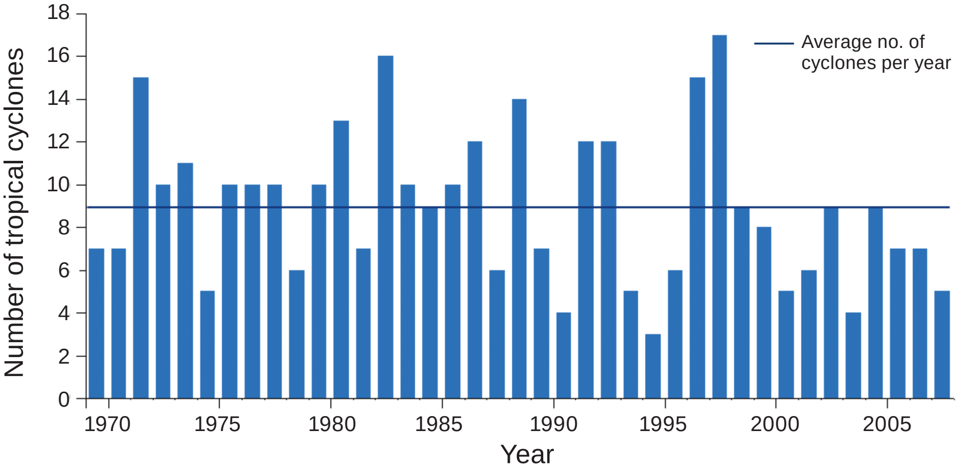


Figure 2.24 Annual number of tropical cyclones in the southwest Pacific, 1969/70–2007/08.

What is more common across the models is the tendency for an 'El Niño-like' response[78] in the mean climate change. That is, the majority of the models tend to show somewhat greater average warming in the eastern equatorial Pacific compared to the western equatorial Pacific (**Figures 2.25** and **2.27**). This tendency does not, however, suggest there will be a more permanent El Niño-like state in the future. In any case, all models show El Niño and La Niña events continuing in the future no matter which scenario is followed and thus they should be considered as an ongoing source of interannual climate variability and extremes in the tropical Pacific.

2.5.4 Tropical cyclones

As with any future climate change projection, we must rely on climate models to provide estimates of how tropical cyclones and their devastating consequences may change with continued global warming. The current generation of climate models discussed here has grid points (where the equations calculate winds, temperature, pressure, etc.) spaced about every 150 km in the atmosphere, and about every 100 km in the ocean. Near the equatorial Pacific, the grid spacing is closer, at about 50 km, to provide better representation of the dynamical mechanisms in the ocean associated with ENSO events. Given this resolution, El Niño and La Niña events are indeed simulated in the models, and large-scale temperature and rainfall changes (such as those depicted in **Figures 2.25** and **2.26**) are relatively well represented. However, it has been estimated that to simulate the most intense tropical cyclones, resolution of about 5 km is required. The ultimate climate model for studying the possible future changes to tropical cyclones in detail would be a global coupled atmosphere-ocean-land-sea ice model with an atmospheric model resolution of about 5 km. However, the expense of running such a climate model at such high resolution is prohibitive with present-day computing capabilities.

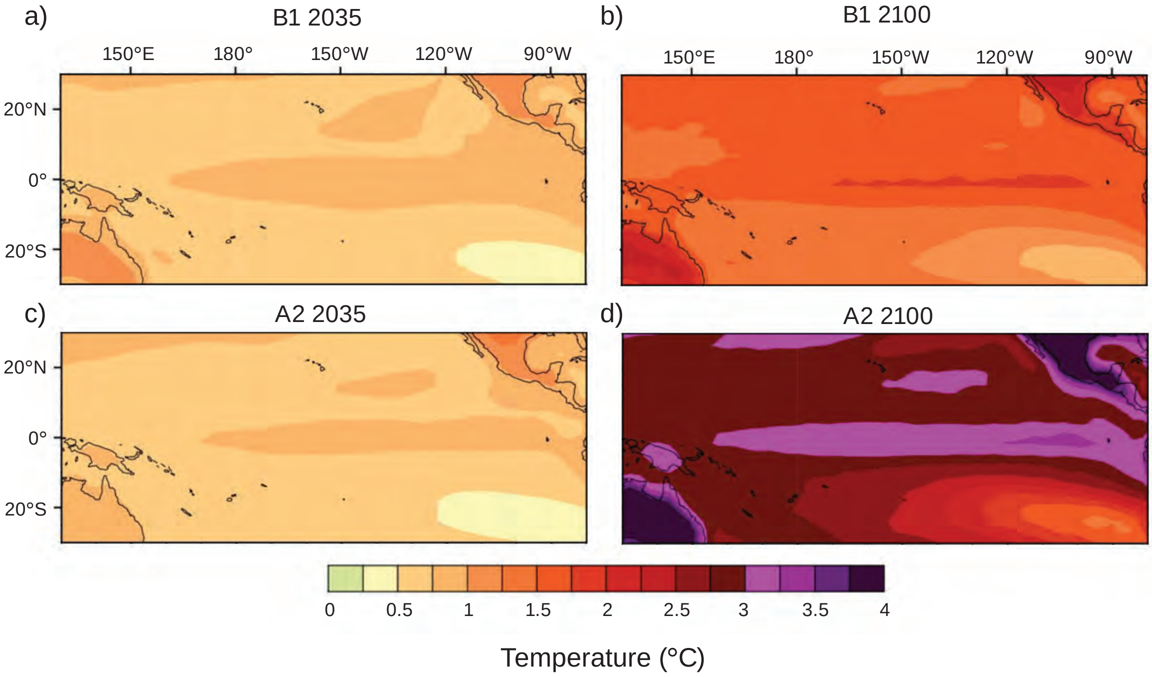


Figure 2.25 Differences in multi-model annual mean surface temperature relative to 1980–1999 for the low emissions (B1) scenario for (a) 2035 and (b) 2100; and for the high emissions (A2) scenario for (c) 2035 and (d) 2100.

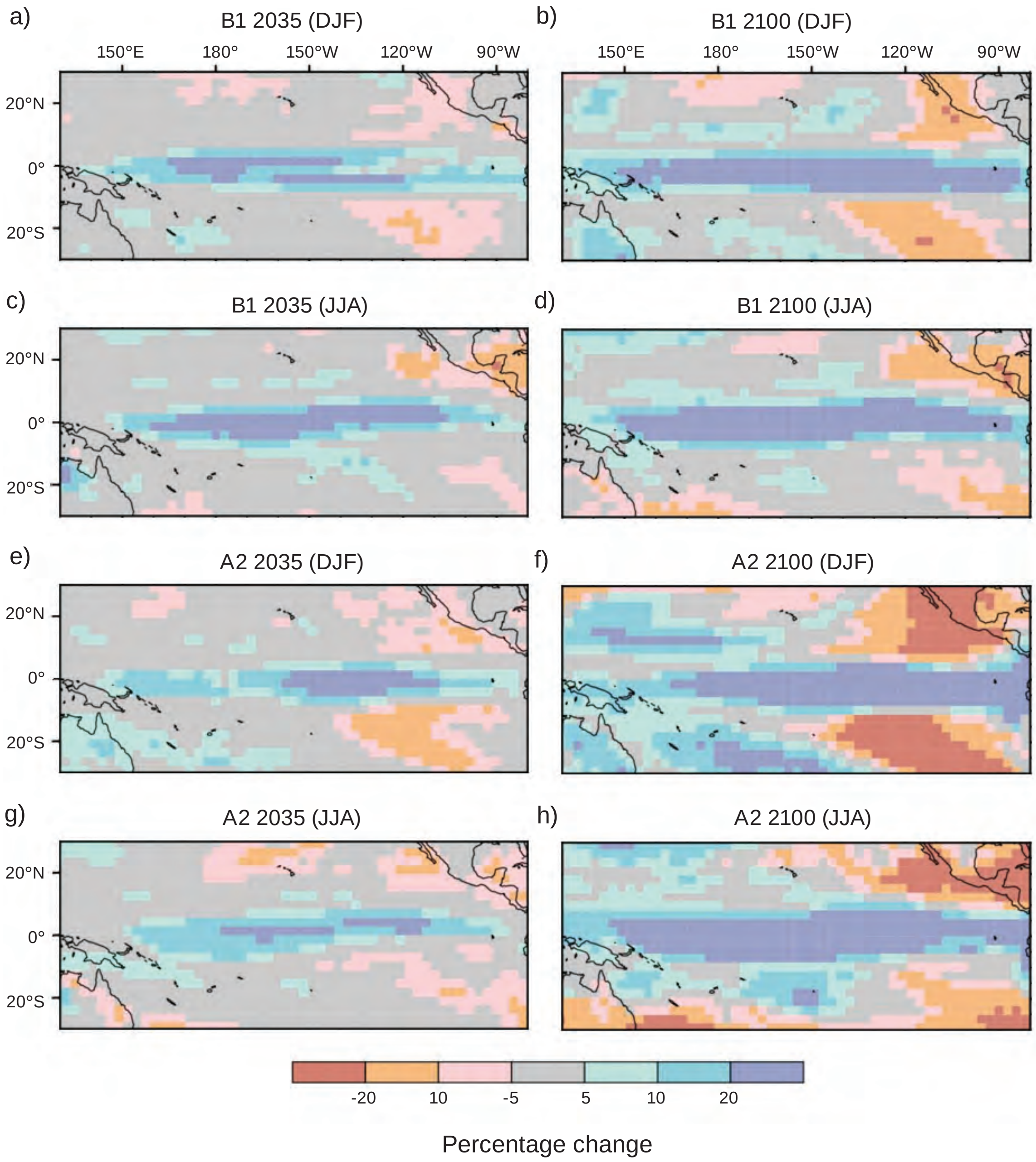


Figure 2.26 Differences in multi-model seasonal mean rainfall, relative to 1980–1999, for the low emissions B1 scenario for (a) December–February (DJF) 2035, (b) DJF 2100, (c) June–August (JJA) 2035, and (d) JJA 2100; and for the high emissions A2 scenario for (e) DJF 2035, (f) DJF 2100, (g) JJA 2035, and (h) JJA 2100.

Since the appropriate climate model to quantify possible future changes in tropical cyclones is well beyond what is currently feasible, there has, by necessity, been a reliance on other climate modelling tools. High-resolution (closer grid spacing) regional models have been embedded in the global climate models to better represent tropical cyclones and estimate future changes in a warmer climate[79–81]. Global atmospheric models with much higher resolution have been run for short periods of time (without being coupled to ocean models) to estimate possible future changes in tropical cyclones.

Overall, the results from these various modelling studies have shown that in a warmer climate, it is likely there will be an increase in the intensity of tropical cyclones. It has been estimated that for every 1°C of tropical SST increase, core rainfall rates would increase by 6–18%, and surface wind speeds of the strongest tropical cyclones would increase by about 1–8%[82]. These relatively small percentage changes in wind speed actually translate into quite large increases in the destructive potential of a tropical cyclone. There is less certainty with regard to the future number of tropical cyclones; several studies have suggested there could be fewer in a warmer climate, but those that form would be more intense[71,82,83].

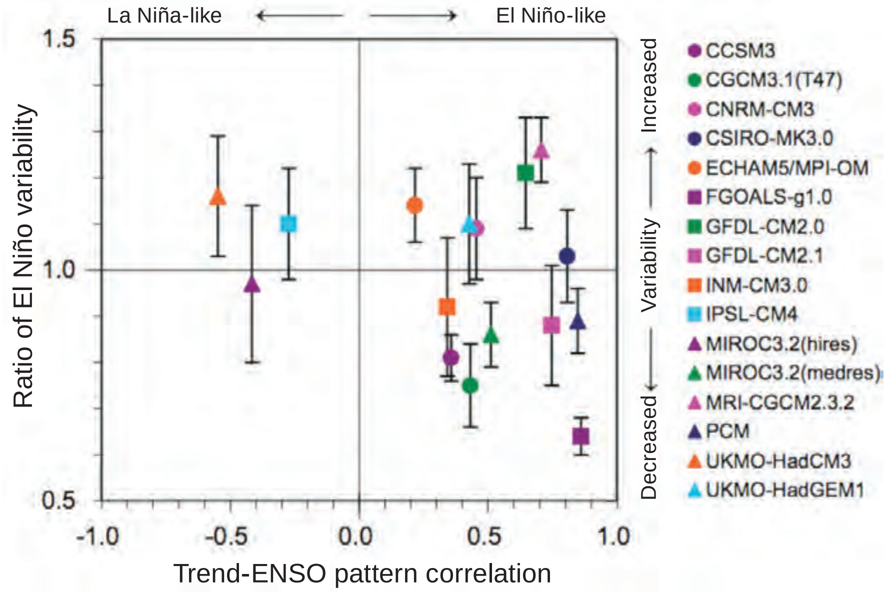
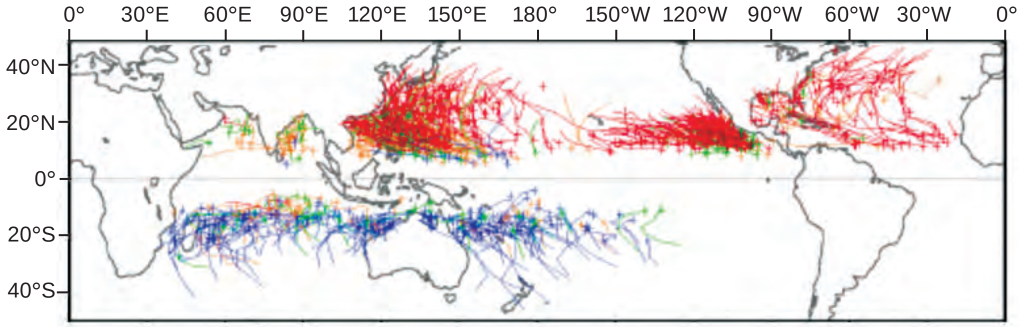


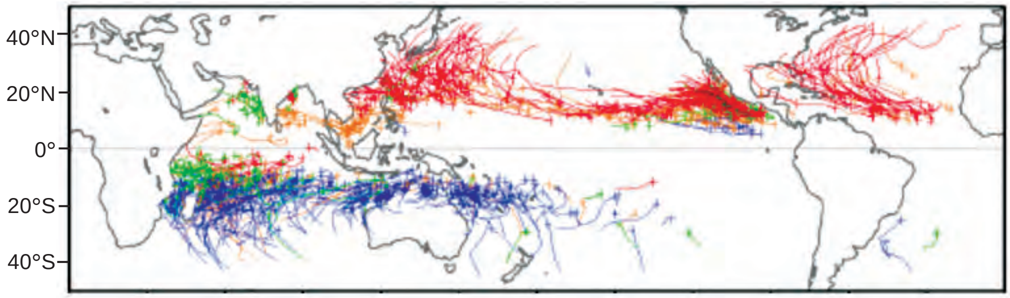
Figure 2.27 Variability among 16 global climate models in projecting future ENSO activity in the tropical Pacific, based on models producing more El Niño- and La Niña-like conditions (horizontal axis) and more or less interannual variability (vertical axis). Error bars indicate 95% confidence limits. If all models were agreeing about future ENSO changes, then values would cluster within one quadrant[71,110,111].

An example of one such study that showed this result used a global atmospheric model with 20-km resolution that could simulate up to strong category 3 or weak category 4 cyclones[84] (**Figure 2.28**). The atmospheric model was forced with observed time series of SSTs for a 10-year period at the end of the 20th century to generate the model's present-day climatology of tropical cyclones (**Figure 2.28b**). This was then compared to observed tropical cyclones for that same period (**Figure 2.28a**). Future ocean temperatures were derived from a lower resolution, global coupled climate model, and those SST anomalies were added to the 20th century SSTs to produce a future 10-year time series of warmer SSTs. The atmospheric model was run with those SSTs along with double the atmospheric concentration of CO_2 and 2.5°C global warming by the end of the 21st century. The resulting simulation (**Figure 2.28c**) shows fewer cyclones in the tropical Pacific, but more intense winds in those that do form (**Figure 2.29**).

a) Observation 1979–1988



b) Present-day climate



c) Future (2100)

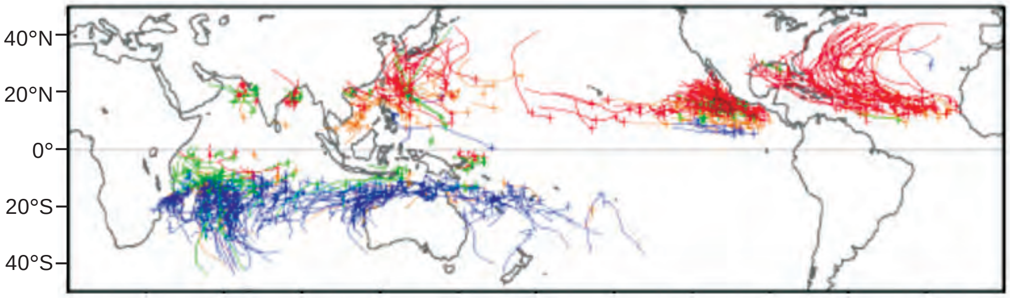


Figure 2.28 Tropical cyclone tracks worldwide from (a) observations (1979–1988), (b) simulations from a 20-km resolution atmospheric model for a 10-year present-day climate, and (c) simultations from a future 10-year period around 2100. Red tracks are for the northern summer, and blue tracks are for storms occurring during the southern summer (source: Oouchi et al. 2006)[84].

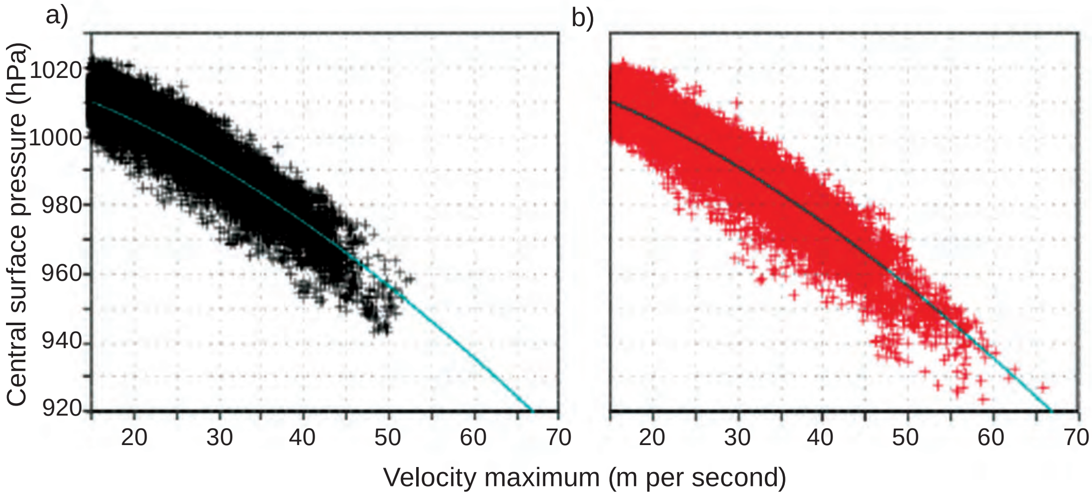


Figure 2.29 Relationship between central surface pressure (hectopascals, hPa) and maximum tropical cyclone winds (m per second) simulated for (a) present-day climate and (b) future climate. The 20-km resolution atmospheric model is able to capture the observed non-linear relationship between central pressure and wind for present-day and future climates, with an increase in deeper central pressures and strongest winds in the future warmer climate (source: Oouchi et al. 2006)[84].

2.6 Summary

The surface climates of PICTs are dominated by the vast Pacific Ocean surrounding them. Until recently, the size of the area has severely limited observational coverage of the surface climates of the region, i.e. collection of the long-term information necessary to detect changes in present-day climatic conditions. The surface climate of the tropical Pacific Ocean is significantly modulated by the major source of interannual global climate variability, ENSO. The two phases of ENSO produce distinct and different temperature and rainfall anomalies that affect Pacific islands. Tropical cyclones, which are the most destructive of the world's weather systems, significantly impact island communities north and south of ~ 5–10° latitude of the equator through high winds, heavy rainfall and storm surges. The usual locations of tropical cyclones are also modulated by ENSO events. Superimposed on these interannual sources of climate variability are slower (decadal time scale) modulations of Pacific climate and the strength of ENSO climate anomalies associated with the IPO/PDO.

The surface climate of the tropical Pacific Ocean is already showing evidence of significant changes with the relatively modest global warming observed to date. Temperatures are significantly warmer in large parts of the tropical Pacific, although there is considerable spatial variability in the observed pattern of warming and some regions have not warmed significantly. There have also been some significant observed changes in rainfall that are related mainly to changes in the position of the SPCZ. Unlike in other ocean basins, there is as yet no evidence for significant changes in either the frequency or intensity of tropical cyclones in the Pacific.

There are several limitations in projecting how the surface climate of the tropical Pacific will continue to change with continued global warming. These limitations include the inadequacies of the existing climate models for the tropical Pacific Ocean region, the lack of reliable model projections at the small scale required for Pacific island communities and, of course, uncertainty in projecting how future concentrations of greenhouse gases will change. The latter depends on the now extremely urgent requirement for global leadership and responses to drastically reduce the atmospheric concentrations of greenhouse gases to levels that will curtail the magnitude of future global warming within manageable limits[85].

Even with rapid and drastic actions, the world – including Pacific island communities – is committed to having to cope with a rapidly changing climate for the foreseeable future. Some components, such as sea level, will continue to rise for centuries (Chapter 3). Indeed, it is not simply a question of a change to a new climate regime, to which we could adapt, but that climate will continue to change for the coming centuries at least. The contributions of PICTs to the present global climate predicament are small, yet they will have to deal with many of the worst of the consequences.

Model projections for future climates of the tropical Pacific show that the emissions trajectory does not make much difference to the magnitude of climate changes in the near-term (to 2035), but the trajectory that is followed makes a big difference by the end of the century. Average changes in temperature for the tropical Pacific range from less than 1°C near 2035, to > 3°C by 2100. On average, precipitation in the tropical Pacific increases in proportion to the temperature increase, with decreases in the subtropical Pacific and some areas of the tropics depending on the season.

The large, natural multi-decadal variability of ENSO events in observations and models contributes to difficulties in attributing past ENSO fluctuations to a particular cause and in making credible future projections to changes in ENSO from the models. However, all global climate models show ENSO events continuing in the future, superimposed on the warmer average tropical Pacific SSTs, which the models project will increase more in the eastern equatorial Pacific than in the west. Using a combination of modelling tools that simulate some aspects of tropical cyclones, the most recent science suggests that while there may be fewer tropical cyclones in a warmer climate, those storms that do form are likely to be more intense.

The main projections from the analyses reported in this chapter are summarised below (see also **Table 2.6**).

- Temperatures are expected to continue to warm.
- Rainfall is likely to increase in the convergence zones near the equator and decrease in the subtropics. As the hydrological cycle intensifies with continued warming, the intensity of extreme rainfall events is also very likely to increase.

Even without significant changes in average rainfall, the intensity of future droughts associated with a given rainfall deficit are very likely to be greater than at present due to warmer temperatures and greater evaporation.

- There may be fewer tropical cyclones, but those that do occur are likely to be stronger and more destructive.
- Significant interannual surface climate anomalies associated with the El Niño and La Niña phases of ENSO are expected to continue.
- Although the magnitude of anthropogenic greenhouse gas emissions is tracking above the A2 emissions scenario, the differences in the climatic consequences between the two scenarios considered here are not expected to emerge until towards the end of the 21st century.
- Even with the 'low emissions trajectory' (B1), significant changes to the tropical Pacific climate are inevitable and may have devastating consequences when superimposed on other threats to Pacific livelihoods[86].
- Even the B1 trajectory may be too high to avoid dangerous climate change[87].
- Most of these projections are likely or very likely to occur, and can be made with high confidence (**Table 2.6**). The exceptions are for changes in the frequency and intensity of ENSO events and variability in the PDO, for which projections are made with low confidence. More detailed projections of future climate changes at the scale of individual PICTs requires both improvements in global climate models for the tropical oceans and more reliable downscaling of such models to finer spatial scales[v].
- Planning is already underway for the IPCC's Fifth Assessment Report (AR5) due to be published in early 2014[88]. This will be based on a new set of four time-dependent scenarios known as Representative Concentration Pathways (RCPs) and a new generation of global climate models that will be compared and integrated through the Coupled Model Intercomparison Project phase 5[89]. In addition, compared to AR4, AR5 will have an increased focus on the impacts of a changing climate on oceanic ecosystems. All these activities will, over the next few years, provide greater certainty about the consequences and impacts of a rapidly changing global climate for PICTs.

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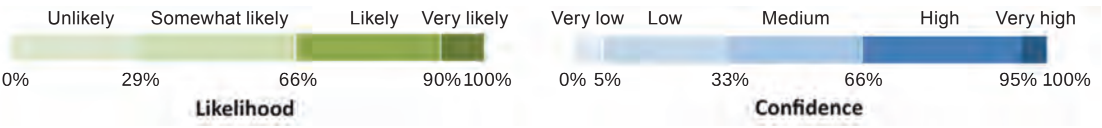
[v] This work is now being done for the tropical Pacific by the Australian Bureau of Meteorology, CSIRO and partners, under the Pacific Climate Change Science Programme; see www.cawcr.gov.au/projects/PCCSP

Table 2.6 Summary of projected changes to key Pacific surface climate variables relative to 1980–1999 values. Estimates of likelihood and confidence are provided for each projection, as defined in Chapter 1 (see key below).

Climate variable	2035		2100	
	B1	A2	B1	A2
Surface temperature (°C)	0.5–1.0 🟩🟦	0.5–1.0 🟩🟦	1.0–1.5 🟩🟦	2.5–3.0 🟩🟦
Sea surface temperature*	➢ SST changes similar to those for surface temperature, although slightly smaller in magnitude 🟩🟦 ➢ Spatial variation occurs in projected SST warming, with greater warming in the eastern than western equatorial Pacific and less warming in the southeast Pacific 🟩🟦			
Rainfall	5–15% increase in equatorial regions 🟩🟦	5–20% increase in equatorial regions 🟩🟦	10–20% increase in equatorial regions 🟩🟦	10–20% increase in wider region equatorial 🟩🟦
	5–10% decrease in subtropics 🟩🟦	5–20% decrease in subtropics 🟩🟦	5–20% decrease in subtropics 🟩🟦	5–20% decrease in subtropics 🟩🟦
	➢ Extremes in wet and dry periods become more extreme 🟩🟦 ➢ Drought associated with decreases in rainfall become more intense due to warmer temperatures 🟩🟦			
Tropical cyclones	➢ Total number of tropical cyclones may decrease 🟩🟦 ➢ No changes in usual locations 🟩🟦 ➢ Cyclones that do occur likely to be more intense 🟩🟦			
ENSO events	➢ ENSO events continue as a source of interannual climate variability 🟩🟦 ➢ Unclear as to whether changes in frequency and intensity of ENSO will occur 🟩🟦			
PDO-decadal variability	➢ PDO continues as source of decadal modulation in Pacific basin climate and ENSO events 🟩🟦 ➢ Unclear as to whether this will change 🟩🟦			
Prevailing winds and circulation	➢ More vigorous hydrological cycle 🟩🟦 ➢ Enhanced Hadley circulation 🟩🟦 ➢ Expansion of area encompassed by 'tropics' 🟩🟦			

* See Chapter 3 for more detailed projections of sea surface temperature.



2.7 Recommendations to reduce uncertainties in projecting the future climate

There has been a shortage of peer-reviewed science relating to small islands and climate change in recent IPCC assessment reports[90]. The measures that need to be taken to address this problem and reduce the uncertainties involved in projecting the future climate of PICTs are set out below[vi]:

- Commitment and support for new, high-quality surface weather observations for PICTs, and maintenance of existing facilities, to allow:
    - detection of the nature and significance of changing climates;
    - responses to these changes in natural and managed ecosystems to be characterised;
    - linking of island-scale climates of most relevance to PICTs to larger-scale climate observations now available through, for example, remote sensing; and
    - linking of changes in rainfall to variations in the river flow and groundwater regimes of islands.
- Improved high-resolution paleoclimatic reconstructions for the Pacific from, for example, annually banded corals, to allow:
    - detection of current changes and their significance; and
    - improved climate models.
- Identification of PICTs as a regional focus for climate change observations and modelling, including downscaling to island-specific scales to allow more rigorous assessment of local sensitivity and vulnerability to a changing climate[91] and specific inclusion of PICTs as a regional focus for the Coordinated Regional Climate Downscaling Experiment (CORDEX)[72].
- Improved climate modelling for the tropical ocean regions and, in particular, the capacity to realistically assess how the frequency and intensity of ENSO events and tropical cyclones are likely to change[25].
- Ongoing commitment to, and support for, improved weather forecasting and short-term seasonal climate outlooks for PICTs (e.g. tropical cyclones, ENSO), and appropriate, accessible warning systems for severe weather events with associated support for disaster-recovery strategies[92].

[vi] The Pacific Climate Change Science Program CCiP report ('Climate Change in the Pacific: Scientific Assessment and New Research') now covers, in detail, many of the aspects of tropical Pacific climate change summarised in this chapter.

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Chapter 3

Observed and expected changes to the tropical Pacific Ocean

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> *'The oceans are warming.'* (Bindoff et al. 2007)[i]

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[i] Bindoff et al. (2007) Observations: Oceanic climate change and sea level. In: S Solomon, D Qin, M Manning, Z Chen, M Marquis, KB Averyt, M Tignor and HL Miller (eds) *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press, Cambridge, United Kingdom, and New York, United States of America, pp. 385–428.

Contents

3.1 Introduction

The fish and invertebrates harvested from the tropical Pacific Ocean and the coastal waters of the region, and the ecosystems that support these species, are influenced not only by surface climate; they also depend intimately on the oceanic environment. Large- and small-scale circulation patterns influence larval dispersal and the migration of species; water temperature, salinity, nutrient availability, dissolved oxygen concentration and pH affect biological activity; and oceanic currents, waves and sea level shape coastal habitats. Together, these properties of the tropical Pacific Ocean[ii] have a profound effect on the productivity of oceanic and coastal fisheries, and coastal aquaculture.

Understanding how these features of the ocean vary is one of the primary keys to forecasting production from the fisheries sector. Resolving this puzzle is a major challenge, however, because the tropical Pacific Ocean varies across an enormous range of spatial and temporal scales. For example, within just a few days, cloud cover, local upwelling, surface mixing due to storms or oceanic eddies can substantially modify sea surface temperature, salinity, currents and nutrient supply at the scale of reefs and islands. On larger spatial scales, seasonal changes in nutrient upwelling have a significant effect on primary productivity (Chapter 4). Closer to the equator, key properties of the Pacific Ocean are dominated by the interannual variations of the El Niño-Southern Oscillation (ENSO) (Chapter 2). On longer time scales, variations in the strength of the mid-latitude westerly winds produce climate 'regime shifts', like those recorded in 1925 and 1943[1], and in 1976–1977[2]. Regime shifts are characterised by abrupt ENSO-like changes that can last for several decades, commonly associated with the Interdecadal Pacific Oscillation (IPO) or the closely related Pacific Decadal Oscillation (PDO)[3–5]. Profound changes over and above natural climate variability are also occurring, due to the build-up of anthropogenic greenhouse gas emissions in the atmosphere (Chapters 1 and 2).

The purpose of this chapter is to provide fisheries scientists and managers with fundamental information on the main features of the tropical Pacific Ocean, how these features have changed over the past few decades due to climate change (Chapter 2), and how they are projected to change as the levels of CO_2 increase and the earth continues to warm.

The oceanic features we examine include: large-scale currents, sea surface temperature and salinity, subsurface temperature, eddies, nutrients, dissolved oxygen, ocean acidification, wave height, sea-level rise and coastal and island effects.

[ii] Defined as the area 25°N to 25°S and 130°E to 130°W.

3.1.1 Use of climate simulations

To describe the features of the tropical Pacific Ocean listed above, and to make projections, we have drawn on published knowledge of the oceanography of the region and our analyses of a suite of coupled-atmosphere and ocean climate models from the Coupled Model Intercomparison Project Phase 3 (CMIP3) (Chapter 1). These state-of-the-art CMIP3 simulations formed the basis of the Intergovernmental Panel on Climate Change (IPCC) projections of future climate in the Fourth Assessment Report (AR4)[6]. They cover a large range of grid resolutions and use a diverse set of parameterisations to account for processes not simulated explicitly. The models often perform very differently with respect to their realism in simulating various features of the atmosphere and ocean. Before performing our analyses of future projections, we validated individual models against the observed (1980–1999) mean state of the ocean and assessed the ability of the models to reproduce ENSO-like behaviour – the dominant driver of interannual variability in the region (Chapter 2). To do this, we analysed the strength, spatial structure and temporal characteristics of the simulated ENSO, in conjunction with the results from previous studies[7–10].

As discussed in Chapter 2, while most models reproduce some form of ENSO-like variability, the level of realism differs markedly. A few, for example, produce an ENSO that occurs almost every second year. There are also considerable differences in the strength and seasonality of anomalies in sea surface temperature[7]. Of major concern is a systematic bias in the spatial structure of ENSO in almost all the models, whereby the maximum warming that occurs during El Niño events is displaced too far to the west. As a result, we retained 13 of the CMIP3 models (Appendix 3.1) that exhibited ENSO-like behaviour with a dominant frequency between 2 and 7 years, and a reasonable representation of the Warm Pool in the western Pacific (Chapter 2).

Even after model selection, some biases persisted. Where these biases did not occur across a large number of models, we used the ‘multi-model mean’ to ‘average out’ many of the biases in individual models. This averaging process generally gives a consistently more realistic representation of the real world than any individual model[11] (Chapter 1), but masks the possibility of more extreme changes. We used the multi-model mean to provide the best estimate of (1) the present state of the tropical Pacific Ocean centred on 1990 (1980–1999); and (2) future projections for the main features of the ocean described above of interest to fisheries in the tropical Pacific.

As outlined in Chapter 1, we considered the future projections for both a relatively low emissions (B1) and a relatively high emissions (A2) scenario for 2035 and 2100. To this end, we used 20-year segments of each model’s output for 2025 to 2044 (hereafter referred to as 2035) and 2080 to 2099 (hereafter referred to as 2100)[iii], respectively, to define a mean climate and to average out any short-term variability. Most of the diagnostics are based on the mean of the selected subset of climate models (multi-model mean). Student's *t*-tests were used to determine whether the climate-driven

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[iii] Some global climate models only make projections to 2099, so we have used the 20-year period 2080–2099 to represent 2100.

changes in oceanic features could be considered to be statistically significant. Although some long-term (multi-decadal to millennial) variability may be present in the simulations, resulting in a bias in mean-state estimates, this is essentially removed by using the multi-model mean.

3.2 Features of the tropical Pacific Ocean

3.2.1 Large-scale currents

Both large- and small-scale currents play a major role in the distribution and abundance of fish and invertebrates that support the oceanic and coastal fisheries of the tropical Pacific. The movement of tuna is linked to the horizontal displacement of water of a suitable temperature, and to vertical changes in the depth of the mixed layer that determines their surface habitat (Chapters 4 and 8). Areas where currents diverge or converge are of major importance because they are associated with the thermal fronts, upwelling and eddies described later in this chapter. These processes enhance local productivity and create good feeding areas for tuna (Chapter 4). For species reliant on coastal habitats, changes in currents can affect the distribution and abundance of corals and other invertebrates that create coral reef habitats (Chapter 5). Currents also influence the replenishment of key species supporting coastal fisheries at the end of their pelagic phase: postlarvae of fish and invertebrates use currents to find the habitats on which they depend as adults (Chapter 9).

3.2.1.1 Currents flowing into the region

The main currents in the tropical Pacific Ocean (Figure 3.1) are driven by the easterly trade winds[12] (Chapter 2). The primarily westward flow of these currents extends over the top few hundred metres of the ocean and reaches the western boundary of the basin. In the first few tens of metres, an interaction between the Coriolis force (associated with the rotation of the earth) and the trade winds cause 'Ekman transport' (Box 3.1), where the surface waters in the tropics move poleward in both hemispheres. Conversely, at latitudes poleward of 25°N and 25°S, the prevailing westerly winds force the surface waters towards the equator, resulting in a convergence of these waters between 15°–30°N and 15°–30°S. This convergence produces a build-up in sea surface height (SSH) around 10°–15°N to 10°–15°S. The sea-level slope is associated with pressure forces that drive two broad geostrophic westward flows (Box 3.1): the North Equatorial Current (NEC) and the South Equatorial Current (SEC) (Figure 3.1b). The NEC and SEC are the equatorial branches of two basin-scale circular circulation patterns: the large subtropical gyres in the northern and southern Pacific Ocean, with their poleward margins outside the domain at higher latitudes. Near the surface (0–80 m), frictional forces from the wind are superimposed on the geostrophic NEC and SEC, adding a component that is perpendicular to the local wind direction due to Ekman transport (see blue streamlines showing Ekman currents in Figure 3.1). For example, south of the equator the southeasterly trade winds bend the surface streamlines to the southwest.

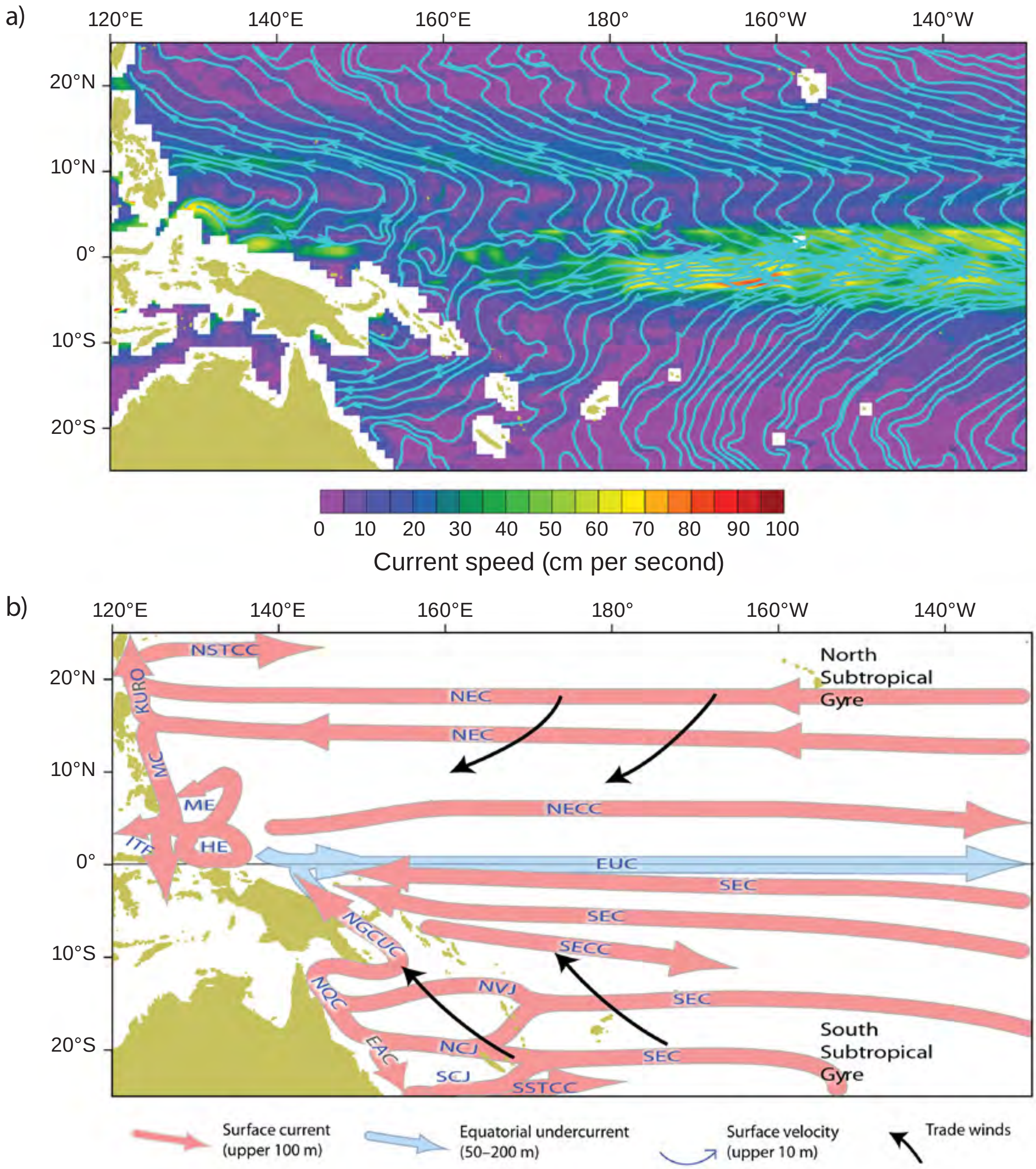
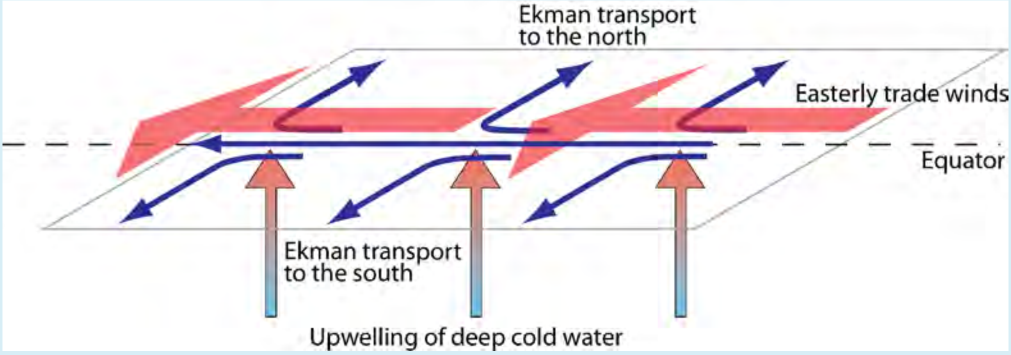


Figure 3.1 (a) Ocean surface currents in the tropical Western and Central Pacific Ocean, based on satellite data and *in situ* climatology (source: Sudre and Morrow 2008)[189]. As indicated by the stream lines, surface flow is generally directed to the left of the wind in the Southern Hemisphere, and to the right in the Northern Hemisphere, due to Ekman transport (Box 3.1). (b) The main ocean currents in the upper 100 to 200 m of the water column. Currents shown are: North Subtropical Counter Current (NSTCC); Kuroshio Current (KURO); Mindanao Current (MC); Mindanao Eddy (ME); Halmahera Eddy (HE); North Equatorial Current (NEC); North Equatorial Counter Current (NECC); Equatorial Undercurrent (EUC); Indonesian Throughflow (ITF); New Guinea Coastal Undercurrent (NGCUC); North Queensland Current (NQC); East Australian Current (EAC); North Vanuatu Jet (NVJ); North Caledonian Jet (NCJ); South Caledonian Jet (SCJ); South Equatorial Counter Current (SECC); South Equatorial Current (SEC) and South Subtropical Counter Current (SSTCC).

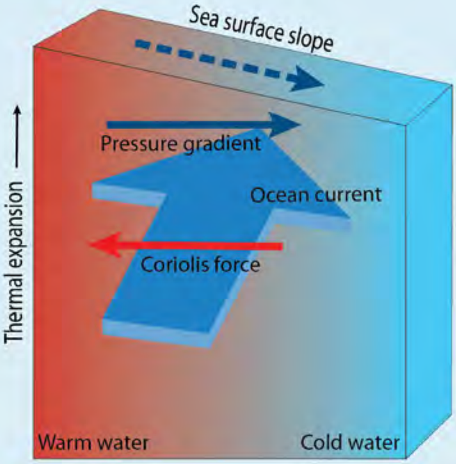
Box 3.1 Motion in the ocean

At any particular place in the ocean, a number of different forces act to create a current and determine its direction and strength. The main forces that cause water to move and generate currents are related to (1) the gravitational attraction by the moon and sun, causing tidal circulation; (2) the wind, which exerts a stress at the surface of the ocean and can directly drive currents in the upper few tens of metres; and (3) pressure gradients, which may be formed either through differences in sea surface height or via horizontal differences in water density. Once water is in motion, two additional forces also influence currents. The first is friction, which always retards motion. Friction is important mainly near coastlines and the bottom of the ocean, or where adjacent currents are moving at different speeds or in different directions. The second is the Coriolis force. This (apparent) force is a consequence of being on a rotating planet. The effect of the Coriolis force is to deflect water in motion to the left in the Southern Hemisphere and to the right in the Northern Hemisphere. The effect of the Coriolis force diminishes at the equator. This force results in the two ubiquitous but counter-intuitive types of current described below.

Ekman transport (see diagram below): Away from the equator, if a wind continues to blow on the surface of the ocean for an extended period, the resulting surface current does not flow in the direction of the wind as might be expected. Instead, the average flow is 90° to the left of the wind direction in the Southern Hemisphere, or to the right of the wind in the Northern Hemisphere, as a consequence of the Coriolis force. An important example of Ekman transport occurs on either side of the equator, where the easterly trade winds cause southward water motion in the Southern Hemisphere (i.e. 90° to the left of the direction of the wind) and northward water motion in the Northern Hemisphere (i.e. 90° to the right of the direction of the wind). The result is water flowing away from the equator on either side. To compensate for this surface divergence caused by Ekman transport, cool water is drawn up from the subsurface, a process known as 'upwelling'. At the equator, there is no Coriolis force and the surface water flows in the same direction as the wind.



Geostrophic motion (see diagram below): Horizontal pressure differences exist in the ocean when there is a slope at the surface of the ocean (e.g. set up by a strong wind) or via lateral changes in water density (e.g. cold water abutting warm water). Where pressure differences like these occur, water does not flow directly from the high-pressure region to the low-pressure region as one might expect. Instead, it flows at 90° to the left of the pressure gradient force in the Southern Hemisphere (or to the right in the Northern Hemisphere) because of the Coriolis force. A result of geostrophic motion is that any horizontal change in water density (e.g. due to a front in temperature or salinity) will be associated with a current that is perpendicular to the front.



Different forces are important in different regions of the tropical Pacific Ocean. In the surface layer (i.e. the first few tens of metres), Ekman transport occurs and surface currents tend to move perpendicular to the wind direction. Away from the surface, and other oceanic boundaries, the flow tends to be geostrophic and is dictated by horizontal density gradients due to changes in temperature and/or salinity, or variations in sea surface height. If density gradients become very strong, or large current shears exist, flow can become turbulent and form eddies. The large-scale currents of the tropical Pacific Ocean are formed by the combination of the processes described above. Horizontal differences in the wind field drive surface Ekman currents, which change from location to location. These shifts cause upwelling and downwelling and ultimately pressure gradients that in turn lead to large-scale geostrophic currents that extend into the deep ocean.

3.2.1.2 Western boundary current system

The westward flowing NEC and SEC both encounter islands in their passage, and eventually the western boundaries of the basin. On average, the NEC occupies a broad region from 8°N to 20°N[13]. As the NEC reaches the western boundary, it divides to feed the Kuroshio Current to the north (called the 'Philippines Current' at this latitude[13]), and the Mindanao Current and Mindanao Eddy to the south (**Figure 3.1**). The average latitude where the surface NEC bifurcates is 13.3°N (including Ekman transport) but this varies seasonally from 15°N in July to 17°N in December[13]. A similar process occurs in the southern Pacific, with the SEC splitting into the equatorward North Queensland Current and the poleward East Australian Current, with the bifurcation located at 16°S near the surface and 22°S at a depth of 1000 m[14,15]. The location of this bifurcation also varies seasonally by 1.25° latitude, with a displacement toward the equator in November to December[16].

When these broad currents encounter islands and land masses, the flow is diverted (Section 3.2.9). The pathways of the SEC are complicated by the presence of many islands and ridges in the western Pacific. As a result, the SEC splits into three jets, the South Caledonian Jet, the North Caledonian Jet and the North Vanuatu Jet[17–19] (Figure 3.1). The northern component of the bifurcation enters the Solomon Sea as the New Guinea Coastal Undercurrent and exits towards the equator through three narrow straits within Solomon Islands[20]. This latter flow, along with the Mindanao Current flow, converges towards the equator, feeding the Warm Pool (Section 3.2.2), the Indonesian Throughflow[21,22] and, at greater depth, the eastward flowing Equatorial Undercurrent[23] (**Figure 3.1**).

3.2.1.3 Eastward flowing counter currents

The westward-flowing NEC and SEC are also altered by the presence of the Intertropical Convergence Zone (ITCZ) and the South Pacific Convergence Zone (SPCZ) (Chapter 2). These convergence zones alter local wind conditions, generating horizontal shear ('curl') in the wind field. This wind curl produces two eastward-flowing, surface-intensified counter currents through Ekman transport and geostrophic processes (Box 3.1), known as the North Equatorial Counter Current (NECC) under the ITCZ[24], and the South Equatorial Counter Current (SECC) under the SPCZ[14,25] (Figure 3.2). Another modification to the flow comes from local changes in the trade winds as they interact with island topography. This interaction modifies the flow of water downwind of islands (Section 3.2.8). In the southern Pacific, similar counter currents occur in the Coral Sea west of Vanuatu[26] (**Figure 3.2**) and near the Marquesas Islands[27,28], causing the upwelling of nutrients. Near Hawaii, an eastward flowing current is created that flows against the NEC, named the Hawaii Lee Counter Current[29]. Eddies are formed at the boundaries where the westward flowing NEC and the eastward flowing NECC meet. These eddies also have the potential to bring nutrients to the surface waters[30].

3.2.1.4 Variability in large-scale currents

Currents in the central south Pacific remain fairly constant throughout the year, whereas currents in the western Pacific vary substantially in both intensity and direction (**Figure 3.3**). In the central eastern equatorial region, current direction actually reverses in different seasons. For example, there are strong seasonal variations in the NEC, NECC, SEC and SECC associated with the migration of the SPCZ and ITCZ[31] (**Figure 3.3**). Variations in currents on interannual time scales can be even more dramatic, due to the influence of ENSO. A change in wind forcing in one location can have large effects that extend well outside the region directly affected by the wind. During El Niño events, there is a weakening or even a reversal of the southeast trade winds, particularly in the west of the Pacific basin. The resulting oceanic disturbance propagates eastward at high speed along the equator as equatorial waves[32] (Section 2.3.2.3). These waves can result in a reversal of the large-scale westward current direction, with eastward velocities reaching up to 50 cm per second[33].

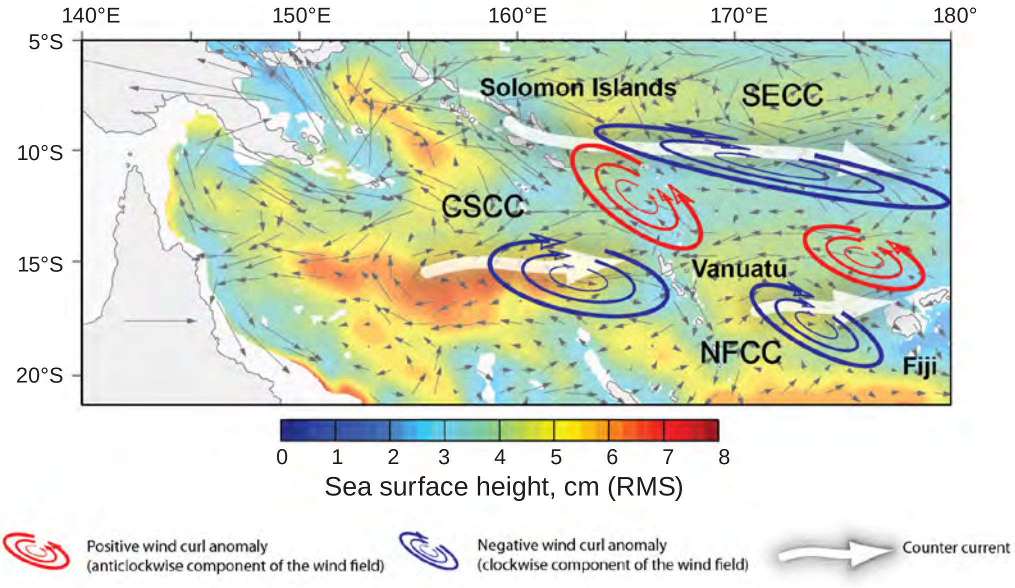


Figure 3.2 Formation of counter currents in the tropical Pacific Ocean. Weakening trade winds towards the north of the South Pacific Convergence Zone area create a clockwise forcing on the ocean by the wind field (negative wind curl). This generates pressure forces in the ocean that set in motion a counter current, the South Equatorial Counter Current (SECC) that flows against the broad westward South Equatorial Current (Figure 3.1). West of Vanuatu and Fiji, similar disruptions to the trade winds create wind stress curl dipoles that generate the Coral Sea Counter Current (CSCC) and the North Fiji Counter Current (NFCC). The presence of counter currents is also revealed by variability in sea surface height, as measured by satellite data (colour) over short time scales (180 days or less) (source: Qiu et al. 2009)[26], RMS = root mean square of sea surface height, in cm.

3.2.2 Ocean temperature

Water temperature is another key feature of the ocean that strongly affects the abundance and distribution of the fish and invertebrates supporting fisheries and aquaculture in the tropical Pacific. Each species has adapted to tolerate a specific range of temperatures under which it can optimise its growth and reproductive success (Chapters 8, 9 and 11). As a result, ocean warming is likely to have an effect on egg production, which may be either positive or negative depending on whether the target species is close to its thermal optimum. However, increases in temperature above normal maxima are expected to have negative effects on the overall viability of some populations of fish and invertebrates. The effects of water temperature on the distribution and abundance of skipjack tuna are of special interest to Pacific Island countries and territories (PICTs) considering the strong influence that ENSO events have on this species (Chapter 8).

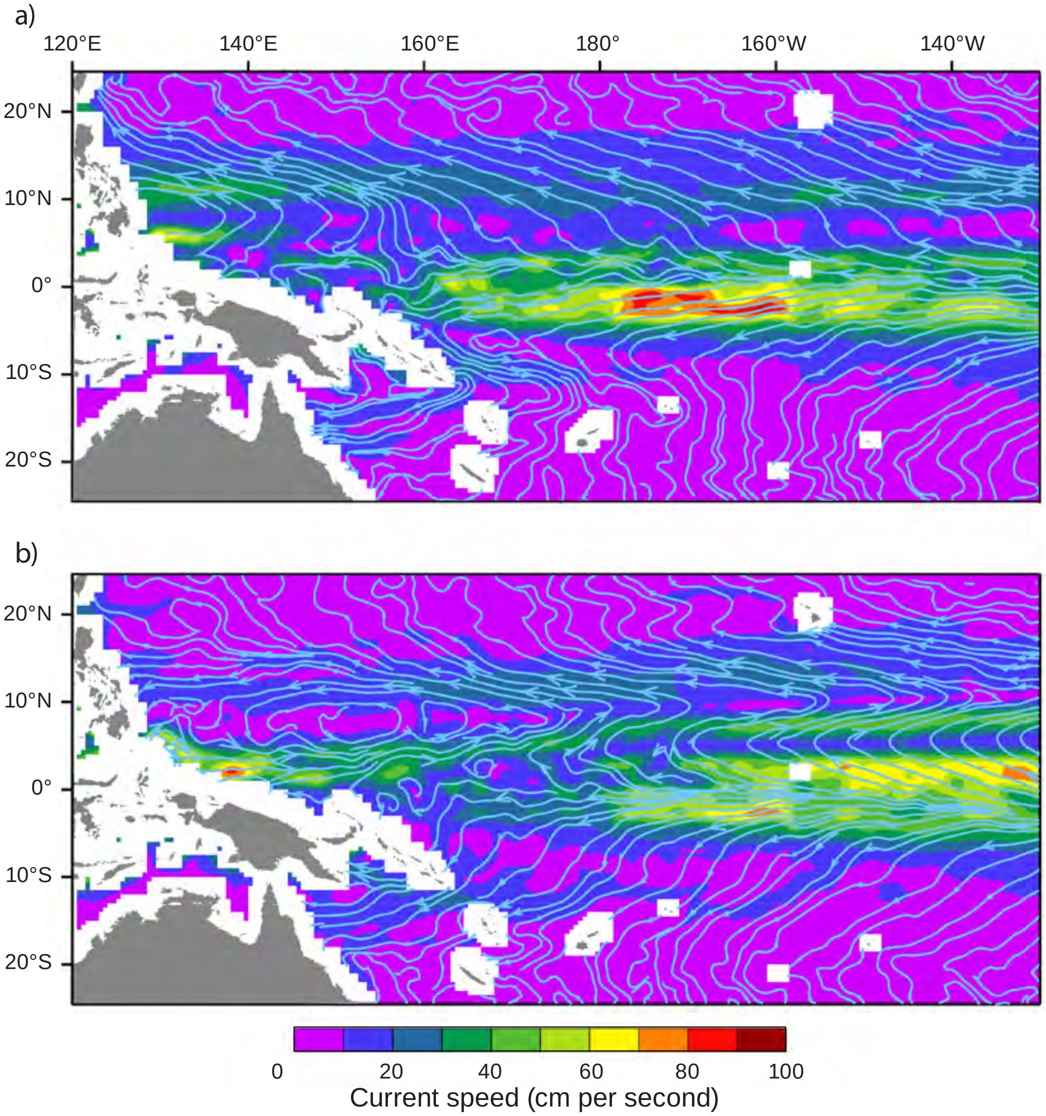


Figure 3.3 (a) Average seasonal variations in the speed of the surface currents of the tropical Pacific Ocean (1999–2007) from June to August, and (b) December to February, based on satellite data and *in situ* climatology (source: Sudre and Morrow 2008)[189]. The blue streamlines indicate the direction of currents.

3.2.2.1 Sea surface temperatures

As explained in Chapter 2, the sea surface temperature (SST) of the tropical Pacific Ocean varies spatially and temporally. More solar heat is absorbed by the ocean near the equator than at higher latitudes. This rise in temperature results in a pole-to-equator SST gradient (Chapter 2). However, there are regional deviations from this large-scale pattern. For example, the southeast trade winds push the warmest waters to the western side of the Pacific basin, forming the Warm Pool – a large heat reservoir intimately associated with ENSO. Along the equator and the coastline of South America, the prevailing winds cause equatorial and coastal upwelling, respectively, bringing cool, deep waters rich in nutrients to the surface. This process results in a relatively cool tongue of water extending from South America along the equator to the central Pacific, where it meets the eastern edge of the Warm Pool near the dateline. Sea surface temperature also varies seasonally. Away from the equator, SST varies by up to 7°C throughout the year; whereas seasonal changes in SST near the equator are weak and the largest variations (2 to 3°C) occur from one year to another. This interannual variability is mainly associated with ENSO (Chapter 2). Thus, SST at any given location and time depends on a broad range of processes, including diurnal and seasonal solar heating modulated by cloudiness, air-sea heat exchanges, heat transport by oceanic circulation, eddies (Section 3.2.3) and other local ocean processes, such as vertical mixing and upwelling (**Figure 3.4**).

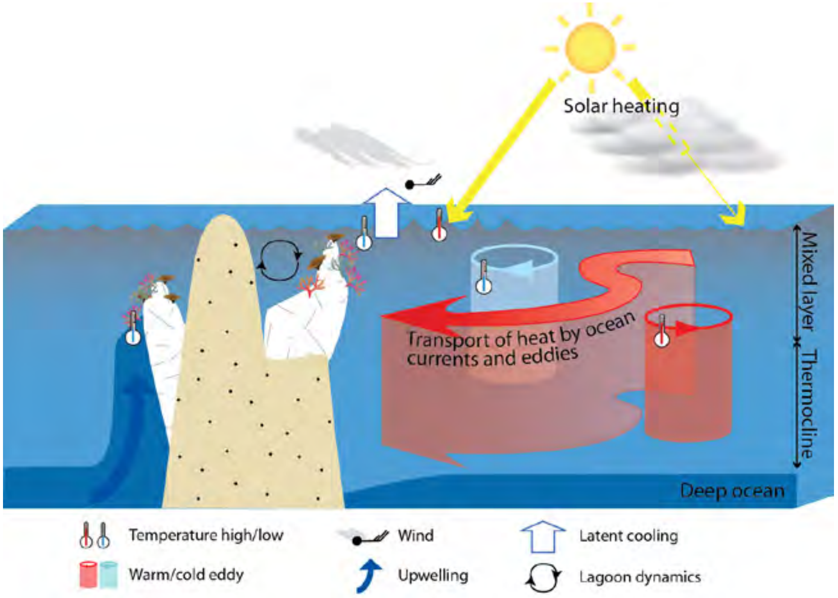


Figure 3.4 Factors affecting the temperature of the upper layer of the ocean. Surface waters are heated by incoming solar radiation, modulated by cloud cover. Winds create increased evaporation, which extracts latent heat from the ocean causing it to cool. Contact between the atmosphere and ocean also drives direct heat fluxes. The wind generates mixing with deeper and colder waters, resulting in cooling at the surface and more homogenised temperatures within the 'mixed layer' (Section 3.2.4). Currents, eddies and upwellings also transport warmer or colder water into or away from the upper layer of the ocean (Sections 3.2.3 and 3.2.9).

3.2.2.2 Vertical temperature structure

The temperature of the tropical Pacific Ocean also varies with depth – it declines as depth increases (**Figure 3.5**). This variation in temperature occurs because most of the sun's heat is absorbed near the surface, with little energy reaching below the first 100 m. The warmer surface water has lower density than the deeper cooler waters below and where these two layers meet at the 'thermocline', the water temperature changes rapidly. The thermocline is the part of the water column with the strongest vertical temperature gradient. In the tropical Pacific Ocean, the thermocline usually lies within the upper 500 m of the water column and the temperature drops by about 20°C. Below this layer, the ocean remains cold to abyssal depths.

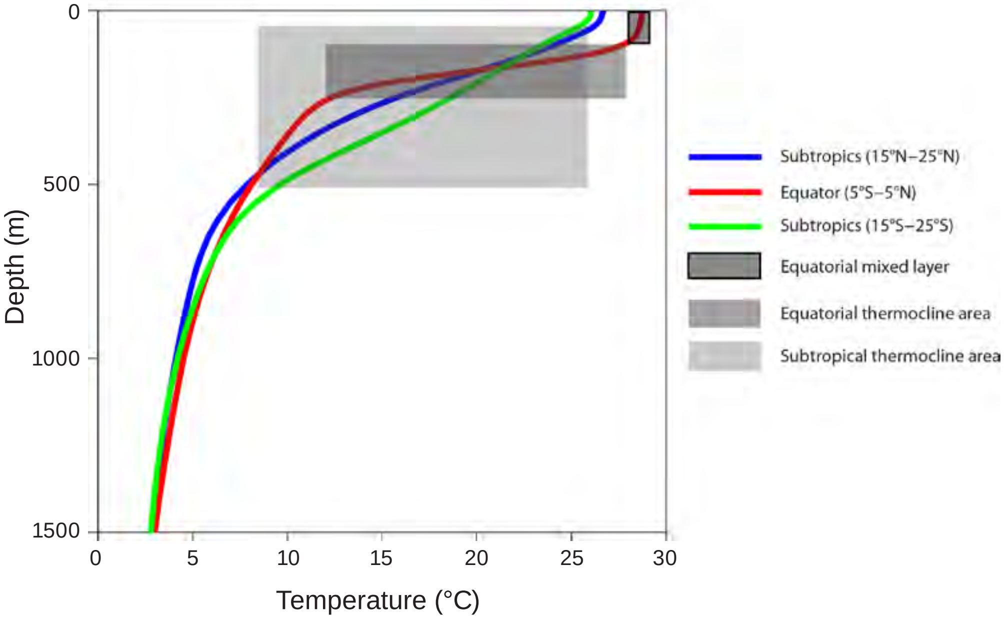


Figure 3.5 Average water temperature from the surface to a depth of 1500 m for three typical locations in the tropical Pacific: equator (red line); north subtropics (blue line); and south subtropics (green line). The equatorial thermocline area is indicated by the darker grey bar; the lighter grey bar indicates the area of the thermocline in the subtropics. All profiles are averaged between 160°E and 160°W (source: Climatological Atlas of Regional Seas, Ridgway and Dunn 2003)[190].

Because water density decreases with increasing temperature, and increases with increasing salinity (but to a lesser extent), 'stratification' occurs in the water column. That is, lighter surface water remains separated from the denser deeper layer, like a layer of oil sitting on water. Increased stratification makes the water column more stable because more energy, in the form of wind or buoyancy-driven convection, is needed to mix water between the two layers. This requirement has important implications for fisheries because when the water column is stable the transfer of nutrients to the sunlit (photic) zone where primary production occurs is inhibited.

The stratification across the tropical Pacific is generally strong but decreases with increasing latitude (**Figure 3.6**). The strongest stratification occurs below the main atmospheric convergence zones (ITCZ and SPCZ) (Chapter 2). Nevertheless, several processes occur in the surface layer of the ocean, which can act against stratification. In addition to generating surface currents (Box 3.1), wind causes strong mixing in the upper layer. Evaporation, and loss of heat from surface waters at night or during winter at higher latitudes, also causes strong convective mixing in the upper layer and weakens the stratification. These forms of turbulence and mixing homogenise temperature, salinity and other properties of the ocean in the first few tens of metres (**Figure 3.7**), resulting in the surface 'mixed layer'. This homogenisation of properties results in a very sharp gradient at the base of the mixed layer. Below this level, the properties of the water column are affected by deeper oceanic processes[34,35].

The depth of the mixed layer varies substantially on daily to interannual time scales and ranges from about 0 to 200 m at low latitudes[34,35]. In nutrient-poor (oligotrophic) waters, the mixed layer depth is vitally important because it determines the depth from which nutrients are brought up to support biological activity at the surface[34,35] (Box 3.2, Section 3.2.4).

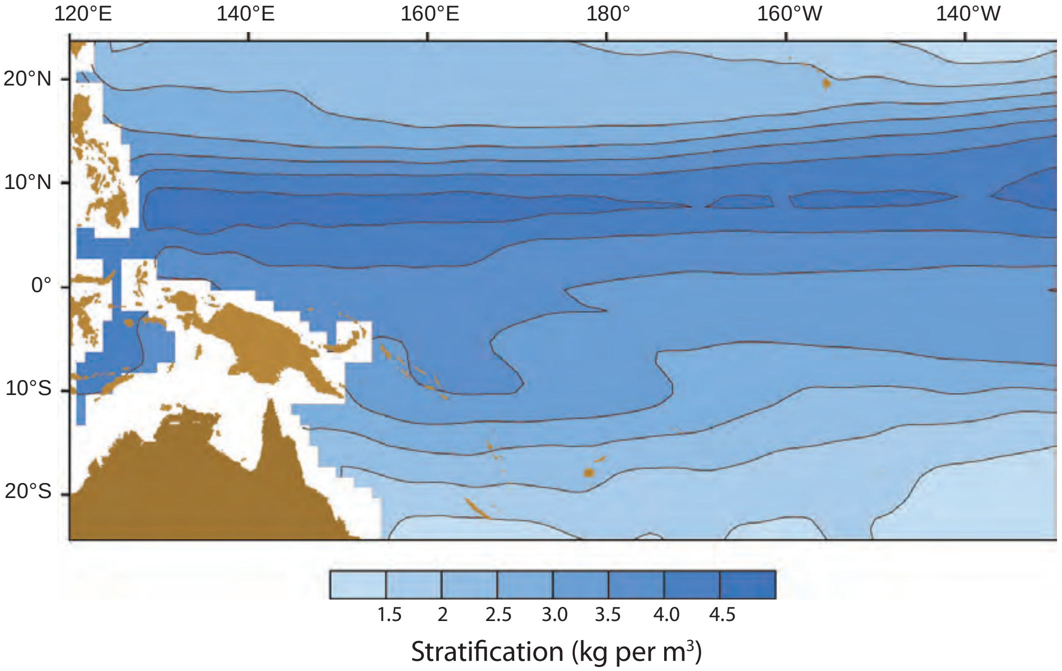


Figure 3.6 Average stratification of the tropical Pacific Ocean from 1980–1999 from the Simple Ocean Data Assimilation (SODA) (source: Carton et al. 2000)[191]. Stratification is defined here as the difference in water density (kg per m^3) between depths of 13 m and 200 m (13 m was chosen for compatibility with the common upper level of IPCC-AR4 model analyses). The highest vertical stratification is found under the Intertropical Convergence Zone and the South Pacific Convergence Zone.

The general vertical temperature structure described here varies with latitude. Deeper water within the thermocline is sourced from surface waters in the subtropics that are subducted into the thermocline to depths of around 200 m. This water then flows towards the equator where it eventually upwells. In the upper ocean, two warm water 'bowls' appear between 10°–20°N and 10°–20°S and extend to depths of 500 m (**Figure 3.8**).

These bowls are formed by the convergence of surface waters under the influence of Ekman transport (Box 3.1); the easterly trade winds drive the flow of warm surface water in the tropics poleward, whereas at 40°N–40°S westerly winds drive surface water towards the equator. This leads to a convergence that pushes the surface water downwards and creates the bowls of warmer water.

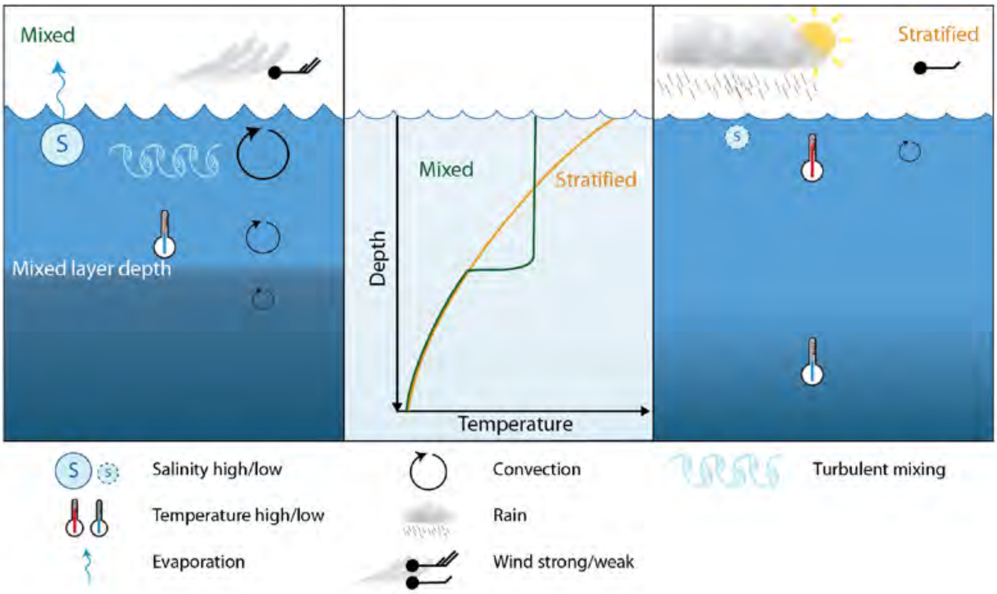


Figure 3.7 Factors affecting the mixed layer depth. The left panel shows a well-formed mixed layer with homogenised properties in the upper part of the water column; the right panel shows a smoothly stratified field. The corresponding temperature profiles are given in the middle panel. The formation of the mixed layer is enhanced by cooling, evaporation and strong winds, and weakened by heating, precipitation and slight winds.

In many parts of the tropical Pacific, the most important factor affecting water density, and therefore stratification, is temperature. However, in some regions, such as the Warm Pool, salinity becomes equally important (Section 3.2.2.3). The effects of temperature and salinity changes on density are significant because the motion of the ocean is controlled largely by spatial differences in water density (Box 3.1). For example, the downward tilt (towards the north) in the temperature structure below 100 m between 10° and 15°N (**Figure 3.8**) causes a westward flowing geostrophic current – the NEC (Section 3.1). Similarly, the upward tilt (towards the north) in the deeper isotherms of the Southern Hemisphere is associated with the westward flowing, geostrophic SEC.

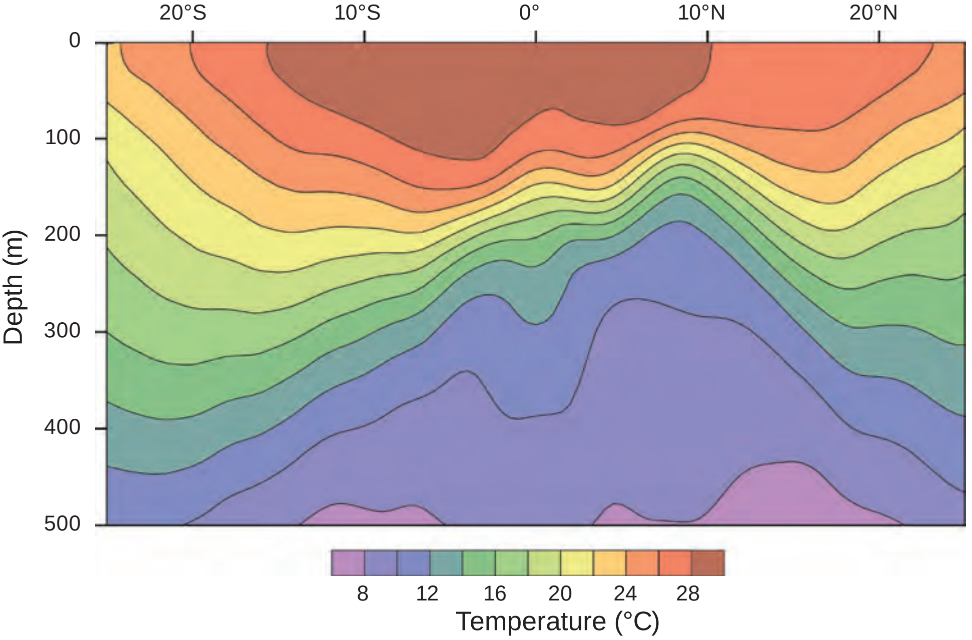


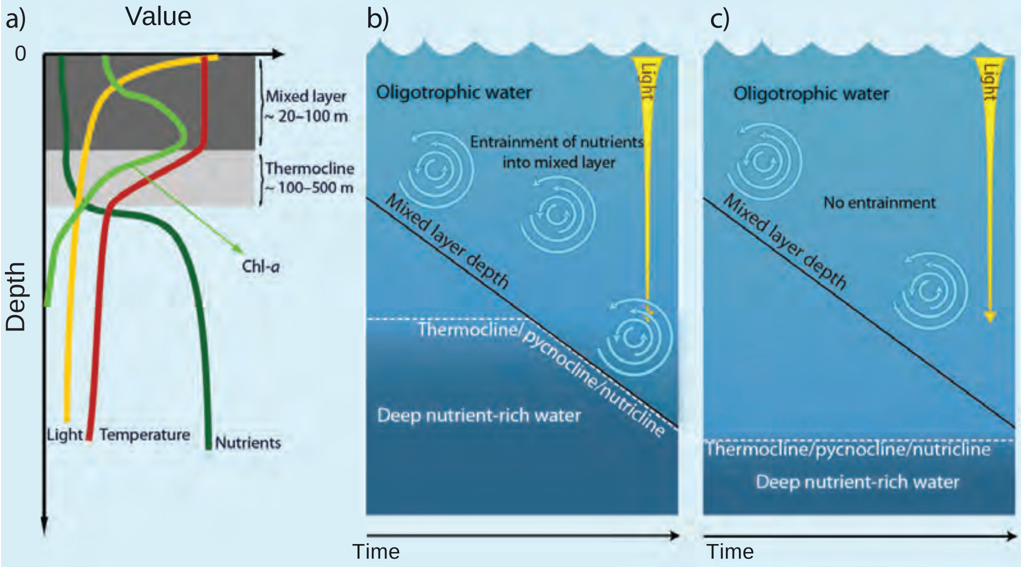
Figure 3.8 Vertical temperature structure (°C) of the water column, to a depth of 500 m, from 25°S to 25°N (averaged across the area from 160°E to 160°W). Note that warmer surface water penetrates to greater depths between 15°–20°N and 15°–20°S (source: Climatological Atlas of Regional Seas, Ridgway and Dunn 2003)[190].

3.2.2.3 The Warm Pool

The Western Pacific Warm Pool Province[36] (Section 3.2.2.4), is of major significance to tuna fisheries in the tropical Pacific (Chapter 8) and requires special attention in this description of ocean temperatures. The combined Warm Pool waters of the equatorial western Pacific Ocean and equatorial eastern Indian Ocean cover a vast area characterised by the world's warmest oceanic temperatures, the deepest atmospheric convection and the heaviest precipitation (Chapter 2). This Indo-Pacific Warm Pool is often defined by SSTs greater than a threshold value – usually 28°C. By this definition, it extends over ~ 12 million km^2 of the tropical Pacific Ocean (1.5 times the size of Australia) and ~ 6 million km^2 of the Indian Ocean. The interactions between the ocean and the atmosphere in this part of the world occur through radiative and latent heat transfers that drive vigorous convective clouds, winds and precipitation (Chapter 2). Small changes at the ocean-atmosphere boundary are enhanced through convection and can lead to self-amplification and eventually large changes in atmospheric circulation. The high precipitation levels above the Warm Pool strongly affect salinity, resulting in a relatively warm and fresh (less dense) pool of well-mixed water overlaying a cold and relatively saline (denser) ocean interior (**Figure 3.9**).

Box 3.2 Influence of the thermocline and mixed layer depth on transfer of nutrients to surface waters

In much of the subtropical northern and southern Pacific Ocean the potential for transferring nutrient-rich water from the deeper layers to the photic (sunlit) zone, where it can enhance the growth of phytoplankton (known as 'primary productivity') (Chapter 4), is constrained by stratification. Stratification is strongest at the depth of the pycnocline (the layer in the ocean where water density increases relatively rapidly with depth). As density is determined by temperature (and to a lesser extent salinity) the pycnocline depth usually corresponds to the depth of the thermocline, where temperature decreases relatively rapidly with depth (see panel a). Biological activity, commonly measured as Chlorophyll *a* (Chl-*a*) produced by phytoplankton, depends on both light (from above) and nutrients (from below), and is usually greatest in the lower part of the mixed layer.



This vertical structure varies with time. Where the thermocline is shallow (panel b), mixing of the upper part of the water column by wind or convection reaches down to the nutrient-rich waters and transfers nutrients into the photic zone, where they are used for primary productivity. Where the thermocline is deep (panel c), nutrients remain out of reach below the mixed layer. The gradient in density at the thermocline/pycnocline also acts as a barrier to the downward penetration of the mixing, reinforcing the vertical structure. The time scales over which the processes that transfer nutrients occur vary from a few hours (e.g. strong wind events) to seasons (e.g. winter cooling and wind enhancements). The area of the water column where the maximum change in nutrients occurs with depth is called the nutricline and, like the thermocline, it is often co-located with the pycnocline.

The Warm Pool is at the heart of the ENSO mechanism (Chapter 2). Under 'normal' conditions, the trade winds generate surface currents that push and accumulate warm water to the west (Section 3.2.1), creating a large heat reservoir that maintains the easterly trade winds via the Walker circulation (Chapter 2). When an El Niño event occurs, the trade winds weaken, allowing the Warm Pool to spread eastwards across the equatorial Pacific over a period of ~ 2 months, along with its wind and precipitation systems. The displacement of the Warm Pool occurs through wave dynamics that set the speed and structure of the Warm Pool's motion to the east. After an El Niño event, westward propagating waves reset the system towards a 'normal' situation, replenishing and relocating the Warm Pool. Sometimes an 'overshoot' gives rise to a period of more extreme trade winds and a westward contraction of the Warm Pool – the Pacific shifts to a La Niña situation. El Niño events are associated with a 'shoaling' of the Warm Pool thermocline, which enhances primary productivity (Chapter 4). Conversely, the thermocline deepens during La Niña episodes, leading to lower productivity.

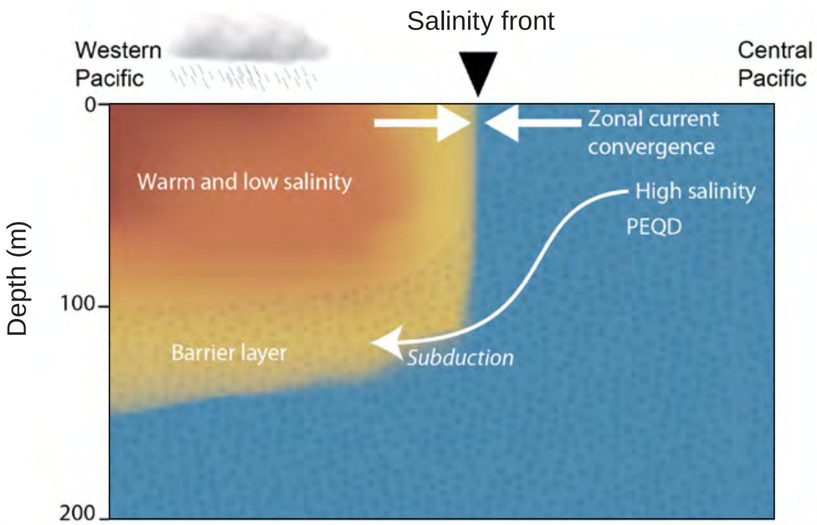


Figure 3.9 Temperature structure of the equatorial Pacific showing the Warm Pool. The thermally homogeneous waters of the Warm Pool, freshened by heavy rainfall in the western Pacific, converge with the colder, saltier waters originating in the Pacific Equatorial Divergence Province (PEQD) to the east. This convergence is one of the mechanisms that leads to the formation of a salinity-stratified layer in the lower part of the Warm Pool known as the 'barrier layer'. Upwelling occurs to the east of the salinity front, bringing nutrient-rich waters to the surface. In contrast, the Warm Pool has low nutrient levels.

At the eastern edge of the Warm Pool, there is a convergence zone where the incoming westward SEC weakens and there is a small eastward flow within the Warm Pool (**Figure 3.9**). The interannual movements of the Warm Pool (and its eastern edge) are controlled by the relative strength of these zonal currents and are subject to variations that are in phase with ENSO[37]. Because of the contrasting water properties to the east and west of this boundary, the convergence zone is characterised by a sharp change in salinity (**Figure 3.9**). Displacements of this convergence zone are an intrinsic part of the ENSO system[38] and can reach several thousands of kilometres, between 140°W during El Niño conditions and as far west as 140°E during La Niña episodes[39]. These displacements also determine the boundary between the Pacific Equatorial Divergence Province (PEQD) (Section 3.2.2.4) and the Warm Pool[40].

The relative contributions of temperature and salinity to the density of sea water are similar in the Warm Pool – a situation that is uncommon in most other parts of the tropical Pacific Ocean, where temperature normally dominates. On average, temperature is homogeneous in the upper 60 m of the water column in the Warm Pool with a sharp thermocline below this surface layer. In contrast, the salinity 'halocline' in the Warm Pool is much shallower, resulting in a mixed layer (where both temperature and salinity are well-mixed), which is only about 30 m deep[41]. The stratified layer between the thermocline and the base of the mixed layer is called the 'barrier layer' (**Figure 3.9**). Within the barrier layer regions, any mixing driven by the wind is restricted so that the waters below the barrier layer are insulated from the influence of the atmosphere, and vice versa. This stratification acts as a barrier to the vertical exchanges of heat, fresh water and nutrients, and suppresses mixing[42]. The location and strength of the barrier layer are important to both ENSO dynamics[43,44] and biological production[45].

3.2.2.4 Boundaries of ecological provinces

Differences in water temperature, salinity and the convergence zones related to the major surface currents define five ecological provinces that cover the area of the tropical Pacific[36] (Chapter 4).

The Pacific Equatorial Divergence Province is generated by the diverging surface Ekman transports (**Figure 3.1**, Box 3.1), which drive upwelling of nutrient-rich water, creating the most productive surface waters in the region. The waters in this province are also characterised by a high salinity and high partial pressure of carbon dioxide (pCO_2). These nutrient-rich waters span much of the equatorial Pacific and drift westward and poleward before submerging at the convergence with the NECC (ca. 5°N) and SECC (ca. 6–8°S).

To the west, the Warm Pool forms a province by itself. In contrast to the PEQD, the surface waters of the Warm Pool are relatively nutrient-poor but, for reasons explained in Chapters 4 and 8, support high populations of tuna. At the equator, the salinity front marks the boundary between the Warm Pool and PEQD. Seasonal and interannual (ENSO) displacements define the extent of these two provinces.

On both sides of the equatorial band are the large oceanic gyres (**Figure 3.1**). These oligotrophic regions are associated with the convergence of warm surface water from the North Pacific Tropical Gyre (NPTG) and the South Pacific Subtropical Gyre (SPSG)[36] (Chapter 4).

The western part of SPSG is characterised by a large number of islands and shallow seamounts, referred to as the Archipelagic Deep Basins Province (ARCH). This province is subject to a range of mesoscale processes (Section 3.2.9), and the current regimes are complex because of the way islands, archipelagos or seamounts divert oceanic circulation. ARCH has a mixture of surface waters with different characteristics, and differs from the other provinces, which are generally dominated by more stable large-scale currents.

3.2.3 Ocean eddies

Eddies are large, horizontally-rotating vortices that can extend from the surface to considerable depths (**Figure 3.10**). Eddies in the ocean, and in coastal areas, affect the distribution and abundance of the species supporting fisheries in the tropical Pacific in two main ways. First, they help draw nutrient-rich water from the deeper layers of the ocean towards the surface, stimulating primary production (Chapter 4). This is important not only for oceanic fisheries, but also for the coastal fisheries around the islands in the generally nutrient-poor waters of the western Pacific (Section 3.2.4). Second, eddies help entrain the larvae of fish and invertebrates close to favourable habitats that support the spawning adults, increasing the probability that juveniles will recruit successfully[46]. This is particularly important for isolated PICTs, where stocks are usually dependent on self-replenishment.

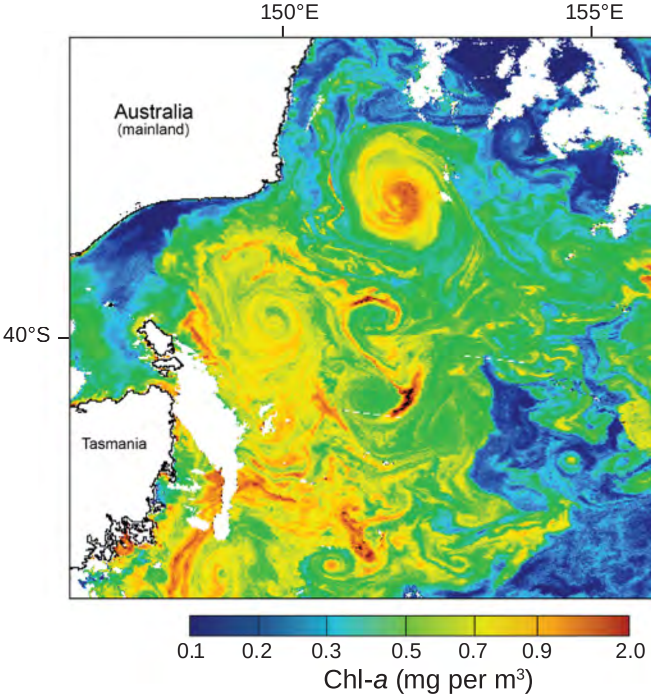


Figure 3.10 An example of mesoscale eddy activity in the southern Tasman Sea, illustrated by reconstructed Chlorophyll *a* concentration in mg per m^3 (see colour scale), from NASA SeaWiFS satellite data. White areas over the ocean correspond to data gaps.

Most of the energy in the ocean is not contained in the massive basin-scale circulations, but rather in pervasive, smaller-scale features, like eddies[47]. The energy that drives eddies and much of the other motion in the ocean is derived from the atmosphere (via wind and heat) or the sun (via radiation) (Box 3.1). Similar to the atmospheric mid-latitude depressions/anticyclones, mesoscale eddies are generated by instabilities in the large-scale flow, and occur throughout the ocean. The size of mesoscale eddies depends strongly on latitude – in the tropical Pacific they range from ~ 150 to 300 km across[48]. As a result of the Coriolis force, mesoscale eddies tend to propagate to the west in the Pacific at speeds ranging from 5 cm per second at 25°N–25°S to 10 cm per second at 10°N–10°S[49,50].

On larger scales (up to ~ 1000 km), horizontal water displacements associated with Rossby waves are also evident away from the equator[51]. Rossby waves are generated by large-scale fluctuations in the surface winds. Like eddies, Rossby waves only travel in a westward direction as a consequence of the Coriolis force.

The passage of mesoscale eddies and Rossby waves is associated with important variations in local currents, sea level and the vertical structure of the water column. A warm, anticyclonic eddy raises sea level in the order of 10 cm over a horizontal distance of a few tens of kilometres[52] and depresses the thermocline (**Figure 3.11**). A cold, cyclonic eddy has the opposite effects.

The impact of eddies can be dramatic. For example, an anticyclonic eddy delivers warm water that can boost the energy of an ongoing cyclone. Cold eddies, through their capacity to reduce the depth of the thermocline, can bring nutrients into the photic zone (Section 3.2.4.1). The passage of Rossby waves also enhances the availability of nutrients in a similar way, and 5% to 20% of the variability in ocean productivity is associated with these phenomena[53].

Because eddies result in changes in sea surface height, areas of vigourous variation in sea surface height correspond to places of intense eddy activity. Satellite images of such variability reveal that eddies are distributed unevenly across the tropical Pacific[54] (**Figure 3.12**). Near the equator, variability in sea surface height is dominated by ENSO.

Away from the equatorial region, five areas of relatively high variability occur close to strong currents and in the places where currents and counter currents interact (1) near Australia at 25°S, which is the northern end of the high energy zone associated with the EAC[55,56]; (2) east of Solomon Islands, in the wake of the SECC; (3) near 6°N in the NECC, and in two bounding areas where surface counter currents intrude into the domain; (4) south of 20°S and between 160°E and 150°W in the South Pacific Subtropical Counter Current; and (5) near 22°N in the North Pacific Subtropical Counter Current[57,58] (**Figure 3.1**, Section 3.2.1).

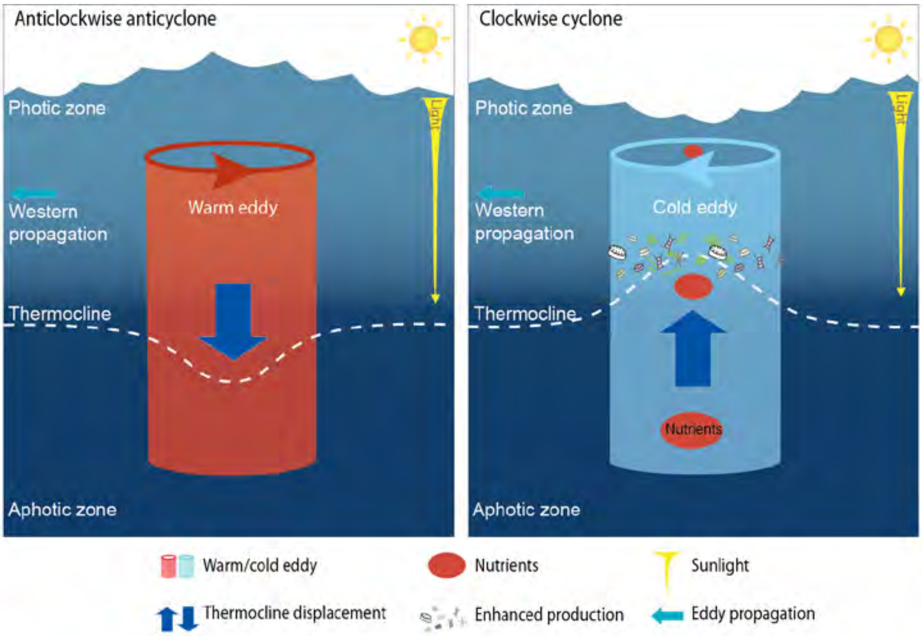


Figure 3.11 Effects of an oceanic eddy on the vertical temperature structure of the water column in the Southern Hemisphere. In the case of an anticlockwise warm eddy (left panel), the thermocline is pushed downwards and the sea surface is slightly raised within the eddy as it propagates westward. A cold eddy, on the other hand, which rotates in a clockwise direction (right panel), raises the thermocline, potentially making nutrients available for enhanced biological production. In the Northern Hemisphere, the direction of rotation is reversed but the thermocline displacements are in the same direction.

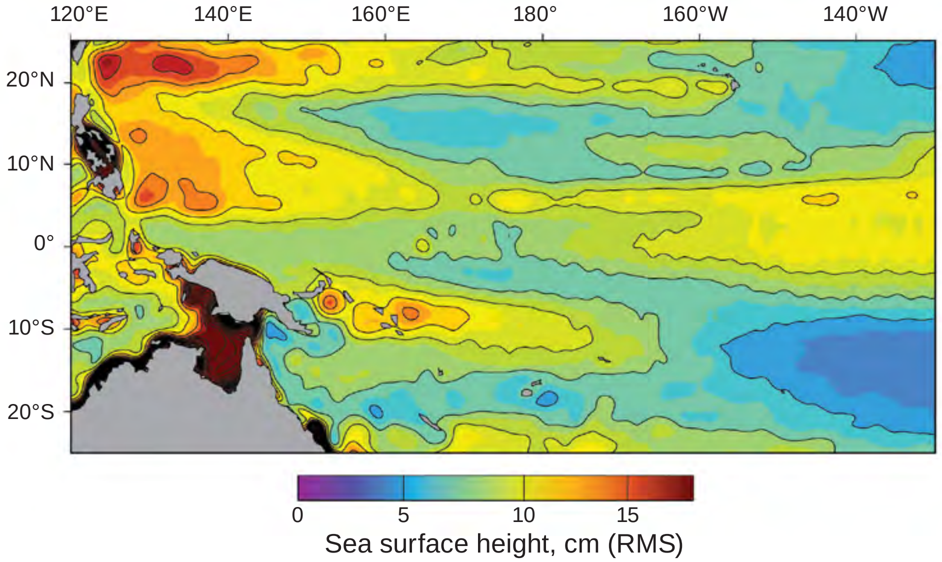


Figure 3.12 Eddies in the tropical Pacific Ocean, shown as variability (standard deviation) in sea surface height (SSH) anomaly from a merged satellite altimetry dataset (including Topex/Poseidon, Jason, ERS and Envisat from 1992–2007) (source: Ridgway 2007)[192]. Contour interval is 2.5 cm. Note that passing eddies cause a temporary change in sea level.

3.2.4 Nutrient supply

The availability of nutrients in the ocean is of great significance to fisheries. Together with sunlight, nutrients underpin the primary productivity associated with phytoplankton at the base of the food webs that support the stocks of tuna and other large pelagic fish harvested throughout the tropical Pacific Ocean (Chapter 4). The main nutrients associated with biological productivity are nitrates, phosphates and silicates. The maintenance of this productivity can be fragile, however, because nutrients are not distributed evenly – they are depleted near the surface, where they are needed, but abundant in the deeper ocean. This variation occurs because the phytoplankton use up the available nutrients in the photic zone, where there is sufficient light for photosynthesis and, although a small part of the nutrients pass down the food web, most of them eventually sink as organic matter into the deep ocean. There, bacteria remineralise the organic matter, releasing nutrients. As a result, concentrations of nutrients are much greater below the pycnocline than they are at the surface (**Figure 3.13**). The sinking of organic material is also one of the main ways that CO_2 is transferred into the deep ocean from the atmosphere and is known as the 'biological pump'[59].

Ocean circulation, or deep mixing of the water column, is needed to transfer the nutrients back to the surface layers. The strong density stratification (pycnocline) usually associated with the thermocline (Box 3.2) effectively inhibits the vertical exchange of water (and therefore nutrients) between the deep and shallow layers of the ocean. Molecular mixing is too weak to transport significant amounts of nutrients towards the surface. The main processes that can overcome the stratification barrier and deliver nutrient-rich water to the upper layers – turbulence in the mixed layer, wind-driven upwelling and eddies – are outlined below.

3.2.4.1 Mechanisms that make nutrients available

- **Turbulence in the mixed layer:** The strong mixing in the upper ocean (Section 3.2.2.2) entrains nutrient-rich deeper waters and circulates them within the photic zone. The extent of nutrient input is determined by the depth of mixing in relation to the depth of the nutricline (Box 3.2). A strong wind, for example, may deepen the mixed layer to 100 m in several hours and entrain the nutrient-rich deep waters from greater depths. On seasonal time scales, and at subtropical latitudes, the mixed layer deepens during winter because of stronger winds and surface cooling, and becomes shallower during summer as surface warming acts to stratify the water column (**Figure 3.14**). In oligotrophic waters, the maximum mixed layer depth determines the depth from which nutrient-rich waters can be mixed to the surface to replenish nutrient supplies depleted by biological activity in the photic zone. Thus, mixed layer depth is a useful indicator of biological production[60.]

  Maximum yearly mixed layer depth in the tropical Pacific Ocean ranges from 70 to 80 m in the highly stratified Warm Pool (**Figure 3.15**), where warm water accumulates over the cold waters of the Equatorial Undercurrent, to more than

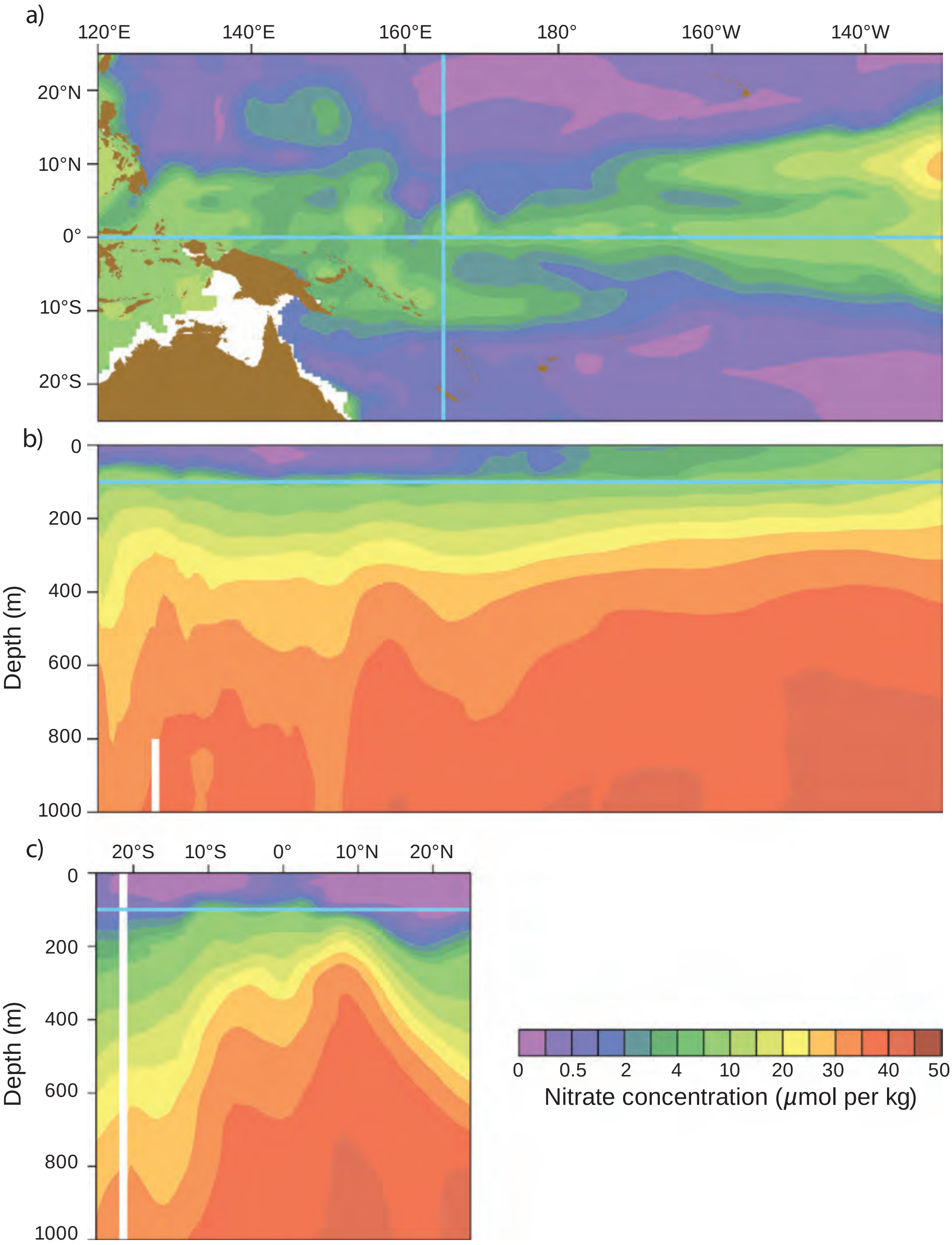


Figure 3.13 (a) Average dissolved nitrate concentration (µmol per kg) in the tropical Pacific Ocean at a depth of 100 m; and average dissolved nitrate concentrations for vertical sections of the water column to depths of 1000 m at (b) the equator, and (c) 165°E. The positions of the vertical sections are indicated as blue lines on (a); horizontal blue lines in (b) and (c) represent values at a depth of 100 m as shown in (a) (source: CARS 2006 CSIRO climatology, Ridgway and Dunn 2003)[190]. White areas in (b) and (c) correspond to topography.

200 m in the low rainfall regions at the centre of the two gyres (NPTG and SPSG), where relatively high-salinity waters are cooled during the winter, causing convection and much deeper mixing.

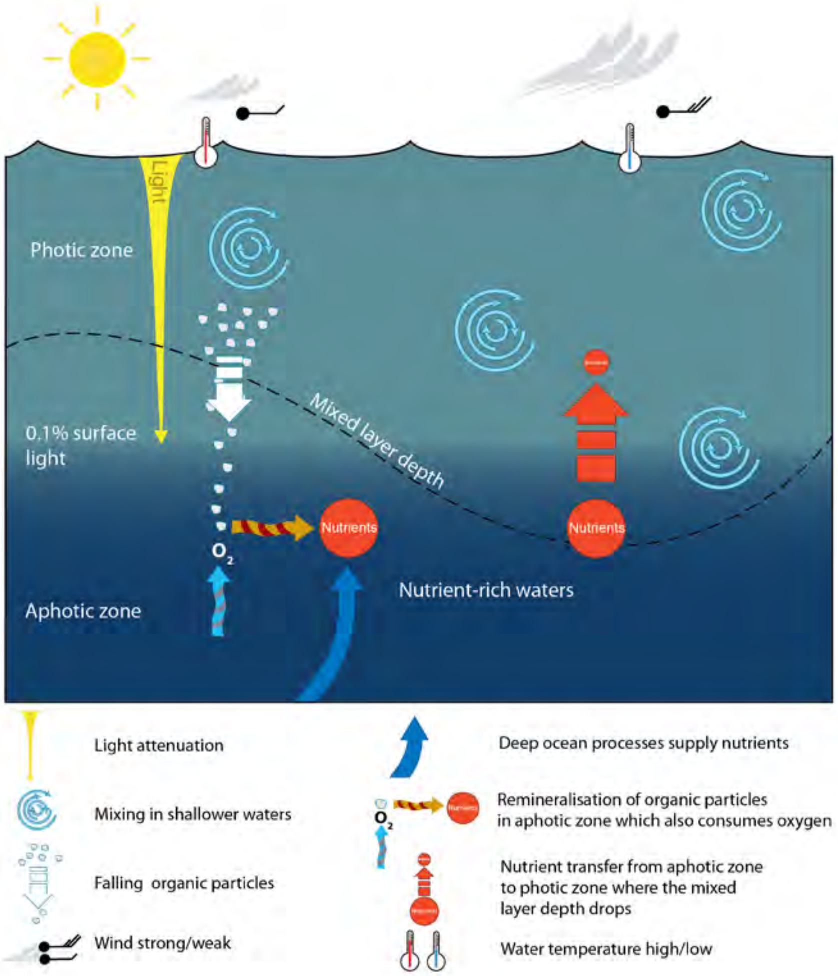


Figure 3.14 Factors contributing to nutrient concentration in the surface waters of the tropical Pacific Ocean. A deeper mixed layer, caused by stronger winds and lower surface temperatures during winter, helps to transfer nutrients to the photic zone, where they are available to contribute to biological production. Advection by ocean currents and decomposition of organic matter by bacteria (remineralisation) maintains a reservoir of nutrients below the mixed layer (see Chapter 4 for more details).

- **Upwelling:** As explained in Section 3.2.2.1, upwelling of deep, nutrient-rich waters is created by the divergence of surface water, when wind-driven surface currents move in opposite directions (e.g. at the equator), or when surface water is pushed away from the coast (e.g. near islands, or along the Peru-Chile coast). The surface divergence 'draws' deeper waters towards the surface, creating an 'upwelling'. If these waters originate from a sufficient depth, they deliver nutrients into the mixed layer. This occurs in PEQD, where strong upwelling occurs within

4 to 5° of the equator driven by the easterly trade winds (Chapter 4). In contrast, the subtropics (NPTG and SPSG) are dominated by convergence of surface waters and downwelling, making them areas of low productivity. Weak upwelling is found, however, near the poleward edge of the SPCZ and ITCZ, and near islands in NPTG and SPSG, where sharp changes in the direction of ocean currents or the wind can lead to local upwelling events that enrich surface waters. The local influence of coasts and islands is more pronounced in ARCH, where boundary currents, jets, wind-driven upwelling, enhanced internal waves or tidal mixing activity more commonly bring nutrients into the photic zone (Section 3.2.9) (Chapter 4).

- **Eddies:** Surface divergence associated with oceanic eddies and Rossby waves, both within the eddies or waves (mesoscale) and at their edges (submesoscale) (Section 3.2.3), can raise the thermocline temporarily and bring nutrient-rich waters into the photic zone[52,61,62] (**Figure 3.11**) to increase primary productivity (Chapter 4). Because oceanic eddies are ubiquitous in the subtropics (**Figure 3.12**), they are believed to be the main nutrient supply system along with frontal processes in NPTG and SPSG[53,59,63–66].

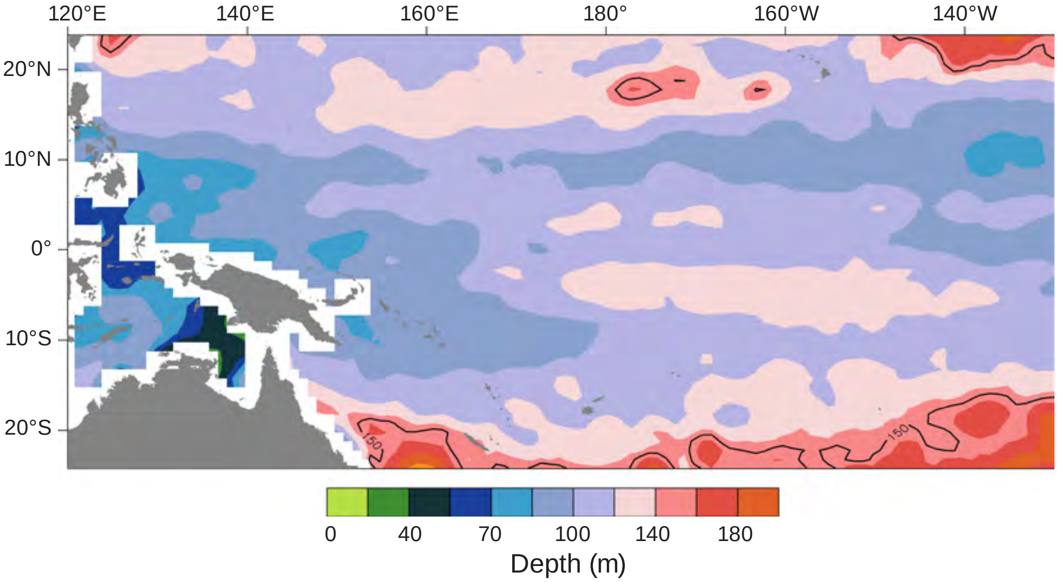


Figure 3.15 Maximum mixed layer depths across the tropical Pacific Ocean for the period 1980–1999, based on the Simple Ocean Data Assimilation (SODA) (source: Carton et al. 2000)[191]. The mixed layer depth (MLD) is defined as the depth at which the density of the water increases by 0.1 kg per m^3 with respect to the density at the surface (source: Sarmiento et al. 2004)[60]. The 150 m MLD contour is shown in black.

Overall, the supply of nutrients to the photic zone in the tropical Pacific Ocean is the result of the interplay between mixed layer depth, upwelling and eddies against the background of the stratification and nutrient structure of the particular province (Box 3.2). Upwelling, for example, driven by the easterly trade winds, plays an important part in supplying nutrients in PEQD, where the thermocline is shallow. In addition, ENSO-related equatorial waves can lead to displacements in the thermocline, which affect the supply of nutrients (Section 3.2.2.2). Following a westerly wind burst in the western Pacific (an important precursor to El Niño events), a 'downwelling' equatorial wave moves across the basin to the east deepening the thermocline on its way and suppressing upwelling. The strength and depth of the EUC is another important factor controlling productivity in the tropical eastern Pacific as it provides a source of iron, which is the element that limits primary production in that region[45,67] (Chapter 4).

The sporadic nature of phytoplankton blooms in the tropical Pacific Ocean (Chapter 4) suggests that occurrence and coincidence of the various processes affecting biological production along the equator are highly irregular. A single biological bloom associated with a La Niña episode can dominate the average conditions over a 5-year period[45].

3.2.5 Dissolved oxygen

Adequate levels of dissolved oxygen (O_2) throughout the water column are essential for the growth and survival of the zooplankton and micronekton in the food webs for tuna, and for tuna themselves (Chapters 4 and 8). Where the concentrations of dissolved oxygen are too low, the distributions of these animals are restricted because they require O_2 for energy, and for oxidising organic substrates, such as carbohydrates.

The levels of dissolved oxygen in surface waters are determined by the rate at which oxygen is transferred from the atmosphere (which is highly dependent on SST and surface mixing), the rate it is produced from photosynthesis by phytoplankton, and the rate at which the oxygen-rich surface waters are submerged via ocean currents and mixing. At high latitudes, some cold surface waters rich in O_2 are pushed dynamically to lower latitudes, below lighter subtropical waters – a process called 'subduction'. These waters gradually lose O_2 as it is used up in the decomposition of organic matter by bacteria, a process termed 'remineralisation'. Therefore, dissolved oxygen concentration at any point in the water column is a balance between the original O_2 content, the effect of remineralisation of organic matter, and the rate at which water is replaced through ocean circulation. As a result, vertical O_2 concentration is usually inversely related to nutrient levels in the upper 500 m (compare **Figures 3.13** and **3.16**).

In regions of high remineralisation, consumption of O_2 can exceed replenishment from ocean circulation, causing part of the water column to become depleted in oxygen. This depletion results in anoxic conditions (see for example the areas around 10°N and 5°S in **Figure 3.16**). Unlike CO_2 (Section 3.2.6), changes in the dissolved oxygen content in surface waters are insensitive to changes in atmospheric O_2 concentrations because such changes are negligible relative to total oxygen concentration.

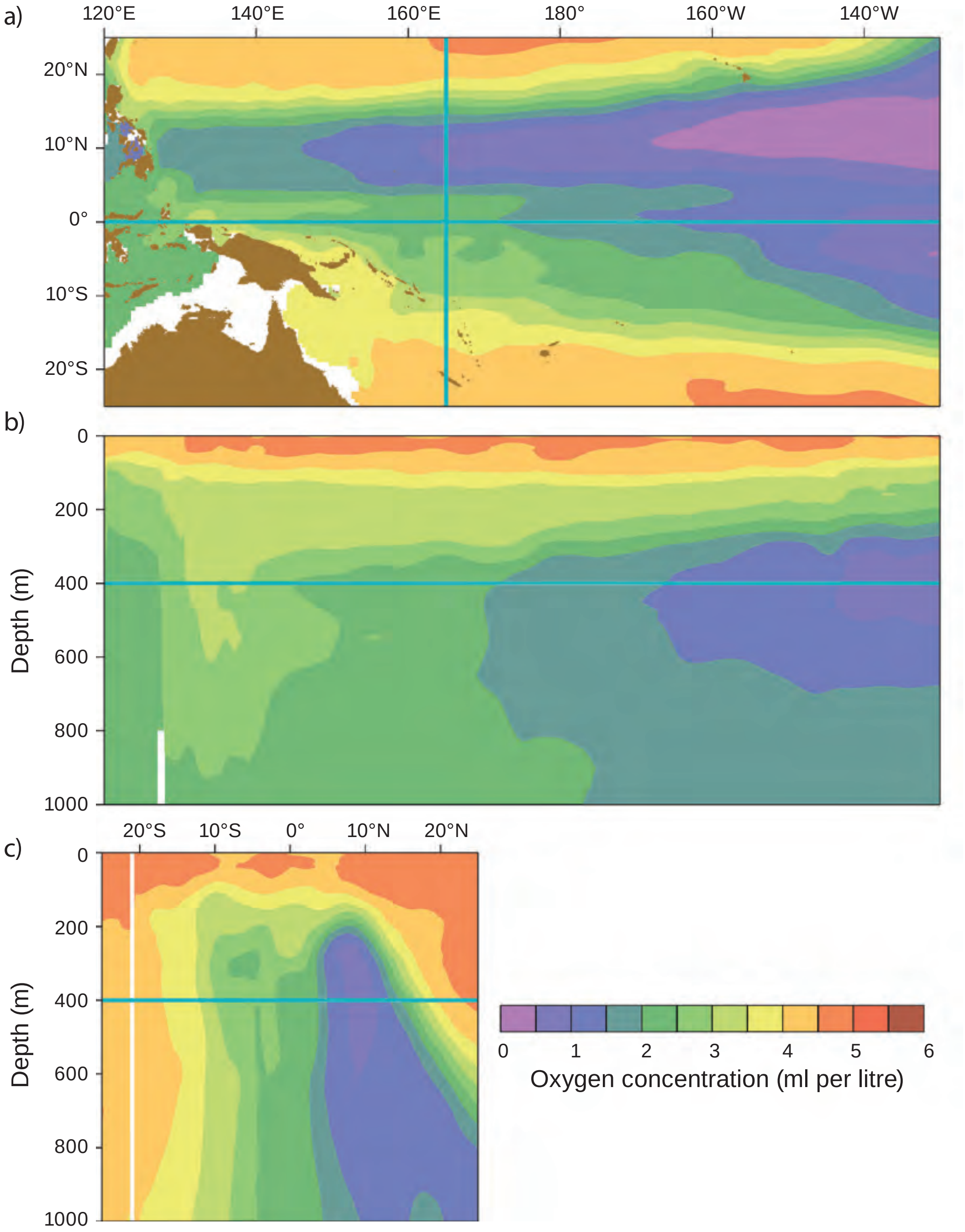


Figure 3.16 (a) Average dissolved oxygen (O_2) concentration (ml per litre) in the tropical Pacific Ocean at a depth of 400 m; and average O_2 concentrations for vertical sections of the water column to depths of 1000 m at (b) the equator, and (c) 165°E. The positions of the vertical sections are indicated as blue lines in (a); horizontal blue lines in (b) and (c) represent values at a depth of 400 m as shown on (a) (source: CARS 2006 CSIRO climatology, Ridgway and Dunn 2003)[190]. White areas in (b) and (c) correspond to topography.

3.2.6 Ocean acidification

The acidity of the open ocean has been relatively stable for millions of years. Due to this stability, carbonate ions (CO_3^{2-}) are so naturally abundant that the common pure minerals of calcium carbonate ($CaCO_3$) in the ocean (aragonite and calcite) are formed in surface waters and do not dissolve. This availability of carbonate ions is important to the corals and other calcifying organisms that build the reefs that support coastal fisheries (Chapters 5 and 9). Carbonate ion availability is also important to a range of organisms in the food webs for tuna (Chapter 4), and for many of the invertebrates that are collected for food and income by villagers throughout the tropical Pacific (Chapter 9). These organisms extract calcium (Ca^{2+}) and CO_3^{2-} from sea water to secrete the $CaCO_3$ they use to build their skeletons and shells.

The stability of ocean acidity and the supply of carbonate ions are likely to be threatened by increasing levels of anthropogenic CO_2. The problem is that the increased concentration of CO_2, much of which dissolves in the ocean (**Figure 3.17**), is changing the chemistry of sea water (Box 3.3). The consequence is that less CO_3^{2-} is expected to be available for use by calcifying organisms, reducing their growth and their chances of survival. Although the responses of species are likely to vary, depending on their physiology and the composition of their skeletal material (aragonite, calcite)[68,69], there is serious concern that ocean acidification will cause difficulties for the growth of corals and the maintenance of the essential habitats they provide for coastal fisheries. Indeed, a decrease of 0.3 units in oceanic pH is expected to inhibit formation or limit the growth of many marine organisms[70–76]. If CO_3^{2-} declines sufficiently, aragonite (the most common form of calcium carbonate used by marine species) actually begins to dissolve[70,76,77] (Box 3.3).

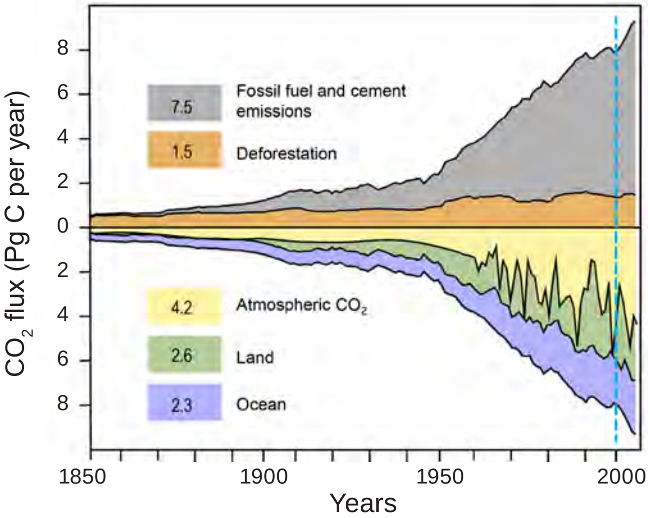


Figure 3.17 Sources of anthropogenic emissions of carbon dioxide (CO_2) and the 'sinks' that absorb CO_2, including the atmosphere. The flux is expressed in 10^{15} g of carbon (C) per year (Pg C per year); numbers in the colour legend represent the 2000–2007 average of the yearly flux for each component of the anthropogenic emissions (the period to the right of the dashed blue line) (source: IPCC-AR4 and Canadell et al. 2007)[193].

Box 3.3 The chemistry of ocean acidification

When carbon dioxide (CO_2) is dissolved in the surface waters of the ocean, certain chemical reactions take place. In particular, CO_2 combines with water to form carbonic acid (see Equation 1 below). The carbonic acid (H_2CO_3) dissociates into hydrogen ions (H^+) and bicarbonate ions (HCO_3^-) (Equation 2). The bicarbonate can also split into a further hydrogen ion and a carbonate ion (CO_3^{2-}) (Equation 3).

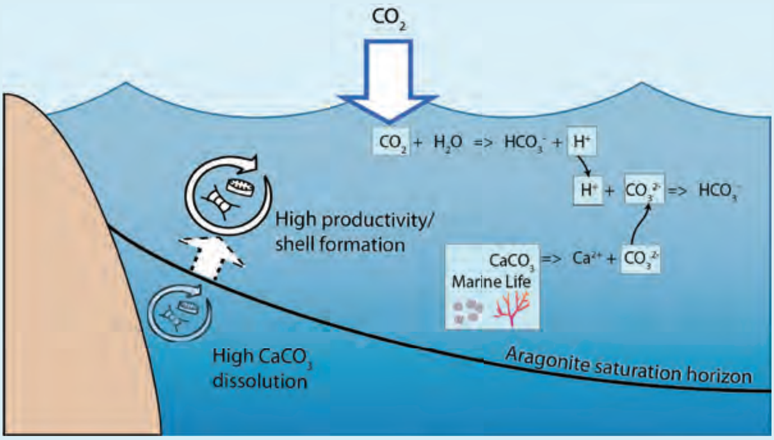
$$CO_2 + H_2O \leftrightarrows H_2CO_3 \tag{1}$$

$$H_2CO_3 \leftrightarrows H^+ + HCO_3^- \tag{2}$$

$$HCO_3^- \leftrightarrows H^+ + CO_3^{2-} \tag{3}$$

Rather than creating a chain reaction, these equations represent two-way reactions that equilibrate continuously so that three dissolved inorganic carbon species occur simultaneously: carbonic acid, bicarbonate and carbonate (with relative concentrations of about 1%, 91% and 8%, respectively). These contributions shift, however, depending on the physical, chemical or biological conditions of the ocean. The fourth component in these reactions is the hydrogen ion. If there are more H^+, the water becomes more acid, i.e. its pH ($= -\log_{10}[H^+]$) decreases.

Fortunately, these chemical reactions self-regulate in such a way as to minimise the changes in pH. For example, if extra CO_2 is dissolved in the surface ocean (as is presently occurring) the balance shifts via chemical reactions (1) and (2) to higher concentrations of HCO_3^- and H^+, thus reducing pH. However, some of the excess hydrogen ions are removed as they combine with free CO_3^{2-} via reaction (3). This greatly reduces the rate at which acidification of the ocean occurs (although not entirely), but there is an environmental 'cost' because free carbonate ions are removed from the water. This tempering of the pH by free carbonate ions is known as 'carbonate buffering'. However, as more CO_2 is added to the ocean, the number of free carbonate ions decreases. As a result, the capacity for buffering will be reduced and pH is expected to continue to decline.



Both increased acidity (lower pH) and lower CO_3^{2-} concentration ('carbonate saturation') can have adverse effects on the growth and survival of marine organisms, especially those that build their shells and skeletons from $CaCO_3$, which is formed when calcium combines with carbonate ($Ca^{2+} + CO_3^{2-} \leftrightarrows CaCO_3$). As concentrations of CO_3^{2-} decrease, such species find it more difficult to secrete $CaCO_3$. At some 'saturation' concentration of carbonate, the ambient water becomes corrosive to $CaCO_3$ and the shells and skeletons of organisms actually begin to dissolve. This saturation level is sensitive to ocean temperatures, however, and cold high-latitude regions reach 'undersaturation' before tropical and subtropical waters. Also, as depth increases, a threshold is reached where $CaCO_3$ starts to dissolve due to increased pressure. This threshold is known as the 'aragonite saturation horizon'.

Organisms whose growth is naturally limited by the availability of CO_2, such as some phytoplankton and benthic microalgae, may benefit from rising levels of CO_2 in sea water. For example, the cryptic, bioeroding microalgae on coral reefs grow faster under elevated CO_2 concentrations, which exacerbate reef erosion through chemical dissolution[78]. Chemical dissolution in reef carbonate sediments can also increase due to enhanced bacterial activity under higher CO_2 levels[68,69,79].

Average ocean pH is now about 8.1, but it varies both seasonally and spatially by ~ 0.3 units across the oceans of the world due mainly to changes in SST and the upwelling of deep waters rich in CO_2 in the open ocean. Higher temperatures reduce the amount of CO_2 that can be dissolved in sea water, so that where the ocean is warmer, CO_2 is released and pH increases. Upwelling affects pH because concentrations of CO_2 are higher in deep water due to the remineralisation of the organic matter that accumulates there (Chapter 4). Where deep water upwells, for example, in PEQD, the pH of surface waters is reduced. This process is also affected by seasonal and spatial changes in biological productivity[80].

3.2.7 Wave height

The height (or energy) and direction of waves affect the ecosystems that support fisheries and aquaculture. For example, waves have a major influence on ocean surface mixing[81], sediment suspension and transport[82]. They also affect the structural complexity of coral reefs[83–85] (Chapter 5) and the extent and form of mangrove and seagrass habitats (Chapter 6), which provide shelter and feeding areas for the fish and shellfish that sustain coastal fisheries (Chapter 9). Where the wave climate is too strong, these ecosystems may be damaged by the direct force of the waves, and by turbidity resulting from coastal erosion or resuspension of sediments (Chapters 5 and 6). Wave height and direction also determine the locations where the infrastructure needed to support oceanic and coastal fisheries and aquaculture can be located securely, and where fishers can operate safely.

3.2.7.1 The nature of waves in the region

The waves on the surface of the ocean are generated by wind. Depending on location, they vary in length or period, from ripples (centimetres) to long swells (hundreds of metres). The period of a wave is measured as the time taken for two consecutive wave crests to pass the same point. The average wave conditions, or 'wave climate' of an area can consist of waves of many periods and heights, collectively called the 'wave spectrum'. The height of waves is usually recorded as 'significant wave height' (SWH), which is the average height (trough to crest) of the highest one-third of the waves over a given time.

The height and period of surface ocean waves are a function of wind energy, the distance over which the wind blows (fetch), the length of time the wind has been blowing and, in shallow water, the water depth (see below). Waves generated by local winds are called 'wind-sea waves', and generally have periods of < 8 seconds. Longer-period waves, which have travelled from remote regions where they were generated by storms, are known as 'swell'. These larger swell waves may traverse many thousands of kilometres in less than a day before they reach shallow waters and break on the shore. Most swells that arrive in the tropical Pacific are generated by storms in higher latitudes (**Figure 3.18**). However, the tropical cyclones described in Chapter 2 cause the local generation of much larger waves than those produced by remote storms.

In the tropical Pacific Ocean, long-term *in situ* wave data are generally lacking, and we rely on model re-analyses, i.e. a model simulation that is constrained by observations[86] and satellite data[87]. Such re-analysis suggests that the average SWH ranges from 1.5 to 2.5 m, but generally decreases to the west[86] (**Figure 3.18**). The wave spectrum is dominated by two types of waves: (1) short period 'wind-sea' waves generated locally by the trade winds, which have a westward direction but also move towards the equator (**Figure 3.18**); and (2) long-period swell waves generated by storms at mid to high latitudes in the band of easterly winds, which enter tropical regions with a dominant south-eastward direction in the north and a north-eastward direction in the south.

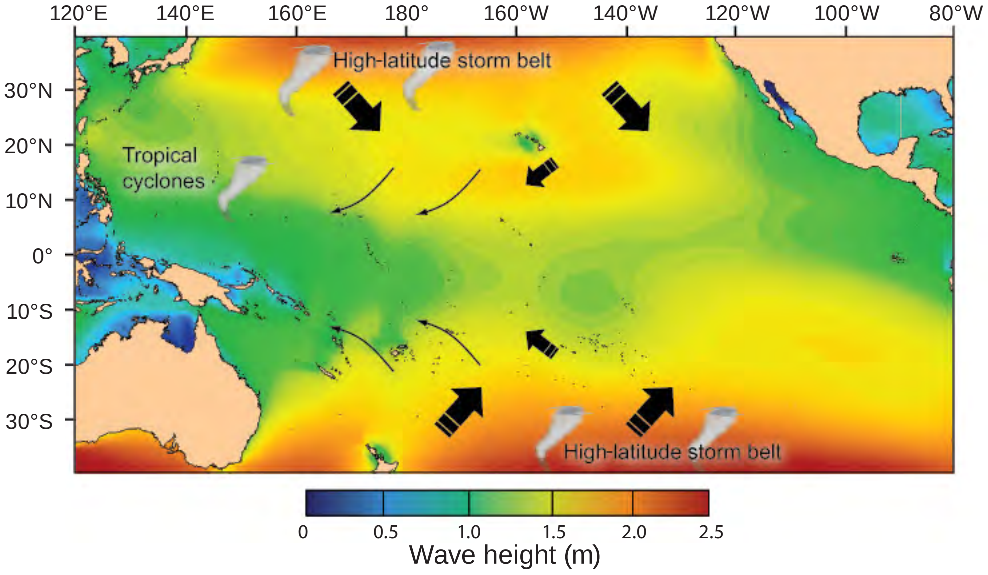


Figure 3.18 Long-term (1958–2002) average annual significant wave heights (SWH) in the tropical Pacific Ocean. Block arrows show the dominant wave direction. Size of block arrows indicates approximate relative wave height. Curved black arrows represent the trade winds (source: Sterl and Caires 2005)[86].

3.2.7.2 Effect of waves coming ashore

When swell waves enter water that is shallow compared with their wavelengths (i.e. equal to or less than about half the wavelength) they interact with the bottom. The waves slow, and their amplitude increases, to conserve energy (**Figure 3.19**). This causes the steepness of the wave to increase and, when the wave height reaches about 80% of the water depth (ignoring wind effects), the wave begins to break. The wave energy is then released, generating currents, sediment transport, and an increase in local sea level. Because longer wavelength swells interact with the bottom at greater depth, they generally break further offshore compared with wind-sea waves, which break closer to reefs. Thus, wind-sea waves penetrate further over the reef. This means that a 2 m wind-sea wave can actually cause the same damage on the inner parts of the reef as a 6 m swell which has broken further offshore[88].

The persistent arrival and breaking of waves on the shore creates an increase in water level over reef flats, which is about 20% of the offshore SWH. This increase is known as 'wave setup' (**Figure 3.19**)[89]. For enclosed lagoons and atolls, the lagoon water level can remain above the average ocean height throughout the tidal cycle, and rise significantly during large wave events[90]. Wave setup can create additional habitat space, enabling the vertical growth of a reef above the mean height of living corals[91,92]. Wave setup also creates a water level gradient sloping towards the less energetic side of an atoll, resulting in wave-driven flushing of lagoons[93]. For example, a swell event in Aitutaki, Cook Islands with a SWH of 4.5 m and a wave period of 15 seconds, resulted in a water level gradient of 30 cm across the lagoon. This caused a tripling of current speeds inside the lagoon[94]. Therefore, both average wave conditions, as well as individual events, can have important implications for the renewal of lagoonal water.

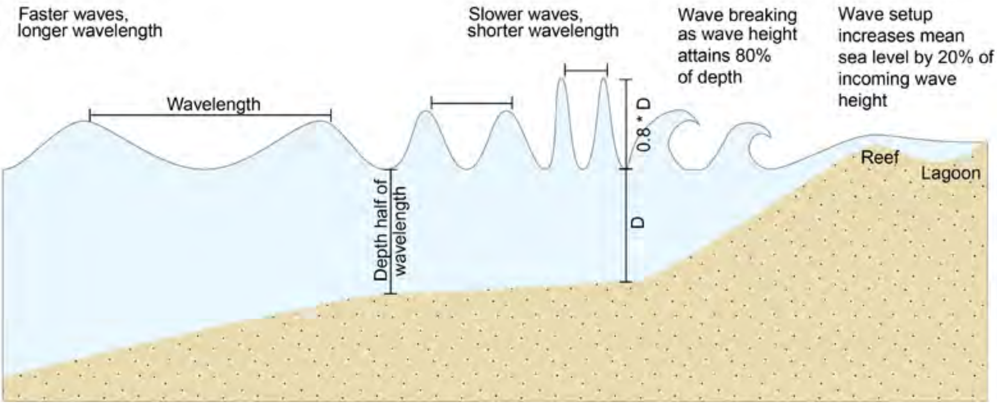


Figure 3.19 Changes in the characteristics of waves as they approach the shore. Waves approaching a reef interact with the bottom – their speed decreases, wavelength shortens and height increases. When the wave height reaches about 80% of the water depth the wave breaks, producing an accumulation of water that increases the mean sea level near the reef and over the lagoon. As a result, longer wavelength swells break earlier than shorter wavelength wind waves, and do not penetrate as far into reef and lagoon waters.

3.2.7.3 Variability in wave height

There are large natural variations in the wave conditions of the tropical Pacific Ocean. As the formation of waves is driven by wind, SWH and wave period in the region can be related to large-scale climate patterns (Chapter 2). ENSO events are a major source of this variability. An El Niño event is associated with higher waves east of about 170°E during the austral summer (Figure 3.20). West of 170°E, waves generally decrease during El Niño. The opposite occurs during La Niña events. The larger El Niño waves in the central southern Pacific also tend to come from a more southerly direction than normal[87]. During the rest of the year, the pattern of increase in the east and decrease in the west is shifted towards the west (**Figure 3.20**).

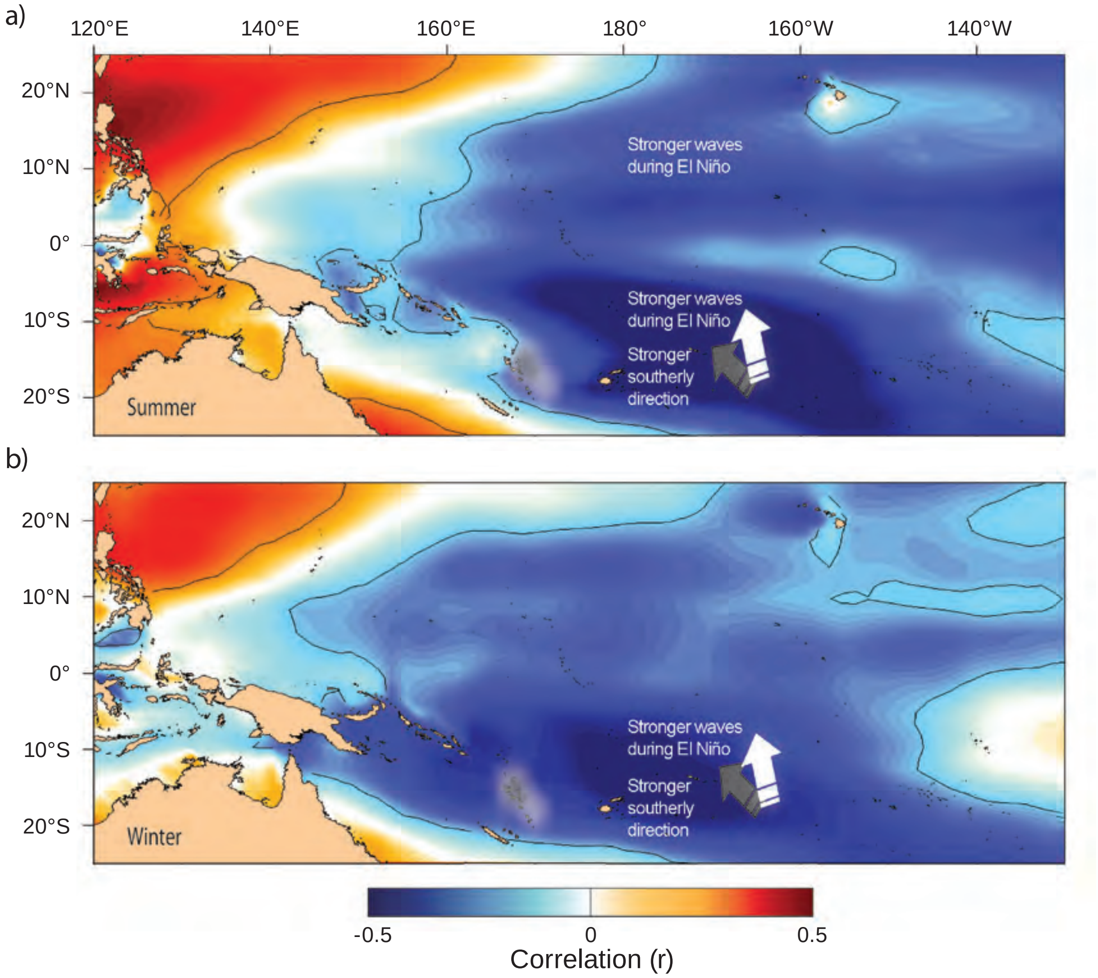


Figure 3.20 Effect of El Niño on wave height and direction (arrows) in the tropical Pacific Ocean during (a) austral summer (December to February) and (b) austral winter, which also represents the remainder of the year. The colour scale represents the (dimensionless) correlation coefficient between mean significant wave height (after annual mean cycle is removed) and the Southern Oscillation Index for the period 1958–2002 (source: Sterl and Caires 2005)[86]. Regions of negative correlation correspond to higher waves during El Niño conditions (a rotation from the grey arrow to the white arrow), or to lower waves during La Niña, with a less southerly direction.

Variation in the intensity and position of storms outside the region to the south also influences SWH in the tropical Pacific Ocean. Storm activity in the mid-latitudes is related to another characteristic climate pattern – the Southern Annular Mode (SAM)[87] (Chapter 2). A positive (negative) SAM is associated with stronger (weaker) mid-latitude westerly winds and increased (decreased) storm activity. The SAM has undergone a robust trend towards a more positive state over recent decades[95].

In the northern Pacific, there is also a strong relationship between wave conditions in Hawaii and ENSO[96]. During El Niño years, high swell events (SWH > 4 m) can occur. This difference is related to a combination of different storm generation regions, intensities and trajectories. During El Niño events, the central northern Pacific experiences the highest winter wave heights north of the equator. In contrast, during La Niña episodes, the region with the highest waves is nearer to the coast of North America[96].

3.2.8 Sea level

Several PICTs are acutely aware that land they depend on may be lost unless there is urgent mitigation of CO_2 emissions to prevent the inundation of low-lying islands. In the worst case scenarios of projected rises of sea level, large-scale relocation of infrastructure and human populations is likely to be required. But the effects of sea-level rise are not limited to the potentially tragic effects on human settlements – they also extend to altering the ecosystems that support the coastal fisheries on which many Pacific people depend for food security and livelihoods (Chapters 5, 6 and 9). Rising sea level will allow damaging waves to penetrate further inshore. It will also change the shape of coastlines and the tidal regimes in some areas as shallow basins are created. In some places, rising sea level may promote increased cover of mangroves and seagrass; in other areas, the extent of these ecosystems will be reduced (Chapter 6).

3.2.8.1 Sea level components and variations

Sea level at a given location is determined by a number of factors (**Figure 3.21**), and the interaction of these factors causes substantial variation on a broad range of time scales (**Figure 3.22**). Tides affect sea level on a predictable periodic basis; storms and eddies are episodic with effects lasting from hours to days; and circulation changes, like those associated with ENSO, can cause large year-to-year variation. The steady driver of global sea-level rise, however, is related to the long-term warming of the ocean and atmosphere which causes the melting of land-based ice and thermal expansion of sea water. Both processes increase the volume of the ocean.

During the peak of the last ice age, when ice sheets covered large parts of the Northern Hemisphere, the additional storage of water on the land led to a drop in sea level of ~ 120 m. Conversely, during the Pliocene ~ 3 million years ago, when global average temperatures were thought to be 2 to 3°C above today's temperatures, sea level was at least 15 to 20 m above present-day values[97].

Today, the main ice sheets are in Greenland and Antarctica, supplemented by ice caps (small ice sheets) such as the one in Iceland, and glaciers. If the major ice sheets were to melt completely, sea level would increase by about 70 m[98]. In contrast, complete melting of the ice caps and glaciers would increase sea level by only about 70 cm. The melting of floating sea ice does not affect sea level.

Regional changes in sea level due to ENSO events can be as great as 20 to 30 cm (**Figure 3.22**)[99]. This high degree of natural variability makes it difficult to extract robust long-term trends from the relatively short-term records for the region. Combining the information from individual tide gauges to produce estimates for the entire tropical Pacific requires advanced statistical methods[100], particularly because of differences in the way ENSO affects sea level in different locations. In general, an El Niño episode will tend to lower the sea level in the west, and raise it in the east, along the equator. In contrast, a La Niña event can significantly raise the sea level to the west. Over long time periods, sea-level rise due to El Niño events balances the fall due to La Niña episodes. Based on the long-term data series from tide gauges in the tropical Pacific, sea level is rising by between 0 and 3 cm per decade, depending on location (**Figure 3.23**).

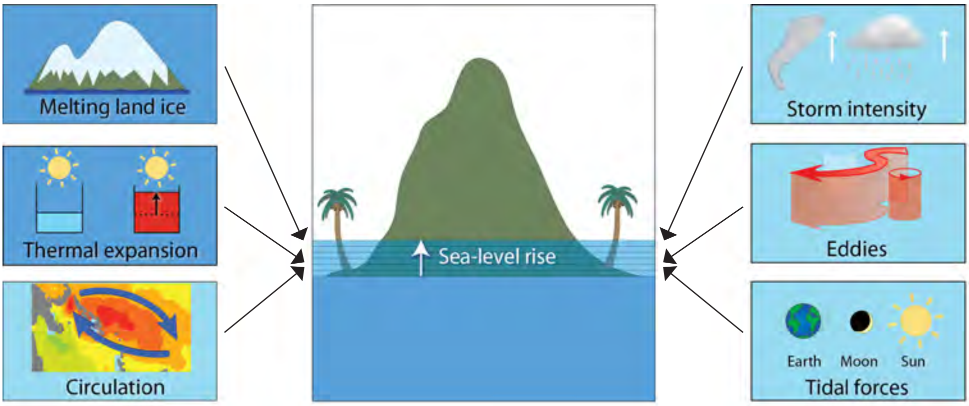


Figure 3.21 Factors determining sea-level rise at any given time and location: melting of land ice, thermal expansion of the ocean, large-scale ocean circulation, atmospheric pressure and storm surges, transient eddies (or ENSO-type waves at the equator) and tides. Melting of land ice and thermal expansion of the ocean are the most important of these factors.

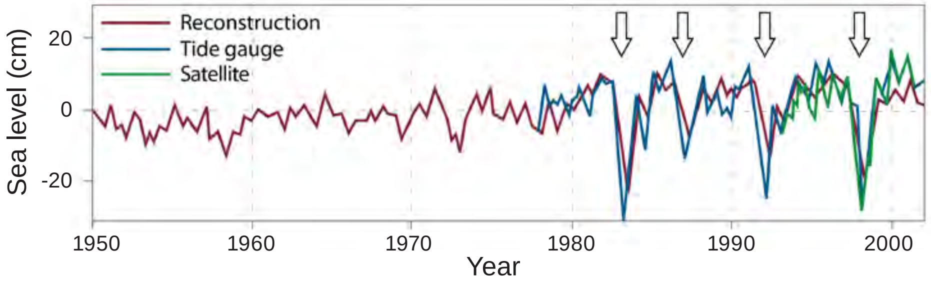


Figure 3.22 Time series (1950–2004) from Funafuti, Tuvalu, showing variation in sea level. Data are from tide gauge (blue), satellite (green) and reconstructions based on the empirical relationship between spatial patterns of variations and tide gauge data (red). Major drops in sea level occur during El Niño events (see arrows). A gradual long-term upward trend can be seen which is particularly pronounced in the second half of the record (source: Church et al. 2006)[99].

Changes in large-scale currents can also alter sea level. An acceleration of the subtropical gyre in the Southern Hemisphere due to long-term changes in the wind field has led to modified sea levels, with local increases or decreases of ~ 10 cm over several years[101]. Oceanic eddies (Section 3.2.3) can alter sea level by ~ 10 cm for several days[102]. Decreases in atmospheric pressure raise sea level by 1 cm for each millibar decrease. This effect is most extreme during cyclones, when the low atmospheric pressure at their centre can draw the water column up by 30 to 50 cm. The amplitudes of each process affecting sea level are usually smaller than those of tides, but they can act in concert. For example, storm surges associated with higher sea levels during cyclones allow destructive waves to penetrate further into coastal habitats.

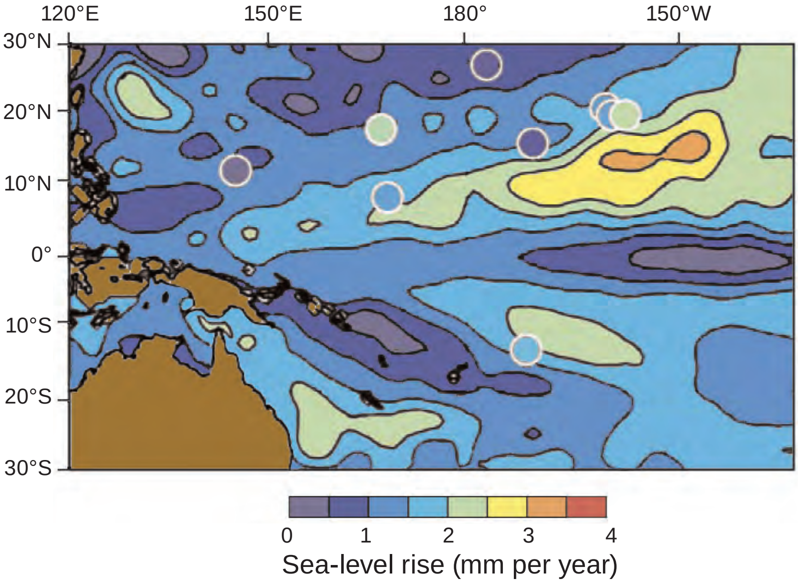


Figure 3.23 Sea level trends from 1950–2001, reconstructed from tide gauge data at several locations across the tropical Pacific Ocean (coloured dots). Recent satellite data have been used to determine the relationship between localised tide gauge data and the rest of the ocean. The longer time-series of tide gauge data are then projected over the region (source: Church et al. 2006)[99].

3.2.9 Coastal circulation and island effects

The description of the tropical Pacific Ocean above has focused largely on the effects of processes in the open ocean that are likely to affect the distribution and abundance of species supporting the important oceanic fisheries of the region. Because coastal fisheries are also vital to the food security and livelihoods of many people in the tropical Pacific (Chapters 1 and 9), it is also important to examine the oceanic processes that influence the productivity of fish and invertebrates close to the coast. We have discussed briefly the effects of waves and sea-level rise on the habitats (coral reefs, mangroves, seagrasses) that support fisheries. Here, we look at the regional oceanic processes that occur along coastlines and around islands, and how these influence the local primary productivity that underpins coastal fisheries production.

These processes generally occur on different scales in the tropical southern and northern Pacific Ocean, largely because the topography in the south is much more complex than in the north. In the south, there are several archipelagos, ranging from rugged high islands to a myriad of coral atolls (Chapter 1). There are also oceanic ridges and many seamounts in the southern and northern Pacific Ocean[103].

The topographic complexity in the south allows the islands there to support rich ecosystems, despite the fact that many of them are located in oligotrophic waters (Section 3.2.4). The presence of islands alters oceanic circulation to bring deep nutrients into the photic zone through at least four processes (**Figure 3.24**), as described below.

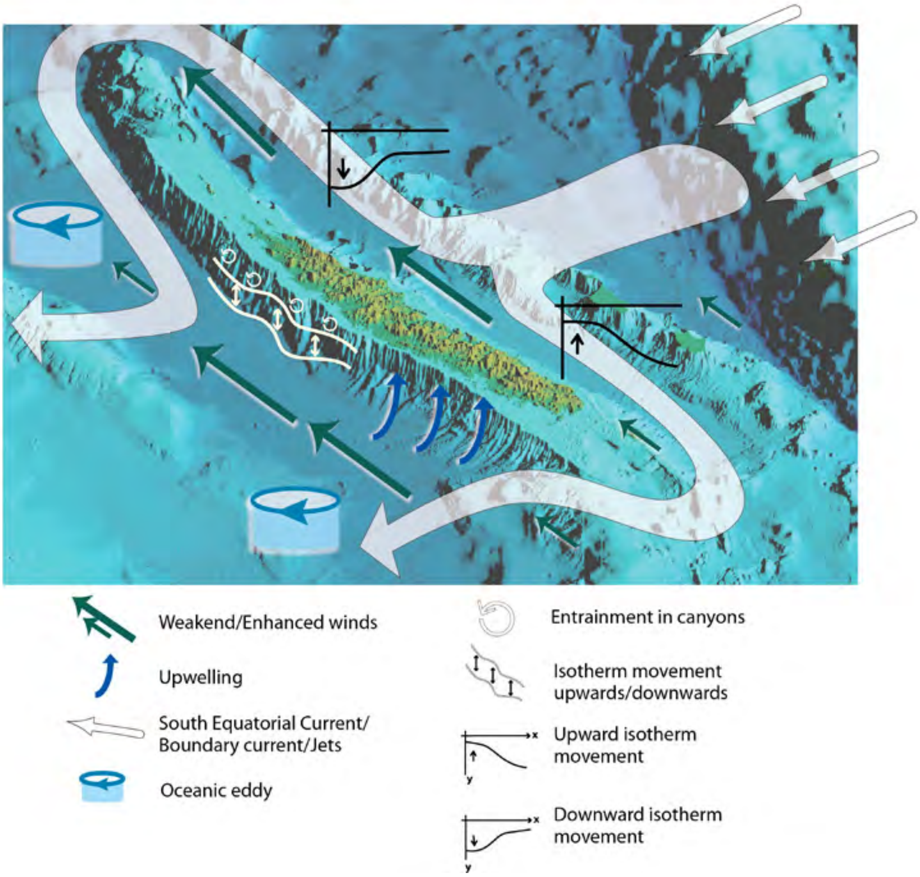


Figure 3.24 The four processes associated with islands that alter ocean circulation and nutrient supply, illustrated over the topography of New Caledonia (1) islands act as obstacles to large-scale currents, generating boundary currents on their eastern sides and eddies downstream, which cause the thermocline to become either deeper or shallower; (2) winds blowing parallel to the coast create local upwelling which enhances nutrient supply; (3) internal waves and tides interact with the topography, generating either temporary upwelling or enhanced mixing that transfers nutrients to the surface (this has been observed at other islands but not at New Caledonia); and (4) orographic effects of high islands that create disturbances to the large-scale winds downstream of an island, resulting in counter currents, upwelling and more intense eddy activity (source: Lefevre et al. 2010 and New Caledonia Remote Sensing and Geomatics Service)[116].

3.2.9.1 Islands as obstacles to flow

Where islands lie in the path of large-scale westward flowing ocean circulation, boundary currents are formed on their eastern coasts. On large islands and coasts (e.g. Australia and PNG), the strong boundary currents formed there have a direct effect on nutrient supply; an equatorward current, such as the North Queensland Current, will deepen the thermocline locally (Section 3.2.2) and restrict access to nutrients. Conversely, a poleward current reduces the depth of the thermocline, facilitating access to deep nutrients[104]. Local counter currents, bottom friction and turbulent interaction with canyons can also result in enhanced mixing of surface and deeper nutrient-rich waters adjacent to the shelves.

An oceanic current encountering an island can also trigger eddy formation 'downstream', reducing the depth of the thermocline in its wake and enhancing nutrient supply and biological production[105–108].

A snapshot of the SST and current velocity around Vanuatu and New Caledonia (**Figure 3.25**) illustrates how the westward flowing SEC interacts with the different islands. Strong boundary currents form on the east coast of New Caledonia, which eventually continue westwards as jets flowing around the northern and southern tips of the New Caledonia shelf. The complex topography leads to the formation of eddies in the lee of islands, or the modification of passing eddies[61]. These eddies are associated with either anomalously warm (anticlockwise on **Figure 3.25**) or cold (clockwise) surface temperatures.

3.2.9.2 Wind-driven upwelling

When the wind blows parallel to the coast, local upwelling can occur that enhances nutrient supply to the surface waters. The snapshot shown in **Figure 3.25** represents the situation during an episode of strong southeast trade winds parallel to the coastline of New Caledonia. The trade winds push surface waters to the southwest by Ekman transport (Box 3.1) away from the coast, resulting in an upwelling of deep water. Such upwelling produces the 'cold patch' to the southwest of New Caledonia and occasionally brings nutrients from deep waters to the surface[109–111].

3.2.9.3 Internal waves

Tidal currents affect the full water column and when they interact with features on the seafloor such as seamounts, they can generate strong vertical displacements of water. Such tidal-bathymetry interactions, as well as quick vertical displacements of water generated by other processes, create 'internal waves'. These subsurface waves can travel large distances away from their source region, and eventually dissipate in areas of rugged topography. The Pacific islands are a major dissipation region for internal waves[112], where their energy is released to produce oceanic mixing. Internal waves can displace water vertically from tens to hundreds of metres, over periods ranging from minutes to several hours. Near islands, vertical movements of water as great as 270 m have been observed[113]. Such displacements can deliver nutrients from the deep ocean to the trenches and channels at the base of coral reefs, a depth of about 50 m. Because of the large amount of mixing occurring at such places, nutrients can then be brought to the surface within just a few minutes. This process provides an efficient mechanism for nutrient enrichment of coastal waters and results in greater biological productivity where it occurs. In summary, internal waves interact with topography, generating either temporary upwelling or enhanced mixing.

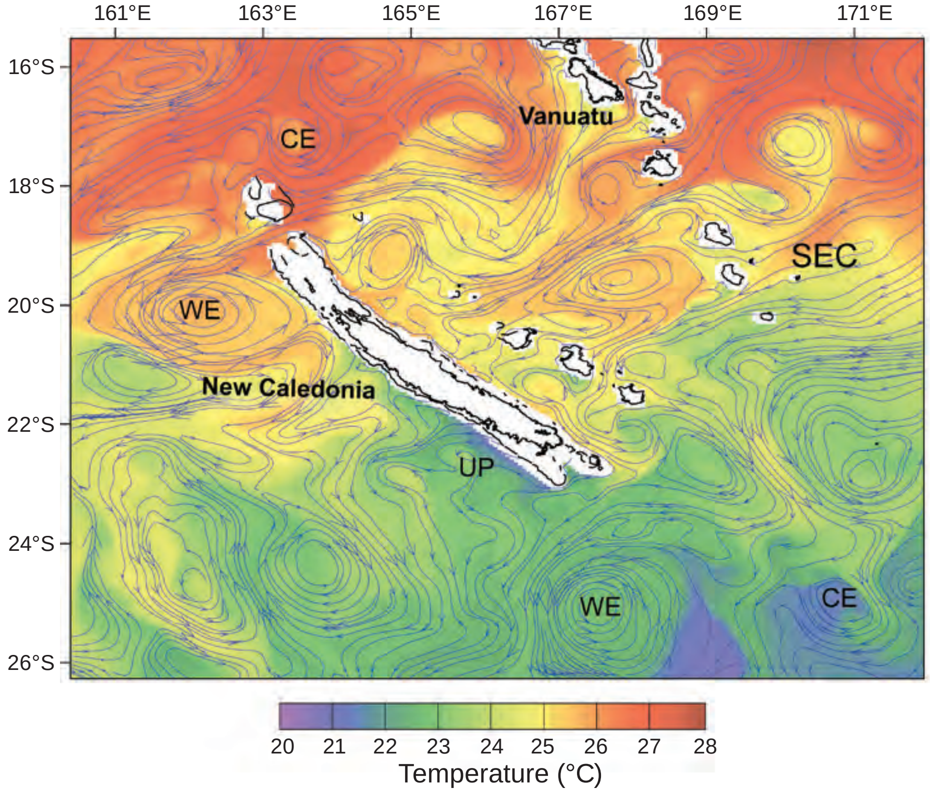


Figure 3.25 Sea surface temperature and surface velocity fields (blue streamlines) on November 9, 2004 near New Caledonia and Vanuatu from a high resolution numerical simulation forced with observed winds. The large-scale easterly flowing South Equatorial Current (SEC) encountering the islands is divided into multiple branches by eddies and islands, and finally splits against the east coast of New Caledonia. This snapshot demonstrates the high variability associated with oceanic eddies that either arrive from the east, or form by interaction with topographic features. Against the southwest coast of New Caledonia, a cold patch of surface water reveals an upwelling event; WE = warm eddy; CE = cold eddy; UP = upwelling (source: Lefèvre et al. 2010)[116].

3.2.9.4 Orographic effects

High islands also modify large-scale wind patterns, creating disturbances 'downstream' which can generate counter currents and more intense eddy activity[27–30] to deliver more nutrients to surface waters. For example, the Hawaiian Islands split the northeast trade winds and induce a westerly oceanic counter current in their wake[114,115]. Similarly, the mountain range with several major peaks running along New Caledonia disrupts the southeast trade winds. This results in areas of both enhanced and weakened surface winds well away from the island, which affect current circulation patterns both in the lagoon and nearby open ocean[116].

3.3 Observed and projected changes in the tropical Pacific Ocean

The features of the tropical Pacific Ocean described above are undergoing changes due largely to the recent observed alterations in atmospheric conditions, particularly surface temperatures and their associated effects on winds in the region, and the increased emissions of CO_2 (Chapter 2). Future changes to surface climate and atmospheric concentrations of CO_2 are also expected to drive profound changes in many features of the tropical Pacific Ocean, including currents, SST, eddies, availability of nutrients, dissolved oxygen, acidification, wave height, sea level and coastal processes. In this section, we outline the changes that have already been observed and those that are projected to occur.

3.3.1 Large-scale currents

3.3.1.1 Observed changes

Substantial changes in the South Pacific Subtropical Gyre (**Figure 3.1**) have been recorded between 1993 and 2003. These changes are thought to be associated with an intensification of the SAM, with the southwesterly winds in the Southern Hemisphere shifting southwards and increasing in intensity[101,117]. There has been an increase in the intensity of the gyre's circulation, the SEC and, as a consequence, the height of the sea surface at its centre (40°S, 170°W) has increased by about 12 cm[101]. In addition, the East Australian Current has intensified over the past 60 years, generating substantial warming of the Tasman Sea[118]. The North Pacific Subtropical Gyre also intensified between 1993 and 2003 but with weaker amplitude[119].

3.3.1.2 Projected changes

The currents of the upper water column across much of the tropical Pacific Ocean are expected to change in the future, particularly as a result of weakened wind regimes at low latitudes[120] and strengthened winds in the subtropical Southern Hemisphere[121,122]. Multi-model mean projections for large-scale surface currents show relatively small absolute changes away from the equatorial band 12°S–10°N. However, major changes occur near the equator.

For the SECC, which flows eastward from the area around Solomon Islands to about 160°W, 10°S (**Figure 3.1**), these changes will take time to appear – in the upper 50 m flow is projected to be ~ 8% weaker under the B1 and A2 scenarios in 2035. However, by 2100 under B1 the strength of the surface SECC is projected to decrease by 28% and by a dramatic 60% in 2100 under A2 (**Figure 3.26**). The surface flow also tends to turn towards the south, reducing the penetration of the SECC to the east. Nearby, at 12°S, the upper 50 m of the SEC is projected to increase in a thin zonal band. In the Northern Hemisphere, a decrease is projected in the eastern half of the surface NECC (180°–130°W; 7°N–10°N), with a slight decrease in the NEC just north of this region (at 140°W–130°W).

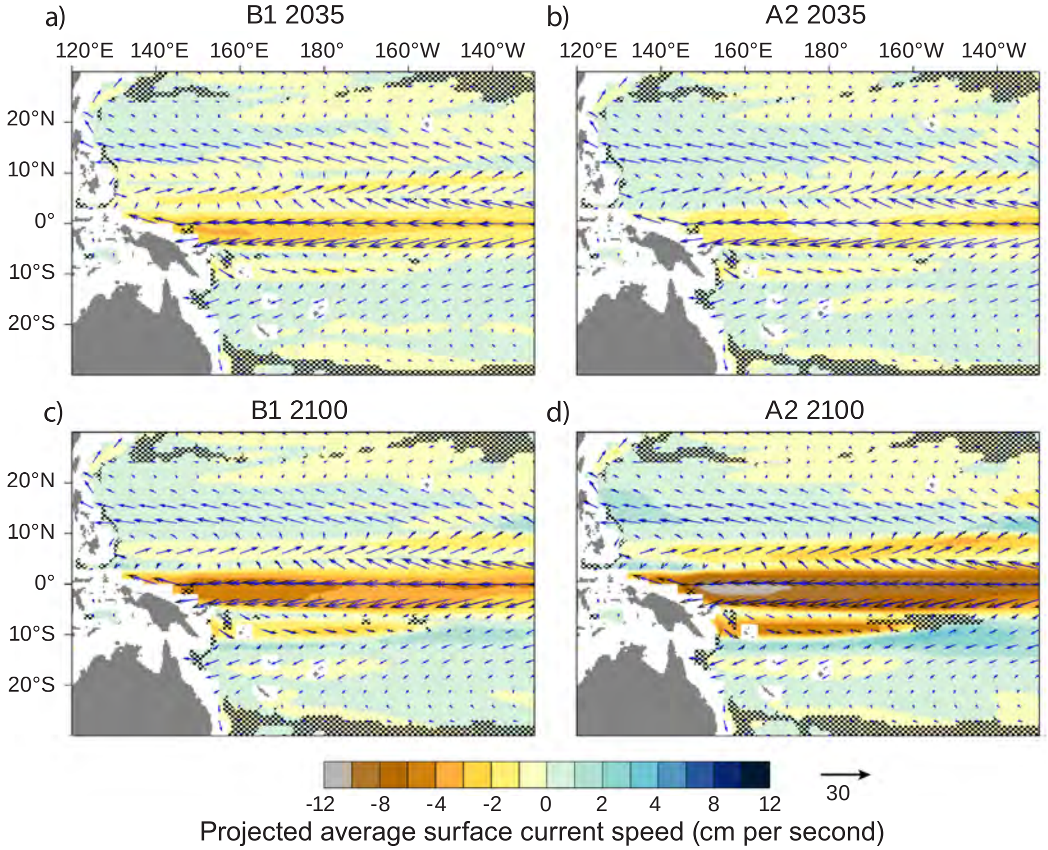


Figure 3.26 Multi-model means of recent and projected average surface current speed (cm per second) down to a depth of 50 m for (a) the B1 scenario in 2035; (b) A2 in 2035; (c) B1 in 2100; and (d) A2 in 2100. Black arrows represent averaged 1980–1999 currents; blue arrows are the projections. The size of the arrows reflects velocity. Shaded areas indicate where either current speed or the change in direction is below the 90% confidence level; white areas represent regions where one or several models have no data.

Within 3° of the equator, the westward flowing SEC also decreases in strength with global warming. Its initial flow, which averages between 30 and 50 cm per second in the upper 50 m, is projected to decrease by only 2 to 3 cm per second in 2035 under both scenarios, and then by about 5 cm per second under B1 and 10 cm per second under A2 in 2100. The corresponding projected reductions in SEC transport (volume of water moved) compared with its average present value between 160°E to 130°W

(~ 28 Sv, Figure 3.27) (1 Sv = 1 Sverdrup = 10^6 m^3 per second) are -0.5 to -1 Sv (3–5%) in 2035, -2 Sv (9%) under B1 in 2100 and -4.5 Sv (18%) under A2 in 2100. A vertical section along the equator shows that just below the SEC the eastward EUC is projected to move progressively upwards by about 10 m under B1 and A2 in 2035 and B1 in 2100, and then by 20 m under A2 in 2100 (Figure 3.27). The eastward EUC is also expected to increase in strength and transport over the 21st century (Figure 3.27), reducing the depth to which the SEC penetrates.

Changes in current strengths are likely to affect biological production and fisheries through the various processes that supply nutrients discussed below. They will also affect the dispersal of larvae and connectivity among populations[123]. Changes to the EUC may have consequences because of the important role of this undercurrent in the transport of iron, sourced from the New Guinea Coastal Undercurrent, to the eastern and central Pacific[124], where iron concentrations limit primary productivity (Chapter 4). Therefore, changes to the depth and strength of the EUC may also have important effects on fisheries in the region.

3.3.2 Ocean temperature

3.3.2.1 Observed changes

As a result of its large heat capacity, the ocean has absorbed most of the additional heat due to recent global warming – about 30 times more anthropogenic heat has entered the ocean than the atmosphere since the 1960s[125]. Globally, SST is estimated to have warmed ~ 0.67°C from 1901 to 2005[126]. In the Pacific basin, warming of SST of 1 to 1.5°C has occurred at the western coastal boundary south of the equator and in the east, north of the equator, during the past 50 years[127,128].

Separating long-term warming of SST from the natural variability of the tropical Pacific Ocean has not been straightforward. For example, ENSO has accounted for ~ 30% of the variability (excluding the seasonal cycle) during the past 100 years, with ~ 10% attributable to global warming[127,129], and the remaining ~ 60% being due to decadal and other modes of variability. But the warming trend is conspicuous, even below the surface – it has been detected in all oceans and at increasing depths since the 1950s[125,130–132].

Over the past 50 years, the water column between the surface and about 200 m in the tropical and subtropical Pacific has warmed by up to 2°C (Figure 3.28). Counter-intuitively, south of 8°N, a consistent and broad-scale cooling has occurred in the central and lower thermocline that extends south to at least 25°S (Figure 3.28), which is most pronounced at around 200 m in the equatorial region. This cooling appears to be related to changes in the surface winds that can raise the thermocline. Despite the addition of heat to the system, the upward displacement of the strongest vertical temperature gradient associated with the thermocline leads to net cooling[133].

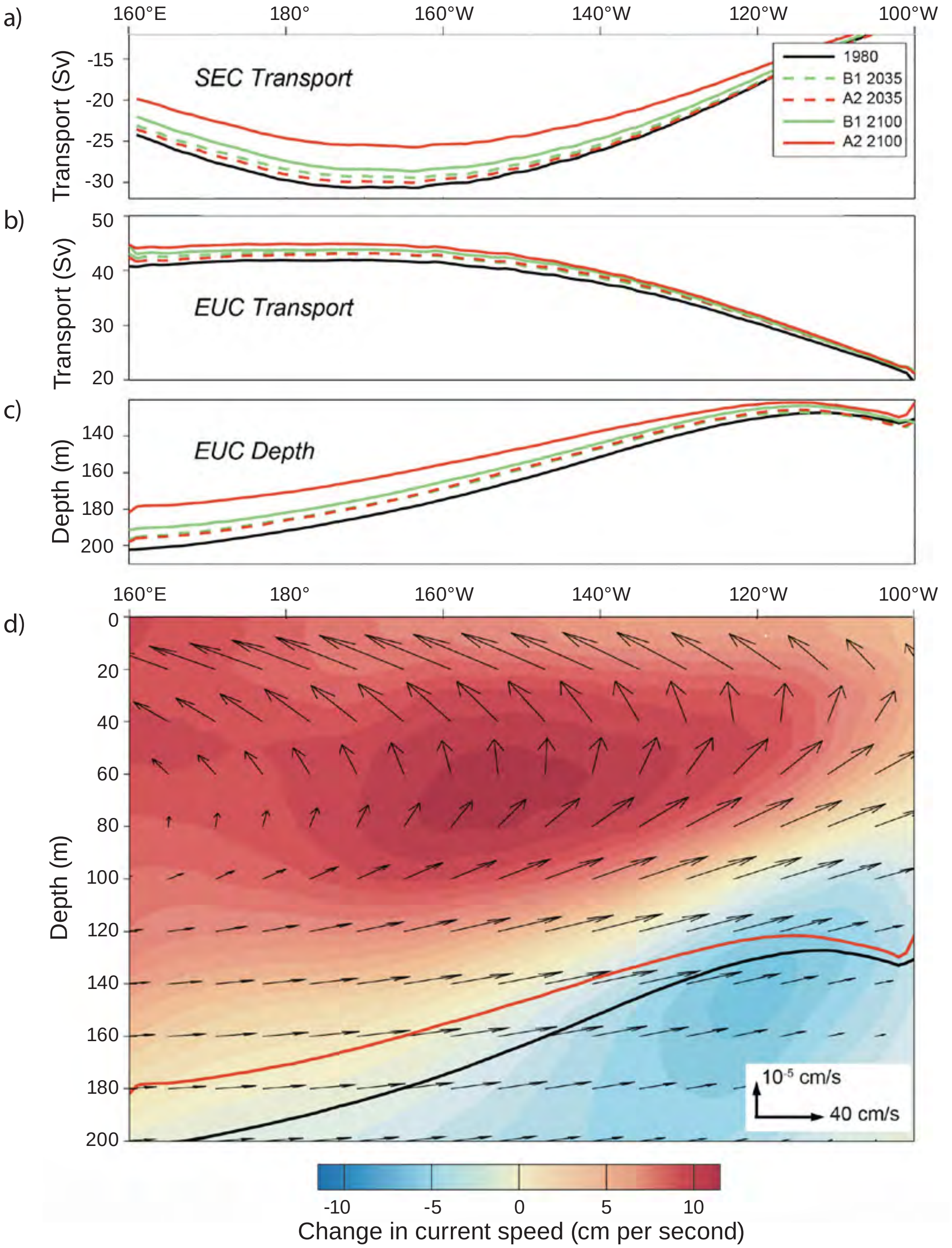


Figure 3.27 Projected changes in (a) transport volume (Sv = 10^6 m^3 per second) of the South Equatorial Current (SEC) as a function of longitude across the equator; (b) transport volume of the Equatorial Undercurrent (EUC); (c) depth of the EUC; and (d) eastward velocity (cm per second) for the A2 scenario in 2100 (2080–2099) minus (1980–1999), with mean velocity vectors superimposed as arrows (averaged between 2°S and 2°N with vertical velocity scale accentuated). Black and red lines indicate the mean position of the EUC core for 1980–1999, and for the A2 scenario in 2100, respectively.

Changes have also been observed in the Warm Pool, which is subject to interannual and longer-term (decadal) fluctuations[134]. Since 1956, a reduction in salinity ('freshening') of 0.1 to 0.4 PSU (practical salinity unit: 1 PSU = 1 g per kg of sea water) has occurred in the Warm Pool[128,135]. The observed freshening, and the intensified surface warming trends described above, combine to reduce the near-surface density of water near the surface of the ocean. Along with the deeper cooling, these trends cause increased stratification (Section 3.2.2.2) and an associated reduction in depth of the thermocline in the Warm Pool. This has important consequences for the availability of nutrients (Box 3.2) (Section 3.2.4). These processes may also cause further increases in SST locally because absorbed heat now warms a thinner surface layer. Such changes in the vertical structure of water density also affect the onset and intensity of ENSO[44].

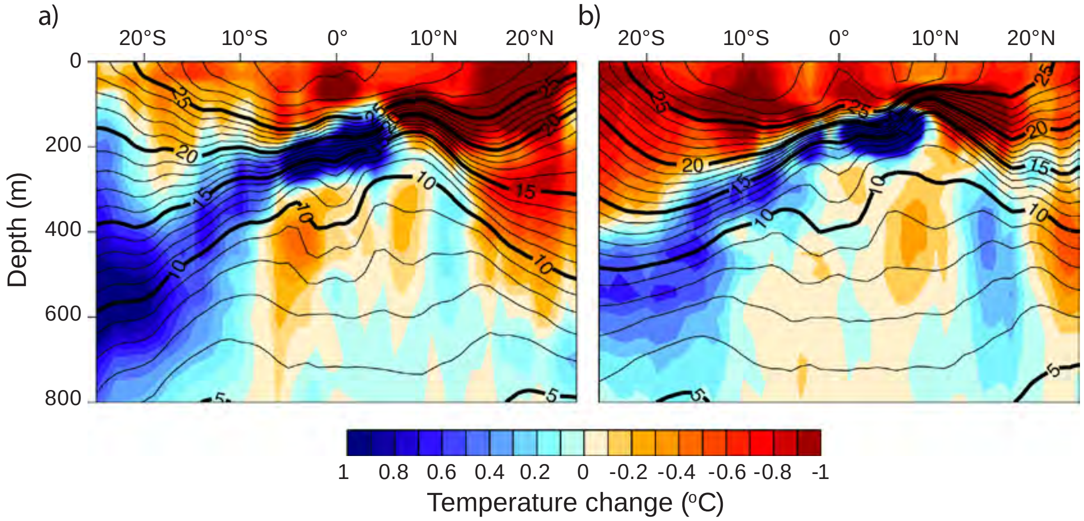


Figure 3.28 Temperature changes in the tropical Pacific Ocean over the past 50 years for a vertical meridional section at (a) 160°E and (b) 160°W. Average temperature is overlayed as black contours (fine lines are 1°C intervals; thick lines 5°C intervals) (source: Durack and Wijffels 2010)[194]. The warming reaches 2°C in dark red areas.

3.3.2.2 Projected changes

Sea surface temperature of the tropical Pacific Ocean is projected to increase under the B1 and A2 emissions scenarios. For both scenarios, annually averaged warming across the region, relative to the 1980 to 1999 average, is projected to increase within a range of 0.5 to 1.0°C by 2035. In 2100, the increase in SST is expected to be within the range of 1.0 to 1.5°C greater under B1, and to increase by 2.5 to 3.0°C under A2 (**Table 3.1**). The greatest warming is projected to occur in the Pacific Equatorial Divergence Province and the least warming at the eastern boundary of the South Pacific Subtropical Gyre (Section 3.2.2.4).

Both scenarios and time periods show a similar spatial and vertical pattern of warming. The increase is greatest near the equator, with warming decreasing with depth. Maximum warming is expected to approach 1°C at the surface and 0.5°C at 80 m by 2035 in both scenarios (**Figure 3.29**). Under B1 in 2100, the multi-model mean projects warming of up 1.5°C at the surface and 1°C at 80 m. Projected warming for the A2 scenario is about twice as great, i.e. up to 3°C at the surface and 1.8°C at 80 m (**Figure 3.29a**). These trends are similar to those observed over the past 50 years (~ 2°C per century at the surface) (**Figure 3.28**). Below 100 m, and west of about 150°E, a distinct cooling pattern is projected to occur, which gets stronger over time: two cooling centres occur north and south of the equator (**Figure 3.29b,c**) at ~ 160 m depth and within 10°N–10°S. This pattern is also similar to the observed temperatures over the past 50 years (**Figure 3.28**) and is probably associated with the projected changes in the overlying wind field, and a shoaling of the thermocline[133] (Section 3.2.2). In 2100, the maximum subsurface cooling is projected to reach about 0.5°C under the B1 emissions scenario and 1°C under A2.

The 28°C isotherm along the equator is projected to deepen in the west by ~ 10 m for the B1 scenario and ~ 15 m for A2, with most of this increase occurring after 2035 (**Figure 3.29**). Poleward of 10°N–10°S, the projected warming penetrates to considerably greater depths than at the equator, with a warming of ~ 0.5°C down to 250 m under both scenarios by 2035. This deep projected warming increases to ~ 1°C under B1 and ~ 1.5°C under A2 in 2100. The uneven warming of the water column increases stratification strongly across most of the region, with associated negative effects on vertical mixing and nutrient uptake, as discussed in Section 3.2.4.

By averaging over multiple climate models, we have removed the more extreme changes that are nonetheless feasible. Individual models show that the projected warming may reach 3.6°C at the surface and that the +2°C contour may deepen to 100 m at the equator by 2100. Also, by examining 20-year averages, we are purposely removing the effect of any year-to-year variations to isolate the global warming signal. In the real world, there is a high degree of interannual variability in this region, associated with ENSO in particular. Thus, in some years we would expect considerably warmer temperatures than the mean values projected here. Based on our multi-model mean for the A2 scenario in 2100, a relatively strong ENSO event (2 standard deviations) is expected to produce year-to-year variations in surface temperature of ~ 2°C.

Simulation of the projected features of the Warm Pool remains a major challenge for the IPCC models due to difficulties in realistically simulating SST, precipitation and salinity. In particular, the tropical Pacific is generally too cold, with the east Pacific cold tongue extending too far into the western basin. The models tend to produce a SPCZ that is zonally elongated and that extends too far to the east in a symmetrical pattern of high precipitation about the equator, forming a 'double ITCZ'[136]. This distortion creates a spurious pattern of rainfall south of the equator, limiting the ability of many models to represent tropical precipitation patterns and ocean surface salinity accurately[137–139]. While the IPCC models used produce ENSO-like variability, they also have biases in ENSO behaviour, e.g. the region of greatest SST variability is displaced far towards the west. We present the following projections for the extent of the Warm Pool, bearing in mind these biases.

The edge of the Warm Pool (as defined by the 29°C isotherm) is projected to move ~ 5000 km eastward in 2100 under the A2 scenario (**Figure 3.29a**). The surface extent

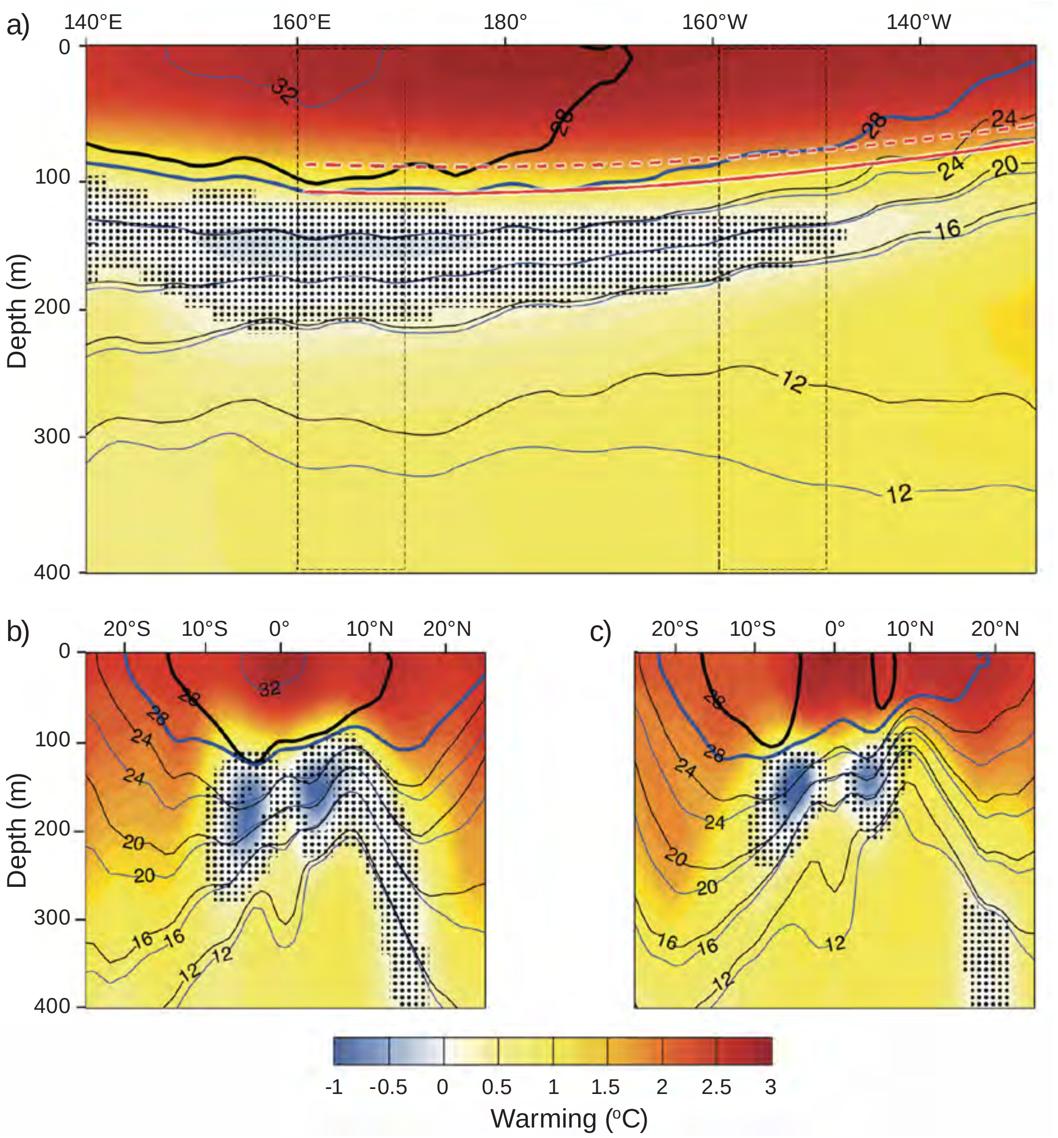


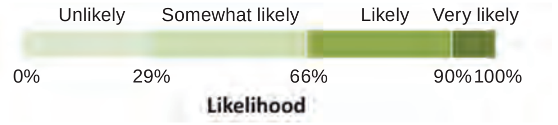
Figure 3.29 Projected warming in the upper 400 m of the tropical Pacific Ocean under the A2 emissions scenario in 2100 (a) along the equator (averaged between 2°S and 2°N); (b) along 165°E (averaged between 160°E and 170°E); and (c) along 155°W (averaged between 160°W and 150°W). Colour shading shows the multi-model mean projected warming in 2100 for the A2 scenario, relative to 1980–1999. Grey mottling indicates areas where warming is not significant at the 90% confidence level. Black contours show mean present day temperatures (based on the CARS 2006 CSIRO climatology) and the blue line represents the mean temperatures projected for 2100 (calculated relative to the CARS 2006 data), with the 28°C isotherms thickened. The red lines in (a) indicate the depth of the thermocline during 1980–1999 (solid) and the depth projected for 2100 (dashed). Thermocline depth is estimated as the depth where temperature is 2.5°C below the temperature at the surface.

of the area comprising the Warm Pool is expected to have an eastern boundary around 170°W in 2035 under both emissions scenarios. This area is projected to increase by a factor of eight, and the eastern limit of the 29°C isotherm is expected to be around 150°W for the B1 scenario in 2100. For A2 in 2100, the area increases by a factor of nine, reaching 61 million km^2. By that time, the 29°C waters are projected to spread across the Pacific basin at the equator, reaching the coast of central America.

Table 3.1 Projected changes to selected key features of the tropical Pacific Ocean, relative to 1980–1999, for 2035 (2025–2045) and 2100 (2080–2099) under the B1 and A2 emissions scenarios, based on a multi-model mean. The confidence intervals provided at 90% confidence for each projection (see key below); percentage change for the multi-model mean is indicated.

Ocean feature	1980–1999	2035		2100	
		B1	A2	B1	A2
Mean equatorial SEC transport (Sv) (160°E–130°W)	28	26–28 (-5%) 🟩	26–29 (-3%) 🟩	25–27 (-9%) 🟩	22–25 (-18%) 🟩
Strength of SECC in upper 50 m* (cm.s^{-1})	6.20	4.9–6.5 (-8%) 🟩	3.9–6.2 (-18%) 🟩	3.2–5.7 (-28%) 🟩	0–5.1 (-60%) 🟩
SECC zonal component isotach* 5 cm per second	187°E	186°E (2°W) 🟩	184°E (3°W) 🟩	181°E (6°W) 🟩	174°E (13°W) 🟩
Zonally averaged zonal windstress* (10^{-2} Nm^{-2}) (2°S to 2°N)	-3.3	-3.26 to -3.06 (-5%) 🟩	-3.24 to -3.08 (-5%) 🟩	-3.23 to -2.91 (-8%) 🟩	-3.20 to -2.73 (-10%) 🟩
Pacific basin SST (°C)**	27.4	28.0–28.2 (+0.7) 🟩	28.0–28.2 (+0.7) 🟩	28.6–29.0 (+1.4) 🟩	29.6–30.1 (+2.5) 🟩
Maximum Warm Pool temperatures (°C)[a,**]	29.6	30.3–30.5 (+0.7) 🟩	30.4–30.6 (+0.8) 🟩	30.9–31.3 (+1.5) 🟩	32.0–32.5 (+2.6) 🟩
29°C Warm Pool area*** (x 10^6 km^2)[b]	7	20–26 (+230%) 🟩	22–27 (+250%) 🟩	36–46 (+480%) 🟩	58–65 (+770%) 🟩
Warm Pool salinity front[c]	~ 166°E	166°E–172°E 🟩	166°E–169°E 🟩	167°E–172°E 🟩	170°E–179°E 🟩

* Average eastward velocity between 165°C and 160°W and 8.5°S to 7.5°S which corresponds to the maximum of the multi-model-mean contour line of constant velocity; ** for region 130°E–130°W, 25°S–25°N; *** for region 105°E–160°W, 30°S–30°N; a = temperature based on the maximum long-term monthly mean sea surface temperatures in the warmest 10% of the region (higher temperatures can be expected in individual years – particularly those associated with ENSO); b = '29°C pool' defined as area with temperature above 29°C; c = defined as the position of the 34.8 salinity at the equator; SEC = South Equatorial Current; SECC = South Equatorial Counter Current; SST = sea surface temperature.



The position of the Warm Pool is intimately tied to ENSO dynamics and the boundary of intense convective rainfall. However, because warming occurs across the whole basin, changes in the 29°C isotherm may not be the best way to identify the edge of the Warm Pool in the future. A more relevant boundary may be the position of the salinity front that highlights the area of strong rainfall occurring over the Warm Pool. At the equator, this front is projected to move east by ~ 1400 km under the A2 scenario by 2100 (**Table 3.1, Figure 3.30**), which is likely to alter the distribution of tuna (Chapter 8).

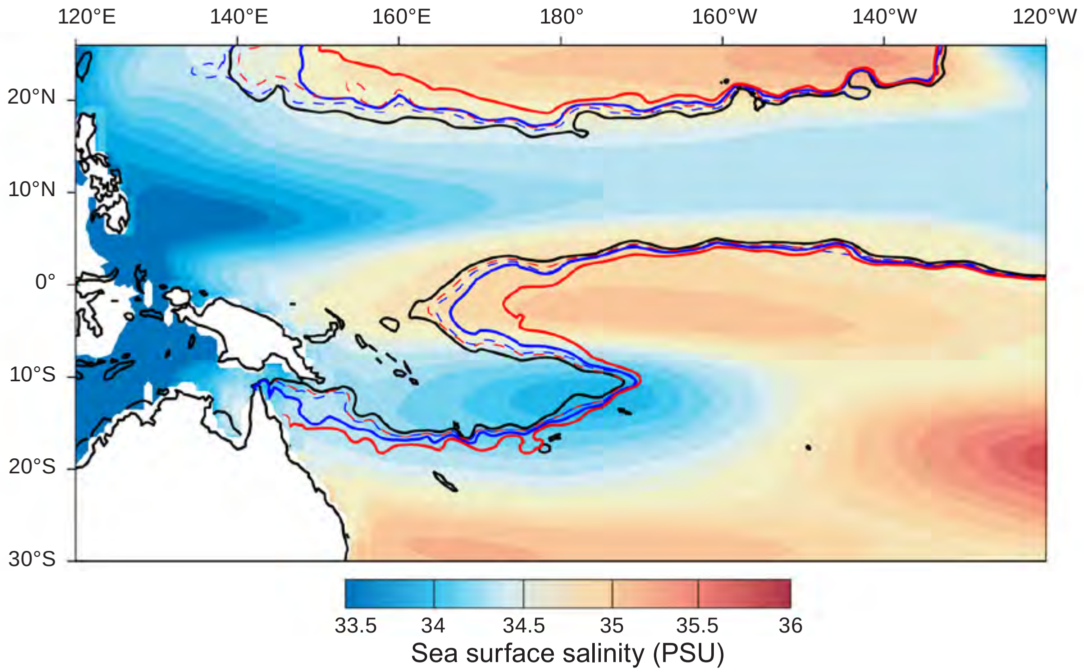


Figure 3.30 Sea surface salinity (SSS), derived from the multi-model mean. The 34.8 contour used to characterise the edge of the Warm Pool at the equator is shown by the black line for the period 1980–1999. The other lines indicate the projected 34.8 contour for 2035 under the B1 (dashed blue) and A2 scenarios (dashed red); and for 2100 under B1 (solid blue) and A2 (solid red). The black line also represents the position of the observed SSS front and the projections are anomalies relative to the observed SSS.

3.3.3 Ocean eddies

3.3.3.1 Observed changes

Energy is generated for eddies when there are strong horizontal density gradients, e.g. when the thermocline is tilted[25,26]. Consequently, eddy activity changes on seasonal, decadal and longer time scales, as the density structure of the ocean varies (Section 3.2.3). Changes in water density are mirrored by those for sea level (e.g. high density/cold patches of water are associated with depressed sea level). As a result, observation of large-scale patterns of eddy activity can be made from satellite data for sea surface height. These altimetric data have been used to reveal important seasonal[52] and interannual[140] variations in eddy activity. Between 1993 and 2001, eddy activity varied by 15–30% in the tropical Pacific Ocean. An extension of the satellite time-series until 2008 revealed even larger interannual variability in strength and distribution of eddies (**Figure 3.31**), with some of the 'high-energy' regions during 1998 to 2002 disappearing between 2003 and 2008. The limited period that satellite observations have been available does not allow us to determine whether this represents natural interannual changes in eddies or a long-term trend.

3.3.3.2 Projected changes

The coarse spatial scales of the CMIP3 climate models do not resolve oceanic eddies. Therefore, projections of future eddy activity can only be qualitative. As eddies are generated at thermal fronts where there are strong oceanic currents (Section 3.2.3), future eddy activity may also be linked to projected changes in ocean currents (Section 3.3.1). The multi-model average suggests that little change in circulation is likely poleward of 15°N–15°S (Section 3.3.1). Nevertheless, significant changes are projected within 15° of the equator in 2100 (**Figure 3.26**). East of Solomon Islands, the SECC is projected to decrease (Section 3.3.1), which may cause a decline in eddy activity[52,141]. At 12°S, the SEC is projected to increase in a thin zonal band. In the Northern Hemisphere, eddy activity can be expected to increase or decrease in association with projected changes in strength in parts of the NEC and NECC (Section 3.3.1), if the same dynamical link between flow strength and eddy activity applies there[52]. Based on **Figure 3.26**, the amplitude of changes in both circulation and eddy activity is expected to be small in 2035.

Rossby waves of planetary scales are resolved in climate models. Because of their sensitivity to the thermal structure of the ocean, the propagation speeds of Rossby waves are expected to increase by up to 35% relative to pre-industrial times under the A1B scenario[142]. Any change in the activity of eddies and Rossby waves may have important consequences for the supply of nutrients to the photic zone, because they are associated with increased vertical water transport.

3.3.4 Nutrient supply

3.3.4.1 Observed changes

The availability of nutrients in the photic zone, and consequently the biological productivity that sustains fisheries, is sensitive to changes in the circulation and stratification of the ocean (Section 3.2.4). Strong variations in the supply of nutrients have been observed as a result of climate variability on decadal time scales[143]. One of the two existing long-term time-series of nutrient levels collected over the past 30 years indicates small net decreases in nutrient supply to the photic zone of the tropical Pacific Ocean. However, poor spatial and temporal data coverage before the satellite era means that any assessment across the region is uncertain.

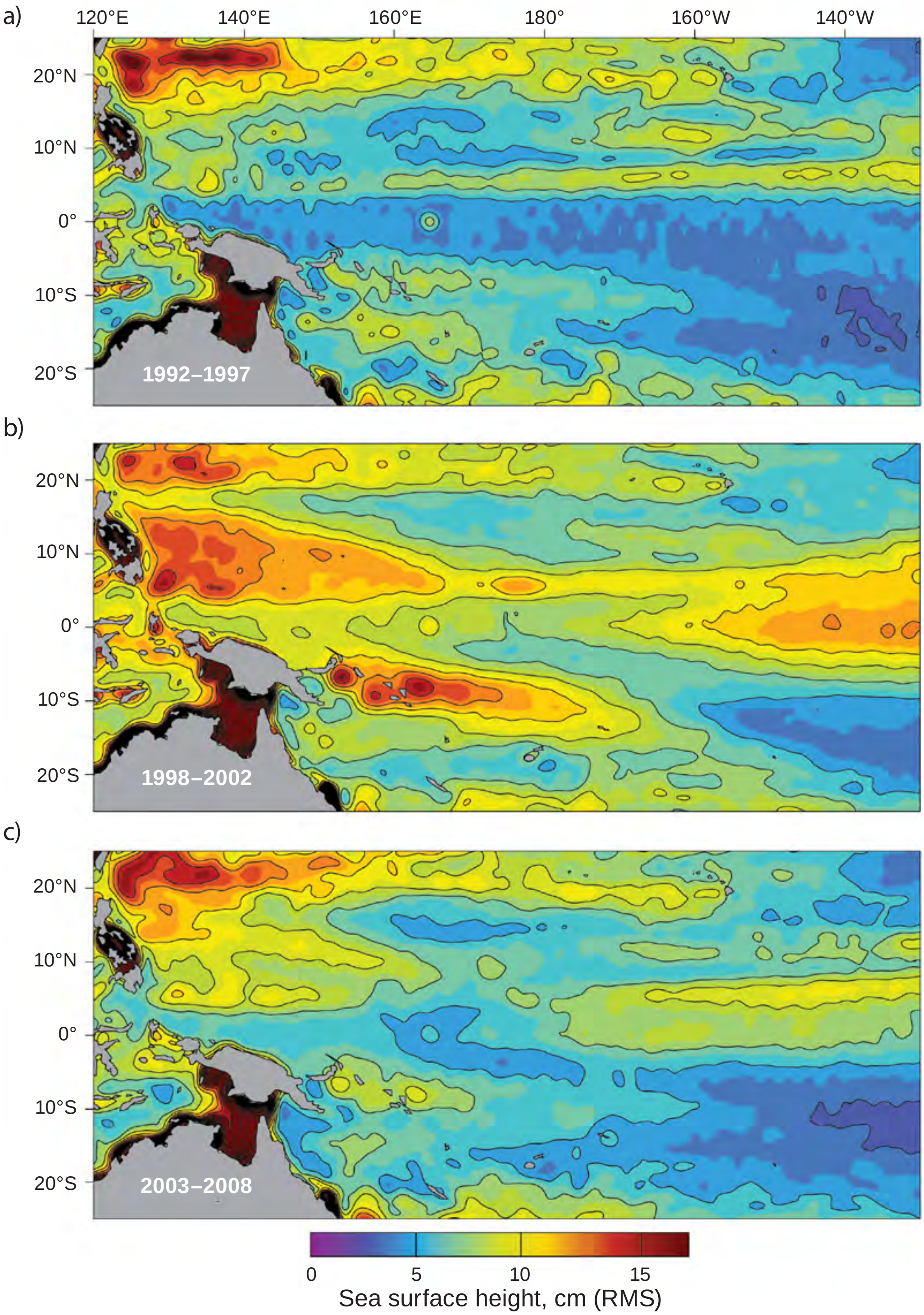


Figure 3.31 Decadal changes in eddy activity, measured from variability in sea surface height (SSH) anomaly for (a) 1992–1997; (b) 1998–2002; and (c) 2003–2008. Each map was obtained using the same procedures as described for Figure 3.12.

The observed decreases in nutrient supply appear to be related to the increased stratification of tropical surface waters (Section 3.3.2) over the past 50 years (**Figure 3.32**). Low-nutrient surface waters are warming and high-nutrient deeper waters are cooling south of 8°N. This may have reduced the efficiency of nutrient transfer into the photic zone (Box 3.2) over broad regions of the tropical Pacific Ocean. North of 8°N, increased stratification is also apparent as the upper waters are warming faster than the waters near and below the pycnocline.

Frequently repeated observations in the western part of the North Pacific Subtropical Gyre Province also demonstrate a decline in nutrient concentration in the mixed layer over the past 30 years. This decline has also been attributed to enhanced stratification acting as a barrier to the transfer of nutrients from the deeper ocean[144]. Below the mixed layer, and down to a depth of 750 m, a comparison of hydrographic data taken ~ 20 years apart in the northern Pacific shows an increase in nitrate. This is attributed to variations in advective transport of nutrients from remote locations rather than changes in the local intensity of remineralisation[145].

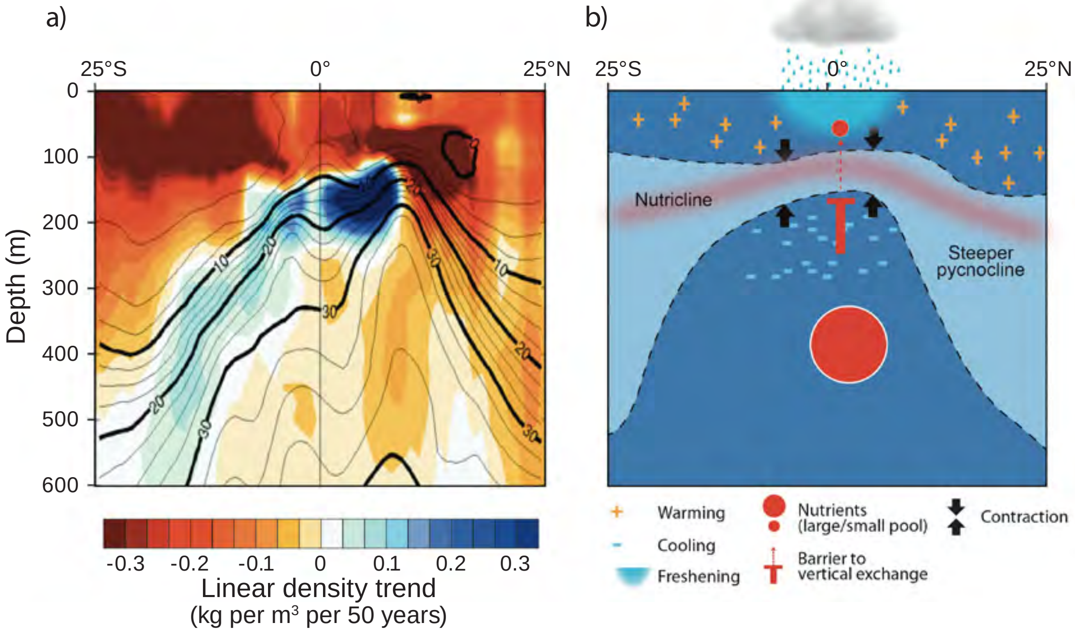


Figure 3.32 (a) Contraction of the pycnocline (shading: zone of maximum vertical density gradient, see Box 3.2) from 1960 to 2008 at 160°W with the mean nitrate concentration overlaid (contour interval = 2.5 μmol per kg) (source: Durack and Wijffels 2010, Ridgway et al. 2003)[190,194]; (b) consequences for nutrient supply: as the surface waters warm and the subsurface waters either cool or warm at lower rates, the vertical density differences increase so that the pycnocline becomes steeper. This limits the vertical exchange that transports nutrients from deeper waters to the surface.

The Hawaii Ocean Time-Series (HOT) station provides the longest continuous records of physical and biogeochemical data throughout the water column for the North Pacific Subtropical Gyre[146]. Although a strong upward trend in primary productivity is evident over the 26 years of records at the HOT station, there is no such trend in the availability of nutrients[147]. The response of the ecosystem there is complex, and the increase in primary production at the HOT station may be linked to nitrogen fixation in the upper layers – a process that does not require a large increase in nitrate supply (Chapter 4). The corresponding productivity may be supplemented by enhanced eddy mixing to provide the necessary phosphate[59]. The larger-scale processes driving the observations at the HOT station are not yet clear, although they appear to be strongly influenced by ENSO and the PDO (Chapter 2). However, the time-series is not yet sufficient to separate the influence of ENSO and the PDO from global warming trends[147].

A 10-year time-series of satellite data shows a steady decrease in integrated primary production for the tropical Pacific Ocean, after a large intensification during the 1997–1998 El Niño[148]. These data also show an increase of 20% in the area of waters with low productivity over 10 years[149] (Chapter 4). However, the relatively short satellite time-series precludes attributing the observed changes to global warming, even though changes in productivity due to the PDO[143] have been detected in the satellite time-series.

3.3.4.2 Projected changes

A series of model projections from the IPCC Third Assessment Report suggested that under the A2 scenario in 2050 (the effects of which approximates B1 in 2100, see Chapter 1), the area of the oligotrophic North Pacific Tropical Gyre is projected to expand by 16% and the South Pacific Subtropical Gyre by 7% due to increased stratification[60]. Climate change could also decrease export production relative to total production (Chapter 4), thereby modifying the vertical structure of the ecosystem (Figure 3.6) and the transfer of nutrients to deeper layers of the ocean[150]. From the close links between nutrients, ocean circulation and stratification (Section 3.2.4, Chapter 4), it is clear that the projected changes to the ocean are likely to cause significant variation in future levels of biological production. However, rather than relying on projections for the levels of nutrients themselves, we concentrate mainly on the changes that are likely to occur to the physical features that demarcate the five ecological provinces of the region defined in Section 3.2.2.4, and control the potential supply of nutrients[60]. Accordingly, we have used multi-model-mean projections for stratification, maximum depth of the mixed layer during winter (as a measure of vertical mixing), upwelling or downwelling at a depth of 50 m, and the regions of convergence as defined by the main currents from the selected IPCC-AR4 models. These changes are closely related to the projected changes in vertical temperature structure and the position of the Warm Pool (Section 3.3.2).

- **Stratification:** The contrast in density of waters between the surface and a depth of 200 m is projected to increase with time and CO_2 emissions, with the most pronounced increase in stratification occurring in the Warm Pool (**Figure 3.33**).

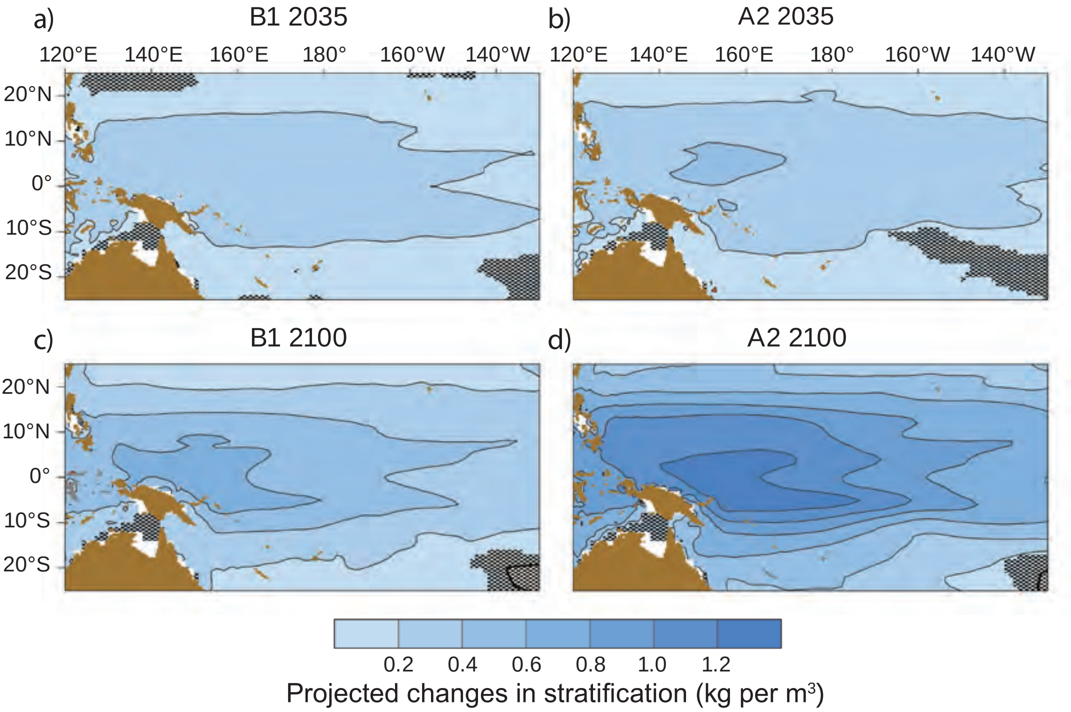


Figure 3.33 Projected changes in stratification (kg per m^3), as defined in Figure 3.14, for (a) the B1 scenario in 2035; (b) A2 in 2035; (c) B1 in 2100; and (d) A2 in 2100, relative to 1980–1999. Shaded areas indicate where the models do not project a consistent trend at the 90% confidence level.

In 2035, the overall increase is expected to be ~ 10% for both scenarios, compared with the average stratification between 1980 and 1999. In 2100, the increase is projected to be 10% to 20% for the B1 scenario, and 20% to 30% for A2, with the greatest changes in the Warm Pool.

- **Mixed layer depth in winter:** Most climate models used in our analysis projected that the maximum depth of the mixed layer during winter will be shallower in the future. This shoaling is projected to be more pronounced with time, and for the higher CO_2 emissions scenario (**Figure 3.34**). It is also most pronounced for the Warm Pool and in the Northern Pacific Tropical Gyre Province. In these regions, a shoaling of at least 5 m is projected under the B1 and A2 scenarios in 2035. By 2100, the mixed layer is projected to be 10 to 15 m shallower under the B1 scenario and 10 to 25 m shallower under the A2 scenario in the Warm Pool[151]. Weak shoaling is projected for the South Pacific Subtropical Gyre Province (SPSG) and the far eastern Pacific between 10°S and 20°S. However, there is considerable disagreement among the models for these regions due to their general failure to represent the SPCZ accurately (Chapter 2).

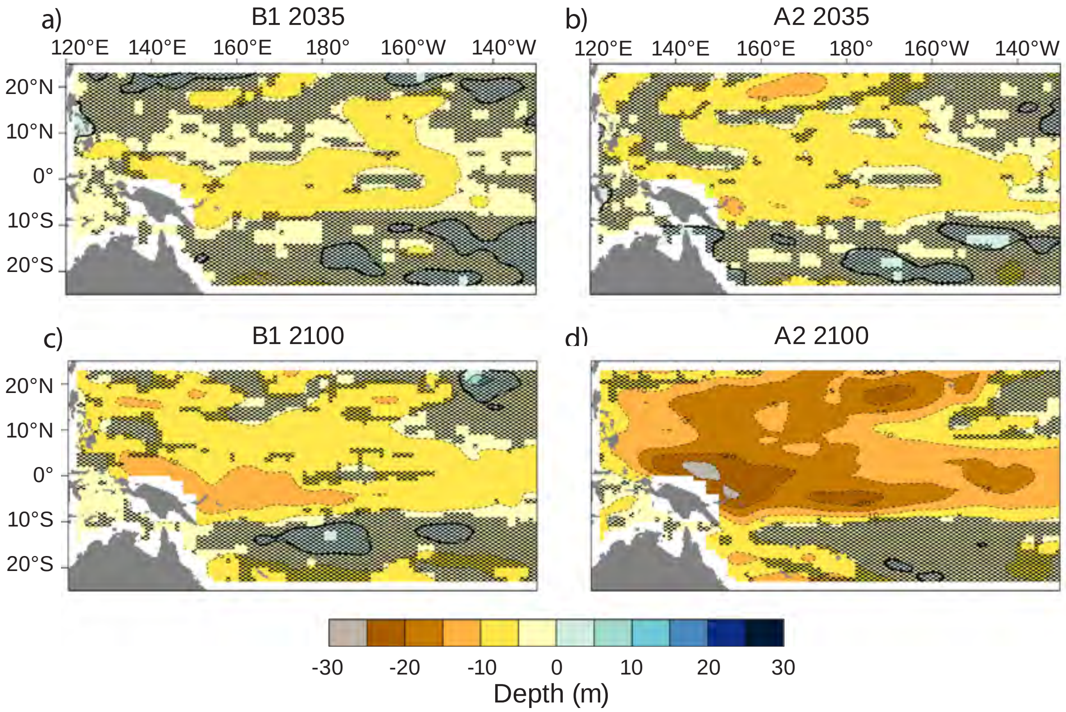


Figure 3.34 Projected changes to the annual maximum mixed layer depth in winter for (a) the B1 scenario in 2035; (b) A2 in 2035; (c) B1 in 2100; and (d) A2 in 2100, relative to 1980–1999. The maximum mixed layer depth is based on the average seasonal cycle from 20-year time-series of AR4 models. Shaded areas indicate where models do not project a consistent trend at the 90% confidence level.

- **Upwelling:** The upwelling in the Pacific Equatorial Divergence Province, integrated between 9°S and 9°N, is very poorly simulated by most IPCC models over the past 50 years, so that projections remain uncertain[152]. Average projected vertical velocity at 50 m is shown in **Figure 3.35**. The multi-model mean suggests that equatorial upwelling at 50 m will decrease over time as atmospheric concentrations of CO_2 increase (**Figure 3.35**). But the vertical velocity at the equator does not result in upwelling of large quantities of nutrient-rich water because it represents a small-scale shallow recirculation ('tropical cell')[153].

The downwelling regions that flank the equatorial upwelling close to this cell are also projected to decrease in concert with the equatorial upwelling. As a result, net upwelling between 9°N–9°S, which is believed to be more relevant to equatorial SST, climate and possibly nutrient supply, is not projected to change significantly. Downwelling is not expected to change significantly in SPSG for either scenario by 2035. However, it is likely to increase by 20% with respect to the 1980 to 1999 average under the B1 scenario in 2100, and by 55% for A2 in 2100. There is little projected change in the North Pacific Subtropical Gyre Province.

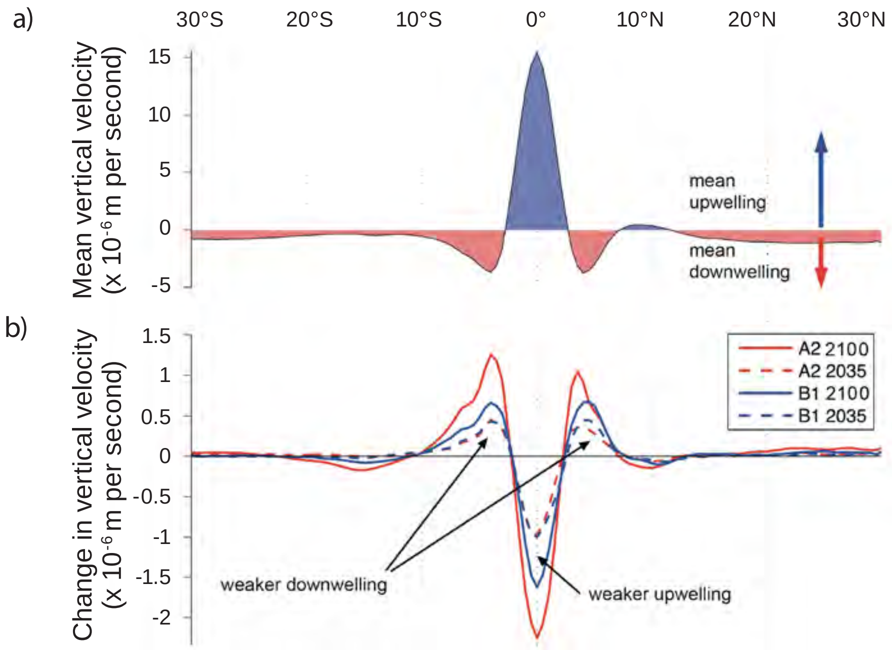


Figure 3.35 (a) Vertical velocities of water (x 10^{-6} m per second) at a depth of 50 m, for 1990 (mean 1980–1999), averaged between 170°E and 110°W, where a positive velocity corresponds to upwelling and a negative velocity to downwelling; and (b) climate driven changes to vertical velocities. The strong equatorial upwelling shows decreases that are immediately balanced by strong downwelling near 4°N–4°S so that net upwelling between 9°N–9°S (which is more relevant to nutrient supply) does not change.

- **Currents and fronts:** In addition to the changes projected for currents (Section 3.3.1), the separation between the westward equatorial flow and the eastward off-equatorial flow, which defines the latitudinal boundaries of the Pacific Equatorial Divergence Province, show little change for either emissions scenario for 2035 or 2100 (**Figure 3.36**). The major projected change occurs in the region of the SECC (around 8°S in the western half of the basin), where the area of eastward flow near the surface is expected to retract west by about 1500 km in 2100 under the A2 scenario (**Figure 3.36**).

These projected changes suggest a general decrease in nutrient supply. Their effects on each ecological province are discussed in Chapter 4, based on a specific simulation (IPSL-CM4 coupled climate carbon model) that includes projections for changes in both the physical and chemical features of the ocean.

Attempting direct modelling of biological production is a major challenge because the model needs to integrate the projected changes in the physical and chemical features of the ocean with the effects of these variables on the biology of organisms. A comparison of 12 climate-ocean biogeochemical cycle model simulations with modern data showed that estimates of average biological production varied by ~ 60% among models, with a high dependence on the realistic simulation of ocean circulation[154]. One such biogeochemical model (which has been coupled to two different climate models) has provided projections for ~ 2080. Export production is estimated to reduce by 20% in the tropics if atmospheric CO_2 concentration increases to 700 ppm under the A2 scenario by ~ 2080[155,156]. This occurs as a result of projected decreases in upwelling and mixed layer depth; the direct effects of higher temperatures on the biology of organisms in oceanic food webs (Chapter 4) appear to be of lesser influence in this simulation.

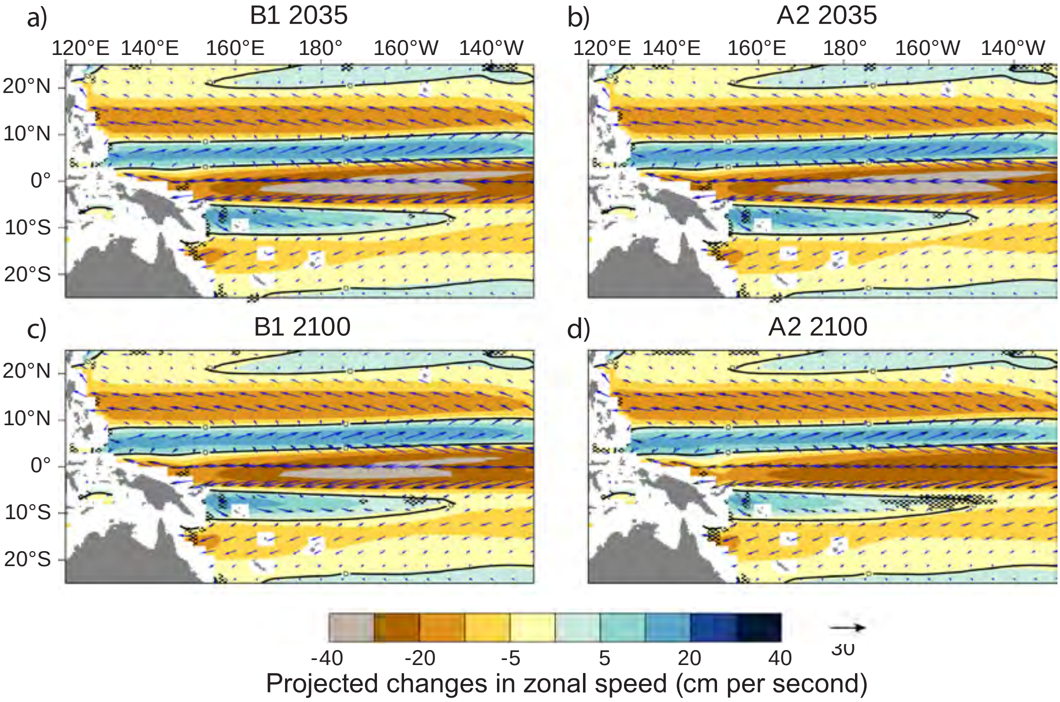


Figure 3.36 Projected changes in the speed of currents in the upper ocean to a depth of 50 m for (a) the B1 scenario in 2035; (b) A2 in 2035; (c) B1 in 2100 and (d) A2 in 2100. Black arrows show the multi-model mean for 1980–1999; blue arrows are projected velocities. The size of arrows reflects velocity; colour shading reflects the zonal component. To help distinguish changes in the extent of the ecological provinces, zero-zonal-velocities (1980–1999) are contoured in all panels. All values are 20-year averages. Shaded areas indicate where models do not project a consistent trend at the 90% confidence level.

3.3.5 Dissolved oxygen

3.3.5.1 Observed changes

Until recently, levels of dissolved oxygen in the tropical Pacific Ocean showed no clear trend[157,158], or decreased with time in regions away from the subtropics at the thermocline level due to decreased water renewal[159]. However, recent data from autonomous profiling floats[iv] have allowed reconstruction of usable time-series at

[iv] Argo, www.argo.ucsd.edu

selected locations. By comparing these data with historical observations, a major westward expansion of the oxygen-minimum waters in the eastern Pacific basin over the past 50 years has been detected[160] (**Figure 3.37**). The thickness of the oxygen-poor layer has also increased over this time in the Pacific Equatorial Divergence Province at 170°W, and in other tropical oceans[160]. This result is consistent with climate projections (see below) and is of concern because low oxygen concentrations can have dramatic consequences for ecosystems (Chapter 4) and the distribution of tuna (Chapter 8).

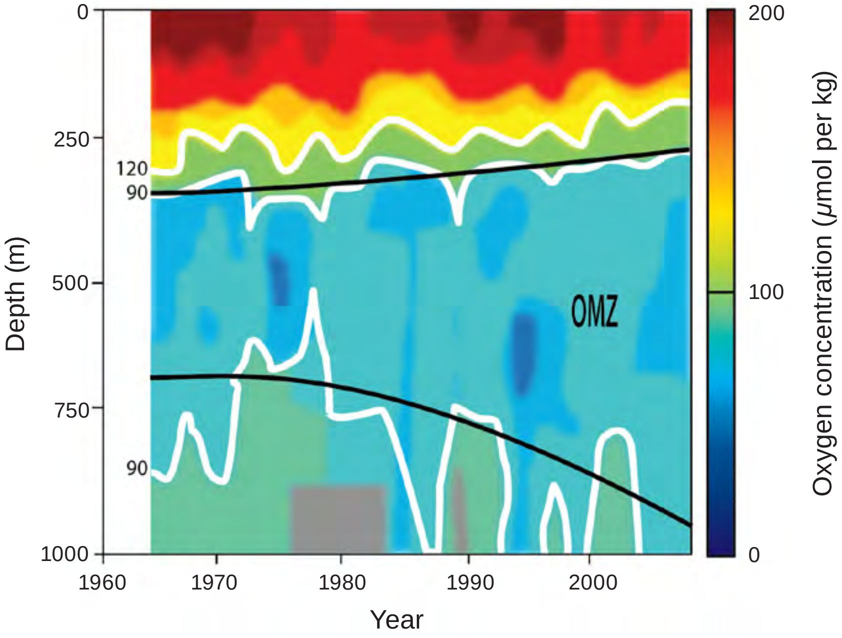


Figure 3.37 Time-series (since 1960) of dissolved oxygen concentrations near 170°W at the equator (5°N–5°S). Measurements were taken between 0 and 1000 m, and show a steady increase in the depth range of low-oxygen waters (< 90 μmol per kg, white line). Black lines denote the Oxygen Miminum Zone (OMZ), superimposed over interannual and decadal variability; grey areas correspond to gaps in the time-series (source: Stramma et al. 2008)[160].

3.3.5.2 Projected changes

Oxygen concentration is not calculated in the CMIP3 climate models and only a small number of biogeochemical models are available to make projections of future levels of O_2 in the tropical Pacific Ocean. Dissolved oxygen is expected to decline in many parts of the region due to larger-scale processes occurring at higher latitudes.

In particular, the increasing temperature and stratification of the ocean at higher latitudes are projected to lead to decreased transfer of O_2 from the atmosphere to the ocean, resulting in lower concentrations of O_2 in the tropical thermocline[156,161,162]. By 2100 under the A2 scenario, average concentrations of O_2 are projected to decrease by 0.2 ml per litre for the subtropical Pacific thermocline[161], where the observed concentrations are ~ 3 ml per litre (**Figure 3.16**) (projections for the other scenarios are not available). The existing low levels of O_2 and suboxic areas in the eastern Pacific are also expected to intensify. In contrast, increased concentrations of O_2 are projected to occur in the equatorial thermocline due to reduced biological production (and therefore remineralisation/oxidation) within the water masses flowing to the equator[162].

3.3.6 Ocean acidification

3.3.6.1 Observed changes

The best estimates of the recent build-up of anthropogenic CO_2 in the ocean come from an indirect approach that uses (1) *in situ* measurements of total carbon and related variables made during a world-wide survey in the 1990s, and (2) a method to remove the natural (non-anthropogenic) component of CO_2. These data-based estimates of dissolved anthropogenic CO_2 show that its accumulation has not been uniform across the world's oceans. The largest inventories (the concentration of CO_2 summed over the full water depth) are found in the northern Atlantic Ocean and in the southern Pacific Ocean.

In the southern Pacific Ocean, the highest inventories of anthropogenic CO_2 are found between 40°S and 50°S, and the lowest inventories occur close to the equator and in the eastern upwelling regions (**Figure 3.38**). This distribution reflects where anthropogenic CO_2 enters the ocean from the atmosphere (the air-sea flux), and where it is transported by ocean currents. The air-to-sea flux of anthropogenic CO_2 is larger in regions where there is enhanced exchange between surface and deep waters. This facilitates the storage of anthropogenic CO_2 in the deeper ocean and keeps surface CO_2 concentrations relatively low, allowing a continued flux of anthropogenic CO_2 from the atmosphere to the ocean. Away from the equator, surface and subsurface currents generally move dissolved CO_2 towards the subtropics, where the inventory is generally greatest (**Figure 3.38**).

In the subtropical Pacific, the anthropogenic CO_2 penetrates to greater depths as a result of downwelling associated with convergence zones. Anthropogenic CO_2 in the deeper ocean reaches a peak at 50°S, where cold surface waters loaded with this gas sink to depths exceeding 1000 m in winter. Conversely, in the Pacific Equatorial Divergence Province, anthropogenic CO_2 is confined to the upper ocean because of upwelling, so that the inventory over the full depth range is small (**Figure 3.38**).

The ocean currently absorbs about 25% of the additional anthropogenic CO_2 emitted by human activity into the atmosphere each year[164] (**Figure 3.17**). As a direct consequence of emissions during the industrial era, and the uptake of a substantial fraction of this CO_2 by the oceans, the pH of sea water has decreased by ~ 0.06 pH units in the tropics and subtropics and ~ 0.12 units at high latitudes compared with a pre-industrial level of about 8.2. The current rate of decrease is ~ 0.02 units each decade[126]. Due to the log scale used to define pH, a 0.1 decrease in pH corresponds to a 30% change in H^+ ion concentration (Box 3.3).

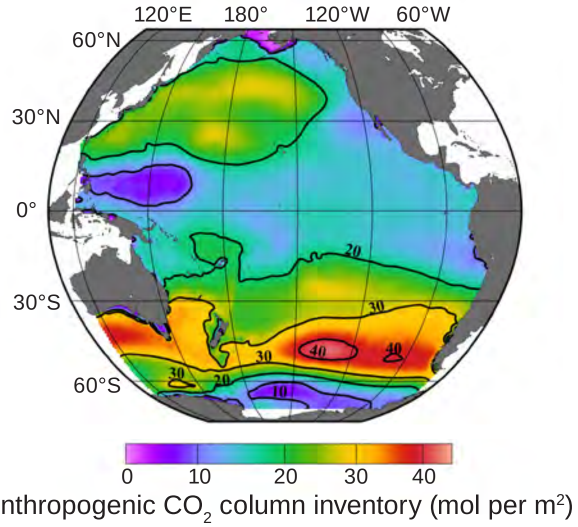


Figure 3.38 Anthropogenic component of depth-integrated, dissolved inorganic carbon concentration in the ocean (mol per m^2), known as the 'Anthropogenic CO_2 Column Inventory'. By the 1990s, dissolved anthropogenic CO_2 had invaded the first 1000 m of the water column near latitudes 30°N–50°S and 30°N–50°S. The largest inventories were found in these regions because the surface waters there sink quickly after taking up atmospheric CO_2. At lower latitudes, stronger stratification and equatorial upwelling limited the penetration of anthropogenic CO_2 to depths of about 500 m. Such measurements are now being repeated to document recent changes (source: Sabine et al. 2002, 2008)[195,196].

The current rate of change in pH is unprecedented in the climate record – changes to ocean pH are unlikely to have exceeded 0.6 units over the past 300 million years[165], despite large changes in atmospheric concentrations of CO_2. This stability is ensured by ocean chemistry, which buffers any changes in pH due to increases in CO_2 that occur over time scales > 1000 years[166]. The unprecedented rate at which CO_2 has accumulated over recent decades means that the buffering capacity of the ocean (Box 3.3) has been unable to keep pH levels stable[167].

3.3.6.2 Projected changes

The projected increase in atmospheric CO_2 (Chapter 1) will drive increased levels of dissolved anthropogenic CO_2 into the tropical Pacific Ocean. This change will cause further acidification of the water column (Box 3.3), and decrease the availability of carbonate ions. It will also promote increased dissolution of carbonate substrates at shallower depths in coral reef ecosystems[68,69,78]. The median projection of future changes in pH and CO_3^{2-} from 13 ocean carbon cycle models shows that the average aragonite saturation state in surface waters is expected to drop from 3.9 (350% saturation) in 1994 to 2.4 in 2100 in the surface waters for the A2 scenario (Figure 3.39). Under the more conservative S650 emissions scenario[v], the average surface aragonite saturation in the tropical Pacific Ocean is projected to be 3.0 in 2100 (**Figure 3.40**).

[v] The S650 scenario is similar to B2 and slightly above B1. Under this scenario, atmospheric CO_2 concentration would reach 562 ppm in 2100.

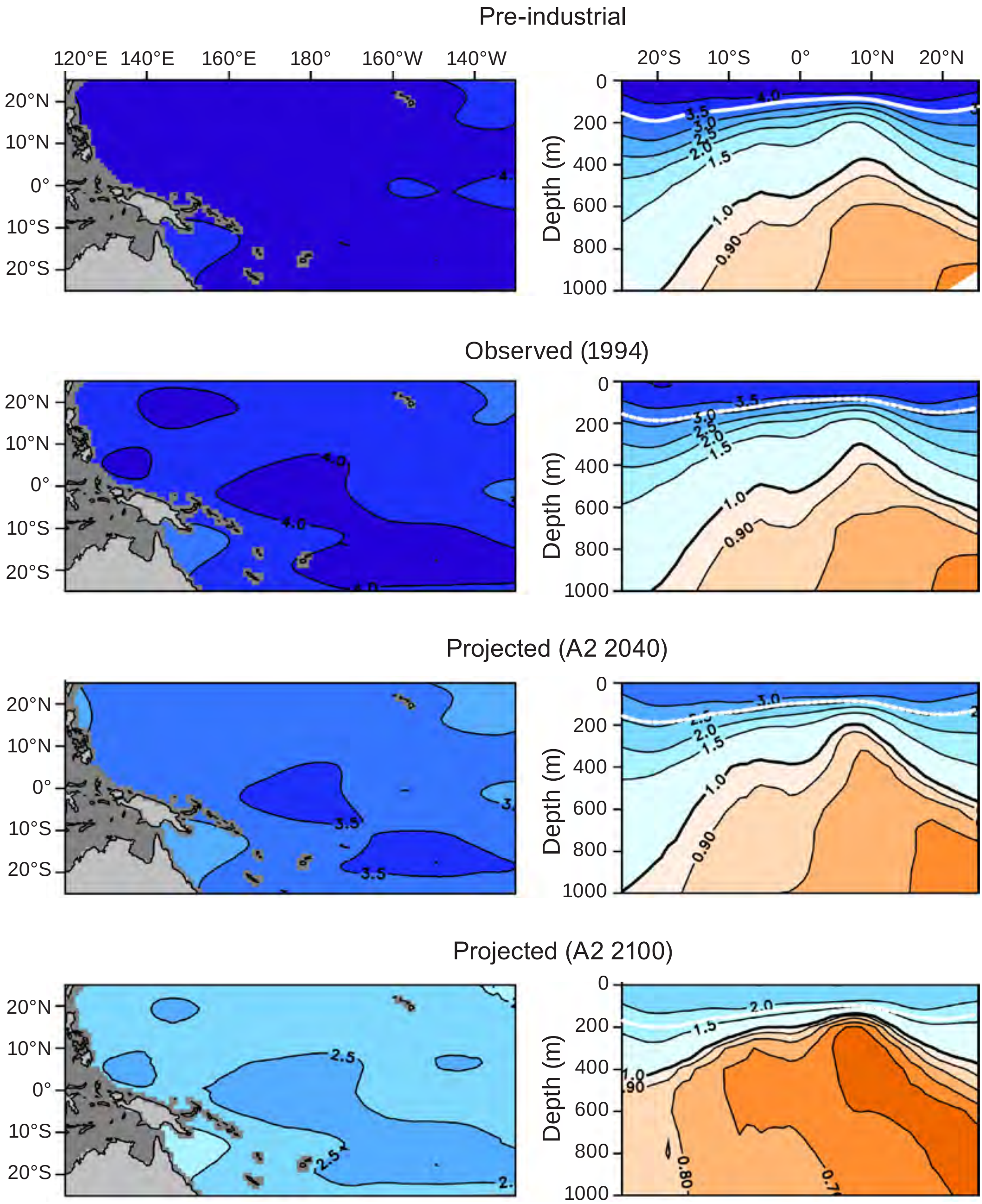


Figure 3.39 Aragonite saturation levels in the tropical Pacific Ocean at the surface (left panels) and to a depth of 1000 m (zonal averages) (right panels) during pre-industrial times and 1994, together with median projected values for the A2 scenario around 2035 (2040) and 2100. The thick white line on the upper right panel is reproduced as a dashed white line on the other three depth sections below. It indicates the depth level where pre-industrial waters have a saturation state that is 3.5 times the value where pure aragonite begins to dissolve, which is indicated by the 1.0 contour (thick black line), known as the aragonite saturation horizon (source: Orr et al. 2005, Key et al. 2004)[77,197].

Average sections to a depth of 1000 m across the domain (**Figure 3.39**) show that although the declines in aragonite saturation are greatest near the surface, there are also noticeable changes at greater depths. In particular, there is a shoaling of the aragonite saturation horizon, below which aragonite dissolves (Box 3.3). In 1994, the aragonite saturation horizon zonal average was at a depth of 300 m at 8°N, and deeper to the south and to the north. It is projected to become shallower over time, reaching 150 m in 2100 under the A2 scenario.

These projections do not account for the physical effects of global warming on ocean acidification: they only simulate geochemical changes due to increases in atmospheric CO_2. However, some feedback effects may be expected due to changes in temperature, ocean stratification, biological production, and remineralisation. Projected increases in SST, for example, would reduce CO_2 solubility and increase CO_3^{2-} near the surface. Overall, the combined physical effects of climate change on ocean acidification are projected to be small, i.e. < 10% of the change directly due to the increase in atmospheric CO_2[77]. Changes in concentrations of CO_3^{2-} associated with natural interannual climate variability are also projected to be small compared with projected long-term changes[77].

Declining aragonite saturation levels have significant implications for coral reefs (Chapter 5). In particular, sustained coral reef accretion and structural density is expected to be jeopardised if the aragonite saturation drops below 3.25[72] and/or when the atmospheric CO_2 concentration exceeds 450 ppm[168]. This threshold is likely to be reached in average surface waters of the tropical Pacific Ocean shortly after 2035 (2040) under the A2 scenario (**Figure 3.39**).

Future decreases in pH due to anthropogenic emissions of CO_2 under the B1 and A2 scenarios are projected to be 0.2 to 0.3 pH units below present levels by the end of this century. Under a worst case scenario, if all known fossil-fuel reserves (~ 5000 Pg C) were combusted, the reduction in pH could reach 0.7 units[165].

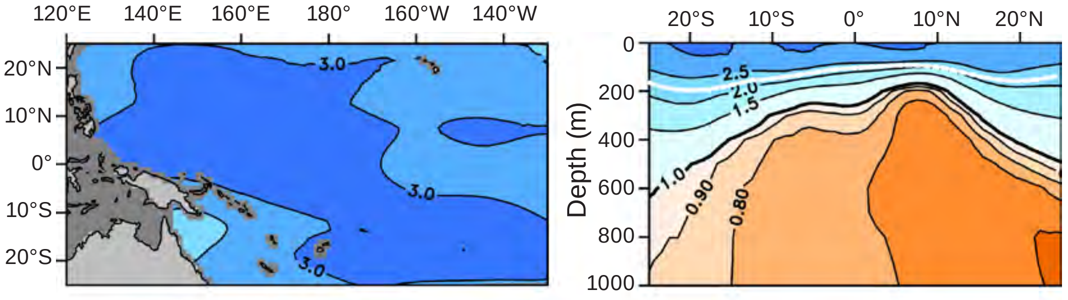


Figure 3.40 Projected levels of aragonite saturation in the tropical Pacific Ocean in 2100 for the S650 scenario. Projections for the B1 scenario in 2100 are expected to be slightly higher than those for S650 (see text for details). Other details as per Figure 3.39.

3.3.7 Wave height

3.3.7.1 Observed changes

Around the world, visual reports from shipping show an increase in significant wave heights (SWH) at mid- and high-northern latitudes since 1950[169]. However, in the far western part of the Warm Pool, SWH has decreased at a rate of 8 cm per decade. Unfortunately, there are insufficient data from other parts of the tropical Pacific Ocean to determine whether SWH has changed over recent decades[169].

Regardless of any changes in SWH, it is plausible that the current wave climate may result in more frequent damage to coastal fish habitats. The combined effects of reductions to the structural complexity of coral reefs, due to more frequent bleaching and increased ocean acidification (Chapter 5), and sea-level rise, means that the force of waves on the shoreline is unlikely to dissipate to the same extent as in the past. The increased wave force is likely to reduce the complexity of coral reefs further; it is also expected to affect mangrove and seagrass habitats (Chapter 6).

3.3.7.2 Projected changes

The CMIP3 climate models do not include wave projections. However, estimated changes can be derived from an empirical relationship between sea-level pressure and SWH. Based on multi-model means from three climate models, an increase in SWH of 8 to 10 cm in the southern tropical Pacific is projected for 2100 under the A2 emissions (**Figure 3.41**), and is expected to be most pronounced in the east. No change or a decrease of about 4 cm is expected by 2100 in the northern tropical Pacific[170,171]. An estimated decrease of 6 to 8 cm for the B2 scenario, which is intermediate between B1 and A2, is projected for 2100[170]. The 20-year return SWH (the value that significant wave height exceeds at least once over a 20-year period) is projected to increase by about 30 cm in the eastern half of the southern tropical Pacific under A2 in 2100.

In general terms, interannual variability of SWH is strongly linked to ENSO. As such, future changes in the wave climate of the tropical Pacific Ocean would also be expected to depend on future changes in ENSO. However, although ENSO events are projected to continue, there is little agreement about how they may change in amplitude or frequency (Chapter 2). Thus, it is only possible to state that waves will continue to be influenced strongly by El Niño and La Niña episodes.

There is more certainty about projections for the SAM. Almost all CMIP3 climate models project a continued southward intensification of the mid-latitude westerly winds, causing the associated increase in storm activity outside the tropics to intensify. Observational studies indicate an increase in SWH, as measured by satellite altimeters, associated with positive SAM phases[172]. Because of the projected southward shift of the extra-tropical storm tracks associated with SAM, however, the distance that swells have to travel to the tropics increases, which could counteract any influence that the increased storm intensity may have. As a result, little increase in SWH related to SAM is expected in the tropical Pacific Ocean.

Projections for SWH remain at their early stages, and uncertainties are still large. It is likely, however, that application of outputs from a greater range of climate models, using extensions of statistical wave projections[170], and regional dynamical wave projections[173], will soon improve our knowledge.

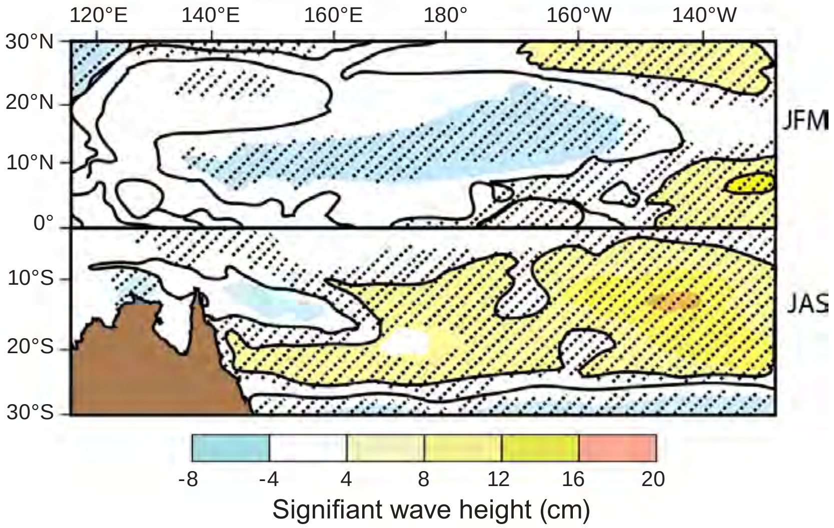


Figure 3.41 Projected increase in significant wave height under the A2 emissions scenario in 2100 for winter months north and south of the equator, relative to levels in 1990. The shaded area corresponds to statistically significant changes from an average over three climate models. JFM = January to March; JAS = July to September (source: Wang and Swail 2006)[170].

3.3.8 Sea level

3.3.8.1 Observed changes

Global sea level has risen ~ 6 cm since 1960 (**Figure 3.42b**) and ~ 17 cm since the industrial revolution[174]. In the past 15 years, the water released from glaciers is estimated to make up 60% of the contribution of melting ice to present-day sea-level rise[175] (**Figure 3.42a**). However, major fluctuations, i.e. periods of a few years with unusually large positive or negative trends, are evident in the record. A good example is the fall in sea level during 1982–1985 as a result of ocean cooling caused by aerosols from the Chichon Volcano eruption (**Figure 3.42**). This temporary reduction in sea level was compensated for within 2 to 3 years as the aerosols were removed from the atmosphere and sea-level rise continued unabated over the longer term. More recently, the rise in sea level has accelerated. More than 60% (~ 4 cm) of the total rise of ~ 6 cm since 1960 has occurred since 1993, and the rate of sea-level rise is now 2.5 cm per decade[176,177]. The rate of sea-level rise varies across the region, as discussed in Section 3.2.8 (**Figure 3.23**).

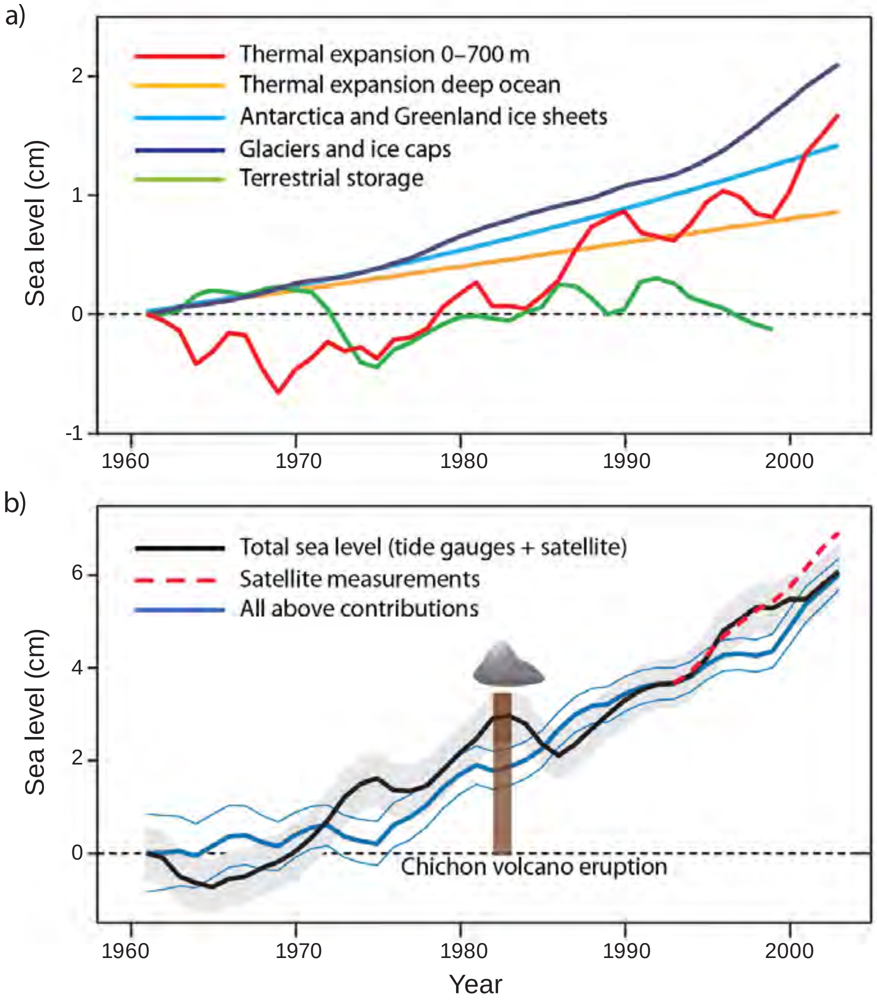


Figure 3.42 (a) Contribution of the different components of global sea-level rise since around 1960; and (b) observed total sea-level rise estimated by tide gauges and satellite data (black) and satellite-only data (dashed red line). Combined contributions of the main factors listed in (a) are shown by the thick blue line (95% confidence limits are indicated by the thin blue lines). Major climate fluctuations are evident in the record, e.g. the drop in sea level during 1982–1985 due to short-term ocean cooling caused by aerosols from the Chichon Volcano eruption (source: Domingues et al. 2008)[177].

3.3.8.2 Projected changes

Short-term drivers of sea level are not expected to change substantially in the next 100 years. Tidal forcing will remain the same and eddies have no clear projected trend in the tropical Pacific (Section 3.3.3). The possibility of stronger tropical cyclones (Chapter 2) would be associated with higher storm surges. The primary drivers of long-term sea-level rise are still expected to be melting of land ice and thermal expansion of sea water.

A comparison of the global sea-level rise simulated over recent decades in the IPCC-AR4 models with recent observations shows that the models generally under-estimate global sea-level rise[178,179]. Nevertheless, projections for the ice melt contributions are recognised as the most important component of future sea-level rise (IPCC-AR4)[180]. Much uncertainty remains, however, because of the limited understanding of mechanisms that control the dynamics of land ice flow into the ocean. With enhanced melting, the flow can accelerate more than expected from classical ice dynamics, as suggested by the most recent observations[175,181].

Indeed, paleo-climatic records suggest that during the last interglacial period (130,000 years ago) when global temperatures exceeded present temperatures by a few degrees, sea level was 3 to 6 m higher than it is today[182,183]. The melting of the Greenland ice sheet contributed about 3.4 m to the total rise that occurred then. According to 2100 projections of surface temperatures in Greenland, similar increases in sea level might be possible[182]. Alternative views are that ice dynamics would limit sea-level rise to between 0.8 and 2.0 m by 2100, regardless of the temperature increase[184]. Extrapolation of present-day acceleration in melting rates suggests that glacier melt alone could cause a sea-level rise of 17–56 cm by 2100[175]. This broad range of estimates in the ice melt component of sea-level rise is expected to narrow in the coming years as understanding of the underlying ice dynamics improves.

Thermal expansion of the water column, which is the second largest factor affecting sea level after ice melt, is diagnosed directly in IPCC-AR4 climate models. The models provide estimates of global sea-level rise due to thermal expansion for B1 and A2 in 2035 of between 5 and 8 cm, compared with the 1980–1999 level. By 2100, the estimates rise to 18–24 cm under the B1 scenario, and between 23 and 31 cm for A2[180]. This component has a much narrower range of estimates than ice melt.

Given the present lack of knowledge about ice dynamics, estimates based on historical reconstructions for global sea-level rise, which include the effects of ice melt and thermal expansion, have been used to provide independent assessments without requiring a detailed understanding of the underlying dynamics. In general, these techniques suggest sea-level rise will exceed the estimates of the IPCC. Using one such empirical estimate, projections are that sea-level rise will be 20 to 30 cm under the B1 and A2 scenarios in 2035, 70 to 110 cm under B1 in 2100 and 90 to 140 cm under A2 in 2100 (**Figure 3.43a**)[185]. Although a rise of almost 2 m by 2100 cannot be ruled out[184], this empirical estimate should be used with caution until the limitations of these projections are more fully understood[vi].

The IPCC-AR4 models project relatively modest regional deviations from the average trend throughout the tropical Pacific Ocean due to differential warming of the water columns. These deviations are projected to be within 5 to 10 cm of the global average rise, based on the multi-model mean (**Figure 3.43b**).

[vi] See ‘Climate Change in the Pacific: Scientific Assessment and New Research’ (www.cawcr.gov.au/projects/PCCSP) for more information.

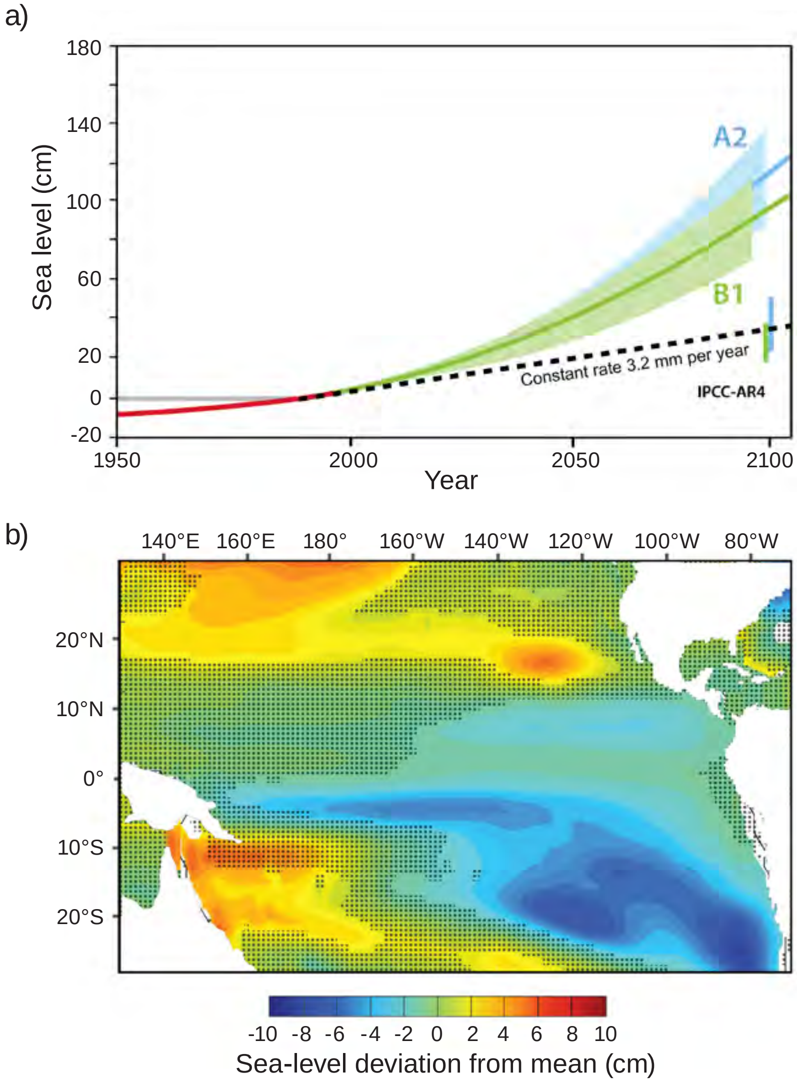


Figure 3.43 (a) Observed and estimated global sea-level rise. The thick dashed black line shows the constant rate hypothesis used by IPCC-AR4. The green (B1) and blue (A2) curves (with uncertainty ranges) show estimates for 2100 from an empirical model based on palaeo-climatic data calibrated against modern data (see text for details) (source: Vermeer and Rahmstorf 2009)[185]; (b) deviations in sea-level rise from global mean sea-level rise within the Pacific basin for A2 in 2100. Shaded areas are regions where model projections do not agree at 90% confidence. At any point, absolute sea-level rise would be the sum of estimates for components in (a) and (b).

3.3.9 Coastal circulation and island effects

3.3.9.1 Observed changes

In the eastern Pacific, recent variations in upwelling systems have been attributed to changes in the wind field and/or the oceanic thermal structure[186,187]. Although the effects of such changes to islands in the Archipelagic Deep Basins Province in the western Pacific have received much less attention than in the Pacific Equatorial Divergence Province, observed changes in the large-scale wind field, ocean currents, and the thermocline depth described above are expected to have affected island and coastal systems to some extent. This change has not yet been quantified.

3.3.9.2 Projected changes

Projecting future changes at the scale of individual islands is a considerable challenge. To a large extent, the climate models used to project future changes are too coarse to resolve small islands and the processes important for delivering nutrients to the photic zone. However, changes to the productivity of inshore waters depend to some extent on the projected changes to large-scale features that can be resolved in the models, particularly those for ocean currents, wind patterns, and depth of the mixed layer. Changes to these and other oceanic features are expected to interact with coastlines and islands to produce distinct local responses, which would need to be assessed on a case by case basis. The discussion that follows, therefore, makes only general qualitative statements.

Island ecosystems in areas with strong projected changes to the large-scale surface currents, i.e. within 15°N–15°S of the equator (**Figure 3.26**), are likely to be the most affected. Areas of increased current strength are likely to have more local eddies and greater associated nutrient supply (**Figure 3.24**). Conversely, areas of decreased current strength are likely to have fewer local eddies and a reduced supply of nutrients. Changes in wind direction will also alter the island wake position and structure. The IPCC-AR4 projections show (1) relatively stable wind stress in the southwest Pacific, with stronger and more southerly winds occurring in the southeastern part of the region; and (2) weakened equatorial and north trade winds. French Polynesia in particular is likely to be subject to such expected changes.

Regional climate models embedded in IPCC class models have been used in the California upwelling system, suggesting a future increase in strength[188], but similar downscaled investigations are not yet available for the area of the Pacific Community. Paleo-climatic records suggest that upwelling activity in New Caledonia has been ongoing for at least 6000 years[85] and the slight change in projected winds suggest that water motion is unlikely to change dramatically in the future. However, the upwelling system in New Caledonia barely reaches the deep nutrient-rich layers[110], so the projected strengthening of the stratification would lower the already weak mechanisms for transferring nutrients to the photic zone.

There is little reason to expect changes in the formation of internal waves as this depends on the interaction between tides and ocean bathymetry. However, the characteristics of these waves, their propagation patterns and impact could be affected by changes in the thermal structure of the water column.

In summary, climate change is expected to have localised effects on the waters surrounding different islands through interactions between large-scale oceanic and atmospheric processes and island topography. However, the necessary local projections are scarce and there is a need for specific studies to downscale future climate simulations (Section 3.5).

3.4 Summary of present-day ocean features, and observed and projected changes

The circulation of the central and western tropical Pacific Ocean is dominated by two broad westward currents, the North Equatorial Current and the South Equatorial Current. These are separated by two eastward counter currents underneath the atmospheric convergence zones (ITCZ and SPCZ) at latitudes 5°–10°N and 5°N–10°S. As the broad flows encounter islands and coasts, they form narrow and powerful currents that can transport heat, nutrients, particles and larval fish and invertebrates over large distances. Because of their strong relation with winds and SSTs, these ocean currents vary substantially with season and with ENSO.

In the central and eastern equatorial region, where the trade winds drive an upwelling of deep water and create the Pacific Equatorial Divergence Province, the surface waters are relatively rich in nutrients (Chapter 4). Most of the rest of the western tropical Pacific Ocean is nutrient-poor (oligotrophic) because warm surface water is piled up by the trade winds, pushing down the deep layers that are rich in nutrients. Wind-induced mixing, oceanic eddies, internal waves and island upwellings all act to reduce this natural stratification barrier supplying the upper layers of the ocean with the nutrients necessary for biological production. In the western equatorial Pacific, an immense pool of warm, nutrient-poor water moves back and forth along the equator according to the phase of the ENSO cycle. The eastern edge of the Warm Pool in the western Pacific defines the limit of the nutrient-rich Pacific Equatorial Divergence Province.

In addition to the substantial natural variability in the position and size of the Warm Pool, the following long-term changes in the other major oceanographic features of the region have been observed over the past 30 to 50 years (**Table 3.2**).

- The South Pacific gyre has increased in strength, driven by a southward intensification of extra-tropical wind. This has altered the complex current system of the southwest Pacific and changed the structure of water temperatures in the region.
- The upper ocean has warmed by 0.6°C to 1.0°C down to a depth of 100 to 200 m, depending on latitude, with cooling in some regions at greater depths. This has resulted in an increase in stratification, which limits the vertical exchange of water and has major implications for nutrient supply (Chapter 4).

- The two longest existing time-series of oceanographic data in the tropical northern Pacific indicate that there has been no increase or decrease in nutrient supply, consistent with increased stratification. The data are insufficient to establish whether a basin-scale trend is occurring. Trends in nutrient supply to the upper layers and biological activity are difficult to gauge with certainty because high-quality long-term observations are not available. Natural variability generally exceeds any possible long-term trends.
- Subsurface concentrations of dissolved oxygen have been decreasing and there has been an expansion of oxygen-depleted waters. This could have some detrimental effects on biological production (Chapter 4).
- Absorption of increasing amounts of CO_2 have decreased the pH of the tropical Pacific Ocean by ~ 0.06 pH units, making the ocean more acidic (or strictly speaking less basic). The acidification of the ocean is close to the point where calcareous organisms, such as corals and a number of planktonic species, could experience a weakening in their shells or skeletal structure, reducing their fitness and resistance to predation.
- Sea level has risen by about 17 cm globally since pre-industrial times, and 6 cm since 1960. The rate of increase appears to be increasing due to accelerated ice melt and thermal expansion of the upper ocean and is currently ~ 2.5 cm per decade.

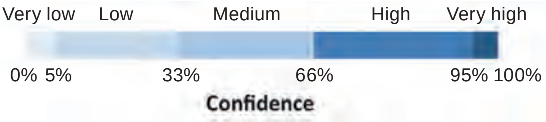
Projected changes to the major features of the tropical Pacific Ocean under the B1 and A2 emissions scenarios in 2035 and 2100 have been assessed using selected CMIP3 models from the IPCC-AR4 climate simulations. This analysis shows that substantial changes in ocean circulation and temperature structure are expected to occur, which are likely to impact biological productivity (**Table 3.2**). The major projected changes are summarised below.

- Alteration in speed and direction of some major ocean currents: the tropical part of the South Equatorial Current (SEC) is expected to weaken progressively (18% by 2100 under A2) and become more confined to the surface layers. The Equatorial Undercurrent is likely to strengthen in the western Pacific and become shallower directly beneath the SEC. South of the equator, the near-surface South Equatorial Counter Current is expected to retract and weaken dramatically (60%) by 2100.
- Ocean temperature is expected to continue rising substantially, with higher warming rates near the surface, especially in the first 100 m. The salinity of the tropical western Pacific Ocean is projected to decrease in line with an intensified hydrological cycle (Chapter 2). The salinity front associated with the Warm Pool will extend further east by ~ 1000 km, while the 29°C isotherm will move much further east at the equator.

Table 3.2 General summary of observed and projected changes to the main features of the tropical Pacific Ocean. Observed changes are relative to the period 1950–1960. Projected changes are relative to 1980–1999. Estimates of confidence are provided for each projection (see key below). Details of currents are provided in Figure 3.1; see Table 3.1 for more detailed observed and projected changes for selected key ocean features.

Ocean feature	Observed changes	2035		2100		
		B1	A2	B1	A2	
Currents	South Pacific gyre has strengthened	SEC decreases at the equator; EUC becomes shallower; SECC decreases and retracts westward in the upper 50 m				▨
Sea surface temperature		Projected to increase significantly over the entire region				■
		+0.6 to +0.8°C	+0.7 to +0.8°C	+1.2 to +1.6°C	+2.2 to +2.7°C	🟦
Ocean temperature at 80 m	+0.6 to 1°C since 1950	+0.4 to +0.6°C		+1.0 to +1.3°C	+1.6 to +2.8°C	🟦
Warm Pool	Warmer and fresher	Extends eastward; water warms and becomes fresher, and area of warmest waters increases				🟦
Equatorial upwelling	Decreased	Integral transport 9°S–9°N remains unchanged				🟦
Eddy activity	No measurable changes	Probable variations in regions where major oceanic currents change				□
Nutrient supply	Decreased slightly in two locations	Decrease due to increased stratification and shallower mixed layer, with a possible decrease of up to 20% under A2 by 2100				▨
Dissolved oxygen	Expansion of low-oxygen waters	Possible decrease due to lower oxygen intake at high latitudes				▨
		Possible increase near the equator due to decreased remineralisation				□
Ocean acidification		Aragonite saturation (Ω) projected to continue to decrease significantly				■
	➢ Ω decreased from 4.3 to 3.9	n/a	Ω ~ 3.3 🟦	Ω ~ 3.0 🟦	Ω ~ 2.4	🟦
	➢ Ω horizon rises from 600 to 560 m	n/a	~ 456 m 🟦	n/a	~ 262 m	🟦
	➢ pH decreased from 8.14 to 8.08	n/a	~ 7.98 🟦	n/a	~ 7.81	🟦
Waves	Decreased in far west Pacific; no data elsewhere	Slight increase (up to 10 cm) in swell wave height; patterns depend on ENSO and tropical cyclones				□
Sea level	+6 cm since 1960	Projected to rise significantly				■
		* +8 cm ■		+18 to +38 cm ■	+23 to +51 cm	🟦
		** +20 to +30 cm ▨		+70 to +110 cm ▨	+90 to +140 cm	▨
Island effects	Not observed	Probable; undocumented				

* Projections from the IPCC-AR4, not including any contribution due to dynamical changes of ice sheets; ** projections from recent empirical models (Section 3.3.8.2); SEC = South Equatorial Current; EUC = Equatorial Undercurrent; SECC = South Equatorial Counter Current; ENSO = El Niño-Southern Oscillation; n/a = estimate not available.



- Stratification of the upper layers of the ocean – a major factor influencing the supply of nutrients from the deep ocean to the photic surface zone – is expected to increase.
- Increases in atmospheric CO_2 are projected to lead to substantial additional acidification of the ocean, reducing the pH of the ocean by 0.2–0.3 units under the B1 and A2 scenarios by 2100, relative to 2000. At such rates of change, aragonite saturation levels in the tropical Pacific Ocean are expected to fall below 3.25 by 2035 to 2040 under the A2 scenario, jeopardising the growth of some corals. The aragonite saturation level is expected to decrease to 2.4 in 2100 under A2, with severe consequences for coral reefs (Chapter 5).
- As a consequence of continued ice melt, and thermal expansion of the upper oceanic layers, the rate of sea-level rise is expected to accelerate. The projections from IPCC-AR4, that sea level will rise between 18 cm under B1 to 51 cm under A2 by 2100, are now considered to be conservative because they underestimate the acceleration of ice sheet melt. More recent empirical estimates based on temperature/sea level relationships based on past records, indicate that sea-level rise could be in the range of 70 to 140 cm by 2100. Even the minimum estimate of 70 cm would mean a profound change for coastal habitats.

3.5 Recommendations to reduce uncertainties in projecting future changes to the tropical Pacific Ocean

3.5.1 SPCZ and ENSO

Much effort during the past decade has been devoted to improving numerical climate simulations and projections. This research has culminated in 22 state-of-the-art climate models (the CMIP3 models used for the 2007 IPCC-AR4 report), which are used to reproduce present conditions and project future changes to the ocean, atmosphere, and sea ice. To test the fidelity of these models, comparisons have been made between observations from the past 20 to 50 years and model simulations forced with historical greenhouse gas concentrations, aerosol concentrations (in some cases) and changes to solar radiation.

A number of important systematic biases are evident in the CMIP3 models that are of particular importance for the tropical Pacific Ocean. These include the position of the SPCZ and the spatial and temporal structure of the ENSO. The overly zonal orientation of the SPCZ in many numerical simulations limits our confidence in projections of the rainfall and wind fields of the central-southern Pacific. ENSO, which acts as a metronome for the ocean-atmosphere system, has a simulated warming (in the case of El Niño events) that is generally situated too far to the west and often occurs too frequently in the models. Both SPCZ and ENSO are the focus of intense research programmes[vii]. A better understanding of the physical mechanisms driving

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[vii] CLIVAR, www.clivar.org, and the Pacific Climate Change Science Programme www.pacificclimatechangescience.org

these characteristics, leading to improved physical parameterisations, combined with higher model resolutions, is expected to help reduce these biases in the new generation of climate models to be used for the 5th IPCC assessment.

3.5.2 Integrating biogeochemical and physical models

Estimating the extent to which climate change is likely to alter nutrients and oxygen concentrations requires the integration of biogeochemistry with physical models. This may be achieved in two ways. Either a biogeochemical model can use the stored output of a physical ocean model (i.e. an 'offline' simulation), or a physical and biogeochemical model can be coupled together so that the components interact throughout a simulation. Such simulations have been used in Chapters 4 and 8 but remain relatively rare, and the results are subject to uncertainties of the physical model. To increase confidence in biogeochemical simulations and their projections, most climate simulations should be supplemented by offline or online biogeochemical simulation.

3.5.3 Dynamical downscaling

Because islands and reefs act as obstacles to wind and water flow, the key features of the tropical Pacific Ocean of significance to fisheries, such as SST, currents and nutrient supply, can all be altered locally. These localised effects are not represented in most of the present climate models due to a lack of model resolution stemming from limited computational power. To overcome this limitation, regional high-resolution numerical models are sometimes used. For example, **Figure 3.25** shows a high-resolution, regional ocean simulation around New Caledonia. This regional simulation relies on a low-resolution global ocean simulation to obtain the information it needs for conditions at the boundary of the region. This technique is referred to as dynamical downscaling. To investigate future changes at these high resolutions, boundary conditions based on projections from the coupled climate models can be used. While downscaling is an economical way of producing high-resolution regional projections, great care must be taken in using such projections. Biases in the low-resolution model will generally be propagated to the high-resolution model, compromising the fidelity of the simulation. Considerable effort is needed to determine how best to implement such downscaling approaches.

3.5.4 Long-term observations and monitoring

High quality, long-term observational datasets with sufficient spatial coverage are vital to understanding climate change and its effects. Such data allow us to distinguish between anthropogenic effects and natural variability, and to validate climate and biogeochemical simulations. The physical state of the tropical Pacific Ocean is now monitored reasonably well over large areas, both by satellite and with *in situ* data systems[viii]. Specific programmes are being developed to monitor highly energetic boundary currents that transport large amounts of heat and other climatically important properties over large distances. On the other hand, measurements of nutrients, oxygen, and ocean pH have relatively poor data coverage and little reliable monitoring. The Hawaiian Ocean Time-Series programme provides the only complete long-term time-series in the region. The replication of such a monitoring system in other parts of the tropical Pacific would be extremely valuable. Such an initiative is presently underway under the auspices of the GOPS[ix]. Ocean acidification, which is expected to be a major perturbation to marine ecosystems in addition to global warming, requires improved and continuous monitoring. This effort must be supplemented by appropriate field-based studies to improve our understanding of the impact of acidification on ecosystems. Sustained field studies, including measurements of physical and chemical variables, such as those initiated for the Great Barrier Reef[x], must be expanded to other sites in the tropical Pacific Ocean.

[viii] CLIVAR, www.clivar.org

[ix] Grand Observatoire de l'Environnement et de la Biodiversité Terrestre et Marine du Pacifique Sud (South Pacific integrated Observatory for environment and terrestrial and marine biodiversity, www.observatoire-gops.org)

[x] Great Barrier Reef Ocean Observing System, www.imos.org.au/gbroos.html

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Appendix 3.1 CM1P3 models

Details of the 13 CMIP3 models from IPCC-AR4 used to make projections for the main features of the tropical Pacific Ocean, as shown below. **Vertical coordinate (VC):** RHO = isopycnal; H = hybrid; Z = depth. **Mixing parameterisation (MP):** GM (Gent and McWilliams 1990)[198]; GM* (Griffies 1998)[199] implementation of GM; BL (Bryan and Lewis 1979)[200] depth varying vertical mixing; PP (Pacanowski and Philander 1981)[201] vertical eddy viscosity and diffusion; NK (Noh and Kim 1999)[202] vertical diffusion and viscosity; EVD = convective mixing parameterisation; TKE (Blanke and Delecluse 1993)[203]; V (Visbeck et al. 1997)[204] controls eddy-induced transport coefficient; KT = Kraus-Turner, wind-generated turbulent kinetic energy; KPP = mixed-layer scheme (Large et al. 1994)[205]. **Bottom boundary layer (BBL):** BBL-NS (Nakano and Suginohara 2002)[206]; BBL-BD (Beckmann and Doscher 1997)[207]; NO-BBL. **Flux correction (FC):** N = none; H = heat; F = fresh water; M = momentum. **Forcing (anthropogenic):** ALL = greenhouse gases, ozone, and sulfate aerosols; -O = no anthropogenic ozone. Further details and references are available at PCMDI website (www.pcmdi.llnl.gov)

Model	Oceanic model	Oceanic resolution	VC	MP	Atmospheric resolution	FC	Forcing	Reference
BCCR BCM2.0	MICOM2.8	1.5° x 1.5°(0.5°) L35	RHO	KT, KPP	T63 L31	N	ALL -O	208
CNRM CM3	OPA8.1	2°(0.5°) x 2° L31	Z	GM, TKE	T63 L45	N	ALL -O	209
CSIRO Mk3.0	MOM2.2	0.84° x 1.875° L31	Z	GM*, BL, PP	T63 L18	N	-	210
CSIRO Mk3.5	MOM2.2	0.84° x 1.875° L31	Z	GM*, BL, PP, V, KT	T63 L18	N	-	210
GFDL CM2.0	OM3P4	1°(1/3°) x 1° L50	Z	GM*, BL, BBL-BD, KPP	2.5° x 2° L24	N	ALL	211
IPSL CM4	OPA	2° x 2° (1°) L31	Z	GM, BBL-BD, EVD, TKE	2.5° x 3.75° L19	N	ALL -O	212
MIROC Medres	COCO3.3	1.4°(0.5°) x 1.4° L43	H	GM, NK, BBL-NS, EVD	T42 (2.81° x 2.81°) L20	N	ALL	213
MIROC Hires	COCO3.3	0.19° x 0.28° L47	H	GM, NK, BBL-NS, EVD	T106 (1.12° x 1.12°) L56	N	ALL	213
MIUB ECHO-G	HOPE-G	2.8° x 2.8° (0.5°) L20	Z	PP, EVD	T30 (3.75° x 3.75°) L19	HF	ALL	214
MRI CGCM2.3	Bryan-Cox	2.0°(0.5°) x 2.5° L23	Z	GM	T42 L30	HFM	ALL-O	215
NCAR CCSM3	POP	1.1°(0.27°) x 1.1° L40	Z	GM, KPP, NO-BBL	T85 L26	N	ALL	216
NCAR PCM1	POP	2/3°(0.5°) x 2/3° L32	Z	GM, KPP, NO-BBL	T42 L18	N	ALL	217
UKMet HadCM3	Bryan-Cox	1.25° x 1.25° L20	Z	GM*, V, KT, PP	2.75° x 3.75°L19	N	ALL	218, 219

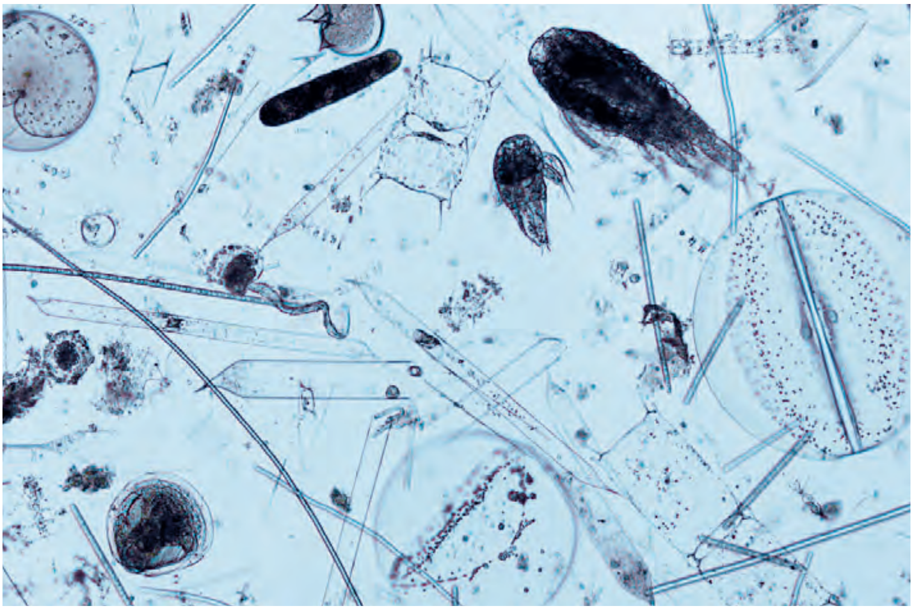
Photo: Gustaaf Hallegraeff

Chapter 4

Vulnerability of open ocean food webs in the tropical Pacific to climate change

Robert Le Borgne, Valérie Allain, Shane P Griffiths, Richard J Matear, A David McKinnon, Anthony J Richardson and Jock W Young

> *'The immense size of the Pacific is reflected in strong longitudinal differences in mixed layer depth and other physical circulation features, themselves reflected in the regional phytoplankton ecology.'* (Longhurst 2006)[i]

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[i] Longhurst AR (2006) *Ecological Geography of the Sea.* Academic Press, New York, United States of America.

Contents Page

4.1 Introduction

The open sea areas of the tropical Pacific Ocean represent a vast area of fish habitat[1]. This expanse of ocean dwarfs the land in the region and makes up 98% of the total area under the jurisdiction of all Pacific Island countries and territories (PICTs) (Chapter 1).

Although much of this open ocean domain is relatively unproductive, it supports some of the largest tuna fisheries in the world. The total recent catches of skipjack tuna, yellowfin tuna, bigeye tuna and South Pacific albacore from the Western and Central Pacific Ocean (WCPO) is approximately 2.5 million tonnes per year, representing > 25% of the total global tuna catch (Chapters 1, 8 and 12).

The production of the four species of tuna, and other large pelagic fish, is underpinned by food webs based not only on the photosynthetic productivity of phytoplankton (called primary production) in the sunlit surface layer (photic zone) of the ocean, but also by bacteria and detritus, derived from phytoplankton. Most of this primary production occurs where nutrients, such as nitrogen, phosphorus and silicon, are transported to surface waters from the deeper layers of the ocean by the physical processes described in Chapter 3.

The energy produced through primary production moves through a 'trophic pyramid' via a range of zooplankton (such as copepods and larval fish), macrozooplankton (including jellyfish and salps) and micronekton (such as squid, shrimp and small fish), to sustain tuna and other large pelagic fish (**Figure 4.1**). The transfer of energy between each level in the trophic pyramid is generally only about 10% because (1) there are energy losses through respiration and excretion at each stage, and (2) the consumers in the next trophic level do not assimilate all available organic matter[2]. The various levels of the food web also contribute to the oceanic carbon sink by transferring carbon from the upper layers to the ocean depths through sinking of dead particles and the capture of prey from the photic zone by vertically migrating zooplankton and micronekton. This process, referred to as the 'biological carbon pump', helps reduce the concentrations of carbon dioxide (CO_2) in the atmosphere[3,4].

The availability of the nutrients that underpin the food web for tuna, together with suitable water temperatures and dissolved oxygen levels, determine the distribution and abundance of tuna and other large oceanic fish across the WCPO[5,6] (Chapter 8). Therefore, the responses of phytoplankton, zooplankton and micronekton to changes in the ocean processes that deliver nutrients to the photic zone, and to changes in the physical and chemical properties of the ocean projected to occur as a result of global warming and ocean acidification (Chapter 3), are expected to affect all life history stages of large oceanic fish.

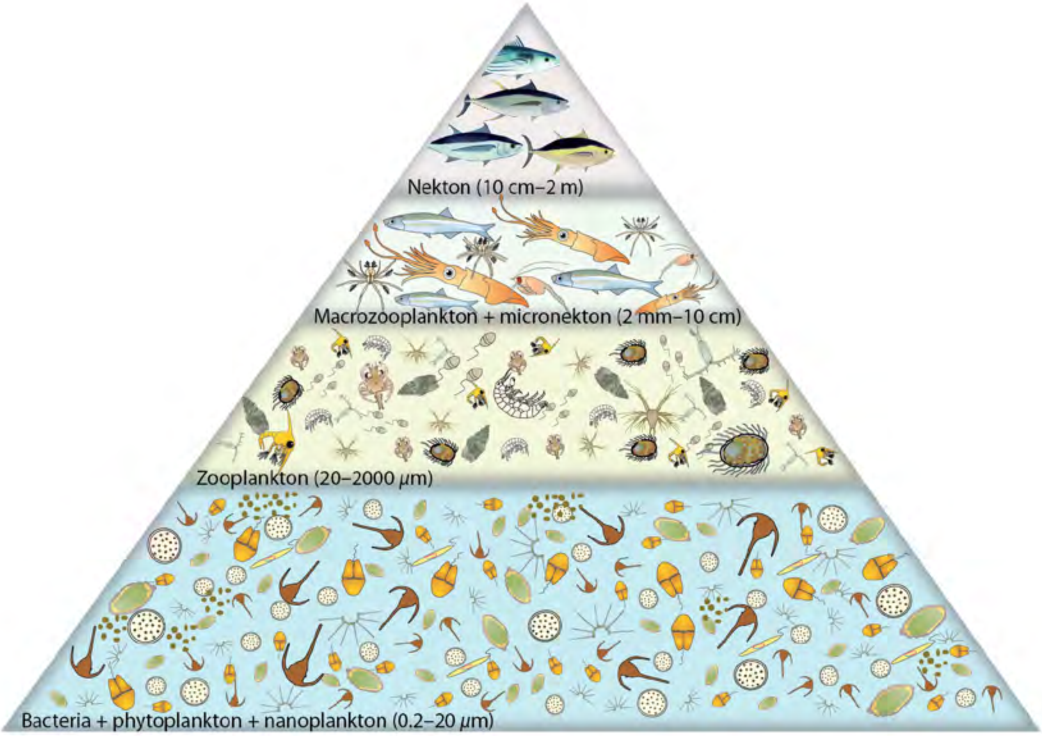


Figure 4.1 Generalised trophic pyramid for the tropical Pacific Ocean. The base of the food web consists of bacteria, small phytoplankton and protists (nanozooplankton), 0.2–20 μm in size. These organisms are ingested by zooplankton, such as crustaceans, molluscs or tuna larvae, up to a size of 2000 μm. In turn, zooplankton are consumed by macrozooplankton, such as jellyfish, and micronekton, such as squid, shrimp and small fish. Micronekton and, to a lesser extent, macrozooplankton are the prey for tuna and other large pelagic fish at the top of the pyramid (see Table 4.1 for size ranges).

The purpose of this chapter is to (1) summarise what is known about the structure of the food webs that underpin the production of tuna across the region and describe how these food webs have changed recently; and (2) project how these food webs are likely to change by 2035 and 2100 under low (B1) and high (A2) emissions scenarios defined by the Intergovernmental Panel on Climate Change (IPCC) and outlined in Chapter 1. In making these assessments, we recognise that we are dealing with a vast part of the tropical Pacific Ocean, and that there is considerable variation in the nature of the food webs that support tuna across this region. To explain and examine this variation, we have arranged this chapter around the well-recognised ecological provinces of the region[1].

To set the scene, we summarise the structure and function of oceanic food webs in general, the physical nature of the ecological provinces in the region, the differences in food webs among these provinces, and the environmental conditions needed to maintain them. We then progress to describing the recent observed changes in the physical nature of the provinces and their food webs, and the projected vulnerability of food webs in each province to climate change. To assess this vulnerability, we have applied the framework outlined in Chapter 1 and used the projected changes to availability of nutrients, water temperature, mixed layer depth, upwellings, solar and ultraviolet radiation, dissolved oxygen and acidification of the ocean described in Chapter 3 to assess the exposure of phytoplankton, zooplankton and micronekton to global warming and increased emissions of CO_2. We have also used an NPZ (Nutrient-Phytoplankton-Zooplankton) model linked to a global climate model[7] (the IPSL-CM4-IPSL-LOOP coupled-climate carbon model) to integrate the projected changes to the physical and chemical features of the tropical Pacific Ocean and estimate changes in net primary production (NPP) and biomass of zooplankton in all provinces. For one province, the Warm Pool in the western Pacific, we then use projected changes in primary production in an Ecopath model to estimate the effects on zooplankton, micronekton and tuna.

Table 4.1 The sources of food that build the food web for tuna and other large pelagic fish in the tropical Pacific Ocean, together with their size, representative organisms, trophic status and depth of their habitat. The first three sources of food belong to the 'paraprimary' level, which is at the base of the food web, like primary production, but is not the direct result of photosynthesis (source: Legand et al. 1972, Dussart 1965, UNESCO 1968)[22,131,132].

Food source	Size range	Representative organisms	Trophic status	Depth of habitat
Dissolved organic matter	< 0.2 μm		Paraprimary level	All depths
Detritus	> 0.2 μm		Paraprimary level	All depths
Heterobacteria	> 0.2 μm		Paraprimary level	All depths
Picophytoplankton	0.2–2 μm	Cyanobacteria (*Prochlorococcus*, *Synechococcus*), pico-eukaryotes	Primary level	Photic zone
Nanophytoplankton	2–20 μm	Diatoms, dinoflagellates, haptophytes, pelagophytes	Primary level	Photic zone
Microphytoplankton	20–200 μm	Diatoms, dinoflagellates, filamentous cyanobacteria (*Trichodesmium*)	Primary level	Photic zone
Nanozooplankton	2–20 μm	Heterotrophic flagellates, small ciliates	Secondary level	All depths
Microzooplankton	20–200 μm	Radiolarians, foraminiferans, tintinnids, larval copepods	Secondary level	All depths
Mesozooplankton	200–2000 μm	Copepods, chaetognaths, larvaceans, ostracods, doliolids, larval fish	Secondary/ tertiary level	All depths
Macrozooplankton	2–20 mm	Pteropods, heteropods, siphonophores, jellyfish, salps	Secondary level and over	All depths
Epipelagic micronekton	2–10 cm	Small fish, amphipods, cephalopods, and shrimp	Secondary level and over	0–200 m
Mesopelagic micronekton	2–10 cm	Small fish, amphipods, cephalopods, and shrimp	Secondary level and over	200–500 m
Deep micronekton	2–10 cm	Fish, cephalopods, and shrimp	Secondary level and over	> 500 m

We conclude by reviewing the uncertainty of these projections, identifying gaps in knowledge and priorities for future research, and recommending a few management measures that could potentially help reduce the vulnerability of the food webs vital to tuna. We emphasise that adaptation options alone may not be sufficient, and that avoiding dangerous outcomes for oceanic food webs will also depend on reducing greenhouse gas emissions worldwide[8].

4.2 General structure and function of food webs for tuna

4.2.1 Phytoplankton production: regenerated and new

All production of phytoplankton at the base of food webs for tuna and other large pelagic fish occurs in the photic zone, where there is sufficient light for photosynthesis (**Figure 4.2**). This primary production uses nutrients regenerated within the photic zone and 'new' nutrients transferred there from deeper water by the processes described in Chapter 3 (Box 4.1). Regenerated nutrients, consisting mainly of ammonium (NH_4) and soluble reactive phosphorus (SRP), lead to 'regenerated production', whereas the nutrients involved in 'new production' are nitrates (NO_3) and di-nitrogen (N_2), SRP and silicates. Availability of nitrogen, in the form of either ammonium or nitrate, is the main factor limiting the primary productivity in most oceanic ecosystems, although the supply of SRP or micronutrients such as iron (Fe) can also limit production. Regenerated nutrients alone are not sufficient to support primary production – a minimum level of new nutrients is needed to compensate for losses that occur within the photic zone, and to maintain the production of phytoplankton.

The vertical structure of the water column determines the availability of new nutrients in the photic zone and four different situations are found in the tropical Pacific (**Figure 4.3**). In regions where there is a pronounced thermocline (Cases 1 and 2), transfer of nutrients to the mixed layer is inhibited because the thermocline acts as a barrier to exchanges between nutrient-rich deep layers and the superficial mixed layer. In such situations, when the thermocline is deep (Case 1), new production is low because it occurs only in the lower part of the photic zone with low light intensity. In Case 1, NPP which is the sum of new and regenerated production, is low. In situations where the thermocline is shallower (Case 2), NPP is higher due to more new production occurring in the nutrient-rich water of the photic zone, below the thermocline. In other words, the deeper the thermocline, the lower the new production and NPP[9].

In regions where the thermocline is weak, exchanges between the deep nutrient-rich layers and the photic zone are easier than in Cases 1 and 2. These exchanges occur through processes like turbulence, mixing, and diffusion, which then drive new production. In the gyres in the northern and southern tropical Pacific, however, the anticyclonic circulation, with prevailing downwelling conditions, leads to a very deep and weak thermocline. In this case, physical nutrient supply is inefficient at transporting nutrients into the photic zone (Case 3), except via temporary eddies linked to wind bursts. Consequently, production in the photic zone of these gyres is very low.

Finally, where there is strong upwelling (vertical transport of deeper water masses to the surface), new nutrients are brought into the whole photic zone, leading to high new production (Case 4).

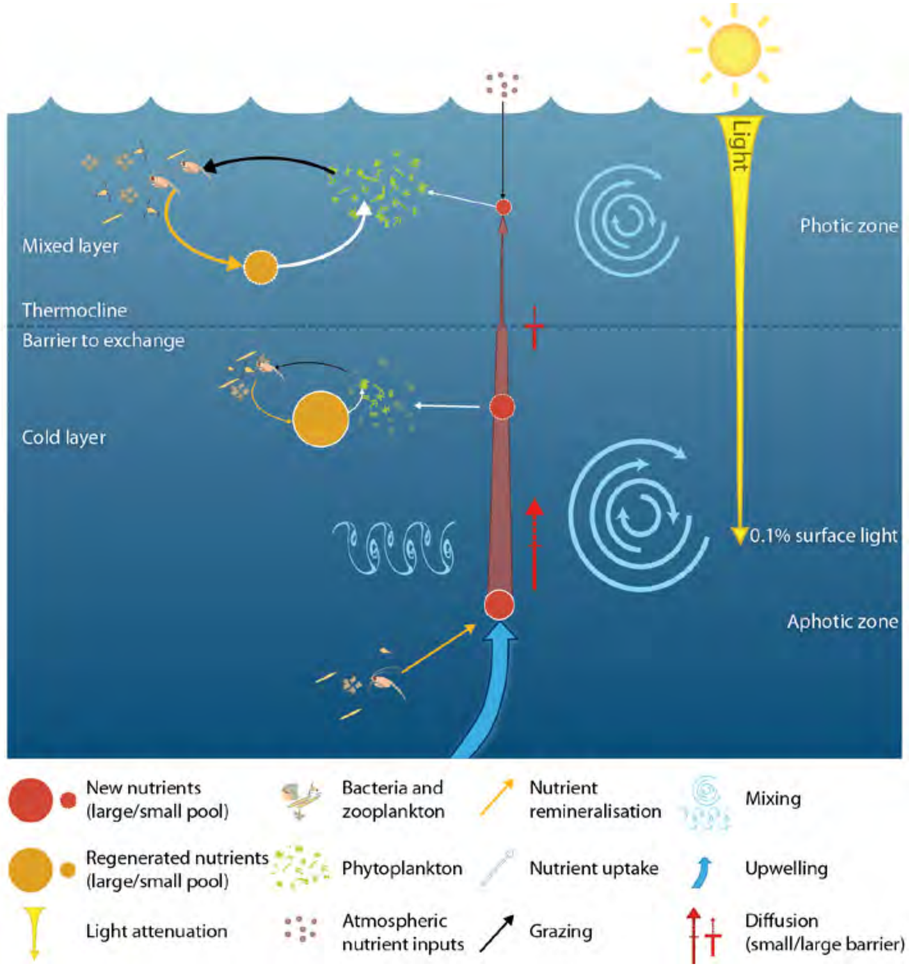
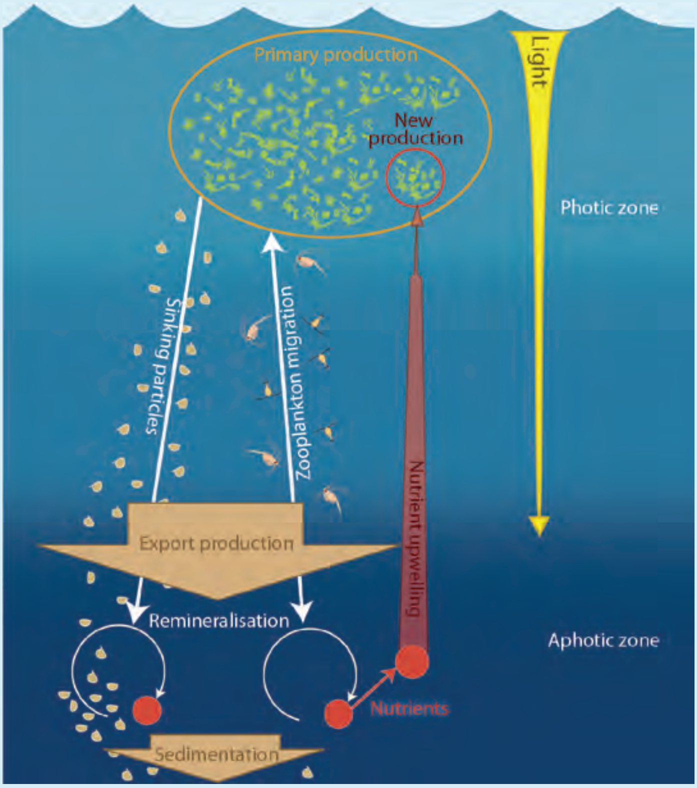


Figure 4.2 Key features of the surface layer of the ocean that determine primary production. The photic zone, where photosynthesis occurs, typically extends to the depth that receives 0.1% of the surface light intensity in tropical areas. Below this, is the aphotic zone, where there is insufficient light for photosynthesis. The warmer mixed surface layer is separated from the deeper cold layer at the thermocline, where water temperature decreases abruptly. The thermocline is a barrier to mixing and the transfer of nutrients from cold, deep water to the surface mixed layer. The cold layer is supplied with nutrients brought up from the aphotic zone by mixing, diffusion and vertical advection (upwelling), depending on the location.

Box 4.1 Primary and export production in the ocean

Primary production is the generation of organic matter in the photic zone by photosynthetic phytoplankton. Primary production is based on two types of nutrients (1) regenerated nutrients released from decaying phytoplankton and zooplankton after they die, and from the respiration and excretion of zooplankton; and (2) 'new' nutrients originating outside the photic zone and delivered there through physical processes such as upwelling, mixing and diffusion.

Export production is the amount of organic matter that leaves the photic zone, typically through sinking of dead plant and animal particles, including faecal pellets, towards the deeper layers of the ocean. Much of the exported organic matter is remineralised by bacteria and zooplankton below the photic zone to produce new nutrients. Part of the export production reaches the sediments at the bottom of the ocean. In balanced ('steady state') ecosystems, the biomass of plankton is fairly constant over the short term, which implies that losses are balanced by inputs to the system. Thus, in the photic zone, export production is balanced by new production, that is, nutrients produced in the deeper layers through mineralisation are brought to the photic layer, converted into organic matter by photosynthesis, and exported.



The source of nutrients also influences the composition of the phytoplankton. New primary production is usually dominated by diatoms because they out-grow other phytoplankton[10]. However, diatoms are replaced by other phytoplankton (e.g. haptophytes and pelagophytes) where the supply of silicon limits growth because diatoms cannot construct their shells without it[11]. In turn, the size composition of the phytoplankton determines the type and size of zooplankton that graze them. Relatively large zooplankton grazers (mesozooplankton), like copepods (**Table 4.1**), dominate areas of new primary production, feeding on the diatoms and large phytoplankton common there. On the other hand, regenerated primary production is dominated by tiny phytoplankton (picophytoplankton) (**Table 4.1**), which are grazed by very small zooplankton (nanozooplankton), such as heterotrophic flagellates and ciliates[12] (**Table 4.1**). In general, therefore, food webs supporting tuna based on significant new production and larger phytoplankton tend to have fewer trophic levels.

New production is augmented by the uptake of N_2, a dissolved gas, in a process called 'diazotrophy'. The main organisms supported by N_2 (diazotrophs) are unicellular cyanobacteria[13], endosymbiots (e.g. *Richelia* sp.) and filamentous cyanobacteria, particularly those of the genus *Trichodesmium* which bloom in summer[14]. Large populations of cyanobacteria can help alleviate the effects of nitrogen limitation in oligotrophic regions, where they can contribute 30–50% of new production[15]. However, the contribution of blooms of cyanobacteria to the food web appears to be highly variable, and is still controversial.

Abundances of zooplankton have also sometimes been linked to blooms of *Trichodesmium*[16]. However, a high biomass of cyanobacteria does not always result in increased productivity of zooplankton because some cyanobacteria are toxic or unpalatable, except to harpacticoid copepods[17]. In such situations, the decayed organic matter from cyanobacteria needs to be mineralised before contributing to a new production cycle that may support other grazers.

4.2.2 Other parts of the food web (bacteria, zooplankton and micronekton)

Whereas primary production by phytoplankton is based on the uptake of inorganic compounds, all other parts of the food web rely on ingesting organic matter, a process known as 'heterotrophy'. This organic matter is consumed in solution by bacteria, but is in the form of 'particles' when consumed by zooplankton and micronekton (**Table 4.1**). The biomass of 'heterotrophic' organisms depends on the amount of organic matter produced by phytoplankton, either as dissolved compounds released by excretion or in a particulate form resulting from NPP. In general terms, therefore, the abundance and diversity of species in the food web of open ocean ecosystems relies primarily on the level of phytoplankton production.

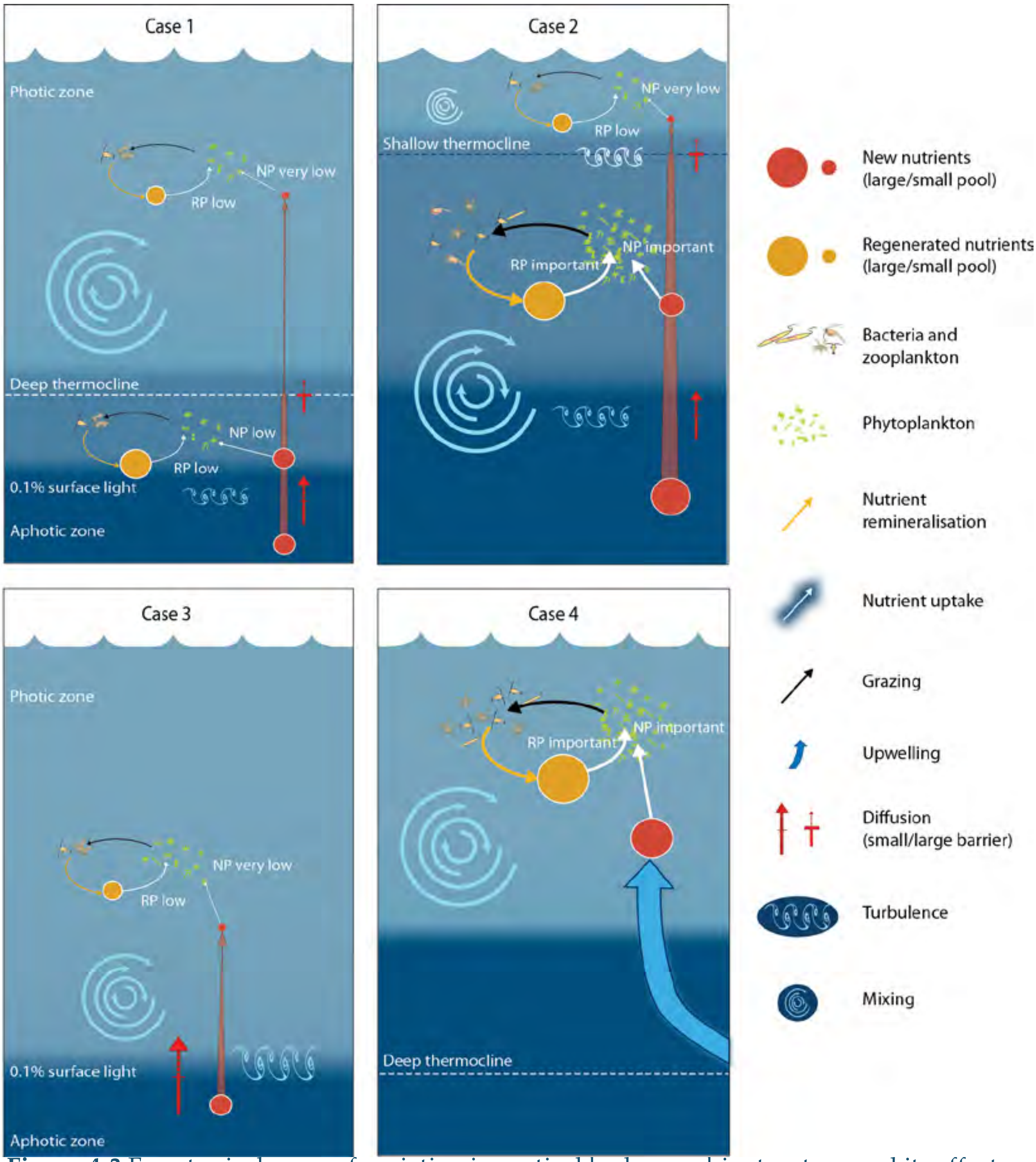


Figure 4.3 Four typical cases of variation in vertical hydrographic structure and its effect on production of phytoplankton in the tropical Pacific Ocean. In Case 1, the thermocline is deep but still in the photic zone; primary production based on regenerated nutrients dominates in the mixed layer but is supplemented by some new production (NP) below the thermocline. In Case 2, the mixed layer remains nutrient-poor (oligotrophic) but a shoaling of the thermocline allows cold, nutrient-rich water to increase both regenerated production (RP) and NP substantially within the photic zone below the thermocline. In Case 3, the thermocline is weak and deep, allowing some inputs of 'new' nutrients from the deep oligotrophic waters to enter the photic zone. However, the biomass of phytoplankton is low and driven mainly by RP. In Case 4, new nutrients delivered by upwelling supply the entire photic zone, even though the thermocline is deep, permitting significant NP and high RP. Note that the photic zone is shallower in Cases 2 and 4 because the higher concentrations of plankton there reduce light penetration.

However, observations have shown that production of small phytoplankton and bacteria are similar and that the production of phytoplankton is supplemented by production based on the contributions of heterotrophic bacteria and detritus (non-living particles) (**Table 4.1**). This resulted in the concept of the 'microbial loop'[18], which was originally pictured as a parallel model of trophic structure to the classical food web[19]. It is now recognised that the classical and microbial food webs are linked through processes of coagulation and the formation of 'marine snow', i.e. particles rich in microbes available to mesozooplankton grazers[20] (**Figure 4.4**).

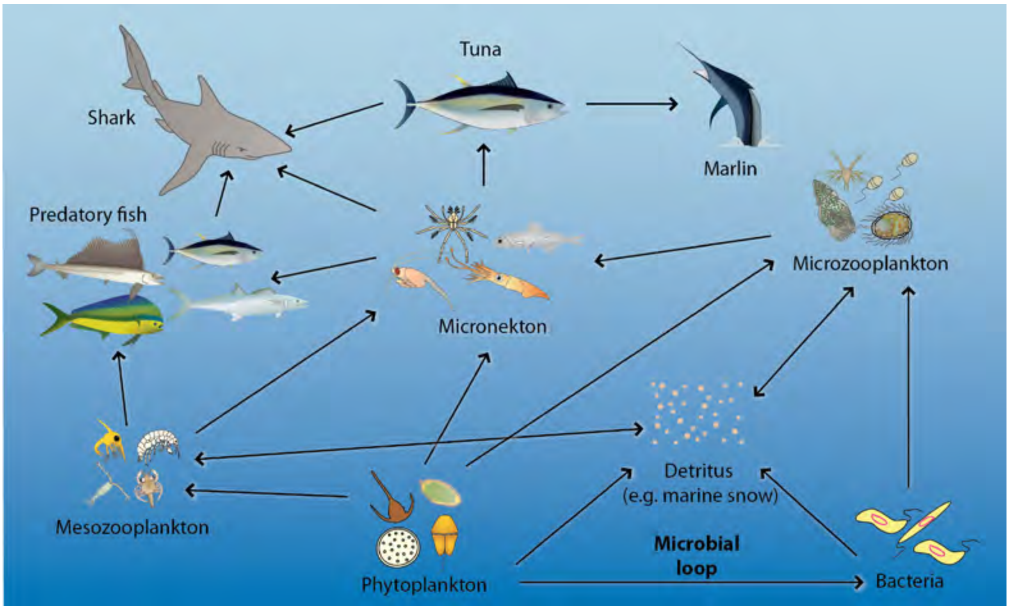


Figure 4.4 Generalised food web supporting tuna and other large pelagic fish. Note that in the lower levels of the food web, the classical and microbial pathways are linked through formation of 'marine snow' and other detritus.

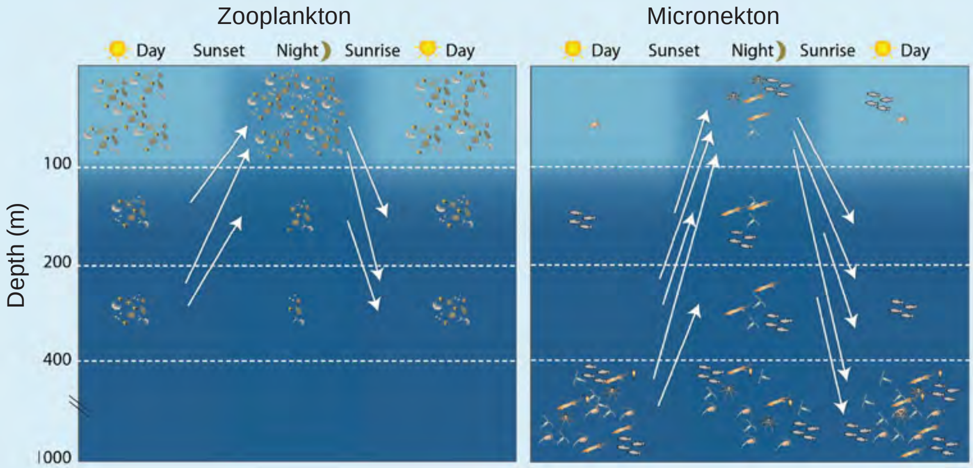
The zooplankton that graze on phytoplankton and 'marine snow', and the micronekton that consume zooplankton, are not distributed evenly in the water column. The main factors that determine their distribution are their swimming ability and the location of the nutrients supporting the phytoplankton on which they depend. Zooplankton and micronekton migrate towards the surface at dusk and to deeper water at dawn in search of food, and to avoid predators (Box 4.2). This results in different biomasses of zooplankton and micronekton within the water column during the day and night. The larger the organisms, the greater the migrations, so that diel variations in abundance of micronekton in the photic zone are greater than those of the zooplankton[21].

There is also a relationship between the minimum depth of the nutrient-rich water below the surface, i.e. the 'nutricline' associated with the thermocline (Chapter 3), and phytoplankton production and mesozooplankton biomass. For example, in the

Box 4.2 Vertical migrations of zooplankton and micronekton

Many zooplankton and micronekton migrate from deeper parts of the water column to the surface at sunset, and return at sunrise. Micronekton move to surface waters from depths of up to 1000 m, whereas zooplankton generally migrate from waters < 400 m deep (see figure below). In addition, some phytoplankton, such as dinoflagellates, make small migrations within the photic zone linked to light intensity. However, not all zooplankton and micronekton migrate as far as the photic zone at night – many species only reach the upper levels of the aphotic zone. Other zooplankton and micronekton do not migrate at all, or do so only on a small scale. These organisms are known as 'non-migrants' and their biomass can only be estimated at night, once the migrants have departed.

Both zooplankton and micronekton migrate at night to feed. The migrating zooplankton prey on phytoplankton and tiny organisms (e.g. bacteria attached to detritus and microzooplankton), which inhabit the photic zone. Micronekton migrate to feed on zooplankton living permanently in the upper layers of the water column, and those that move there at night. The migrating zooplankton and micronekton leave the photic zone at sunrise to avoid predators and seek shelter in the dim waters of the aphotic zone.



The intensity of vertical migrations to the photic zone by zooplankton is linked to the abundance of phytoplankton. Little migration of mesozooplankton (200–2000 μm in size) occurs in areas of the ocean rich in nutrients because mesozooplankton remain closely linked to phytoplankton and the associated small organisms in the photic zone during day and night. In oligotrophic areas, however, mesozooplankton are not tightly linked to phytoplankton and have a more diverse feeding regime. This results in marked differences in the night/day ratio of mesozooplankton biomass within the photic zone between nutrient-rich and nutrient-poor areas. When the nutricline is deep and net primary production (NPP) is low, the mesozooplankton night/day ratio is higher than where the nutricline is shallower (**Figure 4.5d**). The effect of changes in NPP on the intensity of vertical migrations by micronekton is still unknown.

tropical western Pacific (**Figure 4.5**), both the production of phytoplankton and the biomass of mesozooplankton increase as the depth of the nutricline decreases (**Figure 4.5**). The proportion of mesozooplankton occurring within the first 100 m of the water column also increases as nutricline depth decreases because there is greater new primary production when the nutricline is shallow. In addition, the depth of the nutricline also affects the diel vertical migrations of mesozooplankton (**Figure 4.5**). When the nutricline is deep, causing more oligotrophic conditions in surface waters, the vertical night-time movements of mesozooplankton increase, indicating that coupling between mesozooplankton and surface phytoplankton biomass is reduced in such places. Finally, the percentage contribution of small zooplankton (microzooplankton) is greater in oligotrophic areas, where the nutricline is deep. The opposite is true for the larger mesozooplankton (500–2000 μm) (**Figure 4.5**).

The deep and dark ocean below the photic zone follows different rules. Deep currents may have different directions to those at the surface, and vertical hydrological gradients are generally weaker, making exchanges easier between water masses. Nevertheless, as indicated earlier, the photic zone and deep ocean ecosystems are inter-related – organisms living at depth need to get their energy from the photic layer by vertical migrations, or by heterotrophic processes based on sinking particles, or from other organisms of the deep ocean. Even so, non-migrating species living below the photic zone at all times represent more than half of the micronekton biomass[22].

The most important part of oceanic food webs from a fisheries perspective – the link between micronekton and tuna – is still quite poorly understood. Several studies on the feeding ecology of tuna[21,23–26] have shown that their diets consist mainly of small fish, squid and crustaceans. The proportions of these three categories of micronekton vary within and between tuna species, and among life history stages, regions, time of the year and the depth preferences of the fish[25,27–29]. A full understanding of potential changes in the micronekton prey of tuna will eventually involve more specific knowledge of tuna dietary requirements at different stages of development, and for reproduction.

4.3 Physical nature of the provinces in the region

Five ecological provinces cover the area of the tropical Pacific Ocean that is the focus of this book[1]. These provinces are the Pacific Equatorial Divergence, Western Pacific Warm Pool, North Pacific Tropical Gyre, South Pacific Subtropical Gyre and Archipelagic Deep Basins (**Figure 4.6**). The borders of these provinces are generally defined by convergence zones of surface currents, and each province has a specific wind regime and vertical hydrological structure. Note that a simplified definition of the borders of provinces has been used for the modelling described in Section 4.7.

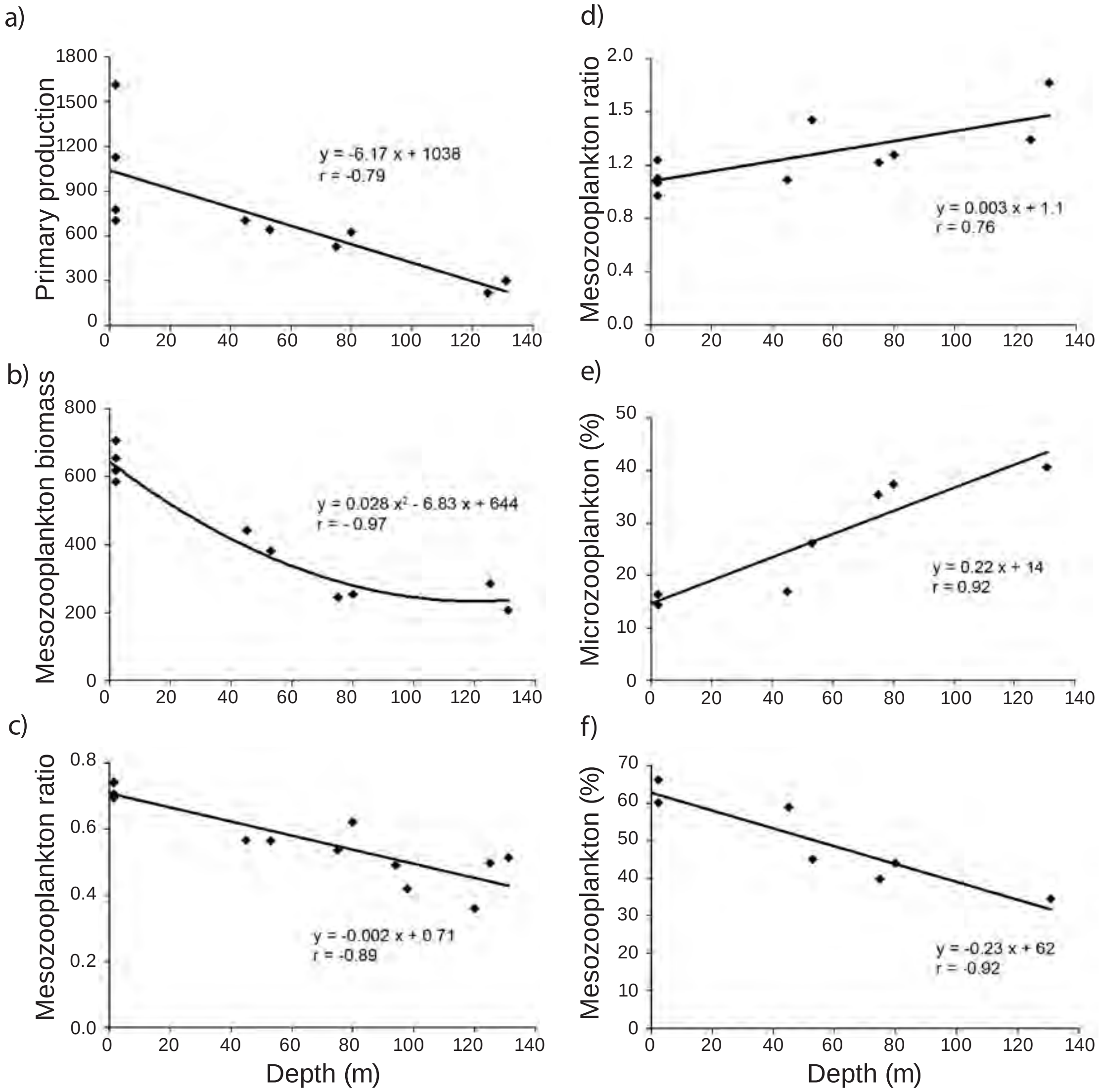


Figure 4.5 Relationships between the minimum depth of the nutricline (defined as NO_3 = 0.1 μM) and (a) primary production (mg C per m^2 per day); (b) mesozooplankton biomass (0–200 m, mg C per m^2); (c) vertical distribution of mesozooplankton (0–100 m: 0–500 m ratio); (d) diel variation in biomass of mesozooplankton within the upper 200 m of the water column (night:day ratio); (e) microzooplankton (35–200 μm) as a percentage of total zooplankton biomass; and (f) large mesozooplankton (500–2000 μm) as a percentage of total zooplankton biomass, in the tropical western Pacific Ocean. Data are from 7-day-long time-series stations in the tropical Pacific (source: Institut de Recherche pour le Développement)[75].

The locations of the Pacific Equatorial Divergence and the Western Pacific Warm Pool can also change dramatically from year to year, depending on the prevailing El Niño-Southern Oscillation (ENSO) conditions, which alters the extent of upwelling in the eastern and central equatorial Pacific and the nitrate concentrations of the surface waters[30]. The Archipelagic Deep Basins Province, as the name implies, is characterised by the occurrence of many archipelagos and seamounts. It is a patchwork of processes, on a variety of spatial scales, with varied vertical structures, driven by the way the landmasses divert surface currents and create eddies (Chapter 3). This province also receives nutrients due to runoff from the high islands located there.

As outlined in Section 4.2.1 and **Figure 4.3**, the vertical hydrological structure and associated physical processes of each province have a profound effect on the phytoplankton productivity available to supply the base of the food web. In particular, the features of each province mediate access to the new nutrients needed for primary production. Although regenerated nutrients also contribute to the growth of phytoplankton, the amount of new production is determined by inputs of nutrients from deep water to the photic zone and varies among provinces, in line with the well known correlation between primary production and the depth of the nutricline[9] (**Figure 4.5**).

The main characteristics of the five provinces are described below, based on the features of atmospheric climate in the region and the tropical Pacific Ocean described in Chapters 2 and 3.

4.3.1 Pacific Equatorial Divergence

The Pacific Equatorial Divergence (PEQD) is generated by the effects of the earth's rotation (Coriolis force) on the South Equatorial Current (SEC) in the two hemispheres (Chapter 3). As a result of this divergence, there is significant upwelling of new nutrients from below the photic zone (Case 4, **Figure 4.3**), creating the richest surface waters in the tropical Pacific. The waters of PEQD are characterised by higher salinity, partial pressure of CO_2 (pCO_2), nutrient concentrations and phytoplankton abundance (chlorophyll *a*) (**Figure 4.7**). These nutrient-rich waters span much of the equatorial Pacific and drift polewards before submerging at the convergence with the North Equatorial Counter Current (NECC) (ca. 5°N) and the South Equatorial Counter Current (SECC) (ca. 6°S–8°S) (**Figure 4.8**). At these convergences, particulate organic matter sinks and is remineralised, leading to low levels of dissolved oxygen (see Chapter 3 for more details).

Ironically, although the macronutrients (nitrate, SRP and silicate) available in PEQD exceed those needed for prolific growth of phytoplankton, primary production in this province is limited by low concentrations of iron (**Figure 4.9**). The iron in PEQD is derived from Papua New Guinea (PNG) and is delivered by the eastward-flowing New Guinea Coastal Undercurrent[31], and Equatorial Undercurrent (EUC), and possibly from thermal vents and atmospheric dust. However, the quantities are insufficient to enable all the macronutrients in PEQD to be used by phytoplankton. Consequently, PEQD acts like a buffer: regardless of the level of macronutrients, phytoplankton biomass remains relatively constant because the large reservoir of nutrients enables primary productivity to continue for several months if nutrients inputs are temporarily reduced for climate-related reasons[30]. This occurred during the strong 1982–1983 and 1997–1998 El Niño events[30,32].

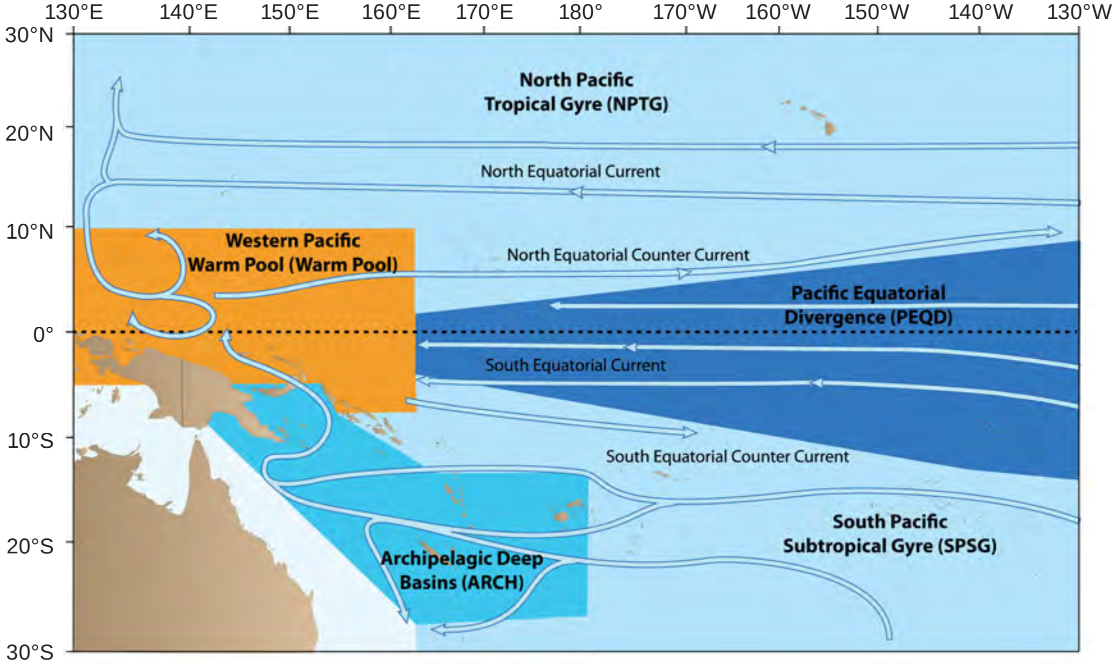


Figure 4.6 The five ecological provinces of the tropical Pacific Ocean defined by Longhurst (2006)[1], together with the major ocean currents of the region.

The surface waters of PEQD also drift to the west until they converge with the Western Pacific Warm Pool (see below) (**Figure 4.8**). The border between PEQD and the Warm Pool is marked by a clear 'front' in salinity, pCO_2, chlorophyll *a* and zooplankton[33]. The convergence zone between PEQD and the Warm Pool changes due to variation in the strength and longitudinal extension of the SEC between seasons and among years, in response to ENSO events (Chapter 3). During strong La Niña episodes, the front reaches the far western side of the equatorial Pacific, causing a great reduction in the size of the Warm Pool. During El Niño events, the front moves to the east and may reach the Galapagos Islands, causing PEQD to disappear[32]. Such fluctuations of the surface area of PEQD and the Warm Pool can be seen by ocean colour imagery[34] and predicted from climatic indices, such as the Southern Oscillation Index (SOI)[35]. From 1980 to 2000, the mean longitude of the border between PEQD and the Warm Pool was 178°W[30], almost on the dateline.

4.3.2 Western Pacific Warm Pool

In contrast to PEQD, the surface waters of the Western Pacific Warm Pool (Warm Pool) have a significantly lower salinity due to high rainfall (Chapter 2), and are nutrient-depleted because there is no upwelling in this province. The thermocline in the Warm Pool is relatively deep (~ 80 m) under average climatic conditions, being located close to the lower limit of the photic zone (Case 1, **Figure 4.3**). The thermocline has a strong temperature gradient (**Figure 4.7**), which forms a considerable barrier to the transfer of nutrients to the surface layer. This situation changes markedly during El Niño episodes, when there is a shoaling of the thermocline to a depth of ~ 40 m (Case 2, **Figure 4.3**). When this occurs, there is an increase in primary production, stimulated by the supply of more new nutrients to the photic zone below the thermocline (**Figures 4.7**). Despite the fact that the Warm Pool is low in nutrients, the greatest catches of skipjack and yellowfin tuna are often made in this part of the region (see Section 4.4.2 and Chapter 8 for a possible explanation for this conundrum).

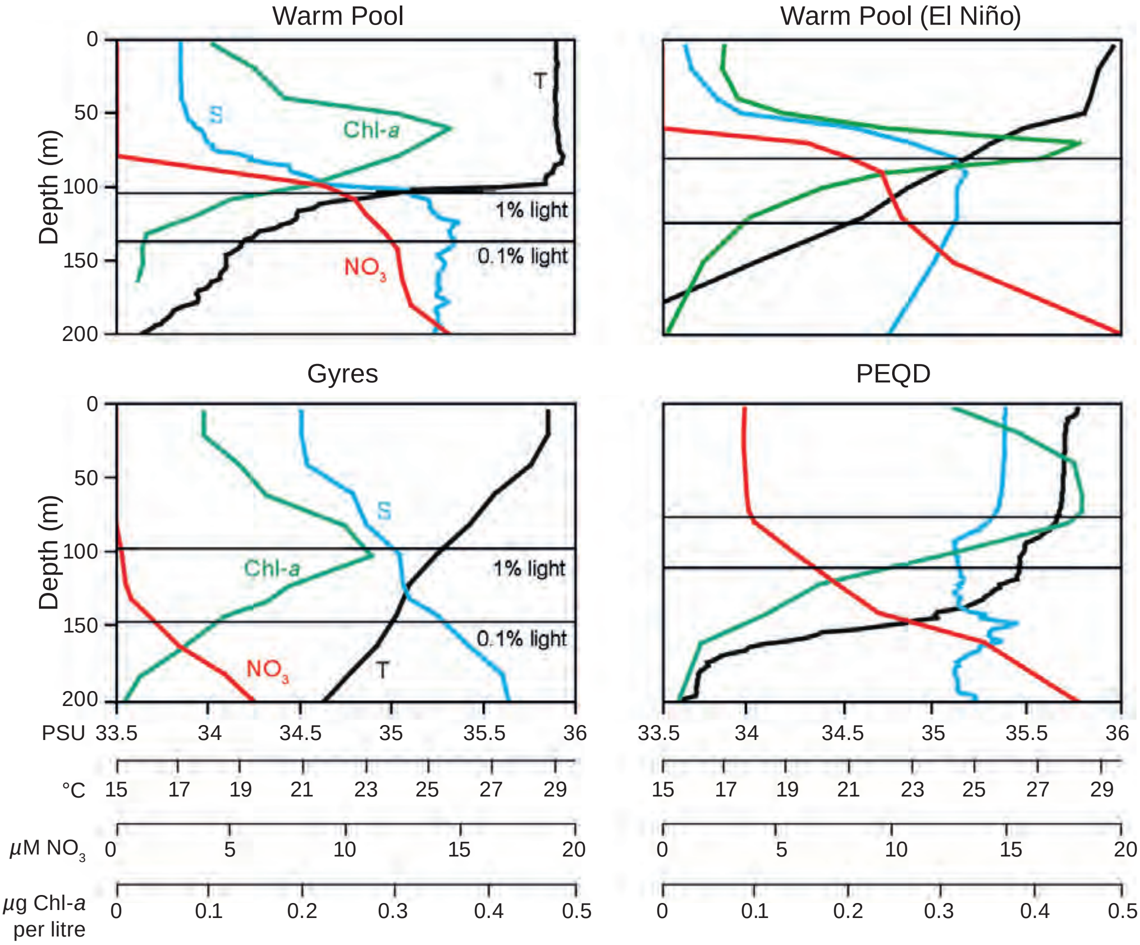


Figure 4.7 Observed vertical profiles of temperature (T in °C), salinity (S in PSU), nitrate concentration (NO_3) and chlorophyll *a* (Chl-*a*) to a depth of 200 m from different provinces to illustrate concepts shown on Figure 4.3. The Warm Pool corresponds to Case 1, the Warm Pool (El Niño) is Case 2, the two Gyres (NPTG and SPSG) are Case 3 and the Pacific Equatorial Divergence (PEQD) is Case 4 on Figure 4.3. Note the more or less steep thermal and salinity gradients between provinces, the associated levels of NO_3 and the depths of maximum chlorophyll *a*. Two different light levels, 1.0% and 0.1%, are presented to indicate the lower limits of the photic zone (source: Institut de Recherche pour le Développement)[75].

4.3.3 North Pacific Tropical Gyre and South Pacific Subtropical Gyre

On both sides of the equatorial band, the large atmospheric anticyclones in the northern and southern subtropical Pacific generate oceanic gyres (Chapter 3). The provinces covered by these large gyres are known as the North Pacific Tropical Gyre (NPTG) (also known as the North Pacific Subtropical Gyre) and the South Pacific Subtropical Gyre (SPSG) (**Figure 4.6**). They are characterised by a very deep but weak thermocline (**Figure 4.7**), which allows some nutrient inputs to the photic zone from deep water through mixing and diffusion (Case 3, **Figure 4.3**). However, during summer, a strong and shallower (40–60 m) thermocline is superimposed on the main thermocline, due to the increase in solar radiation, creating a great barrier to nutrient inputs (Case 1, **Figure 4.3**). This leads to lower primary production in the upper part of the photic zone in summer compared with the rest of the year.

4.3.4 Archipelagic Deep Basins

The western part of SPSG is characterised by a large number of islands and shallow seamounts[36], which alternate with oceanic basins. For this reason, it is referred to as the Archipelagic Deep Basins province (ARCH) (**Figure 4.6**). In this province, availability of nutrients from runoff can be significant in the vicinity of high islands. In addition, current regimes are more complex due to the way islands, archipelagos or seamounts divert oceanic circulation through a range of mesoscale processes (Chapter 3). These processes include upwelling or downwelling, cyclonic or anticyclonic eddies in the lee of the islands, frontal zones and an increase of amplitude in internal waves (Chapter 3). The result is that ARCH is a mosaic of surface waters with different characteristics, in contrast to the other provinces, which are generally dominated by more stable large-scale processes.

4.4 Structure and variability of food webs in each province

4.4.1 Pacific Equatorial Divergence

The biological features of the food web in PEQD are relatively stable along the equatorial band (1°N–1°S) from east to west[30]. However, marked variations occur in relation to the maturation of the ecosystem as waters from PEQD move polewards (**Figure 4.8**), with an increasing contribution of regenerated production to total phytoplankton production[37]. Nevertheless, the ratio between phytoplankton and heterotrophs (bacteria and zooplankton) remains relatively constant[38], thus indicating steady state (or balanced) ecosystems.

Most of the food web in PEQD is concentrated in the upper 100 m of the water column because of the availability of high levels of nutrients within the photic zone (**Figure 4.10a**). Another important feature of this food web is the prominence at all depths of 'marine snow' (particles > 500 μm), studied only in this province[39]. While the nutritional value of marine snow is poorly understood, it may provide zooplankton with a significant source of particulate carbon[39]. Some of the relatively large marine snow particles are produced at the equator and drift to the convergence zone with the Warm Pool (**Figure 4.8**), where they sink and return to the equator due to deep circulation, via the 'latitudinal conveyor belt'[39]. Transfer of phytoplankton and other particles also occurs between PEQD and the Warm Pool (Section 4.4.2).

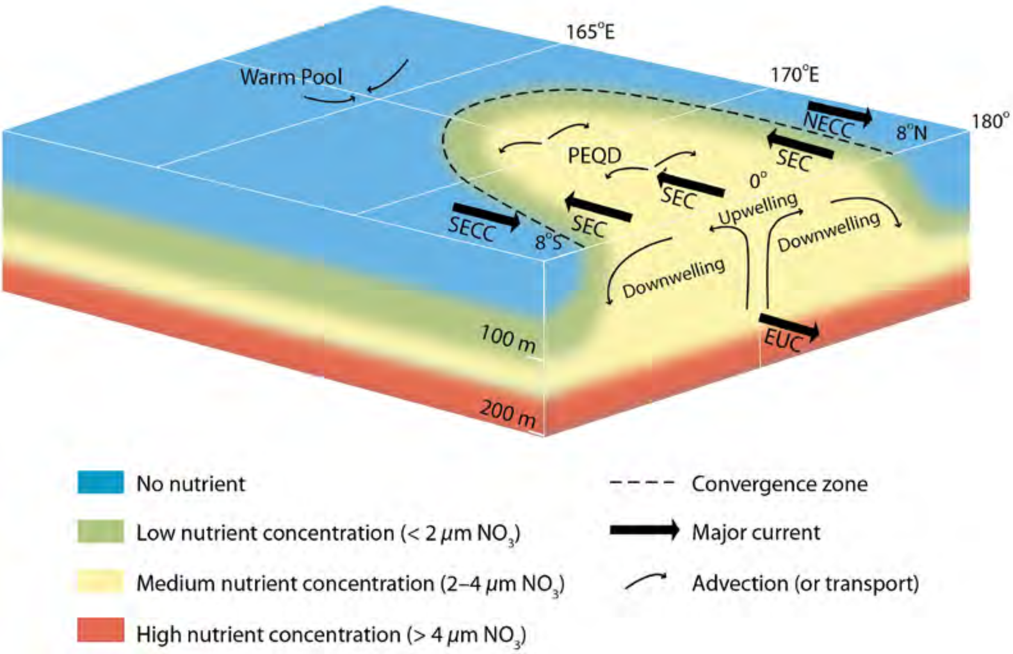


Figure 4.8 Upwelling in Pacific Equatorial Divergence (PEQD) province. Nutrient-rich waters are brought to the surface from the Equatorial Undercurrent (EUC) and carried to the north and south by upwelling. Eventually, they plunge at the convergences between the South Equatorial Current (SEC) and South Equatorial Counter Current (SECC), and with the SEC and the North Equatorial Counter Current (NECC). The SEC also carries the upwelled waters to the west until they converge with the Warm Pool, at a salinity front, a region with distinct concentrations of dissolved carbon dioxide, nutrients and phytoplankton. Based on satellite images and data from the EBENE cruise along 180° in 1996 (source: Eldin and Rodier 2003)[126].

The ecosystem within PEQD is relatively stable due to iron limitation (Section 4.3.1). As a result, interannual changes, as depicted by the SOI, affect the overall surface area of PEQD but not the structure of its ecosystem. For example, when the SOI is positive (La Niña), the PEQD ecosystem remains the same from the Galapagos Islands to its border with the Warm Pool, west of the dateline. However, tropical instability waves (TIWs) can cause temporary spatial rearrangements of hydrography and planktonic biomasses[30], mainly east of the dateline and at the northern convergence between SEC and NECC (**Figure 4.8**).

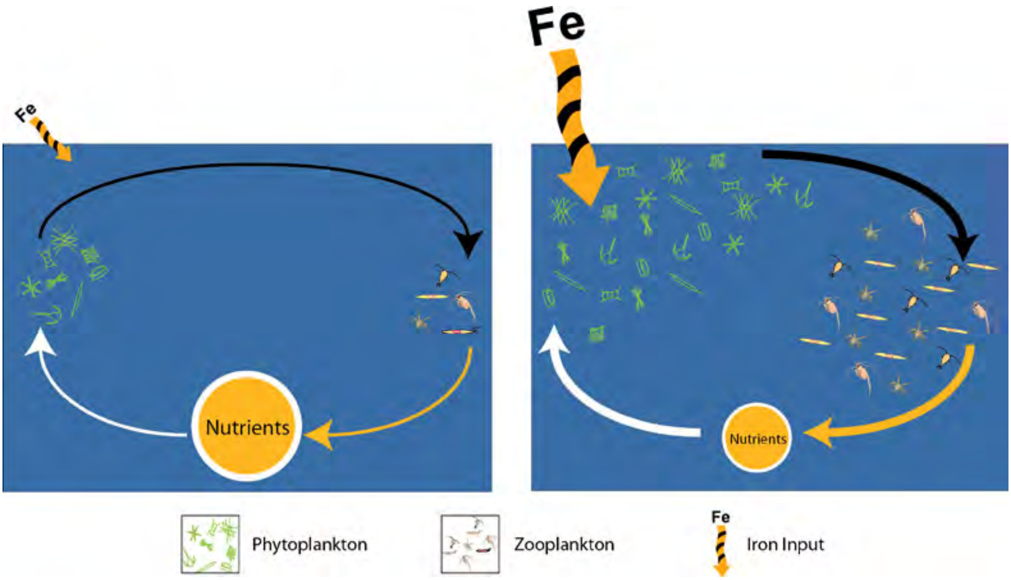


Figure 4.9 Limitation of phytoplankton production due to low concentrations of iron (Fe) and subsequent effects on zooplankton. This situation occurs in the Pacific Equatorial Divergence province, where iron limitation occurs in the presence of significant levels of macronutrients. Such limitation, combined with a balance between prey and their consumers, characterises the 'High Nutrient-Low Chlorophyll' (HNLC) systems of the world's oceans.

4.4.2 Western Pacific Warm Pool

During average climatic conditions, the biomass of both phytoplankton and heterotrophs in the photic zone of the Warm Pool is only half that in PEQD (**Figure 4.10b**). The biomass of heterotrophic bacteria and microzooplankton in the deeper layers remains unknown. However, an intriguing feature of the Warm Pool is that the composition of phytoplankton found at the base of its mixed layer is similar to that of the upper water column in PEQD[12]. This suggests that there may be some continuity between the deeper layer of the Warm Pool and the surface layer of PEQD in the 'transition zone' that stretches across ~ 15 degrees of longitude (1700 km) to the west of the front between the two provinces.

If the same continuity applies to organic matter synthesised in PEQD, this would mean bacteria and detritivorous zooplankton would be available in the Warm Pool to support the larger zooplankton and micronekton that provide prey for tuna. Such a mechanism would explain the relatively high biomass of micronekton in the Warm Pool (**Figure 4.10b**), and the fact that tuna are often abundant there (Chapter 8). At this stage, however, we are lacking data on processes at the front between PEQD and the Warm Pool, and the 'transition' zone between the two provinces that frequently undergoes shifts in longitude (Chapter 3).

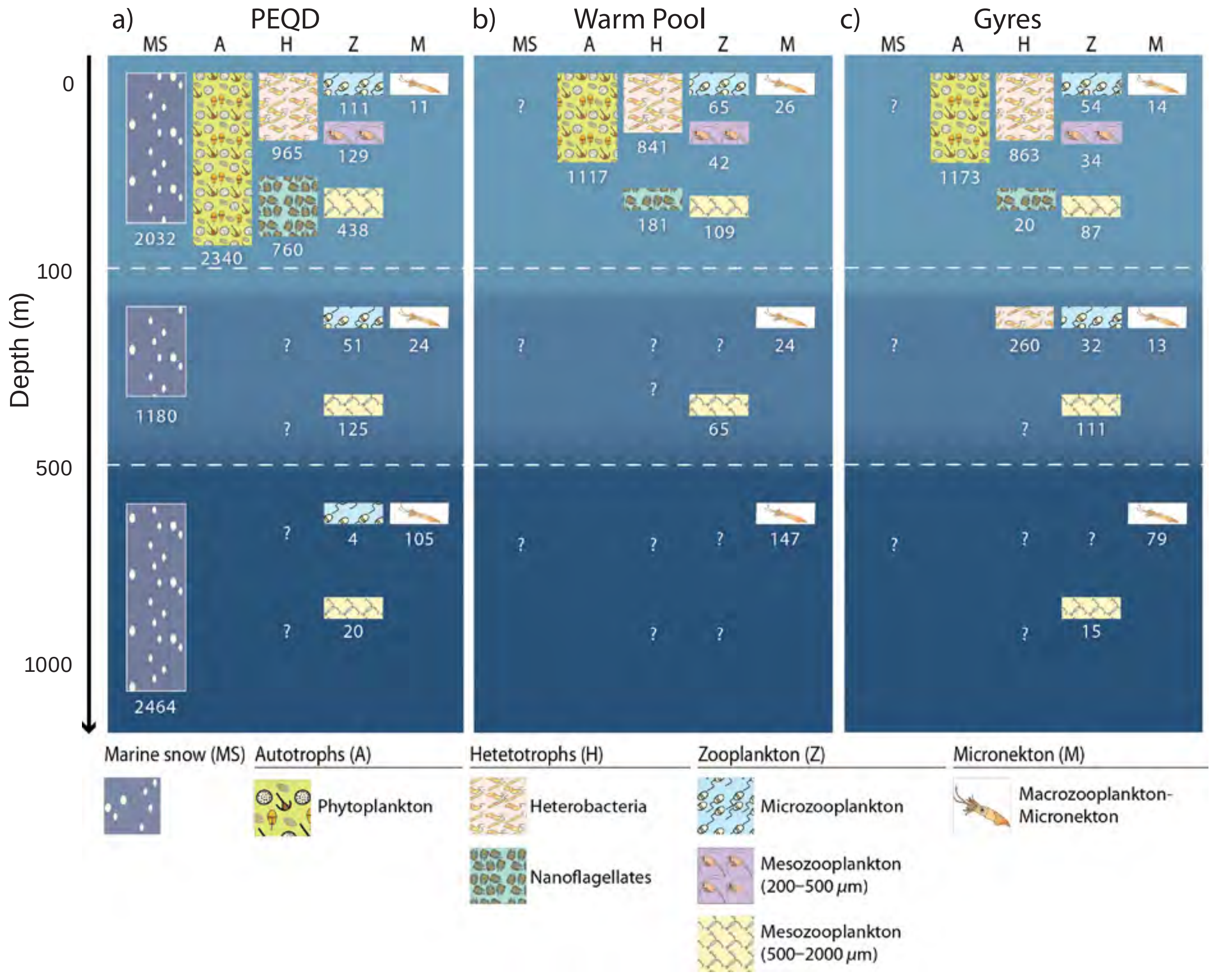


Figure 4.10 Structure of the food webs in (a) the Pacific Equatorial Divergence province along the equator; (b) the Warm Pool along the equator; and (c) the North Pacific Tropical Gyre and South Pacific Subtropical Gyre. Boxes and the figure below them indicate the mean daily biomass of the different components of the ecosystem (in mg carbon per m^2), i.e. taking diel vertical migrations into account. The mesozooplankton biomass below the photic zone (100 m) refers to the sum of the two size fractions (200–500 and 500–2000 μm). ? = no data available (source: Legand et al. 1972, Brown et al. 2003, Gorsky et al. 2003, Hidaka et al. 2003, Ishizaka et al. 1997, Le Borgne et al. 2003, Roman et al. 1995, Le Borgne and Rodier 1997, Le Borgne and Landry 2003)[22,38,39,70,104,105,127–129].

Interannual variations in the vertical structure of the Warm Pool due to ENSO (Section 4.3.2) have a major effect on the food web. During El Niño episodes, the shallower thermocline results in 7.7 times more new production[40]. Consequently, total primary production more than doubles[41] and the biomass of zooplankton is 1.5 times higher. When combined with the increase in the surface area of the Warm Pool during El Niño, the overall productivity of this province is enhanced significantly. Indeed, the increased productivity is probably greater than indicated on the basis of ocean colour imagery because remote sensing of the surface layer does not detect the important components of the food web located in the deeper layers.

4.4.3 North Pacific Tropical Gyre and South Pacific Subtropical Gyre

Based on the concentrations of chlorophyll *a* in surface waters evident in ocean colour images, NPTG and SPSG appear to be among the largest and most oligotrophic oceanic provinces in the world[42]. However, as described for the Warm Pool, this view needs to be tempered to some extent because important biological processes take place much deeper than indicated by remote sensing of the surface layer. Plankton biomass is at a minimum in the centres of these gyres[43]. Overall, the biomass of heterotrophic bacteria and phytoplankton in the photic zone is similar to the biomass in the Warm Pool, although it is significantly lower for microzooplankton, particularly nanoflagellates (**Figure 4.10c**). Reductions in microzooplankton and mesozooplankton for a similar biomass of phytoplankton indicate that there are more trophic links between the phytoplankton and the zooplankton in NPTG and SPSG than in the Warm Pool. This is because energy losses occur during each transfer from prey to consumers, with the result that complex food webs, with more trophic links, are less efficient in producing zooplankton and, above all, top predators, from a given biomass of phytoplankton.

The nutrient-poor nature of these two gyres is due to their vertical structure. Both gyres are regions of downwelling, so that the only way for nutrients to reach the photic zone is by mixing of the deeper nutrient-rich layers with shallower waters, and by eddy diffusion. Moreover, because nitrate concentrations in the deep layers are ~ 3 times lower than in the equatorial area (PEQD and Warm Pool) (**Figure 4.7**), the transfers of nutrients are correspondingly small when mixing and diffusion occur.

The low rate of nutrient transfer to the surface waters of the gyres is reduced further by the formation of a marked thermocline during summer (Section 4.3.3), leading to a decrease in phytoplankton biomass in SPSG[1]. However, this summer minimum may be masked by development of *Trichodesmium* blooms in the surface layer of the southwestern Pacific[45]. In addition to these seasonal fluctuations in the food webs of the gyres, there are similar interannual variations in phytoplankton[44,46] and the biomass of micronektonic fish[47] in NPTG.

4.4.4 Archipelagic Deep Basins

The food webs for tuna and other large pelagic fish in ARCH are based on two sources of nutrients: runoff from high islands, and the mesoscale physical processes described in Section 4.3.4. They also rely on biological linkages between species associated with islands and tuna in the open ocean.

High islands discharge large quantities of sediment and nutrients into the surrounding ocean (Chapter 7), leading to a gradient of increased biological productivity from inshore to offshore[48,49]. In contrast, productivity in the open ocean close to coral atolls and banks is rarely enhanced[50,51] because these low-lying islands release very few sediments and nutrients, with the exception of those from aquifers[52]. Temporal variations in sediment and nutrient inputs from high islands are linked to seasonal and interannual patterns of rainfall (Chapters 2 and 7). Higher food web biomass should, therefore, occur around the islands and archipelagos during the rainy season, i.e. in summer. Indeed, a summer maximum has been observed from ocean colour imagery, attributed to *Trichodesmium* blooms in the New Caledonia and Vanuatu archipelagos[53]. No effect has been observed on subsurface planktonic biomass, however, particularly at secondary and tertiary levels[50].

Photo : Chris Roelfsema

A *Trichodesmium* bloom

Among the mesoscale processes, eddies are the most common. Cyclonic eddies, which bring more nutrients into the photic zone (Chapter 3), have some of the greatest effects on primary productivity. Anticyclonic eddies, however, suppress upward mixing of nutrients, as described earlier for NPTG and SPSG. Although they are not within ARCH, the cyclonic eddies in the Hawaiian archipelago provide a good example of the benefits of these particular mesoscale processes – they uplift nutrient-rich waters by 30 to 140 m, increasing chlorophyll *a* concentration by 1.1 to 5 times[54]. Corresponding variations also occur for other components of the food web, such as microzooplankton[55] and mesozooplankton[56].

Upwellings induced by the divergence of currents around island barrier reefs or coastal zones also deliver more nutrients to supply food webs in some parts of ARCH. This has been observed in southwestern New Caledonia[57], although enrichment of the surface layer there in summer is limited because nutrient concentrations in the source water are very low[58].

Concentrations of chlorophyll *a* and zooplankton may be higher just above seamounts due to other mesoscale processes[59,60], leading to local increases in nutrients in surface waters. Such physical processes may be visible in oceanographic data as a 'doming' of the hydrographical structure[61]. Other processes, such as changes in current regimes around seamounts, can also lead to differences in the abundance and behaviour of micronekton between the seamount and the surrounding ocean[62,63]. In addition, increased amplitude of internal waves in shallow water affects the vertical distribution of phytoplankton[64] and can cause aggregation of this primary food source.

The linkages between islands and continental slopes, and food webs for tuna, can occur via the planktonic phase of coral reef fish, and via micronekton. Postlarvae originating from populations of coral reef fish and invertebrates are often entrained in eddies while they develop to the stage where they are competent to settle on reefs[65] (Chapter 9), and have been recorded from the stomach contents of tuna[66]. Mesopelagic micronekton have a distinct species composition at depths of 400 to 700 m in the vicinity of islands and continental slopes[67,68], indicating that these micronekton represent a distinct source of food for tuna.

The high spatial and temporal variability in primary production makes it impractical to present a 'typical' structure for food webs in ARCH. The variation of food webs across the province is illustrated by changes in phytoplankton and mesozooplankton collected at 19 sites near New Caledonia (**Figure 4.11**). Phytoplankton biomass ranged from 16 to 35 mg chlorophyll *a* units per m² for the photic zone (0–120 m), and zooplankton biomass varied from 190 to 330 mg carbon (C) per m² for the upper 200 m of the water column. The lower values approximate those from the most oligotrophic regions of the tropical Pacific Ocean, whereas the higher values are slightly lower than in PEQD. No offshore-inshore gradient is apparent[50], a pattern that is also true for the macrozooplankton and micronekton near New Caledonia[51].

4.4.5 Overview of differences in food webs among provinces

Some simple comparisons help to highlight the main differences in the food webs for tuna among the five provinces. The ratio of phytoplankton biomass to mesozooplankton biomass is an indicator of the complexity of a food web: food webs based on large phytoplankton supported by 'new' nutrients have fewer trophic links because the herbivores that feed on this phytoplankton are larger. In particular, there is a direct link, or only one intermediate trophic link, between phytoplankton and mesozooplankton. As a result, the ratio between the biomass of phytoplankton and zooplankton is rather low. Based on data in **Figure 4.10**, this ratio varies from 4.1 in PEQD, to 7.4 in the Warm Pool and to 9.7 for the gyres, indicating the existence of more trophic links between phytoplankton and mesozooplankton in the oligotrophic ecosystems (Warm Pool and gyres) than in PEQD. For the reasons explained in Section 4.4.4, the ratio varies greatly within ARCH. In short, a greater biomass of phytoplankton is needed for a given mesozooplankton biomass in oligotrophic systems.

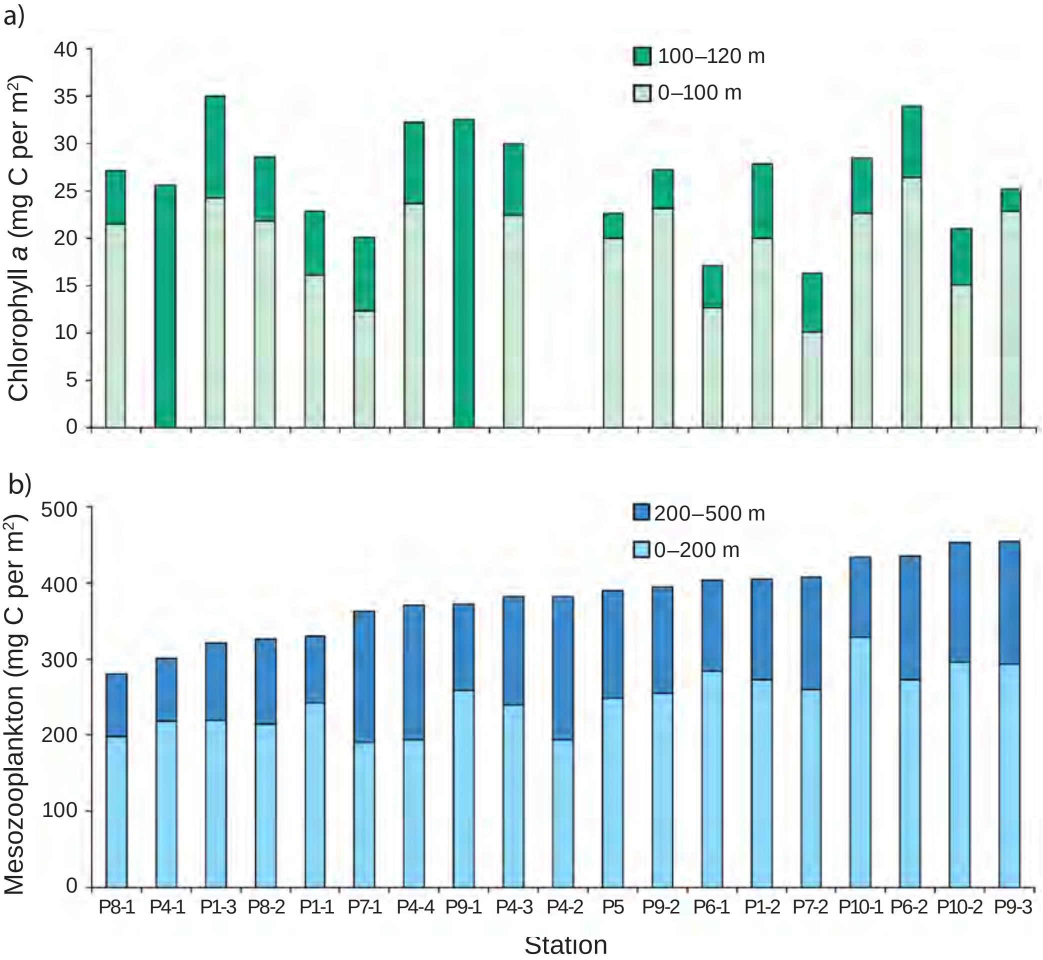


Figure 4.11 Biomass of (a) phytoplankton and (b) mesozooplankton at 19 oceanographic stations in New Caledonia. Sampling at these stations lasted for at least 24 hours to account for any day/night variation in abundance (source: Institut de Recherche pour le Développement)[75].

Interestingly, ratios between the total biomass of primary producers and total heterotrophic biomass are very close in the different provinces (0.9 in the Warm Pool, 1.0 in PEQD and 1.1 in the gyres). This is because a given phytoplankton biomass supports about the same heterotrophic biomass. The composition of the heterotrophs may change, however, with more heterotrophic bacteria and nanozooplankton occurring in oligotrophic ecosystems. The food webs in all provinces, except ARCH, are in a relatively steady state on short- to mid-term time scales (weekly to seasonal periods). In ARCH, short-term physical forcing due to the range of mesoscale processes, leads to an unbalanced ecosystem, with variable ratios between phytoplankton and heterotrophs. While nutrient inputs to the photic zone are more or less constant in the other provinces, they are quite variable over time within ARCH, creating a time lag of several days between the inputs and the subsequent responses of primary productivity and grazing by zooplankton. This means that there is often little correlation between the various levels of the food web in ARCH at any given time.

Comparisons between the deep and surface layers also help to distinguish the food webs from different provinces. For example, the biomass of mesozooplankton down to a depth of 1000 m in PEQD is 3.3 times greater than in the gyres, and the biomass of micronekton is 1.9 times greater. The reason is that most of the mesozooplankton is closely linked to the photic zone in PEQD, whereas part of the micronekton lives permanently at a depth of 500 to 1000 m and depends on different trophic pathways. Thus, only 16% of the micronekton biomass within the depth range 0 to 1000 m is in the photic zone at night in PEQD[22], whereas 40% occurs there in the gyres[69], 44% in ARCH[51] and 50% in the Warm Pool[70]. The taxonomic composition of micronekton is consistent among provinces, however, and includes fish, squid, and carid, sergestid, penaeid and euphausiid shrimp.

It is not yet possible to identify relationships between micronekton biomass and mesozooplankton biomass among provinces, although it appears that ratios between the two biomasses vary considerably, ie 0.18 (PEQD), 0.91 (Warm Pool) and 0.38 (SPSG and NPTG). Several sources of variability need to be quantified to estimate these ratios more accurately. These include (1) the influence of lateral transport of micronekton between provinces, particularly between PEQD and the Warm Pool; (2) the time lag and spatial drift affecting phytoplankton, mesozooplankton and micronekton biomasses; and (3) the differences in complexity of food webs among provinces, especially the amount of micronekton and mesozooplankton derived from a given biomass of phytoplankton.

4.5 Critical requirements for maintenance of food webs in each province

The food web in each province operates differently – it is constrained by lack of macronutrients in the Warm Pool and the gyres, and by iron and, to a lesser extent, by silicate in PEQD[11] (Section 4.3.1). We briefly reiterate these constraints here, and indicate the factors most likely to affect the productivity of the food webs in each province if they are altered by climate change.

4.5.1 Macronutrients and micronutrients

Major nutrients (or macronutrients) are the main limiting factor in the Warm Pool, NPTG, SPSG, and ARCH. Nitrogen in the form of ammonium, urea or nitrate is particularly important, except for diazotrophic organisms like *Trichodesmium* (Section 4.2.2). Availability of new nitrogen, mediated by the vertical structure of the water column, and processes like upwelling and eddies, or mesoscale processes in the case of ARCH, determine the diversity and richness of the food webs for tuna in these provinces. Diazotrophs, on the other hand, require a different mix of elements, including phosphorus and iron[15]. Whether phosphorus or iron is the primary limiting element depends on the area considered. For example, only phosphorus limits diazotrophy in New Caledonia at the end of summer because iron concentrations are high then due to runoff[71].

Photos: Céline Barré

Sampling zooplankton and filtering phytoplankton

In PEQD, iron is the limiting factor. The importance of iron limitation in PEQD led to two mesoscale iron experiments (IronEx I and II) in the equatorial Pacific in October 1993 and May–June 1995[72]. During IronEx II, infusion of iron was followed by a bloom of phytoplankton and, subsequently, a higher biomass of microzooplankton[73]. Mesozooplankton did not respond within the duration of the experimental observations, however, possibly due to a lack of viable young or an abundance of predators[74]. The consequences of iron enrichment on oceanic food webs are still poorly understood, in part because of the small spatial scale of experiments conducted to date.

4.5.2 Temperature

Adequate water temperatures are needed for the efficient metabolism of planktonic organisms. Temperature determines the turnover rates of organisms living in the mixed layer. The warm water temperatures in the tropical Pacific result in short turnover times for phytoplankton biomass in the photic zone: 1.7 days in PEQD, 1.6 to 4.4 days in the Warm Pool and 3.8 days in the gyres[75]. At the top of the food web, all the tuna species have a wide but variable thermal tolerance (Chapter 8), allowing them to occupy a range of depths in much of the area covered by the five provinces. However, the micronekton on which tuna feed are less mobile and/or more restricted physiologically. They are potentially more susceptible to changes in physical conditions resulting from ocean warming. Overall, however, changes in temperature are likely to have their greatest influence on food webs for tuna through their effects on the vertical structure of the water column (i.e. stratification), rather than directly on planktonic organisms. After all, most zooplankton and micronekton are able to cope with drastic thermal changes during vertical migrations (Box 4.2).

4.5.3 Dissolved oxygen

Low concentrations of dissolved oxygen, such as those found in the equatorial convergence zones (**Figure 4.8**), are a limiting factor for aerobic organisms, particularly micronekton. The low biomass of micronekton in PEQD, compared with areas located to the south, may be due to low oxygen concentrations beneath the photic zone of this province, despite the higher productivity within it[69]. However, some mesopelagic species can tolerate waters with very low oxygen concentrations during their diel cycle, and some of them actually reside within these areas, e.g. copepods in the genus *Lucicutia*[76].

4.5.4 Solar radiation

Solar radiation is absorbed and scattered in the ocean and light, therefore, declines exponentially with depth. Phytoplankton cells have the potential to photo-acclimate, having a lower pigment content near the sea surface. Conversely, phytoplankton found at the lower limit of the photic zone have a higher pigment content per cell, which contributes to the deep chlorophyll maximum (DCM), found at ~ 50 m in PEQD (**Figure 4.7**) – note that this is not a biomass maximum nor a production maximum in most instances. Despite ample nutrients, maximum productivity of phytoplankton in PEQD occurs at 30 m and not at the surface due to photo-inhibition. Because light intensity decreases exponentially with depth, spatial and temporal variations in incident solar energy can be expected to affect the vertical distributions of phytoplankton maxima only very slightly. The effects of solar radiation are not as profound for some zooplankton. For example, the cnidarian *Velella velella*, the mollusc *Janthina* sp. and pontellid copepods have developed blue protective pigments to enable them to live at the surface.

4.5.5 Carbon dioxide

The partial pressure of carbon dioxide (pCO_2) in the ocean has direct and indirect effects on pelagic organisms. Increasing pCO_2 may also increase diazotrophy, because there is some evidence that growth of *Trichodesmium* increases at higher concentrations of carbon[77]. This increase in diazotrophy, provided iron and SRP limitations are alleviated, is expected to change the structure of the ecosystem, particularly the relative abundance and species composition of grazers and microbial populations.

Although the nature of these changes is unknown, it is certain that changes in pCO_2 will alter biological communities[77]. An increase in pCO_2 is also likely to exacerbate the effects of low oxygen concentrations on organisms living in the deep ocean[78].

Phytoplankton (haptophytes) and zooplankton (e.g. pteropods) that use calcium carbonate to build their shells also depend on pCO_2 in the ocean staying within a certain range. If it increases, the pH of the ocean decreases, limiting the availability of carbonate ions $[CO_3^{2-}]$ for constructing shells[79] (Chapter 3). However, the effects of ocean acidification are complex because pelagic organisms have to face other environmental changes simultaneously (temperature, nutrient supply) and ecosystem constraints (competition, grazing pressure).

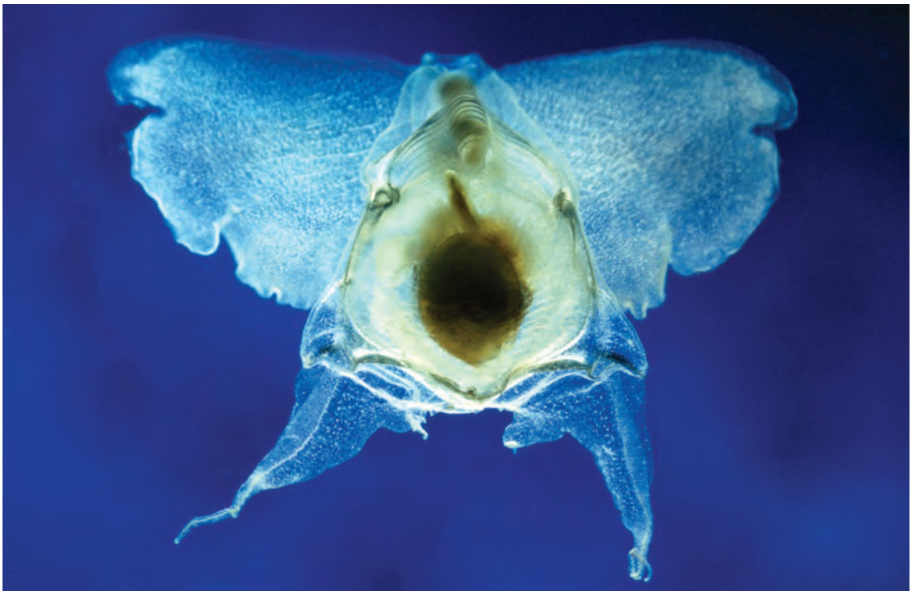


Photo: Photoshot/SuperStock

Pteropod from the tropical Pacific

4.6 Recent observed changes in the food webs of provinces

The extent of recent changes to the food webs in each province are relatively poorly known because there have been few long-term observations of oceanic ecosystems in the region. Instead, far more emphasis has been placed on monitoring the physical features of the tropical Pacific Ocean. Most of our present knowledge comes from (1) satellite remote sensing of phytoplankton biomass based on pigments in the surface layer down to a depth of 20 m in oligotrophic regions; and (2) a single station in NPTG, the Hawaii Ocean Time-Series (HOT), outside our main area of interest. Therefore, we have had to make some inferences from more global information.

Ocean colour satellite imagery from two periods, 1979 to 1986 and 1997 to 2000, shows that surface chlorophyll *a* concentrations in the oligotrophic oceans of the world decreased by 8% from the early 1980s to the late 1990s[80]. More recently, a 9-year time-series of ocean colour data (1998–2006) shows that ocean gyres with chlorophyll *a* concentrations < 0.07 mg per m^3 appear to be expanding rapidly[42]. The area of these gyres increased by 2.2% per year over this period in the northern Pacific, and by 1.4% in the southern Pacific. There was also a corresponding increase in sea surface temperature of the gyres in the northern and southern Pacific of 0.014°C per year and 0.02°C per year, respectively. This lends support to the hypothesis that increased stratification leads to lower primary productivity (Section 4.3.3 and Chapter 3). There is also some evidence that abundance of zooplankton at the surface has declined in the tropical north Atlantic[81].

Samples taken throughout the water column at the HOT station do not reflect the global trend that the planktonic biomass appears to be decreasing. Rather, the data show that primary production increased by 50% in the last 20 years[82] as a result of the influence of ENSO and the Pacific Decadal Oscillation (PDO) (Chapter 2) on upper ocean stratification and the delivery of nutrients. However, there has been an increase in chlorophyll *b*, suggesting a shift towards an ecosystem dominated by cyanobacteria. The biomass of mesozooplankton also increased between 1994 and 2006 (**Figure 4.12**). Although the length of the time-series from Hawaii is still relatively short, it indicates that enhanced stratification and decreased nutrient availability has resulted in selection for N_2-fixing cyanobacteria (including *Trichodesmium*), and a shift to conditions where phosphorus or iron limit the growth of phytoplankton. These regime shifts are linked to changes in the PDO sign, independently of trends, which happen on a much longer time-scale (50–100 years).

Changes in the extent of low-oxygen zones at intermediate depths have also occurred in the last 50 years in tropical oceans, including the eastern equatorial Pacific (Chapter 3). Although this has obvious implications for micronekton, no comparisons of the vertical distributions over time have been made for this important source of prey for tuna.

4.7 Projected changes to the environment and food webs of provinces

Except for one modelling study[83], information about expected changes to the main features of the tropical Pacific Ocean is not always available at the level of the ecological provinces (Chapter 3). To help assess the vulnerability of the food webs in each province to climate change, we modelled the projected effects of the B1 and A2 emissions scenarios for 2035 and 2100 on the surface area, mixed layer depth and other physical and chemical features of all five provinces. Projections were made for the range of physical and chemical variables from the IPSL coupled 3-D atmosphere-ocean climate model (also used in Chapter 8 and included in the ensemble of models used in Chapter 3). Latitude ranges and concentrations of nutrients were used to define the boundaries of provinces in the model (**Table 4.2**).

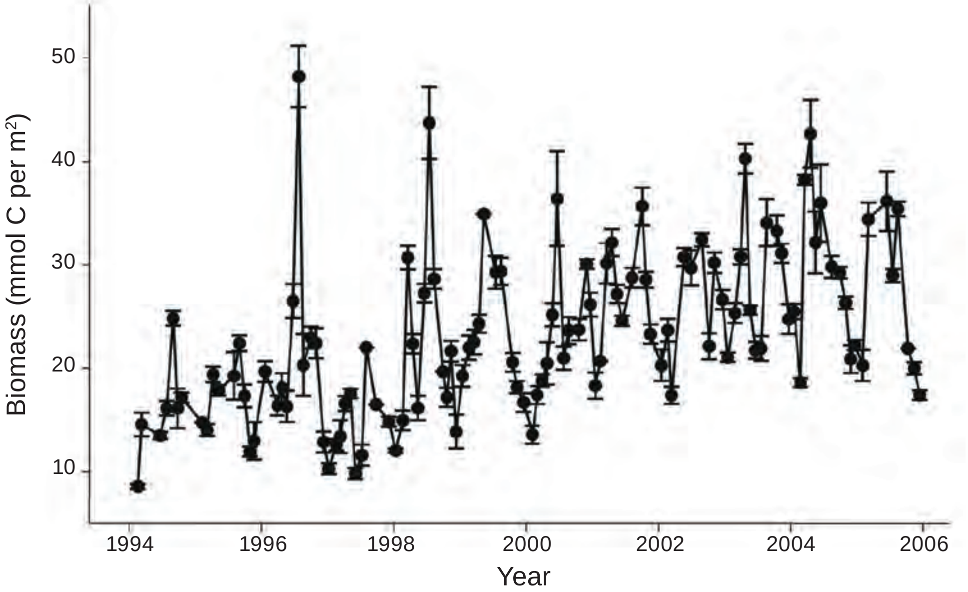


Figure 4.12 Variation in the biomass of mesozooplankton at the Hawaii Ocean Time-series (HOT) station between 1994 and 2006, showing an increasing trend (source: www.hahana.soest.hawaii.edu/hot/hot-dogs/mseries.html, Decima et al. 2010)[130].

The projected changes to the physical and chemical nature of each province were then incorporated into a biogeochemical model (Pelagic Interaction Scheme for Carbon and Ecosystem Studies, PISCES)[84] to assess the likely responses of phytoplankton and zooplankton. Forecasting changes in food webs, using a multi-model mean from an ensemble analysis, similar to the approach used for the physical climate models in Chapter 3, was not possible due to the limited development of biogeochemical models.

The PISCES model simulates the cycling of carbon, oxygen and the major nutrients needed for phytoplankton growth (e.g. nitrate, SRP, silicate). The model has two phytoplankton size classes; one representing picophytoplankton and nanophytoplankton (**Table 4.1**) and the other for the larger phytoplankton (diatoms).

It also has two zooplankton size classes, representing nanozooplankton and microzooplankton for the small size, and mesozooplankton for the larger one. Phytoplankton growth is limited by the availability of nutrients, temperature and light. Iron is supplied to the ocean by aeolian dust and runoff. The sink of iron needed to balance sources of iron is simulated by scavenging of iron onto particulate organic matter. There are two non-living components of particulate organic carbon in the model (small and large) and one for dissolved organic carbon. The model results are based on the IPSL-CM4-LOOP simulations[7].

Table 4.2 Information used to define the boundaries of the five ecological provinces in the modelling described in Section 4.7.

Province	Latitude range	Surface nitrate concentration threshold (μM)
PEQD	10°S–10°N	> 0.1
Warm Pool	6°S–9°N	< 0.1
NPTG	9°N–30°N	< 0.1
SPSG	6°S–45°S	< 0.1
ARCH	Fixed region given in Figure 4.6	

PEQD = Pacific Equatorial Divergence; Warm Pool = Western Pacific Warm Pool; NPTG = North Pacific Tropical Gyre; SPSG = South Pacific Subtropical Gyre; ARCH = Archipelagic Deep Basins.

The results of modelling the projected physical and chemical changes to each province are summarised in the next section, whereas the projections for changes in phytoplankton and zooplankton are presented in Section 4.9.

4.7.1 Projected changes to key physical and chemical features of provinces

The modelled projections of the effects of climate change on the surface areas of provinces under the B1 and A2 emissions scenarios show three main trends. First, a reduction of the area of PEQD as its western border is displaced eastward. A reduction of 20–27% in surface area is expected by 2035, with the western edge of the province moving from 180° to 170°W. A 30% shrinkage of the province is projected to occur under B1 and a 50% decrease under A2 by 2100, with the western edge lying between 160°W and 150°W (**Figure 4.13**, **Table 4.3**). Second, a corresponding increase in the area of the Warm Pool, which is expected to expand by 18–21% in 2035 and by 26% and 48% under B1 and A2, respectively, by 2100 (**Figure 4.13**, **Table 4.3**). Such variations are less than those reported in Chapter 3 because our definition of the Warm Pool province is based on surface nitrate levels, which is a better definition for the biological productivity projections than temperature and salinity. Third, the gyres are expected to expand towards the poles and to the west (**Figure 4.13**, **Table 4.3**). This expansion will be greater for SPSG, where the oligotrophic waters are expected to increase by 4–7% in 2035, and up to 14% for the A2 scenario by 2100 (**Figure 4.13**, **Table 4.3**). No change in the area of ARCH is expected, by definition.

For all provinces, the average mixed layer depth (MLD) is projected to decrease by < 10% for both scenarios in 2035 and 2100 except for PEQD (**Table 4.3**). The decreases in MLD in the Warm Pool are expected to have little effect on the supply of nutrients to the photic zone due to the strong gradient of the thermocline there, as outlined in Section 4.3.2. However, for the gyres (Case 3, **Figure 4.3**), a decreasing MLD is expected to reduce nutrient inputs into the photic zone, because the gradient gets stronger as it usually occurs during summer. In PEQD, the greater decreases in MLD projected to occur by 2100 (**Table 4.3**) are not expected to affect primary production because nitrate concentrations there, due to upwelling, are still likely to exceed levels at which the supply of iron presently limits the growth of phytoplankton.

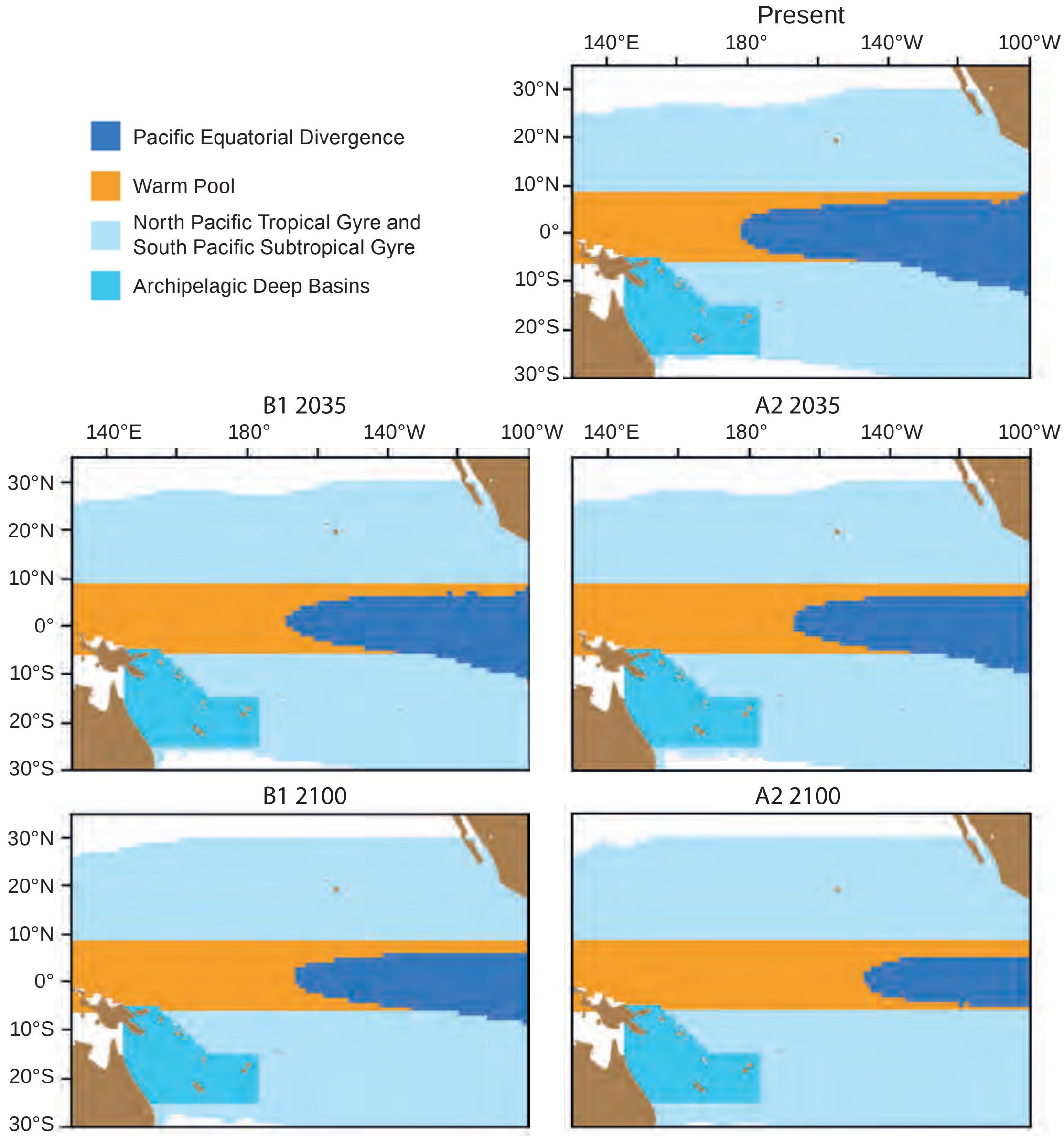


Figure 4.13 Projected changes in surface areas of the five ecological provinces in the tropical Pacific Ocean under the B1 and A2 emissions scenarios for 2035 and 2100, relative to present conditions.

The modelling also shows ubiquitous warming of the region (**Table 4.3**), which is expected to increase stratification (Chapter 3) and inhibit the supply of nutrients to the surface in oligotrophic provinces. Although the greatest warming is projected to occur in the non-upwelling areas of the equatorial Pacific, the enhanced warming of the equatorial region in general is expected to reduce the upwelling of deep, nutrient-rich water, contributing to the contraction of PEQD. This contraction is most pronounced in the A2 scenario (**Figure 4.13**) and helps explain why NPP is expected to decrease across the entire equatorial Pacific by 2100 under high emissions of CO_2[85].

Dissolved oxygen (O_2) is projected to decrease by up to 26% in PEQD to a depth of 300 m by 2100 under the A2 scenario, and increase by 7–8% in NPTG by 2100 under the B1 and A2 scenarios (**Table 4.3**). Elsewhere, changes to O_2 at 300 m are minor and, in all provinces except PEQD, percentage saturation of O_2 is expected to be 50–75%. In PEQD, however, it is projected to drop to 22–28%.

Few differences in the effects of ocean acidification are expected among provinces measured using Omega aragonite (Ω aragonite) (Chapter 3). Depending on the emissions scenario, the projected decrease of Ω aragonite ranges between 8% and 35% (**Table 4.3**), which corresponds to a diminution in calcification rates of 2–9% for corals[86]. For pelagic organisms like haptophytes, the response to ocean acidification is less clear[87,88], with responses ranging from increased growth and calcification[89] to moderate decrease in growth and calcification.

4.8 Projected vulnerability of food webs in provinces

To assess the vulnerability of food webs for tuna and other large pelagic fish in each province, we have applied the vulnerability framework described in Chapter 1. This framework is based on (1) exposure to changes in the key physical and chemical features of the environment; (2) the sensitivity of all levels in the food web to this exposure; (3) the potential impact of this exposure and sensitivity; and (4) the capacity of the organisms to adapt to these changes and reduce the potential impact.

We have assessed the vulnerability of food webs in each province to changes in water temperature, mixed layer depth, nutrient inputs to the photic zone, solar and ultraviolet radiation, dissolved oxygen and ocean acidification. Exposure to these variables is based on the assessments of how they are projected to change according to the modelling described in Section 4.7, and the assessments in Chapter 3.

4.8.1 Water temperature

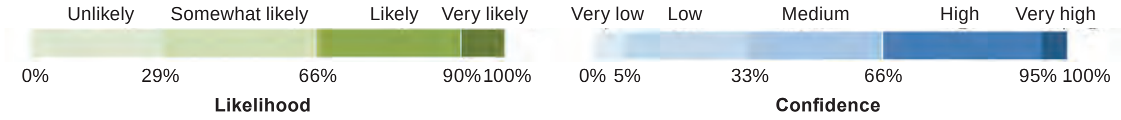
Exposure and sensitivity

As described in Chapter 3, sea surface temperatures (SSTs) are projected to increase by 0.7–0.8°C by 2035 under both the B1 and A2 emissions scenarios across the region. By 2100, SSTs are expected to be 1.4°C greater under B1, and increase by 2.5°C for A2.

Table 4.3 Projected effects of the B1 and A2 emissions scenarios for 2035 and 2100 on the main physical, chemical and biological features of the five ecological provinces in the tropical Pacific Ocean (based on the IPSL/PISCES model). Values are percentage changes relative to present values (2000–2010). Numbers in brackets refer to actual projected changes in SST (°C); actual projected MLD (m); actual projected percentage saturation of O_2 at a depth of 300 m; and actual projected aragonite saturation state (Ω, no unit). Likelihood and confidence values for each projection can be estimated for each cell in the table by combining the likelihood values for scenarios and the confidence values for features of the province.

Province	Year	Scenario		Feature of Province						
				Area 🟩	SST 🟩	MLD 🟩	O_2 🟩	Ω aragonite 🟩	NPP 🟩	ZooBiomass 🟩
PEQD	2035	B1	🟦	-20	+1 (0.3)	-5 (24)	-8 (26)	-10 (3.43)	0	-2
		A2	🟦	-27	+2 (0.5)	-9 (24)	-12 (26)	-9 (3.51)	0	-2
	2100	B1	🟦	-30	+3 (0.9)	-12 (23)	-5 (28)	-15 (3.24)	+2	-3
		A2	🟦	-50	+6 (1.6)	-26 (19)	-26 (22)	-35 (2.49)	+4	-6
Warm Pool	2035	B1	🟦	+18	+1 (0.4)	+3 (32)	0 (50)	-8 (3.82)	-7	-6
		A2	🟦	+21	+2 (0.5)	-5 (27)	-2 (49)	-10 (3.74)	-5	-3
	2100	B1	🟦	+26	+4 (1.2)	0 (30)	0 (50)	-17 (3.46)	-9	-9
		A2	🟦	+48	+7 (2.3)	-5 (29)	-2 (49)	-33 (2.79)	-9	-10
NPTG	2035	B1	🟦	+1	+1 (0.0)	-2 (37)	+1 (61)	-8 (3.57)	-3	-3
		A2	🟦	+1	+1 (0.4)	-3 (36)	+3 (60)	-11 (3.66)	-5	-4
	2100	B1	🟦	+1	+5 (1.3)	-1 (37)	+7 (63)	-18 (3.27)	-11	-10
		A2	🟦	+1	+9 (2.4)	-3 (36)	+8 (64)	-33 (2.66)	-22	-18
SPSG	2035	B1	🟦	+4	+2 (0.5)	0 (40)	-2 (66)	-8 (3.69)	-3	-3
		A2	🟦	+7	+2 (0.5)	-5 (38)	-4 (65)	-11 (3.60)	-5	-4
	2100	B1	🟦	+7	+4 (1.1)	0 (40)	-2 (66)	-18 (3.32)	-3	-5
		A2	🟦	+14	+8 (2.1)	-6 (39)	-4 (64)	-34 (2.65)	-6	-10
ARCH	2035	B1	🟦	0	+2 (0.5)	-3 (38)	-1 (75)	-9 (3.77)	-5	-5
		A2	🟦	0	+2 (0.5)	-3 (37)	-3 (74)	-12 (3.69)	-8	-6
	2100	B1	🟦	0	+5 (1.3)	-7 (36)	-1 (75)	-18 (3.38)	-20	-17
		A2	🟦	0	+9 (2.4)	-9 (35)	-1 (75)	-35 (2.70)	-33	-26

Area = surface area of the province; SST = sea surface temperature; MLD = mixed layer depth; O_2 = dissolved oxygen at a depth of 300 m; Ω aragonite = Omega aragonite; NPP = net primary production; ZooBiomass = zooplankton biomass; PEQD = Pacific Equatorial Divergence; Warm Pool = Western Pacific Warm Pool; NPTG = North Pacific Tropical Gyre; SPSG = South Pacific Subtropical Gyre; ARCH = Archipelagic Deep Basins.



The projected increases in SST at the scale of provinces derived from the IPSL model used here show a similar trend, although warming of all provinces is expected to be limited to 0.5°C by 2035, and warming of PEQD by 2100 is lower than for the other provinces (**Table 4.3**).

Higher SSTs are expected to increase stratification of the water column, with a greater temperature gradient in the thermocline and reduced exchanges between the mixed layer and the colder water below. This has implications for the transfer of nutrients for new primary production in the photic zone for all provinces (see below). However, here we focus on the direct effects of temperature on the organisms that comprise the food webs for tuna.

Temperature affects the metabolism of single-cell plants and animals, and larger animals with a variable body temperature (poikilotherms). Most experiments on the effects of temperature on metabolic rates have shown an exponential increase until a peak is reached, followed by a decreasing trend. The increasing phase follows the same law as the velocity of chemical reactions with temperature (Arrhenius' law) and is characterised by the Q_{10} index, i.e. the slope of the curve to the power 10. Present knowledge of the Q_{10} value for animals in the food webs for tuna is based mainly on cultures or short incubations of organisms collected from the natural environment – longer-term responses of organisms to increased temperatures remain poorly understood.

In phytoplankton[90], cyanobacteria[91] and copepods[92], the effects of increases in temperature lead to higher metabolic capacities, which depend on the metabolic function involved. For example, the Q_{10} of copepods differs for respiration, nitrogen and phosphorus excretions, assimilation, and production rates. In general, respiration increases more rapidly with temperature than excretion for a given food concentration, resulting in greater use of carbohydrates and lipids[92], with the result that temperature affects the growth efficiency of the copepods. The sensitivity of cyanobacteria and copepods also depends on the species involved and their life stage, and food concentration[93] (see also Chapters 8 and 9 for further discussion of the effects of temperature on metabolism).

Potential impact and adaptive capacity

The potential impact of the projected temperature increases on the food webs for tuna in all provinces, particularly under the A2 scenario in 2100, will depend on the capacity of the organisms to adapt to any temperatures beyond those they presently encounter. The Q_{10} index outlined above also describes the capacity of organisms to adapt to increases in temperature over a certain range; it is ~ 2 for adapted organisms and < 2 or > 2 for those species that are unable to control the effects of temperature increase[92]. Both cyanobacteria[91] and copepods[92] have adaptated to the temperature range occurring in the region, which commonly includes temperatures of 31–32°C in the Warm Pool.

Vulnerability

The organisms that comprise the food webs for tuna are already exposed to high temperatures in all provinces and appear to have a low vulnerability to the projected effects of increases in water temperature under the B1 and A2 scenarios for 2035 and 2100. However, vulnerability is expected to vary among this wide range of organisms due to their individual adaptive capacities.

4.8.2 Mixed layer depth

Exposure and sensitivity

The maximum depth of the mixed layer is projected to be shallower under climate change in all provinces, especially in PEQD. This 'shoaling' is expected to be most pronounced under the A2 scenario in 2100 (Section 4.7, Chapter 3). Since the projected shoaling will be accompanied by a greater temperature (and density) gradient, nutrient supply from deeper layers by eddy diffusion and mixing will be reduced as in Cases 1 and 2 (**Figure 4.3**). Shoaling of the MLD to an extent that is similar to that projected under climate change presently occurs in the gyres in summer and reduces the availability of nutrients in these areas during this season. In the Warm Pool, the transfer of nutrients to the mixed layer is of less significance than in the gyres because the thermal gradient is always strong in this province and the key factor is the MLD compared with the depth of the photic zone. As discussed before (Case 1, **Figure 4.3**), when the MLD is deep, NPP is reduced in the Warm Pool. Conversely, a shoaling of MLD will increase NPP by providing more light to the nutrient-rich photic zone below the MLD (Case 2, **Figure 4.3**). Food webs are sensitive to the changes that presently occur in the MLD between summer and winter in the two gyres, and with ENSO in the Warm Pool.

Photos: Anita Slotwinski

Zooplankton: postlarval crab ~ 1 cm (left) and copepod < 1 mm (right)

Potential impact and adaptive capacity

The increase in oligotrophic conditions associated with the projected changes to the mixed layer within the photic zones of the gyres is expected to reduce the biomass of phytoplankton, and increase the proportion of phytoplankton of a small size (Section 4.2.1). In turn, the smaller phytoplankton cells are expected to increase the proportion of small-sized herbivores and carnivores, leading to a greater number of trophic links between phytoplankton and tuna at the top of the food web. In other words, the food web in these provinces is likely to become less efficient and, therefore, poorer as the supply of new nutrients is reduced.

There is little capacity for maintaining existing proportions of larger-sized phytoplankton in the food webs in the gyres if conditions become more oligotrophic. Many of the common species of phytoplankton are unlikely to be able to adapt to more oligotrophic conditions. Instead, they are expected to be replaced by other species.

Vulnerability

Food webs in NPTG, SPSG and the Warm Pool under normal and La Niña conditions have a moderate to high vulnerability to changes in the depth of the mixed layer. In the gyres, a shallower MLD with a strong density gradient, as occurs presently in summer, will lead to a less productive ecosystem. Such a situation, if it persists all year, would result in reduced food for tuna in the gyres. In the Warm Pool, a deeper MLD would lead to a less productive ecosystem, as happens presently during La Niña events. The extent of such vulnerability depends on the effects of global warming on the existing seasonal patterns in the gyres, and the interannual patterns in the Warm Pool in relation to the MLD.

4.8.3 Upwelling

Exposure and sensitivity

Upwellings do not occur in the Warm Pool or the gyres. In ARCH, they occur on a limited scale on a temporary basis. Therefore, exposure of food webs to any changes in upwelling of nutrient-rich water is expected to occur mainly in PEQD. Primary productivity in PEQD is limited by iron (Section 4.3.1), so exposure to changes in iron concentrations also needs to be considered here.

No major changes are expected in upwelling in PEQD under the B1 and A2 scenarios (Chapter 3). However, because iron originates mainly from the Equatorial Undercurrent (EUC), exposure to iron concentrations in PEQD may increase. This is likely to occur because the EUC is projected to increase in strength over the 21st century, and move progressively upwards, by about 10 m under B1 and A2 in 2035 and B1 in 2100, and then by 20 m for A2 in 2100 (Chapter 3). Aeolian inputs of iron to PEQD are negligible at present but this could change with variations in the location of the Intertropical Convergence Zone (ITCZ) (Chapter 2).

The food web in PEQD has a low sensitivity to any changes in macronutrients (Section 4.3.1), except for silicate, which needs to be above a certain concentration for diatoms to grow[11]. However, provided the supply of nutrients is maintained close to its current level, this food web is highly sensitive to any change in iron concentrations.

Potential impact and adaptive capacity

As long as equatorial upwelling remains strong, the supply of macronutrients is unlikely to limit primary production in PEQD. The IronEx experiments (Section 4.5) demonstrate how equatorial phytoplankton are limited by iron concentrations. Therefore, increases in iron, derived from projected changes to the EUC, create the potential for increased primary production and greater proportions of large-sized phytoplankton in PEQD (Section 4.2.1). The potential impact of higher concentrations of iron would be a food web for tuna with fewer links, leading to a larger biomass of top predators.

Vulnerability

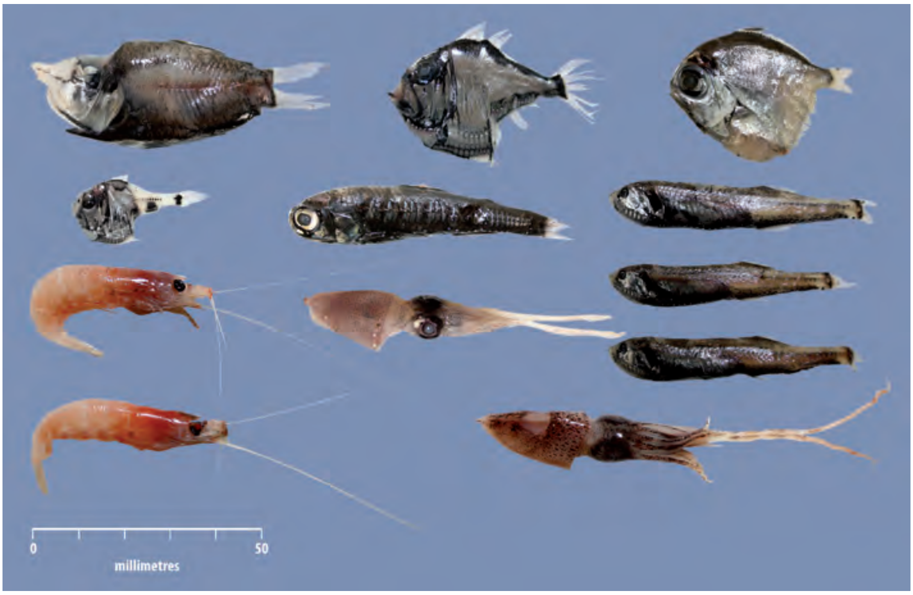
Food webs for tuna in PEQD are expected to have a low positive response to projected increases in upwelling and increased iron concentrations. Whether these benefits materialise will depend on the interactions between the intensity of upwelling and the velocity of the EUC.

4.8.4 Solar and ultraviolet radiation

Exposure and sensitivity

The Warm Pool and much of ARCH (except New Caledonia) are projected to have increased levels of cloud cover in the area of the South Pacific Convergence Zone (SPCZ) associated with the higher levels of rainfall expected to occur there as a result of global warming (Chapter 2). Similar conditions are also expected to eventuate for PEQD around the ITCZ. The projected increases in rainfall are within the range of 5–20% for the B1 and A2 scenarios by 2035, and 10–20% for B1 and A2 by 2100. However, reduced cloud cover is expected for subtropical parts of SPSG and NPTG, where rainfall is expected to decline by 5–20% by 2100 (Chapter 2).

Primary production is sensitive to light in two main ways. First, photosynthesis is reduced in the upper water column due to photo-inhibition, with the result that photosynthesis is usually at its maximum at a depth of 30 m in PEQD (**Figure 4.7**), where macronutrient concentrations do not limit the growth of phytoplankton. In contrast, photosynthesis is at a maximum at a greater depth in the oligotrophic provinces due to nutrient limitation, not photo-inhibition. Second, photosynthesis is lower during overcast days and total primary production throughout the water column can be reduced 1.5 to 3 times when surface light intensity is only 10% of that on a sunny day. Differential susceptibility of microbes to ultraviolet radiation (UVR) is potentially an important determinant of community structure of both bacteria[94] and photosynthetic picoplankton[95]. Because phytoplankton are sensitive to UVR, increased UV-B can result in a decrease in photosynthesis[96]. The effects of changes in UVR are ameliorated by vertical mixing and by the production of UV-absorbing compounds and antioxidants. UVR has also been shown to reduce copepod survival and fecundity[97].



Typical micronekton in the diet of tropical Pacific tuna

Photo: Jean-Pierre Lebars

Potential impact and adaptive capacity

Increased cloud cover is expected to have limited impact on total primary production of the water column in the Warm Pool, ARCH and PEQD. In the gyres, no change is expected due to reduced light, because the vertical distribution of nutrients is the key factor controlling primary productivity. In SPSG, however, greater light intensity and UVR are expected to increase photo-inhibition on more days in the upper 10 m of the water column. However, this is expected to have little impact because only a small part of total primary production typically takes place in this layer in oligotrophic provinces. Zooplankton living at the surface in SPSG are adapted to natural light intensities and should not suffer from extra UVR. Indeed, many zooplankton are adapted to a certain range of light intensities and wavelengths, and migrate to depths where they find their optimal light characteristics[97].

Vulnerability

All parts of the food web are expected to have a very low vulnerability to changes in solar radiation. Nevertheless, alterations in availability of light have the potential to change the structure of the picoplanktonic community in surface waters (down to a depth of 10 m), causing a shift from photosynthetic picoplankton to bacterioplankton, because of their different susceptibilities (see above). However, only a small fraction of the total phytoplankton biomass occurs in the upper layer of oligotrophic provinces, and mixing of the surface layer in all provinces prevents planktonic organisms from staying in the upper part of the photic zone for long. Overall, therefore, changes in the flux of solar radiation on the surface of NPTG and SPSG are expected to have a very weak impact on primary production.

4.8.5 Dissolved oxygen

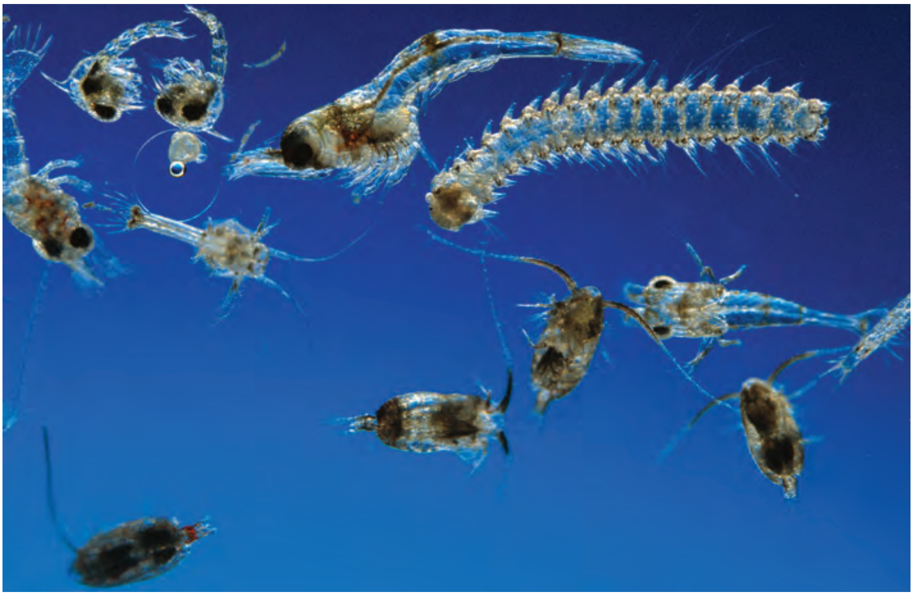
Exposure and sensitivity

In the tropical Pacific Ocean, average concentrations of O_2 at a depth of 300 m are projected to decrease by 0.2 ml per litre by 2100 under the A2 scenario (Chapter 3) (minimum concentrations of O_2 throughout the water column usually occur at this depth). By 2100, O_2 concentrations in the provinces themselves are expected to decline by < 5% at 300 m in most cases, except for NPTG, where they could increase by up to 8%, and PEQD, where they would be 5–26% lower (**Table 4.3**). It is important to note that the projected decreases do not apply to the photic layer, which is largely in equilibrium with atmospheric O_2. Rather, the decreases are expected to be due to oceanic processes occurring at higher latitudes, which result in lower concentrations of O_2 in deeper water in the tropics (Chapter 3).

The food web in deep waters (to a depth of 1000 m) is comprised of organisms which require O_2 to break down organic substrates, such as carbohydrates, and release the products through respiration and excretion. This catabolic process produces energy which is used for locomotion, growth and reproduction. Therefore, many of the organisms in the food web for tuna cannot live in anoxic (no oxygen) conditions for long periods. Some species living below the photic zone, however, e.g. bathypelagic copepods, can tolerate hypoxic conditions (low O_2 concentration)[92,98]. In such situations, these organisms have a decreased respiration rate.

Potential impact and adaptive capacity

In all provinces, except NPTG, the projected decrease in dissolved oxygen is unlikely to have a damaging effect on the food webs for tuna – concentrations of O_2 there are already relatively high (**Table 4.3**) and decreases of < 5% are not expected to affect these organisms. Furthermore, in the event of any localised, more severe, depletions of O_2, macrozooplankton and micronekton that undergo diurnal vertical migrations can escape anoxia by moving to more oxygenated areas within the water column. However, a possible consequence of such movement can be ‘compression’ of the feeding habitat for tuna, leading to greater rates of predation. Depending on where these feeding areas occur, tuna may be more vulnerable to surface fisheries[99] (Chapter 8). Other components of the food web, e.g. micronektonic fish, are usually ‘non-migrants’ and, although some of these species can tolerate anoxic conditions, other species cannot[100,101].



Zooplankton in the food web for tuna

Photo: Photoshot/SuperStock

Vulnerability

Projected changes in O_2 concentrations at a depth of 300 m are thought to be generally too low to cause significant changes in the food webs that support tuna.

4.8.6 Ocean acidification

Exposure and sensitivity

Due to the decrease in pH arising from the increased concentration of CO_2 in the ocean, average aragonite (one of the two forms of calcium carbonate) saturation in surface waters is projected to decline from the present value of 3.9 (350% saturation) to around 3.0 for the B1 scenario by 2100, and to 2.4 for A2 by 2100 across the region (Chapter 3).

Projections for the various provinces show a similar but less pronounced trend in Ω aragonite (Section 4.7.2, **Table 4.3**). These decreases can be converted into declines of 2–9% in calcification rates for organisms like pteropods (pelagic molluscs), which means the projected effects of acidification across the tropical Pacific Ocean are low compared with those for the Southern Ocean[102]. Although these declines are expected to be greatest near the surface, the depth of the aragonite saturation horizon (below which aragonite dissolves) is also expected to decrease to within 150 m of the surface in 2100 under the A2 emissions scenario at 8°N, and to a lesser extent to the north and to the south (Chapter 3).

As described in Section 4.5, some organisms in the food web for tuna, e.g. pteropod molluscs, depend on the present-day supersaturation state for aragonite to build robust shells and skeletons[79]. These organisms will need to expend more energy to form aragonite as the saturation horizon for aragonite becomes shallower, and supersaturation levels in the surface waters decrease[103]. Other organisms, such as coccolithophorids (haptophytes) in the phytoplankton, and foraminiferans and non-pteropod molluscs in the zooplankton, have shells made of calcite. They are expected to be less sensitive because greater decreases in pH are needed for 'shoaling' of the calcite saturation horizon[102].

Potential impact and adaptive capacity

Ocean acidification is expected to reduce the shells of calcareous phytoplankton and zooplankton, making them more fragile and vulnerable to predation. Some of these organisms may eventually disappear, causing changes in the complexity of food webs. For example, the pteropods that feed on very small particles (< 1 μm diameter), might be replaced by tunicates. Since tunicates have very short life spans, the altered grazing pressure and response to variation in picophytoplankton abundance may lead to food webs that function differently. Foraminiferans might also be replaced by silicic radiolarians, which feed in a similar way, thus reducing the concentrations of silicate. Because silicate is vital for diatoms, acidification may have an indirect effect on the species composition of phytoplankton.

Although ocean acidification could have unpredictable and cascading effects on food webs, the calcareous organisms likely to be affected directly are a minor part of the ecosystem. In PEQD, for example, they represent only 1–5% of the phytoplankton[104], 6.1% of the microzooplankton and mesozooplankton[105] and 2.2% of the micronekton[22]. Similar proportions apply to the other provinces. On the other hand, the loss of the calcareous organisms could have a dramatic effect on the transfer of anthropogenic carbon from the photic zone to the deep ocean via the process known as the 'biological carbon sink'[106].

Vulnerability

Organisms living in the upper part of the tropical Pacific Ocean are likely to have low vulnerability to the projected changes in ocean acidification. Calcifying animals living at some greater depths would be more vulnerable due to the reduced depth of the aragonite saturation horizon. However, because of the small contribution of calcareous organisms to micronekton, the impact of acidification on tuna forage should be small.

4.9 Integrated vulnerability assessment

The biogeochemical modelling (Section 4.7) integrated the effects of the projected changes to the physical and chemical features of the ocean on the supply of nutrients, NPP and the biomass of zooplankton in each province. The projected changes in NPP and zooplankton biomass are shown in **Figures 4.14** and **4.15**, respectively, and in **Table 4.3**.

To assess the vulnerability of food webs for tuna in each province, these projected changes also need to be integrated with expected alterations in the surface area of each province (**Figure 4.13**, **Table 4.3**). The main projections resulting from the integration of all the factors above are summarised for each province below.

4.9.1 Integrated assessments for each province

The food web in PEQD is expected to have a moderate vulnerability to the increases in greenhouse gas emissions in 2035, and a high vulnerability by 2100 (**Table 4.3**). This is due mainly to substantial decreases (20–50%) in the size of this important province (**Table 4.3**), and its relocation further east (**Figure 4.13**). Changes to NPP and the biomass of zooplankton in the food webs for tuna themselves within the more limited PEQD are expected to be slight (**Table 4.3**). The possible implications for tuna include an overall reduction in the quantity of forage previously available in PEQD, and relocation of the main feeding area for tuna (the convergence zone between PEQD and the Warm Pool – see Chapter 8) further to the east. Similar changes already occur regularly due to El Niño events, and the effects of projected changes to PEQD can be expected to mimic those due to ENSO closely (Chapter 8).

The food web in the Warm Pool is also expected to have a moderate vulnerability under the B1 and A2 scenarios in 2035, and a high vulnerability in 2100 (**Table 4.4**). Once again, this is driven mainly by the substantial projected changes to its surface area (**Figure 4.13**, **Table 4.3**), which resemble the effects of El Niño on this province. However, an important difference is that whereas the nutricline in the Warm Pool becomes shallower during El Niño episodes and increases nutrient supply to the photic zone and NPP, the projections under global warming show a deepening of the nutricline. Such deepening is expected to lead to reductions of up to ~ 10% in NPP (integrated throughout the water column) and zooplankton biomass by 2100 in the Warm Pool (**Table 4.3**).

The projected reduction in NPP in the Warm Pool is a possible threat to the production of tuna because it presents a markedly different situation than the one that presently appears to operate towards the end of an El Niño event, when the increased NPP from a shoaling of the nutricline appears to trigger the movement of tuna westwards[5].

Taken together, the projected reduction in the area of PEQD, and the expansion of the nutrient-poor Warm Pool, will result in a more oligotrophic equatorial Pacific Ocean.

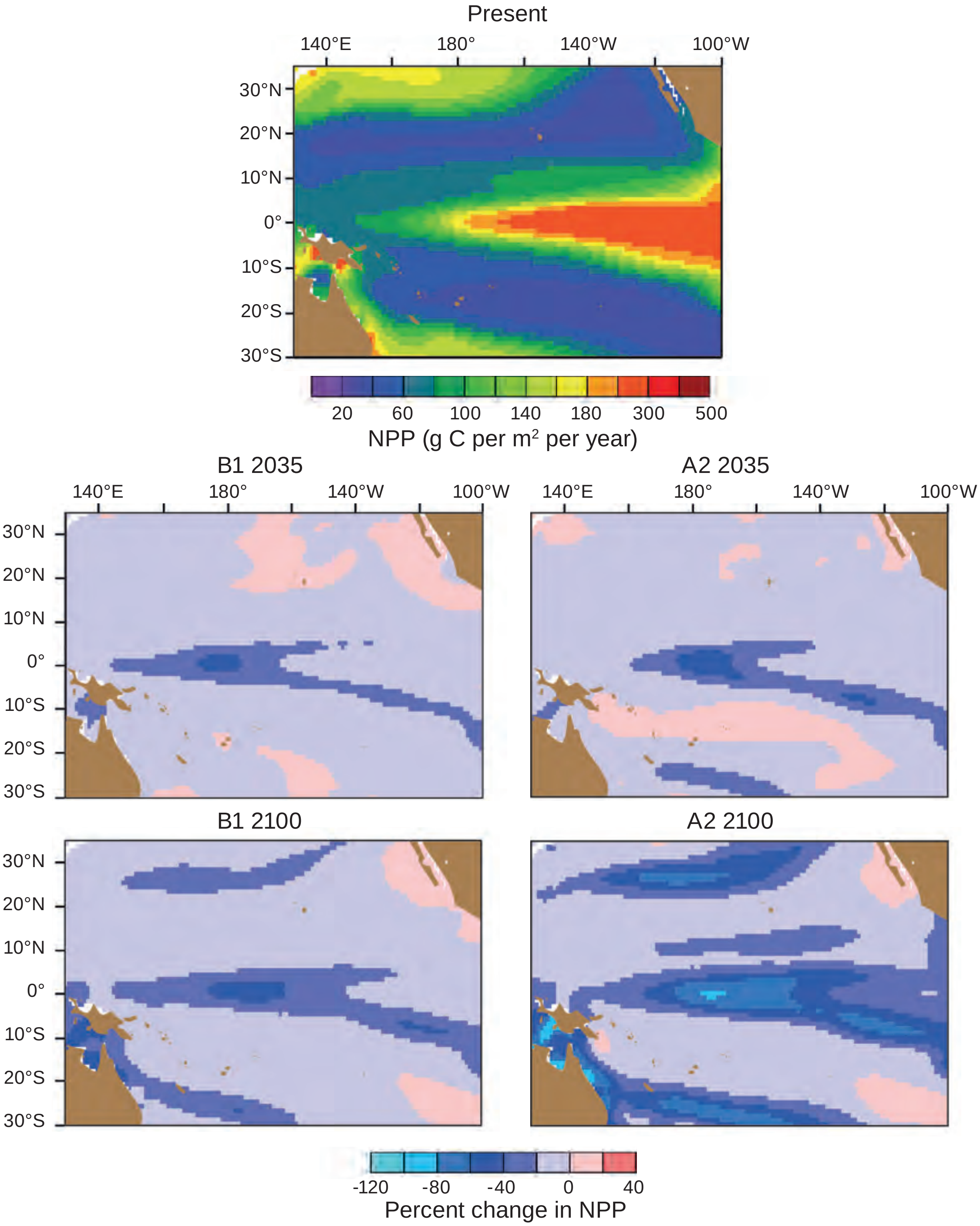


Figure 4.14 Present-day net primary production (NPP) across the tropical Pacific Ocean and projected percentage changes in NPP under the B1 and A2 emissions scenarios for 2035 and 2100, relative to present conditions.

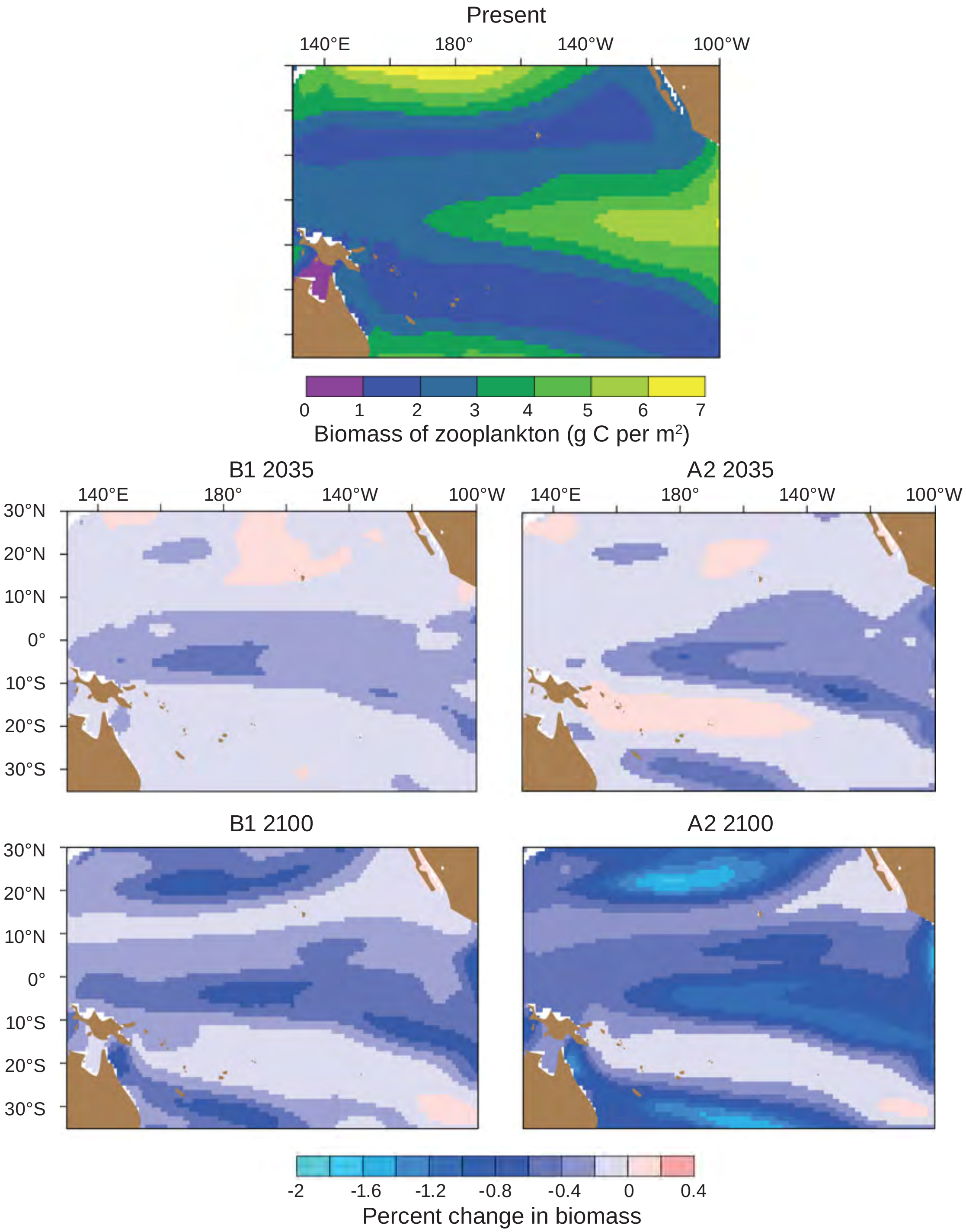


Figure 4.15 Present-day biomass of zooplankton across the tropical Pacific Ocean and projected percentage change in this biomass under the B1 and A2 emissions scenarios for 2035 and 2100, relative to present conditions.

The food web in SPSG is expected to have a low vulnerability in 2035 due to the limited expansion in area and decreased NPP and zooplankton biomass projected to occur by that time (**Table 4.4**). However, continuation of these trends will result in the vulnerability increasing to low-moderate by 2100 (**Tables 4.3** and **4.4**). The vulnerability of the food webs in NPTG is considered to be low in 2035 (**Table 4.4**) due to negligible changes in surface area and only modest changes in NPP and zooplankton biomass. However, vulnerability is expected to be moderate by 2100 under both the B1 and A2 scenarios because NPP is projected to decrease by 11–22% and the biomass of zooplankton is expected to decline by 10–18% (**Table 4.3**). In both gyres, the biogeochemical modelling indicates that the projected decreases in NPP and zooplankton biomass are expected to be concentrated at the poleward extremes of these provinces.

In ARCH, the main effects of global warming are projected to decrease the availability of nutrients through variations in the depth of the mixed layer (**Table 4.3**) and the incursion of more oligotrophic water from SPSG. As a result of these limited changes, the food web for tuna in ARCH is expected to have a low vulnerability in 2035 under both the B1 and A2 emissions scenarios (**Table 4.4**). By 2100, ARCH is expected to have a moderate vulnerability because NPP and the biomass of zooplankton are projected to decline by 20–33%, and 17–26%, respectively (**Table 4.3**) due to greater expansion of nutrient-poor water from SPSG. Note, however, that the magnitude of the decline in ARCH may be questioned because simulations with another global climate model (CSIRO model) indicate that much smaller changes are expected[107].

4.9.2 Ecopath model for the Warm Pool

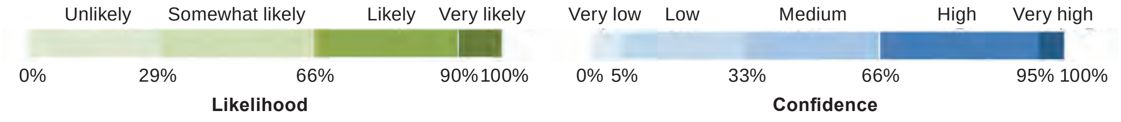
To examine the effects of projected changes to NPP in the Warm Pool in 2035 and 2100 on the food web for tuna, and on the expected catches of tuna from the province, we used 'Ecopath with Ecosim', a trophic mass-balance ecosystem model[108,109]. Ecopath describes the static state of energy flows in a food web that balances the net production of a group with all sources of mortality and migration[110]. Ecosim re-expresses the static Ecopath model in a dynamic form, whereby the dynamics and sensitivity of the model are controlled largely by the predator consumption rates and the proportion of the prey vulnerable to predation.

Ecopath and Ecosim simulations help test the effects of fishing and environmental change scenarios by forcing variations in biomass on selected components of the ecosystem[111,112]. However, Ecopath and Ecosim are sensitive to the relative strengths of indirect and direct physical effects on middle and upper trophic levels. Another important limitation of these models is the absence of direct links with physical oceanography and nutrients.

Table 4.4 Integrated vulnerability assessments (across all variables described in Section 4.8) for each of the five ecological provinces in the tropical Pacific Ocean for 2035 and 2100 for the B1 and A2 scenarios combined. Where ranges of values are provided for the projected changes, the lower and higher values represent the projections for B1 and A2, respectively. The likelihood and confidence values associated with these assessments are also shown.

Province	Year	Vulnerability	Projected changes
PEQD	2035	Moderate 🟩 🟦	Decrease in surface area of 20–27% as western boundary of PEQD moves eastwards from 180° to 170°W. Minor (2%) reduction in zooplankton biomass. No direct effect of higher SST, and lower O_2 and pH, on biomass or composition of plankton.
	2100	High 🟩 🟦	Decreases in surface area of 30–50% and movement of boundary to 160–150°W. A 2–4% increase in NPP and 3–6% decrease in biomass of zooplankton. No direct effect of higher SST, and lower O_2 and pH, on biomass or species composition of plankton.
Warm Pool	2035	Moderate 🟩 🟦	Increase in surface area eastwards by 18–21%, with a 5–7% reduction in NPP and 3–6% decrease in biomass of zooplankton throughout the water column. No direct effect of higher SST, and lower O_2 and pH, on biomass or species composition of plankton.
	2100	High 🟩 🟦	Increase in surface area eastwards by 26–48%, with a 9% reduction in NPP and 9–10% decrease in biomass of zooplankton throughout the water column. No direct effect of higher SST, and lower O_2 and pH, on biomass or species composition of plankton.
NPTG	2035	Low 🟩 🟦	Surface area increases limited to 1% as the province extends to the north. NPP decreases by 3–5% and zooplankton biomass declines by 3 to 4%. No direct effect of higher SST and O_2, or lower pH, on biomass or species composition of plankton.
	2100	Moderate 🟩 🟦	Increase in surface area stabilises at an increase of 1% but NPP decreases greatly (11–22%) and biomass of zooplankton declines by 10–18%. No direct effect of higher SST and O_2, or lower pH, on biomass or species composition of plankton.
SPSG	2035	Low 🟩 🟦	Surface area increases by 3–7%. NPP decreases by 4–5% and biomass of zooplankton declines by 3–4%. No direct effect of higher SST, and lower O_2 and pH, on biomass or species composition of plankton.
	2100	Low-Moderate 🟩 🟦	Surface area increases by 7–14% and extends poleward, with a 3–6% reduction in NPP and 5–10% decrease in biomass of zooplankton due to deepening of the thermocline. No direct effect of higher SST, and lower O_2 and pH, on biomass or species composition of plankton.
ARCH	2035	Low 🟩 🟦	No change in surface area. A reduction in NPP of 5–8% and a 5–6% decrease in biomass of zooplankton due to deepening of the thermocline. No direct effect of higher SST, and lower O_2 and pH, on biomass or species composition of plankton.
	2100	Moderate 🟩 🟦	No change in surface area. Greater (20–33%) reduction in NPP and a 17–26% decrease in biomass of zooplankton due to deepening of the thermocline. No direct effect of higher SST, and lower O_2 and pH, on biomass or species composition of plankton.

SST = sea surface temperature; O_2 = dissolved oxygen percentage saturation at 300 m; PEQD = Pacific Equatorial Divergence; Warm Pool = Western Pacific Warm Pool; NPTG = North Pacific Tropical Gyre; SPSG = South Pacific Subtropical Gyre; ARCH = Archipelagic Deep Basins.



For the purposes of this analysis, we defined the Warm Pool as the area 10°N–15°S and 110°E–165°E. The biota described from the Warm Pool were assigned to one of 44 functional groups (including detritus and fishery discards) based on their ecological similarity, feeding mode, diet, size, and rates of production and consumption. The model simulations were run until 2035 and 2100, relative to 2000–2010, using 2005 as the starting point. Changes in the biomass of mesozooplankton, epipelagic micronekton, mesopelagic micronekton and bathypelagic micronekton were simulated by introducing linear decreases in the biomass of small and large phytoplankton of 6% by 2035 and 9% by 2100, projected by the IPSL/PISCES model (**Table 4.3**). While projections on **Table 4.3** refer to NPP, they can be considered to represent phytoplankton biomass because NPP approximates biomass on a daily basis in the steady-state ecosystems of the tropical Pacific Ocean. The model also simulated the effects of reductions in phytoplankton at the base of the food web on the catches of adult skipjack, yellowfin and bigeye tuna from the Warm Pool in 2035 and 2100. Note that the projected decreases in NPP and, consequently, phytoplankton biomass in 2035 and 2100 are comparable for the B1 and A2 emissions scenarios (**Table 4.3**).

The diet matrix for the functional groups was based on stomach content analyses undertaken by the SPC Oceanic Fisheries Programme and supplemented by other research in Australia and PNG[28,113,114]. Estimates of forage biomass were obtained from the SEAPODYM model[115] (Chapter 8). The key biological parameters (biomass, production/biomass ratio, consumption/biomass ratio, ecotrophic efficiency, diet composition and catch) for each functional group were derived from primary research data, stock assessments, fishery data recorded in logbooks or by scientific observers, or the literature.

To increase the reliability of projections from Ecosim, the model was fitted to time-series of biomass, fishing mortality and catch data for twelve functional groups of predatory fish: juvenile bigeye tuna (ages 0–4 years), adult bigeye tuna (5–10 years), small juvenile skipjack (0–4 months), juvenile skipjack (5–12 months), large skipjack (1–4 years), juvenile yellowfin tuna (0–2.25 years), adult yellowfin tuna (2.5–7 years), striped marlin (1–10 years), South Pacific albacore (1–5 years) and blue marlin (0–21 years), juvenile swordfish (1–2 years), and adult swordfish (3–20 years). These data were derived from spatially-explicit, age-structured stock assessment models for the period 1952–2008[116–119].

The projected reductions of phytoplankton of 6% in 2035 caused approximately proportional decreases in the projected biomass of mesozooplankton and epipelagic micronekton (**Figure 4.16a**). Even greater decreases in the biomass of mesopelagic and bathypelagic micronekton are projected by the model (**Figure 4.16a**). This is primarily due to the production/biomass ratios for mesopelagic and bathypelagic groups being less than half that of the mesozooplankton and epipelagic micronekton group. In other words, the former groups have a lower capacity to recover after biomass declines due to climate change.

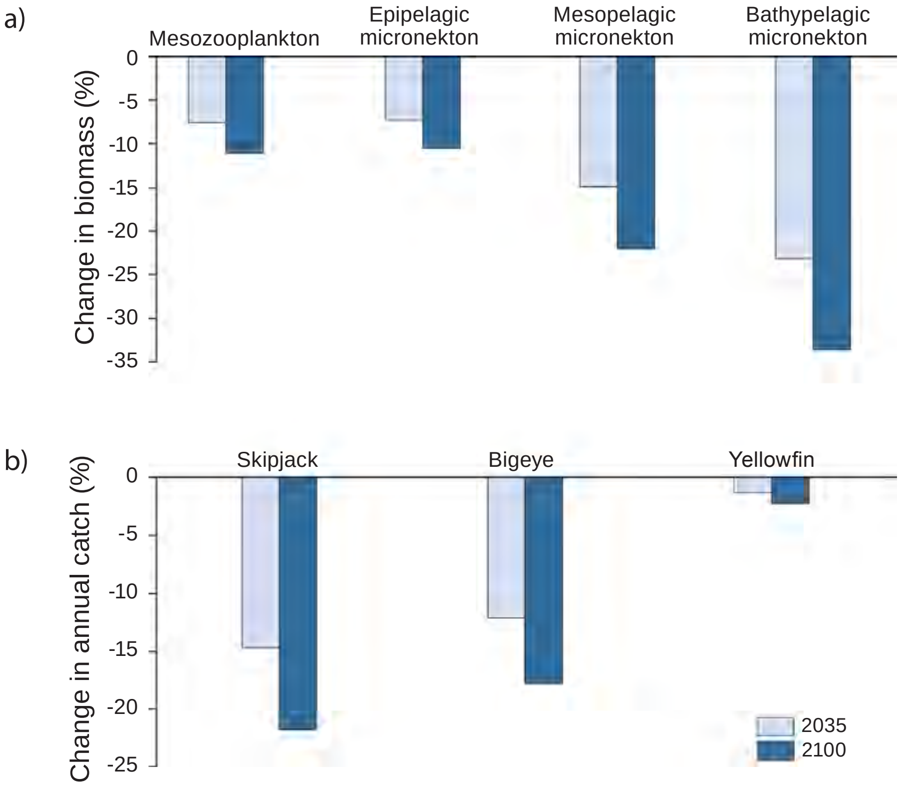


Figure 4.16 Changes in (a) the biomass of mesozooplankton and the various types of micronekton in the food web for tuna; and (b) the catches of the main tuna species, in the Warm Pool in 2035 and 2100 relative to 2000–2010, projected by the Ecopath model.

The expected changes in mesozooplankton and micronekton are projected to have the greatest effect on skipjack tuna, with the simulations indicating that catches of this species in the Warm Pool could fall by ~ 15% in 2035 (**Figure 4.16b**). These projected effects are due to the higher biomass of epipelagic micronekton, compared with mesopelagic and bathypelagic micronekton, and the relative importance of epipelagic micronekton in the diet of skipjack tuna. Significant decreases in catches of bigeye tuna are also projected in 2035, but the effects on the catches of yellowfin tuna are projected to be minor (**Figure 4.16b**). Yellowfin tuna are projected to be less affected for two reasons. First, they have a higher production/biomass ratio, which allows the species to have a greater capacity to withstand changes in their biomass due to external factors. Second, the more diverse diet of yellowfin tuna enables them to shift their feeding preferences towards more abundant taxa in their forage arena, which are less affected by climate change.

The projected 9% decrease in biomass of phytoplankton in 2100 results in proportionally higher declines in the biomass of mesozooplankton and micronekton, and catches of tuna (**Figure 4.16**).

Caution is needed in interpreting the projections of ecosystem-level response to climate change in the Warm Pool Ecopath model. Ecopath does not directly integrate all effects of climate, such as changes in animal movements induced by temperature changes, mixed layer depth variations and oxygen minimum layer depths. Instead, the model primarily relies on external models to be able to predict the effects of climate change on biomass of specific groups (e.g. phytoplankton), which can be used to 'drive' the model.

These features of Ecopath help to explain the differences between the projected catch rates for skipjack made here and those made using the SEAPODYM model in Chapter 8. By driving the model using biomass of phytoplankton, we implicitly assume that the food web is controlled by bottom-up processes. Yet an increasing number of models for pelagic ecosystems worldwide indicate that oceanic food webs have a more complex 'wasp-waist' structure, where the majority of the biomass is comprised of mid-trophic level groups. These groups are critical to the maintenance of ecosystem structure because they function as important predators of zooplankton and are prey of high-trophic level predators, such as tuna. For example, a recent model of the pelagic ecosystem off eastern Australia demonstrated the importance of mid-trophic level mesopelagic fish and cephalopods (micronekton) for exerting top-down control on lower trophic levels, and bottom-up control on these levels as prey for large tuna, billfish and sharks[120]. The inference is that any significant alteration in the biomass of micronekton due to the processes described in this chapter may cause large and unpredictable changes to the biomass of higher and lower trophic levels, and the overall integrity of the ecosystem.

4.10 Uncertainty, gaps in knowledge and future research

Although the modelling described here indicates strongly that changes could occur in the food webs for tuna in some provinces, there is much uncertainty associated with these projections. The uncertainty arises because even though oceanographic science has made huge progress during the last 40 years, the projections are based on rather scant knowledge of natural variability in the dynamics of phytoplankton and zooplankton populations.

In the tropical Pacific Ocean, the only information on long-term changes in abundance of phytoplankton and zooplankton comes from the HOT station in NPTG. Although the 24-year dataset from HOT has documented interannual and decadal variability, the record is not yet long enough to show any trend which could be linked to climate change. The imperative is to establish similar comprehensive monitoring programmes in the other provinces, particularly PEQD and the Warm Pool. The Tropical Atmosphere Ocean (TAO) array of moorings deployed by NOAA between 8°S and 8°N from 1984 to 1994, which are still operating with support from Japan and France provide a basis for a monitoring programme in PEQD and the Warm

Pool. However, biochemical sensors will need to be added to the existing capability, which measures meteorological and hydrographical parameters, and in a few cases, currents, nutrients and chlorophyll *a*.

Ideally, acoustic devices should also be installed among such arrays to monitor zooplankton and micronekton. However, acoustic data still suffer from poor correlations with micronekton sampled with nets, and the species composition and relative abundance of micronekton from stomach contents of tuna and other top predators[69,121,122]. To validate acoustic data, we need reliable information on spatial and temporal variation in the species composition and relative abundance of micronekton. Increasing the reliability of the acoustic data would also open the way for fitting suitable instrumentation to 'ships of opportunity', to build up time-series along the major shipping routes in the region.

A continuous remote sensing record of ocean colour, linked to chlorophyll *a* and other pigments, has been available for all provinces since the inception of the US Sea WiFS (Wide Field-of-View Sensor) mission in September 1997, and from other satellites launched later. With appropriate corrections (e.g. for nebulosity) applied to satellite images, remote sensing is being used to document phytoplankton biomass in the superficial layer of the ocean, down to a depth of 20 m in oligotrophic provinces. The focus is on identifying the relationships between concentrations of chlorophyll *a* in the surface and deep layers. This varies with the type of ecosystem being considered, so the relationship in the Warm Pool, for example, is expected to be different to that for the gyres.

Three key information gaps need to be filled by monitoring programmes to parameterise future models in a better way.

- Spatial and temporal distribution of iron in the EUC, and the bio-availability of the different forms of iron.
- Variability in abundance of micronekton, and the factors driving this variability, including production processes taking place in the photic zone, the complexities of food webs, and the differential life spans of the prey species and their predators.
- Lateral transport of organisms within and between provinces, as described for PEQD[39,123]. Such processes are poorly understood but have been implicated in the transfer of organic matter from rich oceanic zones to poorer ones in the equatorial Pacific[124]. We particularly need to know the extent of exchanges between provinces within the aphotic zone.

The resolution of models also needs to be improved substantially to reduce uncertainty. At present, the coupled atmosphere ocean model used to simulate oligotrophic regions lacks eddies, which are an important mechanism for transferring nutrients into the photic zone (Chapter 3). The current generation of ocean models underestimate NPP, resulting in considerable uncertainty in projecting the effects of climate change on this vital process. In particular, there are several features of the present climate used by the IPSL model that influence the simulated decline in NPP with climate change. For example, the modelled position of the SPCZ in the Southern Hemisphere is too far north, and high productivity occurs along the entire east coast of Australia. This makes the averaged NPP in ARCH and SPSG too great.

At present, modelling the effects on micronekton has only been done using Ecopath with Ecosim for the Warm Pool (Section 4.9.2). Much care is also needed in using these tools to simulate cascading effects of trophic interactions within provinces. Although this suite of models can make trophic links between the different components of the ecosystem, there are no direct connections to physical models. Instead, climate change scenarios are usually simulated in Ecosim by imposing variations in biomass of various components (e.g. phytoplankton biomass).

The uncertainties and gaps in knowledge lead us to conclude that the changes projected to occur by coupled models in the provinces need to be interpreted with caution. Given the great importance of PEQD, it is essential that the confidence for modelling the response of this rich province to climate change is improved. Provided models are able to accurately project the surface areas of PEQD and the Warm Pool, impacts on both ecosystems can be inferred from known ENSO-related changes. The great reductions of PEQD during the two strong El Niño events between 1980 and 2000[30] are examples of such ENSO-related changes.

4.11 Management implications and recommendations

The sheer size of the provinces in the tropical Pacific Ocean makes it extremely difficult to think of any management interventions that could be applied at a meaningful scale. The relatively low concentrations of iron required to increase primary production in PEQD means that iron fertilisation is potentially one such possibility. However, caution is needed because the long-term biogeochemical[125] and ecological effects of iron enrichments are still largely unknown. The code of practice for such geoengineering research specified under the London Convention and Protocol[ii] needs to be applied in any future investigations to improve iron concentrations in PEQD. The single greatest intervention to reduce the effects of climate change on the provinces identified here is global reduction of greenhouse gas emissions.

[ii] www.londonprotocol.imo.org

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Chapter 5

Vulnerability of coral reefs in the tropical Pacific to climate change

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> *'Temperature-related effects of global warming on coral reefs are highly visible, well-defined and extensively documented. The more recently recognised effects of atmospheric carbon dioxide on ocean acidification will have even more profoundly detrimental long-term effects on reefs.'* (Veron et al. 2009)[i]

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5.1 Introduction

Coral reefs are one of the dominant features of the tropical Pacific Ocean, proliferating in shallow, nearshore environments where sediment and nutrient concentrations are generally low. Coral reefs form complex habitats that provide critically important ecological services such as food, resources for livelihoods and coastal protection[1–3]. They are also culturally significant and play a central role in the lives of the Melanesian, Micronesian and Polynesian peoples of the Pacific[4,5].

Corals and a number of other calcifying organisms (e.g. crustose coralline algae) build coral reefs, incorporating the abundant calcium carbonate from the surrounding waters within their tissues to create aragonite structures. Over time, the dead skeletons of these organisms accumulate, forming reefs and islands that provide habitat for thousands of species. Despite their importance, coral reefs are currently threatened by a wide range of local stressors, such as declining water quality, pollution, overexploitation and physical destruction[1,6], and global stressors, such as the warming of the planet and ocean acidification[7]. Ultimately, these changes threaten to destabilise reef-related livelihoods for hundreds of thousands of people throughout the region[8,9].

In this chapter, we assess the vulnerability of the coral reefs that underpin coastal fisheries and aquaculture in the tropical Pacific, by examining the possible effects of climate change on coral communities and other reef-building organisms. Our analysis draws on the projected changes to the surface climate and ocean of the tropical Pacific, described in Chapters 2 and 3, to quantify how coral reefs are likely to be exposed to these effects. The results of that analysis were used in the framework outlined in Chapter 1 to assess the vulnerability of coral reefs in the region under the Intergovernmental Panel on Climate Change (IPCC) B1 and A2 greenhouse gas emissions scenarios[10]. Given the demonstrated potential for local factors to amplify the effects of global climate change on coral reefs[7,11], factors operating at a local level are an important aspect of this analysis.

We set the scene by describing the structure and distribution of coral reefs in the tropical Pacific (25°N and 25°S, 130°E and 130°W), briefly explaining the vital role of coral reefs in supporting coastal fisheries and aquaculture in the region, and summarising the critical requirements for establishing and maintaining corals. We then outline how coral reefs have already been affected by the changing climate and assess the projected vulnerability of coral reefs to continuing climate change. The chapter focuses primarily on the effects of future changes to sea surface temperature (SST), solar radiation, ocean acidity, tropical storms and floods, sea-level rise, and ocean circulation and upwelling. We then integrate these assessments into projections for the structure and biological complexity of coral reefs under the B1 and A2 emissions scenarios for 2035 and 2100.

We conclude by identifying the remaining uncertainty and important gaps in knowledge, outlining the research required to fill these gaps, and summarising the key management responses needed to maintain the important role that coral reefs play in supporting coastal fisheries and aquaculture in the Pacific.

5.2 Structure and distribution of coral reefs in the tropical Pacific

The recent maps of coral reefs from Landsat 7 high resolution (30 m) remote sensing images[12], and the information from the new 'Atlas of Pacific Ocean Coral Reefs', provide the most up-to-date picture of the extent, structure and distribution of the various types of coral reefs within the 22 Pacific Island countries and territories (PICTs)[12,13].

The first major pattern to emerge from this information is that, for several PICTs in Micronesia and Polynesia, the areas of coral reef habitat greatly exceed the area of land (**Table 5.1**). The second is the hierarchy of diverse reef structures. At the apex of the hierarchy, the coral reefs of the region can be divided into 'continental' and 'oceanic' reefs (**Figure 5.1**). Continental reefs are defined by the geological origin of their underlying substrates[14–16], or the size of associated land masses, and are found only in Papua New Guinea (PNG), New Caledonia (on Grande Terre) and Fiji (on Viti Levu and Vanua Levu). All other reef areas in PICTs are considered to be oceanic.

Both continental and oceanic reefs include barrier reefs, fringing reefs and patch reefs, but also atolls and banks. However, the oceanic barrier, fringing and patch reefs are all attached to oceanic island reef complexes, whereas continental barrier, fringing and patch reefs are attached to the continent (**Figures 5.1** and **5.2**). As a sublevel in the hierarchy of continental reefs, continental islands and their associated reefs may also occur in close proximity to the continent (e.g. Belep Islands in New Caledonia). Atolls and banks are distinguished mainly by the presence/absence of a closing rim, and the degree to which their lagoons are closed. Islands differ from atolls and banks in that the land mass is not derived from carbonate sediments. Fringing reefs form around islands and continental masses, and vary in the way they are exposed to oceanic swells or positioned in lagoons and embayments. Barrier reefs are offshore structures, separated from the land by lagoons or large sedimentary terraces. Patch reefs are intertidal or subtidal constructions of varying sizes, which are not continuous (like barrier reefs) or adjacent to land (like fringing reefs). These broad reef types can be divided into finer levels (classes) of reef geomorphology, exposure and depth[17].

Several PICTs made up of oceanic reefs consist almost entirely of atolls (e.g. Marshall Islands, Kiribati, Tuvalu, Tokelau) (**Table 5.1**). Oceanic reef structures in some PICTs are dominated by fringing reefs directly exposed to ocean waves and runoff from high island land masses (e.g. Vanuatu). Most of the PICTs with oceanic reefs, however, have a range of islands, banks and atolls of various sizes (e.g. American Samoa, French Polynesia, Federated States of Micronesia (FSM), Palau, Niue, Wallis and Futuna). At the finest level (class) of reef geomorphology, there is great variation among PICTs, ranging from two classes of reef type in Nauru up to > 150 classes in New Caledonia, Fiji and PNG (**Table 5.1**).

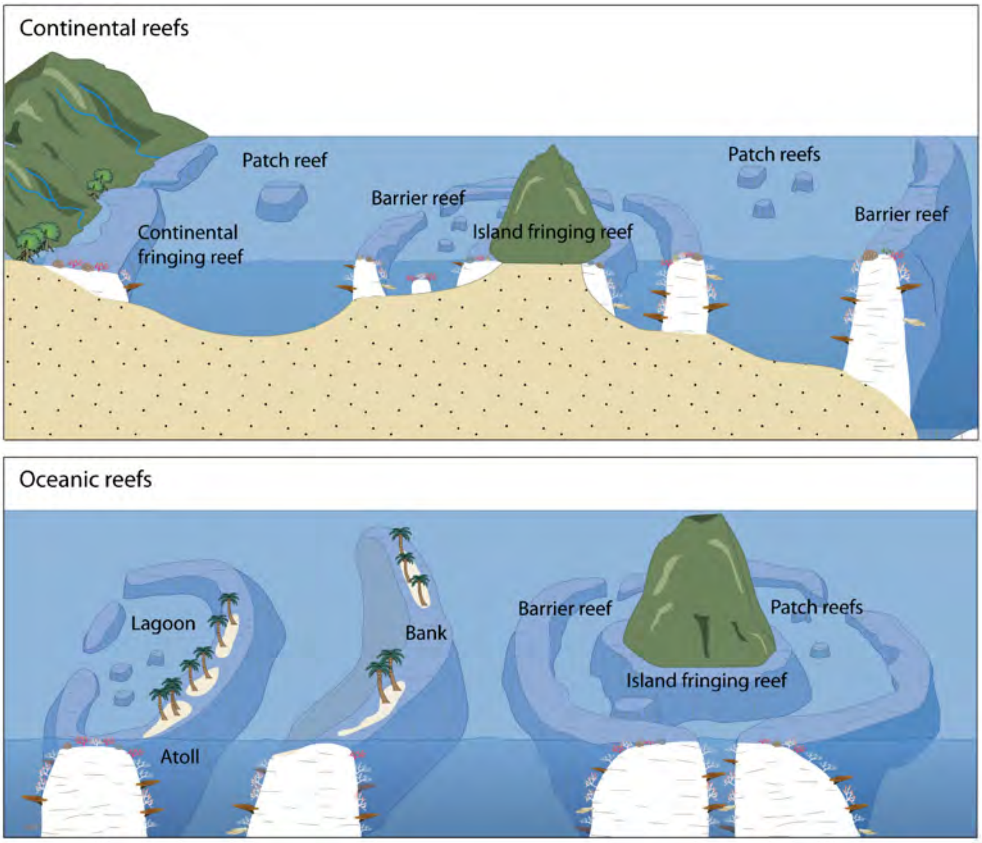


Figure 5.1 The main types of continental (connected to the mainland) and oceanic coral reefs.

This diversity of reef types is significant for PICTs because the various categories and classes of reef differ in their exposure and sensitivity to disturbance, and presumably also to the effects of climate change. The degree to which atolls are 'closed' is a pertinent example. The closed to semi-closed atolls found in the central Pacific differ from the open atolls of the western Pacific in their exposure and sensitivity to hydrodynamic change. Hydrodynamic regimes and average residence times of water in lagoons can easily be modified by sea level and wind/wave variations on short time scales, and presumably also by slowly shifting conditions[18,19]. Changes that switch semi-closed lagoonal waters from being replenished rapidly to being renewed slowly have led to planktonic algal blooms, anoxia and mass mortalities of fish and invertebrates[20,21].

Table 5.1 Total area (km^2) of land and coral reef, and areas of coral reef comprising atolls, banks and formations associated with islands, on Pacific Island countries and territories (PICTs). Values derived from Landsat 7 images and 'Atlas of Pacific Ocean Coral Reefs', except for Fiji and Papua New Guinea. Number of reef classes for each PICT is also shown.

PICT	Land	Total reef	Atoll[a]	Bank[b]	Island				No. reef classes
					Barrier reef	Patch reef	Fringing reef	Inter-reefal[c]	
Melanesia									
Fiji	18,272	10,000*	n/a	n/a	n/a	n/a	n/a	n/a	> 150
New Caledonia	19,100	35,925	15,466	413	3476	733	790	15,047	163
PNG	462,243	22,200*	n/a	n/a	n/a	n/a	n/a	n/a	> 150
Solomon Islands	27,556	8535	2191	599	1471	645	1328	2301	134
Vanuatu	11,880	1244	22	40	59	28	629	466	58
Micronesia									
FSM	700	15,074	11,859	420	523	21	212	2039	72
Guam	541	238	0	113	19	1	75	30	27
Kiribati	690	4320	3986	114	0	0	0	0	23
Marshall Islands	112	13,930	13,910	20	0	0	0	0	20
Nauru	21	7	7	0	0	0	0	0	3
CNMI	478	250	0	33	25	0	67	125	23
Palau	494	2496	555	17	615	86	163	1060	58
Polynesia									
American Samoa	197	368	11	9	5	0	47	296	16
Cook Islands	240	667	548	5	58	1	17	38	37
French Polynesia	3521	15,126	13,524	35	802	27	178	560	66
Niue	259	56	56	0	0	0	0	0	9
Pitcairn Islands	5	48	17	17	0	0	4	10	17
Samoa	2935	466	0	0	203	7	139	117	28
Tokelau	10	204	204	0	0	0	0	0	8
Tonga	699	5811	47	96	564	377	171	4556	70
Tuvalu	26	3175	3040	135	0	0	0	0	18
Wallis and Futuna	255	932	588	75	95	14	56	104	25

* Estimates only; a = area below high water mark, including 'drowned' atolls; b = small area below high water mark, including 'drowned' banks; c = includes lagoons and sedimentary areas within main island reef types; n/a = data not available.

Island size also affects the exposure of reefs to disturbance. Barrier reefs on large islands and continental land masses are more likely to be exposed to plumes of sediments from rivers compared with barrier reefs on small islands. Similarly, fringing reefs surrounding large land masses are more likely to be affected by floods and rainfall than barrier reefs.

Overall, the location, spatial organisation and fragmentation of coral reefs influence their resilience to perturbations. In particular, reefs on small, isolated islands are less likely to be resilient than those on well-connected islands that receive larval coral recruits from a variety of sources. On larger islands, the main threats to the resilience of coral reefs are land-based sediments and pollution.

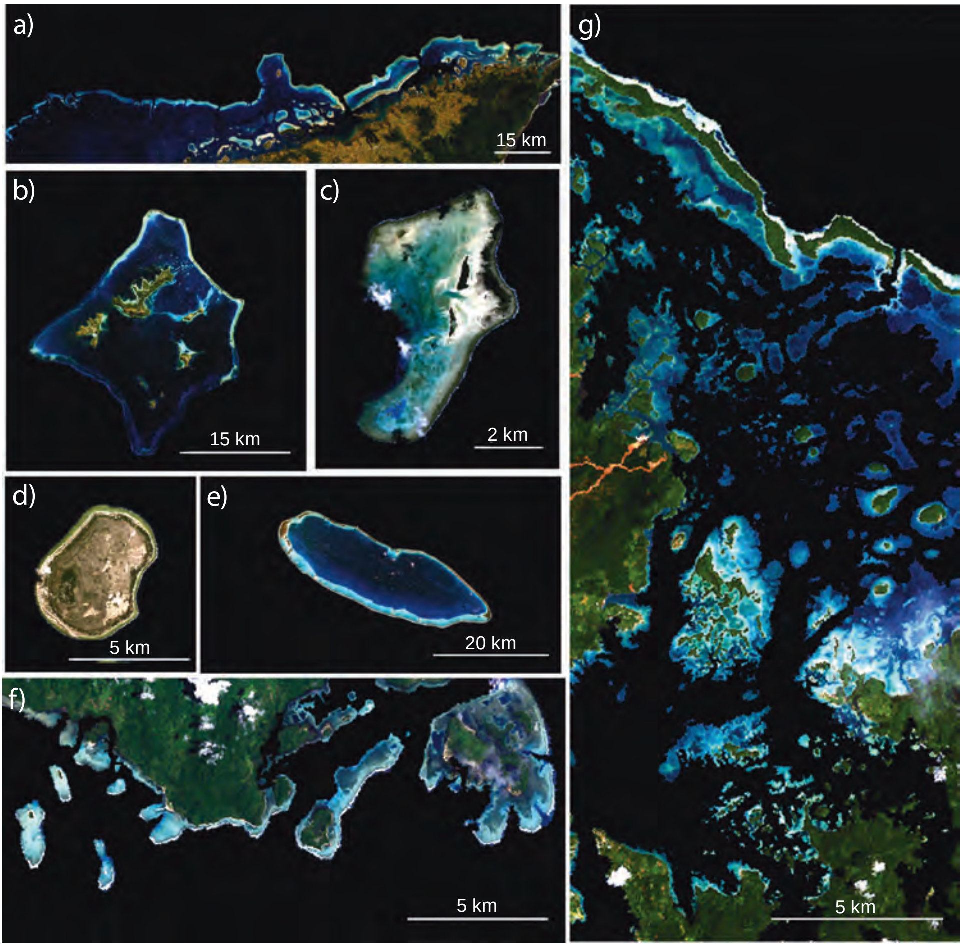


Figure 5.2 Examples of the main coral reef types in the tropical Pacific Ocean: (a) continental barrier reef, protecting lagoonal patch and fringing reefs (Vanua Levu Island, Fiji); (b) oceanic barrier reef surrounding a lagoon with fringing and patch reefs (Mangareva, French Polynesia); (c) oceanic reef island bank (Malekula Island, Vanuatu); (d) oceanic atoll that has been uplifted with a narrow fringing reef (Nauru); (e) closed oceanic atoll (Kaukura atoll, French Polynesia); (f) fringing and patch reefs around an oceanic island (Malekula Island, Vanuatu); (g) lagoonal patch and fringing reefs (Vangunu Island, Solomon Islands).

Regardless of reef size, type and orientation, the location of a reef can also be expected to influence the extent of disturbances. Because the southern barrier reef in New Caledonia is located near an area of strong and frequent upwelling, for example, it is less likely than barrier reefs in Fiji or PNG to be exposed to thermal stress from rising SST[22]. Similarly, reefs located at depths of 30 m or more are unlikely to be severely affected by increases in SST and changes in sea level. Such reefs occur commonly between American Samoa and Tuvalu, and in FSM. Reef crests located in places flushed by oceanic waters often fare better than enclosed basin or lagoonal reef areas during periods of high water temperature associated with mass coral bleaching events[23].

The location of reef classes within reef types also determines exposure and sensitivity. For example, because the fore-reef receives the greatest amount of wave energy, the corals there grow faster due to the high rate of water movement, and hence nutrient and gas exchange. Differences in light intensity can also have large influences on the extent of coral bleaching and mortality[24,25], with high islands sometimes shading coral reefs and reducing stress, as seen in Palau during 1998[26]. Reef flats and terraces are usually sheltered from wave action and have conditions suitable for growth of diverse coral communities. However, reef flats, shallow fore-reefs, and reticulated areas are more susceptible to physical destruction by tropical cyclones than deep areas of fore-reefs and lagoons[27]. Also, reef crests and high energy reef flats create environments conducive for crustose coralline algae, which are susceptible to changes in the pH of sea water[28].

In summary, reef types and classes differ in their exposure and sensitivity to disturbance, often depending on their location. Consequently, PICTs with a large variety of reef structures and types are likely to cope better with the impacts of climate change than those with a limited diversity of reefs.

5.3 Role of coral reefs in supporting fisheries in the tropical Pacific

Coral reefs are the dominant and most readily accessible coastal habitats in virtually all PICTs (**Table 5.1**), and support a wealth of fish and invertebrate species that are used for food and as a source of income. The role of coral reefs in providing food security across the tropical Pacific is significant – fish provide 50–90% of the animal protein in the diet of coastal communities in the region, with the majority of these fish caught by subsistence fishing on coral reef habitats[3,29–31]. The coastal fish and invertebrate resources of the tropical Pacific are harvested by the four types of fisheries described in Chapter 9 and summarised briefly here.

- **Fisheries for demersal fish:** Comprised of bottom-dwelling fish caught mainly near coral reefs using handlines, gill nets or by spearfishing. The extensive range of species caught are used mainly for food by households, or sold locally to earn or supplement incomes[30]. However, specialised fishing operations have occurred in the past in some PICTs to supply large carnivorous reef fish (mainly groupers) to the live reef fish trade[32,33]. A wide range of small colourful species are also caught for the tropical marine aquarium market[34,35].
- **Fisheries for nearshore pelagic fish:** Based largely on the stocks of skipjack and yellowfin tuna that support offshore industrial fishing fleets throughout much of the tropical Pacific (Chapter 8). However, these fisheries also capture significant quantities of other large pelagic species, such as Spanish mackerel, mahi-mahi, wahoo and rainbow runner, and a broad range of small pelagic species (flying fish, scads, mackerel, pilchards and anchovies). The larger species are generally caught by trolling along reef edges, but they are also increasingly targeted by fishing around anchored fish aggregating devices (FADs) deployed in nearshore waters

within ~ 10 km of the coast. Taken together, the large and small pelagic species contribute substantially to the food security and income earning opportunities of coastal communities throughout the region.

- **Fisheries for targeted invertebrates:** Focusing mainly on sea cucumbers and trochus (but also giant clams, spiny lobsters, crabs and green snail), which have long been an important source of revenue for coastal communities[36]. Many of these species are associated mainly with coral reefs and are harvested by specialised fishing operations. Sea cucumbers and trochus, in particular, have been fished extensively throughout the tropical Pacific for more than a hundred years, and exports of the non-perishable, dried product (bêche-de-mer) from sea cucumbers[37], and trochus shells, enable even remote communities to earn income[30,35]. The ease of collecting these invertebrate species, and their high market value, has led to widespread overfishing in the region[35,37]. Spiny lobsters, once collected opportunistically by free divers, are now the target of commercial fisheries based on the use of underwater torches and SCUBA.
- **Fisheries for shallow subtidal and intertidal invertebrates:** Involving the 'gleaning' of a wide range of molluscs (giant clams, other bivalves, gastropods and octopus) and echinoderms (sea cucumbers and urchins) from coastal areas at low tide. These animals are often collected by women and children, and provide an important source of household food, especially when weather conditions prevent other fishing activities. This fishery is an integral part of the social fabric in many PICTs.

Apart from nearshore pelagic operations, all sectors of coastal fisheries are fundamentally dependent on healthy coral reefs. Many species of fish and invertebrates are found only on coral reefs and, in general, reefs with a wide variety of coral formations, and therefore high topographic complexity, support a greater abundance and diversity of reef-associated fauna[38]. Populations of fish and invertebrates associated exclusively with coral reef habitats are typically highly dependent on the complex biological and physical structure created by scleractinian corals. Such populations decline in abundance dramatically after extensive loss or degradation of coral caused by temperature-induced coral bleaching and other environmental impacts, such as tropical cyclones[38–41].

Some fish and invertebrates rely directly on live corals for food, shelter or recruitment, although many of these species (e.g. butterflyfish) are not generally harvested[39]. However, corals are important contributors to primary production on reefs, and decreases in coral abundance may lead to reduced energy transfer to higher trophic levels in ways that could affect important fisheries species[42]. The growth and calcification of reef-building corals and crustose coralline algae need to exceed the losses caused by physical and biological erosion, which may take away as much as 90% of the calcium carbonate laid down by these calcifying organisms[7]. Otherwise, the complex reef frameworks crumble and disintegrate over time, with profound implications for the productivity of coastal fisheries and reef-based tourism.

Human settlements have also had a strong impact on coral reef habitats throughout the tropical Pacific. As human population densities increase, fishing activity becomes more intense and diverse[29,30,43] (**Figure 5.3**), with the effect that ecologically important species such as large predatory, and herbivorous fish, are targeted and depleted (Chapter 9). Other activities, such as pollution, sediment and nutrient inputs, dumping of rubbish and careless anchoring of boats can lead to localised damage to the structural complexity of coral reefs. Collectively, the diverse local effects in many PICTs and other developing countries have led to a 'coral reef crisis'[6] – a reduction in corals, and a rise in the relative dominance of other organisms such as soft corals and seaweeds. Altered reef frameworks and ecological functions in turn lead to reefs that support lower populations of fish and invertebrates important for food and income (**Figure 5.3**). Overcoming this crisis is not straightforward, particularly in developing countries[44], and requires innovative management to prevent the damage occurring in the first place and to provide incentives for restoration.

Fishing can also affect sharks, which often have a special importance and value to tourism. In countries such as French Polynesia, good populations of sharks are attractive to SCUBA divers, and provide a critical advantage for particular locations in competitive tourism markets[45,46].

5.4 Critical requirements for coral reefs

Given the importance of reef-building corals to reef structures, it is important to understand the conditions corals need for their establishment and growth, and how they are likely to respond to climate change. In the Pacific, corals that build reefs are found in warm, alkaline and sunlit waters between latitudes 30°N and 30°S. In these locations, reef-building corals accumulate calcium carbonate (as calcite or aragonite), with their skeletons growing to form the key structural components of coral reefs, glued together by chemical precipitation and by other marine calcifiers, such as crustose coralline algae. Spaces within the coral framework are then filled in by sand and the calcareous skeletons of green algae, such as *Halimeda* spp., and foraminifera, sponges, molluscs and crustaceans. Over time, this accumulation of organisms and their skeletons prevails against the forces of physical, chemical and biological erosion, and reef structures build up. Eventually, complex three-dimensional reef structures are created, which form the habitats for the many fish and invertebrates that provide food security and livelihoods across the tropical Pacific.

The environments in which coral reefs prosper have been explored using a database of the physical and chemical conditions for locations where reefs occur[47]. This analysis showed that corals require SST above ~ 18°C, ample light, and aragonite saturation states > 3.3 (a measure of the amount of calcium and carbonate in the water column relative to the precipitation point of aragonite – a form of calcium carbonate).

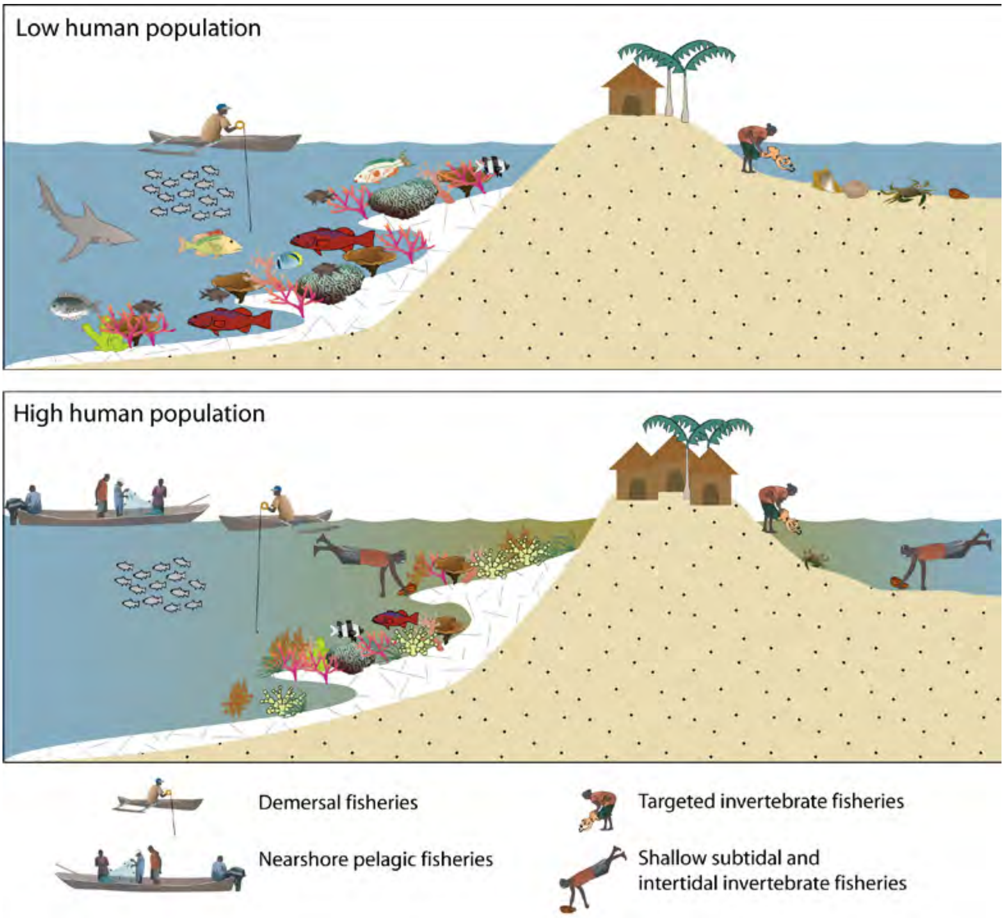


Figure 5.3 Common coastal fisheries activities in the tropical Pacific for demersal fish, nearshore pelagic fish, invertebrates targeted for export and shallow subtidal and intertidal invertebrates which occur on/or near coral reefs. In areas with low human populations, reefs have a greater abundance of reef-building corals and associated fauna. As human populations increase, fisheries resources decrease and reef ecosystems shift towards a mixture of seaweeds and corals, with seaweeds increasing as human activities become more intense. Lower numbers of demersal fish cause people to focus on other resources, such as gleaning invertebrates from shallow subtidal and intertidal areas, and nearshore pelagic fish.

While SST, light and concentrations of carbonate ions are the most important variables determining the formation of coral reefs, other factors such as river runoff, low salinity events and storms also influence the development of reefs. Large rivers often deliver substantial amounts of fresh water, nutrients and sediments to coral reefs, especially where catchments have been disturbed by agriculture, mining and deforestation (Chapter 7). In some cases, corals have been lost in the receiving waters of such catchments[48,49]. Severe rainfall events can lead to local flooding and drainage reductions in salinity, ultimately killing corals and other coral reef organisms. In the parts of the tropical Pacific prone to cyclones, reefs are also damaged by storm surges, which break corals, shift sand, and destroy reef structures. The effects of runoff, salinity and severe storms can also interact. For example, coral reefs affected by coastal runoff may not calcify as fast as those in clear and well-mixed waters, and may be more susceptible to (or take longer to recover from) wave damage. Sometimes greater amounts of particles in the water column may increase the food resources for bioeroders, leading to potentially higher erosion rates. These interactions have the potential to combine with other stresses, such as overfishing, to produce sudden changes (phase shifts) in the structure of coral reefs and the animal and plant communities associated with them[50,51].

5.5 Coral reefs in a changing world

There is growing evidence that the structure and ecological function of coral reefs are undergoing some major changes due to local and global stressors. Studies of coral reefs in the tropical Pacific and Southeast Asia show that the percentage of coral cover in 2007 was only about half that of the early 1980s[52]. This decline suggests that coral reefs are losing their dominant coral populations at about 1–2% per year. Interestingly, coral loss has occurred not only in areas, such as Southeast Asia, under pressure from local factors, but has also been observed in some well-managed regions, such as the inshore Great Barrier Reef. A systematic survey by the Australian Institute of Marine Science showed that although coral cover on offshore reefs of the Great Barrier Reef has not declined at the same rate as on inshore reefs, growth and calcification has slowed significantly (around 15% since 1990) in long-lived *Porites* colonies across the entire Great Barrier Reef [53]. This study suggests that ocean warming and acidification are beginning to play a greater role in the demise of coral reefs than local factors, such as water quality, destructive practices and overfishing.

5.5.1 Effects of global warming on coral reefs in the tropical Pacific

One of the key characteristics of reef-building corals is their mutualistic symbiosis with populations of dinoflagellates (*Symbiodinium*). These tiny plant-like organisms occupy vacuoles within cells associated with the gastrodermal tissues of corals, imparting an overall brown colour to their animal host (**Figure 5.4**). *Symbiodinium* photosynthesise while they are resident within the cells of the host coral, and produce abundant organic carbon. This carbon is transferred to the coral, where it powers growth, reproduction and calcification. As a result of this abundant energy, corals are able to grow and calcify rapidly, providing in return much-needed inorganic nutrients to *Symbiodinium*, and calcium carbonate to the reef community[54].

The symbiosis between corals and *Symbiodinium* breaks down under stressful situations. Sudden reductions in salinity, or increases in chemical toxins, SST or solar irradiance, will cause corals to turn brilliant white, as the brown *Symbiodinium* cells leave their tissues[24]. This phenomenon is referred to as coral bleaching (**Figure 5.4**). Deprived of their energy source, corals become much more susceptible to competitors, such as macroalgae (seaweeds), starvation, disease and death[52,55–57].

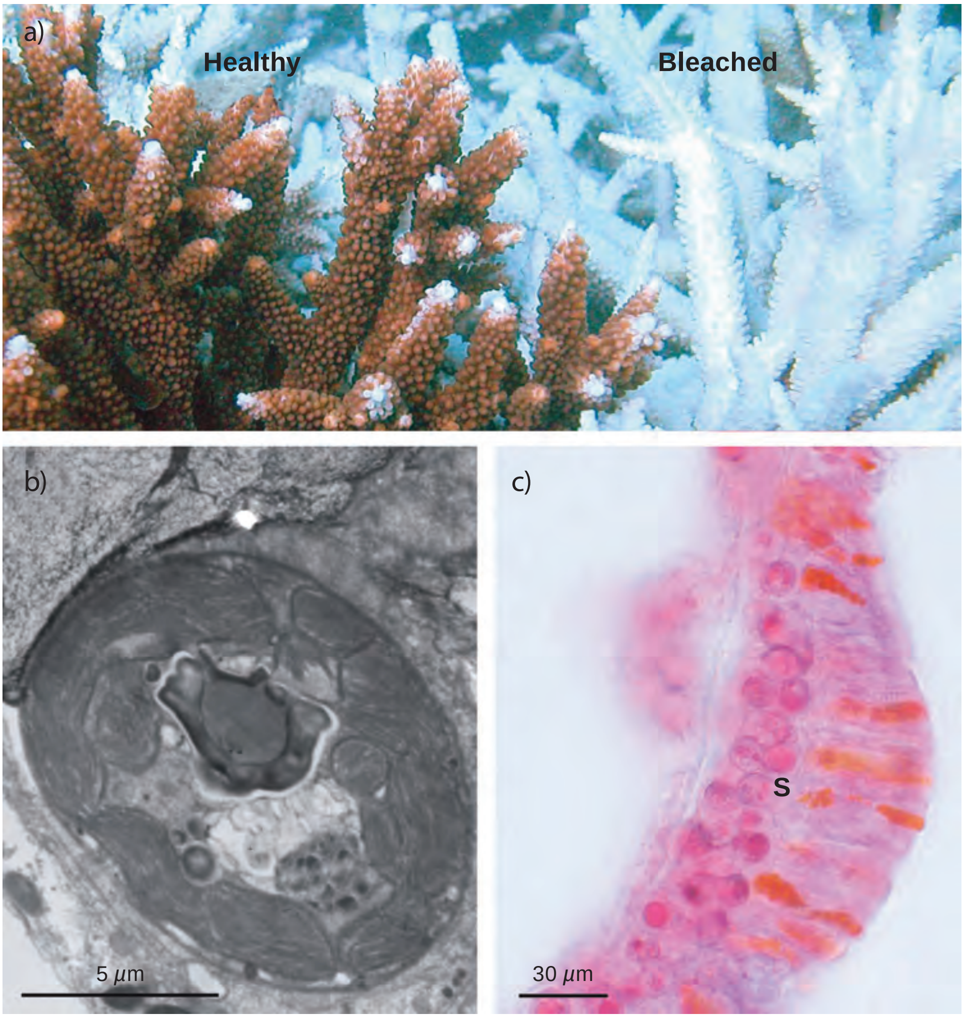


Figure 5.4 Corals, dinoflagellates and coral bleaching: (a) normally pigmented corals (*Acropora*) shown alongside bleached corals; (b) transmission electron micrograph of a single dinoflagellate symbiont (*Symbiodinium*); (c) light micrograph of dinoflagellate symbionts (S) residing within the gastrodermis of a coral polyp (photos: Ove Hoegh-Guldberg).

Coral bleaching has been reported on a local scale (small patches of reef or communities of corals) for around 80 years[58]. Starting in the early 1980s, however, entire coral reefs and regions began to experience 'mass' coral bleaching. Investigation of the environmental factors associated with mass coral bleaching soon revealed a strong causal link to periods of elevated SST, which were often correlated with doldrum-like conditions where seas were both warm and still. Elevated SST destabilises the symbiosis of corals and *Symbiodinium*, resulting in a dramatic decline in the population density of *Symbiodinium* in coral tissues[59–62].

Measurement of SST anomalies by satellites reveals strong correlations between coral bleaching, and periods when SST exceeds the summer maxima by 1–2°C for 3–4 weeks or more, especially during strong El Niño events[63,64]. The extent of mass bleaching and mortality increases as the thermal anomalies in SST intensify and lengthen[24,65]. On a smaller scale, patchiness in bleaching due to local ecological and environmental variability complicates the interpretation to some extent[66,67].

Coral bleaching has affected coral reefs in the tropical Pacific a number of times since large-scale events were first reported in the early 1980s. In each of these worldwide events, coral reefs in the region experienced high levels of mortality, albeit lower than those recorded in the western Indian Ocean, when about 46% of corals perished in 1998[68]. Projections of how SST is likely to change, however, suggest that these conditions could occur more frequently on coral reefs in the tropical Pacific over the coming decades[7,24,69,70]. In September 2010, tropical SSTs were the warmest on the instrumental record and were widespread, with extensive coral bleaching being reported in Southeast Asia and the Caribbean, among other regions. Sea surface temperatures are rising in the tropical Pacific at rates of change which exceed even the fastest rates estimated to have occurred over the past 420,000 years[7] (Chapters 2 and 3).

5.5.2 Additional effects of ocean acidification

About 25% of the extra carbon dioxide (CO_2) injected by human activities into the atmosphere is eventually absorbed by the oceans[71] (Chapter 3). On entry, CO_2 reacts with sea water to create dilute carbonic acid, which interacts with carbonate ions, turning them into bicarbonate ions[72] (**Figure 5.5**) (Chapter 3). The net effect of this process, known as ocean acidification, is a sharp decline in concentration of carbonate ions. Because of the importance of carbonate ions for reef calcification, this change results in a significant reduction in the calcification rate of reef-building corals and other calcifying organisms[73]. Considerable experimental and field evidence indicates that corals may not calcify rapidly enough to keep pace with physical and biological erosion if exposed to aragonite saturation states < 3.3[7,73].

As mentioned in Section 5.3, coral reefs represent a balance between reef calcification (by corals and other calcifiers such as crustose coralline algae) and erosion (by storms, dissolution and biological eroders). If the balance is tipped in favour of erosion, there will be a loss of reef structure and integrity over time. There is generally a close balance between calcification and erosion, with much of the calcium carbonate (> 90%) laid down being removed by biological and physical processes[74]. The precise relationship between reef calcification and erosion, however, depends on a number of factors such as water quality, location and latitude.

There is already considerable evidence that corals on the Great Barrier Reef[53,75] and in Thailand[76] are calcifying at rates that are ~ 15% lower than those before 1990. Importantly, this decrease in calcification was unprecedented in the 400 years of records examined for the Great Barrier Reef. As well as declining calcification rates, reduced carbonate ion concentrations are likely to increase the rate of biological

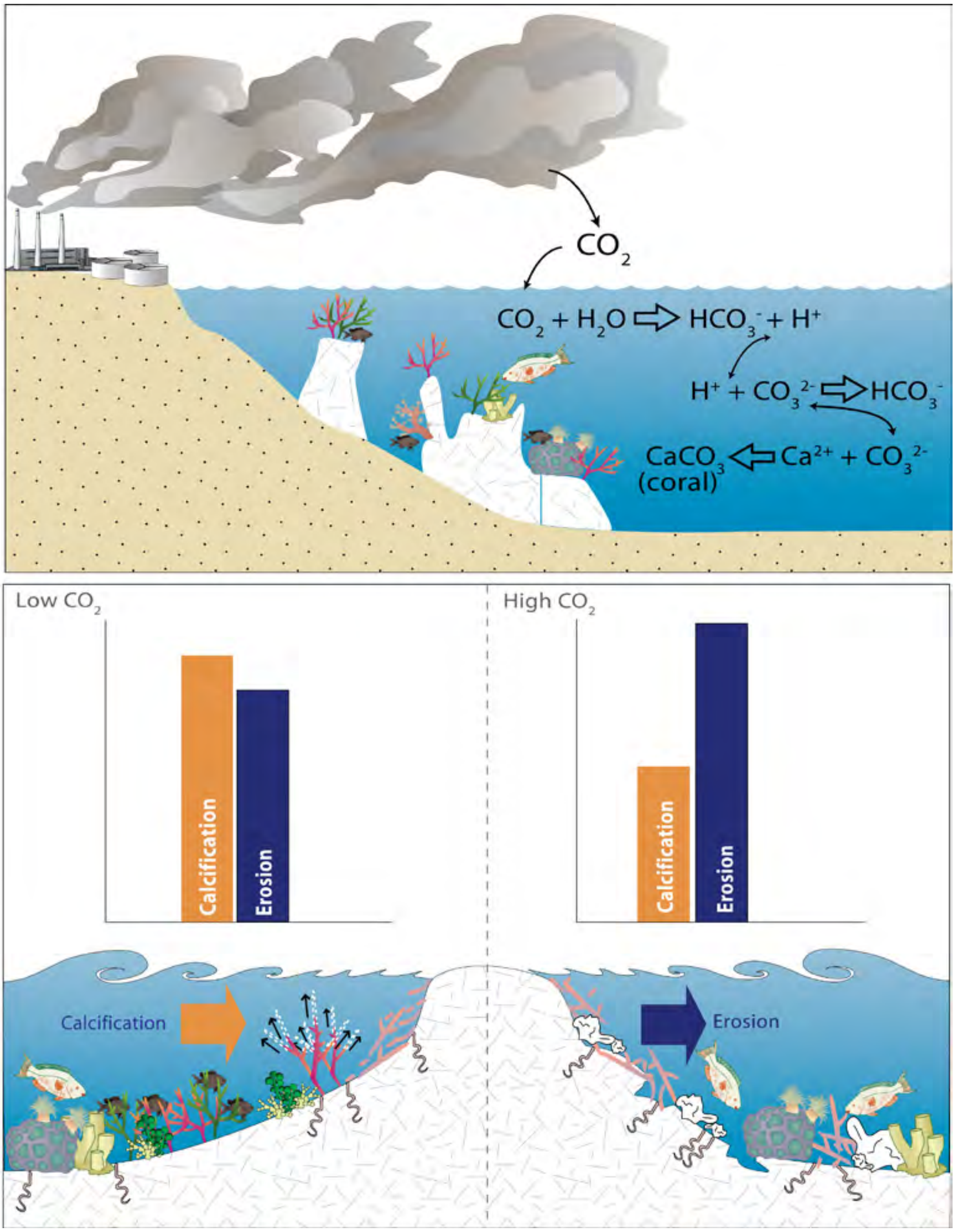


Figure 5.5 Ocean acidification is threatening reef-building corals. Carbon dioxide (CO_2) from the burning of fossil fuels is entering the ocean at greater rates and is reacting with water to produce a weak carbonic acid (upper panel). This reduces the concentration of carbonate ions, and makes fewer of them available for coral calcification (see Chapter 3 for more details). On healthy coral reefs under low atmospheric concentrations of CO_2, calcification by reef-building corals and calcareous algae usually exceeds erosion caused by wave action and biological eroders, such as boring worms, and grazing fish and invertebrates (lower panel). Under such conditions, reefs grow over time. But as CO_2 accumulates in the atmosphere, calcification is expected to decrease below the rates of erosion, with the net loss of reef frameworks over time.

erosion (via reduced density of coral skeletons and increased dissolution) favouring the activities of external bioeroders (e.g. fish and sea urchins) as well as internal bioeroders that bore into skeletons (e.g. worms and sponges)[77–79].

5.5.3 Interactions and synergies

The combination of ocean acidification with other factors that stress corals may also lead to compounding effects. For example, the thermal threshold at which some corals bleach decreases when they are exposed to more acidic conditions[80]. The combination of high SST and increased acidity also leads to a more dramatic loss of coral reef productivity than if each factor acts on its own[80]. There are also likely to be a number of surprises given the complexity of the situation. A potential concern is that coral communities and skeletons weakened by bleaching and ocean acidification could be damaged more severely by more intense storms if they eventuate (Chapter 2), leading to accelerated degradation of reef frameworks.

Interactions between local factors, such as poor water quality and overexploitation of key reef species, and ocean warming and acidification, could also lead to synergistic and accelerated impacts. Crustose coralline algae, for example, play a crucial role within reef habitats as a settlement cue for a large number of invertebrates (including corals) and plants. Recent evidence has suggested that crustose coralline algae may be highly vulnerable to ocean acidification[80], thereby potentially leading to negative impacts on the settlement of corals and other reef-associated organisms, such as sea urchins[28]. Similarly, corals exposed to nutrients, sediments or pathogens are more susceptible to thermal bleaching, and less able to survive a bleaching episode[81]. While the precise details of these interactions remain to be documented, they appear to have the potential to amplify the individual effects of global warming and ocean acidification, leading to a reduced ability of coral reefs to bounce back from catastrophic events (i.e. reduced resilience).

5.5.4 Changes to coral reefs over time

The fossil record provides a strong indication of the changes likely to occur to coral reefs under rapid global climate change[70]. In particular, it shows that the five mass-extinction events that occurred on the planet were associated with 'reef gaps', which typically lasted for at least 4 million years. Coral communities and their associated limestone deposition are more or less missing from the palaeontology record at these times[70]. There is also growing evidence that the major extinction events were accompanied by changes in atmospheric CO_2 which led to global warming and ocean acidification. Interestingly, all but one of the extinction events (during the Cretaceous-Tertiary period 65 million years ago) seem to have occurred at much slower rates of change in the Earth's atmosphere and oceans than those observed over the past 100 years[82]. These past climate events provide compelling reasons for limiting further build-up of CO_2 in the atmosphere.

Photo: Éric Clua

Healthy coral reefs are important fish habitats

5.6 Projected vulnerability of coral reefs to climate change

In this section, we explore the projected vulnerability of coral reefs in the tropical Pacific to a changing climate. The approach we use to assess vulnerability is described in Chapter 1. This vulnerability framework integrates the exposure of coral reefs to climate change with their sensitivity to these changes, and provides a measure of the potential impact which may or may not be reduced through the putative adaptive capacity of corals and other key components of coral reefs. The same set of variables that determine the vulnerability of coral reefs have been assessed for the Great Barrier Reef[81,83,84], where the changes appear to be occurring at rates which are 100–1000 times faster than ice age transitions[7], outstripping the ability of corals and their *Symbiodinium* to keep pace. There is also concern that coral reefs in the tropical Pacific are unlikely to have the capacity to adapt to the high rates of change in their environment.

5.6.1 Sea surface temperature

Exposure and sensitivity

The average annual SST across the tropical Pacific increased by 0.23°C between 1989 and 2008, relative to average annual SST between 1950 and 1969 (Chapter 2). SST is projected to increase by 0.5–1.0°C in 2035 under the B1 and A2 emissions scenarios, by 1.0–1.5°C under B1 in 2100, and by 2.5–3.0°C under A2 in 2100, relative to SST between 1980 and 1999 (Chapters 2 and 3).

As discussed in Section 5.5.1, reef-building corals are very sensitive to these levels of warming, although there are some limited differences in thermal sensitivity between types of corals, and among *Symbiodinium*. The exposure and sensitivity of corals to rising SST have already had large-scale influences on reefs in the tropical Pacific and elsewhere in the world, with coral cover declining globally by 1–2% per year[52]. As outlined below, rising SST is expected to have further impacts on coral reefs.

Potential impact and adaptive capacity

As SST increases, reefs will continue to lose coral cover and may ultimately become dominated by macroalgae (**Figure 5.6**). The impact on corals can be expected to vary among species. Indeed, this is already happening under present-day temperature and bleaching regimes, which are causing changes in the species composition and structure of coral communities[85]. In particular, differential sensitivity to thermal stress between coral genera[86–88] is leading to shifts towards the more tolerant species[89]. However, because the differences in sensitivity between genera are generally limited to no more than about 2–3°C, shifts in coral communities are expected to be characteristic only of the next couple of decades. If SST increases beyond 2°C above preindustrial levels, most species of coral are likely to be rare on tropical reefs[7,24,81,90,91].

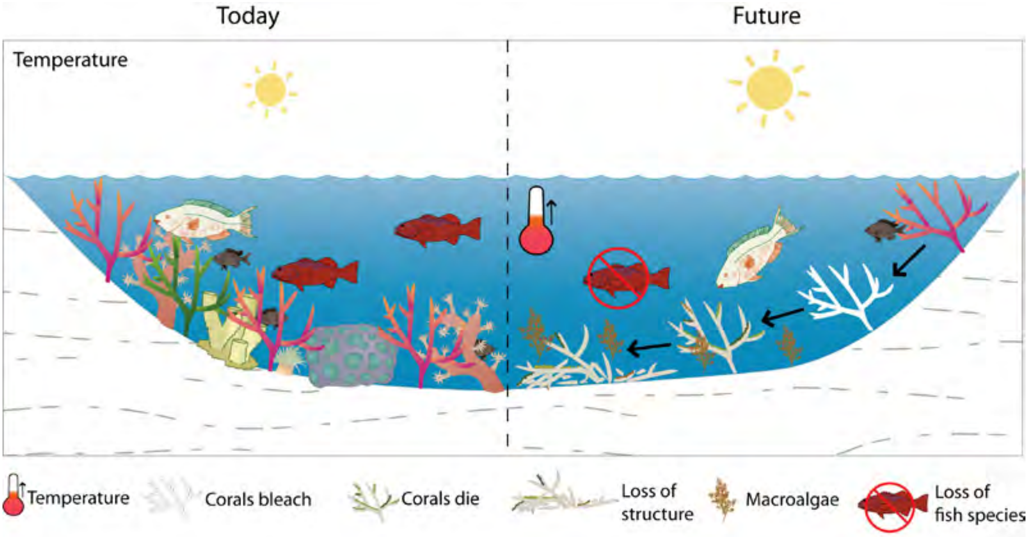


Figure 5.6 Effects of projected increases in sea surface temperature (SST) and light on coral reefs. Under present-day conditions, short periods of warmer-than-average maximum SST cause bleaching events. Healthy coral reefs recover from these disturbances and the abundance of corals remains high. As SST increases by 1°C or more above preindustrial levels, bleaching events are expected to become more intense and frequent, with the loss of corals, reef structure, and associated fauna, and increases in macroalgae, over time.

In addition to the greater tolerance to higher SST, some coral species appear to have some additional capacity to adapt to warmer waters. A few colonies within some populations of the coral *Acropora millipora* can increase the proportion of more temperature tolerant *Symbiodinium* in their tissues[92]. However, this strategy appears to provide an added tolerance to higher SST of up to only 1.5°C, and few of the colonies involved actually survived extreme heat stress. Furthermore, the cost that corals have to pay for such increased temperature tolerance may be slower growth, which is likely to have other negative ecological implications. Thus, this potential adaptive mechanism, called 'symbiont shuffling', is unlikely to protect reefs from the severe and repeated damage projected to occur due to rapid increases in SST.

There has been some discussion about the potential for coral populations to expand their distributions to higher latitudes as these areas begin to warm[24]. Such shifts have been reported in the palaeontological record, when coral communities extended their range by about 100 km in a poleward direction during periods when SST was slightly higher[93]. Nevertheless, there are limits to how far north or south coral populations can shift due to the decrease in pH and carbonate ion concentrations towards the poles. Projected increases in atmospheric CO_2 above 450 ppm are also expected to lead to contraction of suitable conditions for the growth of coral to the small band around the equator[7] (Section 5.6.3). In short, although waters at higher latitudes are expected to be warmer, corals will be unable to adapt by moving poleward.

Vulnerability

All existing information leads to the conclusion that coral reefs have very high vulnerability to further increases in SST, and the projected increase in SST in the tropical Pacific region of 1–3°C by 2100 will strongly influence the structure and function of coral reefs. Effects are expected to be clearly evident by 2035, but given the similarity in projected SST between the B1 and A2 emissions scenarios in 2035 (Chapters 2 and 3), there is little or no difference in the vulnerability of coral reefs to changes in SST under these two scenarios in the shorter term.

5.6.2 Solar radiation

Exposure and sensitivity

Global climate change is altering, and is likely to continue to alter, the weather and general circulation patterns, as outlined in Chapter 2. As a result, the distribution of clouds is likely to change, potentially affecting the amount of solar radiation reaching coral reefs. Climate change is also expected to result in an increase in rainfall in equatorial areas, and a decrease in rainfall in the southwest and southeast Pacific (Chapter 2).

Coral reefs are sensitive to both photosynthetically active radiation (PAR) and ultraviolet radiation (UVR). High levels of PAR will exacerbate coral bleaching[24,94], whereas high levels of UVR have the potential to increase damage to cellular components such as DNA. Sunlit waters without currents and waves amplify the effect of thermal stress on corals. In contrast, shading by high islands[95,96] or unusually cloudy conditions[25] reduces the effect of thermal stress on coral reefs.

Potential impact and adaptive capacity

Within limits, corals have some capacity to adapt to both high and variable PAR and UVR[97]. Acclimation takes between five and ten days, during which time the coral remains physiologically stressed. Corals can also acclimate to lower light levels in turbid waters, with turbidity potentially protecting them from bleaching[26]. The events causing turbidity (e.g. heavy rainfall and strong winds), however, appear to be unlikely to occur during the hot and still conditions that result in higher levels of irradiance. Turbidity is also likely to play a more important role in coastal areas where sediments and nutrients (and associated phytoplankton blooms) may reduce irradiance during stressful periods.

Vulnerability

On the basis of the capacity of corals to photo-acclimate within days, coral reefs appear to have a relatively low vulnerability to the changes in solar radiation expected to occur under either the B1 or A2 scenarios over the coming decades and century.

5.6.3 Ocean acidification

Exposure and sensitivity

As with SST, the current rates of change in atmospheric CO_2 and ocean acidification are believed to be more rapid than during any other period in at least the past 420,000 years[7] (Chapter 3). Ocean pH has already decreased by 0.1 units (representing a 26% increase in hydrogen ions) since the start of the industrial era and will continue to decrease as long as the oceans continue to absorb the increasing concentrations of CO_2 in the atmosphere (Chapter 3). Under the A2 emissions scenario, the aragonite saturation state in tropical surface waters is projected to decrease to 2.4 in 2100 (Chapter 3).

These projected changes will be hostile to coral reefs because the rate of calcification of corals and crustose coralline algae is highly sensitive to declining carbonate ion concentrations[73]. Furthermore, processes such as bioerosion are likely to increase as the concentration of carbonate ions decreases (**Figure 5.7**). Indeed, the current distribution of corals, together with experimental investigations and now field evidence, indicates that the ability of corals and other marine calcifiers to maintain a positive reef carbonate balance falls into deficit when atmospheric concentrations of CO_2 exceed 450 ppm (which translates to carbonate ion concentrations of ~ 200 μmol per kg of sea water at equilibrium). There is also considerable evidence that concentrations of CO_2 above 350 ppm may be too much for the maintenance of carbonate coral reef systems[70].

Potential impact and adaptive capacity

Experimental studies[73] and field studies[53,75,76] indicate that substantial decreases in calcification can be expected to result in more fragile and degraded reef frameworks. There is little evidence of calcifying organisms adapting to the lower carbonate ion concentrations likely under ocean acidification. Indeed, although some temperate coccolithophores (a prominent member of the marine phytoplankton) may grow more quickly[98], corals and other tropical calcifying organisms are highly unlikely to be able to adapt at rates fast enough to keep up with the rapid acidification of the ocean projected under the A2 scenario (Chapter 3).

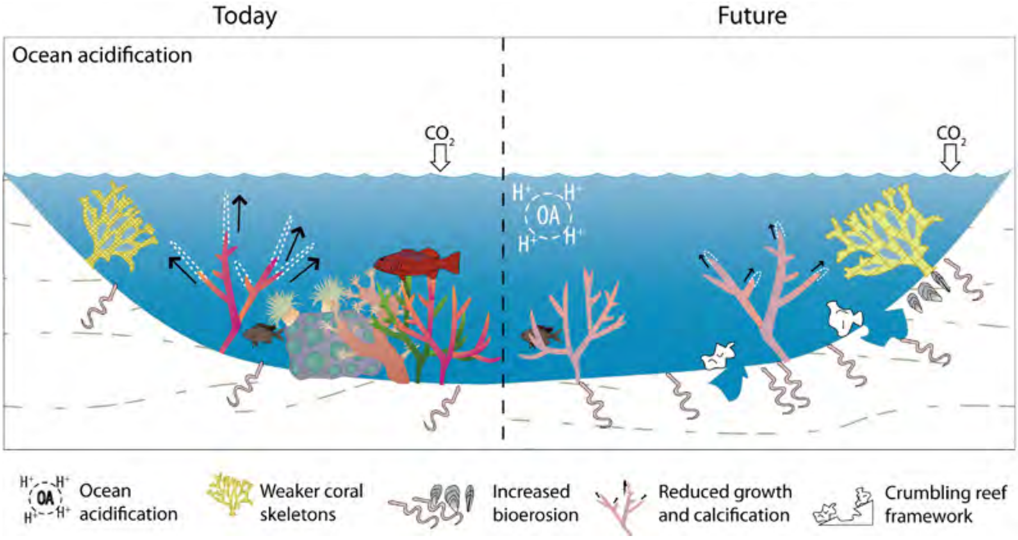


Figure 5.7 Effects of projected ocean acidification (OA) on coral reefs. The rising concentration of carbon dioxide (CO_2) in the atmosphere from the burning of fossil fuels is acidifying the world's oceans and decreasing concentrations of carbonate ions (Figure 5.5). Reduced calcification of reef-building corals and crustose coralline algae when CO_2 exceeds 450 ppm is expected to change the balance of reef processes from net construction to net erosion, leading to loss of corals and reef frameworks.

Vulnerability

The reduction in calcification rates at low carbonate ion concentrations suggests that corals, and the reefs they build, are highly vulnerable to ocean acidification, and that increases in atmospheric CO_2 above 450 ppm are likely to result in a negative carbonate balance (net erosion) of coral reefs throughout the tropical Pacific. This outcome will have important implications for ecological services, such as coastal fisheries (Chapter 9) and coastal protection.

5.6.4 Tropical cyclones and floods

Exposure and sensitivity

Warming of the tropical Pacific climate may gradually increase the intensity of tropical cyclones by 6–12%, equivalent to about half a cyclone category[99,100], over the remainder of the century (Chapter 2). Any such increases will have severe ecological implications because the energy dissipated by a cyclone increases as the cube of its maximum wind speed[101]. In equatorial regions, rainfall is projected to increase by 5–20% in 2035, and by 10–20% in 2100 (Chapter 2), increasing the likelihood of flooding.

Coral reefs are extremely sensitive to local physical damage caused by cyclones and storms because, as explained above, this damage escalates non-linearly with increasing maximum wind speed[102]. Reefs will be affected further by the low salinity, higher turbidity and nutrient-rich waters associated with floods caused by storms[49,103,104] (**Figure 5.8**). Damage from cyclones and storms may also trigger ecological 'phase shifts', especially when reefs are subject to overfishing of key functional groups[50].

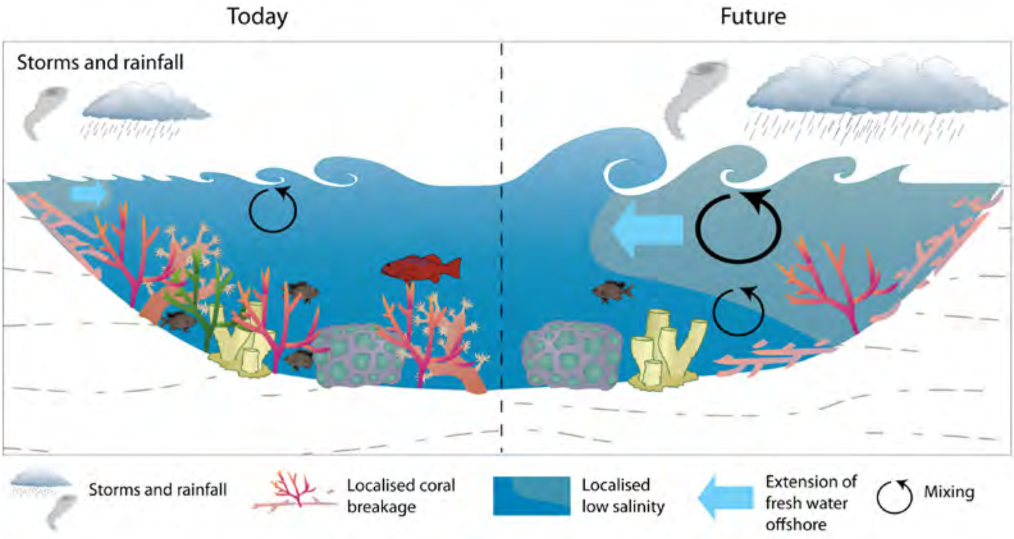


Figure 5.8 Effects of stronger cyclones and heavier rainfall on coral reefs, which are expected to lead to greater loss and degradation of habitat through damage by more powerful waves, reduced salinity and increased turbidity of coastal waters. The effects of stronger cyclones and increased rainfall are also expected to interact with higher sea surface temperatures (**Figure 5.6**), increased acidification (**Figure 5.7**) and local factors, such as poor catchment management, to cause severe problems for coral reefs.

Potential impact and adaptive capacity

There are numerous examples of the impact of cyclones and floods on coral reefs in the tropical Pacific, as well as evidence of recovery over periods stretching from 15–50 years. The effects of intensified cyclones are only just being studied, and can be hard to distinguish from background levels of damage from the normal range of storms. On the Great Barrier Reef, for example, a hypothetical increase in cyclone intensity by half a category is expected to result in a 50–60% increase in the loss of coral, and a substantial reduction in the structural complexity of reefs[102].

Projected changes to rainfall patterns may also lead to drying of coastal areas in the subtropical southeast and southwest Pacific, exacerbating the problem by loosening sediments and nutrients such that they are more easily washed out of coastal catchments during episodic high rainfall events (Chapter 7). More intense rainfall is also expected to exacerbate runoff from high islands in the equatorial Pacific.

There are strong regional differences in the past exposure of coral reefs to cyclones, with coral reefs in the northwest Pacific experiencing more and stronger cyclones than reefs south of the equator (Chapter 2). Coral communities exposed to storms are dominated by species with stout growth forms, and by fast-growing species, such as *Acropora* spp. These reefs have had thousands of years to adapt to local storm intensity. But no level of adaptation protects coral reefs from severe damage by category 4 or 5 cyclones.

Vulnerability

Coral reefs are expected to be moderately vulnerable to increasing cyclone intensities in their own right. Against the background of chronic stress from acidification, higher SST, unsustainable coastal land use practices and overexploitation of key functional groups, such as herbivores, more intense tropical cyclones could, however, also act as key agents for change in coral reef habitats. This compounding of threats can lead to sudden changes in ecological state[50], where any single factor could well cause the collapse of coral reefs.

5.6.5 Sea-level rise

Exposure and sensitivity

Average global sea-level rise has accelerated from 1.8 to 3.3 mm per year within the last century, and the rate is expected to increase with further thermal expansion of the ocean and melting of land ice[105,106] (Chapter 3). The unexpectedly rapid decline and thinning of Arctic sea ice (which does not affect sea level) and land-based polar ice sheets[107–109], shows that our current understanding of ice dynamics is still poor. Even so, research has shown that the western Antarctic ice sheet is breaking up much faster than projected, and that it has broken down at least 60 times over the past 5 million years when concentrations of CO_2 reached 400 ppm[110].

A significant threshold in the rate at which ice melts is expected to occur when average global temperatures are 2°C higher than preindustrial temperatures. At this point, temperatures above the Greenland ice sheet are projected to reach 3°C, which is considered the point at which rapid melting is likely to occur[110,111]. Based on this assumption, many experts recently agreed that sea level could rise by at least 1 m by the end of the century, with a possible possible rise of up to 2 m[112] (Chapter 3).

There is evidence that rapid sea-level rise over several decades has caused major, albeit short-lived, changes to coral reef communities and the structure of reefs due to rapid changes in depth, light and other factors such as wave stress[113]. However, sensitivity of coral reefs to future sea-level rise is expected to depend also on the influence of other factors on coral growth rate. In particular, reefs that are heavily stressed by global warming and ocean acidification are likely to be much more sensitive to sea-level rise. It is difficult to be more specific about the sensitivity of coral reefs to sea-level rise at this stage due to uncertainty about how sea level could change over the coming decades[106].

Potential impact and adaptive capacity

Healthy shallow-water corals can grow at rates which allow them to keep up with the current rate of sea-level rise and to colonise new areas. However, because significant increases in the rate of sea-level rise, over and above the conservative estimates reported by the IPCC[105], seem likely to occur by the end of this century, corals growing in marginal environments (e.g. low light or high latitudes, or in lagoons) may be unable to cope. This projection is supported by the fact that many reefs have 'drowned' throughout geological history. If thermal stress and ocean acidification inhibit the ability of corals to grow and calcify, rapid changes in the rate of sea-level rise may become a significant additional stress factor for coral reefs, even in shallow water (**Figure 5.9**).

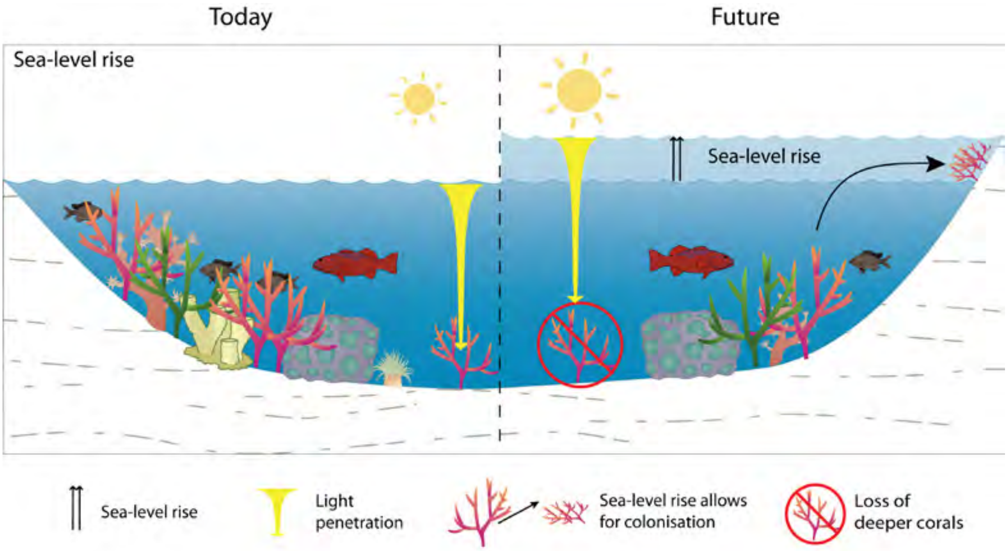


Figure 5.9 Effects of projected sea-level rise on coral reefs. Where corals and other reef building organisms are healthy, reefs should keep up with rising sea levels. Unfortunately, the combined effects of increased sea surface temperatures (**Figure 5.6**) and ocean acidity (**Figure 5.7**) are likely to mean that corals in some places will not grow fast enough to maintain their positions in the water column with the projected rapid sea-level rise. Some coral reefs may 'drown' as sea levels increase, but new areas may also be colonised where conditions for coral growth remain favourable.

Vulnerability

Coral reefs will vary in their vulnerability to sea-level rise. Corals with reduced growth rates due to thermal stress and ocean acidification, or corals with naturally slow growth rates in marginal environmental conditions (e.g. deeper water), may have a high vulnerability to the accelerating rise in sea level.

5.6.6 Ocean circulation and upwelling

Exposure and sensitivity

Ocean circulation patterns are important drivers of the productivity and function of coral reefs, and the connectivity of their populations[114]. The projected decreases in the strength of the equatorial branch of the South Equatorial Current (SEC) and the South Equatorial Counter Current (SECC), and alterations in the location and magnitude of upwellings resulting from these currents (Chapter 3), may therefore lead to changes in the genetic structure and connectivity of marine populations. By 2100, under the A2 scenario, the flow of the SECC is expected to decrease by up to 60%, and the SEC by ~ 20%.

Reductions in net primary production (NPP) and the density of zooplankton are also projected for all ecological provinces described for the tropical Pacific[115], except the Pacific Equatorial Divergence (Chapter 4). The decline in the availability of nutrients is expected to be greatest in the Archipelagic Deep Basins province[115], where NPP is projected to decrease by 20% in 2100 under the B1 emissions scenario, and by > 30% in 2100 under A2 relative to levels in 2000–2010 (Chapter 4). This ecological province includes Fiji, PNG, New Caledonia and Vanuatu, i.e. the PICTs with the vast majority of the population of the region.

Changes in currents have implications for the replenishment potential, and replenishment rate, of coral communities, and for fisheries management strategies, including the design of marine protected areas. Coral reef habitats are also highly sensitive to NPP, which in turn depends on mixing of the water column (Chapters 3 and 4). Increased stratification can be expected to lead to reduced access to nutrients by photosynthetic organisms in the photic zone, and reduced availability of food for organisms at higher trophic levels.

Potential impact and adaptive capacity

There are marked regional differences in oceanic currents, thermal stratification, upwelling and nutrient availability across the tropical Pacific[116] (Chapters 3 and 4). Although coral reefs and their associated organisms have adapted over many thousands of years to such environmental differences, decreases in NPP associated with stratification of the water column in tropical areas[117,118] (Chapter 4) have been associated with disturbances to organisms as diverse as fish, turtles and seabirds[119]. The relatively rapid changes to ocean circulation and upwelling, and the projected decreases in NPP, could lead to greater disruptions to the ecology of both phototrophic species (e.g. phytoplankton and seaweed) and heterotrophic species (e.g. fish and invertebrates) associated with coral reefs.

Vulnerability

Given the projected changes to the strength of the SEC and SECC, and the expected increases in nutrient-poor waters across much of the tropical Pacific (Chapters 3 and 4), coral reefs have a moderate vulnerability to changes in ocean circulation and upwelling as a result of climate change. Ultimately, the locations of coral reefs will have a strong effect on the extent of their vulnerability to changes in currents and upwelling – some will receive fewer nutrients, whereas others will receive more. Either eventuality is likely to alter the local ecosystem. Coral reefs in the Archipelagic Deep Basins province are generally likely to be more strongly affected, although reefs close to localised upwelling, and high islands, should continue to receive adequate nutrients.

5.7 Projected changes: coral reefs under low versus high CO_2 emissions

The primary intention of this chapter is to establish credible pictures of what coral reefs will look like under two distinct CO_2 emissions scenarios for this coming century. In this respect, we extend the analyses of atmospheric climate and the Pacific Ocean undertaken in Chapters 2 and 3, based on the extensive modelling for the Special Report on Emissions Scenarios and the IPCC process[10,120,121] (Chapter 1), to explore the effects of a low emissions (B1) and a high emissions (A2) scenario on coral reefs in 2035 and 2100.

As described above, under these two globally referenced background scenarios, SST in the tropical Pacific is expected to increase within the range of 0.5–1.0°C, atmospheric CO_2 to build up to around 430–450 ppm, and sea level to rise by 6–10 cm by 2035. Given the short amount of time to this point (~ 25 years), changes to the atmosphere and tropical Pacific Ocean under the B1 and A2 scenarios are expected to be largely indistinguishable in 2035, diverging only later this century (Chapters 2 and 3). By 2100 under the B1 and A2 emissions scenarios, SST is expected to be 1.0–1.5°C and 2.5–3.0°C warmer, atmospheric CO_2 is projected to reach 500–600 ppm and 750–800 ppm, and sea level to rise by at least 18–38 cm and 23–51 cm (but see Section 5.6.5), respectively, relative to 1980–1999 (Chapters 2 and 3). In addition, changes to rainfall, ocean circulation and upwelling, and the possibility of more intense cyclones, are projected in 2035 and 2100. The relative vulnerability of coral reefs to each of these variables (Section 5.6) is summarised in **Table 5.2**.

Taken together, these projections define the exposure of coral reefs to the two scenarios for the remainder of the 21st century. By combining exposure with the sensitivity and adaptive capacity of corals described above, it is possible to provide credible projections of how coral reefs are likely to be altered by 2035 and 2100.

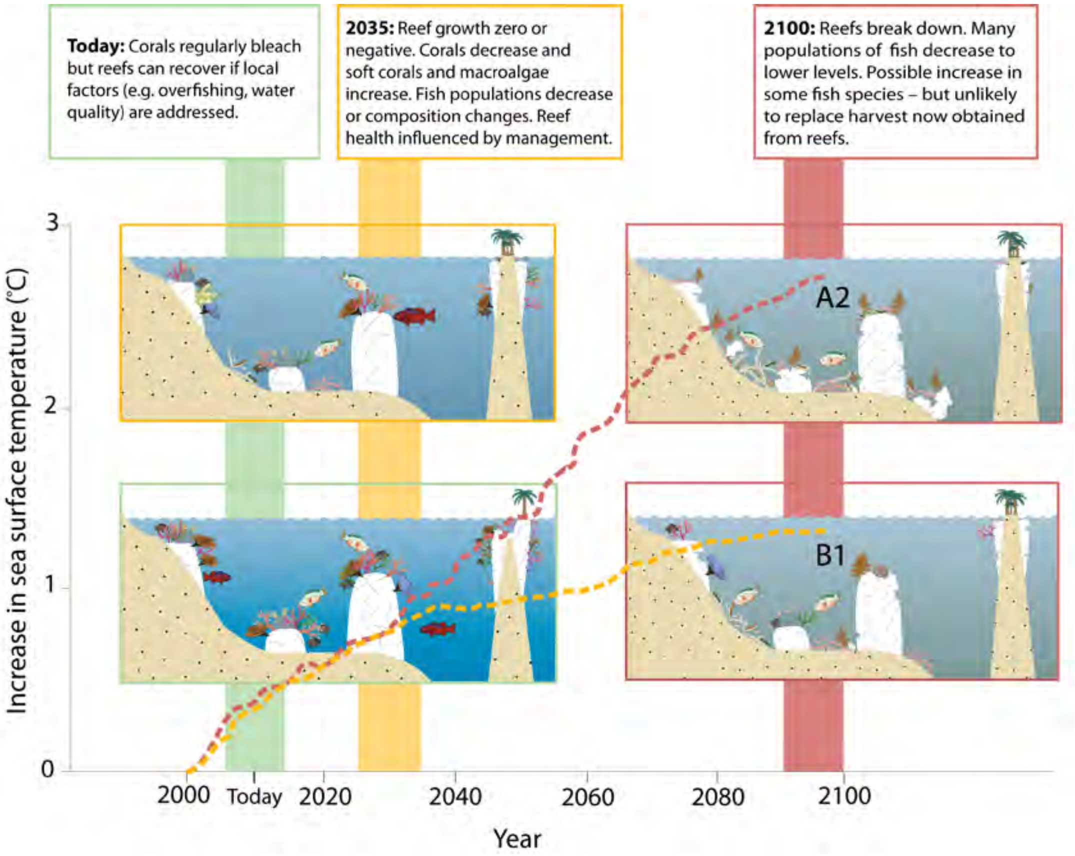
Table 5.2 Summary of the vulnerability of coral reefs to the key variables associated with increases in carbon dioxide and other greenhouse gases.

Sea surface temperature	Solar radiation	Ocean acidification	Cyclones and floods	Sea-level rise*	Ocean circulation
Very high	Low	Very high	Moderate	Low-moderate	Moderate

* There is significant uncertainty regarding the rate at which polar ice will melt (Section 5.6.5), which will be an important determinant of the vulnerability of coral reefs to sea-level rise.

5.7.1 The next two to three decades: coral reefs in 2035 (B1 and A2)

Conditions under the B1 and A2 scenarios are expected to be similar in 2035 (Chapters 2 and 3), therefore they are discussed together here. The projected steady increase in SST is expected to cause coral bleaching to occur twice as frequently as it does today (**Figure 5.10**). Several episodes of mass coral bleaching are likely to have occurred by 2035, equalling or exceeding those of 1998 when coral reefs all over the world bleached and 16% of the world's corals died within 9 months[24,68]. Coral reefs in the Pacific were affected variably by the 1998 bleaching event, with the southwest and northeast parts of the region experiencing minimal bleaching, and the southeast and northwest Pacific experiencing moderate to severe bleaching[68].



Today: Corals regularly bleach but reefs can recover if local factors (e.g. overfishing, water quality) are addressed.

2035: Reef growth zero or negative. Corals decrease and soft corals and macroalgae increase. Fish populations decrease or composition changes. Reef health influenced by management.

2100: Reefs break down. Many populations of fish decrease to lower levels. Possible increase in some fish species – but unlikely to replace harvest now obtained from reefs.

Figure 5.10 The future of coral reefs under B1 and A2 emissions scenarios. Note that the B1 and A2 trajectories are largely indistinguishable by 2035 but diverge after 2050. Under the B1 scenario 2100, coral populations are projected to decrease and reefs are expected to be dominated by non reef-building species. Under the A2 scenario in 2100, sea surface temperatures and ocean acidity, as well as other factors such as turbidity and possibly cyclone intensity, are expected to increase. This is likely to lead to the complete loss of reef-building corals from reefs. Yellow and red vertical columns correspond to the range of years used to model the B1 and A2 emissions scenarios.

The steady downward trajectory of coral cover (1–2% lost per year)[52] is likely to continue until 2035 (Figures 5.10 and 5.11), with loss of another 25–65% of coral cover. Given the increased levels of stress, this annual projected rate of loss is conservative and is expected to be higher than that reported earlier[52]. Average coral cover throughout the tropical Pacific is projected to be around 15–30% in 2035 (**Table 5.3**), compared with 20–40% in 2007[52], and dominated increasingly by more robust species, such as *Porites* and *Favia*, and less by branching species, such as *Acropora* and *Stylophora* (**Figure 5.12**). Some coral reefs are likely to have been significantly affected by more frequent bleaching events, as described above, with coral communities disappearing completely from these reef systems. At this time, management efforts aimed at reducing local threats, such as overfishing and pollution (Section 5.9), will have an important effect on the health of coral reefs, given that reef-building corals are likely to be struggling to remain as significant members of the ecosystem. In particular, effective management interventions should lead to a slower decline in coral cover (**Figure 5.11**).

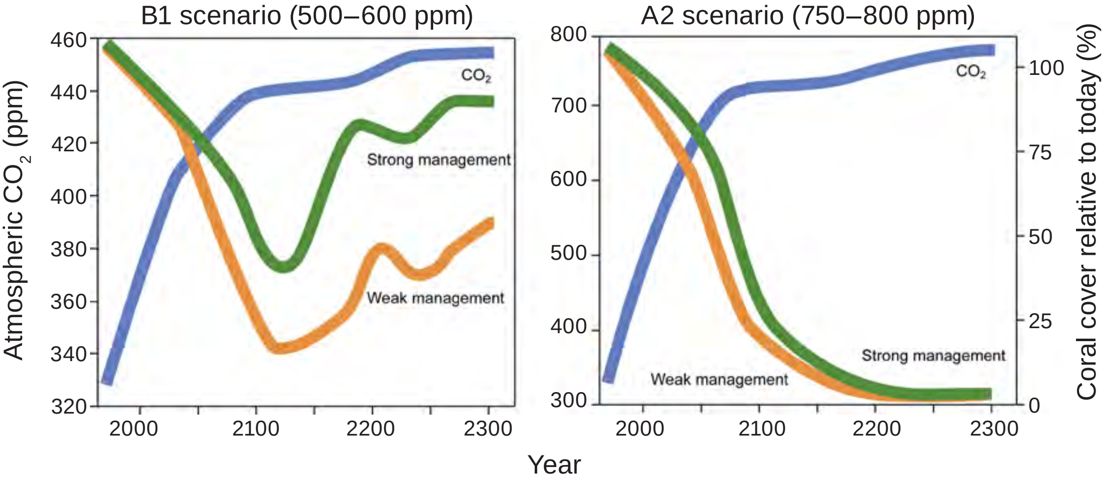


Figure 5.11 Indicative potential changes in carbon dioxide (CO_2) and coral cover over the next three centuries in a world which strongly reduces greenhouse emissions under the B1 scenario (left panel) or does not and follows the A2 scenario (right panel). The orange lines indicate likely changes to percentage coral cover for reefs if they are managed poorly. Green lines depict how coral cover is expected to change where strong policies and actions to manage and reduce local threats are implemented.

Competition between reef-building corals and non-calcareous macroalgae is expected to have intensified by 2035 as coral cover, growth and calcification continue to decrease[53,75]. As a result, macroalgal populations are likely to increase (**Table 5.3**). The projected atmospheric concentrations of CO_2 of 430–450 ppm in 2035 are expected to increase the acidity of the ocean further. Carbonate ion concentrations in large sections of the tropical Pacific Ocean are expected to decrease rapidly towards the levels where growth of many coral species cannot be sustained. The calcification of long-lived *Porites* colonies in 2035 is likely to be 50% less than that seen in the early 1990s. Many reef systems in the Pacific (especially those at higher latitudes and behind the reef crest or in lagoons) are expected to experience physical and biological erosion that exceeds calcification.

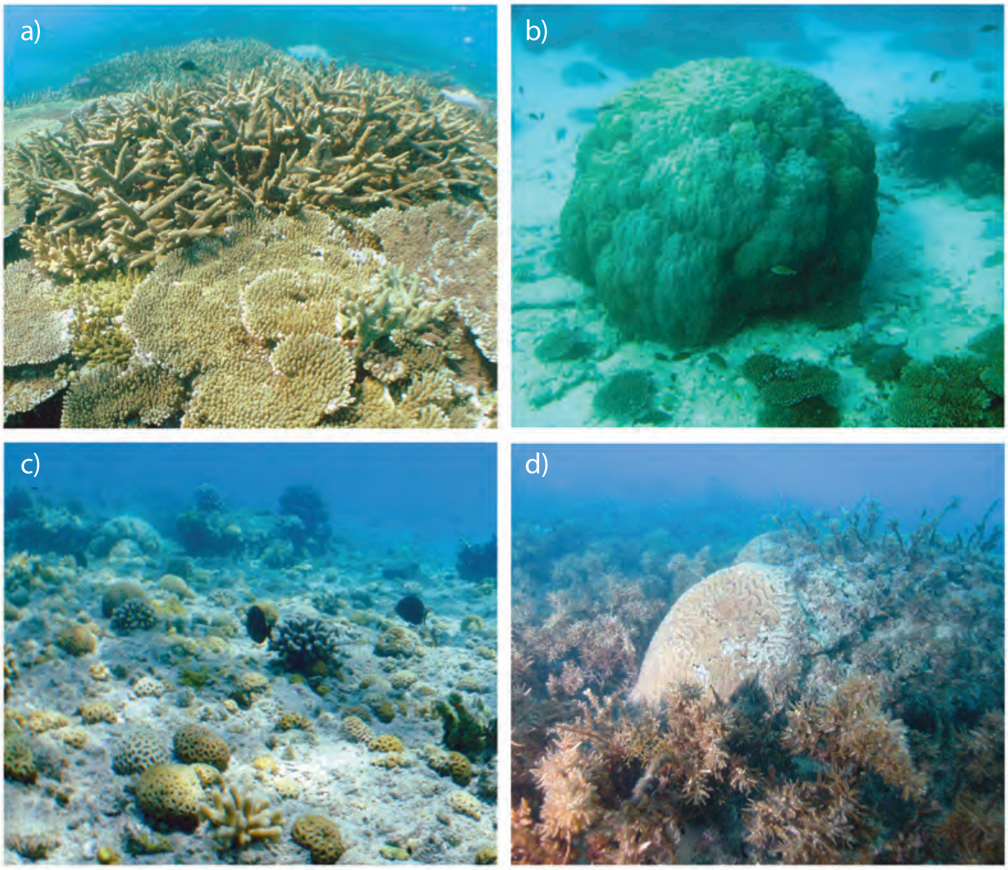


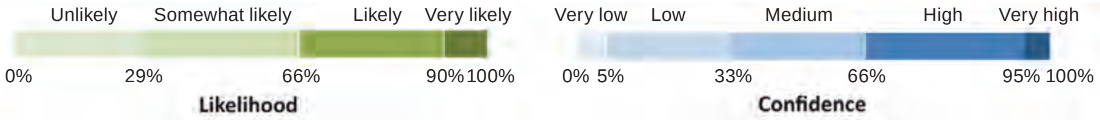
Figure 5.12 Slight differences exist between different coral species with respect to their sensitivity to climate change, particularly increased sea surface temperature (SST). Branching corals, like those shown in (a) are more sensitive (by 1–2°C) than encrusting and massive corals such as the colony shown in (b). These differences in sensitivity are very likely to lead to the reduced presence of branching corals within coral communities depicted in (c). There is less certainty when it comes to the response of other organisms such as macroalgae, which increase in prominence on reefs that have lost reef-building corals, as illustrated in (d). Whether fleshy macroalgae will be able to tolerate future SST of 2.5–3.0°C is not known (photos: Ove Hoegh-Goldberg).

The reduced structural complexity of coral reefs is projected to begin to affect the demersal fish associated with coral reefs. The species composition of this fish assemblage is expected to have greater proportions and abundances of herbivores, such as surgeonfish (Acanthuridae), rabbitfish (Siganidae) and parrotfish (Scaridae), and fewer coral-dependent species, and predatory species (Lethrinidae, Lutjanidae, Serranidae), now prized for their food and income value[41,66,122] (Chapter 9).

The largest impacts on coral reefs by 2035 are expected to occur along coastlines where land use has removed forests and destabilised catchments, causing rivers to transport increasing amounts of sediment and nutrients onto struggling coral reef habitats (Chapter 7). The problems that coral reefs face from declining water quality will be exacerbated where mangroves have been removed or damaged, because of the reduced capacity to retain sediments (Chapter 6). In such nearshore coastal ecosystems, the amount of macroalgae is expected to increase (**Table 5.3**), potentially out-competing corals due to the faster growth rates of macroalgae under higher temperatures and nutrient levels. The greater frequency of more intense droughts and floods and the possibility of intensified tropical cyclones (Chapter 2) are projected to amplify these problems in some parts of the region.

Table 5.3 Estimated projected changes in the percentage cover of live coral and macroalgae on reefs in 2035 and 2100 for the B1 and A2 scenarios under poor and strong management, relative to 2010. The expected remaining cover (%) of coral and macroalgae (including fleshy algae and algal turfs) is also shown. Likelihood and confidence associated with the projections are based mainly on the combined understanding of the expected responses of coral and macroalgae.

Year	**Scenario**	**Management**	**Coral cover**		**Macroalgal cover**	
			%	**% decrease**	**%**	**% increase**
2035	B1/A2	Strong	15–30	25–65 🟩🟦	40	130 🟩🟦
		Poor	15	65 🟩🟦	40–60	130–200 🟩🟦
2100	B1	Strong	10–20	50–75 🟩🟦	50	> 150 🟩🟦
		Poor	< 5	> 85 🟩🟦	80	> 250 🟩🟦
	A2	Strong	< 2	> 90 🟩⬜	> 95	> 300 🟩⬜
		Poor	< 2	> 90 🟩⬜	> 95	> 300 🟩⬜



In summary, reef-building corals will decrease ~ 25–65% by 2035 (**Table 5.3**), reducing the structural complexity of coral reefs and their ability to provide habitat for fish and invertebrates, many of which are currently of great importance to the people of the tropical Pacific for food security and livelihoods (Chapter 9). The projected loss of reef-building corals is likely to occur given that the current annual reduction in coral cover of 1–2%[52] will result in such losses within 20–30 years.

Management actions are likely to reduce the magnitude of the loss, although the benefits of management are not expected to differ between the B1 and A2 scenarios in 2035. Coral mortality is usually followed by algal colonisation, so that coral reefs are also likely to experience a 130–200% increase in benthic algal cover, including algal turfs, and non-calcareous macroalgae (**Table 5.3**), depending on the strength of management. An analogy for this type of change is provided by coral reefs in the Caribbean, which declined in a similar way[50], resulting in < 10% coral cover[123]. In 2035, reef-building corals are likely to have 50% lower rates of calcification than before 1990, with large sections of coral reef frameworks starting to crumble and break down. However, the deterioration of reef frameworks is only expected to start to become a problem in 2035 and coral reefs should still provide substantial benefits at this point, e.g. coastal barriers to ocean waves, and protection for coastal infrastructure and human dwellings. This particular role of coral reefs will grow in importance as sea level rises, and if coastal areas experience more intense tropical cyclones.

5.7.2 Coral reefs in 2100 (B1)

By the middle of this century, the trajectories of the B1 and A2 scenarios diverge (**Figure 5.10**). In the B1 world, growing awareness of the serious implications of climate change compels governments to pursue strong international agreements for limiting greenhouse gas emissions as formulated under the United Nations Framework Convention on Climate Change (UNFCCC). Once adopted, the results of these international agreements lead to a major revolution in how energy is generated, driven by an energised business sector that responds quickly to new emerging markets leading to rapidly declining greenhouse gas emissions in the decades that follow.

The developed nations rapidly convert to renewable energy sources, such as wind, wave, geothermal and solar thermal power, with expansion of nuclear power options via next-generation technologies. Similar transitions and innovation occur in the emerging economic giants, China and India. Atmospheric CO_2, and hence global temperature, continues to rise over much of the century, albeit at much lower rates than under A2. Perhaps more significantly, CO_2 and other greenhouse gases begin to stabilise in the atmosphere towards the end of the century (in contrast to the A2 scenario under which they do not; **Figure 5.11**). The slowing rate of rise in temperature and atmospheric CO_2 concentrations begins to reduce the rate at which coral reefs decline.

Nevertheless, the projected increase in SST in the tropical Pacific of 1.0–1.5°C relative to 1980–1999 is expected to create conditions in which mass coral bleaching occurs every 1–2 years. Many branching corals and other sensitive reef fauna are likely to disappear from coral reefs, which are instead represented by communities of massive coral species, such as *Porites*, and encrusting species, such as *Favia* and *Favites* (**Figure 5.12**). Under strong management of local stressors, total coral populations are expected to continue to decline and are likely to fall to 10–20% cover across the region (i.e. 25–50% of average coral cover today) (**Table 5.3**). At the same time, the growth of algae (mainly algal turfs) is likely to increase by > 150%. If the management of local stressors is poor, coral cover is likely to fall to lower levels (< 5%) and macroalgal cover is expected to increase by > 250% to ~ 80% cover (**Table 5.3**).

Reef calcification is expected to be 50% of the rate before 1980, and physical and biological erosion is likely to dominate the carbonate balance of coral reefs. The structural complexity of reefs is also likely to have decreased, removing much of the habitat for at least 50% of fish species previously associated with them. Herbivore populations may also be reduced due to the ecological requirements of these fish and invertebrate species for structurally complex reefs (Chapter 9), and their dependency on other coastal habitats such as mangroves and seagrasses (Chapter 6). Damage to coastal ecosystems may also increase due to the possibility of an increase in the number of category 5 cyclones in non-equatorial regions, and greater and more fluctuating rainfall close to the equator, which is likely to be 10–20% higher than in 1980–1999 (Chapter 2).

At the end of this century, under the B1 scenario, coral reefs in the tropical Pacific are likely to have reduced coral cover (**Table 5.3**) and to be less diverse. Management of these reef systems will have a significant effect and strong intervention should lead to healthier reefs under the B1 scenario (**Figure 5.11**). Calcification rates are not expected to keep pace with physical and biological erosion, however, leading to the collapse of many reef frameworks and the loss of habitat. As a result, the production of coastal fisheries is expected to decrease by 10–20% (Chapter 9). These changes, together with the expected rise in sea level, will mean that the coastal protection offered by coral reefs is no longer provided. This could have significant consequences for coastal urban areas and infrastructure, especially in those PICTs comprised of low-lying atolls[124].

5.7.3 Coral reefs in 2100 (A2)

Under the A2 emissions scenario , pressure from special interest groups and a lack of effective government leadership result in weak international agreements to address climate change. Politicians preside over minimal responses, with the outcome that CO_2 emissions are reduced by only 30% of 1990 levels by 2050. It is important to note, however, that the A2 scenario results in lower emissions of CO_2 than the present global trajectory, which is adding 2 ppm CO_2 to the atmosphere each year (Chapter 2). Even under the A2 scenario (here 'worst case'), atmospheric CO_2 is expected to increase to > 700 ppm by 2100, driving ocean pH below 7.7 and carbonate ion concentrations well below the level needed to maintain coral reefs. Sea surface temperatures in the tropical Pacific are projected to rise to 2.5–3.0°C above 1980–1999 levels (Chapters 2 and 3), creating conditions hostile to reef-building corals and other calcifying organisms.

The changes projected under the A2 scenario are expected to cause many coral species to become extinct or extremely rare[125]. Other coastal habitats in many parts of the tropical Pacific may also be affected by sea-level rise and the possibility of increasingly strong cyclones (Chapter 6). Many low-lying atoll nations face increasing threats from storm damage, coastal inundation and the loss of fresh water supplies as coastal aquifers become flooded with sea water[9].

By 2100, coral reefs are likely to be dominated by algal turfs and organisms other than corals (e.g. cyanobacteria) (**Table 5.3**) and the few corals present (< 2% of total cover) are likely to be very robust extremophiles. Net reef accretion is projected to be non-existent and reef structures are expected to break down under physical and biological erosion (**Figure 5.10**). Demersal fish populations are also likely to be fundamentally different, with their productivity projected to be 20–50% lower than in 2010 (Chapter 9). No amount of management action to reduce local threats has any effect on reef health (**Figure 5.11**, **Table 5.3**).

Photo: Katharina Fabricius

Coral reef damaged by a severe storm

5.7.4 Beyond 2100: reef recovery versus complete collapse

In exploring the consequences for coral reefs of choosing a B1 versus A2 future path, it becomes important to consider what lies beyond 2100. While seemingly distant, the success or failure of efforts to stabilise greenhouse gas concentrations in the 21st century will have serious ramifications for the future of reefs, and those who depend on them, beyond 2100 (**Figure 5.11**).

Strong action on greenhouse gas emissions, and vigorous attempts to reduce the effects of local threats such as declining water quality from pollution, overfishing, destructive fishing practices and mining, could help coral reefs in the B1 world to redistribute and regenerate around the Pacific as conditions stabilise. Over time, populations of corals adapted to warm conditions at the equator are expected to expand slightly towards higher latitudes. These coral populations will struggle, however, to maintain structurally complex carbonate reef systems because of the low concentrations of carbonate ions in the oceans of the next century and beyond. Nevertheless, these populations should be able to build coral reefs with a degree of diversity, similar perhaps to those currently found in the eastern Pacific[126]. Although these reefs are expected to have low biodiversity and no net accretion of carbonate structure, they should continue to support substantial fish populations and fisheries.

In contrast, the A2 scenario, with its rapid and continuing changes to SST, ocean pH, carbonate ions and sea level, is expected to result in environmental conditions that continue to outpace ecological processes for centuries to come. This would lead to 'chaotic', low-productivity coral reefs, with little value for the people of the Pacific.

5.8 Uncertainty, gaps in knowledge and future research

While there is little doubt that climate change represents a serious threat to coral reefs, and the people who depend on them, there are a number of important gaps in our current understanding of how coral reefs will change, and how we might respond. These important questions and gaps are outlined below.

- How will the climate change at the scale of individual PICTs and their coastlines? Global models for how climate change is projected to affect the tropical Pacific must be 'downscaled' to provide information which managers and policy makers in PICTs can use to respond to the regional and local problems.
- How is warming and acidification of the tropical Pacific Ocean affecting the early life history stages of corals and other key reef-building organisms? What are the knock-on effects of these types of influences on the fundamental biology of coral reef organisms?
- What important synergies might occur between the projected changes to SST and ocean acidity, and other factors such as the possibility of more intense cyclones?
- Is the restoration and remediation of coral reefs damaged by climate change feasible, either biologically or economically?
- What are the most effective management strategies for reefs that have suffered short- and long-term coral bleaching episodes? For example, should a fishing closure be put in place until a reef has recovered from a severe bleaching event?
- Are current monitoring protocols adapted to climate change? What needs to be done to monitor reefs and their communities to separate local versus global effects?
- What are the likely consequences of very rapid rates of sea-level rise (of up to 2 m by 2100) for tropical Pacific coral reefs?
- How should management strategies change as the ecological community composition of coral reefs varies from, for example, branching corals to more massive corals and macroalgal-dominated seascapes?

Forming international science partnerships, for example, with the Global Environmental Facility Coral Reef Targeted Research Programme, Grand Observatoire du Pacifique Sud, Coral Reef Triangle Initiative, Micronesia Challenge, and Pacific Oceans Solutions, will assist the Pacific communities to fill these knowledge gaps. Such partnerships extend the often limited resources of PICTs, and should help to ensure that they understand and address the problems posed by declining health of coral reefs.

Photo: Gary Bell

Coral bleaching

To empower PICTs to respond effectively to the challenges facing coral reefs due to projected climate change, the following four major research activities need to be implemented.

- Support the Pacific Climate Change Science Programme initiatives to increase understanding of changes to surface climate in the region and the tropical Pacific Ocean[ii].
- Improve our understanding of how climate change at regional and local scales is likely to affect critical features of coral reefs. In particular, we need more information on the expected effects on the three-dimensional architecture of coral reefs that is so important for fisheries and many other species, and what can be done to avoid the worst impacts. Real-time information on how environmental stressors, such as SST, vary spatially and temporally will be critical to understanding where vulnerabilities within reef systems are likely to arise, and how to design appropriate management responses. The satellite products provided by the National Oceanic and Atmospheric Administration of the USA (NOAA) through its Coral Reef Watch programme[127] are valuable tools in this respect. The products could be improved further, however, by (1) providing finer-scale measurements (< 1 km) on the scale needed to manage individual reefs; and (2) integrating data on light intensity, pH and turbidity with SST, to assess the risks of damaging synergistic effects that may result from changes in SST, even though thermal stress (degree heating weeks) does not reach threshold levels.

[ii] This work is now being done for the tropical Pacific by the Australian Bureau of Meteorology, CSIRO and partners, under the Pacific Climate Change Science Programme; see www.cawcr.gov.au/projects/PCCSP

- Assess the interaction between the effects of local stressors to coral reefs and global warming and increased emissions of CO_2, and explore possible opportunities to improve the management of coral reefs under a changing climate.
- Map the socio-economic vulnerability of Pacific people to the projected changes in coral reefs, and explore how governments can respond today to avoid the losses of ecological services and their effects on food security and livelihoods.

This last priority is discussed further in Chapters 12 and 13. Actions that are taken today will generally reduce the potential socio-economic effects and be less expensive than waiting to tackle the problems in the future.

5.9 Management implications and recommendations

The difference between the two scenarios discussed here is essentially a world of challenging yet largely manageable impacts (B1) versus a world that will have to address a series of calamitous and unmanageable outcomes caused by the rapidly changing climate (A2). To avoid an A2 world, the international community must commit to immediate and deep reductions in CO_2 emissions. The most credible models recommend that the emission of atmospheric CO_2 and other greenhouse gases must be reduced by at least 90% compared with 1990 levels by 2050[105,128]. Not to act on emissions is to invite a catastrophic future and to fail future generations and societies.

Even if the most decisive action is taken to reduce emission of greenhouse gases, the projected effects of climate change on coral reefs represents a major challenge for PICTs. At a minimum, these valuable habitats are expected to be altered by the consequences of the emissions that have already occurred (as outlined in Chapters 2 and 3), although it is likely to take time for the effects of these emissions to eventuate fully.

In addition to mitigation of the emissions of CO_2 and other greenhouse gases, the onus is on governments to manage coral reefs in a way that will maximise their natural adaptive capacity or ability to cope with future changes (resilience) (**Figure 5.13**). Key recommendations for local management measures are summarised below.

- Strategies to limit the flow of nutrients and sediments from rivers and coastal catchments on to coral reefs must be implemented. These will involve restoring and protecting riparian and coastal vegetation cover, maintaining mangroves and seagrass meadows, and implementing a broad range of integrated coastal zone management measures, as outlined in Chapters 6 and 7. Such interventions will give corals and coral reef organisms threatened by climate change the best chances of resisting, and building tolerance to, thermal stress and rapid sea-level rise. In relation to sea-level rise, the future potential for growth of corals on existing intertidal fringing reefs on high islands will depend on minimising runoff. This will require careful planning given the projected increase in rainfall in equatorial regions (Chapter 2).

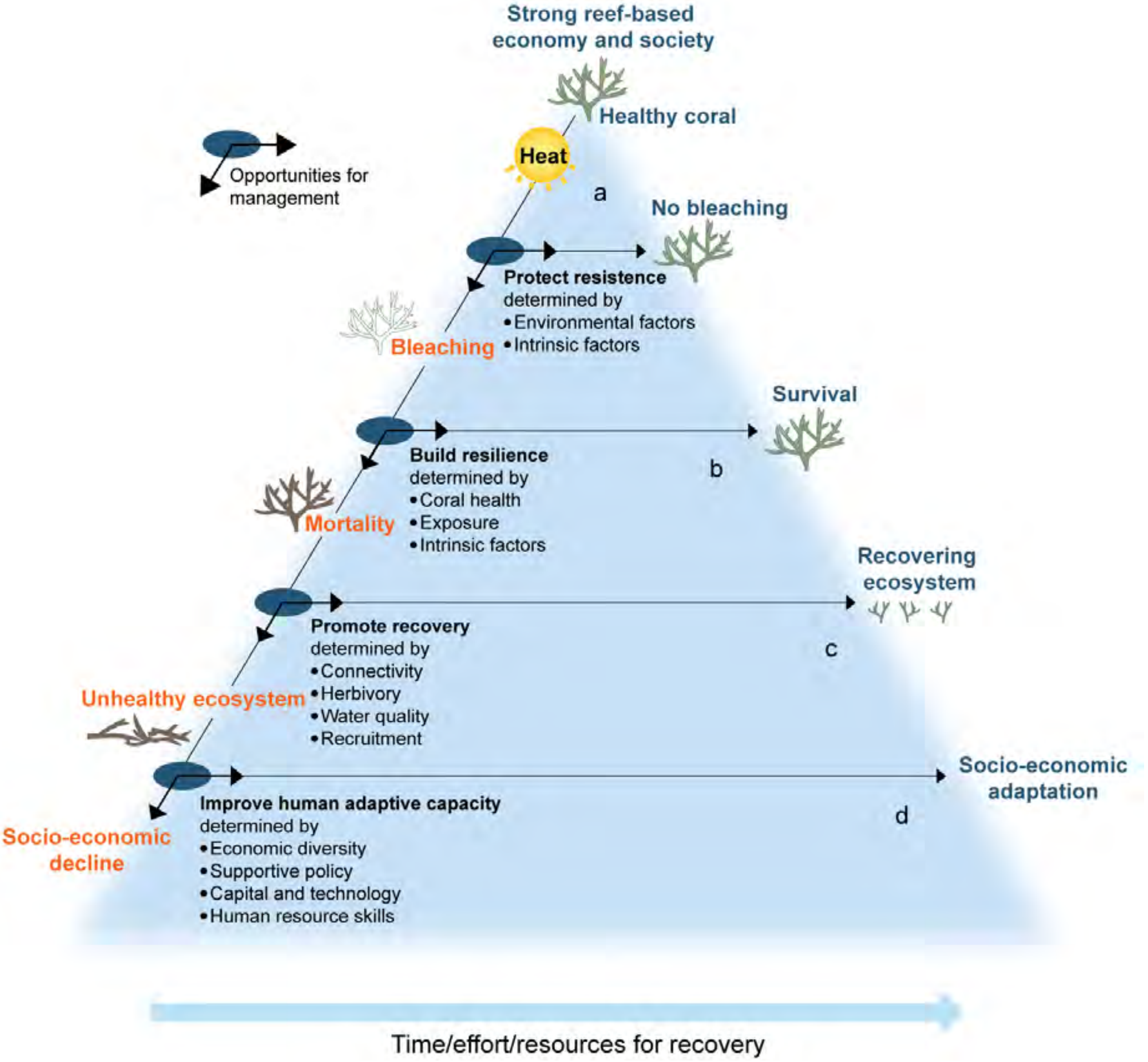


Figure 5.13 Opportunities for management interventions to improve outcomes under increased episodes of mass coral bleaching. Pyramid shows four strategies for responding to climate-driven increases in thermal stress and mass coral bleaching on a typical reef (a) increasing the resistance of reef-building corals to thermal stress will reduce impacts like coral bleaching, which involves minimising local stresses that might weaken the physiological resistance of corals to thermal stress; (b) building the tolerance of corals to regular bleaching will minimise mortality; (c) once mortality has occurred, promoting the recovery of reefs from episodes of mass coral bleaching will be important, for example, protecting herbivores on bleached reefs can improve recovery by grazing algae[130]; and (d) improving the adaptive capacity of dependent human populations to withstand the loss of key coastal resources is an important strategic response (Chapter 13) (source: Marshall and Schuttenberg 2006)[129].

- Measures to assist corals to resist bleaching, and to recover from bleaching events when their thermal tolerances are exceeded[124], must be modified to suit PICTs and applied across the region. These measures are designed to address the hierarchy of effects of thermal stress on corals (**Figure 5.13**). At one end of the continuum, healthy coral reefs support reef-based economies and societies, and at the other, a damaged and unhealthy ecosystem leads to serious socio-economic consequences. At each point in this hierarchy, different strategies are needed. For example, for a relatively healthy reef, reducing the effect of local stressors (environmental factors) should help increase the resistance of corals to bleaching. Also, where bleaching does occur, considerable evidence has shown that populations of corals will recover faster if their ecological resilience is protected and enhanced[57]. Bleached coral reefs, on which grazing fish populations have been maintained to control algal growth, illustrate this point well. Such reefs recover three times as fast as reefs where grazing fish populations have been removed[130].
- Activities that damage the three-dimensional structure of coral reefs need to be prevented, especially because reef frameworks provide habitats for reef-dwelling species, including many fish and invertebrates used for subsistence and livelihoods (Chapter 9). Reef barriers also play essential roles in protecting coastal ecosystems such as mangroves and seagrass meadows, which are often nursery habitats for the juvenile stages of coastal fish species (Chapter 6). Measures that will help preserve reef frameworks in the face of climate change are the elimination of destructive fishing activities (particularly dynamite fishing), mining of coral rock, and damage from boating and tourist operations.

Assisting human populations to adapt to the loss of coral reefs and their associated resources will also be essential. However, the success of management interventions designed to enable coastal communities to adapt to the degradation and loss of coral reefs will depend largely on understanding that governance in many PICTs is weak. Management measures designed for the Great Barrier Reef, for example, will not be appropriate for many PICTs, because they rely heavily on reefs for food security and lack the resources to implement and monitor compliance with such interventions and regulations. A different approach is needed – one that (1) recognises the important role of subsistence and commercial fishing, and livelihoods based on the other attributes of reefs, for the coastal people of the Pacific, and (2) provides incentives for coastal communities to value and nurture coral reefs using simple management measures[44].

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Photo: Christophe Launay

Chapter 6

Vulnerability of mangroves, seagrasses and intertidal flats in the tropical Pacific to climate change

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> *'One of the major challenges in the Pacific Islands region is adjusting to the responses of coastal ecosystems to climate change.'* (Gilman et al. 2006)[i]

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[i] Gilman et al. (2006) *Pacific Island Mangroves in a Changing Climate and Rising Sea*. United Nations Environment Programme Regional Seas Reports and Studies 179, Nairobi, Kenya.

Contents

6.1 Introduction

In addition to the extensive coral reef habitats described in Chapter 5, the shallow subtidal and intertidal zones around the coasts of Pacific Island countries and territories (PICTs) often support large areas of mangroves and seagrasses. Intertidal sand and mud flats[ii] with their associated microalgae and infauna are also common features of most PICTs.

Due to their varying responses to light, temperature and hydrology, and the capacity of mangroves and seagrasses for dispersal[1–4], these three ecosystems usually form a mosaic. Typically, mangroves are located along the shore, whereas seagrasses and intertidal flats can extend long distances away from the shoreline in lagoons and sheltered bays, and often adjoin coral reefs. In many places, coral reefs buffer waves coming ashore to create suitably sheltered environments for the establishment of mangroves and seagrasses[5].

Mangroves and seagrasses are of special interest to coastal fisheries worldwide because of the role they play in providing nursery areas for commonly harvested fish and invertebrates[6–9]. Although the ecology of fish and invertebrates associated with mangroves and seagrasses in the tropical Pacific is not well understood compared with other parts of the world, the connectivity among mangroves, seagrasses, intertidal flats and coral reefs indicates that mangroves and seagrasses throughout the region provide a similar function to such habitats elsewhere.

In addition to their roles as nursery areas, mangroves, seagrasses and intertidal flats provide feeding habitats for many species of adult demersal fish, some of which reside on reefs during the day and forage over seagrasses and intertidal flats at night[10]. Seagrasses and intertidal flats are also permanent habitats for several species of sea cucumbers, the main group of invertebrates targeted as an export commodity in the region[11], and for a wide range of molluscs gleaned for subsistence. Overall, the range of coastal fisheries resources that depend on mangroves, seagrasses and intertidal flats is extensive, with many of these species important to the food security and livelihoods of coastal communities in PICTs (Chapters 1 and 9).

The separate values of each ecosystem are surpassed by the productivity that results when they are inter-connected[7,8,12]. In particular, movement of nutrients, detritus, prey and consumers between habitats can have major effects on the structure and productivity of food webs, with nutrient and detrital subsidies increasing primary and secondary productivity both directly and indirectly[13]. In addition to supporting fisheries, mangroves provide protection against wind and wave energy, and stabilise shorelines; and both mangroves and seagrasses improve water quality by trapping sediments, nutrients and other pollutants[14–18].

[ii] Includes intertidal areas of sand and mud above mean low tide level, but does not include intertidal coral reefs or seagrasses.

Ecosystems dominated by mangroves and seagrasses are being eroded in some PICTs due to their proximity to developments in the coastal zone[19,20]. For example, increases in the turbidity of coastal waters and higher rates of sedimentation, resulting from poor land management in the catchments of high islands, are reducing the area and health of seagrass habitats[21,22]. The problem is not unique to the region – the range and intensity of anthropogenic effects on coastal habitats have been increasing worldwide, reducing the extent and quality of mangroves[23,24] and seagrasses[20,25].

Climate change is expected to exacerbate anthropogenic impacts on mangroves, seagrasses and intertidal flats[3,26,27]. Further losses are expected to occur as a result of greater heat stress, increased sedimentation and turbidity due to higher rates of runoff, changes in suitable sites for growth of mangroves and seagrasses due to rising sea levels, and possibly more physical damage from the combination of sea-level rise and more severe cyclones and storms.

In this chapter, we assess the vulnerability of the mangrove, seagrass and intertidal flat habitats in the tropical Pacific that support coastal fisheries. We do this by examining the effects that changes to surface climate and the tropical Pacific Ocean (Chapters 2 and 3) are expected to have on the plants that define these habitats. This exposure to change is used in the framework described in Chapter 1 to assess the vulnerability of the habitats under representative low (B1) and high (A2) emissions scenarios from the Intergovernmental Panel on Climate Change (IPCC) for 2035 and 2100[28].

We commence by describing the diversity and distribution of mangrove, seagrass and intertidal flat habitats in the tropical Pacific (25°N–25°S and 130°E–130°W), outlining the role they play in supporting coastal fisheries in the region, and summarising the critical requirements for establishing and maintaining these habitats. Next, we summarise the limited information on the observed effects of climate change on mangroves, seagrasses and intertidal flats, and assess the expected vulnerability of these habitats to the projected changes in solar radiation, air and sea temperatures, rainfall, nutrients, cyclones and storms, ocean acidity and sea-level rise. For mangroves and seagrasses, we integrate these assessments to estimate changes in area under the various scenarios.

We conclude by identifying the uncertainty associated with these assessments, the important gaps in knowledge, the research required to fill these gaps, and the key management measures needed to maintain the important roles that the mangroves, seagrasses and intertidal flats of the region play in supporting coastal fisheries.

6.2 The nature of mangroves, seagrasses and intertidal flats in the tropical Pacific

6.2.1 Mangroves

Mangrove forests occur on sediments associated with low-energy shorelines, between mean low-tide and high-tide levels. Mangroves have evolved to tolerate saline sediments and inundation by sea water, with different species displaying a range of tolerances. This variability in tolerance to saline conditions contributes to patterns of species distribution across the intertidal zone.

The tropical Pacific has an extraordinary diversity of mangroves – 31 of the 70 species recognised globally are found in the region, including five hybrids. Twenty-three species occur in Papua New Guinea (PNG), making it the country with the greatest diversity of mangroves in the world[29]. The diversity of mangroves decreases progressively from west to east across the region, with only four species and one hybrid occurring in Samoa (**Table 6.1**). In French Polynesia, the single species of *Rhizophora* is likely to have been introduced[30,31] and has proliferated on all the high islands of the Society archipelago[31]. The natural absence of mangroves in the eastern Pacific is likely to be related to propagule dispersion rather than a lack of suitable conditions.

The area inhabited by mangroves, relative to total land area, is also exceptional in some PICTs. It is as high as 12% for the Federated States of Micronesia (FSM), about 10% for Palau and around 1–2% for another six PICTs[29] (**Table 6.1**). Although the area covered by mangroves in PNG is only ~ 1% of total land area, the 4640 km^2 of mangroves represent > 70% of the mangrove area in the region[29].

Mangrove species form ecological assemblages, based on similarities in their morphology, physiology and reproduction strategies. They occur in highly humid to extremely arid environments, and on soil types that include clay, peat, sand and coral rubble[32]. Mangrove communities do differ markedly from each other, however, due to the variation in tides, wave exposure, river flows and soils associated with different locations[5,33,34]. Mangrove trees create extensive and productive forests where conditions are optimal, but occur as dwarf and scattered shrubs where they are not. Mangrove communities on high islands also usually differ from those found on atolls, because of variation in the availability of fresh water, sediments and nutrients from runoff[35].

As a result of local conditions and the potential for arrival of mangrove propagules[36], each PICT has a unique combination of mangrove species. Nevertheless, two species – *Bruguiera gymnorhiza* and *Rhizophora stylosa* – occur in 15 of the 22 PICTs as a result of their broad environmental tolerances[35].

Table 6.1 Number of mangrove and seagrass species recorded from Pacific Island countries and territories (PICTs), together with the estimated area of mangrove and seagrass habitats.

PICT	Total land area (km^2)	Mangrove			Seagrass			References
		Species (hybrid)	Area (km^2)	% land	Species	Area (km^2)	% land	
Melanesia								
Fiji	18,272	7(1)	424.6	2.32	6	16.5[a]	0.01	29, 54, 260–263
New Caledonia	19,100	15(3)	205	1.07	11	936	5.0	22, 29, 52, 260, 263–267
PNG	462,243	31(2)	4640	1.00	13	117.2	0.03	29, 268–272
Solomon Islands	27,556	17(2)	525	1.90	10	66.3	0.24	21, 22, 29
Vanuatu	11,880	14(3)	25.2	0.21	11	?[a]		29, 40, 44, 261, 273, 274
Micronesia								
FSM	700	15(1)	85.6	12.23	10	44	6.29	21, 29, 260, 263, 274–277
Guam	541	12	0.7	0.13	4	31	5.73	260, 261, 263, 277–280
Kiribati	690	4	2.6	0.37	2**	?[b]		29, 44, 260, 281
Marshall Islands	112	5	0.03	0.27	3	?[b]		29, 44, 260, 274
Nauru	21	2	0.01	0.05	0	0	0	29, 282
CNMI	478	3	0.07	0.01	4	6.7	1.40	29, 44, 260, 274, 283, 284
Palau	494	14(1)	47.1	9.53	11	80	16.19	29, 260, 285–289
Polynesia								
American Samoa	197	3	0.5	0.26	4	?[c]		29, 44, 274, 279, 290
Cook Islands	240	0	0	0	0	0	0	29, 291, 292
French Polynesia	3521	1	?[b]	?	2	28.7	0.82	29, 265, 293, 294
Niue	259	1	0	0	0	0	0	29
Pitcairn Islands	5	0	0	0	0	0	0	295
Samoa	2935	3	7.5	0.26	5	?[b]		29, 44, 54, 279
Tokelau	10	0***	0	0	0	0	0	29, 296
Tonga	699	7	13	1.87	4	?[b]		29, 260, 263, 290
Tuvalu	26	2	0.4	1.54	1*	0	0	29
Wallis and Futuna	255	2	0.2	0	5	24.3	17.0	29, 46, 47, 297

* Local contacts report no seagrass but Ellison (2009)[29] noted the presence of one species; ** based on observations by P Anderson; *** includes one associate species; a = mapping currently in progress; b = not mapped; c = seagrass not encountered during September 2002 and May 2003 surveys of Tutuila, Manua Group, Rose Atoll and Swains Island (source: Analytical Laboratories of Hawaii 2004)[284].

Mangrove assemblages have been classified into seaward, mid and landward zones, according to where they occur in relation to tidal position[37] (**Figure 6.1**). The seaward zone is the outfacing edge of the mangrove forest, which is fully exposed to all tides and frequent inundation. The soils in this zone are normally soft mud and sedimentary in origin. Mangrove species inhabiting the seaward zone usually have aerial roots that anchor and support the plant. The mid zone is subject to less regular tidal influences, with the trees generally being exposed only to inundation during the spring high tides. Soils are also sedimentary but more compacted than those in the seaward zone. They usually contain carbon and sometimes have inorganic fine grain-sizes. The landward zone is generally only inundated during the highest of spring tides, often receiving fresh water from groundwater or land runoff. It is dominated by mangrove 'associates', i.e. plants such as shrubs, vines, herbs and epiphytes generally found at the back of mangrove communities. Indeed, the landward zone is usually a narrow strip of vegetation that may transition to a terrestrial forest[37]. Diversification of mangrove species can occur within these three broad habitat zones, for example, due to salinity gradients[38].

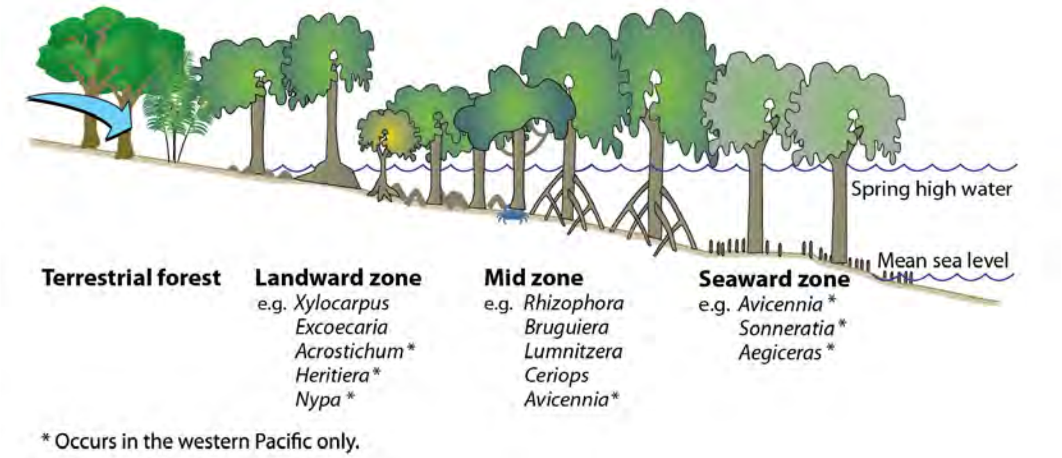


Figure 6.1 The three zones typical of mangrove habitats in the tropical Pacific, showing the differences in mangrove species typical of each zone.

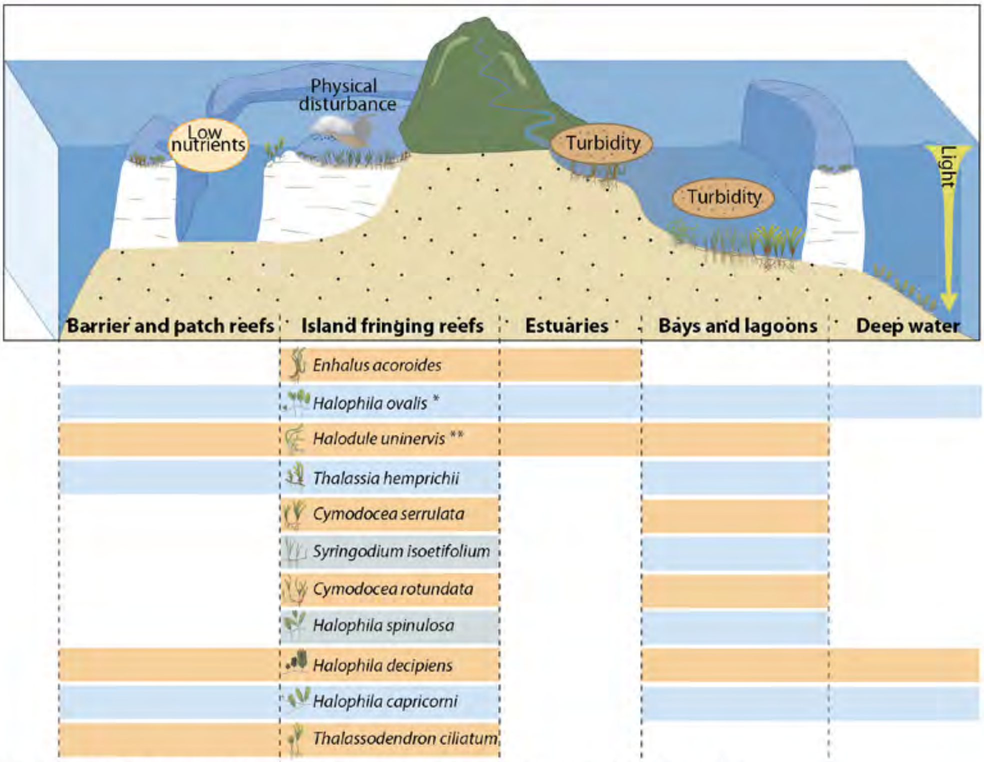
6.2.2 Seagrasses

Fourteen species and one subspecies of seagrass have been reported from the tropical Pacific (**Table 6.1**). Like mangroves, the greatest number of seagrasses occurs in PNG and diversity declines to the east (**Table 6.1**). Seagrasses are absent or unreported from the Cook Islands, Nauru, Niue, Pitcairn Islands, Tokelau and Tuvalu. However, the discontinuity of seagrass in the Cook Islands and Tokelau may be the consequence of limited surveys because both of these PICTs have deep, sheltered lagoons and low-energy environments suitable for establishment of these plants.

The area of shallow coastal waters where seagrasses occur is extensive in several PICTs. For example, seagrasses are an important habitat in much of Micronesia, where they are equal to 16% of land area in Palau, and 5–6% in FSM and Guam (**Table 6.1**). Seagrasses are also important habitats in Wallis and Futuna, and New Caledonia, where they cover areas equivalent to 17% and 5% of land area, respectively (**Table 6.1**). The area of seagrass is particularly significant in New Caledonia, where it covers > 900 km^2. Mapping of seagrass habitats has been conducted by field surveys in some PICTs (e.g. Solomon Islands) or by remote sensing in others, e.g. New Caledonia, Wallis and Futuna, Palau, Guam and Commonwealth of the Northern

Mariana Islands (CNMI)[39]. Unfortunately, some seagrass surveys in the region have not measured the area of habitat (e.g. Vanuatu)[40]. Mapping of seagrass is currently underway in Fiji.

Most seagrasses in the tropical Pacific are found in waters shallower than 10 m. However, there is great variation in the nature of seagrass habitats across the region, depending on water clarity, nutrient availability and exposure to wave action[21,22,40]. Based on the influence of these factors, five main categories of seagrass habitat have been recognised[21,22,40] (**Figure 6.2**). These categories are described below.



* Equivalent to *Halophila ovalis* complex in Waycott et al. (2004)[298]; ** including *Halodule pinifolia*.

Figure 6.2 The five main habitats where seagrasses occur in the tropical Pacific, together with the factors limiting growth of seagrasses in each habitat.

6.2.2.1 Bays and lagoons

Calm clear waters and a range of stable sandy substrates in bays, and in lagoons behind reefs or in atolls, enable a diverse range of seagrass species to establish dense meadows in both subtidal and intertidal areas. *Halodule uninervis* often grows well in such locations, from the intertidal zone to depths of 30 m. In some places, it is patchy and intermixed with other seagrass species (e.g. *Halophila* spp.). Another dominant species in these locations is *Syringodium isoetifolium*, which often occurs in shallow, subtidal areas (1–6 m deep) of lagoons behind barrier reefs. *Syringodium* is more tolerant of oxidised substrata than other species and is usually the first species to re-establish after a disturbance[41]. In French Polynesia, *Halophila ovalis* is a common species on the shallow sandy substrata of Tuamotu atolls, where this seagrass usually mixes with macroalgae, forming dense mats.

6.2.2.2 Island fringing reefs

Wide fringing reefs, found where wave action is slight to moderate, provide subtidal and intertidal areas with stable sediments that support diverse and dense seagrass meadows. Even so, the seagrasses inhabiting fringing reefs may differ widely because of variation in exposure to solar irradiation, nutrient availability, wave action and the associated movement of sediments[3,42]. Where runoff from high islands delivers nutrients, seagrasses on the landward edge of fringing reefs can be highly productive. Pooling of water at low tide on the landward side of fringing reefs allows the seagrasses there to attain greater leaf heights, and prevents desiccation of the plants. In contrast, intertidal areas expose seagrasses to damage, particularly when low tides occur during the day in summer.

Variation in environmental conditions across fringing reefs often results in a succession of seagrass communities. In particular, seagrasses in the genera *Thalassia* and *Cymodocea* often dominate inshore intertidal areas because they tolerate a moderate level of disturbance[43]; *Halophila ovalis*, *Halodule* spp. and *Syringodium isoetifolium* occur in shallow water on fringing reef platforms[44] and *Thalassodendron ciliatum,* which has strong woody rhizomes and roots, attaches to rock and coral rubble banks at depths of 6–8 m on the seaward margin of fringing reefs[45]. In Wallis and Futuna, the seagrass meadows on the fringing reef nearest the beach are dominated by *Halodule* spp., whereas *Halophila ovalis* is most common in the middle of the reef and *S. isoetifolium* on the seaward edge[46,47].

6.2.2.3 Barrier and patch reefs

Physical disturbance from waves and the movement of sediment usually prevent seagrasses from growing on the windward sides of barrier reefs. However, they occur on the leeward side of islands, or where the back-reef is large[21,22,40]. *Thalassia hemprichii* is common on barrier reefs because it is able to tolerate shallow sediments, high temperatures and strong currents. In Solomon Islands, *Enhalus acoroides*, which has robust rhizomes and roots, is common on barrier reefs with strong currents in Malaita. In contrast, seagrasses are not a common feature on the barrier reef in New Caledonia.

In some very rare situations, *Halodule uninervis* can form scattered patches mixed with *Halophila ovalis.* Conversely, *Cymodocea* spp., *Halodule uninervis* and *T. hemprichii* form dense beds on lagoonal patch reefs[48]. Some species of seagrass (e.g. *Halophila decipiens, Cymodocea rotundata* and *T. hemprichii*) also grow on shallow subtidal patch reefs[21]. These environments have suitable conditions for growth because there is limited disturbance from wave action, protection from currents by the reef crest, and availability of coarse carbonate sediments.

6.2.2.4 Estuaries

Seagrasses grow in the lower reaches of estuaries on the high islands of Melanesia. However, growth is limited in these extreme environments by fluctuations in light and salinity, and scouring by currents[49]. Seagrass meadows in estuaries are generally dominated by structurally large species, such as *Enhalus acoroides*, which are tolerant of high temperatures and low salinity[50], and can withstand partial burial[51]. Seagrasses in estuaries have more microalgal and macroalgal epiphytes than seagrasses in other habitats[21].

6.2.2.5 Deep water

Little is known about the few species of seagrass that occur in deeper water in the tropical Pacific. *Halophila decipiens* is commonly reported from depths of 60 m in New Caledonia[52], interesting given that this species commonly occupies coral reef habitats also. This species also occurs in French Polynesia, where it grows on the sandy bottom of channels and embayments, and the outer reef slope[53]. It has also been reported from depths of ~ 40 m in Solomon Islands[22], and 10 to 25 m at the Great Sea Reef, Fiji[54]. In New Caledonia, a closely related species, *Halophila capricorni*, is also commonly observed on the sandy bottom of channels near coral reefs at depths of 20 to 30 m[52].

6.2.3 Intertidal flats

In many PICTs, a proportion of the coastal zone between the active sandy beach margin and mean low tide comprises sandy or muddy intertidal flats. These habitats are also often associated with the margins of lagoons on atolls and high islands. Mangroves frequently border the landward margin of intertidal flats, whereas seagrasses and/or coral reef often occur at the seaward edge. The transition from intertidal sand or mud flats to mangroves or seagrasses is dictated by comparative vertical elevation in relation to mean sea level.

There is limited understanding of the role of intertidal flats, and the associated food webs, in supporting the fish and invertebrates that contribute to subsistence and small-scale commercial coastal fisheries in PICTs (Chapter 9). However, intertidal locations and shallow marine ecosystems (< 1 m deep) in other parts of the world yield some of the highest rates of primary production through growth of the benthic microalgae (BMA) community[55] and, globally, the area of intertidal flats is about three times greater than that of mangrove forests[56]. Although the areas of intertidal flats have yet to be mapped for the vast majority of the main islands in the region, it is clear that they can comprise significant areas, and support important fisheries (Box 6.1).

Box 6.1 Importance of intertidal flats

The extent, and ecological and socio-economic roles of intertidal flats in the tropical Pacific are still poorly understood. However, elsewhere these habitats (1) play a significant role in nutrient cycling and primary production in shallow coastal ecosystems; (2) support high densities and large harvests of burrowing (infaunal) invertebrates, e.g. arc shells *Anadara* spp.; and (3) help mediate pollution (eutrophication) through denitrification by enhanced bacterial processes within the surface layers of sediment and burrows of infauna.

In the 16 equatorial atolls of the Gilbert's Group, Kiribati, and in several other Pacific Island countries and territories (PICTs), the contribution of intertidal flats to the subsistence of coastal communities is frequently overlooked. These habitats can be highly productive, and communities often glean molluscs, polychaetes, crustaceans and echinoderms from these areas at low tide for household food supplies. People also earn income from harvesting edible species from intertidal flats and selling them fresh or preserved to urban markets, or as export commodities in the case of sea cucumbers.

Greater attention must be given to estimating the areas of intertidal flats in PICTs, their ecological function, and their contributions to food security and livelihoods, especially as these habitats are highly vulnerable to being lost as a result of projected sea-level rise. The significance of intertidal flats to coastal fisheries in some PICTs is illustrated by Tarawa Atoll in Kiribati, where (1) the land area of ~ 31 km^2 at high tide, increases to 52 km^2 during low spring tides, expanding the total 'land' area by ~ 170%; and (2) total annual harvests of arc shells have been estimated to be as high as 1800 tonnes per year (Chapter 9).

Photo: Arthur Webb

Women gleaning from an intertidal flat in Kiribati

Although intertidal flats lack conspicuous vegetation, and are often considered to be 'unvegetated' or 'bare', they frequently support a rich diversity and abundance of BMA communities, comprising photosynthetic microalgae (diatoms, dinoflagellates and cyanobacteria) and reducing and oxidising bacteria[57,58]. The high rates of benthic primary productivity by these BMA communities in turn support a rich array of benthic epifauna (animals living on the sediment surface), and infauna (burrowing organisms). Transient fish species feed on this fauna during high tide, and birds frequent these habitats at low tide to prey on the wide range of food found there.

6.3 The role of mangroves, seagrasses and intertidal flats in supporting fisheries in the tropical Pacific

The mosaic of mangrove, seagrass and intertidal flat habitats plays an important role in supporting the demersal fish and invertebrates that contribute to the subsistence and commercial coastal fisheries of the region[59,60] (Chapter 9). For example, several important demersal fish species associated with coral reefs use this habitat mosaic as a nursery area[59,61,62], and for feeding when they are adults[63]. There is also the possibility that juvenile fish may use mangrove and seagrass habitats in sequence as they develop, before residing permanently on coral reefs. As adults, several species of demersal fish venture from reefs into adjacent mangrove or seagrass areas to forage at night, depending on which habitat is nearby. Mangroves, seagrasses and intertidal flats are also the primary habitats of important invertebrate species, such as sea cucumbers, crabs and molluscs[64,65] (Chapter 9).

Below, we describe the specific roles played by mangroves, seagrasses and intertidal flats as habitats for the fish and invertebrates that underpin coastal fisheries in the tropical Pacific, and as fishing areas.

6.3.1 Mangroves

A large number of fish and invertebrate species harvested in the tropical Pacific by subsistence and commercial coastal fisheries are associated with mangroves during their life cycle (**Tables 6.2** and **6.3**). These species contribute to three of the four categories of coastal fisheries described in Chapter 9: demersal fish, invertebrates targeted for export commodities, and invertebrates gleaned from intertidal and shallow subtidal habitats for subsistence (**Figure 6.3**). In PNG, mangroves are also the location of recreational fisheries for barramundi and black bass[66].

Harvesting of fish and invertebrates from mangrove habitats is divided into activities that capture (1) resident species, like arc shells *Anadara* spp., oysters *Crassostrea* spp., mangrove crabs *Scylla* spp. and sea cucumbers *Holothuria scabra*[65–70], or (2) species of fish and shrimp that use mangroves temporarily during high tide, e.g. banana prawns *Fenneropenaeus merguiensis*[71].

Mangroves also contribute to coastal fisheries in two other ways. First, they provide important nursery (feeding and shelter) areas for juvenile fish and invertebrates[27,72–77]. Second, they are intermittent feeding areas for adult fish normally harvested from coral reefs or other habitats[70,78]. The nursery value of mangroves stems from the refuge their dense roots provide[79], the food resources found there[63], and reduced flow rates[80]. The larger species of fish that feed within inundated mangrove habitats include carnivores, such as snappers (Lutjanidae), trevallies (Carangidae) and barramundi *Lates calcarifer*, which feed on the juvenile fish sheltering there[78]; and herbivores-detritivores, such as mullet (Mugilidae)[27], herring (Clupeidae)[81] and shrimp[27,82].

Table 6.2 The number of species associated with mangrove and seagrass habitats, as juveniles and/or adults, for families of fish caught by coastal fisheries in Pacific Island countries and territories (PICTs). All information is preliminary due to the lack of extensive sampling of fish in mangrove and seagrass habitats in many PICTs.

Family*	Common name	Habitat		
		Mangrove	Seagrass	Both
Acanthuridae	Surgeonfish	3	3	3
Atherinidae	Hardy head	5	3	3
Belonidae	Long tom	3	3	3
Bothidae	Flounders	2	2	2
Carangidae	Trevallies	4	2	2
Clupeidae	Herring	7	8	7
Dasyatidae	Rays	5	5	5
Engraulidae	Anchovies	4	4	4
Gerreidae	Silver biddies	5	5	5
Haemulidae	Grunts	5	5	5
Hemiramphidae	Halfbeaks	5	4	4
Labridae	Wrasses	3	3	3
Leiognathidae	Ponyfish	7	4	4
Lethrinidae	Emperors	5	5	5
Lutjanidae	Snappers	7	4	4
Polynemidae	Threadfins	3	3	3
Mugillidae	Mullet	9	6	6
Mullidae	Red mullet	7	5	5
Nemipteridae	Threadfin bream	2	2	2
Platycephalidae	Flatheads	4	2	2
Scaridae	Parrotfish	2	2	2
Serranidae	Groupers	8	3	3
Siganidae	Rabbitfish	4	4	4
Sillaginidae	Whiting	4	4	4
Sphyraenidae	Barracuda	3	3	3
Synodontidae	Lizardfish	3	2	2
Teraponidae	Grunters	3	3	3

* Families of fish mostly with only one species harvested from either mangrove or seagrass habitats include Chandidae (milkfish), Chirocentridae (wolf herring), Cynoglossidae (tongue sole), Drepanidae (sicklefish), Elopidae (giant herring), Lacteriidae (snapper), Megalopidae (tarpon), Monacanthidae (leatherjacket), Scatophagidae (butterfish), Scombridae (Spanish mackerel), Soleidae (sole), Sparidae (bream) and Toxotidae (archer fish).

The value of any given area of mangroves for fisheries is linked, however, to the availability of adjacent habitats. Because many parts of the mangrove habitat drain completely at low tide, fish and shrimp can use these areas only when they are inundated, and must rely on nearby subtidal habitats for shelter at other stages of the tidal cycle[83]. The most commonly used subtidal adjacent habitats are drainage channels within and beside mangroves, which often contain fallen timber from mangrove trees (snags) and areas of seagrass[84]. Thus, mangrove-based food webs are linked to the attributes of nearby areas (**Figure 6.4**), and any assessment of the value of mangroves to fisheries species needs to consider the availability of adjacent habitats.

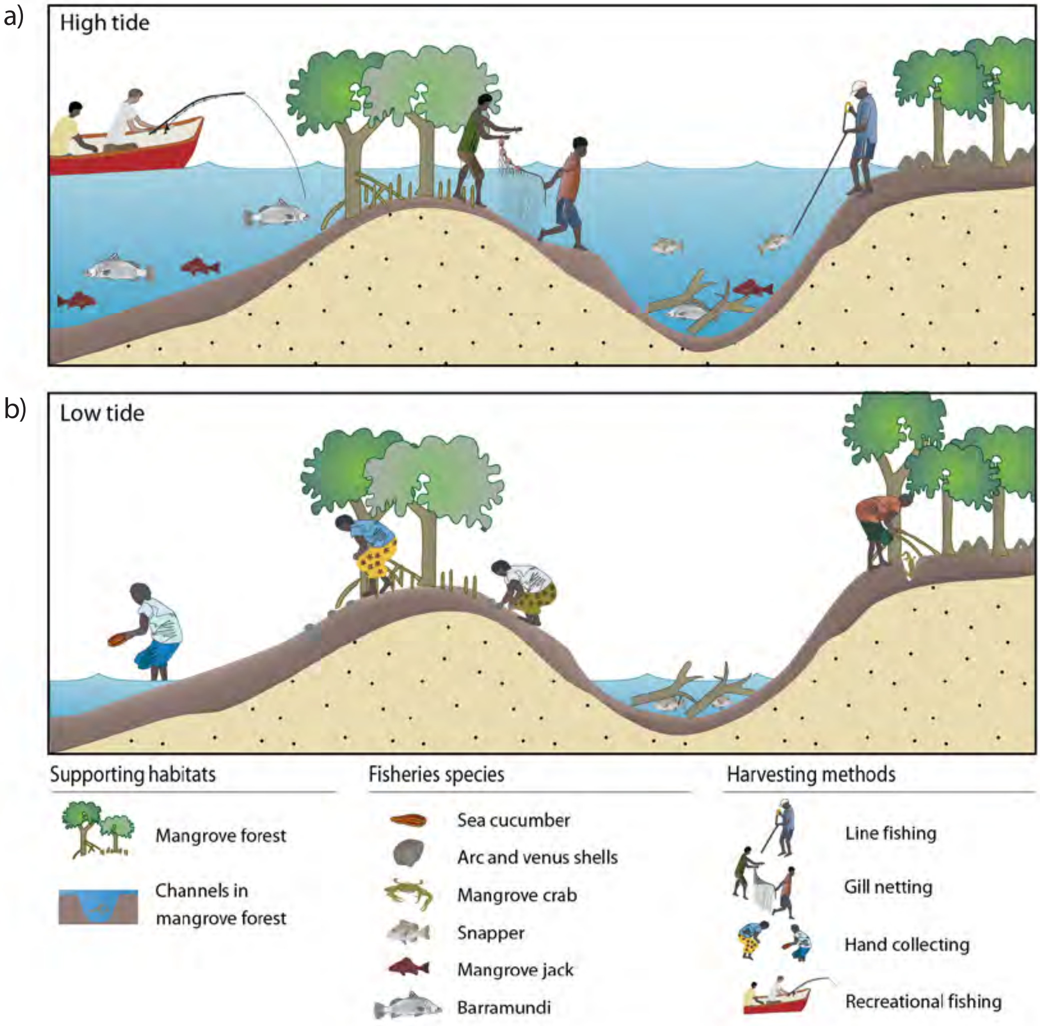


Figure 6.3 The subsistence and commercial coastal fishing activities that occur in mangrove habitats in the tropical Pacific at (a) high tide, and (b) low tide.

Table 6.3 The number of species associated with mangrove and seagrass habitats, as juveniles and/or adults, for the main groups of invertebrates caught by coastal fisheries in Pacific Island countries and territories (PICTs). All information is preliminary due to the lack of extensive sampling of invertebrates in mangrove and seagrass habitats in many PICTs. Blank spaces indicate that the invertebrate group does not commonly occur in the habitat.

Invertebrate group	Common name	Habitat		
		Mangrove	Seagrass	Both
Holothuridae	Sea cucumber		3	
Portunidae	Crab	5	3	3
Penaeidae	Shrimp	6		3
Palinuridae	Spiny lobster		1	
Thalassinoidea	Mud lobster	1		
Paguroidea	Hermit crab	2	3	
Stomatopoda	Mantis shrimp	1	2	
Cephalopda	Octopus		3	
Echinoidea	Sea urchin		3	
Bivalvia	Arc shell*	4	4	2
Gastropoda	Whelk*	3	2	1
Sipunculida	Peanut worm	2	2	2

* Indicates that several species are included under this broad common name.

6.3.2 Seagrasses

Seagrasses are also a vital part of the mosaic of habitats that support many of the demersal fish and invertebrates harvested by coastal fisheries (Chapter 9) (**Figure 6.5**). Seagrasses are thought to play a particularly important role in the coastal fisheries of New Caledonia, Palau, FSM, Guam and Wallis and Futuna, where relatively large areas of this habitat occur (**Table 6.1**), and in the large lagoons of Solomon Islands where rabbitfish (*Siganus* spp.) support subsistence and commercial fisheries[85,86].

Although the physical structure of seagrasses is not as robust as mangrove roots, the leaves of many seagrasses (e.g. *Thalassia* spp., *Thalassodendron* spp., *Cymodocea* spp., and *Syringodium isoetifolium*) are relatively tall and at high leaf densities can provide juvenile fish and invertebrates with much protection from predation[87]. Many seagrass meadows also remain submerged at low tide, which means that juvenile fish, shrimp and crabs can shelter there throughout the tidal cycle, feeding on zooplankton delivered by currents, and the epiphytes and epifauna on seagrass leaves. The seagrass leaves themselves also provide food for large numbers of species[88]. For these reasons, seagrass beds provide nursery areas for a wide range of fish and invertebrates that live on coral reefs or in other habitats as adults[89–91]. Tropical species of seagrass vary greatly in their structural complexity and therefore do not all provide the same degree of shelter. Nevertheless, even seagrasses with comparatively low leaf heights and densities can support high numbers of juvenile fish and invertebrates[87].

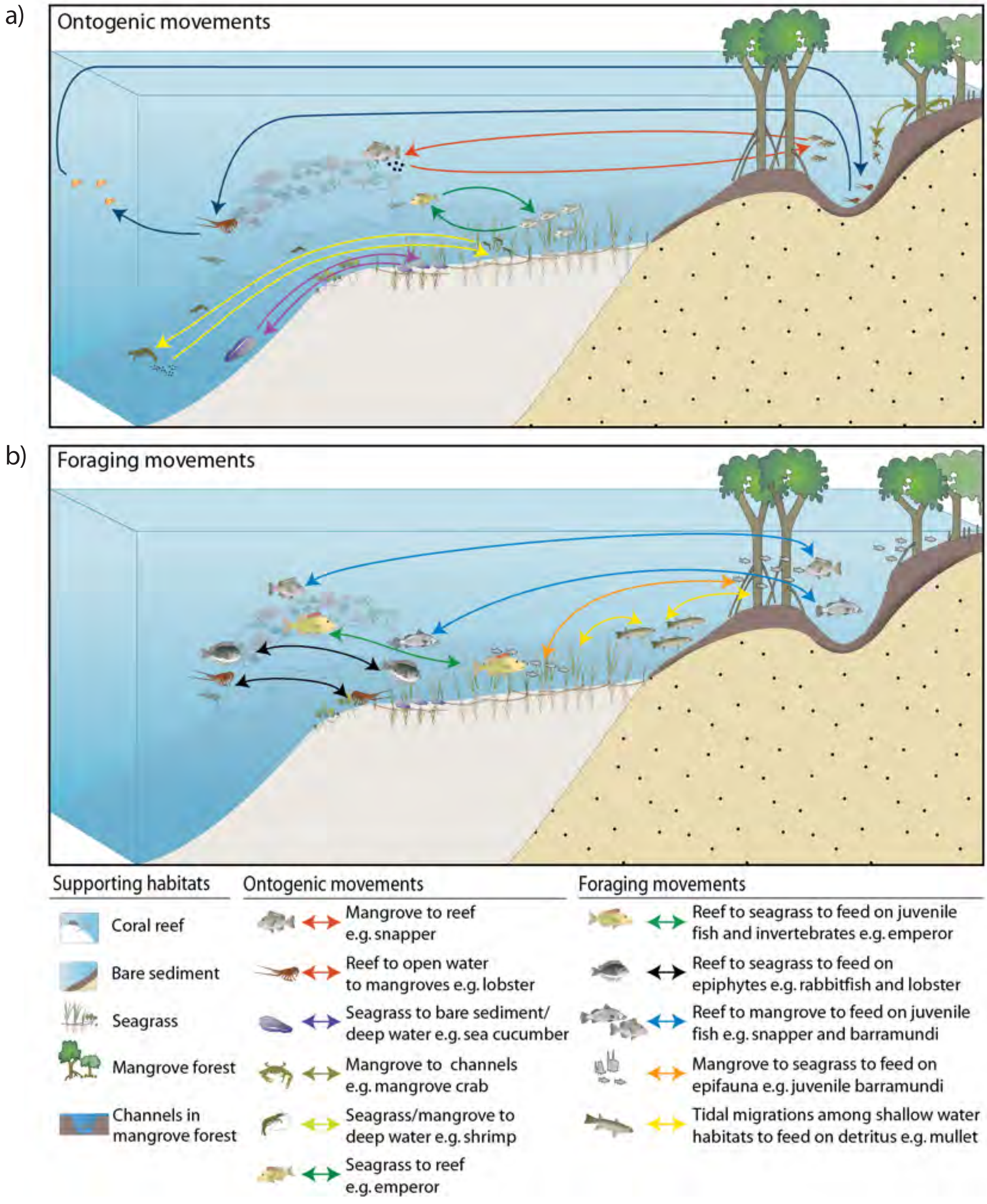


Figure 6.4 The mosaic of mangroves, seagrasses and coral reefs that occur in the coastal waters of many Pacific Island countries and territories, showing (a) the ontogenic movements of fish and invertebrate species among habitats as they grow; and (b) the foraging movements of adult fish and invertebrates from reefs to mangroves and seagrasses at night to feed. Note that diagrams depict high tide.

Many fish also visit seagrass meadows as adults to forage for food. The juvenile fish and invertebrates associated with seagrass attract a range of predatory fish from nearby coral reefs at night to feed. These species include emperors (Lethrinidae)[21] and snappers[92]. Herbivorous and omnivorous fish and invertebrates, such as the barred halfbeak *Hemiramphus far*, scribbled rabbitfish *Siganus spinus* and goatfish *Barberinus* sp. have been observed within seagrass beds in Solomon Islands[85]. Spiny lobsters (Palurinidae) also feed frequently on seagrass epiphytes and seagrass leaves[93].

In addition to the fish and invertebrate species that use seagrass meadows as nurseries or intermittent feeding areas, a wide range of valuable invertebrates live permanently in seagrass habitats, especially sea cucumbers[11,65,85], sea urchins, other bivalves and octopus[85,93–95]. These species are harvested during low tide[96,97], and are often gleaned by women and children for household food (Chapter 9).

6.3.3 Intertidal flats

The species of fish and invertebrates caught over intertidal flats and the methods used to catch them differ depending on geographic location, the tide and the season. The capture of demersal fish using gill nets, seine nets and hand lines occurs during high tide, whereas the gleaning of a range of molluscs, crustaceans, sea cucumbers and polychaetes occurs at low tide[98–100] (**Figure 6.6**). Furthermore, the harvest of some species (e.g. mantis shrimp) relies on first identifying and marking burrows at low tide, and then returning on the incoming tide to capture the shrimp as it emerges to hunt. The responses of fish and invertebrates to phases of the moon and seasons are understood by coastal communities and used to harvest some species over monthly or annual cycles[70,74].

The diversity and abundance of fish of species occurring on intertidal flats at high tide depends on the proximity of mangroves, seagrasses and/or coral reefs, and estuaries. This is not the case for infaunal invertebrates, which have limited mobility. For burrowing molluscs, crustaceans and polychaete worms, the intertidal sediments provide shelter from predation by birds, and desiccation at low tide. However, some species emerge at low tide, e.g. fiddler crabs, which feed on the BMA community that thrives in these shallow, sunlit habitats[101]. Carnivorous fish, such as bonefish *Albula* spp., rays (Dasyatidae) and trevallies (Carangidae) use the flats during high tide to prey on infauna. Herbivorous/detritivorous mullet and milkfish *Chanos chanos* also visit intertidal flats at high tide to feed directly on the BMA community[63,72]. Our preliminary understanding of intertidal flats in the tropical Pacific, like similar habitats in other parts of the world, indicates that their assemblages of BMA and infauna directly and indirectly support a wide variety of species[102].

The diverse range of fishing and gleaning activities that occur on intertidal flats make important contributions to food security and livelihoods in many PICTs. For example, in Kiribati, harvests of arc shells from intertidal flats at low tide have exceeded 3000 tonnes per year in the western Gilberts Group (Chapter 9). These bivalves comprise a regular and preferred part of the daily diet and can be a particularly important food for people in urban areas who cannot regularly catch or purchase fresh fish or other foods.

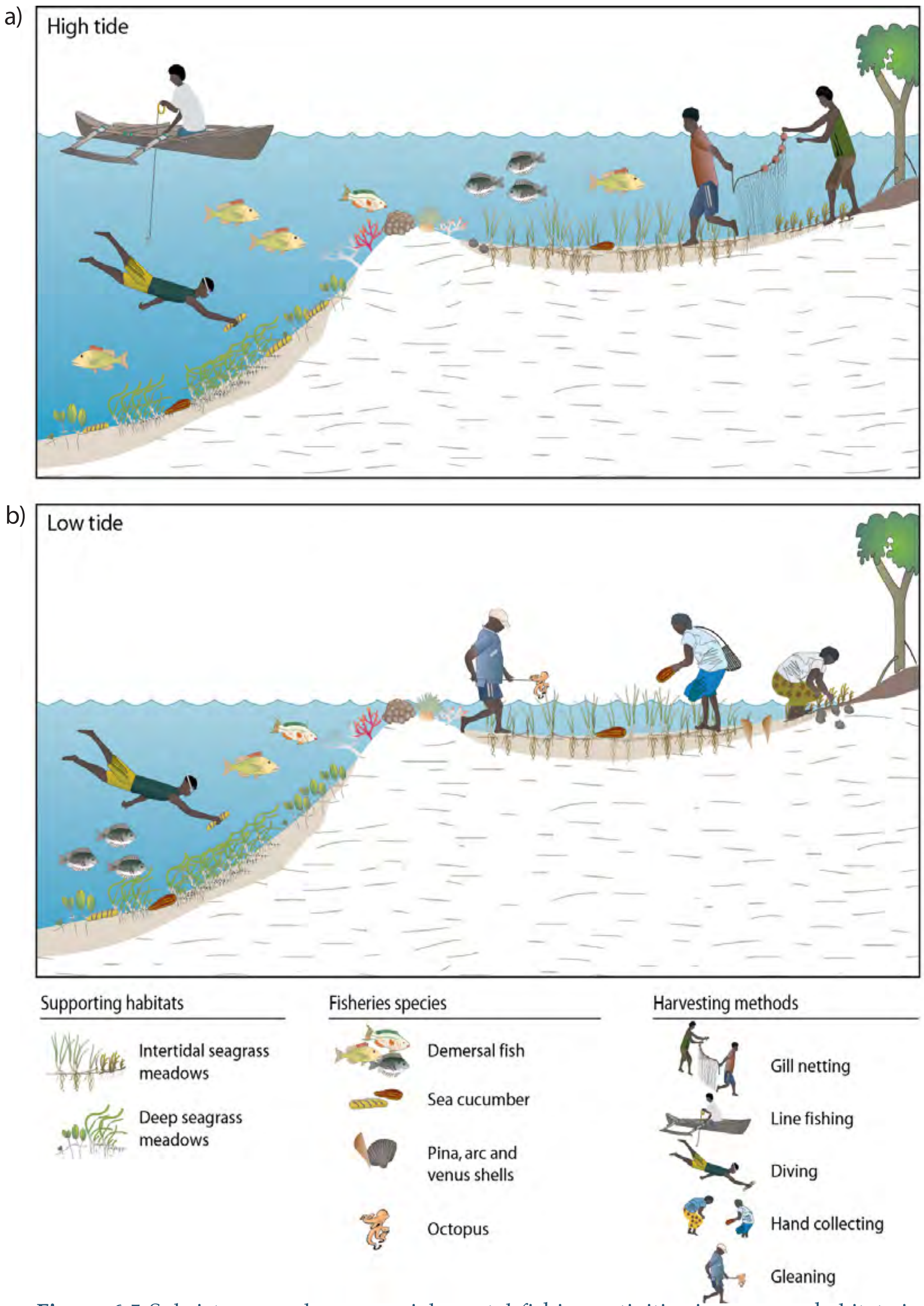


Figure 6.5 Subsistence and commercial coastal fishing activities in seagrass habitats in the tropical Pacific at (a) high tide, and (b) low tide.

Polychaete worms are also harvested and dried in rural areas of Kiribati and shipped to urban South Tarawa. These harvests provide an important source of income for people in rural areas. Recreational fisheries for bonefish (*Albula* spp.) in Cook Islands, Kiribati and New Caledonia also centre on productive intertidal sand flats.

6.4 Critical requirements for maintaining mangroves, seagrasses and intertidal flats

6.4.1 Solar radiation

Like all plants, mangroves and seagrasses need light for photosynthesis. However, light is rarely limiting for mangroves within the tropical and subtropical habitats where they occur – their light requirements for maximal photosynthesis are considerably less than the amount of light available on cloudless days. On the other hand, excessive irradiance can raise leaf temperatures and predispose mangroves to photoinhibition[103,104]. Elevated levels of ultraviolet radiation in the tropics can also inhibit growth of mangroves by disrupting protein synthesis and depressing photosynthesis via stomatal closure.

Mangroves have adapted to their environment by developing 'sun' and 'shade' leaves. Shade leaves are larger and thinner than sun leaves, with a higher volume-to-surface ratio and fewer stomata[103,105]. Also, leaves developing in high light intensity have more adaptations to guard against desiccation than those developing in low light intensity[103,106]. In general, there are two broad groups of mangroves (1) species which are somewhat shade-tolerant both as seedlings and adults (e.g. *Rhizophora stylosa* and *Bruguiera parviflora*), and (2) those that are shade intolerant (e.g. *B. gymnorhiza* and *Laguncularia racemosa*).

In contrast, light often limits the distribution, species composition, biomass and growth rates of seagrasses[107–110]. These flowering plants have high minimum light requirements compared with other marine primary producers[111] because they (1) have a high respiratory demand to support a large non-photosynthetic biomass of roots and rhizomes, (2) can only use a restricted spectral range of light, and (3) must regularly oxygenate their root zone to compensate for anoxic sediments. The high minimum light requirement restricts seagrasses to shallow coastal areas where sunlight can penetrate. There are, however, differences in light requirements among species. For example, *Halophila* spp. generally have a low minimum light requirement and can grow at greater depths than other species[112].

The BMA communities which inhabit the upper few centimetres of intertidal flats typically have high turnover rates and are composed of a diverse range of heterotrophic and autotrophic species which include photosynthetic algae[57,58].

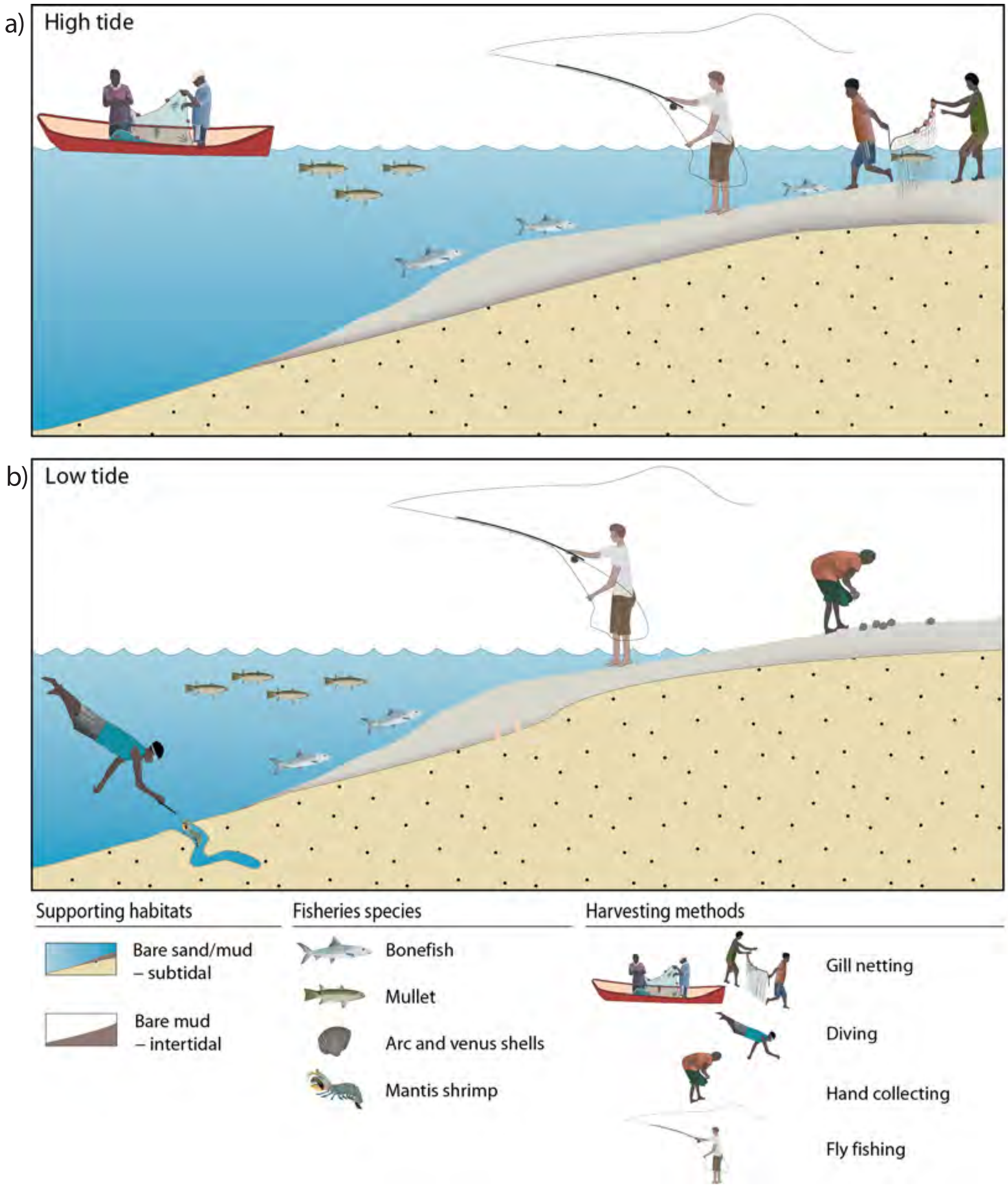


Figure 6.6 The subsistence and commercial coastal fishing activities that occur over intertidal sand and mud flats in the tropical Pacific at (a) high tide, and (b) low tide.

The greater proportion of the BMA population is usually confined to the upper 10 mm or so of the sediment surface[113–115] and primary productivity within the BMA community, derived from autotrophic species, such as cyanobacteria and diatoms, is the main source of *in situ* organic matter production in this habitat. Intertidal BMA species may also migrate vertically within the upper few centimetres of sediment.

This may be a response to avoid excessive heat, light, desiccation and/or predation[114]. Benthic microalgal assemblages can also adapt physiologically to ambient light conditions by varying the amount of chlorophyll they contain; this photo-adaptation response can occur in, for example, turbid estuary conditions[116]. Given the exposed nature of intertidal BMA communities at low tide, and shallow water depths during high tide, light is not generally considered to be a significant limiting factor to BMA productivity in the intertidal zone.

6.4.2 Temperature

Temperature is a critical factor for the survival and growth of plants because the enzymes involved in most cellular processes operate most efficiently within specific temperature ranges. Mangroves need warm temperatures for photosynthesis, respiration and energy processes involving salt regulation and extrusion, water uptake and growth. As a result, the northern and southern limits of most mangrove species coincide with the 20°C winter isotherm[117]. The heat tolerance of mangroves is less well studied, although the optimum temperature for photosynthesis of mangroves is < 35°C, and little or no photosynthesis occurs at 40°C[118,119]. Also, the rates of assimilation and water evaporation from plant pores are more efficient at leaf temperatures of 25–35°C, and decline sharply with increases above 35°C[120,121].

Tropical seagrasses require water temperatures of 25–35°C, otherwise the energy created from photosynthesis may not exceed the energy used for respiration[122]. Where water temperature rises to 35–40°C, photosynthesis declines due to the breakdown of photosynthetic enzymes[123] and the carbon balance of the plants goes into deficit because respiration continues to increase. Under such circumstances, growth rates of some tropical seagrasses can decrease because they have a limited capacity to store carbohydrates. These temperature thresholds vary among species[122] and seasons[124]. Thus, tropical seagrasses usually occur only in intertidal habitats where maximum summer temperatures are < 40°C[122,123]. They can survive higher temperatures for short periods, but prolonged exposure leads to the ‘burning’ of leaves or plant mortality.

The BMA communities of intertidal flats often live in extreme physiochemical conditions, especially during periods when low tide corresponds to midday sun exposure (high temperatures and UV exposure) or heavy rainfall (large changes in ambient salinity). Studies of temperature-related control over BMA community composition and productivity are limited mainly to temperate climates[125–127], where temperature appears also to be linked to changes in light[128]. Increases in temperature within the optimum range in these temperate environments marginally increase microalgal photosynthetic rates and nutrient uptake[129]. However, the effects of higher average temperatures on BMA communities within the environments of the tropical Pacific are unknown.

6.4.3 Nutrients and salinity

Growth and production of mangroves also depends on adequate supplies of macronutrients and micronutrients. Key plant macronutrients are: nitrogen, phosphorus, sulphur, magnesium, calcium and potassium. Micronutrients required for plant growth include: iron, manganese, copper, zinc, nickel, boron chloride, sodium, silicon, cobalt, selenium and aluminium. Sulphur, magnesium, potassium, boron, chloride and sodium are rarely limiting because they occur naturally in sea water. The critical need for nitrogen and phosphorus by mangroves has been demonstrated repeatedly through nutrient addition experiments[130,131], with most studies reporting limitation of one or both nutrients. However, the importance of nitrogen and phosphorus varies with location and position in the mangrove forest[131,132].

Mangroves have adaptations that allow them to tolerate high levels of salinity – membranes in cells at the root surface exclude most of the salt. The salt that does enter the plant is either excreted via the leaves or stored in leaves until they die and are shed, depending on the mangrove species. Because of the limited availability of fresh water in the soils of the intertidal zone, mangrove plants have also developed ways of limiting the amount of water they lose through their leaves. They can restrict the opening of their stomata, and have the ability to vary the orientation of their leaves to reduce evaporation during the harsh midday sun[133].

The most important macronutrients for seagrasses are carbon, nitrogen and phosphorus. Seagrasses do not grow at their full capacity unless these macronutrients are available in sufficient quantities[134,135]. The carbonate sediments found in reef environments typically bind phosphorus, reducing its availability for seagrasses, whereas sediments derived from the land are limited in nitrogen[136]. This general pattern can vary, however, depending on local nutrient inputs and sediment properties[137]. The levels of nutrients in some sediments in the tropical Pacific, e.g. those at Dravuni in Fiji, are among the lowest recorded for seagrass ecosystems[138].

Where nutrients are added to seagrass meadows that are normally nutrient-limited, the plants generally show an increase in growth and biomass[139,140]. However, excessive nutrients can lead to proliferation of phytoplankton, macroalgae or algal epiphytes on seagrass leaves and stems, reducing the amount of light reaching the seagrass[141,142]. Eutrophication of shallow estuaries and lagoons can also lead to the proliferation of bloom-forming ‘ephemeral’ macroalgae, which can shade and eventually displace seagrasses[143]. The impacts of nutrients on seagrasses in the tropical Pacific are usually localised to small bays, areas near human settlements[21,22], or areas adjacent to activities such as shrimp aquaculture, which have damaged some mangroves or seagrasses in New Caledonia[144]. Seagrasses generally grow best at salinities of 35 practical salinity units (PSU), although seagrasses have been observed growing in salinities of 4 to 65 PSU, with some species being more tolerant of extremely low salinity[145].

Benthic microalgae communities at the sediment surface obtain nutrients from the water column and interstitial water below the illuminated upper sediment layer[146]. However, due to tight coupling between mineralising bacteria and BMA production within the upper sediment layers, nutrients from the water column can play a relatively unimportant role[147]. The BMA community also intercepts and assimilates nutrients which may otherwise be fluxed from sediments to the overlying water column and may limit pelagic primary productivity in this way[58,148]. Indeed, significant concentrations of ammonium (NH_4^+), nitrate (NO_3^-), silicate (SiO_2) and phosphate (PO_4^{3-}) may be intercepted and prevented from entering the overlaying water column by BMA communities[149–151].

Benthic microalgae communities have relatively ready access to nutrients in sediments, which results in an inconsistent response to addition of nutrients to the water column. Nutrient loading has been shown to either increase BMA biomass and productivity[125,152] or have little effect[150,153]. Also, 'blooms' of BMA that occur in response to nutrient loading, seasonal change and removal of BMA grazers[154,155] are controlled by the two-dimensional nature of the BMA habitat. The ready supply of organic matter associated with productive BMA communities, and the mineralisation of this material by bacteria, are also associated with important processes such as denitrification[150,151,156]. Just as cyanobacteria are associated with nitrogen fixation[57], denitrifying bacteria in the lower anoxic layer of sediments can contribute to the substratum being a net sink for dissolved inorganic nitrogen and its removal via denitrification as nitrogen gas[151,157]. Net rates of denitrification are enhanced by the presence of burrowing infauna[157,158]. Thus, it is likely that the typically bioturbated intertidal flats of the tropical Pacific may play an important mediating role in nutrient processing and productivity.

Photo: Johann Bell

Women collecting arc shells ('palourde') in New Caledonia

In nutrient-limited systems typical of the more pristine coastal habitats of the tropical Pacific, the productivity of BMA is likely to be a more important contributor to primary production than phytoplankton (Chapter 4). In fact, BMA communities can be a major source of organic carbon input into shallow coastal ecosystems via the assimilation of sediment-born nutrients[57,113,156]. This in turn supports benthic epifauna and infauna populations, which contribute directly and indirectly to subsistence and commercial coastal fisheries and other biogeochemical processes that mediate or enhance the release of nutrients[157–159]. The vital role of BMA can change, however, in shallow areas subject to eutrophication, sustained high turbidity and/or intense physical disturbance. Under such conditions, BMA productivity may be greatly depressed and phytoplankton productivity in the upper water column can become more dominant[160].

6.4.4 Soils/sediments

Mangroves grow in various combinations of sand, silt and clay, which are often rich in organic matter (detritus). Sandy soils are porous and facilitate water percolation and aeration during low tide, while clays are less well aerated. Differences in soil types can have an effect on the distribution of mangrove genera, e.g. *Avicennia* and *Sonneratia* thrive in sandy areas, *Rhizophora* are found in peat soils and contribute to the formation of peat[161], and *Bruguiera* favour heavy clays containing little organic matter[162]. The subsoils in mangrove ecosystems are typically waterlogged, have little aeration and a heavy load of organic material decomposing at a slow rate. The oxygen content of only the first few millimetres of soil is replenished by the circulation of tidal water and exchange with the atmosphere. Below that, the organic load and fine particle size result in anoxic conditions. A supply of oxygen to the roots is vital for plant growth and nutrient uptake[134]. Consequently, mangroves in many locations rely on internal transport of gases to meet their oxygen requirements. The metabolic costs involved in this process reduce the rate of plant growth[163].

Sediment characteristics are also important in determining the growth, germination, survival and distribution of seagrasses[164–166]. In particular, sediment texture affects levels of nutrients and diffusion of oxygen[167]. Sandy sediments have lower fertility and diffuse oxygen more readily[167,168]. Conversely, finer-textured sediments usually have higher fertility and greater levels of anoxia because pore water has less interaction with the overlying water column[169]. The effects of anoxia on seagrass are complex – anaerobic conditions can stimulate germination in some species[170] but can also result in elevated sulphide levels, which inhibit production of leaf biomass in mature plants[171,172]. Sulphide is also toxic to seedlings of some species[173]. Overall, however, there is still insufficient information to identify the 'ideal' sediment types for seagrass[169].

Low-energy intertidal environments (i.e. lagoon sands and mud flats) generally yield the greatest BMA production[55]. Comparatively larger BMA communities are found in sandy sediment rather than fine silt and mud due to limited penetration of light into the finer sediments (e.g. light penetration into quartz sands may be more than twice as deep as into mud)[174]. Sandy sediments also tend to allow enhanced movement of interstitial water and therefore dissolved gases (e.g. oxygen and carbon dioxide) and nutrients. This provides a deeper habitat with favourable conditions for the BMA community[58].

Benthic microalgae communities can also influence the physical properties of sediments by enhancing the stability of the sediment surface via the secretion of mucous threads that bind sediment grains. In some cases, this results in formation of continuous mats over the sediment surface[58,114,175]. These mats greatly reduce resuspension of sediments due to wave action and water movement, and nutrient flux due to interstitial sediment flushing. This effectively regulates nutrient release into the water column from comparatively nutrient-rich deeper sediment zones[58,156,176].

6.5 Recent variation in mangroves, seagrasses and intertidal flats linked to climate change

6.5.1 Mangroves

Mangroves are sensitive to even minor transitions in coastal conditions, such as altered drainage patterns, saltwater intrusion, accretion or erosion in response to changes in sea level[35]. The response of mangroves to these changes can be seen through variations in the composition and relative abundance of plant species within the mangrove habitat[23,177,178]. Although the responses may be gradual, particularly in undisturbed systems, the alterations in coverage and composition of species can be used to assess the effects of climate change and other environmental impacts on mangrove habitats. This can be demonstrated through palaeo-environmental reconstruction[178], geographic information systems (GIS)[179], or ecosystem monitoring[180].

Examples of recently observed changes in mangrove ecosystems in the tropical Pacific associated with sea-level rise include (1) gradual retreat of mangrove zones in southern PNG in response to rates of sea-level rise similar to those projected globally[178,181] (**Figure 6.7**); and (2) GIS analysis of shoreline change over four decades in three mangrove areas in American Samoa, where there was landward movement of seaward margins of 25, 64, and 72 mm per year during sea-level rise of ~ 2 mm per year[179]. A study from the Caribbean also demonstrates the response of mangrove ecosystems to changes in sea level – the largest area of mangroves in Bermuda has been reduced by 26% due to retreat of the seaward edge, owing to inundation stress caused by sea-level rise of 2.8 mm per year[182,183]. In parts of Micronesia, mangrove sediment accretion rates are also not keeping pace with current rates of sea-level rise[184,185].

The success of flowering and ‘seed set’ of three species of mangroves in Fiji has been influenced by rainfall patterns[186,187]. Higher success was found on the west coast of Viti Levu relative to the dry coast, and in normal years relative to drought years.

In general, detection of changes in mangrove cover and health in the tropical Pacific has been limited and difficult because adequate baseline data and monitoring are usually lacking[29]. A shortage of meteorological, hydrological, hydro-geological and water quality data in many PICTs[188] compounds the problem. In addition, the limited data on the physical, chemical and biological processes in catchments, including soil erosion, loss of biodiversity and land clearing[189] (Chapter 7), make it difficult to separate the effects of coastal development and land use practices on mangrove habitats from any effects of climate change.

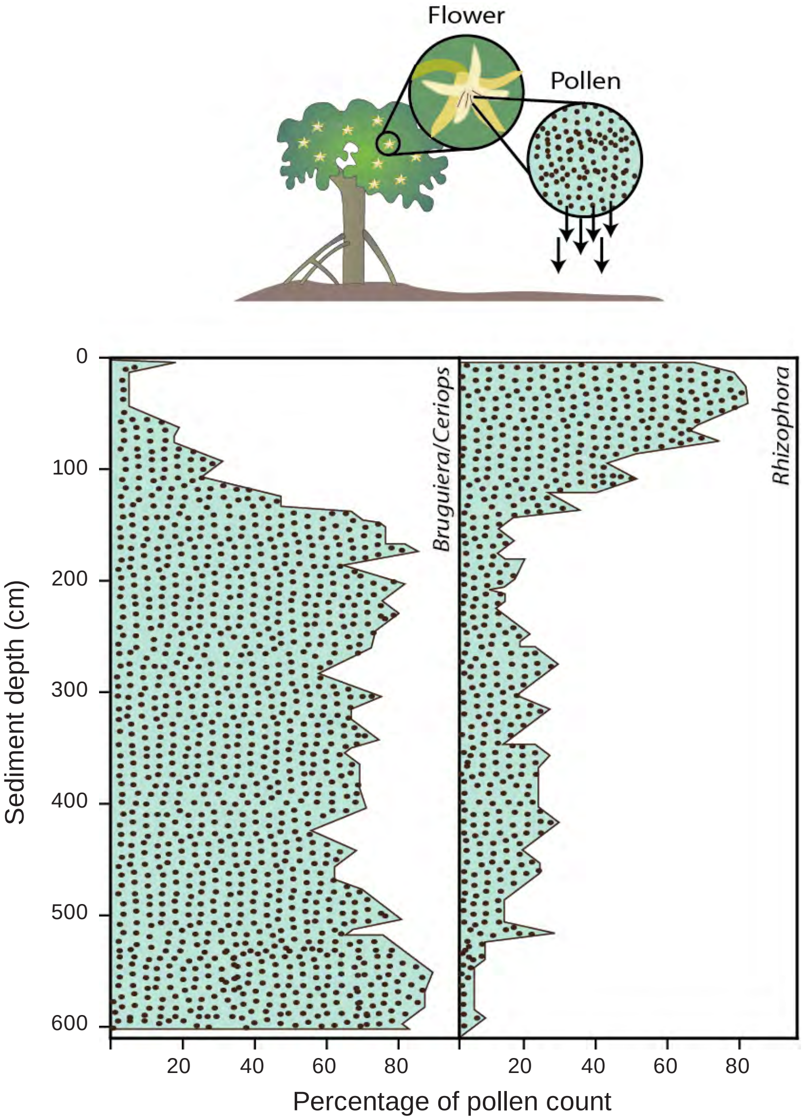


Figure 6.7 Replacement of the mangrove *Bruguiera* by *Rhizophora* within the past 3000 years in the Tipoeka Estuary, Papua New Guinea (based on sedimentary rock strata and pollen data), demonstrating gradual landward retreat of high island mangroves during sea-level rise rates of 0.7 mm per year (source: Ellison 2008)[181].

6.5.2 Seagrasses

Estimates of recent changes in seagrass habitats across the tropical Pacific are difficult to make because (1) seagrass meadows are known to fluctuate seasonally, and change from year to year[190,191]; and (2) maps of the distribution of seagrass area and biomass are either limited or imprecise. Isolated instances of seagrass burn-off (blackened dying leaves) have been observed on fringing reefs in Fiji. Although this burning is caused by exposure to elevated temperatures[122], there are insufficient data to conclude that these events are occurring at increasing rates. In other parts of the world, temperature-related seagrass losses have been recorded (e.g. southern Australia), and high temperatures have caused large-scale diebacks of *Amphibolis antarctica* and *Zostera muellerii*[192].

6.5.3 Intertidal flats

There has been little research on the impacts of climate change on intertidal flat habitats and their associated BMA communities and infauna in the tropical Pacific. The most likely impacts are from rising sea levels. However, the gradual rates of sea-level rise since the beginning of the industrial era, and the effects of atmospheric pressure and El Niño-Southern Oscillation (ENSO) on sea level (Chapter 3), make any effects difficult to detect, particularly against the background of high natural variability. The task is made all the more difficult because where intertidal flats are close to urban areas any effects of climate change would be confounded by direct human impacts, such as pollution, extraction of sand and coral for construction, coastal development, over-harvesting of infauna and changes in water quality.

6.6 Projected vulnerability of mangroves, seagrasses and intertidal flats to climate change

6.6.1 Mangroves

6.6.1.1 Solar radiation

Exposure and sensitivity

Mangrove habitats in much of the tropical Pacific are expected to be exposed to reductions in light as a result of the increase in the percentage of cloudy days due to intensification of the hydrological cycle (Chapter 2). Conversely, in New Caledonia, projected decreases in rainfall of 5–10% by 2035 and 5–20% by 2100, and in cloudy days, are expected to increase solar radiation.

Because the requirements of mangroves for light are lower than the average levels of solar radiation in the region, mangroves are not expected to be sensitive to the projected changes in levels of solar radiation caused by a more intense hydrological cycle. During periods of high solar radiation, however, the absorption of light translates into heat energy, which can be expected to exacerbate the effects of higher temperature on water loss (Section 6.6.1.2).

Potential impact and adaptive capacity

The potential impact of altered solar radiation on mangroves is expected to be low, except where mangroves have high exposure to solar radiation combined with limited freshwater supply. These conditions occur, for example, on the leeward side of high islands such as Viti Levu and Vanua Levu in Fiji, and on the west coast of New Caledonia where total rainfall is projected to decline (Chapter 2). If slow rates of sea-level rise were to occur they may enhance the adaptive capacity of mangroves to increased exposure to light by increasing tidal flushing and freshwater supply. However, such slow rates are not expected and thus limited adaptive capacity is expected for mangroves which are exposed to high levels of solar radiation.

Vulnerability

Relative to other factors, the vulnerability of mangroves to projected changes in solar radiation is low, except in areas of combined high radiation and restricted runoff and tidal inundation, where vulnerability is expected to be moderate.

6.6.1.2 Temperature

Exposure and sensitivity

Mangroves in the tropical Pacific will be exposed to projected increases in air temperature and sea surface temperature (SST) of 0.5–1.0°C in 2035 for the B1 and A2 emissions scenarios, 1.0–1.5°C for B1 in 2100 and 2.5–3.0°C for A2 in 2100 (Chapters 2 and 3).

The sensitivity of mangroves to increased surface air temperature and SST is not well known[193] but is likely to be moderate. For example, *Rhizophora mangle* develops more silt roots per unit area when subjected to a 5°C increase in water temperature and produces more but significantly smaller leaves[194]. Also, young seedlings of a species of *Avicennia* are killed by water temperatures between 39°C and 40°C, although established seedlings and trees are not affected[16,180]. On the other hand, mangroves growing near coastal power stations show little or no visible effects from warmer effluent water[195].

Potential impact and adaptive capacity

Mangroves have a high degree of tolerance to heat stress compared with other plants[196]. Thus, even for the A2 scenario in 2100, the projected increases in air temperature are not expected to have substantial effects on the growth and survival of mangroves because the projected increases are below those known to cause detrimental effects. Respiration (CO_2 efflux) from plants and microbial communities in sediments approximately doubles with every 10°C increase in temperature, so that on hot days there would be reduced net carbon gain, increased methane emissions and decreases in soil carbon storage[26]. In addition, mangroves have a range of adaptations, such as reducing the apertures of their stomata, to cope with water loss induced by increased evaporation under heat stress[103,180].

Vulnerability

Mangroves are expected to have very low vulnerability to the projected increases in air temperature and SST. However, an indirect vulnerability to increases in SST may result from the projected decreases in coral cover due to thermal bleaching (Chapter 5), which are expected to reduce sediment supply to mangroves on low islands, and increase exposure to wave action.

Mangrove habitats can be important fishing areas

Photo: Nicolas Petit

6.6.1.3 Rainfall

Exposure and sensitivity

In equatorial areas of the Pacific, rainfall is expected to increase by 5–15% for the B1 emissions scenario and 5–20% for the A2 scenario in 2035, and by 10–20% in 2100 for both emissions scenarios (Chapter 2). In the subtropics, rainfall is projected to decrease by 5–10% for B1 in 2035, and by 10–20% for A2 in 2035 and for both scenarios in 2100 (Chapter 2). Extremes in wet and dry periods are likely to become more extreme, and droughts associated with the projected changes in rainfall are expected to be more intense due to the increase in temperature (Chapter 2).

Mangroves are expected to be moderately sensitive to these changes because soil salinity along the intertidal gradient is affected by the interaction of tidal inundation and rainfall. At locations with low rainfall and high evaporation, soil salinity in the upper intertidal gradient may be high, even though inundation is infrequent. On the other hand, where rainfall greatly exceeds evaporation, for example, in Kosrae, FSM[197], salinity levels do not build up in the soil, and soil salinity is negatively correlated with distance from the seaward edge of the mangrove habitat.

Potential impact and adaptive capacity

The effects of lowered salinity associated with increases in rainfall are likely to benefit mangrove ecosystems in equatorial areas, but are expected to be negative in the subtropics where decreases in rainfall (increases in salinity) are projected. Reduced runoff from catchments in New Caledonia may decrease the delivery of sediment to mangrove habitats near estuaries, making it more difficult for the trees at the seaward margins to accumulate sediment and adapt to rising sea levels[35]. Increased drought conditions may also reduce the flowering and fruiting of mangroves[186,187], and perhaps increase the areas of upper intertidal salt flats currently found in the drier areas of the region, such as the leeward side of Viti Levu in Fiji.

Depending on environmental conditions, mangroves can minimise water loss and maximise growth by using water more efficiently and reducing transpiration rates. Such physiological plasticity is one reason why mangroves are so successful across the intertidal seascape and these attributes may assist them to adapt to drier conditions. Too much fresh water also poses problems for mangroves. In stagnant flooded soils, roots of many mangroves develop a very thin, slightly oxidised zone that can effectively isolate the actively growing root area[198]. Seedlings without well-developed aerial roots would suffer more in this situation than mature trees.

Vulnerability

Mangroves are expected to have low to moderate vulnerability to the projected changes in rainfall, and subsequently salinity, under both scenarios in 2035, with some benefits to plant growth possible from increasing rainfall in equatorial areas. However, as rainfall changes are magnified over time, the vulnerability of mangroves will increase to moderate in 2100 under both scenarios, particularly in areas of the Pacific that experience declining rainfall.

6.6.1.4 Nutrients

Exposure and sensitivity

The projected changes in rainfall outlined above are expected to alter runoff patterns and the delivery of nutrients to mangrove habitats. Future changes in nutrient supply are hard to quantify because they will be related to the intensity of rainfall. However, increases in nutrients derived from runoff are expected in equatorial areas of the Pacific, and decreases in New Caledonia.

Nutrient enrichment enhances vertical accretion and surface elevation of mangrove forests through increased deposition of roots[161]. Where nutrients are limited, the responses of mangroves are complex; they differ across different types of mangrove forests or locations, depending on the availability of the various nutrients required[132,133]. For example, *Rhizophora mangle* in Belize is limited to different degrees by nitrogen and phosphorus, depending on the zone in which it occurs[131,199]. Below-ground decomposition is generally enhanced by additional phosphorus but not additional nitrogen[131]. In contrast, both nitrogen and phosphorus are limiting for mangroves in Florida, USA[133].

Potential impact and adaptive capacity

In equatorial areas, the addition of nitrogen and phosphorus is likely to increase plant productivity by altering both tree growth and nutrient dynamics, with the magnitude and pattern of response differing for different nutrients[131,132]. In general, increased nutrients may benefit mangroves, or assist them to adapt to rising sea levels[161,200]. But changes in nutrient delivery, when coupled with low rainfall, have the potential to affect mangroves negatively. For example, projected decreases in rainfall (e.g. New Caledonia) may be expected to increase mangrove mortality where nitrogen concentrations increase[201]. Ultimately, community composition could be affected, with different mangrove species surviving at different rates, depending on their requirements for nitrogen and phosphorous[131,133].

Mangrove roots provide shelter for fish at high tide

Photo: Gary Bell

Because mangroves have large nutrient and carbon stores in soils and plant biomass[202,203], small changes in nutrients alone are not likely to have significant effects. However, when a decrease in nutrients is coupled with increases in temperature and atmospheric CO_2 (and associated increases in respiration), negative effects on plant tissue balance may occur[204] (Section 6.6.1.6).

The adaptive capacity of mangroves to changes in nutrient delivery will mostly be at the community level, with different species dominating under different nutrient conditions, and community composition shifting accordingly. This will have implications for the diversity and structure of mangrove habitats[204], and the services they provide to fish and invertebrate species harvested by coastal fisheries.

Vulnerability

The effects of the projected increases in nutrient delivery on mangroves around high islands in the equatorial Pacific are likely to be positive. In contrast, mangroves in New Caledonia are expected to be negatively affected by the projected decreases in availability of nutrients. The vulnerability of mangroves in New Caledonia is assessed as low, however, due to their inherent adaptive capacity.

6.6.1.5 Cyclones and storms

Exposure and sensitivity

Although global climate models do not project an increase in the frequency of cyclones in the tropical Pacific, there is the possibility that cyclones and storms will become more intense within the cyclone belt over the remainder of this century. In particular, wind speeds associated with cyclones may increase by 1–8% for every 1°C rise in SST (Chapter 2).

Mangroves are sensitive to strong winds associated with cyclones and storms, which damage foliage, desiccate plant tissues, and increase evaporation rates and salinity stress[35]. The landward margin of mangroves is particularly prone to high evaporative loses and drying-out of the substrate. Increased wave surge during cyclones erodes sediments in the seaward mangrove zone and reduces the stability of plants normally provided by their root systems[64,80]. On the positive side, stronger winds may facilitate pollination of species such as *Rhizophora* and *Excocaria,* and the dispersal of seeds.

Potential impact and adaptive capacity

Under prolonged and severe wind conditions, evaporative losses may result in die-back of mangroves. Stronger wave surges are also likely to remove mangroves from the seaward edge of mangrove habitats. While the logs from fallen trees may provide some shelter for juvenile fish if washed into subtidal areas, losses in primary productivity can be expected to exceed such benefits in many places. The movement of large, woody debris in mangrove areas during high tide can also disturb establishment of seedlings.

After a cyclone, there is usually a narrow zone of damage to mangroves along the coast due to storm surge, and complete defoliation in the path of the storm. Mangrove species have different tolerances to cyclone damage[205]. Rhizophoraceae have low tolerance and cannot resprout from dormant buds, whereas species of *Avicennia* can resprout. Mortality of mangroves as a result of storms has led to collapse of peat soils and changed hydrological conditions[206]. In general, mangroves grow new leaves after cyclones and storms unless there is structural damage to the trees or burial of the roots by sediments. Over time, recruitment of seedlings occurs from adjacent undamaged areas, and the mangrove habitat is re-established. This natural adaptive capacity can be enhanced and accelerated by replanting programmes.

Vulnerability

Mangrove habitats in the tropical Pacific are considered to have moderate vulnerability to the effects of more intense cyclones. Damage is expected to occur during these high-energy events, but the trees should eventually recover from the effects of wind and waves, prolonged inundation and sediment deposition, where the physical conditions required for growth and survival are restored.

6.6.1.6 Carbon dioxide

Exposure and sensitivity

For the B1 and A2 emissions scenarios, atmospheric concentrations of CO_2 are projected to be ~ 400 ppm in 2035. By 2100, CO_2 levels are expected to be 450–500 ppm for B1, and 750–800 ppm for A2[207]. The projected levels of CO_2 are also expected to increase the acidity of the ocean, and reduce the availability of carbonate ions (Chapter 3).

The few studies on the impacts of elevated CO_2 on mangroves suggest that primary production of mangroves is likely to be enhanced under future climate change scenarios. In situations of increased moisture stress, enhanced CO_2 may also partially reduce the negative effects of reduced humidity and rainfall[208]. Increased levels of CO_2 may also change the patterns of species dominance and accelerate mangrove encroachment into adjacent inland brackish and freshwater environments. However, when increases in CO_2 are combined with higher temperature and nutrient levels, there may be negative effects on plant tissue balance (Section 6.6.1.4).

Potential impact and adaptive capacity

The projected increases in atmospheric CO_2 are expected to increase productivity of mangroves, provided that salinity and humidity are also conducive to tree growth. The increased acidification of the ocean is not likely to affect mangrove habitats greatly, although the process by which dissolved calcium from dead shells makes some brackish waters alkaline may be weakened as acidification increases. Even if soil acidity increases, however, mangroves are not expected to be affected adversely, because many mangrove soils are neutral to slightly acidic due to sulphur-reducing bacteria and the presence of acidic clays[162]. In Malaysia, mangroves occur in very acidic brackish waters, probably due to the aeration of soil sulphates, forming sulphuric acid.

A common plant adaptation to elevated CO_2 concentrations is decreased nitrogen investment in leaves and a concomitant increase in the carbon:nitrogen ratio of plant tissues[209]. If mangroves respond in this way, the changes in plant tissue balance will have knock on effects for food webs[210], and on nutrient cycling[211].

An indirect impact of increased ocean acidity on mangrove systems could be reduction in the supply of carbonate sediment, expected to result from reduced rates of calcification by corals (Chapter 5). This may reduce the ability of mangroves on low islands to adapt to sea-level rise.

Vulnerability

Mangroves are unlikely to suffer negative effects as a result of increased atmospheric CO_2 alone. Rather, they are expected to grow faster and become carbon sinks in some places. There may also be increased allocation to below-ground biomass with elevated CO_2, resulting in greater gains in soil surface elevation and stability under sea-level rise[212]. In some locations, synergies with increased temperature and altered nutrient delivery may result in negative effects on plant tissue balance. In such places, mangroves are likely to have a very low to low vulnerability to elevated CO_2.

6.6.1.7 Sea level

Exposure and sensitivity

The conservative projections for sea-level rise made in the IPCC Fourth Assessment Report (IPCC-AR4) of ~ 10 cm for the B1 and A2 emissions scenarios in 2035, ~ 20–40 cm for B1 and ~ 20–50 cm for A2 in 2100, have now been increased substantially. More recent estimates are 20–30 cm for the B1 and A2 scenarios in 2035, 70–110 cm for B1 and 90–140 cm for A2 in 2100 (Chapter 3).

Mangroves grow between mean sea level and mean high water, and the zonation of mangrove species (**Figure 6.1**) is determined by inundation frequency controlled by the tides. If the tidal conditions under which mangroves grow are altered, the growth and survival of the trees are affected. In experiments to simulate the effects of inundation due to sea-level rise on the growth of *Rhizophora mangle*, for example, seedlings maintained under conditions where an increase of 16 cm was imposed on normal tidal water levels were 10–20% smaller than control plants after 2.5 years[213].

Potential impact and adaptive capacity

The projected rise in sea level could potentially have a powerful effect on mangroves. However, where mangroves can continue to accumulate sediments at appropriate rates, the effects are likely to be less severe. The capacity of mangrove forests to resist sea-level rise is likely to depend on the source of sediment, and the rate of sedimentation, which in turn is influenced by rainfall, tidal amplitude, coastal currents and wave energy[214]. Biogenic processes, particularly root growth rates, will also be important in the response of mangroves to sea-level rise[161].

Sedimentation is expected to be slower in areas of natural subsidence, such as southern PNG, American Samoa and western Viti Levu in Fiji[178,179,215]. Mangroves on low islands may be able to compensate for low rates of sea-level rise through accumulation of peat[161,182]. Most continental and high island mangroves are expected to adapt if the rate of sediment deposition exceeds the rate of sea-level rise. However, various surface and subsurface processes, such as sediment accretion and erosion, biotic contributions, below-ground primary production, sediment compaction, fluctuations in water-table levels and pore water storage, make sedimentation rates alone a poor indicator of mangrove responses to rising sea level[216,217].

The potential impact of sea-level rise on mangroves will be greatly reduced in those locations where they can migrate landward[217]. The scope for migration will depend on the rates of sea-level rise and accumulation of sediments, and changes in elevation. Historical records show mangrove die-back under accelerated rates of sea-level rise, followed by re-establishment as sea level falls (**Figure 6.8**). Landward migration will, however, be constrained in many locations by barriers such as coastal roads and settlements, and where steep terrain occurs behind mangroves. In addition, the projected acceleration in the rate of sea-level rise after 2050[207] is expected to make it difficult for mangroves to re-establish and reach reproductive maturity before their intertidal elevation envelope is reduced again. PNG, Solomon Islands and FSM have freshwater swamp forest or marsh on the landward margin of mangroves that could become mangrove habitat with rising sea level.

Thus, establishment of mangroves in new landward areas is only likely where (1) the topography is suitable for colonisation, (2) the rate of sea-level rise is compatible with the life cycles of mangrove species, (3) the hydrology and sediment composition is suitable, and (4) there is limited competition with non-mangrove species[214,217].

Vulnerability

The vulnerability of mangroves to projected sea-level rise is high for both scenarios in 2035, particularly in locations where the coastline is subsiding and sedimentation rates are low. Vulnerability is expected to be very high for both B1 and A2 scenarios in 2100 where landward migration is blocked by infrastructure, where there is intensive land use and steep gradients, and as the magnitude of sea-level rise increases later in the century.

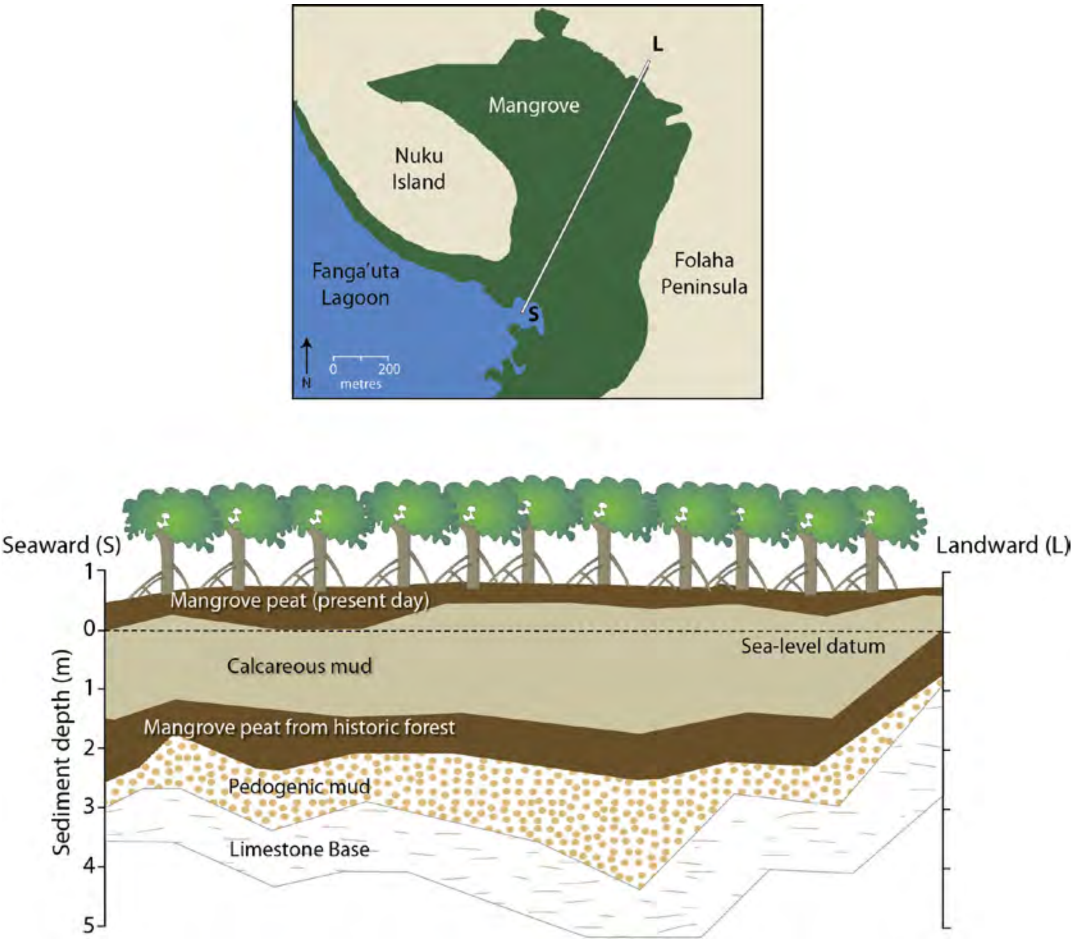


Figure 6.8 Sedimentary evidence of the extent of mangroves at Folaha, Tongatapu, Tonga, 7000–5500 years ago when forests growing 1.5–2.5 m below present sea level were exposed to accelerated sea-level rise (1.2 mm per year). The mangroves died back to create a lagoon, ultimately re-establishing after a fall in sea level[181].

6.6.2 Seagrasses

6.6.2.1 Solar radiation

Exposure and sensitivity

Seagrass habitats in the tropical Pacific are expected to be exposed to reductions in light as a result of climate change. The projected increases in rainfall (Section 6.6.1.3) (Chapter 2), are likely to reduce the availability of light by < 1–15% in 2035 and 5–20% in 2100 due to (1) increased turbidity of coastal waters from higher levels of runoff from high islands (Chapter 7); (2) greater growth of phytoplankton and epiphytic algae from the associated nutrients; and (3) a possible increase in the percentage of cloudy days due to intensification of the hydrological cycle (Chapter 2). No reduction in availability of light is expected for the large areas of seagrass habitat in New Caledonia due to the projected decreases in rainfall of 5–10% by 2035 and 5–20% by 2100 (Chapter 2). Indeed, increases in the number of cloud-free days are likely to occur there in winter.

The seagrasses found in the tropical Pacific have varying tolerances to low levels of light, and grow at different depths (**Figure 6.9**). These species are sensitive to reduced levels of light because the resulting decreases in photosynthesis affect growth rates. In extreme cases where carbon reserves are depleted and respiration demand outstrips photosynthesis, plants will die[111,142,218–223]. Light limitation, caused by suspended sediment and excess nutrients, has a major impact on seagrass meadows[218,224].

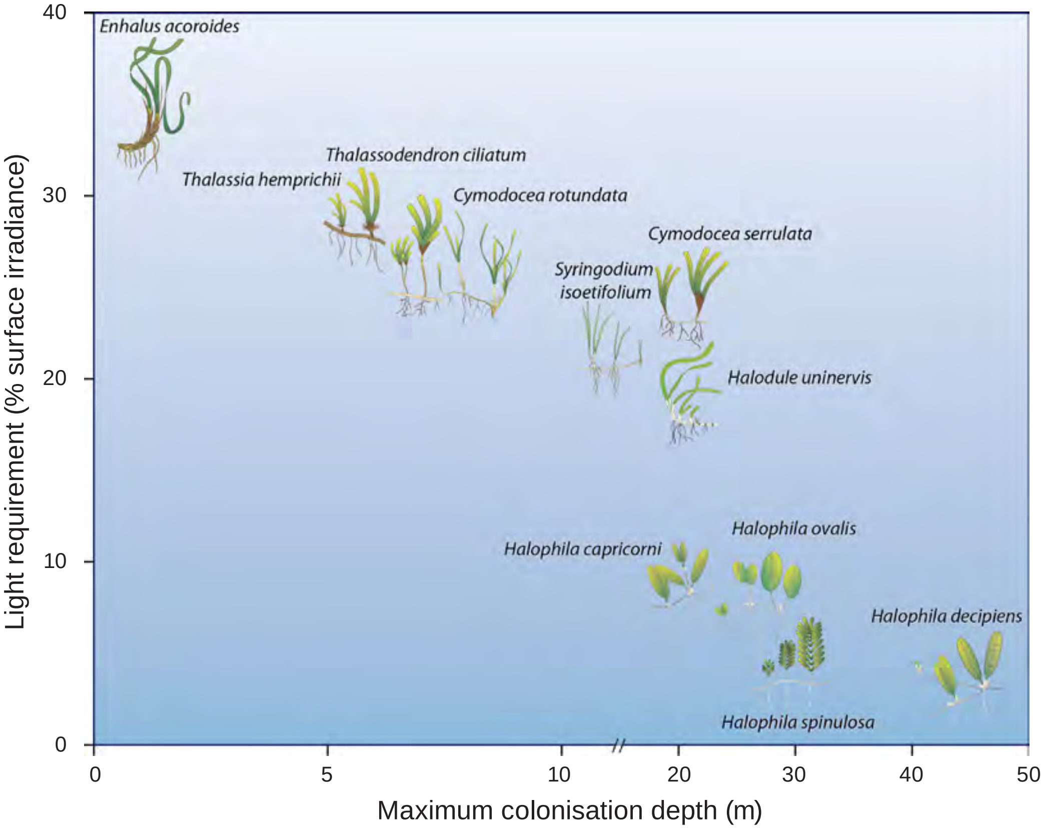


Figure 6.9 Estimated light requirements and maximum depth limit of various seagrass species in the tropical Pacific (source: Collier and Waycott 2009)[4].

The mechanisms that seagrasses use to recover from periods of reduced light are species-specific[43,225–227] and vary due to differences in the morphological plasticity, storage products, life-form and growth rates of species[109]. In general, morphologically large and slow-growing species, such as *Thalassia* spp., tolerate prolonged periods of low light but are slow to recover if severely affected. In contrast, small rapidly-growing species, such as *Halophila* spp., cannot tolerate extended periods of low light because of limited storage reserves. They can recover from such impacts quickly if conditions improve, however, by regenerating through seed production and rhizome extension[221].

The response of seagrasses to reduced light is rapid. When seagrasses from the Pacific were exposed to low light levels (< 14% incident light), the rate of leaf extension changed within 7 days, and significant losses of leaves per shoot occurred after 14 days[221,228,229]. After 46 days, shoot density was reduced and complete loss of shoots was predicted after 100 days.

Seagrasses may also be affected by over-exposure to UV irradiance[230]. High levels of UV reduce production of chlorophyll *a* and enhance production of anthocyanins (vacuolar pigments), causing 'reddening' of plant leaf tissues[230].

Potential impact and adaptive capacity

Changes in solar radiation are expected to have profound effects on seagrasses in the tropical Pacific, ranging from changes in the relative abundance and species composition of species, including loss of large, slow-growing species where exposure to low light levels are severe and prolonged, to changes in leaf colour where exposure to UV increases. Significant losses to the area of seagrass meadows are expected to occur where light availability is reduced for long periods (~ 100 days)[221]. Possibly up to 20% of seagrass area in the region could be lost by 2100 due to light reduction alone. Such losses are expected to occur mainly in locations with significantly higher rainfall, where the resulting turbid conditions persist for months.

Seagrasses are able to respond to shorter-term (days to weeks) reductions in light through a range of morphological and physiological adjustments[2]. When the factors limiting light are removed, and if the seagrasses have not completely drained their reserves, they can recover from vegetative fragments left in the meadows. If whole meadows have been lost, then recovery can only occur through recruitment of seedlings. Seagrass communities comprising small species, such as *Halophila* spp. and *Halodule* spp., have a greater capacity for recovery, because they produce copious quantities of seed and have rapid colonisation rates due to their growth form[4,43].

Vulnerability

The seagrasses expected to be most vulnerable to changes in light conditions are those that occur in estuaries or in coastal habitats subject to runoff. Vulnerability is expected to be moderate in 2035 and 2100 for most locations, increasing to high around islands with large, steep catchments, where runoff remains in bays and lagoons for long periods. Complete loss of seagrass is expected to occur if turbidity and light reduction persist at below the minimum light requirements for periods > 100 days[221,229].

6.6.2.2 Temperature

Exposure and sensitivity

Seagrasses in the tropical Pacific are projected to be exposed to increases in SST in the range of 0.5–1.0°C in 2035 for the B1 and A2 emissions scenarios, 1.0–1.5°C for B1 and 2.5–3.0°C for A2 in 2100 (Chapters 2 and 3).

Seagrasses are likely to be highly sensitive to increases in SST, whether they occur as short-term 'spikes' in maximum temperature over periods of hours, or as chronic exposures for weeks or months, because in many locations seagrasses are already growing at their maximum temperature tolerance[122,229]. Short-term exposure to temperatures > 40°C causes death of seagrass leaves. Such effects have been recorded regularly for the tropical seagrass meadows of the region[231]. However, there is a wide range of responses to short-term increases in temperature > 40°C among seagrasses, with death of leaves occurring more rapidly for the smaller species[122,229] (**Figure 6.10**).

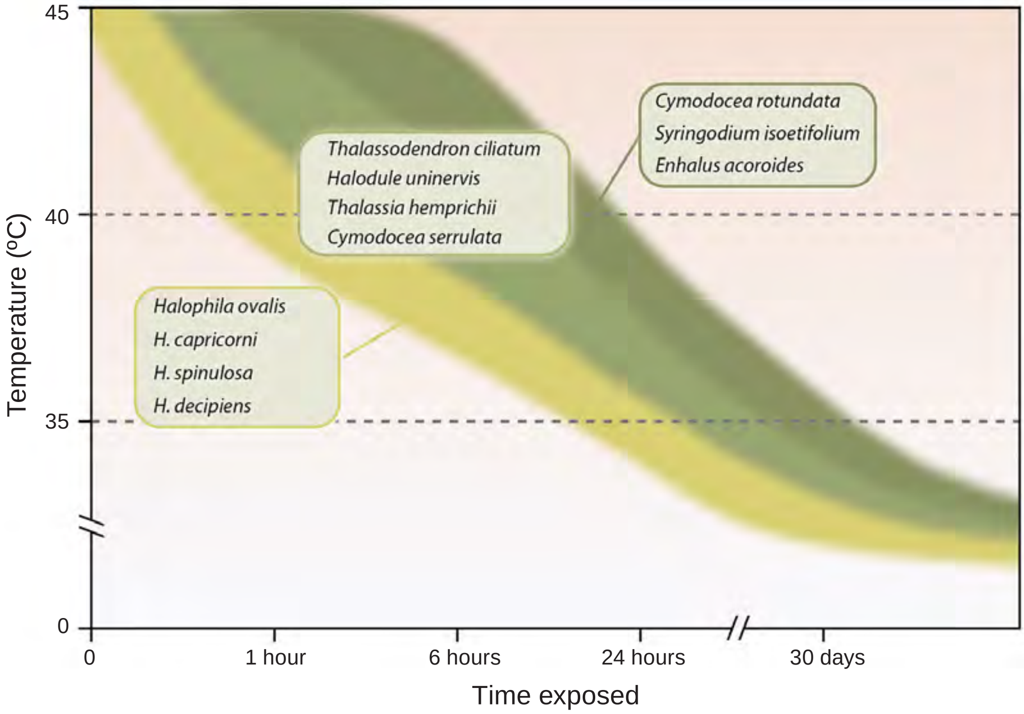


Figure 6.10 Thresholds for survival of seagrass species in the tropical Pacific under elevated sea surface temperatures (SST) and increasing exposure. Species of *Halophila* are the most sensitive to high SST, and *Cymodocea rotundata* and *Syrigodium isoetifolium* are the most tolerant (source: Campbell et al. 2006, Collier unpublished data)[122]. Note, however, that all species shown here can co-exist throughout the region and may have similar long-term (> 30 days) temperature thresholds.

Chronic elevated SST of up to +3°C results in increased respiratory demand and loss of seagrasses when respiration outstrips photosynthesis[229]. Once again, responses are likely to be species-specific, although data on the effects of chronic temperature stress for tropical seagrasses are limited.

Potential impact and adaptive capacity

The projected increases in SST are expected to cause changes in the species composition, relative abundance and distribution of seagrasses in the tropical Pacific. Short-term temperature 'spikes' are likely to reduce biomass through 'burn off', whereas overall increases in SST are expected to drive the more chronic changes in species composition (structural complexity) and distribution[229]. The fact that the roots and rhizomes of seagrasses are buried in sediments, offers some protection against the impacts of short-term changes in SST. However, as seagrasses possess high light requirements[111], their ability to adapt to longer-term increases in SST will be limited by their overall respiration demand[229]. Thus, the impact of increasing SST will depend on light availability, with interactions between elevated temperatures and reduced light levels resulting in greater potential impacts. Where seagrasses are not stressed by light, temperature may become the primary driver for responses by seagrasses. However, because seagrasses are typically light-limited, light levels are expected to continue to dominate their responses to changing environmental conditions.

Vulnerability

Many of the seagrass meadows in the region are expected to have moderate to high vulnerability to increases in SST. Shallow intertidal seagrass meadows are likely to be at the greatest risk, particularly where the less robust *Halophila* spp. and *Halodule* spp. dominate. Where seagrasses are already experiencing lower light levels, meadows will have high vulnerability to increases in SST because their relatively high respiration demands are expected to exceed their capacity for gaining carbon through photosynthesis.

6.6.2.3 Rainfall

Exposure and sensitivity

In the equatorial areas of the Pacific, rainfall is projected to increase by 5–15% for the B1 emissions scenario and 5–20% for the A2 scenario in 2035, and by 10–20% in 2100 for both emissions scenarios (Chapter 2). In the subtropics, rainfall is expected to decrease by 5–10% for B1 in 2035 and by 10–20% for A2 in 2035 and both scenarios in 2100 (Chapter 2). Extremes in wet and dry periods are also projected to become more extreme.

In addition to affecting light, greater runoff from higher rainfall is expected to reduce salinity and increase the transfer of sediments, nutrients and toxic chemicals from catchments to seagrass meadows. Strong reductions in salinity inhibit the growth of seagrasses[145]. However, the effects of salinity are usually localised, being more significant in bays and lagoons where the residence times of water are in the order of weeks to months.

Seagrasses are sensitive to the deposition of sediments because physical burial prevents their ability to grow[21,22,49,219,222,232]. Modest additions of sediments can benefit seagrass habitats through provision of new substrate and the addition of nutrients. However, where deposition rates are greater than the ability of seagrass to grow through the new sediments, plants will die. Movement of sediments can also cause scouring of seagrass habitats[3], with damage being proportional to sediment loads and the volume of runoff. Scouring of seagrasses has been a problem in Pohnpei[233]. Chemical pollutants such as diuron, known to be poisonous to seagrasses, have been documented to occur in tropical seagrass sediments[234]. Where chemical pollutants are present, the effects are generally proportional to sediment loads and the volume of runoff. The effects of variation in nutrient loads on seagrasses are discussed in Section 6.6.2.4.

Potential impact and adaptive capacity

The potential effects of changes in rainfall on seagrass habitats are complex, but expected to be significant in several PICTs. The greatest impacts are likely to occur around high islands in the tropics, where runoff and sediment loads are projected to increase in the future. Intertidal seagrass habitats close to land are likely to be affected more severely than subtidal meadows because they are directly exposed to both rainfall and runoff. Particularly significant impacts are expected where soil erosion associated with coastal agriculture (e.g. palm oil plantations), land clearing (e.g. logging and mining) and mine tailing discharge occurs (Chapter 7).

The capacity for seagrass habitats to adapt to reduced salinity will be correlated to the species that occur in each region. Some species, such as *H. ovalis*, have broader salinity tolerances[235] and are likely to become more prevalent in lower salinity environments. Limited adaptive capacity is expected among species that do not tolerate freshwater flushes, although research is still needed to identify the thresholds and responses of species. Similarly, seagrasses are unlikely to have much adaptive capacity to pollution, which is expected to have a cumulative effect on the plants. Low chronic loads of some toxins have been reported to have a positive effect on plant growth. However, further research is needed to identify specific plant responses, in particular the relationship between toxicant loads and seedling germination and growth[3].

Vulnerability

The large seagrass habitats in nearshore bays and lagoons around high islands in the tropics are expected to have a moderate to high vulnerability to reductions in salinity and increases in sediments and toxic chemicals resulting from increased rainfall and runoff. Seagrasses in New Caledonia are expected to have low vulnerability to future patterns of rainfall, providing that future management can ensure that runoff from mining activities does not damage the plants.

6.6.2.4 Nutrients

Exposure and sensitivity

The projected changes in rainfall described immediately above are also expected to change the availability of nutrients in seagrass habitats because of altered runoff patterns. As outlined in Section 6.6.1.4, changes in supply of nutrients are hard to quantify, but increases in equatorial areas, and decreases in New Caledonia, are expected.

A tropical seagrass habitat

Photo: Andre Seale

In general, seagrass meadows throughout the tropical Pacific occur in reef-associated, carbonate-dominated sediments and are phosphorous limited (Sections 6.2.2 and 6.4.3). Delivery of additional phosphorus, nitrogen and other micronutrients through increases in runoff is expected to enhance seagrass growth. However, elevated concentrations of nutrients in the water column are also expected to result in increases in epiphytic algae on seagrass leaves[236]. These algae block light, retarding the growth of seagrasses[111]. They also increase the resistance of leaves to water movement and can be expected to increase the loss of leaves during storm surge.

Potential impact and adaptive capacity

The height and density of seagrass leaves, and the area of seagrass, could potentially increase under the influence of more nutrients where nutrients are limiting[130,139,140]. However, where other factors limit seagrass growth, the potential for seagrass habitats to benefit from increased nutrients will not be realised. For example, in areas where increased runoff reduces salinity and/or water clarity in coastal waters for extended periods (i.e. in bays and 'ponded' lagoons with high residence times), e.g. parts of Marovo and Roviana Lagoons in Solomon Islands, seagrass growth is unlikely to increase. The inhibiting effects of turbidity are expected to be common in those catchments where agriculture, forestry and mining have not been managed to minimise runoff (Chapter 7). The potential effects of increased epiphytic algae may be reduced where herbivorous invertebrates and fish are common. This may rarely occur, however, because increased nutrient loads are likely to be associated with areas under active development and fishing pressure can also be expected to be more intense in such places (Chapter 9).

The seagrass habitats of New Caledonia are not expected to benefit from increased nutrients because of projected reductions in rainfall. However, the possibility of more intense rainfall events and cyclones means that local areas may periodically receive excessive nutrients (and sediments) due to increased rates of removal of drier topsoil and reduced catchment vegetation when these events do occur (Chapter 7).

In locations where nutrient concentrations are relatively low, and where light is not limiting, seagrasses have the capacity to absorb increased nutrient levels and increase their biomass[130]. Higher nutrient loads may also increase nutrient concentrations in tissues[140], to the point where the plants are unable to use or store any more nutrients and where other factors become limiting. When nutrient loads exceed the ability of seagrasses to use them given the available light, blooms of epiphytic algae occur, further reducing light availability[111].

Vulnerability

Modest increases in availability of nutrients is expected to have a small positive effect on seagrass habitats in the tropical Pacific. Where levels of runoff and nutrients are high, the potential benefits will be over-ridden by the adverse effects of low salinities, reduced light due to turbidity or algal blooms and, in poorly managed catchments, the effects of chemical pollutants. Such problems are expected to be more pronounced under the A2 scenario in 2100, when seagrasses are likely to have low to moderate vulnerability to the combined impacts of altered nutrients, salinity and turbidity.

6.6.2.5 Cyclones and storms

Exposure and sensitivity

As outlined in Section 6.6.1.5, cyclones and storms may possibly become more intense within the cyclone belt over the remainder of this century (Chapter 2). In addition to increasing sediment loads and nutrient levels, more intense cyclones and storms are expected to increase the power of waves affecting coastal habitats (Chapter 3).

Wave surge strips leaves from seagrasses and often uproots the subsurface rhizomes, removing the plants from large areas of the intertidal and shallow subtidal zones[3]. Reductions in light caused by greater turbidity following cyclones can also be expected to affect seagrasses[219].

Succession in species composition of seagrasses is expected to occur in those areas where cyclones remove plants[4,237]. Small species (e.g. *Halophila ovalis* and *Halodule uninervis*) would be expected to dominate initially and then be replaced gradually by the larger, climax species (e.g. *Cymodocea serrulata*, *Thalassia hemprichii* and *Enhalus acoroides*). Note, however, that this succession does not usually proceed to a fully stable community in locations where other factors, such as reduced light, limit the colonisation by structurally large species. Such moderate levels of disturbance generally result in seagrass communities being dominated by smaller species of seagrass[4].

Potential impact and adaptive capacity

Severe storms can devastate seagrass habitats through the combined effects of physical disturbance, reductions in light and salinity, and movement of sediments. Such impacts are expected to be greatest in shallow, subtidal and intertidal areas because they receive the full force of wave energy (Chapter 3). However, the degree of change to seagrass habitats due to the more moderate effects of cyclones and storms depends on the species composition of the meadow. Small seagrasses, such as *Halophila* spp. or *Halodule uninervis*, are likely to suffer more damage than larger species with rhizomes buried deeper into the sediment, such as *T. hemprichii*.

Vulnerability

Intertidal and shallow subtidal seagrasses are expected to be highly vulnerable to any increase in cyclone intensity. The effects of wave surge on seagrass habitats in the path of a cyclone are likely to be devastating, except for seagrasses growing in relatively deep water (Section 6.2.2.5). In addition, scouring by mobile sediments associated with high energy water movements would significantly affect seagrass meadows. Small species of seagrass are expected to be more vulnerable than large species in areas where the physical effects of cyclones and storms diminish away from the trajectory of the storm. However, because these species also have the capacity to recover rapidly[4], the effects may only be short-term provided propagules are available to re-establish the meadows.

6.6.2.6 Carbon dioxide

Exposure and sensitivity

Future emissions of CO_2 are projected to reduce the pH of the tropical Pacific Ocean by 0.1 units by 2035, and by 0.2 to 0.3 units by 2100 for the A2 emissions scenario (Chapter 3). All seagrass meadows will be directly exposed to these declines in pH.

However, the pH in seagrass meadows can vary by up to 0.9 units over diurnal cycles as a direct result of carbon uptake by seagrasses and other autotrophs (including epiphytic algae). The largest changes in CO_2 concentrations occur during the day, when photosynthesis is at a maximum, and in shallow water[238–241].

The most critical effect of increases in CO_2 concentration and reductions in pH for seagrasses relate to changes in the availability of dissolved inorganic carbon, and the rate at which the plants take up dissolved inorganic carbon. Seagrasses use both HCO_3^- and CO_2, with HCO_3^- requiring conversion to CO_2 at some stage, either external to the leaf (within the boundary layer) or after uptake[235]. Seagrasses obtain about 50% of their dissolved inorganic carbon from HCO_3^-; the remainder coming from direct CO_2 uptake[242–244]. The photosynthetic rates of seagrasses are currently limited by the availability of CO_2 at the present-day average pH of 8.2 but higher concentrations of CO_2 at lower pH result in faster photosynthetic rates[242,243,245,246]. In the temperate seagrass *Zostera marina*, higher photosynthetic rates at lower pH for one year are translated into increased productivity and reproductive output[247]. These findings are consistent with the evolution of seagrasses at a time of higher CO_2 concentration[224].

If changes in dissolved inorganic carbon alone are considered, seagrasses could benefit from projected increases in CO_2 concentrations[248]. However, there are differences among seagrass species in their uptake mechanisms and sensitivity to higher CO_2 concentrations[246]. These differences could affect the species of seagrass within meadows and the value of the habitat.

Calcifying epibiota growing on seagrass leaves, including foraminifera, bryozoa, spionid polychaetes and algae, are expected to be sensitive to changes in pH, with reductions in calcification and growth occurring at reduced pH[249,250]. Although the abundance of these calcifying organisms may be reduced on seagrass leaves, elevated CO_2 could enhance photosynthetic rates in non-calcifying epiphytes[249] and the total coverage of epibiota may not be altered significantly.

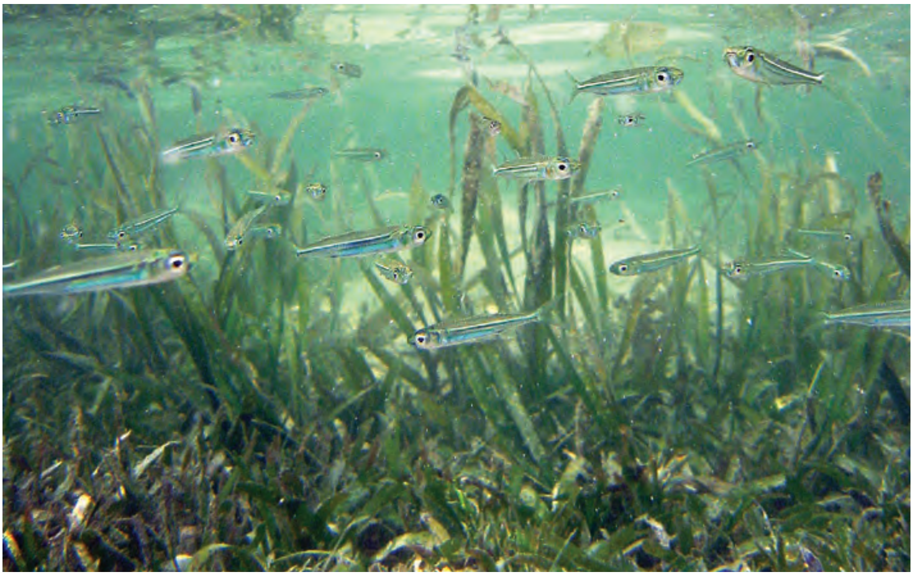
Potential impact and adaptive capacity

The most likely effects of elevated CO_2 on seagrasses will be increases in their productivity, biomass and reproductive output[247]. Higher CO_2 can also reduce the amount of light-saturated photosynthesis required to meet daily carbon budgets[245]. This should allow seagrasses to colonise deeper areas with lower light. However, differences in the sensitivity of seagrass species to elevated CO_2[246] could result in some seagrasses benefiting more than others. Any notable effect on seagrasses of changes in the epibiota on their leaves caused by increased CO_2 concentrations is unlikely.

The greater projected productivity of seagrasses, and the changes in their species composition, under higher levels of CO_2 are expected to flow-on to increase the ecosystem services provided by seagrasses in places where other impacts are minimised. In particular, the richness and productivity of food webs supported by seagrasses may increase, and the shelter that the plants provide for juvenile fish and invertebrates (Section 6.3.2) may be enhanced.

Vulnerability

Seagrasses are not expected to be vulnerable to increasing concentrations of CO_2. Instead, the effects of such increases on seagrass meadows in the tropical Pacific are expected to be higher photosynthetic rates, and greater productivity, biomass and reproductive output.



Seagrasses provide important habitats for small fish

Photo: Len McKenzie

6.6.2.7 Sea level

Exposure and sensitivity

The most recent estimates for future sea-level rise are considered to be 20–30 cm for the B1 and A2 emissions scenarios in 2035, 70–110 cm for B1 and 90–140 cm for A2 in 2100 (Chapter 3). Typically, seagrass habitats are limited by light availability on their deeper edges and should be sensitive to projected sea-level rise, with the increased depth likely to reduce light to the point where some of the deepest plants may not survive[3].

Surveys of seagrasses throughout the tropical Pacific have not generally estimated the proportion of meadows likely to be limited by light at the deeper edges of their distributions. As a result, we cannot determine the percentage of habitat exposed to sea-level rise. However, some seagrass species, e.g. *Halophila decipiens*, have a greater tolerance for lower light conditions and so the species composition, or relative cover of species at the deeper margins of meadows, i.e. their lower depth limit, may shift in favour of such species as sea level rises[49].

Potential impact and adaptive capacity

The expected rises in sea level are likely to result in the loss of seagrass cover or changes in species composition along the seaward edges of deeper meadows. Species growing on the deeper margins of seagrass habitats are likely to be at the limit of their light tolerance range and unable to adapt to further reductions[3] in light. In other parts of the meadows, however, the structure of the seagrass canopy is likely to change through the varying responses of species to reduced light[2,3,221]. This shift in composition is expected to be towards species with lower biomass. The effects of such changes on the ecosystem services provided by seagrasses to coastal fisheries have not been studied in the tropical Pacific, although the influence of changes to leaf height and density of seagrasses on fish and invertebrate communities have been described for temperate areas[251].

Seagrasses are capable of growing both vertically and horizontally and are expected to adapt to rising sea levels by growing landward in pace with their upper depth limit, provided the newly inundated sediments are suitable[3]. Coastal developments, such as rock walls or groynes, would prevent the potential colonisation of suitable habitat. Colonisation of newly inundated habitat will also be limited where the accretion of sediments favours establishment of mangroves.

Vulnerability

Seagrass meadows are estimated to have moderate vulnerability to sea-level rise where their depth is limited by light, and where expansion landward is blocked. Elsewhere, seagrass habitats are expected to have low vulnerability to sea-level rise.

6.6.3 Intertidal flats

The aspect of projected climate change of greatest relevance to intertidal flat habitats is sea-level rise. As outlined in Chapter 3, intertidal flats are expected to be exposed to rises in sea level of 20–30 cm for the B1 and A2 scenarios in 2035, 70–110 cm for B1 in 2100, and 90–140 cm for A2 in 2100. Intertidal flats are likely to be highly sensitive to these changes where this habitat cannot expand landward, or where rates of sedimentation do not keep pace with sea-level rise. Indeed, considerable losses of intertidal flats are expected to occur as a result of permanent inundation.

The potential impacts of the exposure of intertidal flats to sea-level rise are permanent changes to BMA communities and the associated epifauna and infauna. Many intertidal species preferentially inhabit vertical zones corresponding to subtle changes within the intertidal area above or below mean sea level[58]. The relationship between sediment surface height and average sea level is expected to be disturbed by ongoing sea-level rise. Consequently, gradual shifts in composition and/or abundance of intertidal BMA communities, epifauna and infauna are expected. In turn, this is likely to have significant knock on effects on the fish and invertebrates harvested from intertidal flats. In particular, permanent inundation of intertidal flats will allow continuous access by demersal fish species and exclude species that forage at low tide (e.g. birds and crabs). Benthic microalgae communities and fauna now common in the subtidal zone can be expected to gradually colonise permanently submerged intertidal areas. The new shallow subtidal zones created by rising sea levels may be ecologically challenging environments, with low water exchange and large temperature and salinity fluctuations.

A sea-level rise of 50 cm is expected to permanently inundate intertidal flats in PICTs with micro-tidal conditions (e.g. parts of Cook Islands), whereas a rise of ~ 1 m would be needed to permanently inundate the greater proportion of existing intertidal flats in PICTs with larger tidal ranges (e.g. central Pacific atolls). Although this is a simplistic analysis, species which have a strong dependence on a functioning intertidal flat habitat are expected to be gradually forced landward until they can no longer migrate. The burrowing crabs *Uca* spp., which feed when they emerge from their burrows at low tide, provide an example of the expected effects of sea-level rise on intertidal species. These crabs are restricted to upper intertidal flats where there is adequate time between tides for them to emerge and feed on sediments with the necessary moisture content – *Uca* spp. scrape the upper layers of sediment, filter BMA, meiofauna and detrital material, and then deposit balls of 'cleaned' sediment 3–4 mm in diameter. Changes in the appropriate levels of moisture in the sediment, and the time between falling and rising tide due to sea-level rise, will probably displace these species.

Photo: Tony Falkland

Intertidal flats, Tarawa Island, Kiribati

Progressive replacement of species dependent on intertidal flats may occur due to colonisation by species adapted to permanent submergence, but a loss of biodiversity is also expected. The impacts of such losses on subsistence fishing communities in the region will vary based on their dependence on these habitats. In some PICTs, intertidal gleaning is one of the main ways that low income urban and rural families secure dietary protein because they do not have the equipment or skills to catch fish. In other locations, collection of intertidal species is less important, because they are not a traditional component of the diet, or because harvests are already reduced from over-exploitation or pollution (Chapter 9).

6.7 Integrated vulnerability assessment

6.7.1 Mangroves

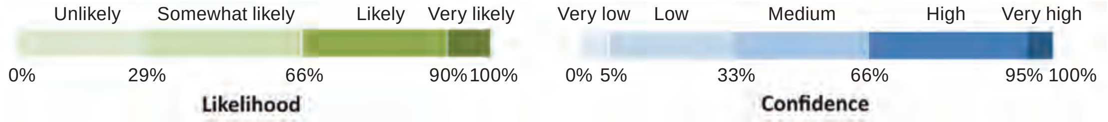
The projected changes in solar radiation, temperature, rainfall, nutrients and CO_2 are expected to have minimal effects on mangrove habitats in the tropical Pacific and, in principle, could work together to increase growth and productivity. However, these potential benefits are likely to be negated by the adverse effects of sea-level rise (**Table 6.4**). The projected rates of sea-level rise are expected to cause mangroves on the seaward fringes of their habitats to retreat[180] because they are unlikely to be able to accumulate sediments or produce sufficient root biomass to contribute to soil volume at the same rate as the rise in sea level[29] (Section 6.6.1.7). Even where rates of sedimentation are high, there is no guarantee that mangroves will survive because many species are intolerant of rapid sedimentation[252]. Thus, mangroves are likely to incur inundation stress in low intertidal positions, leading to reduced productivity, mortality and reduced forest area.

Mangroves have the potential to adapt in many areas by migrating landwards[179,180] (Section 6.6.1.7) but the maintenance of mangrove habitats through this process will depend on the rate of sea-level rise. If the rate accelerates, as projected (Chapter 3), migrating mangroves are unlikely to be able to escape the stress of inundation. Mangroves located where sedimentation rates are low, e.g. in places remote from river discharge, are expected to be particularly vulnerable. Mangroves in New Caledonia may be more vulnerable than those elsewhere in the region because not only will the projected decreases in rainfall reduce the supply of sediment, the lower precipitation may also increase salinity stress.

When the effects of changes to all the various features of the environment are integrated, mangroves are expected to have moderate vulnerability to climate change for the B1 and A2 emissions scenarios in 2035, increasing to a high vulnerability for B1 in 2100, and a very high vulnerability for A2 in 2100 (**Table 6.4**).

Table 6.4 Summary of the projected effects of climate change variables on mangrove and seagrass habitats in the tropical Pacific for the B1 and A2 emissions scenarios in 2035 and 2100 (based on the information in Sections 6.6.1 and 6.6.2), together with an assessment of the overall vulnerability of mangrove and seagrass habitats by integrating these effects. The likelihood and confidence associated with the integrated vulnerability assessments are also indicated. Note that the projected effects of each climate change variable can be negative (-) or positive (+); nil = no projected effect.

Scenario	Variable							Integrated vulnerability
	Light	**Temp.**	**Rainfall**	**Nutrients**	**CO_2**	**Cyclones**	**Sea level**	
Mangroves								
B1/A2 2035	Low (-)	Very low (-)	Low (+/-)	Low (+/-)	Very low (+/nil)	Moderate (-)	High (-)	Moderate 🟩 🟦
B1 2100	Low (-)	Very low (-)	Moderate (-)	Low (+/-)	Very low (+/nil)	Moderate (-)	Very high (-)	High 🟩 🟦
A2 2100	Low (-)	Very low (-)	Moderate (-)	Low (+/-)	Very low (+/nil)	Moderate (-)	Very high (-)	Very high 🟩 🟦
Seagrasses								
B1/A2 2035	Moderate (-)	Moderate (-)	Moderate (-)	Low (+/nil)	Very low (+)	Moderate (-)	Low (-)	Moderate 🟩 🟦
B1 2100	Moderate (-)	Moderate (-)	Moderate (-)	Low (+/nil)	Very low (+)	Moderate (-)	Moderate (-)	Moderate 🟩 🟦
A2 2100	High (-)	High (-)	High (-)	Moderate (+/-)	Very low (+)	High (-)	Moderate (-)	High 🟩 🟦



The effects of sea-level rise are expected to result in losses of around 10% of mangrove habitat in most PICTs where mangroves are common today by 2035 for the B1 and A2 emissions scenarios (**Table 6.5**). By 2100, losses are expected to be around 50% for the B1 scenario and 60% for the A2 scenario in most of these PICTs, with losses of up to 80% possible in some PICTs (e.g. Tonga).

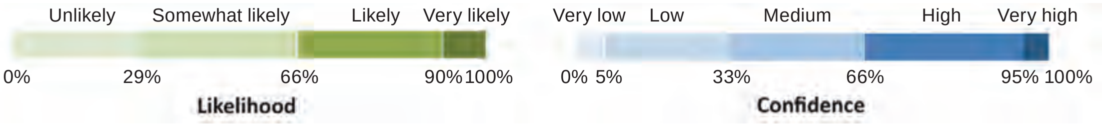
6.7.2 Seagrasses

On balance, the combined changes to the key attributes of the environment for seagrasses are expected to cause moderate losses of these important fish habitats (**Table 6.4**). In intertidal and shallow-water habitats, the projected increases in air temperature, SST, sediment deposition, turbidity, storm surge and algal overgrowth from elevated nutrient loads, and decreases in light and salinity from higher runoff are expected to interact to create more hostile environments for many seagrass species. Seagrasses growing in estuaries, and in fringing reef and bay or lagoon habitats adjacent to high islands heavily exposed to increased runoff, are likely to be more vulnerable than those growing on atolls or on barrier and patch reefs (Section 6.2.2). Although deepwater seagrasses will be relatively protected from disturbances caused by stronger waves, reductions in light will affect their survival and productivity.

Sea-level rise is expected to result in the loss of those seagrasses growing in deep water at their present depth limit. Although there will be opportunities for seagrass to expand landward in some places, physical barriers or unsuitable substrate will prevent colonisation in other areas.

Table 6.5 Projected percentage loss in areas of mangrove and seagrass habitats for the B1 and A2 emissions scenarios in 2035 and 2100 in Pacific Island countries and territories (PICTs) that have total areas of mangroves and seagrasses > 5 km^2. These estimates are based on the expert opinion of the authors because data on the land area to be inundated for the B1 and A2 scenarios are not yet available to inform a quantitative assessment. The estimates include the perceived scope for the major areas of the existing mangroves and seagrasses in each PICT to migrate, or not migrate, landwards as the case may be.

PICT	Mangroves				Seagrasses			
	B1/A2 2035	B1 2100	A2 2100		B1/A2 2035	B1 2100	A2 2100	
Melanesia								
Fiji	10	50	60	🟩 🟦	< 5	5–10	10–20	🟩 🟦
New Caledonia	10	50	60	🟩 🟦	5–10	5–20	10–25	🟩 🟦
PNG	10	50	60	🟩 🟦	5–20	5–30	10–35	🟩 🟦
Solomon Islands	10	50	60	🟩 🟦	5–20	5–30	10–35	🟩 🟦
Vanuatu	10	50	60	🟩 🟦	5–20	5–30	10–35	🟩 🟦
Micronesia								
FSM	10	50	60	🟩 🟦	< 5–10	5–25	10–30	🟩 🟦
Guam	10	60	70	▧ ▨	5–20	5–35	10–50	🟩 🟦
CNMI	30	70	80	▧ ▨	< 5–10	5–25	10–35	🟩 🟦
Palau	10	50	60	🟩 🟦	< 5–10	5–25	10–35	🟩 🟦
Polynesia								
French Polynesia	10	50	60	🟩 🟦	< 5	5–10	10–20	🟩 🟦
Samoa	10	50	60	🟩 🟦	5–20	5–35	10–50	🟩 ▨
Tonga	30	70	80	▧ ▨	5–10	5–20	10–20	🟩 ▨



When the effects of changes to all the various features of the environment are combined, seagrass habitats are expected to have moderate vulnerability to climate change for the B1 and A2 emissions scenarios in 2035 and the B1 scenario in 2100, increasing to a high vulnerability under the A2 scenario in 2100 (Table 6.4).

Based on a simple application of observed impacts from such synergistic effects in present-day seagrass habitats, future losses of seagrasses in the tropical Pacific could be in the range of 5–20% by 2035 for the B1 and A2 emissions scenarios. By 2100, the losses could be as great as 5–30% for B1 and 10–35% for A2 (Table 6.5). Seagrass losses are not expected to be as great in subtropical areas because the projected decreases in rainfall (Chapter 2) are likely to limit impacts. Nevertheless, reductions in seagrass habitat of 5–10% may occur in these parts of the region for the B1 and A2 scenarios in 2035, increasing to potential losses of 5–20% for B1 and 10–25% for A2 in 2100.

6.7.3 Intertidal flats

The intertidal flat habitats of the region are expected to be primarily vulnerable to sea-level rise, so that any conclusions about the integrated effects of climate change are essentially the same as those presented in Section 6.6.3. As sea level rises, it is highly likely that intertidal flats will be lost around many high islands due to steep terrain or infrastructure barriers. There will also be limits on the landward progression of intertidal lagoonal habitats on atolls with narrow land areas.

Intertidal flats are expected to have low to moderate vulnerability to climate change for the B1 and A2 emissions scenarios in 2035, increasing to high for the B1 and A2 scenarios in 2100. Projections are being developed based on currently available topographic mapping to estimate the percentage loss of intertidal sand and mud flats from the expected rises in sea level for the B1 and A2 emissions scenarios in 2035 and 2100.

6.8 Uncertainty, gaps in knowledge and future research

There are still major gaps in knowledge of the distribution, diversity and coverage of mangrove and seagrass habitats, and the areas of intertidal flats, across the tropical Pacific. Indeed, caution is needed in interpreting the information on coastal fish habitats presented here because much of it is outdated, or based on limited surveys. In many cases, the areas of mangroves, seagrasses and intertidal flats are likely to be (often gross) underestimates. The best estimates are for mangroves and seagrasses in New Caledonia due to the extensive research efforts there. Reasonable estimates are also available for mangroves in some other PICTs, such as FSM, American Samoa, Tonga, and Wallis and Futuna, despite the fact that assessing changes in mangrove area over time in the tropical Pacific is difficult[253].

Systematic mapping of mangroves, seagrasses and intertidal flats for all PICTs, including habitat area, plant density and species composition, is a research priority. In the case of seagrass habitats, mapping is also needed to show the depths to which existing meadows extend. This information will (1) raise awareness among coastal planners about the locations and scale of these important fisheries habitats; and (2) provide a baseline for monitoring changes in the area, density and species composition of mangroves and seagrasses, and the area of intertidal flats.

The species composition and relative abundance of mangroves and seagrasses are relatively well known in most PICTs (**Table 6.1**), but this is not the case for the epifauna and infauna associated with these habitats. Faunal studies are needed at a basic level, followed by comparisons of biodiversity, relative abundance and size composition of fauna among mangroves, seagrasses and intertidal flats, and between different mosaics of these habitats. Movements of animals among these habitats and between them and coral reefs, in terms of life history development and foraging behaviour described for other parts of the world[7–9,12], remain poorly understood in the tropical Pacific. Such research will greatly improve our understanding of food webs and the other ecosystem services provided by mangroves, seagrasses and intertidal flats to coastal fisheries. It will also allow knowledge to progress from the limited range of examples of habitat roles to an understanding of the processes underpinning these roles.

More reliable data on sea-level rise and sedimentation rates are needed throughout the region to enable more accurate predictions of the responses of mangroves and intertidal flats and the possible mitigating effects of sedimentation[254]. Reliable data on sea-level rise are now being collected in many PICTs with instrumentation installed through the South Pacific Sea Level and Climate Monitoring Project (Australian Bureau of Meteorology[iii]). However, the time-series is not long enough to elucidate a trend and recordings must continue for many years. Caution will also be needed in interpreting these data for the reasons outlined in Chapter 3, and because the tectonics of coastlines within PICTs vary[215]. It will also be important to improve the resolution of topographic maps so that the areas projected to be inundated, which may be suitable for colonisation by mangroves and seagrasses, can be estimated more accurately and protected.

Even with a concerted effort to address the large gaps in knowledge outlined above, it will be difficult to separate the effects of climate change on coastal habitats from other natural and human impacts. Despite the need to understand the potential effects of climate change, it is imperative that existing research on the effects of changes to catchments and shorelines on these habitats continues to receive the necessary funding. The possible impacts from agriculture, forestry and mining, for example, are likely to be much greater than those from climate change in the short to medium term. Understanding the processes behind such impacts, and the most appropriate measures to ameliorate the adverse effects, is also likely to build the resilience of coastal fish habitats to climate change. Ideally, monitoring programmes should be designed that enable managers to separate the effects of climate change from local stressors. Managers can then identify adaptations needed to maintain the habitat mosaic in the face of climate change[5,217,255], and assess the effectiveness of these adaptations.

The need to downscale global climate models to provide more accurate assessments of projected changes in surface climate and features of the tropical Pacific Ocean at scales more relevant to PICTs is also important for integrated coastal zone management in

[iii] www.bom.gov.au/pacificsealevel

PICTs[iv] (Chapters 2 and 3). When combined with the results of the research outlined above, this information will enable managers to identify (1) the mangrove areas and seagrass meadows most at risk from local impacts, e.g. higher levels of runoff; and (2) the locations where management effort should be focused.

The substantial research list described above is beyond the capacity of most PICTs. Many will need to form partnerships with scientific institutions within and outside the region, and seek the assistance of the communities who live adjacent to these habitats, to fill the gaps. Location-specific studies at representative sites across the region are especially needed, because most of the present knowledge and assessments are extrapolated from other parts of the world. The Seagrass-Watch[v] programme offers a model for providing useful and spatially extensive environmental monitoring data for some of the necessary surveys in PICTs where resources are limited.

6.9 Management implications and recommendations

The high level of connectivity among coral reefs, mangroves, seagrasses and intertidal flats (the coastal habitat mosaic) means that the loss of one habitat could have implications for the other components of the mosaic. Therefore, an over-riding priority for management should be to secure connectivity among all these habitats to enhance the resilience of coastal ecosystems[7] and help safeguard coastal fisheries production[6] in the face of future climate change (Chapter 9). The practical management measures for maintaining this mosaic are summarised below.

- Improve integrated coastal zone management to reduce existing impacts on mangroves, seagrasses and intertidal flats from agriculture, forestry, mining and road construction in catchments, and sand mining and construction on the coast. These measures will help maximise the natural potential of these habitats to adapt, and will be particularly important in reducing the synergistic effects of terrestrial pollution and climate change on coastal habitats[2,21,256–259].
- Strengthen governance and legislation to ensure the sustainable use and protection of vegetated coastal habitats[29]. There is a continuing need to build the capacity of management agencies to improve (1) the ability of staff to understand the threats to coastal fish habitats; (2) the networks for transferring this knowledge to communities through co-management or community-based management arrangements; (3) the national regulations needed to underpin effective protection for mangroves and seagrasses; and (4) local and national systems to achieve compliance with regulations.

[iv] This work is now being done progressively for the tropical Pacific by the Australian Bureau of Meteorology and CSIRO, and partners, under the Pacific Climate Change Science Programme; see www.cawcr.gov.au/projects/PCCSP

[v] www.seagrasswatch.org/about.html

- Implement and facilitate interventions that are likely to support coastal fish habitats to adapt to climate change. For example, plan to allow for landward migration of mangroves, seagrasses and intertidal flats where possible. This will involve placing infrastructure on higher ground and removing existing barriers in low-lying areas.
- Initiate regular high-level discussions between planners and fisheries managers to ensure that barriers to adaptation of coastal fisheries habitats are minimised as plans are developed to assist all sectors respond to climate change.
- Engage local communities in sustainable management of coastal habitats, such as supporting community-based conservation areas where local committees manage or restrict use of areas based on the state of resources[29]. This requires regular transfer of research and monitoring information to communities to build local capacity.
- Promote community-based co-management approaches, where management is carried out primarily by local stakeholders in close cooperation with relevant local and national government institutions and non-government organisations. Adaptive co-management makes optimum use of social capital, such as existing (or assigned) resource rights, local governance, traditional knowledge, self-interest and self-enforcement capacity. It is increasingly seen as an effective way to implement conservation and management measures where customary tenure exists, e.g. throughout much of Melanesia.

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Chapter 7

Vulnerability of freshwater and estuarine fish habitats in the tropical Pacific to climate change

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> *'In tropical systems it is possible that the effects of global climate change will be overshadowed by other, larger disturbances such as deforestation and land-use changes.'* (Ficke et al. 2007)[i]

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7.1 Introduction

People living in the tropical Pacific have a strong affinity for rivers – an identity that is reflected in local languages[1]. On Kadavu Island in Fiji, for example, river names describe many of the traditional fishing and subsistence activities, such as:

Nubunisici – 'snail pool'	a pool where edible freshwater snails (sici) can be found;
Waidoidoi – 'doi stream'	where the bark of doi trees, a buckthorn variety (*Alphitonia zizyphoides*), can be used to tie bundles of fish together;
Wainituva – 'tuva stream'	source of tuva or derris vine (*Derris trifoliata*) roots yielding a poison used to stun and collect fish and prawns;
Nubuniura – 'pool of prawns'	*Macrobrachium* spp.;
Waikana – 'food stream'	a river known to contain edible species, a rich source of food.

Throughout the tropical Pacific, from the large rivers in Papua New Guinea (PNG), to the small streams on high islands, freshwater fish and invertebrates contribute to food security. Although the quantities harvested for subsistence are still poorly quantified[2,3] (Chapter 10), awareness of the reliance on freshwater and estuarine resources is increasing.

There is concern that the freshwater and estuarine habitats in the region that support these subsistence fisheries, by providing areas and structures where fish and invertebrates can reproduce, feed, recruit, grow and migrate, may be vulnerable to climate change. Consequently, the rich culture of people who use these rivers as part of their daily lives may also be at risk.

In this chapter, we describe the nature of freshwater and estuarine habitats in the tropical Pacific, their role in supporting fisheries, and the critical requirements needed to maintain them. We then evaluate the vulnerability of freshwater and estuarine habitats to climate change and consider the interactions between the effects of a changing climate and existing impacts on these habitats. We conclude by assessing the constraints to adaptation, the gaps in knowledge to be filled by future research, and the management interventions needed to help maintain the resilience of freshwater and estuarine habitats in the face of climate change.

7.2 The nature of freshwater and estuarine habitats in the tropical Pacific

7.2.1 River systems

The total land area of all Pacific Island countries and territories (PICTs) combined is < 0.6 million km^2, with 83% of this land in PNG and much of the remainder in the other larger islands of Melanesia. Despite their limited size, the array of about 200 high islands in the tropical Pacific, have a high diversity of river types in terms of catchment area, drainage density, annual discharge and geomorphology. This diversity decreases from west to east, in line with island size (Chapter 1). The wide range of river systems has a strong influence on the freshwater and estuarine habitats in the region, and the species of fish and invertebrates supported by these habitats. Ultimately, differences in river form account for variations in the production of freshwater and estuarine fish among PICTs.

7.2.1.1 Catchment size and drainage

Only the larger, high islands in the region have rivers of substantial length and discharge. The three largest river systems in PNG, the Sepik-Ramu, Fly and Purari, have a combined catchment area of more than 200,000 km^2. The flows per catchment area for these rivers are among the highest in the world and their catchments represent more than one-third of the area of PNG[4,5]. The larger rivers of Fiji and Solomon Islands have smaller but significant catchment areas. For example, the 3000 km^2 catchment of the Rewa River covers one-third of the island of Viti Levu in Fiji (**Table 7.1**).

Most rivers in the tropical Pacific differ, however, from those on continental land masses such as PNG, and they are characterised typically by relatively short (< 100 km), straight, steep channels with small, narrow catchments and few tributaries[6] (**Figure 7.1**). For example, Kadavu Island in Fiji has 240 separate catchments draining to the coast, but more than 90% of these are less than 3 km^2 and contain only minor channels[7].

The disparity in catchment area between rivers in PNG and those on other islands in the region highlights a clear distinction in the nature of rivers based on island size, and elevation. At the smallest extreme, Bora Bora in French Polynesia, with an area of 29 km^2 and an elevation of 727 m, is at the lower end of island size and elevation capable of producing running water[8].

Drainage networks tend to radiate outward where island geomorphology is dominated by central highlands, such as on Ambrym (Vanuatu), Rarotonga (Cook Islands) and Tahiti (French Polynesia). Where chains of volcanic peaks have created elongated islands, rivers form linear networks draining away from the mountain ranges (e.g. Pentecost in Vanuatu, Santa Isabel in Solomon Islands and Savai'i in Samoa). Intact volcanic craters develop centripetal channel networks that drain towards the centre of the crater to establish permanent freshwater lakes, such as on Ambae Island, Vanuatu.

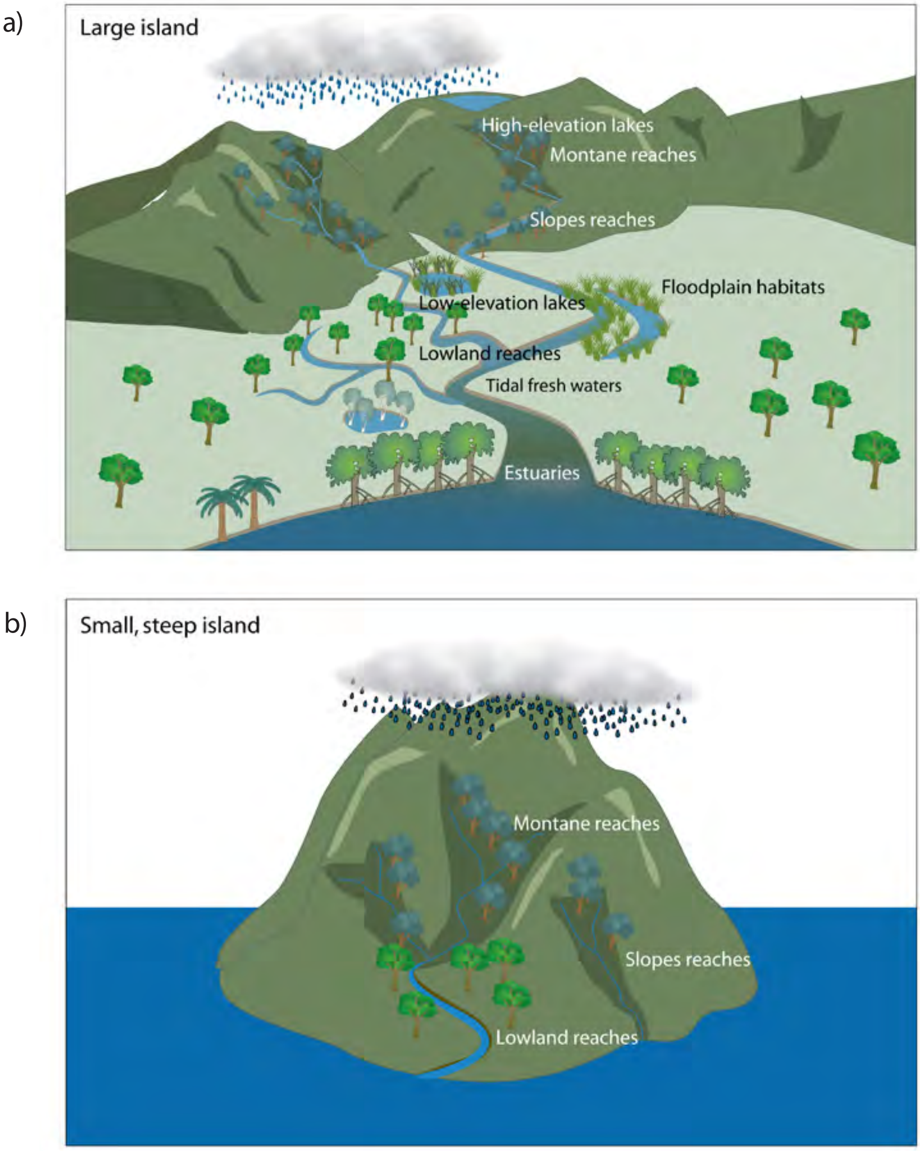


Figure 7.1 Principal freshwater and estuarine habitat types (functional process zones) in the tropical Pacific. River systems on larger islands (a) may consist of montane, slopes and lowland river reaches, and estuaries. Lakes may occur from montane regions downstream to the floodplain. Floodplains provide a diversity of wetland habitats (see text). Rivers on smaller steep islands (b) have small catchments with few tributaries, and may lack typical lowland, floodplain and estuary habitat types.

Steep volcanic islands with low permeability bedrock allow rainwater to run off to form river channels. In contrast, permeable limestone islands with low gradients enable rainwater to percolate rapidly into the groundwater rather than running off to create surface drainage channels (**Figure 7.2**). For this reason, landscapes dominated by raised coral reefs have few rivers.

Table 7.1 Largest river basins in selected Pacific Island countries and territories (PICTs), with estimates of the human populations within catchments (source: SPC Statistics for Development Programme).

PICT	Island	Largest river	Basin area (km²)	River length (km)	Population
Melanesia					
Fiji	Viti Levu	Rewa	2918	145	98,183
	Vanua Levu	Dreketi	317	65	14,176[a]
New Caledonia	Grande Terre	Le Diahot	589	100	2500
PNG	Mainland	Sepik–Ramu	96,000	1126	339,640
	Mainland	Fly	76,000	1050	132,881
Solomon Islands	Malaita	Wairaha	486	33	160,000
	Guadalcanal	Lungga	394	50	5532
Vanuatu	Espiritu Santo	Jourdain	369	53	1229
	Efate	Teouma	91	28	3462
Micronesia					
FSM	Pohnpei	Nanpil Kiepw	7.8	10	525
Guam	Guam	Talofofo	60	12.6	4475
Palau	Babeldaob	Ngerdorch	39	15	250
Polynesia					
American Samoa	Ta'u	Laufuti	8	3	n/a
Cook Islands	Rarotonga	Avatiu	5.5	5	2600
French Polynesia	Tahiti	Papenoo	91	23	3521
Samoa	Savai'i	Sili	51	11	2270
	Upolu	Vaisigano	33	12	12,180
Tonga	'Eua	Fern Gully	2.3	2	1626

a = Entire Bua province; n/a = no estimate available.

7.2.1.2 Habitat-forming processes

As water moves through the landscape, it forms and shapes river channels and fish habitats by the processes of erosion, sediment transport, and sediment deposition. Changes in rainfall and runoff are likely to alter these habitat-forming processes, which in turn may affect the number of fish and invertebrates that can be supported.

The processes that form habitats for fish are affected by local geomorphology, which varies along rivers. In the headwaters, catchments of most rivers in the tropical Pacific are separated by narrow ridgelines. The terrain is usually rugged, with relatively impermeable volcanic rock, and channel gradients are steep, often approaching 30° or more. The coarse river bed deposits within channels are arranged in riffle-and-pool sequences. The majority of highland channels also contain large rounded boulders, and waterfalls occur frequently where resistant bedrock is exposed by erosion.

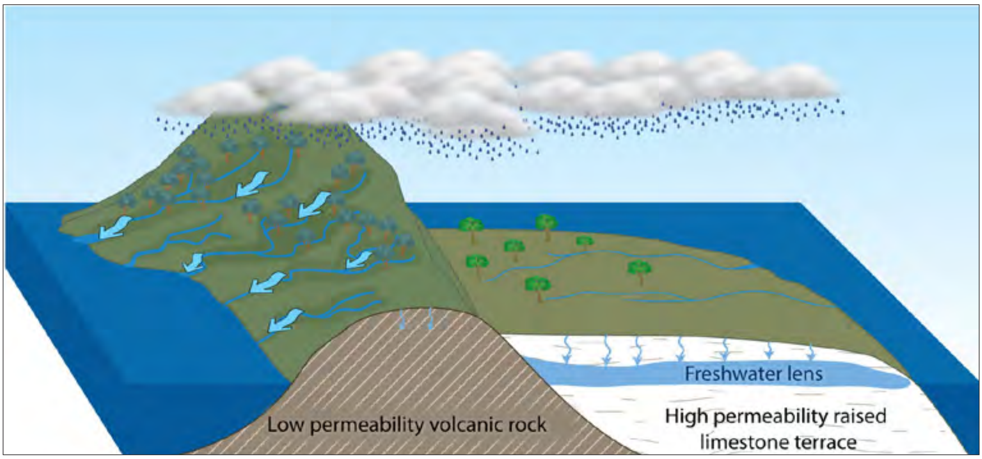


Figure 7.2 River channel density is high on steep volcanic islands because the underlying bedrock has low permeability, and rainfall runs off to form river channels. Low gradient raised coral reef landscapes have few rivers because the underlying limestone is highly permeable, allowing rainwater to percolate into the groundwater rather than forming river channels.

Deep ‘down-cutting’, resulting from high annual rainfall has produced a highly dissected riverine landscape on many islands. This has formed impressive gorges along some of the larger rivers[9,10], such as the Namosi Gorge on Viti Levu in Fiji. Amphitheatre-headed valleys are another common feature at the source of rivers – the Ngatoe valley in Rarotonga in the Cook Islands is a good example[11].

These characteristics, combined with small catchment sizes, promote flash-flooding, where runoff during tropical storms flows quickly into water courses, leading to rapid increases in flow.

Lower sections of river basins generally have more subdued terrain, often with alluvial terraces and floodplains or braided channels. The Fly River floodplain in PNG is the largest wetland in the region, occupying an area of 4.5 million hectares. This vast, low-elevation floodplain has promoted the formation of numerous oxbow lakes, and lateral lakes where tributaries have been blocked by accretion of deposits along the main channel. The larger rivers in PNG, Solomon Islands, Vanuatu, New Caledonia and Fiji transport large quantities of sediment and have deltas at their mouths.

Despite the humid tropical climate, most Pacific rivers have modest daily flow rates because of their small catchments. The Labasa River on Vanua Levu in Fiji is a case in point – it has a catchment area of 86 km^2 and a mean daily flow of about 3500 to 7000 megalitres per day. Most PICTs also experience distinct rainfall seasons (Chapter 2), although even the smallest rivers tend to flow year-round, except during prolonged drought. For example, Nabukavesi Creek in southern Viti Levu, Fiji, has a low but persistent flow throughout the dry season (**Figure 7.3**).

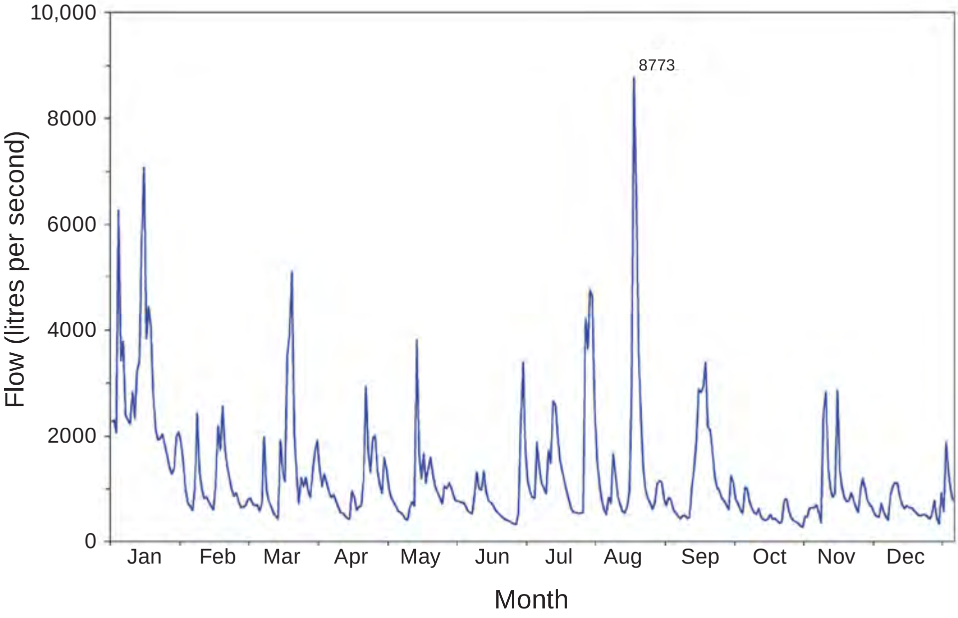


Figure 7.3 Average daily flows for Nabukavesi Creek, southern Viti Levu, Fiji, for 1995. Baseflow is maintained even during dry periods with no rainfall (source: Fiji Public Works Department, Hydrology Section).

In catchments with undisturbed natural vegetation, erosion of hill slopes is minor, and suspended sediment loads in rivers are source-limited. Bedload (sand and gravel) transport is minimal in such catchments and confined mostly to periods of high flow.

The alluvial reaches of rivers shift across valley floors as part of the natural cycle of channel migration. In the Jourdain River (Espiritu Santo, Vanuatu), for example, the lower braidplain is traversed by multiple interconnecting channels, separated by coarse gravelbars. In the lower Wainimala River, Fiji, unconfined meandering channel sections migrate by as much as 5 to 15 m per year[12,13].

7.2.2 Flow as the driver of riverine ecosystems

Flow has a dominating role in rivers – it underpins the links between environmental conditions and habitats, and influences the processes that support fish and invertebrates[14,15]. Flow transports the materials on which fish feed from upstream habitats to progressively larger habitats downstream[16]. This is an important process in the small, steep, ecologically simple rivers that dominate many Pacific islands[17].

In larger rivers, high flows connect floodplains with the main channel, and allow food and other materials to be exchanged between these two habitats[18,19]. Indeed in large floodplain river systems, the spawning, recruitment, growth and migration of fish often depend on annual or episodic flood cycles. The Fly River system is a good example of the role of lateral connections to the floodplain, and local production in the river channel, as sources of energy for aquatic food webs[20]. Floodplain habitats are particularly important for fish production in this river.

The main energy source for fish production comes from algae and microbial decomposition of plant material in upstream, channel and floodplain habitats[21,22], connected by flow, but the processes that drive food webs in freshwater rivers are a source of ongoing debate.

The dynamic nature of hierarchical habitat patches in rivers amplifies the interactions between habitats across a range of scales[23]. Changes in flow and habitats over time are just as vulnerable to climate change as these spatial roles of habitats within river catchments.

7.2.3 Hierarchical nature of riverine ecosystems

River ecosystems consist of a hierarchy of habitats at different scales (**Figure 7.4**), all of which are affected differently by climate, seasonality of climatic events, and climate variability. At the largest scale, freshwater fish that migrate between islands can link rivers across considerable expanses of ocean. Individual river systems form basins[24] that include entire catchments from the headwater tributaries downstream to the coastal environments that are influenced by freshwater discharge. At finer scales, individual habitat patches exist as snags, macrophyte beds, sandbars, pools and riffles. Each of these habitats can be further subdivided into discrete smaller patches. Accordingly, fish habitats in river systems can be considered as a hierarchy of patches at different scales over space and time[23]. The arrangement of habitat patches at any given time is influenced by interactions between adjacent patches at higher and lower levels of the hierarchy, under the dominant influence of river flow.

Larger river systems, such as the Fly and Sepik-Ramu systems in PNG, have more complex hierarchical organisation and may experience more complex responses to climate change than the simpler rivers on smaller islands.

7.2.4 Habitat templates

Fish and invertebrates have specific habitat requirements, and the pattern of habitats often represents a physical template of the species likely to occur within an area. Sections of rivers with common characteristics, such as bed gradient and sediments, have been described as functional process zones[25] (**Table 7.2**). These broadly defined zones are a useful way to consider fish habitats in freshwater and upper estuarine sections of rivers in the Pacific.

Rivers on Pacific islands can be classified into three main functional process zones[26], similar to classifications used elsewhere[27,28].

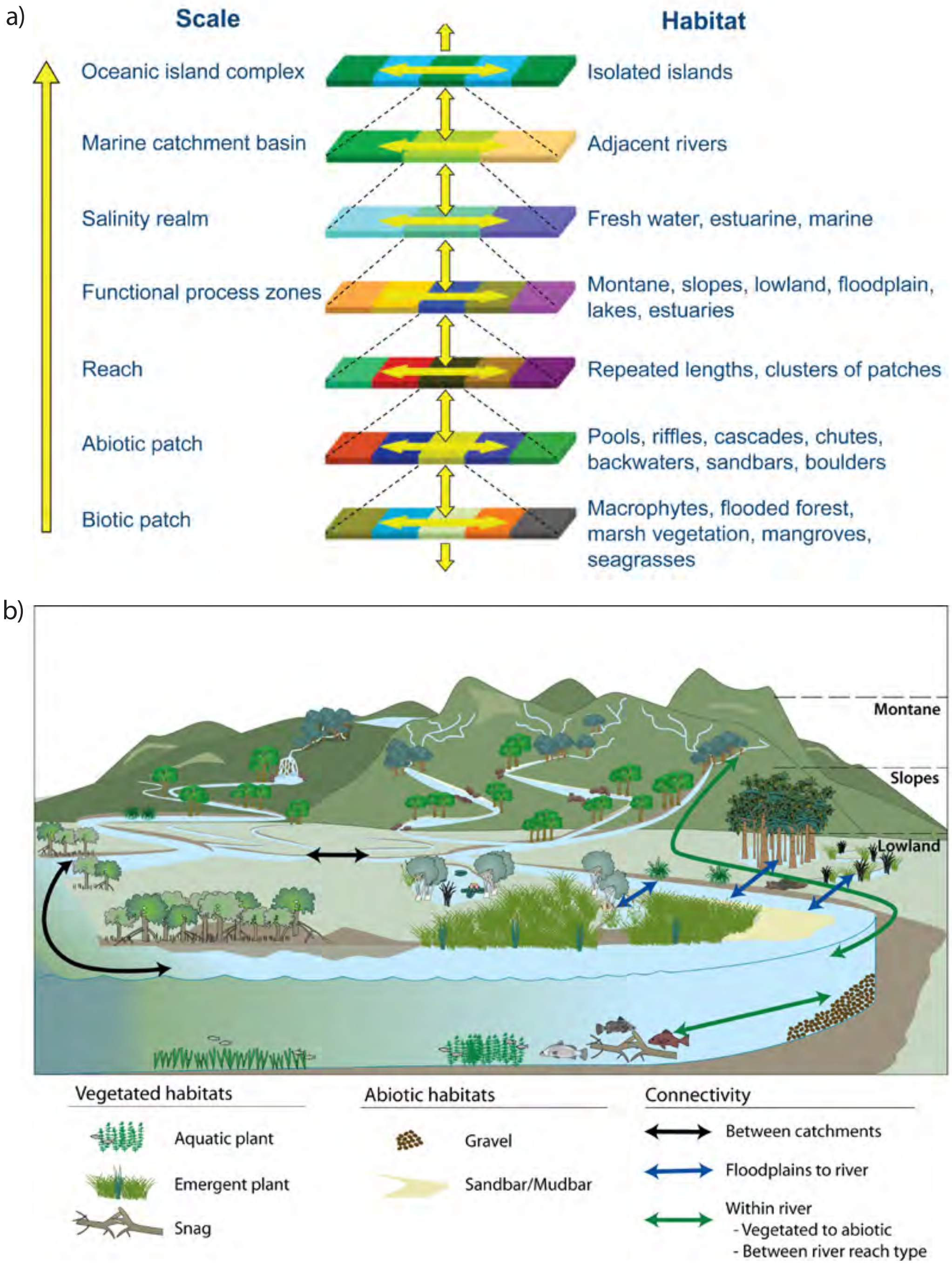


Figure 7.4 (a) Freshwater habitats are arranged hierarchically from biotic patches to entire islands, and interact with other habitats (depicted here in different colours) within and between scales; (b) vegetated and abiotic habitat patches are influenced by interactions with adjacent patches, and by larger-scale processes within river reaches, functional process zones, and marine catchment basins. Connectivity between habitats at different scales is critical for habitat use by fish.

- **Montane reaches:** > 800 m elevation, gradient commonly > 30%, and substratum mostly bedrock;
- **Slopes reaches:** > 50 m and < 800 m elevation, gradient 5–30%, with boulder, rock and gravel substrata; and
- **Lowland reaches:** < 50 m elevation, gradients < 5%, and substrata predominantly cobble, gravel, sand and fine sediments.

A further subdivision of montane reaches is required in PNG highland rivers above 1200 m, where coldwater temperatures also influence fish and invertebrates.

Each functional process zone contains a diversity of smaller-scale habitats, such as pools, runs, riffles and rapids, which tend to form a sequence according to stream gradient and flow, from rapids in steep upland reaches to slow-flowing pools in lowland reaches. Each habitat in turn contains smaller habitat patches (e.g. undercut banks, woody habitats, rocks, overhanging vegetation, plunge pools, scour holes, chutes), which provide the shelter requirements and food resources needed by different fish species (Section 7.2.3).

Freshwater lakes, floodplains and estuaries also represent distinct functional process zones. The wide range of functional process zones and habitat types in the tropical Pacific is summarised in **Figure 7.1** and **Table 7.2**, and described in more detail in Section 7.2.5.

7.2.5 Freshwater and estuarine habitats

7.2.5.1 Montane reaches

High-elevation headwaters are usually shaded by tropical rainforest, and flow from groundwater springs to form a defined channel with swift flowing water. Montane reaches are often interrupted by waterfalls, and provide fish habitat as a series of deep, slow-flowing pools and fast-flowing cascades.

Channel gradient and the height of waterfalls have a strong influence on the size and frequency of pool habitats, and the fish species that can access them[29]. Volcanic rocks are more acidic than limestone and sedimentary rocks, and produce water chemistry that is favoured by certain fish species[30,31].

Coldwater montane rivers above an elevation of 1200 m in PNG have very low fish species diversity. The lower altitudinal limit for rainbow trout, which have been stocked in the highland rivers and lakes of PNG, is 1760 m. Eels, gobies and gudgeons are the only native species inhabiting rivers above 800 m[32,33].

Table 7.2 Examples of freshwater and estuarine fish habitats in the tropical Pacific.

Habitat type	Functional process zone	Examples	Description
Rivers	Montane > 800 m elevation	Upper Jourdain River, Vanuatu	Narrow (< 5 m) constrained bedrock and boulder-strewn channel
	Slopes < 800 m and > 50 m	Papenoo River, Tahiti	Constrained channel, boulders, gravel beds, pools and cascades, length 20 km, fine sediments rapidly transported
	Lowland < 50 m	Lower Fly River, PNG	Over 846 km from the coast to Kiunga (18 m elevation), floodplain 15–20 km wide
Lakes	Large, mid-high elevation	Lake Kutubu, PNG	50 km^2 surface area, maximum depth 70 m, 800 m elevation, oligotrophic
	Small, mid-high elevation	Lake Tagimaucia, Fiji	16 ha, 5.5 m deep, 820 m elevation
	Large, low elevation	Lake Murray, PNG	647 km^2 surface area (~ 2000 km^2 wet season), maximum depth 7 m, 20 m elevation, mesotrophic
		Lake Tegano, Solomon Islands	155 km^2 surface area, maximum depth 43 m
	Small, low elevation	Kiunga Oxbow, Pangua Lake, PNG	> 8 ha on the Fly floodplain, up to 30 m deep, may connect to river via tidal channels
Flood-plains	Pools	Matevulu bluehole, eastern Santo, Vanuatu	Includes oxbows < 8 ha and smaller spring-fed blueholes (flooded dolines) in limestone terrain
	Swamp forests	Jourdain River floodplain, Vanuatu	Single species or multi-species swamp forests, e.g. *Melaleuca, Campnosperma, Inocarpus, Eugenia*
	Springs, marshes and swamps	Bonatoa peat bog, Fiji	Sedge vegetation over deep accumulations of organic material interspersed with alluvial sediments from floods
	Blocked valleys	Bossett Lagoon, PNG	4–6 m deep, intermittent, alternates seasonally between grassy floodplain, floating grasses, and limited vegetation
Estuaries	Coastal plain large estuary	Fly River estuary, PNG	Tidal range 3.5–5 m, length 100 km, prominent delta, extensive mangroves, some seagrasses, highly turbid, sand and mud sediments
	Coastal plain small estuary	Labasa River, Fiji	Tidal range ~ 2 m, length 11 km, mangroves on delta, intensively cultivated floodplain, moderately turbid from soil erosion
	Tidal river	Dagi River, west New Britain; Gumini River, Milne Bay, PNG	Tidal range 0.5–1.2 m, 100 m–2 km in length, delta variously developed, mangroves may be extensive, tidal fresh waters extensive, turbidity low

7.2.5.2 High-elevation lakes

High-elevation lakes are commonly formed as flooded craters. Lake Tagimaucia, with a surface area of 16 ha at an elevation of 820 m, is the largest lake on Taveuni Island, Fiji[34]. The vegetation around the lake is mainly swamp sedges. Other crater lakes exist in PNG (Lake Kutubu), Vanuatu (Lake Letas), Wallis and Futuna (Kikila) and Tonga (Tofua and Tao)[35]. Other highland lakes are formed by blocked valleys and basins[35]. Many of these lakes contain no fish because of their lack of connection with rivers, although some lakes have been stocked with introduced species.

7.2.5.3 Slopes reaches

Riverine slopes reaches lie at intermediate elevations below the downstream limit of the major waterfalls and rapids that characterise montane rivers, and upstream of the well-developed floodplains typical of lowland rivers. Fish habitats in this zone have intermediate channel gradients. The steep topography of many islands determines that slopes reaches are often poorly defined, and may discharge directly to the coast at waterfalls where lowland reaches and floodplains do not exist. Examples include the coastal waterfall at Katurasele on Choiseul Island, Solomon Islands, and Waitavala Stream on Taveuni, Fiji.

In contrast, the Fly River system in PNG has a well-defined slopes region, extending from an elevation of 800 m upstream of Olsobib, downstream to an elevation of 50 m near Kiunga, a distance of over 140 km. Within this section of the river, fish habitat alternates between pools 20 to 70 m wide and narrower, constrained runs, riffles and rapids interspersed with sandbars and gravelbars, sand islands and secondary channels.

7.2.5.4 Lowland reaches

Lowland coastal rivers, from an elevation of 50 m downstream to the tidal limit, typically have long, meandering channels where the river cuts across the floodplain. On smaller islands, channel width usually ranges from 1 to 25 m. These habitats are often shaded by tropical rainforest, in contrast to the larger rivers on bigger islands where the water surface is mostly exposed to sunlight. The substrate types of fish habitats in lowland reaches include silt, sand, gravel, fused rock beds and boulders.

The lowland reaches of the Fly River in PNG extend for hundreds of kilometres inland, meandering across the floodplain at an elevation of only 20 m. The channel varies from 100 to 200 m wide in the upper floodplain, increasing to more than 1000 m before reaching the upper estuary. The low gradient produces well-sorted sandy sediments, with distinctive open-water channel habitats for fish, and well-developed floodplain habitats[36].

7.2.5.5 Floodplain habitats

- **Oxbow lakes** are prominent fish habitats of the floodplain in meandering rivers. They are formed as bends in the river become cut off from the main channel. Oxbow lakes are conspicuous features of the Fly River (PNG). Oxbow lakes provide a wide range of fish habitats, from dense overhanging trees and submerged roots, to overhanging grasses, ferns and floating vegetation. Bottom sediments commonly consist of fine, sandy deposits, fine mud, and organic material, depending on the velocity of flood waters when the habitats connect to the river.

- **Swamp forests** are found in only a few PICTs[35] and provide shelter, among tree roots and trunks, for fish that can live in stagnant water. The most extensive areas occur in PNG, although other swamp forests are also found in Fiji, New Caledonia, Palau, Solomon Islands, Vanuatu and Samoa, and on a number of the high islands of Micronesia. The main trees found in this habitat may include paperbark, palms, pandanus and swamp forest vegetation associated with freshwater mangroves.
- **Freshwater marshes** usually occur in lowland areas such as the floodplains of PNG, river delta margins, behind beach ridges and in the coastal valley wetlands of Fiji[35]. In these habitats, fish shelter among the vegetation and some species spawn on vegetated surfaces. Vegetation includes grasses, reeds, herbs, sedges and ferns, often creating a peaty substrate.
- **Blocked river valleys** are characteristic of the Fly River system where sediment deposition during high flows obstructs smaller tributaries, forming large, deep off-river pools for fish. Other blocked valleys are also created when high-water levels in the Fly River stop water from draining from the broad, shallow valleys on the floodplain[37].

7.2.5.6 Low-elevation lakes

These large, relatively shallow lakes provide extensive fish habitat. The largest low-elevation lake is Lake Murray, near the confluence of the Strickland and Fly rivers in PNG at an elevation of 20 m. Despite its large surface area (647 km^2), it has a maximum depth of only 7 m during normal water levels. Lake Tegano on the island of Rennell, Solomon Islands, is the largest lake in the non-continental islands of the Pacific, with a surface area of 155 km^2 and a maximum depth of 43 m[38]. The low lakes of Tetepare Island (Lakes Bangatu and Saromana) have diverse fish communities with riparian vegetation dominated by palms and pandanus[39]. Other low-elevation lakes include the blueholes fed by springs on Santo Island, and small low-elevation crater lakes such on Ambae Island, in Vanuatu.

7.2.5.7 Tidal fresh waters

The extent of tidal fresh waters on most islands is limited because of low tidal range and steep channel gradients. Significant tidal fresh waters occur in large rivers, e.g. the Fly River, and support fish habitats such as channel pools, sand and mud banks and islands. Although the water level rises and falls with tidal movement, freshwater flow exceeds the upstream movement of saline water, maintaining freshwater habitats and preventing the establishment of estuarine vegetation. Smaller rivers such as the Rewa River on Viti Levu, Fiji, have much shorter tidal freshwater sections.

7.2.5.8 Estuaries

Estuaries are semi-enclosed tidal waters where salt water is diluted by inflowing fresh water[40]. Many estuaries in the tropical Pacific extend for distances of only a few metres in small, steep rivers[41] to hundreds of kilometres in the Fly River estuary. They are generally small and less complex than estuaries elsewhere because of the limited size of most rivers. However, the estuarine habitats of the region support a wide diversity of fish species, which can tolerate fluctuating salinity.

Several types of estuaries exist in PICTs, including coastal plain estuaries where rivers flow through low-lying floodplains, tidal rivers where freshwater flow largely prevents salt intrusion, and coastal lagoons where the entrance to the sea is partially blocked[40].

- **Coastal plain estuaries,** such as the Fly River estuary, are formed by rivers that cut a channel across deposited floodplain sediments. They have sandy or muddy sediments, often with extensive branching creek networks, and are fringed with mangrove forests and seagrass beds. These ecosystems support very productive food webs and provide nursery habitats for many species of fish. Paradoxically, these systems also provide feeding habitats for both large and small predators[42].

Dumbea River estuary, New Caledonia

Photo: Sebastien Mérion

- **Tidal rivers, or drowned river valleys,** such as the Dagi River in West New Britain, PNG, are formed as sea level rises and floods former freshwater channels. These estuaries often lack floodplains, have limited intrusion of salt water because fresh water flow dominates tidal flows, and may have long reaches of tidal fresh water. Sediments deposited by floods may form mud banks and delta islands that support mangroves, providing habitats for fish and invertebrates.

- **Coastal lagoons** are formed by some smaller rivers, such as the Vurulata River on Choiseul Island, Solomon Islands, where sediments block the mouth. These lagoons may be predominantly fresh water or brackish, depending on the volume of freshwater inflows.

Estuarine conditions, such as low or fluctuating salinities, high turbidity, and protection from wave action, often extend outside the river mouth, so that fish species in coastal habitats are often the same as those within the semi-enclosed estuary. As a consequence, the distinction between estuarine and coastal habitats, and the fisheries they support, is sometimes blurred[43].

7.2.6 Natural variability in freshwater and estuarine habitats

All freshwater and estuarine habitats are influenced strongly by river flow. Variability in flow, habitat condition, and habitat availability is a powerful force that determines the fish and invertebrate assemblages supported by each habitat[23]. Short-term variability in river flow is linked closely to rainfall because of the small sizes of catchments, and short runoff durations of rivers in the tropical Pacific, compared with continental rivers.

Similarly, seasonal river flow patterns reflect rainfall. Several PICTs in the western Pacific (e.g. PNG and Solomon Islands) do not have a distinct dry season, and river flows are relatively constant throughout the year. Guam, the Commonwealth of the Northern Mariana Islands (CNMI), and the Marshall Islands north of the equator have a distinct winter dry season. South of the equator, islands experience a distinct summer wet season, and higher islands are strongly influenced by orographic influences on rainfall distribution.

Annual variability in river flows across the tropical Pacific is also influenced on a 2- to 5-year time scale by the El Niño-Southern Oscillation (ENSO) (Chapter 2). During El Niño events, the central and eastern Pacific experiences increased rainfall, whereas islands in the western part of the region experience droughts with a virtual absence of rain for several months to 1 year (Chapter 2). Most PICTs experienced severe El Niño events in 1997–1998 and 2000–2001, when many smaller rivers and freshwater wetlands dried[37,44]. The La Niña event that followed the 2000–2001 El Niño, brought cyclones and flooding to many rivers.

River flows during the wet season are influenced by cyclones that bring intense rainfall, resulting in severe floods that can devastate freshwater ecosystems. Snail populations in the Wainibuka River, Viti Levu, were reduced from 1475 individuals per m^2 before a cyclone, to 250 individuals per m^2 afterwards[45]. Tropical Pacific rivers typically have low biodiversity, and recolonisation after disturbance can result in changes in species composition[46].

Regular flow, Tutusù River, Solomon Islands

Photo: Ron Englund

7.3 Role of freshwater and estuarine habitats in supporting fisheries

7.3.1 Use of riverine habitats by fish

The combination of functional process zones, habitats and habitat patches enable rivers and estuaries in the tropical Pacific to support a diverse range of fish and invertebrates (**Figure 7.5**). Each habitat performs multiple roles for different species and life stages[47]. Many species of fish and invertebrates are specialists, requiring particular habitat features. For example, climbing gobies are adapted to live in fast-flowing habitats such as riffles, rapids, and even waterfalls. Deeper-bodied, mid-water species, such as jungle perch *Kuhlia rupestris* and *K. marginata*[48] and mangrove jack *Lutjanus argentimaculatus* tend to live in deeper fast-flowing pools. Some gobies prefer shallow water, whereas gudgeons, and glassfish *Ambassis miops* are commonly found in river edge habitats beneath overhanging vegetation[30,31,37]. Through these associations, flow has a strong influence on fish species richness among habitats[30].

Many freshwater fish in the region have amphidromous migratory behaviour[49,50] (Section 7.3.3) and spawn in freshwater habitats. Newly hatched larvae are transported downstream to the ocean and migrate back upstream to complete their life cycle[29,51–53]. Other species encountered in fresh water are visitors from estuarine and marine habitats, such as *A. miops*, mangrove jack and trevally *Caranx papuensis* which migrate upstream into fresh water as juveniles and return to the sea later in life[54]. Milkfish *Chanos chanos* and oxeye herring *Megalops cyprinoides* can reproduce in lakes that become isolated from river channel habitats[39].

Barramundi *Lates calcarifer* occupy different habitats at different life-history stages. Juvenile barramundi migrate into the main river channel as their off-channel wetland nurseries become inhospitable in the dry season[55].

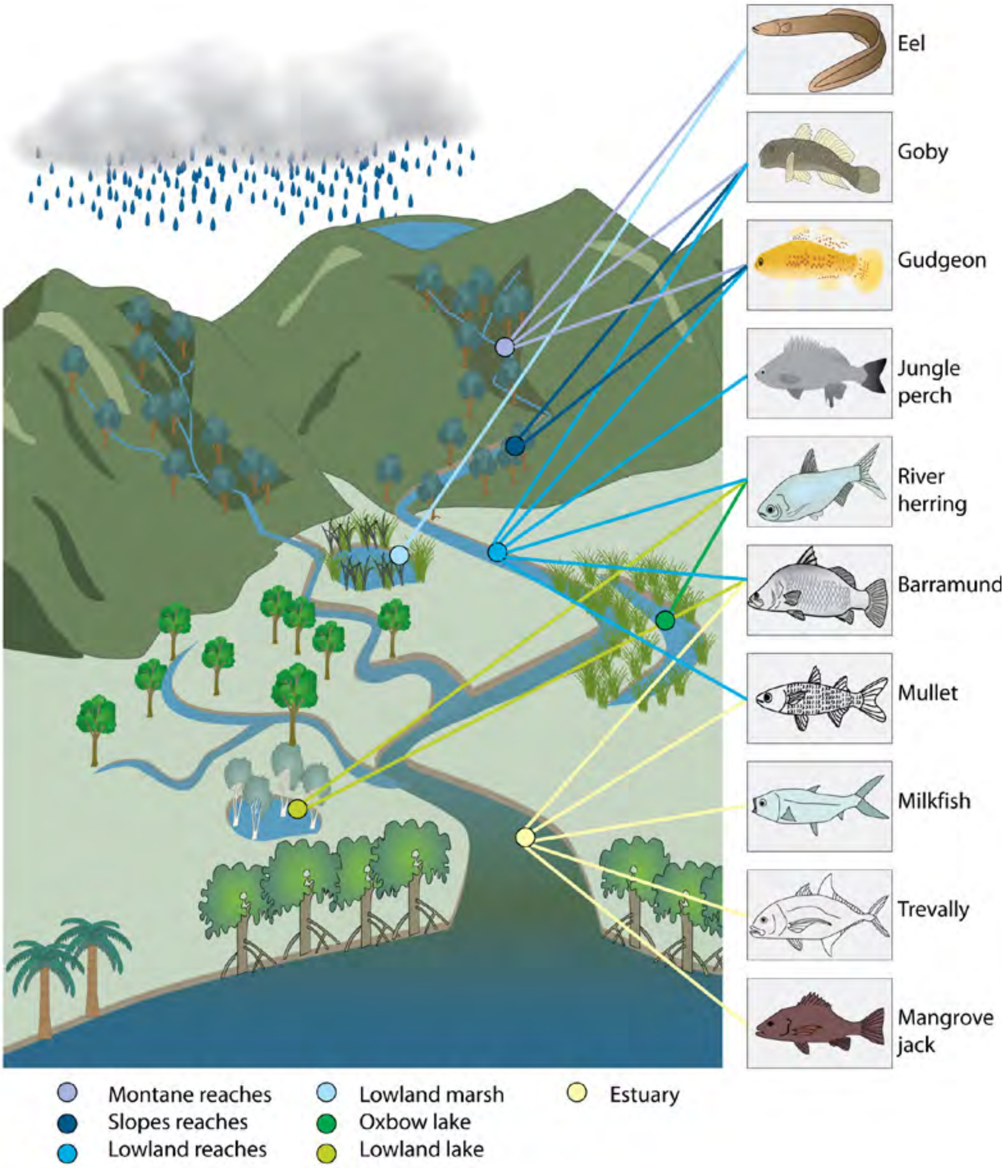


Figure 7.5 Examples of fish species that use freshwater and estuarine habitats in different functional process zones. Habitat use is not fixed for individual species. Catadromous species like barramundi migrate to sea to spawn, larvae return to coastal wetlands and move further upstream as juveniles (Section 7.3.3). Potamodromous species like river herring migrate exclusively within fresh water in the lowland river channel and floodplain habitats (Section 7.3.3).

Freshwater habitats are often discontinuous, being separated above and below waterfalls or between the main channel and floodplain habitats. For some fish species, essential habitats are sometimes separated in different catchments or occur on different islands, so that the fish need to migrate through coastal or oceanic waters to reach their required habitats. Fragmented habitats can mean that the diversity of freshwater fish is highly localised, and that even small lakes or river systems may harbour unique species. For example, the Tamavua River on Viti Levu provides habitat for half of all the endemic fish species in Fiji[56].

Connections between habitats are needed to enable fish to move between different habitats during their life cycle, particularly adults moving to spawning grounds, and recruits entering nursery habitats. This connectivity is critical to fisheries production because migration between habitats is an essential component of the life-cycles of most fisheries species in tropical rivers[57,58]. Fast flowing riffles connect pools and provide aeration, algal production, feeding and habitat areas for invertebrates and the fish that prey on them. Riffles also often provide spawning sites[59]. Slow flowing pools, in contrast, provide low-flow refuges[60], resting places for migrating fish, deposition zones for particulate organic matter and feeding areas for the large predatory fish typically targeted by fisheries.

River edge habitats provide shallow refuges for juveniles[47] and small species[61], and access to bankside vegetation[57], which provides shelter and food in the form of insects and fruit. Complex structures (e.g. fallen trees, rocks, undercut banks, and vegetated edges) are used as refuge and feeding habitats by barramundi, and by snappers (Lutjanidae)[62,63].

7.3.2 Use of off-channel habitats by fish

Off-channel habitats offer refuge during the wet season, feeding areas and spawning sites, and refuge from predators[64,65]. Many of these habitats are temporary, and dry out from time to time.

Oxbow lakes on Viti Levu, off-channel tributaries on Choiseul, and floodplain lakes on Malaita and Tetepare, each support species of fish that are rare in other habitats[30,31,39,66]. Gudgeons are commonly found near overhanging vegetation and soft mud substrate at the water's edge. Deeper waters in lakes support species such as milkfish, oxeye herring and mullet *Liza vaigiensis*[30,31,39].

Floodplain habitats of the Fly River system in PNG support 66 fish species, compared to 86 species recorded from lowland river channels[67]. Oxbow lakes, blocked valleys, and grassed floodplain habitats also support up to 46 species[37], with river herring *Nematalosa papuensis* being the most abundant species. Small species are usually more abundant in the shallower, well-vegetated blocked valleys, while the deeper oxbow lakes support larger numbers of barramundi and other predators. Twenty-three species found in riverine habitats have not been recorded in floodplain habitats[37,67].

7.3.3 Contribution of habitats to fish reproduction

Many freshwater fish species in the tropical Pacific migrate between habitats to complete their life cycles[41,50]. Depending on the species, connectivity is required between upstream and downstream freshwater habitats, river channel and off-channel habitats, and between fresh water and the sea, for successful reproduction. Since changes in flow and increasing salinity in the lower reaches of rivers are likely to occur as a result of climate change, differences in connectivity between habitats may affect fish production.

The limited availability of freshwater habitats on smaller islands dictates that the ability to migrate through the sea is an important attribute to maintain species distributions. Different migratory and reproductive strategies have evolved for this purpose.

- **Catadromous species** live in fresh water as adults and migrate to the sea to spawn. Larvae and juveniles then occupy a variety of habitats as they make their way back upstream. Examples of this reproductive behaviour are barramundi[68], jungle perch[48] and eels[69]. Larval and juvenile stages have limited swimming ability, and small environmental changes, such as low-level stream blockages, can prevent access to habitats upstream and cause populations to decline.
- **Amphidromous species** spawn in fresh water and their larvae are carried to the sea by river flow (**Figure 7.6**). Gobies and gudgeons are common amphidromous fish throughout the Pacific islands. Juveniles may spend more than 250 days at sea or in inshore waters[70,71] before re-entering fresh water. Goby larvae begin to change into their adult form once they enter a river[72]. Other common amphidromous species in the Pacific islands include six genera of atyid shrimp (*Macrobrachium),* decapod crabs (*Varuna*), and freshwater gastropods (*Neritina*)[50]. This behaviour allows species to maintain freshwater populations on islands separated by ocean[50,73].
- **Potamodromous species** migrate wholly within fresh water and complete their life cycle without going to sea. These species typically produce pelagic eggs, and migrate upstream to counter the downstream drift of eggs and larvae[66]. Examples include freshwater mullet *Cestraeus plicatilis* and river herring, which are believed to be potamodromous, based on the behaviour of the closely related *Nematalosa erebi* in Australia[74,75].

Migration between habitats is also a feature of the life-cycles of marine species that inhabit fresh water or estuaries. These species include mangrove jacks, which spawn on offshore reefs but spend their early life in fresh water and estuaries[76], penaeid shrimp with riverine nursery areas[57,77], and mangrove crabs (*Scylla* spp.), which migrate from estuaries to inshore coastal waters to spawn[78].

Irrespective of the migratory behaviour exhibited, most freshwater and estuarine fish and invertebrate species require access to a chain of connected habitats to complete their life cycle[63,76,77,79]. Rivers are the major migration corridors linking habitats[58]. The disruption of the connectivity between habitats by climatic events, such as changes in seasonal rainfall cycles, episodic floods and droughts, or changes in sea level, may limit successful recruitment.

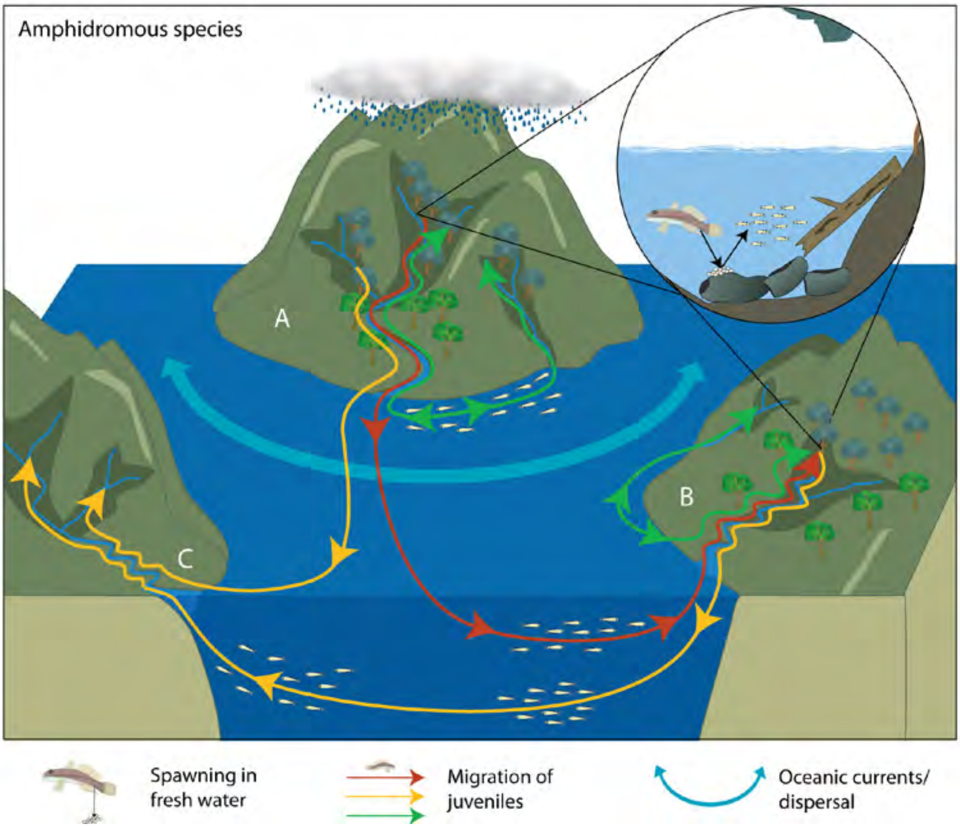


Figure 7.6 Amphidromous species may require a wide range of habitats, including all river types, estuaries, and coastal and oceanic habitats to complete their life cycles (Island A). Spawning occurs in freshwater habitats. Larvae are carried to sea by river flow, where they are transported by ocean currents (blue arrow), and develop into adults upon re-entering fresh water in the same river, adjacent rivers, or rivers on other islands (Island B). Islands without suitable spawning habitats (Island C) rely on other islands as sources of recruitment.

Freshwater habitats used for spawning and recruitment commonly experience elevated water turbidity, changes in water chemistry, and smothering by fine sediments in catchments affected by logging, mining, agriculture and urban development. Climate change has the potential to affect fish reproduction by exacerbating these threats, and by altering habitat connectivity for species that migrate within and among rivers.

7.3.4 Role of freshwater and estuarine habitats in fish growth

Four different food web pathways operate across habitats in major river systems to provide the energy sources for fish growth[20]:

1. planktivorous pathways, involving phytoplankton, zooplankton and the fish that feed on them, such as river herring;
2. epiphyte-grazer pathways, based on aquatic insects and shrimp, herbivorous fish, such as fork-tailed catfish *Arius berneyi* and mullet *Liza diadema* and predatory fish (piscivores), such as barramundi and longtom *Strongylura kreffti*;
3. terrestrial carbon pathways providing energy for species such as long tom, Papuan black bass *Lutjanus goldiei*, saratoga *Scleropages jardini* and fork-tailed catfish *Arius latirostris* and *A. leptaspis* which derive their energy from terrestrial sources, and by feeding on species such as *Macrobrachium* that ingest plant detritus; and
4. other riparian pathways, involving species such as archerfish *Toxotes chatareus* and fork-tailed catfish, which feed directly on terrestrial insects and fruits associated with streamside vegetation.

The simplified food webs from an oxbow lake and a forested reach of the Fly River channel show that fish eat a wide selection food types in different habitats (**Figure 7.7**). Changes in habitat condition such as turbidity, nutrient availability, shading by plants, extent of inundation, and flushing of detritus during flow events, influence which pathways will predominate in particular habitats at any point in time.

There are also differences in productivity between habitats in PNG; for example, barramundi grow more quickly in fresh water than in salt water[80]. Barramundi gain condition through the dry season in habitats such as oxbow lakes, when their prey are more concentrated, and lose condition in the wet season during spawning migrations[68,81].

The primary food sources for fish and invertebrates in steep gradient rivers are benthic algae growing on rocks, and low densities of attached macroinvertebrate larvae, because there is little sand to support benthic fauna. This epiphyte-grazer pathway is common in such habitats, and the herbivorous gobies living there face competition from algal-grazing molluscs[41] (**Figure 7.8**).

7.4 Critical requirements for maintaining freshwater and estuarine habitats

Flow is the primary process that shapes freshwater habitats (Section 7.2.2). Furthermore, components of the flow regime influence the nature of habitats over annual, decadal and longer time-scales[82]. Alterations in flow, as a result of changes in the timing, intensity and variability of rainfall, may therefore affect the processes that create and maintain fish habitats.

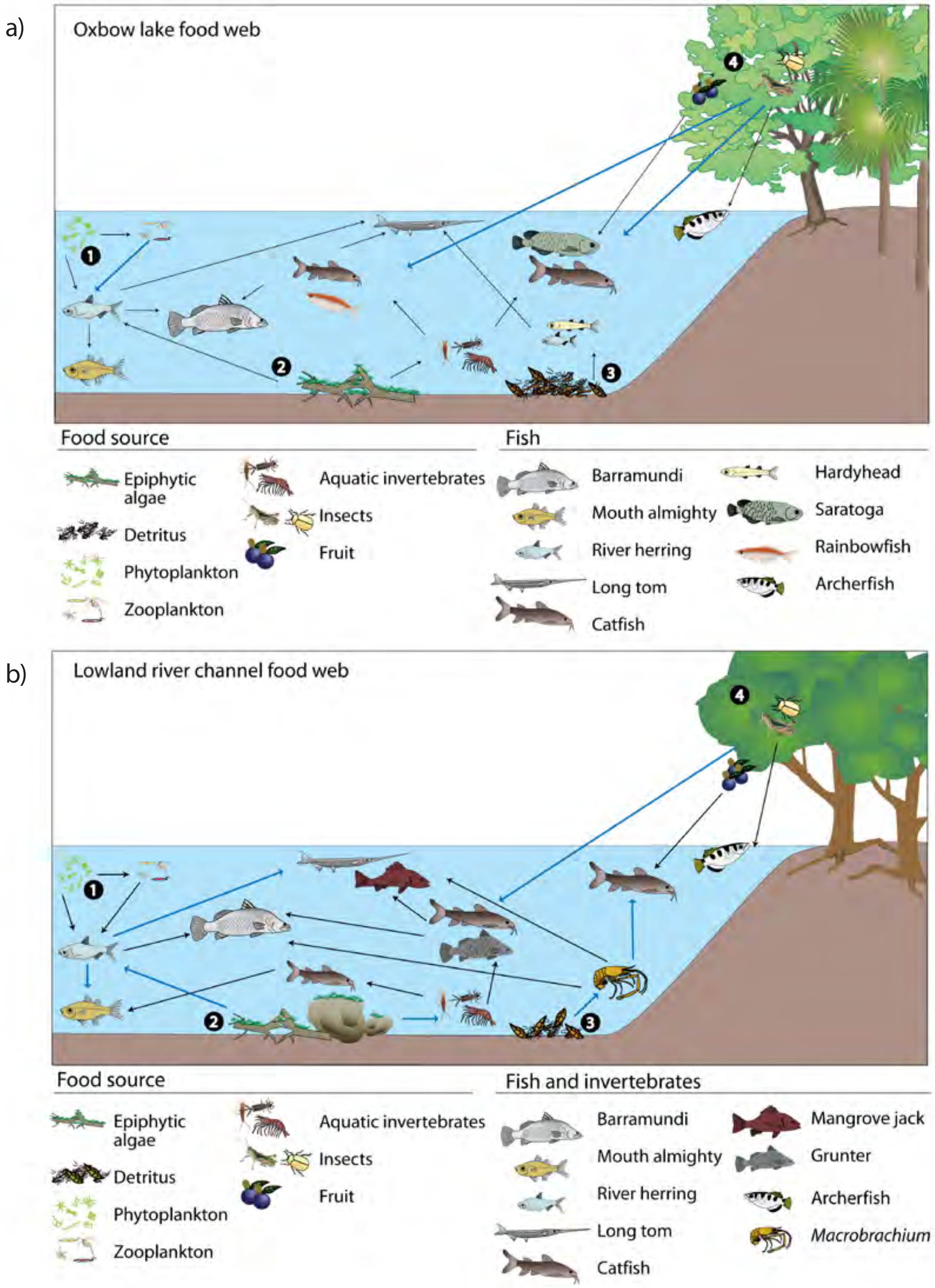


Figure 7.7 Simplified food webs typical of (a) an oxbow lake and (b) a lowland river channel in Papua New Guinea, showing energy pathways based on (1) phytoplankton, (2) algae and epiphytes, (3) terrestrial plant detritus, and (4) riparian fruits and insects[23]. Heavier blue lines show stronger relationships. Note that some fish and invertebrates harvested for subsistence are eaten by larger fish.

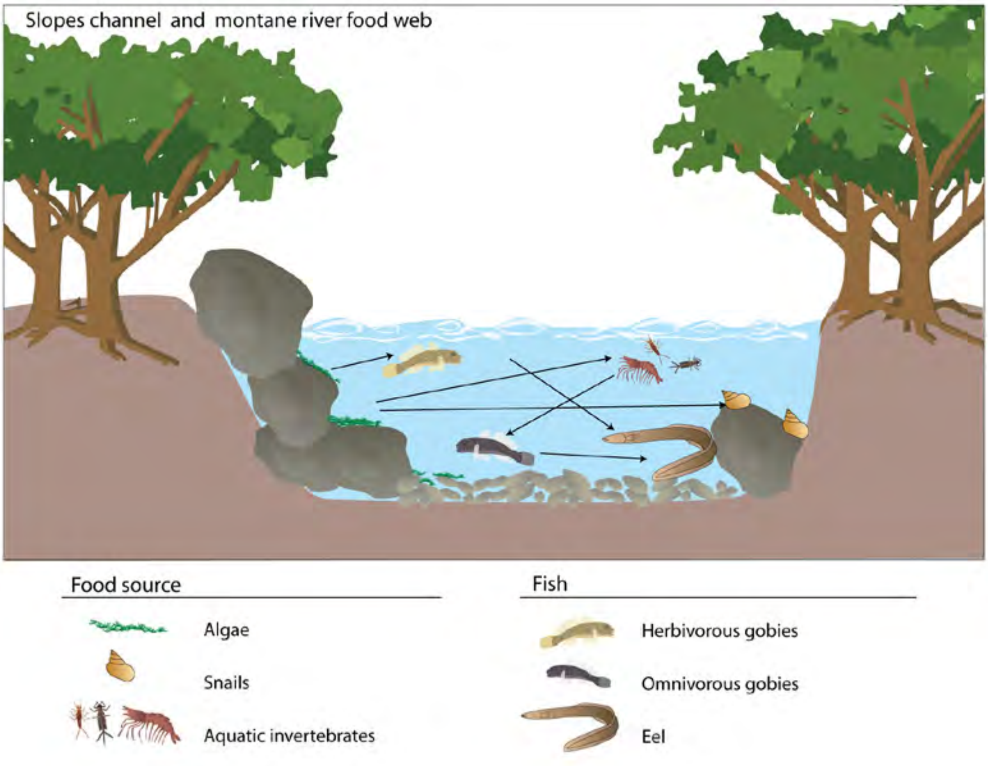


Figure 7.8 A generalised food web for habitats typical of montane rivers and the slopes reaches of rivers in the tropical Pacific.

The magnitude of river flows determines seasonal availability of habitats within river channels and floodplains, as well as providing longitudinal connectivity within the river channel, and lateral connectivity between channel and floodplain habitats. Prolonged low flows result in contraction of the river channel and reduction in the availability of habitats, whereas long-term high flows increase channel capacity and access to habitats[10].

The timing of flow determines when habitats such as gravel and macrophyte beds are available for spawning, feeding or shelter. Because growth of aquatic plants depends on the availability of both light and nutrients, macrophytes and benthic algae may experience suitable conditions for growth only at specific times of the year. Because benthic algae and macrophytes are often scoured away by high flows in rivers with pronounced wet season flows[83], the timing of flow determines the presence of vegetated habitats.

The frequency of flow events determines how often, for example, floodplain wetland habitats are refilled, how often species can enter floodplain habitats[84], and how often amphidromous larvae are carried to the sea to begin their marine migration[29].

The duration of flow events controls how long off-channel habitats are available to support rapid growth of juvenile fish before they re-enter riverine habitats[79], or migration of fish to reach upstream pools that become disconnected during low flows[29].

The rate of change in flow affects how quickly habitats become connected or disconnected, and may lead to fish becoming stranded in off-channel habitats during rapid recession of flood waters[37].

The variability and predictability of flows controls how regularly habitats connect to meet fish requirements for breeding, feeding and migration, and allow fish to synchronise their behaviour to habitat conditions. Where flows are predictable, fish may develop life-history strategies to maximise recruitment[85], such as using off-channel wetlands as nursery habitats[68], or spawning during floods to carry larvae to sea[29].

Flow is also important in maintaining estuarine habitats. The estuary of the Fly River in PNG has a daily tidal water flux about 18 times greater than the freshwater discharge[86] of 6000 m^3 per second. The funnel shape of the Fly delta, combined with the opposing freshwater and estuarine tidal flows of up to 2 m per second, produce estuarine habitats that are continuously changing.

In summary, river systems in the tropical Pacific are driven primarily by rainfall and its effect on river flow. In particular, flow is affected by seasonal patterns of precipitation, episodic events such as cyclones, and longer-term periods of high or low rainfall under the influence of ENSO (Chapter 2). Temperature also plays a role because it affects persistence of freshwater and estuarine water bodies through evaporation, as well as the suitability of habitats for individual species of fish and invertebrates (Chapter 10). The location and extent of estuaries is governed by topography, freshwater flow, tides and long-term changes in sea level.

7.5 Climate change scenarios for Pacific island river systems

Existing climate change models for the tropical Pacific emphasise the role of ocean-atmosphere interactions as forces driving island climates (Chapter 1). These models do not, however, adequately account for the ability of high islands to generate local weather patterns through cloud capture by mountains within the larger, ocean-scale climate pattern[8,87]. The spatial resolution of current climate models therefore creates uncertainty in developing projections for rainfall, runoff and river flows, all of which will shape future river and estuarine habitats.

Despite the low resolution of rainfall projections, it is likely that most rivers will receive more runoff as a result of the expected increases in rainfall of 5–20% by 2035, and 10–20% by 2100 (Chapter 2). The area receiving higher rainfall is also expected to expand towards 2100. However the southwest of the region around New Caledonia may expect a decline in rainfall of up to 20% during winter by 2100, increasing the variability of seasonal flow in the rivers there. In the southeast, French Polynesia may expect more uniform annual rainfall and river flow, with a 5–20% decrease in rainfall over summer, and a 20% increase in winter by 2100 under the A2 scenario (Chapter 2). The habitats described in earlier sections are likely to be affected by changes in flow as a result of changing rainfall patterns.

Expected increases in surface temperature of up to 0.8°C under both B1 and A2 emissions scenarios by 2035, and up to 3°C by 2100 under the A2 scenario (Chapter 2) are difficult to extrapolate directly to freshwater habitats and estuaries. Shaded rivers fed by groundwater may experience little change from present-day temperatures, whereas shallow saline wetlands exposed to the sun may warm by more than the projected increase. Actual temperatures will be driven by a combination of regional temperature changes and local conditions.

Existing models suggest that cyclones will occur in the same locations, and will become less frequent, but possibly more intense, with stronger, more damaging winds and potentially larger storm surges (Chapter 2). Projected sea-level rise (Chapter 3) will affect mainly estuaries and low-lying freshwater habitats, and will interact with altered rainfall patterns and cyclone intensity. Estuaries in lowland floodplain rivers are likely to expand inland with rising sea levels, as inundation by freshwater inflows increases during rainy seasons. Tidal movements and salinity will extend further inland. These effects will be accentuated by storm surges during any cyclones of higher intensity.

7.5.1 Direct and indirect climate change effects

Taken together, the projected changes to the climate of the tropical Pacific are expected to have profound effects on freshwater and estuarine habitats. These changes are described in more detail below and summarised in **Table 7.3**. Note, however, that due to the spatial and temporal variability in the direction and extent of projected climate change across the region, the outcomes for freshwater and estuarine fish habitats will differ according to the type and location of islands, and their local climate.

7.5.2 Effects of rainfall on river flow and habitats

Freshwater habitats are likely to be extensively affected by altered rainfall[88]. River discharge is estimated to increase by 9% in the Fly River and by 33% in the Sepik River by 2050 under the A2 emissions scenario[89], increasing further towards 2100. Higher rainfall will lead to flows of increased magnitude and duration, greater flooding, increased erosion and sedimentation downstream, and enhanced connectivity. Increased flow allows channels to cut through river bends, creating new oxbow lakes[90]. Increased flow is also expected to alter the distribution of sandbars and gravelbars[91], fill crevices among rocks and gravel, and accelerate infilling of oxbow lakes[90].

Table 7.3 Expected alterations to freshwater and estuarine fish habitats in the tropical Pacific under projected climate changes.

Habitat	Climate feature				
	Increased temperature	**Increased rainfall**	**Increased rainfall variability**	**Increased cyclone intensity**	**Sea-level rise**
Rivers	• Warming of high-elevation habitats • Warmer lowland habitats	• Greater duration of high flows • Increased depth • Greater scouring and bank collapse • Increased habitat area • Increased fallen tree habitat	• Depth and flow more variable • Greater mobility of macrophyte beds and riparian vegetation • Increased habitat variability	• Increased physical damage, erosion and sedimentation • Variable supply of woody snags	• Increased salinity in downstream pools
Lakes	• Increased stratification • Accelerated nutrient cycling and production	• Improved flushing and water quality • Increased nutrient delivery and productivity • Elevated contaminant inputs • Increased depth or stability in maximum depth	• Greater depth fluctuation • Periodic reduction in water depth	• Increased sediment, nutrient and contaminant inputs • Increased connectivity among isolated habitats	• Salinisation of coastal lakes • Increased marine connectivity
Flood-plains	• Increased production and decomposition rates • Increased evaporation and loss from small pools	• Increased river-floodplain connectivity • Increased inundation of seasonal wetlands • Increased or decreased area of shallow vegetated habitats • Increased wetland depth	• Increased variability in river-floodplain connectivity, wetland depth, area and duration • Transition to wet-dry tolerant vegetated habitats • Increased drying during droughts	• More variable connectivity of isolated wetlands • Greater physical disturbance to vegetated habitats • Increased sedimentation of floodplain • More variable habitat diversity	• Increased salinity in coastal floodplain wetlands • Loss of salt-intolerant vegetation • Expansion of mangroves into floodplain habitat
Estuaries	• Potential for inhibition of intertidal primary production	• Increased connectivity of supratidal pools • Enhanced longitudinal connectivity • Increased area with low salinity • Depth reduced by sediment deposition	• Connections to freshwater channel and freshwater pools more irregular • Increased variability in estuary area	• Increased connectivity with floodplain and upstream freshwater habitats • Increased habitat dynamics through sedimentation and scouring	• Inundation of intertidal habitats • Increased connectivity of supratidal pools and upstream habitats • Change in area subject to topography • Greater depth

Under normal conditions, the regular seasonality in flow regimes maintains a dynamic equilibrium in the mosaic of habitats. This means that as habitat features such as pool-riffle sequences or channel bars move or are lost, they will be replaced by similar features. Thus, the habitat mosaic remains relatively stable when stream power remains within a defined range.

Projected increases in rainfall under both the B1 and A2 scenarios (Chapter 2) will increase habitat availability, and the links between freshwater habitats (**Figure 7.9**), but the timing, intensity, frequency and variability of rainfall will determine which aspects of the flow regime have the strongest influence on habitat quality. Modest increases in annual flow will produce proportional increases in habitat availability, and the arrangement of habitats with respect to other habitats. The magnitude of changes will increase markedly during severe cyclones.

Reduced rainfall in the southwest Pacific by as much as 20% under the A2 scenario by 2100 in winter, and in the southeast by 5–10% in summer (Chapter 2), will reduce river flow on islands such as Grande Terre in New Caledonia and Tahiti in French Polynesia, potentially leading to a narrowing of river channels and reduced connectivity between pool habitats (**Figure 7.9**).

7.5.3 Cyclones and tropical storms

During flows from severe cyclones, stream power increases above normal levels resulting in dramatic changes in the riverine landscape[92]. If cyclones become more intense, changes such as the carving of new channels, coarse sediment transport and floodplain sedimentation will occur on a larger scale.

Cyclones typically cause high flows[93] (**Figure 7.10**) which result in dramatic changes in the freshwater habitat mosaic, such as deposits of new sediment, and re-organisation of pool-riffle sequences. Bedrock channels may be swept clear of fine materials. In lowland channels, riverbanks may collapse, meander bends may be cut off, and riverbeds scoured and filled. Cyclone Namu in 1986 caused sediment deposition up to an astonishing thickness of 8 m in rivers on Guadalcanal, Solomon Islands[94].

Increased flooding of low-lying areas is expected to provide additional aquatic habitat and enhanced connectivity between channel and floodplain areas, although potential advantages to fish may be offset if rainfall becomes unpredictable and access to floodplain habitats becomes more irregular[58].

Storm surges created by cyclones are likely to become larger as cyclones intensify, increasing exposure of floodplain and freshwater habitats to saline intrusion. Coastal lagoons protected by sand barriers may experience increased damage during cyclones, changing the salinity regime. Coastal plain estuaries and tidal rivers with topography that funnels storm surges upstream may also experience accentuated penetration of salt water.

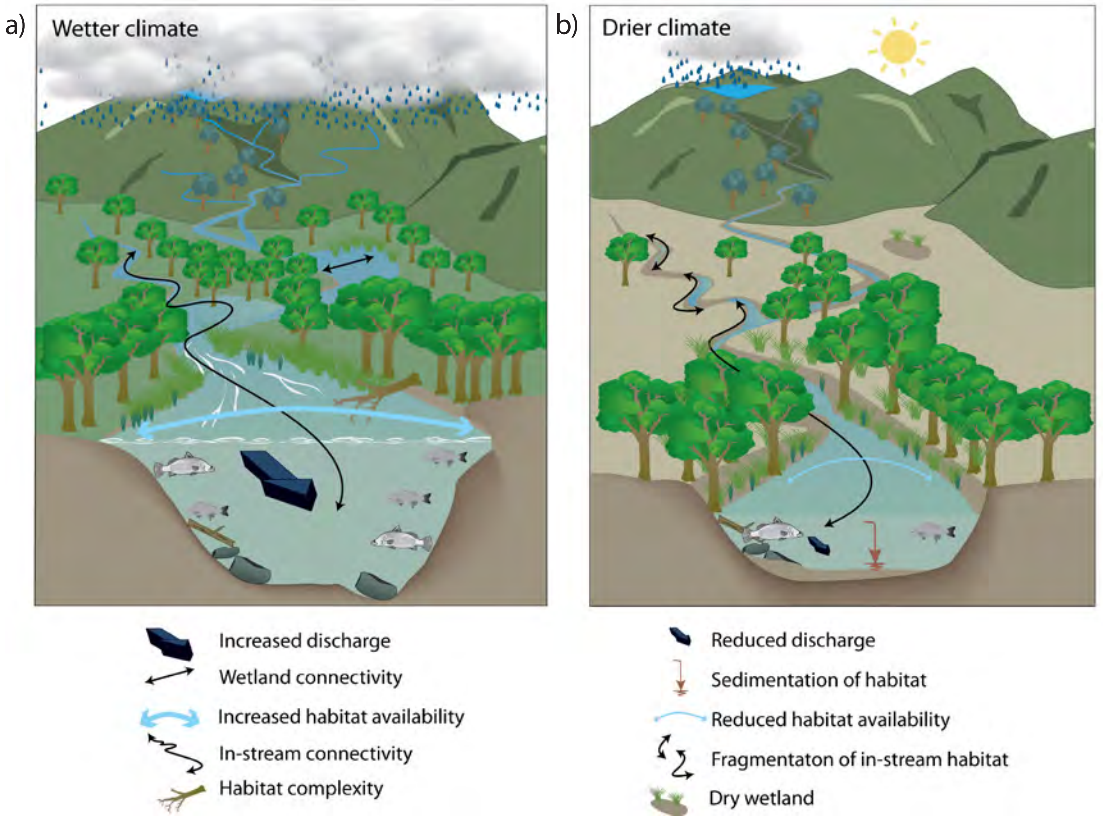


Figure 7.9 Effects of projected changes in rainfall and river flow on freshwater and estuarine habitats. (a) Wetter climates will promote increased habitat availability and diversity, increased connectivity between riverine and floodplain habitats, and expansion of floodplain wetlands. (b) In drier climates, channel habitats will contract and become shallower, with increased fragmentation of in-stream habitats and drying of floodplain habitats.

7.5.4 El Niño-Southern Oscillation events

ENSO events are projected to continue to be a strong feature of the climate of the tropical Pacific (Chapter 2), and can be expected to maintain their influence on river flow. Low flows are often associated with El Niño droughts[95] (**Figure 7.11**), which result in periods of stability and low habitat availability, for example, floodplain habitats may lose their connection to rivers, or dry completely[37]. In regions projected to have drier climates (southwest Pacific in winter and southeast Pacific in summer), reduced river flows may enable salt water to penetrate further upstream. Such intrusion has happened previously in the region, for example, during the 1997 to 1998 El Niño event in the Torassi River in PNG[96].

7.5.5 Temperature

Because of their propensity for evaporation, shallow freshwater habitats with little or no flow, such as backwaters, river edge habitats and shallow floodplain wetlands, are likely to be most vulnerable to the projected warming. The limited potential for mixing in these habitats is also expected to cause water temperatures to exceed the tolerances of many species of fish and invertebrates. Warming of coldwater rivers and lakes in the highlands of PNG will cause a contraction of these habitats to higher elevations[15] (**Figure 7.12**). Intertidal flats currently exposed to daily temperature fluctuations > 10°C might be expected to show little sensitivity to mean temperature increases of up to 0.8°C under both B1 and A2 emissions scenarios by 2035. However, projected increases of up to 3°C by 2100 may inhibit microbial production on mudflats or exceed upper thermal tolerances for infauna.

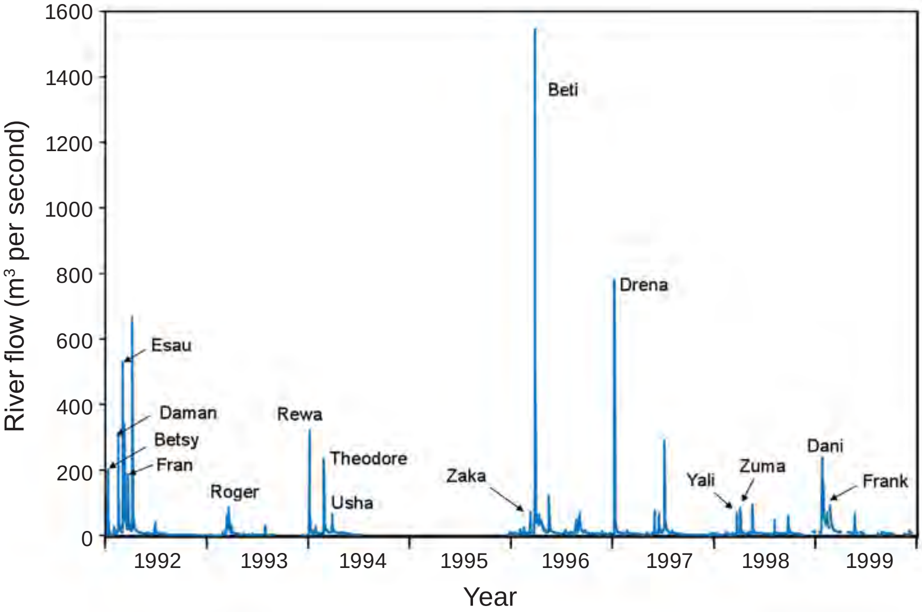


Figure 7.10 Average daily flows for the Tontouta River, New Caledonia, from 1992 to 1999. High flows caused by cyclones (named peaks) and other tropical storms (unnamed peaks) have a major role in shaping channel and floodplain habitats (source: Fiji Meteorological Service and Observatoire de la Ressource en Eau, New Caledonia)[93].

7.5.6 Sea-level rise

Intertidal estuarine habitats are particularly exposed to sea level rise[63,97]. Changes in intertidal area will be governed by local topography. Coastal plain estuaries surrounded by low-lying salt marsh, salt pan, swamps or swamp forests may increase in intertidal area. Increasing inundation of supratidal habitats will allow landward encroachment of mangroves, salt marsh and salt pan vegetation, on low-lying terrain.

Coastal wetlands will have increased depth and a higher salinity as sea level rises[35,98], leading to replacement of freshwater plants by salt-tolerant species. Under both the B1 and A2 emissions scenarios, sea-level rise is likely to be rapid, relative to the life-cycles of forest trees[99], limiting their ability to colonise new habitats. These wetlands are likely to become more variable under the combined effects of increased sea level, increased and more variable rainfall, and increasing temperatures[58].

Exposure of supratidal habitats to saline water from rising sea levels by 2035 under the B1 scenario is likely to have little impact in estuaries like the Fly River system which have a tidal range of up to 5 m[100]. But because of the low elevation of the Fly River floodplain, even the minimum projected sea-level rise of ~ 1.0 m by 2100 under the A2 scenario (Chapter 3) would inundate vegetated habitats that currently experience limited exposure to salt water (**Figure 7.13**). In contrast, supratidal habitats in estuaries with as little as 0.5 m tidal range, such as the Wagulani River in Mullins Harbour, PNG, would receive proportionally higher saline exposure. Some mangrove areas are expected to be particularly vulnerable to sea-level rise, because they are unlikely to be able to migrate landward in pace with inundation (Chapter 6).

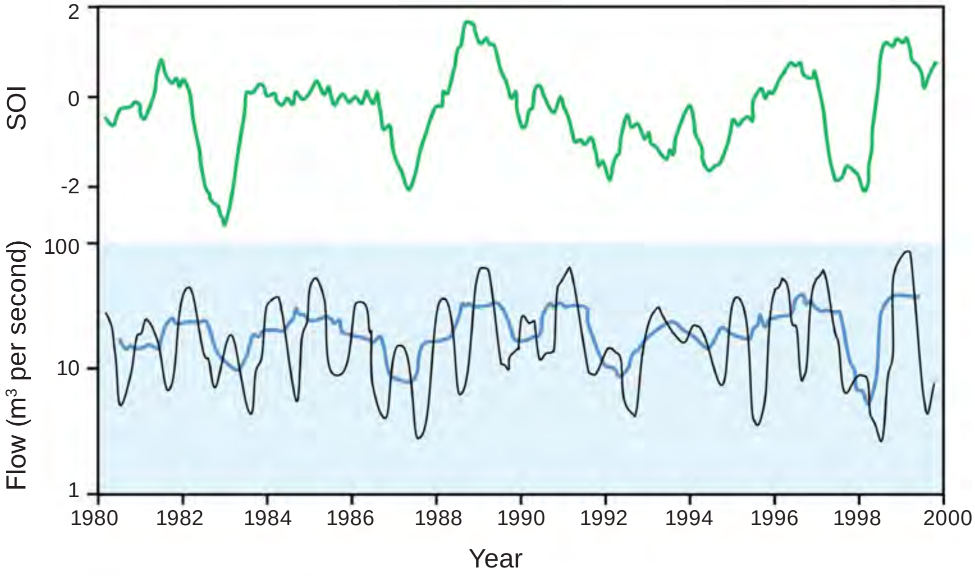


Figure 7.11 Effects of the El Niño-Southern Oscillation on river flows for the Ba River in northwest Viti Levu, Fiji. Flow seasonality (black line, 5 month running mean) reflects strong seasonality in rainfall. Low flows (blue line, 13 month running mean) correspond to low Southern Oscillation Index (SOI) periods (green line, 5 month running mean) during the drought of 1983, 1987, 1993 and 1998 (source: Fiji Public Works Department, Hydrology Section, and Fiji Meteorological Service, Terry et al. 2001)[95].

7.6 Vulnerability of freshwater and estuarine habitats

This assessment follows the approach outlined in Chapter 1, and considers the vulnerability of habitats as a function of exposure to climate change effects, their sensitivity to those changes, and the capacity of habitats to adapt to reduce the potential impact.

All habitats are exposed in a similar way to projected changes in rainfall, temperature and possibly cyclone intensity, whereas sea-level rise affects only low-lying habitats. On the other hand, the sensitivity of freshwater and estuarine habitats varies widely. In particular, differences in stream power between headwaters and tidal reaches caused by channel gradient mean that large volumes of water in lowland reaches have greater thermal stability compared with small montane tributaries. Topography can also be expected to mediate the potential impacts of climate change on riverine habitats, and the effects of mountains will influence local weather patterns. In general, as riverine habitats change from the headwaters to the sea, their relative areas and locations can be expected to adapt in different ways.

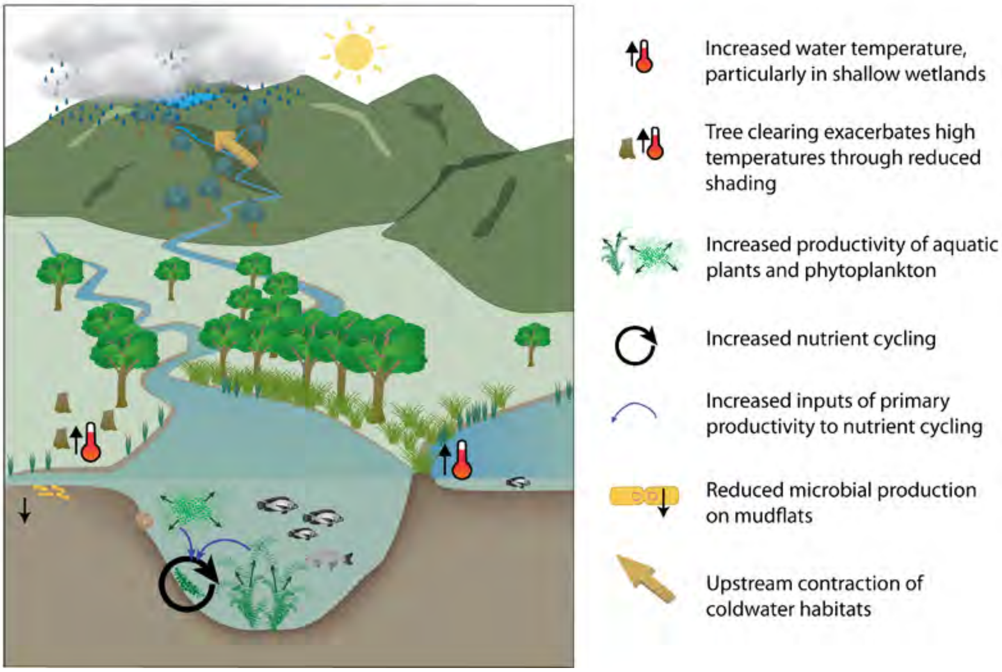


Figure 7.12 Effects of projected increases in water temperature on freshwater and estuarine habitats. Highland coldwater habitats are expected to contract upstream. Temperature extremes will be greatest in shallow floodplain habitats and intertidal flats. The greatest increases in water temperature are expected where shading of the water surface is diminished by clearing of vegetation.

7.6.1 Adaptive capacity of abiotic and vegetated habitats

Abiotic habitats such as rocks and sand respond to climate change in a purely physical way. In contrast, vegetated habitats are able to adapt to climate change because plants alter their growth rates and reproduction in response to variation in temperature, water availability, and water quality.

Abiotic habitats in rivers are influenced by climate-related events through a combination of longitudinal and lateral processes. Increased flow erodes sediments in upstream river reaches and transports them downstream where they are deposited on floodplains, within the river channel, or in the estuary, changing the shape of river habitats over time. The vulnerability of abiotic habitats is a function of exposure and sensitivity to climate change, since the habitats themselves have no adaptive capacity. Bedrock channels are largely resistant to changes in flow as a result of increased rainfall, but decreasing sediment sizes from boulders, cobbles, gravel, sand, silt and clays are progressively more sensitive to flow and require less energy to be transported downstream. Although sediment particles are unable to adapt to changes in flow or temperature, bacterial films, attached algae and macrophytes bind sediments together, making them less sensitive to changes in flow. Increasing temperature and changes in nutrient supply may affect this structural binding capacity, making sediment habitats either more or less vulnerable to changes in flow.

Vegetated habitats, such as macrophyte beds, wetland grasses, algal mats, flooded vegetation and swamp forests, have the capacity to adapt to climate change. They can do this through temperature-dependent changes in photosynthesis and growth, by responding to altered inundation patterns, or by colonising new habitats with suitable salinity. Grasses on the Fly River floodplain clearly have capacity to adapt to short-term changes in climate by colonising dry blocked valleys during El Niño droughts[37]. Mangroves are able to grow at rates similar to historical changes in sea level and sedimentation to avoid being inundated or buried by sediments[35] but may not be able to keep pace with anticipated rates of sea-level rise (Chapter 6).

As long as the quantity and quality of abiotic and vegetated habitats remain in equilibrium within a functional process zone, effects on fish and invertebrates should be restricted to local scales. But if climate change results in a net loss or gain of specific habitats, the species composition of fish and invertebrates is likely to change[23].

Photo: Nick Rains/Corbis

Macrophytes, Sivoli River, Papua New Guinea

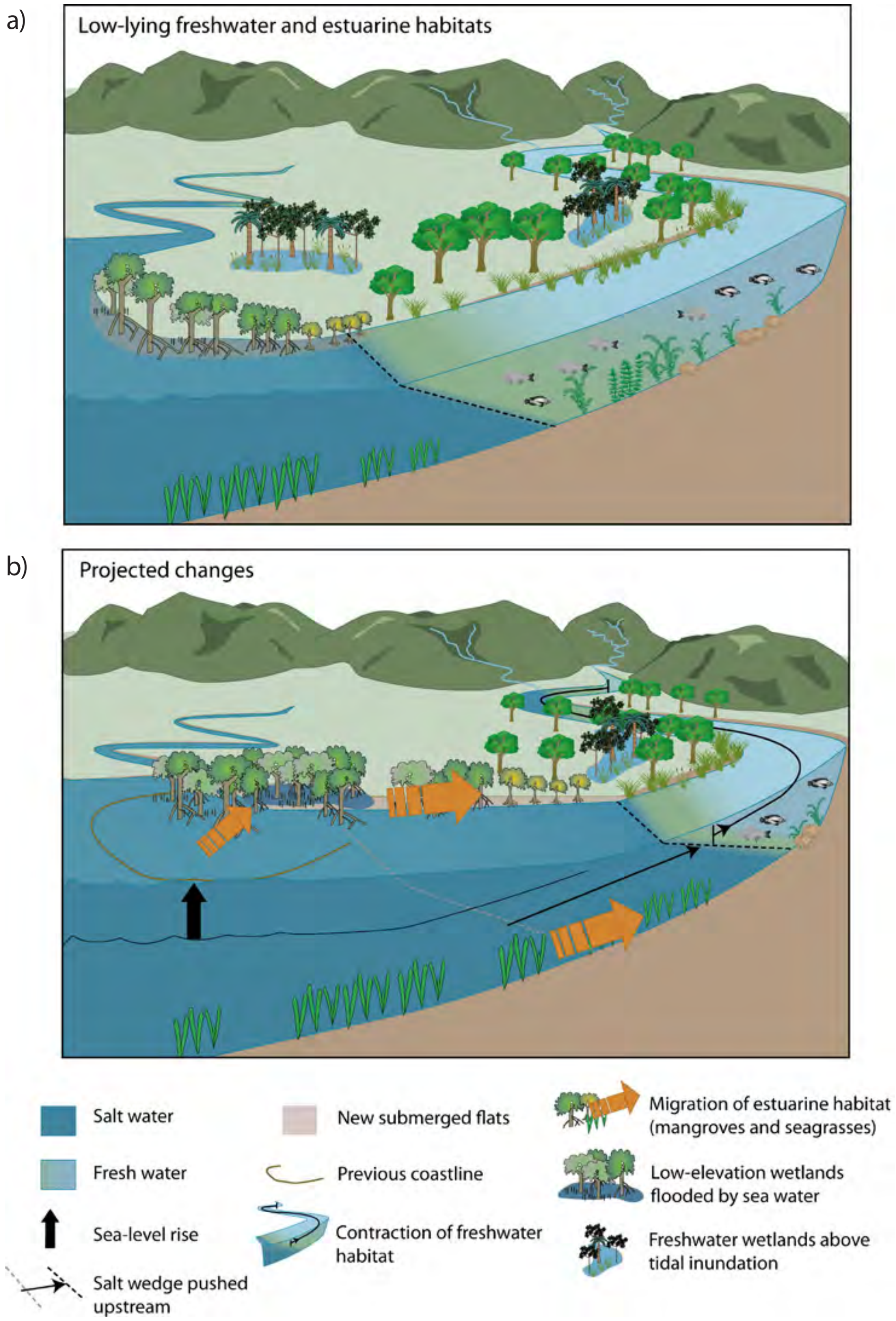


Figure 7.13 Effects of projected increases in sea level on (a) the general present-day structure of low-lying freshwater and estuarine habitats; and (b) the likely effects of sea-level rise, i.e. upstream retreat of lowland freshwater habitats and riparian vegetation, landward migration of mangroves, and salinisation of freshwater coastal wetlands.

7.6.2 Vulnerability of key habitats

7.6.2.1 Montane reaches

Exposure and sensitivity

Exposure of the montane reaches of rivers to climate change is restricted to PNG, and to small areas of Espiritu Santo (Vanuatu), Guadalcanal (Solomon Islands), Viti Levu (Fiji) and Grande Terre (New Caledonia). Nevertheless sensitivity to climate change may pose a significant risk at a local scale.

Montane reaches are principally exposed to increases in temperature, and increased flow and flow variability associated with changes in rainfall and cyclone intensity. As temperatures rise, the amount of coldwater habitat for rainbow trout in PNG will decline. Elevated temperature is likely to increase production rates of benthic algae and riparian vegetation, resulting in increased supply of organic material to the channel subject to the availability of nutrients. The accompanying increase in river flow and material washed from the catchment will also result in increased throughput of organic material. Elevated flow may increase scouring of fine sediments, resulting in small increases of substrate particle size.

Potential impact and adaptive capacity

The most extreme effects can be exemplified as a transition from clear water, with sediment-free, rocky substrata supporting low levels of algal growth, to episodic turbid water with substrata covered in fine sediments, which inhibit attachment of benthic algae. The effects of rising temperatures may be most extreme in cleared montane catchments, when runoff is warmed as it flows over exposed land. These changes are likely to reduce the amount of suitable habitat for mountain-dwelling fish.

The adaptive capacity of undisturbed catchments through enhanced vegetation growth, in response to increasing temperature and rainfall, should make montane river habitats more resilient to the impacts of climate change.

Vulnerability

Undisturbed montane rivers have low vulnerability to habitat changes resulting from increased flow, but will experience elevated water temperatures. The exception is likely to be in New Caledonia, where montane rivers are expected to be more vulnerable to channel reduction or drying, and habitat fragmentation caused by reduced winter rainfall, in addition to increased sedimentation after cyclones.

7.6.2.2 Slopes reaches

Exposure and sensitivity

River habitats in slopes reaches are common throughout the tropical Pacific, with fish penetrating well upstream[56]. These habitats are exposed to elevated temperatures, increased flow and flow variability, except in New Caledonia where river discharge is expected to decline.

In the slopes reaches of large rivers, such as the Fly and Sepik rivers, and smaller rivers, such as the Rewa and Ba rivers on Viti Levu and Papenoo River on Tahiti, elevated temperature is likely to have a modest effect by increasing production rates of benthic algae and riparian vegetation. This increase should result in improved food availability for fish species grazing on algae. Warming will be more pronounced where the water surface is not shaded by riparian vegetation. However, warming is also likely to be moderated by groundwater inflows and the extent to which groundwater is protected from increasing temperatures.

The greatest exposures in slopes reaches are from increased flow and flow variability associated with changes in rainfall and cyclone intensity. Physical habitat patches are expected to become more dynamic, with high-flow events increasing the redistribution of sediment[23]. Channels armoured by coarse sediments are likely to retain their characteristic stability, but may become more exposed to scouring where the bed is disturbed by other factors. Scouring during high flows is likely to increase channel capacity, enlarging slopes habitats by making pools deeper and wider. Where vegetation is largely intact, sensitivity of these habitats to increased runoff is likely to be low.

Potential impact and adaptive capacity

The effects on slopes habitats, and their adaptive capacity, differ between tropical and subtropical regions because of differences in projected rainfall and river flows. In tropical regions, the combination of warmer temperatures and higher rainfall is expected to increase the density of catchment and riparian vegetation, as well as aquatic macrophytes. This should expand the area of aquatic habitat, and protect rivers from erosion and sediment deposition.

In the subtropical rivers of New Caledonia, where winter rainfall is expected to decrease, baseflow is likely to have diminished capacity to transport sediment, resulting in channels contracting and becoming shallower. This is expected to result in a reduction in habitat area. Reduced flow leads to increased drying of small rivers, fragmentation of pool habitats, and increased warming. When cyclones occur, flood damage is more likely because of the combined effects of increased cyclone intensity and reduced channel capacity.

Vulnerability

Slopes reaches have low vulnerability to the expected changes in water temperature and rainfall. Transient negative effects are likely to follow cyclone damage, and diminish as vegetation recovers. New Caledonia has moderate to high vulnerability associated with the expected reduction in river flow and increased water temperature. This vulnerability arises from reduced habitat area during normal flows, and possibly greater disturbance by cyclones.

7.6.2.3 Lowland reaches

Exposure and sensitivity

Lowland river habitats are expected to warm slightly, which in isolation would result in increased growth of macrophytes, benthic algae and phytoplankton. Higher flows are expected to increase habitat area through channel expansion, although erosion stemming from increased rainfall and cyclone intensity may also expose the lowland reaches of rivers to increased turbidity and sedimentation[101,102].

Sensitivity of lowland reaches to increased rainfall and flow is expected to be low because channels already experience elevated flows regularly. Habitats are likely to become more dynamic as sand and mud banks are scoured and reformed by high flows associated with increased rainfall and more intense cyclones. Vegetated channel habitats may be sensitive to increased sediment instability and turbidity.

Downstream, lowland reaches are likely to be exposed to progressive increases in salinity caused by rising sea levels and storm surges, and changes in the distribution of primary production.

At the upstream tidal limit, greater salinity may cause suspended clay particles to flocculate and settle out of the water column during low flows. These changes are expected to increase water clarity and improve conditions for the growth of brackish water macrophytes, benthic algae and phytoplankton[100].

Lowland river reaches, Fiji

Photo: Ashley Cooper/Corbis

Potential impact and adaptive capacity

Lowland reaches are expected to be affected over a wider habitat area than upstream slopes habitats, because of their greater channel width. Lowland reaches are typically much wider than the fringing vegetation, so that the habitat area shaded by riparian vegetation and stabilised by root development is proportionally smaller than in upstream reaches. In rivers projected to have increased discharge, such as the Fly and the Sepik rivers in PNG[89], increased channel capacity caused by erosion is likely to be the dominant effect, coupled with more frequent overbank flooding and sediment deposition, and increased channel migration.

Adaptive capacity in lowland reaches will be related to the condition of vegetation on the floodplain and in the upper catchment. Vegetation reduces the rate of runoff and the potential for erosion of the river bed and banks. Where riparian vegetation is effective in protecting against bank erosion, increased discharge is expected to cause greater inundation of floodplain habitats, or scouring to deepen the channel.

Increased rainfall and warmer temperatures are likely to enhance the growth of macrophytes and riparian vegetation, thus improving the resilience of river habitats.

Vulnerability

Lowland reaches typically have low vulnerability to increased discharge, increased habitat variability resulting from extreme flows, and increased rates of channel migration. The potential negative effects of these changes are expected to be offset by greater availability of fish habitats due to increased discharge. Vulnerability of individual rivers will be determined by the combined effects of climate change and the condition of catchment vegetation. In New Caledonia, the lowland reaches of rivers are expected to be vulnerable to channel contraction stemming from reduced winter flow and increased sedimentation after cyclones, resulting in shallowing of river channels.

7.6.2.4 Lakes

Exposure and sensitivity

Lakes at both high and low elevation are exposed to increases in temperature, rainfall and possibly cyclone intensity, except in PNG where high-elevation lakes are minimally affected by cyclones because of their distance from the coast.

High-elevation lakes may be particularly sensitive to even moderate increases in temperature, which are likely to reduce the amount of suitable habitat for coldwater fish species[103]. High-elevation lakes are also sensitive to increased stratification, which may result in deoxygenation below the thermocline[103]. However, warmer lake temperatures will accelerate nutrient cycling and primary production in the pelagic zone.

High rainfall throughout most of the region means that high-elevation lakes are full of water most of the time, and higher rainfall is expected to have little effect on lake water levels. Instead, increased runoff can be expected to increase inflows and outflows from lakes, with the reduced residence time improving water quality.

Lowland lakes, such as the small but highly productive Lake Bangatu in Solomon Islands[39], will experience elevated inflows, allowing increased connectivity with the sea for amphidromous and catadromous fish species. Similar increases in connectivity are expected in larger lowland lakes, such as Lake Murray in PNG, which increases from a nominal surface area of 647 km^2 to over 2000 km^2 in the wet season. Larger increases in area and connectivity are likely to occur under wetter climate regimes, and these changes are expected to improve habitat access and quality.

Lakes in drier regions such as New Caledonia will be exposed to reduced inflows and increased evaporation, resulting in a reduction in size and increased sensitivity to warming.

Impact and adaptive capacity

The effects of climate change on lakes in the region are expected to be generally positive – most lakes will experience increased inflows to maintain habitat quality and quantity. The adaptive capacity of vegetation in intact catchments is expected to mitigate increased erosion and sediment transport under conditions of increased rainfall.

Coastal lakes may experience saline intrusion via groundwater as sea level rises, however, and increased freshwater inflows may form a freshwater layer above the saline water. Damage to coastal vegetation by cyclones may breach the narrow land barrier separating coastal freshwater lakes from the sea, transforming them into more saline habitats.

Contraction of natural and artificial lake habitats in response to reduced winter rainfall in New Caledonia under the A2 scenario is likely to occur. Littoral vegetation is expected to adapt by colonising edge habitats as the water level recedes.

Lake Owa, Papua New Guinea

Photo: Boga Figa

Vulnerability

Natural lake habitats in the tropical Pacific are likely to have low vulnerability to climate change, because the projected conditions favour processes that form or maintain lakes. However, in New Caledonia, the expected reduction in winter rainfall, and increased temperature and evaporation, make lakes highly vulnerable to climate change in drought years when summer rainfall is also reduced.

7.6.2.5 Floodplain habitats

Exposure and sensitivity

Floodplains are most extensively developed along the Fly and Sepik-Ramu rivers in PNG[35]. Elsewhere in the region, they are small in comparison, but nonetheless provide important fish habitats.

The pools, oxbow lagoons, swamp forests, marshes and blocked valleys found on floodplains are all exposed to increased temperature, higher rainfall, and more intense cyclones. Close to the coast, floodplains will also be exposed to sea-level rise, either through direct intrusion of saline water, or by the damming effects of rising tides on increased flows, forcing fresh water onto the floodplain. In the Fly River, where tidal oscillations extend upstream of the confluence with the Strickland River[104], rising sea level may lead to significant increases in inundated area, accompanied by elevated salinity intrusion during El Niño drought periods.

Greater and more regular inundation is expected to increase the area of floodplain, and enhance fish access to the range of associated habitats. Warmer temperatures are likely to increase production and decomposition rates of floodplain vegetation, leading to broad increases in productivity. However, some aquatic and riparian vegetation will be sensitive to increased water depth, and the duration of inundation. These plant species are expected to retreat into shallower habitats.

Floodplain sedimentation rates on tropical Pacific islands are among the highest in the world, in the range of 3.2 to 4.0 cm per year[105]. Increased flooding from more intense cyclones would accelerate sediment deposition on floodplains across the region.

Potential impact and adaptive capacity

Exposure to climate change is expected to increase primary production and decomposition rates, the duration and extent of connectivity among river and floodplain habitats, and the salinity of low-lying areas.

Rapid sediment deposition rates on floodplains provide an opportunity for vegetation to colonise new areas so that smothering of plants is largely transient. Slower-growing trees are presumably more likely to adapt by colonising locations less exposed to inundation and accumulation of sediment. Increased bank stabilisation by riparian vegetation offers some adaptive capacity to limit erosion and sedimentation[102].

The combination of adaptive capacity of floodplain vegetation, increased sedimentation, scouring of floodplain channels during extreme floods, and greater productivity of shallow inundated areas suggests that (1) the mosaic of floodplain habitats may be preserved; and (2) their distribution and spatial arrangement across the floodplain may become more dynamic. As floodplain grasses adapt to a wetter climate, fluctuations in the habitats they form may be accentuated between 'normal' years with increased discharge, and drought years when some habitats dry completely.

In New Caledonia, where winter rainfall is expected to decline, the effects of sedimentation on floodplains may be more marked than elsewhere, due to a decline in catchment vegetation in response to a drier climate and increased exposure to erosion.

Photo: Australian Doctors International

Floodplain habitats, Sepik River, PNG

Vulnerability

Floodplain habitats in the tropics are likely to be enhanced by increases in rainfall and water temperature and, in general, have low vulnerability to climate change. As floodplain vegetation adapts to a wetter climate, however, habitats will become more vulnerable to El Niño drought episodes. Low-lying areas of floodplain near estuaries are vulnerable to saline inundation from sea-level rise. Floodplains further upstream should be covered by fresh water more extensively as rising sea levels 'dam' the estuary and force freshwater flows laterally. Vulnerability of floodplains is greatest in New Caledonia, where the expected reductions in winter rainfall are likely to result in more frequent drying and disconnection of habitats, and increased sediment deposition during cyclones.

7.6.2.6 Estuaries

Exposure and sensitivity

Estuaries are exposed to a greater range of effects from climate change than other aquatic habitats. As the interface between fresh water and the sea, estuaries are exposed to the combined influences of climate change on rivers, and effects from the coastal environment (Chapter 6). These opposing changes have potential to create unexpected responses where they meet.

Based on the projected alterations to rivers, estuaries are likely to be exposed to moderate increases in water temperature, increases in freshwater flows and greater flow variability. Although most estuaries are also expected to extend further upstream with sea-level rise, freshwater inflows are likely to increase flushing of estuaries, resulting in greater discharge of fine sediments and greater variability in turbidity and salinity. These changes may result in increased variability in production of benthic and planktonic algae and smothering of some seagrass habitats.

Smaller estuaries on steep islands, which have intact catchment vegetation and carry low loads of fine sediment, should have low exposure to increased sedimentation. Although New Caledonia is expected to receive less winter rainfall, especially under the A2 scenario, estuaries there may experience greater variability in salinity and sediment deposition during floods and storm surges associated with stronger cyclones.

Exposure to increased water temperature is likely to vary according to the size and depth of the estuary. Small, steep, rocky estuaries in regions with tidal ranges of 1 m or less may have minimal exposure to a mixture of warmer freshwater flows and sea water. Estuaries such as the Fly River, with a large tidal range, may experience greater warming of intertidal flats, potentially inhibiting benthic production and increasing water temperature during the rising tide.

In places where sea-level rise allows inundation of extensive areas of low-lying land, the tidal regimes within estuaries can be expected to change.

Potential impact and adaptive capacity

As sea level rises, tidal movement in estuaries with a large tidal range will deliver marine sediments further upstream. This is expected to result in increased deposition and subsequent scouring of sediments during high flows[106], and a more dynamic physical habitat. The ability of macrophytes such as seagrasses and mangroves to stabilise sediment deposits will be determined by the rates of sediment delivery, scouring, and plant growth. The Ord River estuary in Western Australia provides an example of changes that might be expected elsewhere under climate change scenarios[107]. There, upstream tidal transport of marine sediments has made the estuary shallower, and formed sand banks that have been colonised by mangroves[106], forcing flood flows towards the banks. The resulting erosion has widened the estuary and much of the eroded sediment is redeposited in the channel, making the estuary even shallower and reinforcing the process.

Sea-level rise is expected to increase inundation of supratidal habitats and promote shoreward migration of the associated vegetation. Depending on location, mangroves and other estuarine plants may have a key role in the ability of estuaries to adapt to the effects of increases in freshwater flows, water temperature and sea level by enabling estuarine habitats to migrate landward at a similar rate to rising sea levels (Chapter 6).

Vulnerability

Estuarine habitats are expected to have low vulnerability to climate change because they are already exposed to great variation in freshwater inflows, temperature and salinity. On the other hand, estuaries are moderately vulnerable to sea-level rise. Where the upstream extent of estuaries is not constrained, estuarine habitats are expected to migrate landward. However, estuaries that are unable to retreat because of steep topography or other barriers are likely to be reduced in area.

Fish habitat created by mangroves

Photo: Gary Bell

7.7 Interactions between effects of climate change and existing impacts

The effects of climate change on freshwater and estuarine habitats will not occur in isolation. Rather, existing environmental conditions and land use will have a strong influence on the exposure, sensitivity, adaptive capacity and vulnerability of individual habitats.

7.7.1 Effects on exposure and sensitivity

Many river catchments have been cleared of vegetation by logging, mining or agricultural activities. Cleared catchments experience accelerated erosion, which causes rivers to become more turbid. For example, on Babeldaob Island in Palau, vegetation clearing in the Ngerikil River catchment produced estuarine sediment loads 10 to 19 times higher than in the neighbouring Ngerdorch catchment, with mangroves trapping about 30% of sediments from each catchment[108]. Mining near the Ok Tedi River in PNG discharges about 80 million tonnes of waste rock and mine tailings into the river each year, increasing the fine sediment load from 3 to 5 million tonnes to 45 million tonnes per year[36] and affecting fish habitats for large distances downstream[109]. On la Grande Terre, New Caledonia, the vegetation in many catchments has been reduced, causing river channels to fill partially with coarse sediments and increasing turbidity[110]. Similar impacts are associated with forestry in Solomon Islands and Fiji[31,111,112]. In short, clearing vegetation increases the exposure of river habitats to the effects of increased rainfall[31,39,109,111].

Rivers that carry naturally high sediment loads, such as the Fly River system, appear to have low sensitivity to increased sediment delivery arising from a wetter climate. Smaller rivers appear to be much more sensitive to increased sediment, however[93,101].

Riverine habitats likely to be most exposed to sedimentation are low-gradient channels, and slow-flowing lowland reaches that become permanently turbid because of high, suspended sediment loads. Excessive deposition of sediments causes homogenisation of river habitats, by infilling pools and covering complex habitats such as rocks and macrophyte beds, creating a more uniform, rectangular cross-sectional channel profile[113].

Clearing vegetation from river banks reduces shading of the water surface, resulting in higher water temperature[114,115]. Streams with cleared catchments and banks are commonly 1 to 2°C warmer than streams with intact vegetation, and removal of riparian forest may increase water temperature by an alarming 8°C[116].

7.7.2 Effects on potential impact and adaptive capacity

Clearing of catchment vegetation has already reduced the capacity of rivers to adapt to moderate effects of climate change. The loss of adaptive capacity is roughly proportional to the percentage of catchment area cleared. However, the regenerative capacity of catchment vegetation after disturbance is likely to be enhanced by warmer air temperatures, CO_2 enrichment and increased rainfall, so that rivers are expected to recover relatively quickly from heavy rainfall or cyclone damage in the future. Where topsoil has been lost, however, vegetation will recover more slowly and exposure of rivers to sedimentation will be prolonged.

7.7.3 Effects on vulnerability

The most critical feature determining the vulnerability of river habitats to increasing temperature, and rainfall, and the possibility of more intense cyclones, is the extent of intact catchment and riparian vegetation. The ability of rivers to absorb these changes is provided through shading of the water surface by the forest canopy, and stabilisation of soils through root development (**Figure 7.14**).

In subtropical regions with drier climates, sediment inputs from cleared catchments are expected to decrease during years with normal rainfall. More intense cyclones would increase erosion and sediment delivery on a decadal scale compared to rivers with intact catchment vegetation.

Estuaries will be more vulnerable to sea-level rise where infrastructure constrains landward migration of estuarine habitats. Clearing mangroves for urban development, and construction of sea walls and similar barriers, inhibits any inherent adaptive capacity of these trees (Chapter 6). In such circumstances, the area of estuarine habitats is likely to be reduced.

The interactions between the effects of climate change and catchment conditions described here occur largely in riverine habitats, but similar conclusions apply to lakes, floodplains and estuaries. All habitats are expected to be more vulnerable to climate-related increases in erosion, sedimentation and shallowing where catchment vegetation has been managed poorly.

7.8 Integrated vulnerability assessment

7.8.1 Vulnerability of habitats

When the expected effects of higher temperatures, altered flow rates (stemming from increased rainfall, more severe droughts and more intense cyclones), and sea-level rise are integrated, all major river habitats in equatorial areas, are projected to have a low vulnerability to climate change (**Table 7.4**) Indeed these habitats are expected to expand under the influence of increased rainfall. Even in montane rivers where coldwater habitats are likely to contract, the positive effects of increased flow are expected to dominate. The associated benefits are projected to increase progressively for both the B1 and A2 scenarios until 2100 (**Figure 7.15**).

Projections for the integrated effects of temperature, altered flow rates and sea-level rise are in the opposite direction for the subtropical rivers in New Caledonia. There, freshwater habitats are projected to have a low vulnerability resulting in negative impacts by 2035 under the B1 and A2 scenarios (**Table 7.4**). By 2100, the vulnerability of subtropical freshwater habitats is projected to increase to moderate to high for B1 and A2 scenarios.

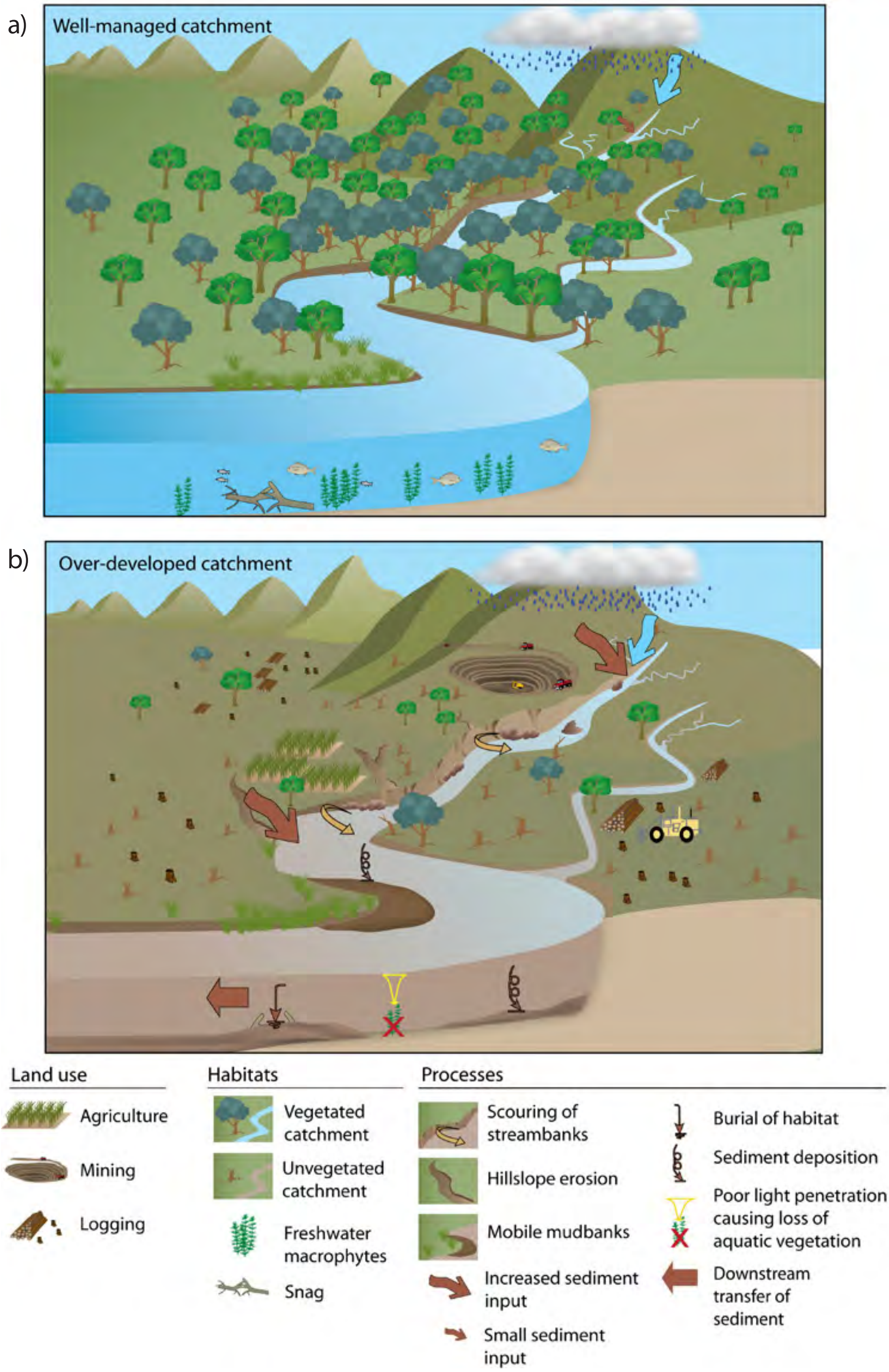


Figure 7.14 Catchments with good forest cover (a) are less vulnerable to increased temperature and rainfall, and more intense cyclones, than catchments with cleared vegetation. Erosion of hill slopes and river banks and increased burial of fish habitats by sediments (b) is much more common in rivers where vegetation has been removed from the catchment.

The vulnerability of equatorial estuaries to the combined effects of increased temperatures, greater freshwater flow and sea-level rise is projected to be low (**Table 7.4**). Unconstrained estuaries may become larger or remain the same size as they extend inland, whereas constrained estuaries may become smaller. Vulnerability to changes in habitat area, coupled with improved water quality, is projected to increase progressively until 2100 under both the B1 and A2 emissions scenarios (**Figure 7.15**).

In the subtropical estuaries of New Caledonia, vulnerability to negative impacts of increased temperature, reduced river discharge and sea-level rise is expected to be low by 2035 under the B1 and A2 scenarios (**Table 7.4**), increasing to moderate for B1 and high for A2, in 2100.

The possible positive and negative effects on all habitat types will be mediated by the way catchments are managed. Physical processes in river systems are strongly driven by the rate of runoff and river flow, which are in turn influenced by topography, geology and catchment vegetation. Where catchment vegetation has been removed excessively, the physical processes have greater effects, adaptive capacity is reduced, and the vulnerability of habitats to climate change increases (**Figure 7.16**). Catchment runoff models are required to provide more detailed assessments.

For some of the larger countries in Melanesia, climate change is projected to increase the total area of freshwater habitats substantially by 2100 (**Table 7.5**). The largest increases are likely to occur through increased inundation of floodplains. However, as indicated above, the quality of those habitats will be affected by catchment management.

7.8.2 Constraints to adaptation

Global projections for the effects of climate change on freshwater fish and their habitats[117,118] are consistent with the habitat vulnerability assessments provided here, based on projections of higher temperatures and increased river flow for most of the region (the projections for New Caledonia and the southeast Pacific are different).

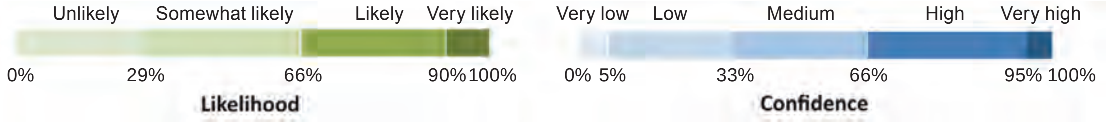
Increased river flow makes freshwater and estuarine habitats in the tropical Pacific especially likely to be affected by climate change. Where greater flows occur without excessive erosion and sedimentation, increases in availability and complexity of fish habitats are expected. Clearly, the chances of positive effects occurring are greatest in catchments with intact vegetation where sedimentation rates are relatively low[108,119]. In well-managed catchments, the adaptive capacity of natural vegetation may be sufficient to limit increased erosion of river banks and deliver benefits from increased flows. However, where natural vegetation has been removed, the inherent adaptive capacity to mitigate the damaging effects of higher rates of runoff and flow is reduced.

The primary constraint to adaptation of freshwater and estuarine habitats to climate change is, therefore, the need for development in catchments to support rapidly growing human populations, which are predicted to grow from 9.86 million in 2010 to ~ 15 million

Table 7.4 Vulnerability of freshwater and estuarine habitats to climate change under the B1 and A2 emissions scenarios for 2035 and 2100. Expected benefits (+) and negative impacts (-), in response to projected changes in surface air temperature (Temp), rainfall and sea level, are integrated to provide an overall vulnerability rating of low, moderate, or high. Ratings apply to undisturbed catchments with low levels of vegetation clearing. Disturbed catchments with high levels of clearing will experience higher vulnerabilities than indicated.

Habitat	B1/A2 2035				B1 2100				A2 2100			
	Temp	Rain-fall	Sea level	Overall	Temp	Rain-fall	Sea level	Overall	Temp	Rain-fall	Sea level	Overall
Equatorial												
Rivers												
Montane	-	+	n/a	Low 🟩🟦	-	+	n/a	Low 🟩🟦	-	+	n/a	Low 🟩🟦
Slopes	+	+	n/a	Low 🟩🟦	+	+	n/a	Low 🟩🟦	+	+	n/a	Low 🟩🟦
Lowland	+	+	-	Low 🟩🟦	+	+	-	Low 🟩🟦	+	+	-	Low 🟩🟦
Lakes												
High elevation	+	+	n/a	Low 🟩🟦	+	+	n/a	Low 🟩🟦	+	+	n/a	Low 🟩🟦
Low elevation	+	+	-	Low 🟩🟦	+	+	-	Low 🟩🟦	+	+	-	Low 🟩🟦
Floodplains	+	+	+/-	Low 🟩🟦	+	+	+/-	Low 🟩🟦	+/-	+	+/-	Low 🟩🟦
Estuaries	+	+	+/-	Low 🟩🟦	+	+	+/-	Low 🟩🟦	+/-	+	+/-	Moderate 🟩🟦
Subtropical												
Rivers												
Montane	-	-	n/a	Low 🟩🟦	-	-	n/a	Moderate 🟩🟦	-	-	n/a	High 🟩🟦
Slopes	+	-	n/a	Low 🟩🟦	+	-	n/a	Moderate 🟩🟦	-	-	n/a	High 🟩🟦
Lowland	+	-	-	Low 🟩🟦	+	-	-	Moderate 🟩🟦	-	-	-	High 🟩🟦
Lakes												
High elevation	+	-	n/a	Low 🟩🟦	-	-	n/a	Moderate 🟩🟦	-	-	n/a	High 🟩🟦
Low elevation	+	-	-	Low 🟩🟦	-	-	-	Moderate 🟩🟦	-	-	-	High 🟩🟦
Floodplains	+	-	-	Low 🟩🟦	-	-	-	Moderate 🟩🟦	-	-	-	High 🟩🟦
Estuaries	+	-	+/-	Low 🟩🟦	-	-	+/-	Moderate 🟩🟦	-	-	+/-	High 🟩🟦

n/a = Not applicable.



by 2035 (Chapter 1). Continued population growth and urbanisation until 2100, particularly in Melanesia, may also see increased demand for hydroelectricity generation to support economic development[15]. The extent of water resource development in the region may reduce the anticipated responses of freshwater and estuarine ecosystems to climate change in wetter regions, and intensify habitat impacts in drier subtropical islands, in line with global predictions[117].

7.9 Uncertainty, gaps in knowledge and future research

Considerable uncertainty about the projected effects of climate change on freshwater and estuarine fish habitats remains for two main reasons. Firstly, the existing climate models provide coarse-scale projections that do not reflect the effects of island topography on local climates (Chapters 1 and 2). Downscaling of these models is needed to improve forecasts of island climate, especially rainfall[ii]. Secondly, ecological understanding of rivers in the tropical Pacific is generally limited compared with knowledge of rivers elsewhere. In practice, knowledge of other rivers will need to be applied to guide adaptation processes until more is learned about our local rivers.

The global studies that have projected the effects of various climate scenarios on large river systems, including the Fly and Sepik-Ramu rivers in PNG[88], can help build knowledge of local habitats to improve confidence in the projected affects on river flows and habitat availability. These studies should also help identify the best approaches to assist freshwater and estuarine fish habitats adapt to climate change. The differences between regions mean, however, that the relevance of lessons learned from other rivers will need to be interpreted with caution.

This study has identified five main avenues of research needed to improve future assessments of the likely effects of climate change scenarios on freshwater and estuarine habitats, and the suitability of adaptation strategies. These avenues of research are listed below.

- Development and validation of ecosystem models for representative river types.
- Application of flood modelling to low-lying habitats, to improve vulnerability assessments and help evaluate options to maintain habitat availability in response to sea-level rise, and increased river flows and storm surge.
- Modelling of sediment transport, and tracing studies, to refine and target strategies to optimise vegetation in catchments.
- Quantitative inventory and mapping of river and estuary habitats, to set benchmarks for identifying changes in habitat area, quality and connectivity, and to manage their vulnerability.

[ii] This work is now being done for the tropical Pacific by the Australian Bureau of Meteorology and CSIRO, and partners, under the Pacific Climate Change Science Programme; see www.cawcr.gov.au/projects/PCCSP

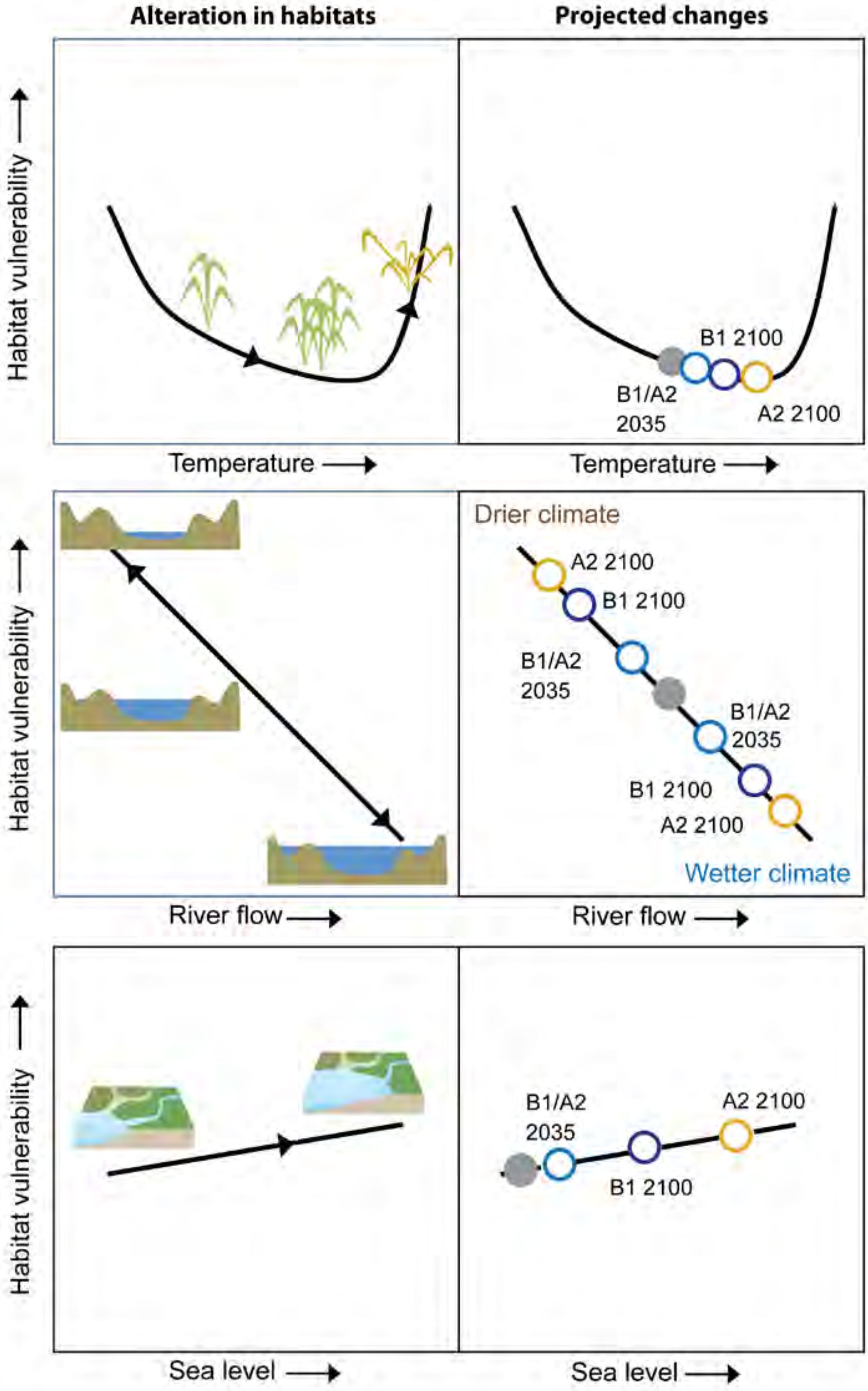


Figure 7.15 Projected vulnerability of freshwater and estuarine habitats to aspects of climate change. Left panels depict the general nature of alterations in habitats expected to occur as climate changes progressively. Arrows indicate direction of change. Right panels show relative changes projected under the B1 and A2 emissions scenarios in 2035 and 2100 compared to present-day conditions (solid circle). River flow is derived from the combined projections for rainfall, drought and possibly more intense cyclones.

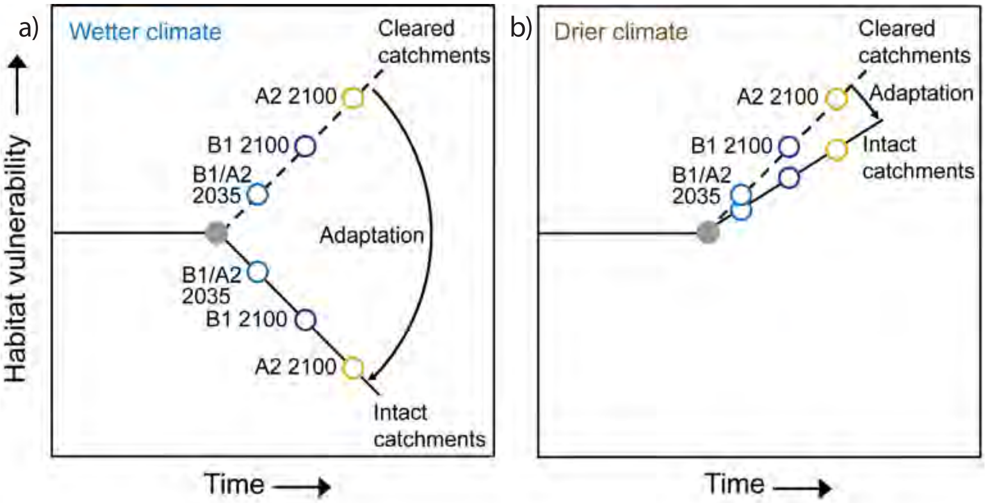


Figure 7.16 Vulnerability of freshwater and estuarine habitats in cleared catchments, and in catchments with intact vegetation, in regions projected to have (a) a wetter climate and (b) a drier climate. Regions with wetter climates have low vulnerability provided catchment vegetation is intact. Potential to reduce vulnerability through revegetation of catchments is much greater in wetter climates than in drier climates.

- Identification of the most important habitats used during the life cycles of migratory fish and invertebrate species (Chapter 10), to ensure that these habitats are included in adaptation strategies.

Due to the lack of scientific capacity in many PICTs, cooperation with regional and international institutions will be needed to complete this research, and identify and implement effective adaptation.

7.10 Management implications and recommendations

7.10.1 Habitats at greatest risk

The overwhelming outcome of this assessment is that the projected vulnerability of freshwater habitats to climate change is due largely to increases in river flow, and therefore the capacity of these habitats to adapt to climate change will depend largely on the condition of vegetation in catchments. River flows are projected to increase throughout much of the region, except in New Caledonia where rainfall may decline by up to 20% by 2100 under the A2 emissions scenario. These potential benefits will be tempered by how catchments are managed.

In their Call to Action on Climate Change in 2009[iii], the Pacific leaders identified the provision of solutions to deforestation and forest degradation as a key government response to climate change in the region. This vulnerability assessment for freshwater and estuarine habitats reinforces revegetation of catchments as a critical process.

[iii] Pacific Islands Forum Secretariat, Forum Communiques; www.forumsec.org.fj/pages.cfm/documents/forum-communiques

Revegetation will not only mitigate emissions and boost carbon sequestration, it will maximise the adaptive capacity of catchments to reduce the vulnerability of freshwater and estuarine habitats to the damaging effects of increased temperature, erosion, sedimentation and reduced water quality.

The single most important management recommendation, therefore, is to restore vegetation in the regions that contribute the most sediment to river networks. Because of the time needed for vegetation to become sufficiently established to reduce erosion and trap sediments, catchment rehabilitation must be an urgent priority.

Low-lying freshwater habitats are vulnerable to sea-level rise. In some cases it may be possible to prevent salinisation of critical habitats by constructing tidal barriers[120,121], but such barriers will also prevent landward migration of estuarine habitats, with the overall outcome still being a reduction in total habitat area.

Table 7.5 Estimated upper and lower ranges of projected changes in total area of freshwater habitat in selected Pacific Island countries and territories (PICTs) in 2035 and 2100. Estimates are based on projected changes in rainfall under the B1 and A2 emissions scenarios (Chapter 2), and anticipated river discharge. Confidence in projections is relatively low because local runoff conditions have not been included in the assessment. Grey cells indicate little or no change from existing habitats; blue cells indicate an anticipated increase in habitat area and availability; orange cells indicate that habitat area and availability are more likely to be reduced.

PICT	B1/A2 2035		B1 2100		A2 2100	
	Lower	Upper	Lower	Upper	Lower	Upper
Melanesia						
Fiji	-5%	5%	-5%	5%	5%	20%
New Caledonia	-5%	5–10%	-10%	5%	-20%	20%
PNG	-5%	5–10%	-5%	20%	-5%	20%
Solomon Islands	-5%	5–10%	-5%	20%	5%	10%
Vanuatu	-5%	5–10%	-5%	5%	5%	10%
Micronesia						
FSM	-5%	5%	-5%	5–10%	-5%	20%
Guam	-5%	5–10%	-5%	10%	-5%	20%
Palau	-5%	5%	-5%	5–10%	-5%	20%
Polynesia						
American Samoa	-5%	5%	-5%	5%	-5%	10%
Cook Islands	-5%	10%	-5%	10%	-5%	> 20%
French Polynesia	-5%	10%	-5%	10%	-10%	> 20%
Samoa	-5%	5%	-5%	5%	-5%	10%
Tonga	-5%	5%	-5%	10%	-5%	> 20%
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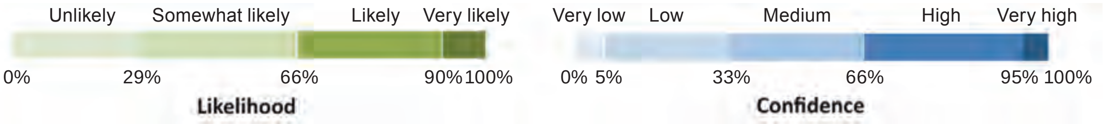

Except for locations where levees are required to prevent inundation of existing urban and rural settlements, or habitats of high conservation value, structural intervention is unlikely to be justified. Where seawater exclusion is considered, comprehensive flood modelling is recommended, to identify the risks to floodplain and lowland channel habitats, and to enable alternative approaches to be identified.

Increased sedimentation as a result of higher rainfall is expected to affect water quality and channel habitats, especially those used by substrate-spawning fish and invertebrates. Effective strategies to limit sediment and associated pollutants entering rivers, such as catchment and riparian revegetation, will reduce the effects of existing catchment disturbance, and build adaptive capacity to reduce vulnerability to intense cyclonic rainfall.

El Niño drought events will cause reduced flow and habitat reduction in rivers and floodplains. Few freshwater fish in the tropical Pacific are adapted to survive in intermittent water bodies. Protection of drought refuges will enable surviving fish to recolonise habitats when normal flow conditions return.

7.10.2 Interventions to limit damage to non-vegetated habitats

It is necessary to distinguish between change, an important component of the dynamic habitat mosaic, and damage that reduces habitat quality or area. Natural channel migration, erosion, sediment deposition and infilling of wetlands typically maintain a dynamic equilibrium among habitats, so that as one habitat patch moves or is lost, another is created[23]. Damage occurs when habitat patches are lost and not replaced.

Human interventions commonly implemented to limit damage, such as stabilisation of river banks, construction of levees, floodgate systems and tidal barrages[122] may actually increase habitat damage, for example, by limiting sediment supply or accelerating erosion. Accordingly, interventions to reduce the vulnerability of aquatic habitats need to maintain the dynamic equilibrium among habitats and not seek to prevent habitat change.

Habitat dynamics can often be preserved through low-cost approaches using riparian vegetation. Assessment of local hydrological conditions, sediment dynamics, mobility of existing habitat features, and habitat quality and quantity is required before modification of natural river systems is attempted. Where habitat vulnerability is low, little can be gained by trying to prevent natural geomorphological adjustment.

In contrast, where catchment degradation has increased habitat vulnerability, targeted intervention to prevent further habitat damage is warranted. This can be achieved through revegetation of catchments and riparian areas with native species, and preventing access of livestock to riverbanks. Adoption of farming, forestry and mining practices that minimise soil loss is a key element in minimising sediment delivery to rivers[108,112,119].

Photo: Chris Roelfsema

'Gardening' on hillsides can cause loss of soil

7.10.3 Interventions to maintain vegetated freshwater habitats

Saltwater intrusion poses a threat to aquatic vegetation in lowland river reaches and floodplains. Interventions to minimise the effects of a rise in sea level of up to 1.4 m by 2100 (Chapter 3) need to be considered within the predominantly micro-tidal context of the tropical Pacific. A rise in sea level of this extent will result in extensive landward relocation of the high tide mark in many places, resulting in replacement of freshwater forests with retreating mangroves[123].

Three principal scenarios exist for vegetated freshwater habitats threatened by sea-level rise. Where topography permits, natural succession will allow vegetation to retreat inland as sea level rises. Management interventions should facilitate natural adaptation in these situations. Where the coastal zone is constrained by elevated ground, aquatic vegetation will be unable to retreat and salt-intolerant species will be lost or reduced in area. Adaptation measures will not be possible under this scenario. Where urban and rural development prevent the retreat of vegetation, adaptation to maintain habitat will require replanning the use of the landscape to allow habitat succession in conjunction with ongoing land use. Similar scenarios can be applied to vegetated floodplain habitats facing increased inundation during high flows and storm surges.

Where the effects of climate change occur more rapidly than the capacity of vegetation to adapt naturally, assisted adaptation can be planned by replanting resilient species, including mangroves (Chapter 6).

7.10.4 Management limitations

The level of legislative protection afforded to aquatic habitats varies among PICTs but is generally limited[35]. Furthermore, establishment of benchmarks for environmental change is not yet common practice. Some of these constraints are addressed by community-based management approaches, such as the Locally-Managed Marine Area Network in Fiji[35].

The Secretariat of the Pacific Regional Environment Programme identified four challenges to improving wetland management (1) limited awareness of conservation management at government and community levels; (2) insufficient knowledge to support conservation management decisions; (3) limited ability of local communities to influence wise use of wetlands; and (4) inadequate frameworks for management of natural resources and biodiversity[124]. It is also acknowledged that governments and communities in many PICTs have limited resources to reduce vulnerability to climate change.

Recognising these limitations, priorities for management include (1) increasing community education and awareness of the importance of freshwater and estuarine ecosystems to fisheries; and (2) building natural resource inventory databases to provide benchmarks for monitoring changes in habitats and the processes that drive these ecosystems. An important role of policy-making for adaptation to climate change is to ensure that developments in catchments do not compromise the ability of fish habitats to adapt.

7.10.5 Opportunities for investment to reduce vulnerability

The most critical aspects of freshwater fish habitat vulnerability to climate change are accelerated sedimentation of river channels and wetlands in disturbed catchments, and accessibility of floodplain wetlands to fish during El Niño drought events. Sedimentation risks are expected to intensify by 2035 and 2100, especially under the A2 climate scenario. However, vulnerability to these changes can be managed by early intervention.

Vulnerability of river habitats can be reduced by improved management of vegetation, and by active revegetation of cleared areas. Investment in strategic revegetation and sediment interception to prevent sediment from entering streams is a high priority[108,112].

Revegetation of entire catchments is usually not feasible, either because of the cost involved or because the land is used for food production. Targeted investment to stabilise the largest sediment sources is needed, because most sediment comes from only a small proportion of the catchment[119,125]. Establishing riparian buffer zones may also prevent mobilised sediment from entering river channels. These interventions need to be supported by environmental legislation and community awareness and compliance.

Channels can be constructed to maintain wetland water levels and sustain fish production during El Niño drought events, but the high cost of this approach restricts its use to high-value selected habitats rather than widespread application to entire floodplains. Cost-effective approaches are likely to emerge from targeted studies of vulnerable wetlands combined with local knowledge.

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Chapter 8

Vulnerability of oceanic fisheries in the tropical Pacific to climate change

Patrick Lehodey, John Hampton, Rich W Brill, Simon Nicol, Inna Senina, Beatriz Calmettes, Hans O Pörtner, Laurent Bopp, Tatiana Ilyina, Johann D Bell and John Sibert

> *'The Pacific Islands region is the most important tuna fishing area in the world.'*
> (Gillett et al. 2001)[i]

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[i] Gillett et al. (2001) *Tuna: A Key Economic Resource in the Pacific*. Pacific Studies Series, Asian Development Bank, Manila, Philippines.

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8.1 Introduction

The oceanic fisheries of the tropical Pacific Ocean are of great importance to many of the economies and people of the region[1–3]. In the waters surrounding the Pacific Islands[ii], the four main species that underpin these oceanic fisheries, skipjack tuna *Katsuwonus pelamis*, yellowfin tuna *Thunnus albacares*, bigeye tuna *T. obesus* and South Pacific albacore tuna *T. alalunga*, yield combined harvests well in excess of 1 million tonnes each year, and support fishing operations ranging from industrial fleets to subsistence catches. Across the wider Western and Central Pacific Ocean (WCPO) these four species of tuna provide catches of about 2.5 million tonnes a year[4] (Chapter 1).

The key benefits of oceanic fisheries to Pacific Island countries and territories (PICTs) are economic development, government revenue, significant contributions to food security, and employment. In five PICTs, the licence fees associated with access agreements for distant water fishing nations to harvest tuna from their exclusive economic zones (EEZs) provide between 10% and 42% of all government revenue[2]. In another two PICTs, fishing and processing operations for tuna contribute ~ 20% to gross domestic product (Chapter 12). Across the region, tuna fishing and processing operations employ > 12,000 people[2]. Tuna is also a major part of the diet for both rural and urban communities in many PICTs[2,5].

Serious efforts are being made to 'domesticate' more of the tuna fishing and processing operations to deliver even greater benefits to the region (Chapters 1 and 12). At present, about 25% of the purse-seine vessels participating in the industrial fishery in the WCPO are flagged to, or otherwise considered to be part of, the domestic fleets of PICTs. There are plans to increase this percentage in the years ahead. Several PICTs have also attracted investments in onshore processing facilities recently. Papua New Guinea (PNG) in particular is positioning itself to process a larger proportion of the 400,000–500,000 tonnes of tuna caught each year within its waters, as well as catches from the EEZs of other PICTs. Such development would double the 8550 people, mostly women, currently employed in existing processing facilities in PNG (Chapter 12).

All such plans depend, however, on sustainable management of resources. Because tuna are highly migratory, such management involves the cooperation of all countries within the distribution zones of the main species, and the distant water fishing nations from outside this region that also harvest these fish. Consequently, management is focused on the entire WCPO, i.e. the Pacific Ocean west of 150°W. The institution mainly responsible for managing tuna resources and fisheries across the WCPO is the Western and Central Pacific Fisheries Commission (WCPFC), supported by the Forum Fisheries Agency (FFA), the Parties to the Nauru Agreement (PNA), and the members of the Te Vaka Moana Arrangement. National fishery services and agencies including the Western Pacific Regional Fishery Management Council (WPRFMC) for the US Pacific Islands (Chapter 1), are also actively involved in management.

[ii] Approximately 130°E to 130°W and 25°N to 25°S.

As a result of the concerted and combined action of these institutions, the status of most of the tuna resources of the tropical Pacific is considered to be healthy by global standards (Section 8.2.3). Nevertheless, the populations of tuna in the region are coming under increased pressure as stocks in other oceans become overfished, and global demand and prices for tuna increase, encouraging even more fishing effort and capacity. The need for effective management is greater than ever. However, assessing the size of the stocks of the four species of tuna, and the effects of fishing, to provide a sound scientific basis for management decisions is not straightforward. In particular, the effects of fishing on these highly migratory species is complicated by variation in the vast WCPO (Chapter 3), and the food webs supporting tuna (Chapter 4). Some of the most profound changes in the tropical Pacific Ocean affecting the catches of tuna are related to the El Niño-Southern Oscillation (ENSO), especially the effects of El Niño and La Niña episodes on water temperature and primary production[6,7] (Section 8.3).

Given the very strong influence of ENSO on the distribution and abundance of tuna in the equatorial Pacific, there is considerable concern that projected changes to the WCPO and oceanic food webs (Chapters 3 and 4) may also have significant effects on tuna resources. The purpose of this chapter, therefore, is to assess the likely effects of climate change in the tropical Pacific on the oceanic fisheries that are so important to the economies of PICTs, and the livelihoods and food security of their people.

To set the scene, we describe the composition of the oceanic fisheries in the region, how the main species are caught and used, the status of the stocks, and the estimated harvests they can sustain. Because ENSO events have such a profound effect on the distribution and abundance of tuna, we also describe how these fish respond to El Niño and La Niña episodes. We then assess the vulnerability of tuna to the direct and indirect effects of climate change under low (B1) and high (A2) Intergovernmental Panel on Climate Change emissions scenarios[8] for 2035 and 2100, using the vulnerability framework outlined in Chapter 1. We conclude with an assessment of the consequences of this vulnerability for future harvests from oceanic fisheries, remaining uncertainty, gaps in knowledge, the research required to improve future assessments, and management recommendations to help PICTs maintain the benefits of their important oceanic fisheries in the face of climate change.

8.2 Nature and status of oceanic fisheries

8.2.1 Main species and their uses

The oceanic fisheries of the tropical Pacific are comprised of large fish species that complete their life cycles in the open ocean and have only limited dependence on coastal habitats for food. As outlined above, the oceanic fisheries of the WCPO are dominated by skipjack, yellowfin and bigeye tuna and South Pacific albacore, which together represent > 90% of the total catch taken by industrial fleets. The remainder of the catch is comprised predominately of billfish (marlin and swordfish), oceanic sharks and Pacific bluefin tuna (*T. orientalis*).

The industrial tuna fisheries in the EEZs of PICTs are based on the use of large vessels owned by major fishing companies, with much of the catch marketed by multinational fish trading corporations[4]. The largest of the two main fisheries is commonly referred to as the 'surface fishery', where purse-seine and pole-and-line vessels (**Figure 8.1**) target schools of skipjack tuna, and the smaller size classes (< 80 cm) of yellowfin tuna, in the equatorial regions of the WCPO[9]. The catch from the surface fishery is used for canning. Although juvenile bigeye tuna are not the target of the surface fishery, the use of floating fish aggregating devices (FADs) now aids the capture of this species. The surface fishery also includes boats that use trolling gear to target albacore, and small-scale artisanal fisheries using various fishing gear such as handlines and ringnets.

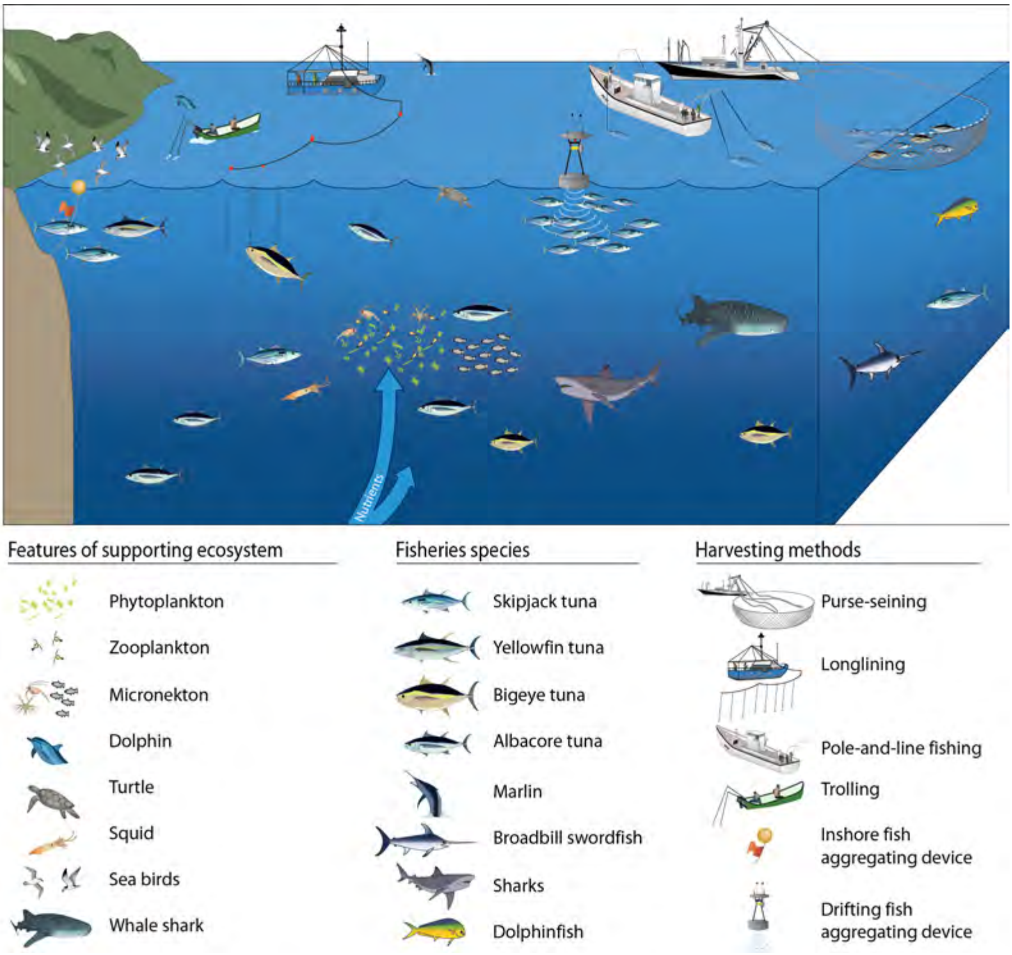

Figure 8.1 The main species caught by oceanic fisheries in the tropical Pacific Ocean and the vessels used by the industrial surface and longline fisheries.

The second of the two main fisheries is based on longline vessels (**Figure 8.1**) that target mature bigeye and yellowfin tuna in equatorial waters for the Japanese sashimi trade and other high-value markets. In southern subtropical waters, the longline fishery catches mainly albacore for canning, but also a proportion of high-value yellowfin and bigeye tuna. The fleets engaged in the surface and longline fisheries are a mix of domestic vessels from PICTs and those from distant water fishing nations[4].

8.2.2 Recent harvest levels

Over the past five years, the total catch of the four main species of tuna from the WCPO has increased, with the catch of ~ 2,468,000 tonnes in 2009 being the highest recorded[4] (**Figure 8.2a**). The catch by pole-and-line, longline and artisanal fisheries has remained relatively stable over time; the increase has been due mainly to the development of the purse-seine fishery. The purse-seine and pole-and-line vessels in the surface fishery landed 77% and 7% of the total catch from the WCPO, respectively. The longline fishery accounted for 9%, and the remainder (7%) was taken by troll gear and a variety of artisanal fishing methods, mostly in eastern Indonesia and the Philippines. The catches from the WCPO represented 58% of the estimated global tuna catch in 2009. Based on an average for 2005–2009, ~ 48% of the catch from the WCPO comes from the waters of PICTs. In this area, 96% of the catch is taken within the EEZs of the eight countries that are the Parties to the Nauru Agreement (PNA)[iii].

Skipjack dominates the total catch of tuna from the WCPO (**Figure 8.2a**) and almost all the catch of this species is taken by purse-seining. In 2009, the skipjack catch from the WCPO was ~ 1,790,000 tonnes, of which 52% was caught within the area under the juridiction of PICTs (**Figure 8.2b**). In this area, 99% came from the EEZs of PNA members. The distribution of skipjack tuna catches by purse-seine vessels in equatorial areas is not constant, but varies greatly according to ENSO events[6] (Section 8.3).

The annual catch of yellowfin tuna in the WCPO has generally been between 400,000 and 470,000 tonnes in recent years[4]. Most of this catch (64%) is taken by purse-seine vessels, with 60% of the total purse-seine catch from the WCPO in 2009 coming from the area of PICTs, harvested almost exclusively (99%) from the EEZs of PNA members. The longline catch of yellowfin tuna has ranged from 75,000–82,000 tonnes in recent years, which is well below the catches taken in the late 1970s to early 1980s (90,000–120,000 tonnes). The east-west distribution of yellowfin tuna caught by purse-seine is also strongly influenced by ENSO events, with larger catches taken east of 160°E during El Niño episodes[9].

Landings of bigeye tuna increased during the late 1990s in association with the expanding use of drifting FADs by purse-seine vessels[4]. In 2009, the catch of bigeye tuna from the WCPO – the lowest since 2003 – was ~ 119,000 tonnes, with 36% taken

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[iii] PNA members are: Federated States of Micronesia, Kiribati, Marshall Islands, Nauru, Palau, Papua New Guinea, Solomon Islands and Tuvalu (www.pnatuna.com). Their EEZs represent ~ 12% of the WCPO convention area.

by purse-seine, and 62% by longline. The lower catch in 2009 was due mainly to a sharp decline in longline catches[4]. Much of the bigeye tuna caught by longline is taken in the central Pacific, contiguous with the important area for catching bigeye tuna by longline in the eastern Pacific. Bigeye tuna are also caught by longline in subtropical areas (e.g. east of Japan and off the east coast of Australia).

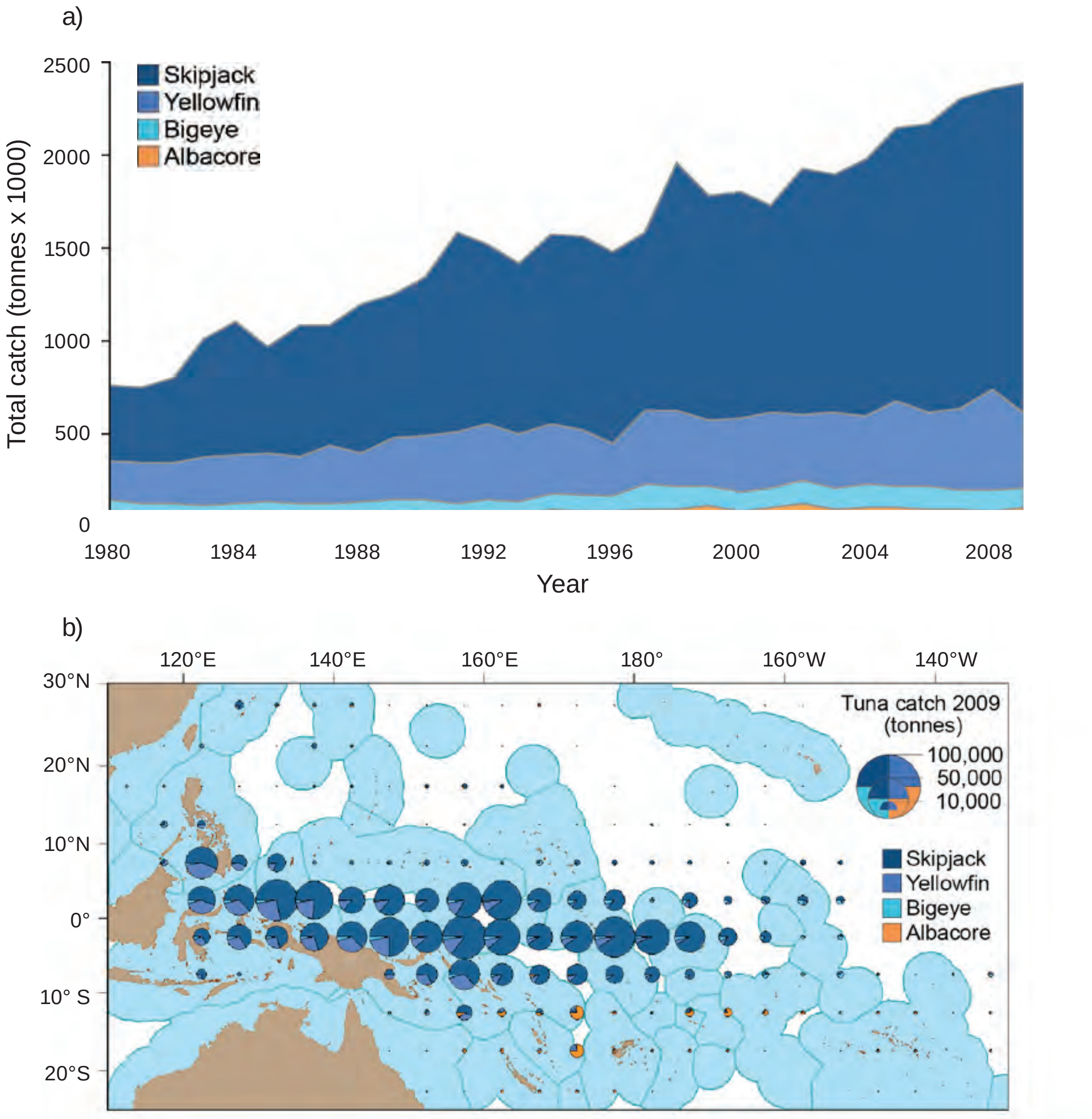


Figure 8.2 Catches of the four species of tuna that dominate oceanic fisheries in the Western and Central Pacific Ocean: (a) time-series of total catch by species; (b) distribution of catch by species in 2009.

Since 2001, annual catches of South Pacific albacore have exceeded 50,000 tonnes, partly as a result of the growth in domestic longline fisheries of PICTs. In 2009, the total catch (66,996 tonnes) was the highest on record, with good catches from the longline fishery[4]. The longline catch of albacore in subtropical waters of PICTs was 30,943 tonnes (46% of total catch), with the remaining catch coming mainly from the distant water longline fleet (34,026 tonnes) and the troll fishery (2027 tonnes) in New Zealand waters and the adjacent subtropical convergence zone[iv].

Among the other species, the greatest catches are of swordfish, which are targeted by longliners in the northern Pacific off Japan and Hawaii, off eastern Australia and in the subtropical waters of the south-central Pacific. Since 2000, the annual catches of swordfish from the WCPO have averaged about 20,000 tonnes. The catches of striped and black marlin have averaged ~ 4700 and ~ 2000 tonnes, respectively. Reliable catch statistics for other species in the oceanic fishery are not available.

8.2.3 Status of stocks

The status of tuna stocks in the WCPO, and in the area of the juridiction of PICTs, is assessed regularly using models that describe the population dynamics of each species[9,10] and discussed at the annual scientific meeting of the WCPFC[11]. The most sophisticated of these models integrate catch, fish size and tagging data[12]. The purpose of using these models to monitor the status of the four species of tuna is to estimate parameters that determine the probability that a stock has breached key management thresholds. The key indicators for each species of tuna are the ratios of current fishing mortality (F) and stock biomass to the values of these variables that result in the maximum sustainable yield (MSY)[13] (Box 8.1).

The most recent stock assessments for skipjack tuna show that this species is currently exploited at a moderate level relative to its biological potential (**Figure 8.3**). Current fishing mortality rates are estimated to be below the F_{MSY} reference point (Box 8.1) and overfishing is not occurring (i.e. $F_{CURRENT} < F_{MSY}$)[10]. Similar conclusions have been drawn for albacore[14] and yellowfin tuna[15] (**Figure 8.3**). However, caution is warranted for yellowfin tuna, because in the equatorial zone where 95% of the WCPO catch is taken, levels of fishing mortality and spawning biomass (SB) are close to their MSY levels.

The latest stock assessments for bigeye tuna are less optimistic (**Figure 8.3**). The current estimated fishing mortality rates are significantly greater than the F_{MSY} level ($F_{CURRENT} > F_{MSY}$) and overfishing is occurring for this species[16]. In the WCPO, recent catches of bigeye tuna have been sustained by higher-than-average levels of recruitment, which have also maintained spawning biomass above the SB_{MSY} level (Box 8.1). Future levels of recruitment are highly uncertain and a return to long-term average levels of recruitment is expected to result in a rapid decline in spawning biomass to below the SB_{MSY} level[16].

[iv] Note that catch estimates for all four species of tuna are revised regularly – see www.wcpfc.int/statistical-bulletins for improved estimates for 2009.

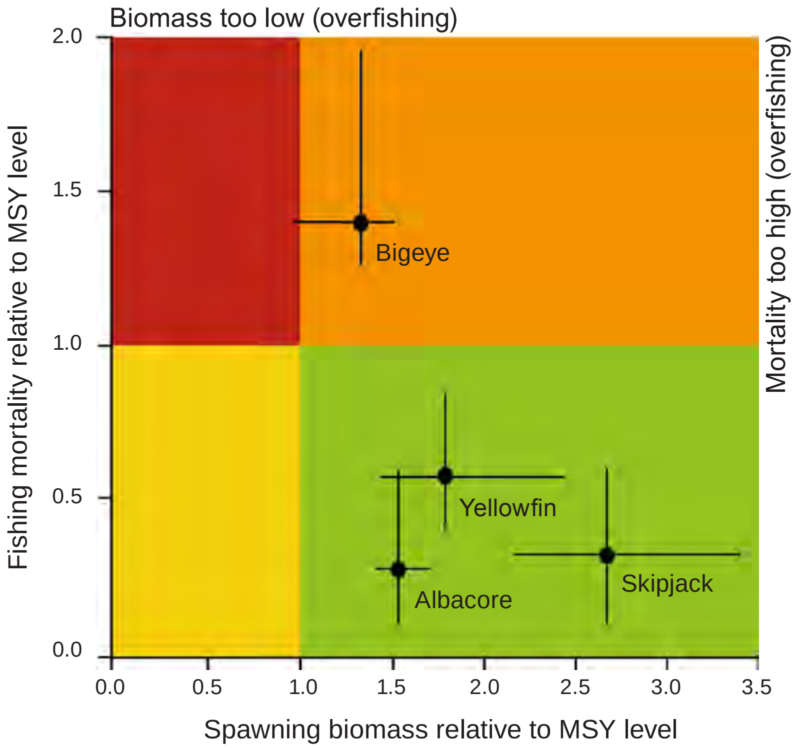


Figure 8.3 Status of the stocks of the four main species of tuna caught in the tropical Pacific in 2009. The horizontal axis represents the level of spawning biomass (population of mature fish) relative to the level resulting in the maximum sustainable yield (MSY) (Box 8.1). The vertical axis represents the level of fishing mortality (intensity of fishing) compared with the level resulting in MSY. The area of the graph above the horizontal line (red and orange) indicates that overfishing is occurring, while the area to the left of the vertical line (red and yellow) indicates that the stock has been overfished. Lines represent confidence limits for the assessments of each species in 2009. Changes in the stock status of each species over the history of the fishery are provided in recent stock assessment reports[10,14–16].

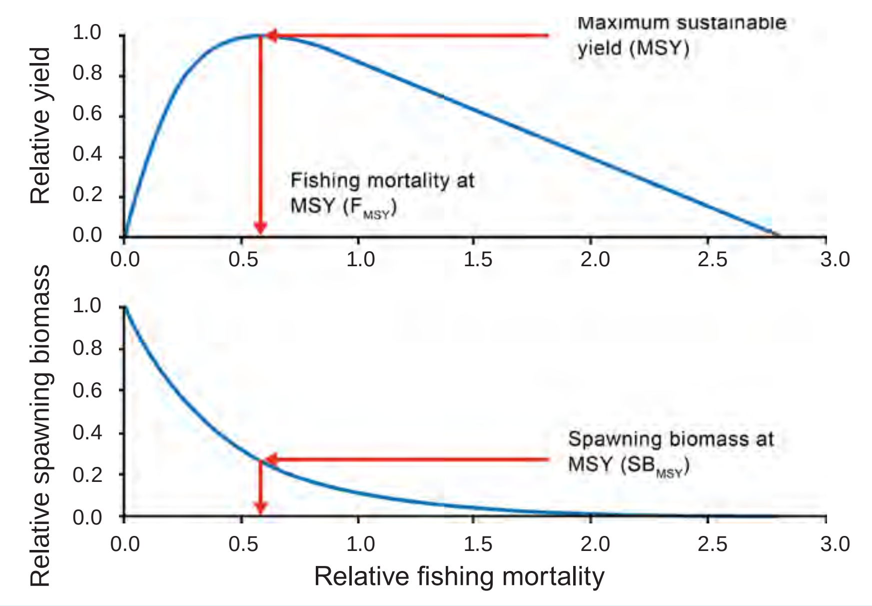
8.2.4 Estimated current sustainable production

The sustainable harvest for each species of tuna can be estimated from the stock assessment models. If skipjack tuna recruitment remains at recent above-average levels, which may not necessarily occur because of the natural, climate-related, variability of fish stocks[19], it is estimated that around 1.8–2.0 million tonnes can be harvested each year from the equatorial zone of the WCPO[11]. The annual maximum sustainable yield of yellowfin tuna from the WCPO is estimated to be ~ 440,000 tonnes, whereas the MSY for bigeye tuna is calculated to be ~ 120,000 tonnes, and ~ 98,000 tonnes for albacore[10,14–16].

Box 8.1. Maximum sustainable yield

The concept of maximum sustainable yield (MSY) is often applied to the management of large-scale fisheries. This simplistic model relates long-term average catch (or yield), fishing mortality, and spawning biomass, based on the assumption that key characteristics of the fish stock, such as natural mortality rates, growth rates and recruitment for a given level of spawning biomass, do not change over time[17,18]. Either the MSY itself, or the F_{MSY} and SB_{MSY} (see diagram below) are frequently used as 'reference points'. If these reference points are exceeded, appropriate management actions to reduce fishing are then implemented.

When fishing mortality exceeds F_{MSY}, overfishing is said to be occurring, and when the spawning biomass falls below the SB_{MSY}, the stock is said to be in an overfished state. Management systems using MSY-based reference points need to accommodate variability in the population processes that result from fluctuations in environmental conditions, such as recruitment, natural mortality and catchability. Such systems also need to make allowances for changes in the fishery, such as increasing efficiency of fishing effort or changes in the sizes of fish being targeted.



Maximum sustainable yield (MSY): The maximum average long-term catch that can be taken from a fishery assuming that the productivity characteristics of the stock do not change over time.

Fishing mortality at MSY (F_{MSY}): The level of fishing mortality, or intensity of exploitation, that results in the MSY being achieved.

Spawning biomass at MSY (SB_{MSY}): The level to which the spawning biomass of a fish stock will fall if the MSY is taken on a continuous basis.

Fishing mortality for these species is currently constrained by a combination of conservation and management measures (CMMs) implemented by WCPFC, PNA and individual PICTs. Total effort in the purse-seine fishery is currently constrained mainly by the total number of fishing days allowed in the EEZs of PNA members, and on the high seas, as provided under the WCPFC's CMM 2008-01. This CMM presently incorporates a 3-month closure each year for purse-seine fishing on FADs, other floating objects and whale sharks – a measure designed to reduce fishing mortality on juvenile bigeye and yellowfin tuna. In addition, the CMM specifies certain limits on the catch of bigeye tuna by longline. The aim of CMM 2008-01 is to reduce fishing mortality of bigeye and yellowfin tuna, but it also serves to limit to some extent future growth of skipjack tuna catches by restricting the expansion of purse-seine effort. Various exemptions mean, however, that the limits to effort specified by the CMM actually allow for a considerable expansion in purse-seine fishing from present levels[20]. Furthermore, the efficiency of purse-seine fishing effort is increasing because of the use of new technology, resulting in progressively higher catches of skipjack.

The PNA members are also placing limits on purse-seine fishing effort within their EEZs, through a 'vessel day scheme'. PNA also introduced a policy in 2010 of licencing only those purse-seine vessels that do not fish in the two tropical high-seas pockets, a policy subsequently adopted by WCPFC. PNA recently decided to extend this policy in 2011 to other areas of the high seas between 10°N and 20°S in the tropical WCPO. WCPFC and PNA have also implemented a catch retention policy whereby all skipjack, yellowfin and bigeye tuna captured by purse-seine must be retained on board and landed (or transshipped). Observers are now also generally required on all purse-seine vessels fishing in the region to monitor compliance with these measures. The prohibition on discarding tuna will also help meet the need to use fish for food security (Chapters 1 and 12) by making tuna available at low cost in those urban centres where transshipping occurs.

For albacore, catch and effort are limited mainly by the individual licencing policies of PICTs. However, WCPFC, through CMM 2005-02, has also restricted the number of vessels fishing for albacore in the region south of 20°S to no more than the average number in 2005, or 2000–2004.

8.3 Observed effects of climate variability on tuna

It is now evident that the dynamics of many marine fish stocks are linked to multiple scales of climate variability[19,21,22]. Changes in climate, manifested through variation in sea surface temperature (Chapters 2 and 3), for example, can affect the distribution and migration patterns of marine fish, and the survival of larvae and subsequent recruitment of young fish (Chapter 1). An important case in point is the large-scale, east-west displacements of skipjack tuna in the equatorial Pacific, which are correlated with ENSO events[6]. ENSO is an oscillation between a warm

(El Niño) and a cold (La Niña) state, which evolves under the influence of the dynamic interaction between atmosphere and ocean, with an irregular frequency of 2–7 years (Chapter 2). Because the interannual variation in abundance and distribution of skipjack tuna is fundamental to this chapter, we explain the known effects of ENSO events on this important species in more detail below.

The physical oceanography of the tropical Pacific Ocean is influenced strongly by the North Equatorial Current (NEC) and the South Equatorial Current (SEC) (Chapter 3), which are driven by the prevailing trade winds blowing from east to west. En route, the water temperature of the currents at the surface increases, resulting in the formation of a thick layer of warm water (> 29°C) on the western side of the Pacific basin, commonly known as the 'Warm Pool'. In the eastern and central Pacific, the NEC, SEC, and the rotation of the Earth create a divergence at the equator, which causes an upwelling of deeper cold water and a relatively shallow thermocline (Chapter 3). This region, known as the Pacific Equatorial Divergence (PEQD) province[23], is rich in nutrients that increase the primary production in the upper layer of the ocean (Chapter 4), creating a productive 'cold tongue' of surface water. In comparison, productivity in the adjacent provinces, the North Pacific Tropical Gyre, the South Pacific Subtropical Gyre and the Warm Pool, is markedly lower (Chapter 4).

The general east-west water transport is counter-balanced by the North Equatorial Counter Current (NECC) and the South Equatorial Counter Current (SECC), the Equatorial Undercurrent (EUC) and the retroflexion currents (Kuroshio and East Australian Currents), which constitute the western boundaries of the northern and southern subtropical gyres (Chapter 3). There is limited seasonal variation in these prevailing oceanographic conditions in the tropical Pacific, but strong interannual variability due to ENSO.

During La Niña episodes, stronger trade winds increase the intensity of the SEC and push the Warm Pool to the extreme west of the equatorial Pacific. Upwelling intensity in PEQD also increases, bringing the thermocline closer to the surface, while it deepens in the Warm Pool (Chapters 3 and 4). Conversely, during El Niño events, the trade winds weaken and allow the warm waters of the Warm Pool to spread far to the east in the central Pacific. The upwelling of nutrient-rich waters in PEQD decreases in intensity. The thermocline deepens in the central and eastern Pacific, and rises abnormally in the western Pacific.

The extension of the warmer water preferred by skipjack tuna to the east during El Niño episodes results in greater catches of this species in the region where the Warm Pool and PEQD converge: this convergence appears to promote the aggregation of the macrozooplankton and micronekton that are the prey of skipjack[6] (Chapter 4). The longitudinal displacement of the front of the Warm Pool to the east can be followed using the 29°C isotherm. However, the sea surface salinity gradient, and the formation of a subsurface density barrier layer at the convergence[24], are better markers of the eastern edge of the Warm Pool.

These displacements of skipjack tuna related to ENSO occur over the entire western-central equatorial Pacific (**Figure 8.4**), and lead to large fluctuations in catches from the EEZs of PICTs. During El Niño events, higher purse-seine catches are made in PICTs in the central Pacific, such as Kiribati (Line Islands). However, the eastward extension of the Warm Pool during El Niño episodes is also associated with a shallowing of the thermocline, and stronger wind stresses than usual in the western Pacific, leading to an increase of primary production in the western equatorial Pacific[7] (Chapters 3 and 4). As a result, catch rates in the Solomon Islands and PNG increase several months after the completion of an El Niño episode in response to the increased productivity, higher recruitment and contraction of skipjack habitat. This is especially the case if an El Niño event is followed by a La Niña episode, when the nutrient-rich waters of PEQD typically extend as far west as 160°E.

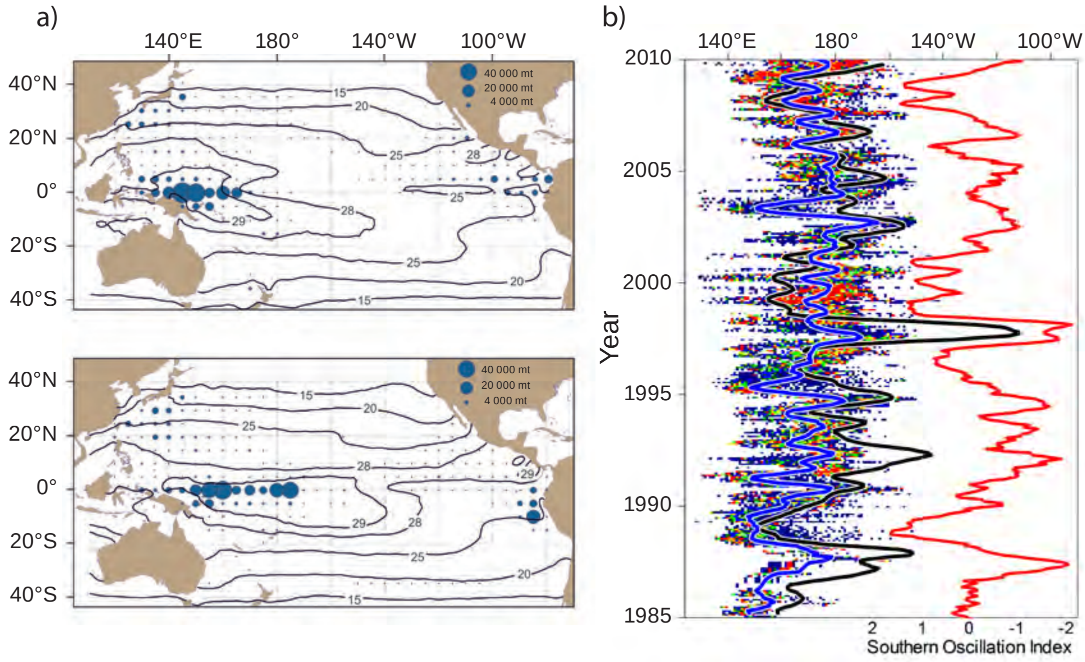


Figure 8.4 Impact of El Niño-Southern Oscilla
and movement in the Western and Central Pacific Ocean. (a) Skipjack tuna catch (tonnes) and mean sea surface temperature (°C) in the tropical Pacific Ocean during the first half of 1989 (La Niña period) (top panel), and in the first half of 1992 (El Niño period) (bottom panel), showing effects of ENSO on the location of the Warm Pool (28–29°C) and distribution of skipjack catch. (b) Average monthly skipjack catch per unit effort (CPUE) by purse-seine vessels in the western equatorial Pacific; blue line is the longitudinal gravity centre of CPUE, black line is the 29°C SST isotherm, and red line is the Southern Oscillation Index (SOI); each variable was smoothed with a 5-month moving average.

Changes in the depth of the thermocline in the Warm Pool associated with ENSO events not only influence the abundance of tuna, but also affect the catchability of some species. The shallowing of the thermocline during El Niño episodes reduces the depth at which yellowfin tuna have access to abundant food, which increases catch rates of this species by the surface fishery[25]. The opposite happens during La Niña events, when a deeper thermocline extends the vertical habitat of both yellowfin and bigeye tuna, reducing the concentration of these species in shallower water and their vulnerability to surface fishing gear. Catches of skipjack tuna are not greatly affected by the depth of the thermocline because this species lives in the surface layer, and is vulnerable to being caught by purse-seine and pole-and-line vessels at all times.

Longline catch rates of both bigeye and yellowfin tuna also seem to increase in regions of increased SST and greater vertical stratification[26]. For albacore, higher catch rates are recorded from the southern subtropical areas of the Pacific Ocean six months before, or at the onset of, El Niño episodes[27]. This pattern is linked to a shallowing of the mixed layer depth in equatorial waters (Chapter 3), and a reduction in extent of the 18 to 25°C isotherms in the water column, which are the preferred temperature range of adult albacore[28].

There is also evidence that recruitment of tuna is influenced strongly by variability in ENSO. Recent estimates from a population dynamics model showed a link between skipjack tuna recruitment and ENSO events[29], with the biomass of fish recruited to the stock being correlated with the Southern Oscillation Index (Chapter 1) eight months earlier (**Figure 8.5**). Thus, it seems that the dominance of either El Niño or La Niña episodes during multi-year periods, possibly in correlation with the Pacific Decadal Oscillation (Chapter 1), can result in either high or low productivity of tuna.

The frequency and intensity of the southern oscillation may also have a key role by regularly resetting the equatorial system, i.e. when a La Niña event starts after an El Niño event. This mechanism affects reproduction and growth of many organisms in the food web, allowing populations of tuna to produce strong cohorts regularly.

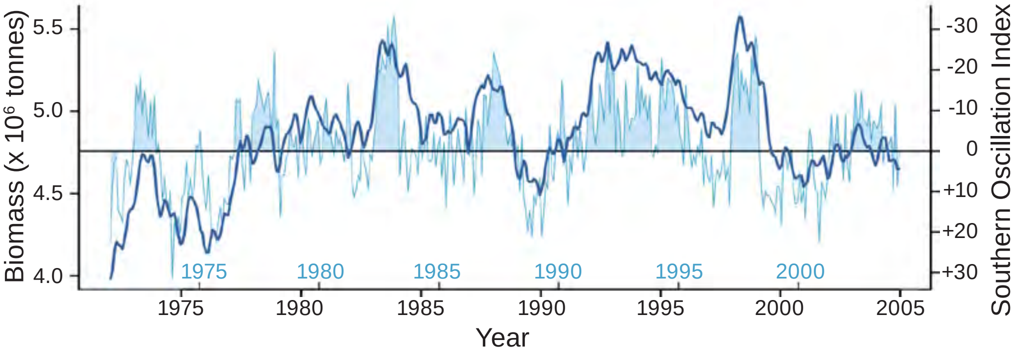


Figure 8.5 Estimated biomass (tonnes) of young skipjack tuna (heavy blue line) in the Western and Central Pacific Ocean, and the Southern Oscillation Index (SOI) lagged by 8 months (shaded blue line) (source: Senina et al. 2008)[29]. Note that SOI has been multiplied by 10 to highlight the variation.

8.4 Vulnerability of oceanic fisheries to the direct effects of climate change

Much evidence suggests that, like many other marine organisms, the four main species of tuna in the tropical Pacific Ocean are likely to respond to the projected changes in water temperature, dissolved oxygen (O_2), ocean currents and ocean acidification described in Chapter 3. Such responses allow species to optimise their use of energy for growth, movement, predation and reproduction[30,31]. Species with more efficient physiological O_2 supply systems have greater geographical and thermal distributions[32,33]. Moreover, the greater the thermal window of aerobic performance (or thermal niche), the more competitive a species is at the ecosystem level[34]. The direct effects of climate change have much scope to alter the physiological performance of the main species of tuna and, therefore, their survival, distribution and abundance. The effects on the thermal niche of a species are particularly important in the context of climate change because multiple stressors, such as hypoxia, predation pressure or competition, may narrow this thermal window and decrease physiological performance.

In this section, we assess the vulnerability of the four species of tuna to projected changes in ocean temperature, dissolved O_2, ocean currents and ocean acidification described in Chapter 3. Because the modelling we report in Section 8.6 is based on the IPSL coupled climate model (IPSL-CM4), we refer in some places to the changes projected by this model, rather than the multi-model means from the Coupled Model Intercomparison Project Phase 3 (CMIP3) multi-model dataset[35] given in Chapter 3. We assess the vulnerability of tuna species by integrating their exposure and sensitivity to the projected physical and chemical changes in the tropical Pacific Ocean to provide a potential impact, which may or may not be reduced through the adaptive capacities of tuna.

8.4.1 Ocean temperature

Exposure and sensitivity

The sea surface temperature of the tropical Pacific Ocean, based on the CMIP3 models, is projected to rise by 0.7–0.8°C under the B1 and A2 emissions scenarios by 2035 relative to 1980–1999; and by 1.4°C under B1 and 2.5°C under A2 in 2100 (Chapter 3). Changes in SST simulated by IPSL-CM4 for the tropical Pacific Ocean project greater warming. By 2035, SST is projected to rise by 1.5°C under the B1 and A2 scenarios relative to 2000–2009; and from no change to 5°C under B1 and 1.5–6°C under A2 by 2100. At a depth of 80 m, water temperature is expected to rise by 0.5°C in 2035 under B1 and A2, and by 1.0°C and 1.5°C under B1 and A2 in 2100, respectively (Chapter 3).

Sea surface temperatures in the central and east equatorial Pacific are expected to warm more than those in the west. However, the size of the Warm Pool (as defined by the 29°C isotherm) is projected to increase by 230–250% by 2035 under B1 and A2, and by 480% under B1 and 770% under A2 in 2100 (Chapter 3). This increase is likely to result in average background SST conditions which may be described as 'El Niño-like'. ENSO events themselves are projected to continue for the remainder of the 21st century at least, although there is little agreement among models about the frequency or amplitude of El Niño and La Niña episodes in the future[36] (Chapter 2).

Tuna have specialised anatomy (i.e. a vascular counter-current heat exchanger) allowing them to sustain muscle temperature significantly above ambient temperature, thus increasing both their physiological performance and the range of temperatures in which they can live[37–43]. A potential disadvantage of this heat-conserving mechanism is that it may cause overheating, especially at large body size[39,44,45]. Tuna can, however, reduce the efficacy of their vascular counter-current heat exchangers, i.e. they can thermoregulate physiologically, to dissipate a large part of metabolically produced heat at reduced excess muscle temperatures[46–50].

Excess heat can also be dissipated simply by moving into colder waters, either temporarily through regular descents[51,52], or with seasonal migration to higher latitudes. In this way, the feeding habitat of adult fish can be extended to the rich, deep forage layer[53], or to more productive temperate surface waters.

Nevertheless, each species of tuna has a limited range of SST within which it occurs (**Table 8.1**). In addition, it is not always appropriate to use SST for estimating the distributions of tuna, because these fish species make extensive vertical movements to feed. For example, albacore in tropical areas are commonly caught where SSTs are ~ 30°C, but they are captured on longline gear at depths of 150–250 m, where water temperatures are 18–25°C[54].

Table 8.1 Range of sea surface temperatures (SSTs) throughout the distributions (all occurrences) of tuna species in the Pacific Ocean, together with the SST range where substantial commercial catches are made (abundant occurrences) (source: Sund et al. 1981)[30].

Common name	Species	All occurrences (°C)	Abundant occurrences (°C)
Skipjack	*Katsuwonus pelamis*	17–30	20–29
Yellowfin	*Thunnus albacares*	18–31	20–30
Bigeye	*T. obesus*	11–29	13–27
Albacore	*T. alalunga*	13–25	15–21
Southern bluefin	*T. maccoyii*	10.5–21	17–20

The different life stages of each species of tuna can be expected to have different sensitivity to changes in SST because the difference between body temperature and ambient water temperature is linked to (1) the whole-body heat-transfer coefficient, (2) the rate of temperature change due to internal heat production, and (3) ambient water temperature and body temperature[48,55]. Indeed, tuna are most sensitive to water temperature during their larval and juvenile life stages and widen the range of their thermal habitat as they grow.

At the scale of a population, thermal habitat at steady state can be represented by a size-based Gaussian distribution, i.e. a distribution with an optimal temperature and a standard error for each size cohort, where the optimal temperature decreases with size and the standard error increases with weight[56]. This model relies, however, on the assumption that each species has evolved an intrinsic body (cellular) temperature at which its physiological performance is optimal. Our general knowledge on the reproductive biology and ecology of tuna also indicates that the optimal temperature window is narrowest and warmest for spawning.

Potential impact and adaptive capacity

The projected warming of the tropical Pacific Ocean may have two main effects on the basin-scale distributions of the four species of tuna. The first involves possible changes in spawning location and success. Because all tuna species return to the tropics to reproduce[30], they may face greater overheating problems, and more limitations to their activity, as SST increases as a result of global warming. Although tuna are known to make regular descents into colder water at high ambient temperatures to alleviate elevated heat transfer, electronic tagging data suggest that their physiological thermoregulatory mechanisms are of limited value in preventing overheating. Changes in temperature (and other environmental variables) may, therefore, lead to phenological adaptation, i.e. arriving earlier on spawning grounds, or use of more subtropical areas for spawning. Spatial shifts in the distributions of young fish are expected to occur if new spawning areas are used, with possible consequences for recruitment due to altered feeding success and rates of predation.

The second potential impact relates to changes in the distribution of the fish outside the spawning season. This is likely to be more subdued, however, due to the physiological thermoregulatory abilities of tuna, and their freedom to simply occupy greater depths, or more temperate waters, to seek out their preferred temperatures. Increased stratification of the water column, resulting from higher SST, may alter the vertical distribution of tuna and affect their access to deep-forage organisms (Chapters 3 and 4), especially skipjack and yellowfin tuna because they seem to be more sensitive to strong vertical temperature gradients. Projected decreases in dissolved O_2 concentration with depth (Chapter 3, Section 8.4.2) may also interact with increasing temperatures to create an even greater barrier to vertical migration for the most sensitive species. For bigeye tuna and swordfish, which are known to be able to penetrate some dissolved O_2 barriers and feed at depths > 500 m, spending more time at greater depth due to higher water temperatures at the surface may compromise the capture of prey due to the lower levels of light[57–59].

Vulnerability

The vulnerability of tuna to increased SST is considered to be low due to their mobility, which is expected to enable them to move to areas within their preferred temperature ranges, both for spawning and feeding. However, the expected changes in distribution of tuna are likely to have consequences for tuna fishing operations. The location of prime fishing grounds may change, and the catchability of tuna by surface and longline fisheries may alter in a way similar to that which now occurs during ENSO events (Section 8.3). In particular, good fishing grounds could be displaced further eastward along the equator, or shift to higher latitudes. Regardless of where fishing is concentrated, increased stratification could enhance the catch rates of the surface-dwelling skipjack and yellowfin tuna where SST remains within their preferred ranges.

8.4.2 Dissolved oxygen

Together with temperature, the availability of dissolved oxygen is the other fundamental variable that constrains the physiology of marine organisms. Both variables are intimately linked because the concentration of O_2 in water is related to temperature (Chapter 3). The performance of oceanic fish species is related to the availability of dissolved oxygen, and the capacity of their ventilatory and circulatory systems to supply sufficient O_2 to meet their physiological requirements over and above basic maintenance functions. However, this aerobic capacity is thermally limited, which means that it quickly decreases outside the optimal temperature window of the species[34,60].

Exposure and sensitivity

Information about the exposure of tuna to changes in O_2 concentrations in the tropical Pacific Ocean is limited and somewhat conflicting. Oxygen concentration is not calculated in the CMIP3 climate models and only a few biogeochemical models are available to make projections of future levels of O_2 in the region. In surface waters, these models indicate that a minor decrease in O_2 under the B1 and A2 emissions scenarios by 2100 is likely, due to the reduced solubility of gases in warmer water. In subsurface waters, the increased temperature and stratification of the ocean at higher latitudes are expected to lead to decreased transfer of O_2 from the atmosphere to the ocean due to less ventilation and advection, resulting in lower concentrations of O_2 in the tropical thermocline (Chapter 3). As a result, under the A2 scenario in 2100, average concentrations of O_2 are projected to decrease by 0.2 ml/l in the subtropical Pacific thermocline, where the observed concentrations are now ~ 3 ml/l (Chapter 3).

A recent simulation[61] projects a large decrease in O_2 in tropical subsurface waters under global warming, therefore reinforcing the existing low levels of O_2, and suboxic areas in the eastern Pacific. This change is due to an increase in the carbon-to-nitrogen (C/N) ratio of organic matter formed in the ocean at higher CO_2 levels, and the respiration of this excess organic carbon. In contrast, using a fixed C/N ratio, the IPSL-CM4 simulations projected increased concentrations of O_2 in the equatorial thermocline due to reduced biological production (and therefore remineralisation/oxidation) within the water masses flowing to the equator (**Figure 8.6**).

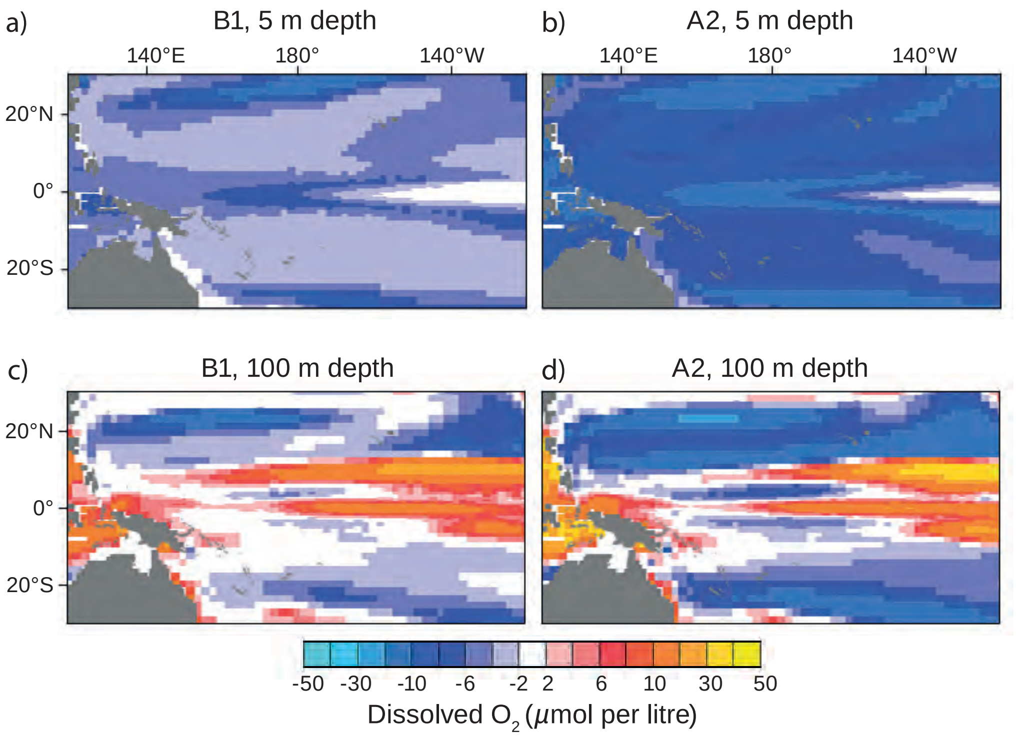


Figure 8.6 Projected differences in dissolved O_2 (µmol per litre) in the tropical Pacific Ocean in 2100, relative to 2000–2009, under (a) the B1 emissions scenario at a depth of 5 m; (b) A2 at 5 m; (c) B1 at 100 m; and (d) A2 at 100 m. All simulations are from the IPSL-CM4 coupled global climate model.

In general, there is closer agreement among the various models for the WCPO, where a decrease or limited change in O_2 levels in surface waters is expected. However, the models project opposite trends for the eastern Pacific in subsurface waters, where there is still little consensus on the most probable mechanisms likely to control O_2 concentrations.

Marine fish are highly sensitive to the availability of dissolved O_2 – many species cannot maintain their metabolic rate and swim when O_2 decreases to 1 mg/l or less[62]. The four species of tuna conform to this general pattern, although the lower, lethal, O_2 levels vary considerably among them (**Table 8.2**). The species also have different behavioural responses to reduced ambient O_2 levels[55,63–67].

In general, yellowfin tuna have slightly better tolerance of low ambient O_2 concentrations than skipjack tuna. For example, skipjack tuna increase their swimming speeds when O_2 levels fall below 4 mg/l, whereas yellowfin tuna show no such behaviour until O_2 concentration reaches 2.5 mg/l[63]. Although there is a general level of O_2 that limits the vertical movements of tuna, skipjack spend less than 10% of their time at depths where O_2 levels are below ~ 5.0 mg/l (3.8 ml/l, 75% saturation), whereas yellowfin tuna spend less than 10% of their time at depths where ambient O_2 levels are < 4.3 mg/l (3.3 ml/l, 65% saturation)[68,69].

Table 8.2 Lower lethal oxygen (O_2) levels for the four species of tuna in the tropical Pacific, based on the ratio of the minimum hydrostatic equilibrium speeds of a skipjack tuna of 50 cm to those of other tuna species and other body sizes. The lower lethal O_2 level for a 50 cm skipjack tuna has been estimated by converting mg O_2 per litre to ml O_2 per litre. Percentage saturation was calculated at a temperature of 25°C for skipjack, yellowfin and bigeye tuna, and 15°C for albacore.

Common name	Fork length (cm)	Lower lethal O_2 levels		
		mg/l	ml/l	% saturation
Skipjack	50	2.45	1.87	37
	75	2.83	2.16	43
Yellowfin	50	1.49	1.14	23
	75	2.32	1.77	35
Bigeye	50	0.52	0.40	8
	75	0.65	0.50	10
Albacore	50	1.67	1.23	21
	75	1.39	1.03	18

Although early research suggested that albacore was tolerant of low O_2 levels[70], more recent studies have shown that this species has a reduced uptake of O_2 in water containing < 5 mg/l (3.7 ml/l, 64% saturation at 15°C)[71]. This implies that their cardiorespiratory system is unable to extract sufficient O_2 from the water under these conditions to meet metabolic O_2 demand. Absence of albacore in the areas of the eastern equatorial Pacific with minimum O_2 levels supports the conclusion that these fish have low tolerance to hypoxic waters.

In contrast, bigeye tuna routinely reach depths where ambient O_2 content is below 1.5 ml/l[53,72]. The much greater tolerance of bigeye tuna to low levels of O_2 allows them to make extensive daily vertical excursions, mirroring the movements of their micronekton prey (squid, euphausiids and mesopelagic fish) when they descend to the deep layers at dawn[73,74] (Chapter 4). Bigeye tuna have evolved blood with an unusual characteristic that enables them to tolerate low ambient O_2, and simultaneously maintain the elevated metabolic rates characteristic of tuna species[75]. In particular, the blood of bigeye tuna has a large decrease in O_2 affinity as it is warmed during its passage through the vascular counter-current heat exchangers. As a result, offloading of O_2 in the swimming muscles is not compromised, even though the blood has a high O_2 affinity during its passage through the gills.

Potential impact and adaptive capacity

The uncertainty in the projected concentrations of dissolved O_2 makes it difficult to assess the impact of changes in O_2 on the availability of suitable habitat in the tropical Pacific Ocean for tuna. The more optimistic IPSL-CM4 simulations (**Figure 8.6**), even under the B1 scenario, would improve the conditions for tuna. The effects are likely to be greatest in the eastern equatorial Pacific, which is presently characterised by low O_2 concentrations in subsurface waters (Chapter 3), and even suboxic conditions (e.g. dissolved O_2 < 0.2 mg/l) at relatively shallow depths[76]. The expansion of areas in the eastern equatorial Pacific suitable for tuna may not be reflected accurately in catches because the vertical extension of the habitat is likely to make yellowfin tuna less vulnerable to the surface fishery.

The decreases in O_2 concentrations in surface and subsurface waters at mid to high latitudes that occur as the ocean warms may limit the extension of tuna habitat into more temperate areas. Restrictions on the use of subsurface areas by tuna are expected to be greater in the northern than in the southern Pacific, due to marked differences in projected O_2 levels in subsurface waters in the two mid-latitude regions (**Figure 8.6**). In the tropical region, the projected change in O_2 levels in surface waters is limited and is likely to have minor effects. In subsurface waters, the effects are expected to depend on the real change observed in the subsurface layer, for which there are currently opposite projections according to proposed mechanisms.

The distribution and catchability of tuna are well known to be influenced by levels of dissolved O_2[55,63,68–70,72,77–79]. Even so, changes in O_2 in subsurface waters should have limited impact on skipjack tuna inhabiting the surface layer. Such changes would have a greater impact on species that swim regularly between the surface and subsurface (yellowfin tuna and albacore), and to deeper layers (bigeye tuna). Yellowfin tuna and albacore would be affected most by lower O_2 levels in the thermocline – reductions in O_2 below 2.5 mg/l would constrain yellowfin to the surface layer, or cause them to move to areas with more favourable concentrations of O_2 in the upper water column. Where the distribution of yellowfin is restricted in this way, they are likely to be more vulnerable to capture by the surface fishery. The effects of limited distribution on productivity, and changes in catchability, would need to be taken into account when identifying appropriate levels of catch and effort for these species (Section 8.10). Bigeye tuna would be less affected due to their greater tolerance of lower levels of O_2 (**Table 8.2**), unless anoxic conditions or 'dead zones' (with O_2 concentration < 1 ml/l) develop.

Vulnerability

Skipjack tuna are considered to have a low vulnerability to the projected changes in O_2 because they live near the surface and the greatest potential changes in O_2 for all models are expected to occur in subsurface waters. Furthermore, the core habitat for skipjack tuna is in the WCPO, where the lowest changes in O_2 are expected to occur.

The vulnerability of yellowfin tuna cannot be identified with confidence until global climate models can provide more consistent simulations of O_2 levels in subsurface waters. In the event that the projections made by the IPSL-CM4 model are supported, climate change would have a positive effect on yellowfin tuna through substantial expansion of the depth to which this species can forage. Changes associated with O_2 concentrations in the WCPO would have no major effect on yellowfin tuna and albacore, although suitable habitats for these species may extend further south and east.

Regardless of the direction of changes in dissolved O_2, bigeye tuna appear to have a very low vulnerability to changes in O_2 levels because of their high natural tolerance of low concentrations.

Reproduction of the four species of tuna is not considered to be vulnerable to the projected changes in O_2 alone because their spawning grounds are all largely distributed in the WCPO[80], where future variation in O_2 concentrations is expected to be low. However, it remains to be determined whether interactions between the effects of increased temperatures (Section 8.4.1) and changes in O_2 concentrations could affect spawning success in tuna in a much greater way than expected for either variable on its own. This is likely to be a possibility because the thermal range suitable for spawning of tuna is expected to narrow due to the greater O_2 demand needed to produce large quantities of eggs or sperm at higher temperatures[34].

Bigeye and yellowfin tuna are also known to spawn in the eastern Pacific Ocean. Uncertainty about the likely changes in O_2 concentration in that part of the region does not permit any conclusions about the vulnerability of these species in those spawning grounds.

8.4.3 Ocean currents

Exposure and sensitivity

The currents of the upper water column across much of the tropical Pacific Ocean are expected to change in the future, particularly as a result of weakened wind regimes at low latitudes and strengthened winds in the subtropical Southern Hemisphere (Chapters 2 and 3). The transport volume of the SEC is expected to decrease by 3–8% under the B1 and A2 emissions scenarios by 2035, by ~ 10% under B1 in 2100 and ~ 20% under A2 in 2100 (Chapter 3). Even greater changes are projected for the SECC, which is expected to decrease in velocity by ~ 10–20% by 2035 under B1 and A2, and by ~ 30% under B1 and 60% under A2 by 2100 (Chapter 3).

The eddies and upwellings associated with the SEC and SECC are expected to decline, and the vertical stratification of the tropical Pacific Ocean is projected to increase due to the weakened tropical circulation associated with global warming[81] (Chapter 3). The simulations of mixed layer depth under the B1 and A2 scenarios for 2100 from the IPSL-CM4 model are illustrated in **Figure 8.7**. These simulations show shoaling of the maximum mixed layer depth by up to 20 m in the tropical Pacific Ocean. As explained in Chapter 3, upwelling in the Pacific equatorial region, and in coastal areas, is still simulated rather poorly by many global climate models.

All four species of tuna will be sensitive to changes in oceanic circulation because currents determine (1) the location of spawning grounds with the temperatures required for successful reproduction; (2) the dispersal of larvae and juveniles and their retention in areas favourable for growth and survival; and (3) the distribution of prey for adults. For example, skipjack tuna spawn mainly in the waters of the Warm Pool above 28°C, and the adults feed primarily around the convergence of the Warm Pool and PEQD, where their prey are concentrated (Chapters 3 and 4). The increasing use of satellites and archival tags to investigate the behaviour of tuna suggests that eddies also create favourable, smaller-scale, foraging areas for these species[82,83]. In addition, circulation around islands and seamounts produces complex oceanographic features, including eddies, that appear to play an important role in the spawning strategies of tuna species.

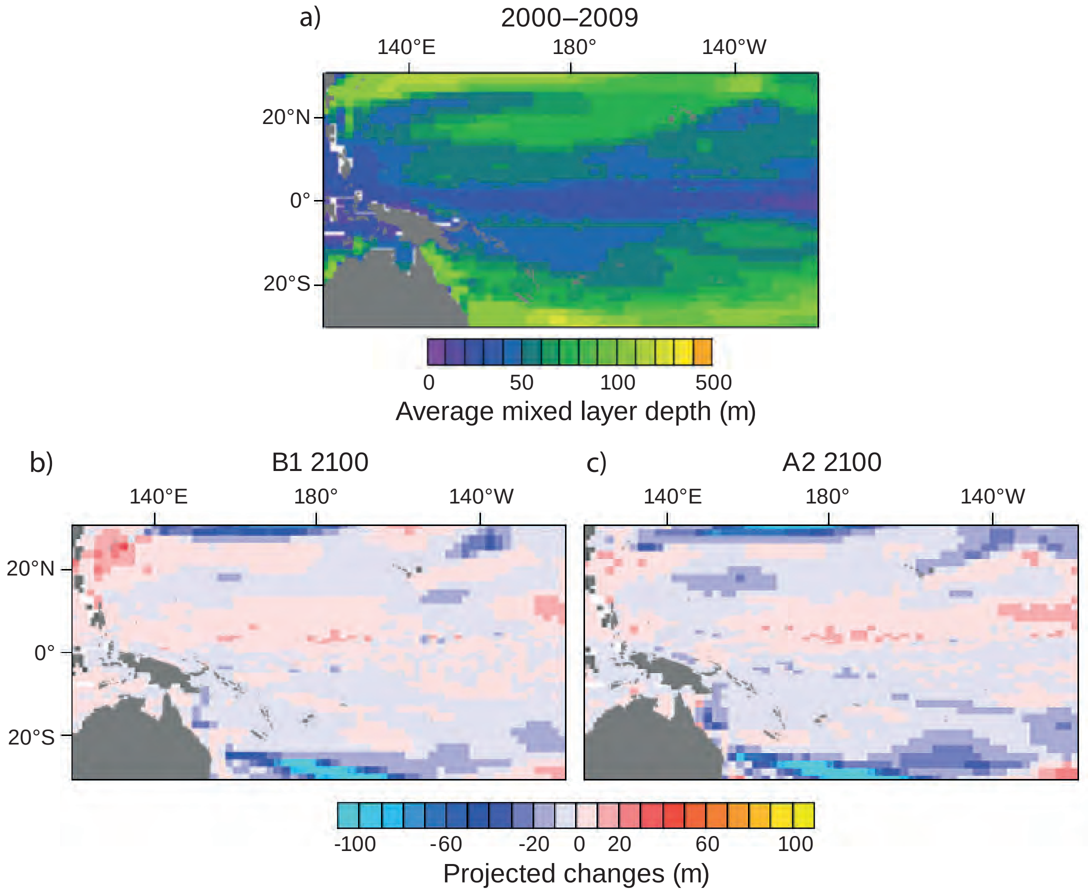


Figure 8.7 (a) Average mixed layer depth (MLD) for the tropical Pacific Ocean during 2000–2009; (b) projected changes in MLD in 2100 under the B1 emissions scenario relative to 2000–2009; and (c) projected changes in MLD in 2100 under the A2 scenario. All simulations are from the IPSL-CM4 coupled global climate model.

Tuna are not only sensitive to surface currents; they are also affected by the stratification of the water column resulting from the effects of ocean circulation, water temperature and density (Chapter 3). Each species swims and forages to a different depth, depending on optimal or threshold temperature and dissolved O_2 values (Sections 8.4.1 and 8.4.2). However, the area of suitable habitat for each species changes with seasons and interannual climate variability. For example, the deepening of the thermocline in the eastern Pacific and shoaling of the thermocline in the west during El Niño events (Chapters 2 and 3), changes the area of habitat available for yellowfin tuna because this species occupies the entire mixed layer.

Potential impact and adaptive capacity

The projected decreases in the strength of major currents in the tropical Pacific Ocean, changes in the formation of eddies around islands, and warmer and more stable surface waters extending further eastwards, are likely to affect the location of spawning grounds of tuna, and the survival rates of larvae. As a result, tuna are expected to move from the western to central, and central to eastern, equatorial and subequatorial regions to spawn (unless there is a severe decrease in O_2 concentration in the eastern Pacific). Spawning areas may also shift or expand to higher latitudes. Any selection of new spawning grounds would be expected to differ among tuna species because they have different optimal temperature ranges for spawning. For example, bigeye tuna and albacore spawn where SST is > 24–25°C, i.e. in water cooler than the temperatures preferred by skipjack tuna (> 28–29°C).

Although tuna larvae have the ability to swim, they can be considered to be transported passively by currents at the large to mesoscales over which the life histories of tuna occur. Thus, larvae presumably have little adaptive capacity for selecting or moving to more favourable habitat if new spawning areas place them in zones with a reduced supply of food. Any such impact would have implications for recruitment.

The effects of changes to circulation, in combination with warmer water temperatures, which alter the stratification of the water column, are expected to affect the catch of some tuna species. This is foreshadowed by variation in catch of yellowfin tuna due to ENSO events. As outlined above, higher catches of yellowfin tuna are made by the surface fishery in the Warm Pool during El Niño episodes due to the contraction of the vertical habitat for this species there at such times[84]. Changes in circulation may also indirectly affect the distribution of favourable foraging areas for tuna across the region, as discussed in Section 8.5.

Vulnerability

The four species of tuna in the tropical Pacific are considered to have low vulnerability to the direct effects of changes in ocean currents, and the associated effects due to eddies and stratification, because they presently have extensive spawning grounds, spawning seasons and high fecundity. In addition, they have considerable capacity to adapt their behaviour and life strategies to spawn effectively. Whether the effects of altered currents are likely to be amplified through interactions with increases in temperature and decreases in primary productivity remains to be determined.

Knowledge is also limited concerning the interaction of tuna with their environment at fine spatial scales. For example, we do not know the effects of turbulence on the predation success of tuna larvae, or the energy advantage offered to adult tuna by easily detectable eddies that concentrate their forage species. The increasing use of electronic tags to investigate movements of individual fish should help reveal whether the reduced currents and increased stratification projected under climate change scenarios have consequences for recruitment and growth of tuna.

8.4.4 Ocean acidification

Exposure and sensitivity

As explained in Chapter 3, anthropogenic emissions of carbon dioxide (CO_2) are leading to long-term perturbations of the ocean carbon cycle. Uptake of this CO_2 by the ocean results in a decrease of carbonate ions and an increase in hydrogen ions (H^+) in sea water. As a result, the pH of the ocean is decreasing – it has already been reduced by 0.1 units since 1750[85] – and is now decreasing at about 0.02 units per decade. Accordingly, the pH of the tropical Pacific Ocean is projected to decline by a further 0.2 to 0.3 units under the B1 and A2 scenarios by 2100 (**Figure 8.8**). This translates into an increase of 60–100% in the concentration of H^+ ions[86], and represents the fastest rate of change in ocean pH over the past 300 million years[87,88]. The decreases projected for equatorial regions, which are the prime habitat of tropical tuna are lower, however, than for other areas of the Pacific Ocean (Chapter 3).

The main species of tuna in the tropical Pacific are expected to be sensitive to the projected changes in pH in at least four ways. First, an increase in carbonic acid in the body fluids (acidosis) is likely to cause lower blood pH levels. Although most fish tolerate a wide range of dissolved CO_2 and pH[89,90], there may be associated physiological costs, especially for species or life stages with high metabolic demands[89]. Higher metabolic demands at elevated temperatures may compound these costs[34].

Second, there is the possibility that the growth and formation of the ear bones (otoliths) of tuna may be susceptible to lower pH because they are composed of aragonite. Contrary to expectation, the very limited research on this subject shows that a marine fish reared under elevated CO_2 levels had otoliths that were significantly larger than those in individuals of the same size/age grown under control conditions[91]. Although the effects of abnormally large otoliths are still unknown, they could be significant because otoliths are important for orientation and hearing, especially during the larval stage[92] (Chapter 9). The effects of ocean acidification on otolith formation may depend on species-specific capacity for acid-base regulation in the tissues surrounding the otoliths[93].

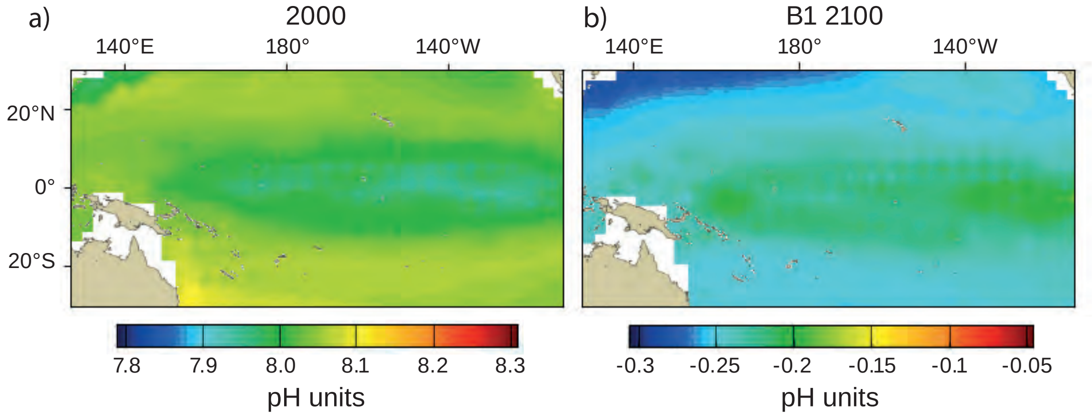


Figure 8.8 (a) The acidity (pH) of the tropical Pacific Ocean in 2000; and (b) the projected decrease in pH by 2100 for the B1 scenario (source: Iliyna et al. 2010)[95].

Third, the effects of decreased pH on reducing the availability of calcium carbonate (Chapter 3) can be expected to have indirect effects on the distribution and abundance of tuna by changing the availability of species of calcifying phytoplankton and zooplankton within the lower trophic levels of the food webs that support tuna (Section 8.5, Chapter 4).

The fourth possible effect of ocean acidification on tuna may occur due to the influence of pH on acoustics in the ocean. Sound attenuation under water is driven mainly by absorption due to the viscosity of sea water, and to chemical resonances of some of the constituents of sea water (e.g. magnesium sulphate and the boric acid/carbonate system). Contribution of these two mechanisms is frequency-dependent, and attenuation of sound in the range between ~ 100 and 10,000 Hz is driven mainly by chemical absorption due to relaxation of boron species. Because of the contribution of boric acid to the alkalinity of sea water, changes in pH also alter sound absorption underwater. Ambient salinity, temperature and hydrostatic pressure also affect sound attenuation. In particular, decreases in pH and increases in temperature of sea water lower the sound absorption coefficient[94]. The projected changes in pH and temperature are expected to reduce the sound absorption coefficient by 20–60% in the upper few hundred meters of the Pacific Ocean by 2100, making it more transparent to low-frequency noise[95] (**Figure 8.9**). This is expected to create a noisier environment, and possibly propagate sound further.

Relatively little work has been done on the sensitivity of tuna to the sound waves that propagate well underwater, compared with the echo-location systems used by marine mammals[96], although yellowfin tuna are sensitive to sounds between 200 and 800 Hz at least[97]. These frequencies are within the low range of sounds produced by the false killer whales that prey on tuna. False killer whales produce sounds for echo-location with peak frequencies around 40 kHz[98] and use lower frequencies for communication.

Thus, although tuna may detect killer whales at long distances during low frequency communication phases, they are unlikely to hear the high frequencies used by these top predators when being chased by them.

Furthermore, because tuna and dolphins in the eastern Pacific Ocean feed on similar fish species, natural selection could have occurred to enable tuna to detect the sounds made by dolphins as an aid to finding food[99,100]. Experimental measurements of low-frequency sounds produced by dolphins indicate that tuna can detect dolphin jaw pops and breaches at a range of 340–840 m and 660–1040 m, respectively[101]. In addition, it is possible that tuna use sound propagation to detect schools of prey directly, or to recognise special topographic features (e.g. seamounts, reefs and islands) where prey are likely to be found[53].

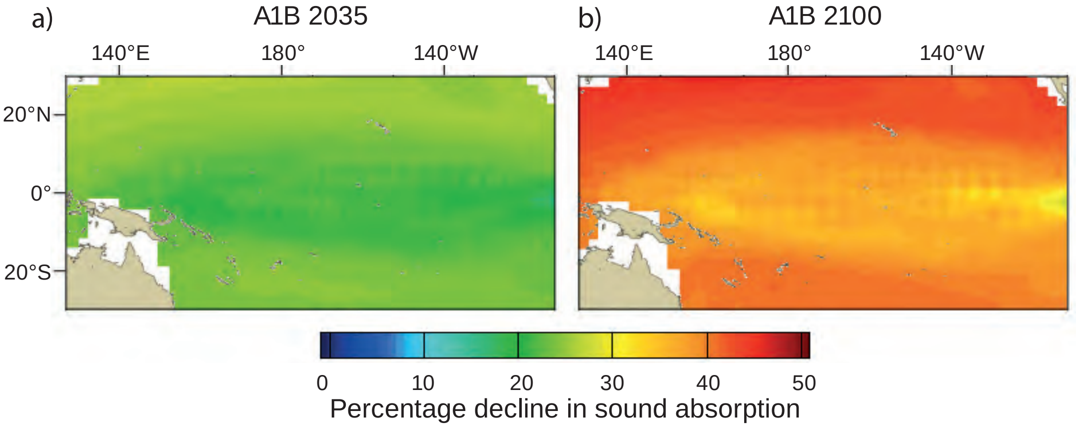


Figure 8.9 Percentage decline in sound absorption coefficient projected under the A1B emissions scenario (similar to A2) in (a) 2035; and (b) 2100 (source: Ilyina et al. 2010)[95].

Potential impact and adaptive capacity

Acidosis could lead to a narrowing of the optimal thermal performance window and, consequently, altered resistance, metabolic rate and behaviour of tuna[90]. In particular, the additional energy required to compensate for acidosis could lead to lower rates of growth and egg production.

Given the demonstrated effects of reduced pH on the behaviour of the larvae of coral reef fish[92,102] (Chapter 9), there is concern that similar effects may affect the survival of tuna larvae. Any consistent changes in survival of tuna larvae are likely to have significant effects on the recruitment of juveniles, so the effects of reduced pH on larval behaviour must be a priority for research.

The possible effects of ocean acidification on the productivity of calcifying organisms in the oceanic food webs that support tuna are likely to be minor. For example, in PEQD such organisms represent only 1–5% of the phytoplankton, 6.1% of the microzooplankton and mesozooplankton, and 2.2% of the micronekton (Chapter 4). Furthermore, because tuna are opportunistic predators feeding on a diverse range of micronekton[103], they are expected to be able to adapt by switching to micronekton that do not depend heavily on calcifying organisms lower in the food chain, provided that nutrients are adequate to maintain overall productivity (Chapter 4).

The projected changes in sound absorption and propagation could be significant and impair the ability of tuna to assess their physical and biological environment, including the detection of their prey and predator species. Assessing the vulnerability of tuna to these changes requires laboratory experiments and *in situ* observations.

Vulnerability

On the basis of the very limited existing knowledge, juvenile and adult tuna in the tropical Pacific could have a low vulnerability to projected changes in pH. Nevertheless, ocean acidification may exacerbate thermal stress and restrict tuna to narrower thermal ranges, and affect the processes of growth or maturation. Acidification may also indirectly affect productivity of tuna stocks, and changes in sound absorption due to reduced pH may have possible implications for detection of both predators and prey by tuna.

8.5 Vulnerability of oceanic fisheries to the indirect effects of climate change

Global warming is expected to have profound indirect effects on tuna by altering the productivity of the lower- and mid-trophic levels of the food webs that support them (Chapter 4). In this section, we assess the exposure, sensitivity, potential impact, adaptive capacity and vulnerability of tuna to changes in the lower- and mid-trophic levels of the ecosystems in the five ecological provinces of the tropical Pacific Ocean described in Chapter 4.

8.5.1 Lower levels of the food web

Exposure and sensitivity

As outlined in Chapter 3, the increase in the temperature of the tropical Pacific Ocean is expected to result in greater stratification of the upper water column. Stratification reduces the supply of nutrients from deeper layers, but can increase light availability due to lower turbulence in the mixed layer[81]. Such changes can have opposing effects on phytoplankton but, overall, there are likely to be changes in primary production and zooplankton in the lower trophic levels of the food web.

The overall effects of global warming on primary productivity are also projected to vary among the five provinces of the tropical Pacific Ocean. For example, simulations using IPSL-CM4 indicate that there is likely to be a 9% decrease in net primary productivity in the Warm Pool by 2100 under the B1 and A2 scenarios, and a 20–33% decrease in the adjacent Archipelagic Deep Basins province (Chapter 4) (**Figure 8.10**). The modelling also shows that the biomass of zooplankton in these two provinces is expected to decrease by 9–10%, and 17–26%, respectively, in 2100 (Chapter 4). Substantial increases in the surface area of the oligotrophic Warm Pool and South Pacific Tropical Gyre, and decreases in the nutrient-rich PEQD, are also projected[104,105] (Chapter 4). Taken together, significant changes in the production of phytoplankton and zooplankton are expected across the region.

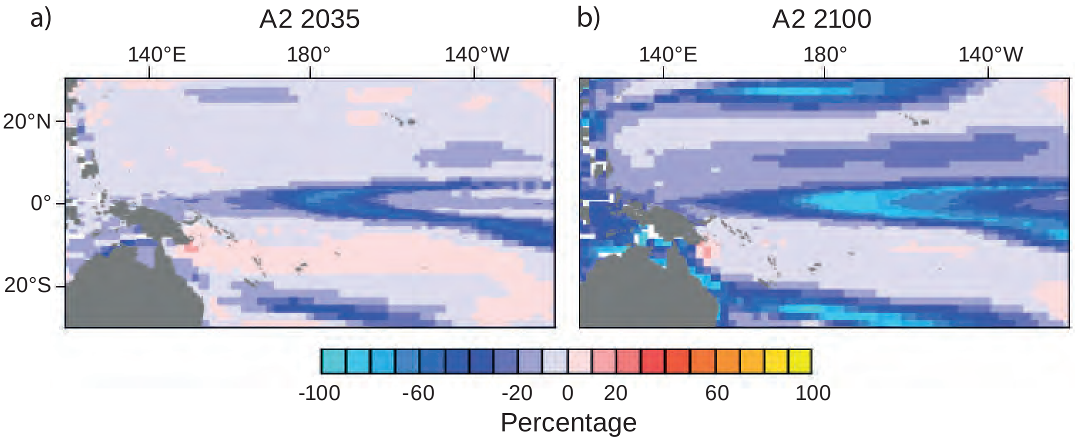


Figure 8.10 Percentage changes in primary production for different provinces of the tropical Pacific Ocean projected by the IPSL-CM4 model under the A2 emissions scenario in (a) 2035; and (b) 2100; relative to 2000–2009 (see Chapter 4 for location of provinces).

The degree to which primary production may be reduced further due to the effects of ocean acidification is yet to be determined because of the wide range of responses of these organisms to reduced pH[106–110]. As mentioned earlier, however, the proportion of phytoplankton and zooplankton composed of calcifying organisms is relatively low (Chapter 4).

Oceanic fisheries are acutely sensitive to alterations in primary productivity. Any changes in nutrient supply in the photic zone cascade down the food web through their effects on productivity of phytoplankton and, in turn, on microzooplankton, zooplankton and micronekton (Chapter 4). Ultimately, the abundance of larvae and juveniles, and the number of fish available to harvest, are affected.

In reality, the match/mismatch of periods of high primary productivity with spawning events often causes much of the variability in survival of larvae and subsequent recruitment success among pelagic fish[111,112]. For tuna, the presence or absence of the predators of their larvae also plays an important role. Indeed, exceptional peaks of larval recruitment occur when ample food for larvae, and absence of predators, coincide. Such favourable events have been observed during transition from El Niño to La Niña phases in the equatorial Pacific[7].

The response of skipjack tuna to the strong ENSO events of 1997–1998 demonstrated the sensitivity of the link between primary production and tuna recruitment. An exceptionally high catch of skipjack tuna was made in the second half of 1998 after the onset of a La Niña phase that immediately followed a powerful El Niño event. The catch was concentrated in a small area (0°–5°N, 160°–170°E) at the convergence of the Warm Pool and the cold tongue waters of PEQD (**Figure 8.11**). This episode followed an exceptional phytoplankton bloom that occurred in the same location 6 to 9 months earlier, which was clearly visible on satellite images (**Figure 8.11**). Length frequency data for skipjack tuna catches for the last two quarters of 1998 showed an unusually high proportion of small-sized fish (20–35 cm), with estimated ages of 5–9 months. Evidently, the bloom of phytoplankton and subsequent production of zooplankton led to an increase in survival rates of larval and juvenile skipjack tuna. These fish produced a strong cohort that recruited to the fishery 6–12 months later.

Potential impact and adaptive capacity

The projected changes to productivity of the lower levels of the food web could have two potential impacts on the distribution and abundance of tuna, over and above those known to be due to ENSO events. First, lower primary productivity in the western-central tropical Pacific Ocean may result in a decrease in survival of larvae there. This would increase the representation in the population of individuals that spawn in more favourable areas towards the eastern equatorial region, where the primary productivity is projected to remain relatively high (Chapter 4).

Second, the projected shift eastwards of the convergence between the Warm Pool and PEQD, from its present average longitudinal position of 180°–170°W in 2035 and 160°–150°W in 2100 (Chapters 3 and 4), would be expected to change the location of the best feeding grounds for skipjack tuna. This species is presently able to thrive within the resource-poor warm waters of the western Pacific partly because of the high productivity of this convergence zone. It seems inevitable, therefore, that if the location of the convergence changes, the fish will move as well.

Two other processes could also help maintain the productivity of tuna in the western Pacific. The subsurface density barrier layer of the Warm Pool is also expected to move eastward, reducing stratification in the western Pacific (Chapter 3). This should allow better mixing of surface waters with deeper nutrient-rich water, enhancing primary production. In addition, increases in rainfall of 5–15% in 2035 and 10–20% by 2100 (Chapter 2) are expected to increase the supply of nutrients to archipelagic waters in PNG through greater flows from the Sepik-Ramu River system (Chapter 7).

Vulnerability

Tuna larvae are expected to have moderate to high vulnerability to reduced primary productivity because of the possible higher risk of starvation resulting from the mismatch of spawning events and suitable food supply. However, this risk may be offset partially in some locations due to (1) the relocation of the subsurface density layer associated with the Warm Pool; and (2) the greater availability of nutrients through increased levels of runoff, particularly in the archipelagic waters of PNG.

The vulnerability of adult tuna to reduced rates of growth and reproduction due to the reduced area of the nutrient-rich PEQD is difficult to assess because the productivity within PEDQ is projected to change little, and much of the feeding occurs at the convergence of the Warm Pool and PEQD.

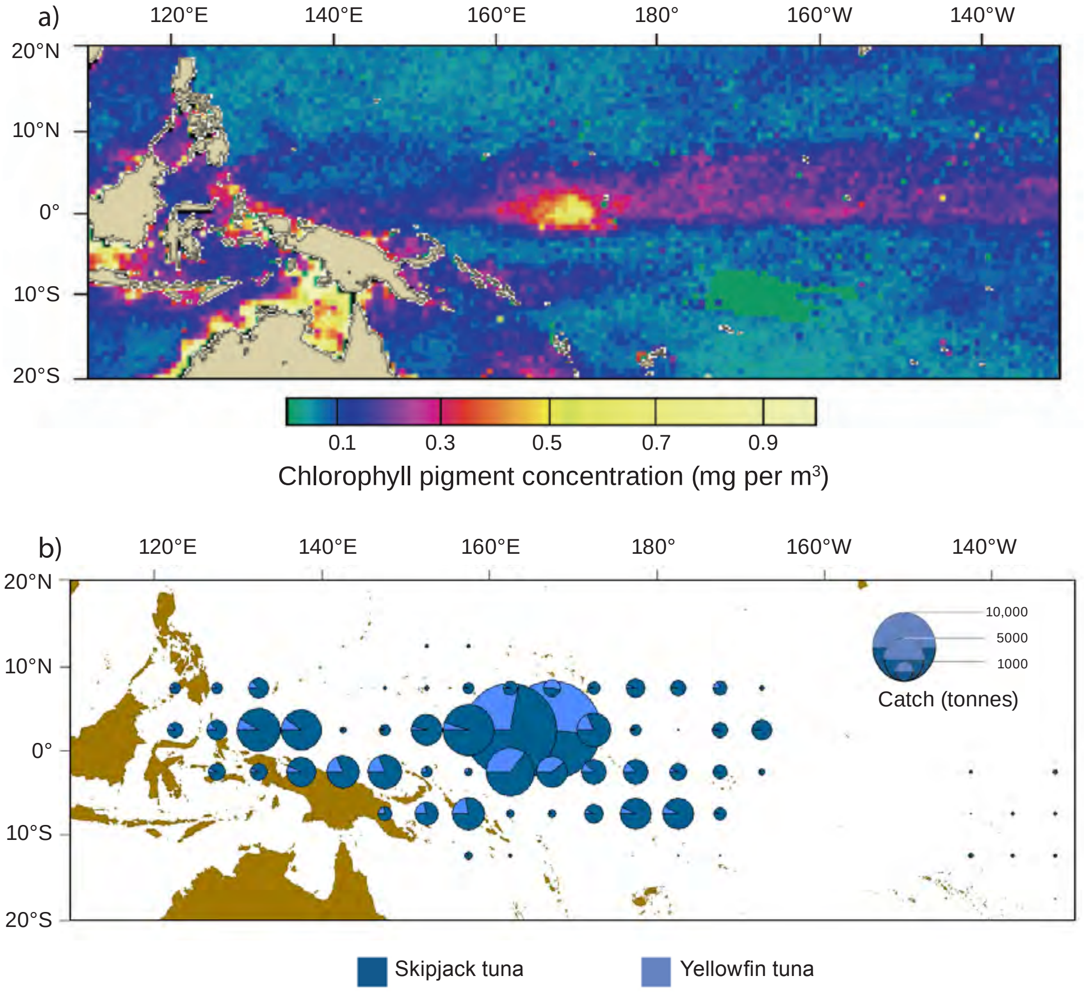


Figure 8.11 Recruitment of skipjack tuna associated with a phytoplankton bloom in the tropical Pacific Ocean: (a) satellite image showing a large phytoplankton bloom following the termination of the El Niño event of 1997–1998 and the onset of the La Niña event of 1998–1999 on the equator at 165°E (SeaWiFS composite image: April–May 1998); (b) distribution of the purse-seine catch of skipjack and yellowfin tuna in the last quarter of 1998 (source: Lehodey 2000)[84].

8.5.2 Mid levels of the food web

Exposure and sensitivity

Due to the direct link between production of lower- and mid-trophic levels in the food webs that support tuna (Chapter 4), the exposure of the lower-trophic levels described in Section 8.5.1 also applies to the micronekton that comprise the mid-trophic level. However, the temperature increase of the surface layer associated with increased stratification could result in a greater production to biomass (P:B) ratio, and more pronounced differences between micronekton at the surface and in the deeper layers in equatorial regions. In addition to a change in biomass, the pathways between these different components of the pelagic food web are likely to be reorganised because new environmental conditions may become detrimental for some species, or groups of species, and advantageous for others. The nature of these pathways may ultimately affect the relationships between top predators and the rest of the food web through bottom-up and top-down cascades.

Tuna are expected to be particularly sensitive to any decrease in the productivity of the micronekton they feed on due to their energy requirements for rapid growth, high rates of egg production, and constant and fast swimming activity. Early research indicated that yellowfin tuna have an average daily ration between 3.9% and 6.7% of their body weight, and the energetic cost of swimming accounts for 33–50% of their energy budget[113].

A more recent bioenergetics approach, to identify how energy acquired from food is allocated to maintenance metabolism, growth, reproduction and movement, has produced annual consumption to biomass (Q:B) ratios of 32.4, 19.8, and 13.4 for skipjack tuna, yellowfin tuna, and albacore, respectively[114]. Such ratios are substantially higher than estimates for other species of fish and reflect the high metabolic demands of tuna. This approach also estimated that skipjack and yellowfin tuna allocate 20–24% of consumed energy to somatic and gonad growth, compared with only 6% for albacore. As a general rule, adults of tuna species that develop a swim bladder after the juvenile phase (e.g. yellowfin and bigeye tuna) need less energy than skipjack tuna to maintain themselves in the water column.

Because much of the micronekton migrates to the surface at sunset to feed on zooplankton at night and returns to the deeper layers at sunrise (Chapter 4), tuna and other large pelagic predatory fish have morphological and physiological features allowing them to chase prey in the dark and cold deep layers of the water column. These attributes enable the predators to take advantage of the large biomass of mesopelagic and bathypelagic micronekton in the tropical Pacific Ocean. The specialised morphological and physiological features of predators include the 'rete mirabile' in tuna, which allows them to maintain body heat in cold water, olfaction in sharks, and enhanced vision in bigeye tuna and swordfish. The range of micronekton prey captured by tuna in the deep layers differs among species. It also varies within tuna species, once individuals reach a size where they can access the deeper, colder and often less-oxygenated layers.

Potential impact and adaptive capacity

A decrease in productivity of micronekton forage organisms in the tropical Pacific Ocean is likely to increase the risk of natural mortality and, therefore, lower overall production of tuna from the region. These risks vary among the five ecological provinces, but are substantial for the Warm Pool, where tuna currently occur in abundance and where the primary productivity is relatively low. In addition, access to micronekton in the deeper layers of the Warm Pool by adult tuna could become more difficult due to increased stratification and decreased O_2 concentrations. The eastward shift of the mean position of the eastern edge of the Warm Pool, and the associated density barrier layer would, however, allow more efficient mixing of nutrients in the surface layer and easier access to mesopelagic prey.

Where there are no physiological constraints to movement of tuna within and among provinces, the highly mobile nature of these fish is expected to assist them to adapt to changes in the availability of micronekton prey by moving to more favourable (new) foraging grounds where concentrations of prey are more accessible. However, the reorganisation of feeding and spawning grounds may lead to differences in the use of energy. For example, higher allocations may be needed for maintenance metabolism or locomotory activity, leading to a reduction in energy available for growth and reproduction, especially in the context of decreasing production of prey.

Vulnerability

The vulnerability of tuna to alterations in the mid-trophic level of ocean food webs is considered to be low if new, favourable feeding grounds replace the existing but declining grounds. Any changes in species composition of micronekton prey are not expected to reduce the food available for tuna in general because interactions among prey species are weak – a situation that helps to maintain the general resilience and stability of micronekton communities[115]. This resilience, together with the mobility and specialised morphology and physiology of the majority of tropical tuna species that permits them to feed in the deeper layers of the ocean, should assist tuna to continue to find suitable food within the Pacific Basin.

Such resilience is likely to break down locally, however, especially in the Warm Pool and the subtropical gyres. In particular, the location of prime feeding areas in these provinces is expected to change. Tuna may also become more vulnerable to a reduced supply of their micronekton prey in the face of a large increase in populations of gelatinous organisms or voracious competitors, such as large squid. These outcomes are unlikely in the deep tropical ocean but could occur as a result of warm anoxic waters developing in coastal regions and on the continental slopes.

8.6 Integrated vulnerability assessment

The relationships between tuna and their biophysical environment described in Sections 8.3 to 8.5, combined with the relationships between species, and among life stages within species, can lead to complex interactions, feedback loops and nonlinear effects (**Figure 8.12**). For example, simultaneous shifts in temperature, and in O_2 and CO_2 levels, may enhance vulnerability of larvae relative to a change in just one of these variables. Such synergies could lead to significant basin-scale redistribution of tuna stocks with important consequences for domestic tuna fisheries and the revenue from fishing agreements with distant water fishing nations (Chapter 12).

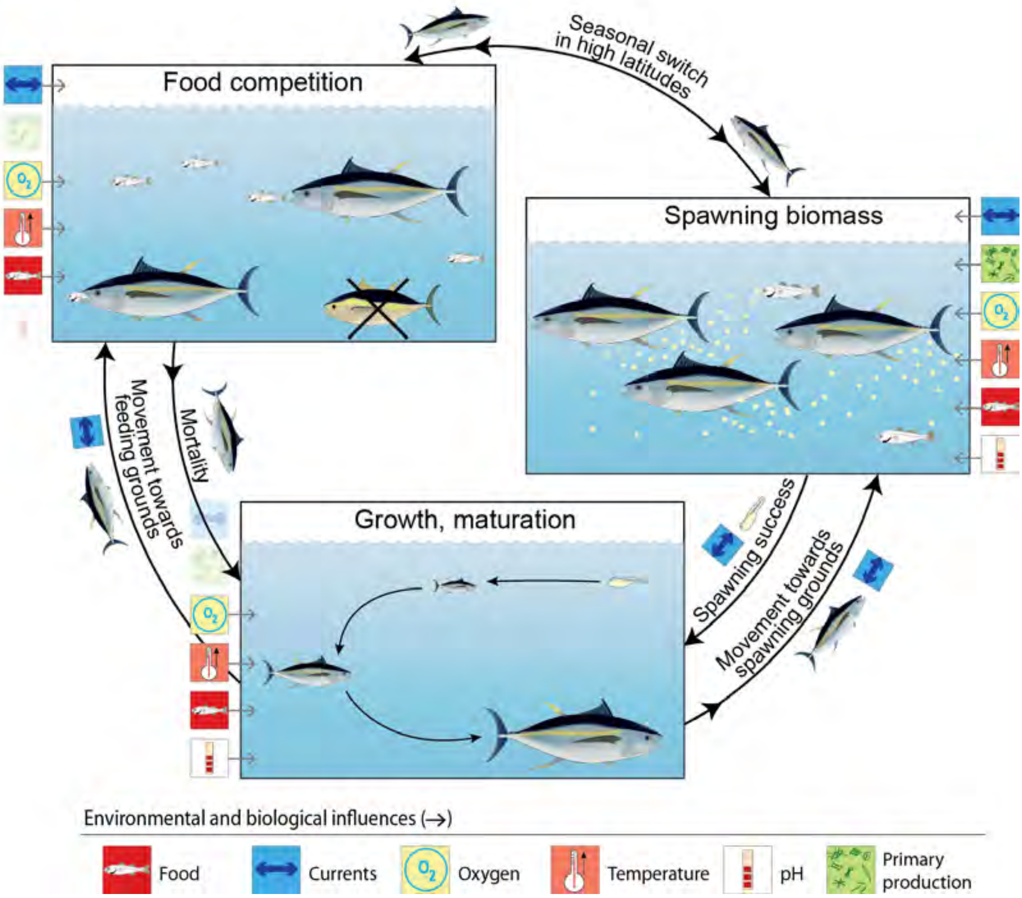


Figure 8.12 Interactions between the biological functions of tuna species, their spatial population dynamics, and key features of the tropical Pacific Ocean.

To integrate these processes and to assess the vulnerability of tuna to climate change, a modelling framework is needed that simultaneously evaluates interactions between environmental changes, the main biological functions of tuna, and the spatial dynamics of the fish populations. SEAPODYM (Spatial Ecosystem and Population Dynamics Model) (Box 8.2) is such a modelling tool. Here, we outline how SEAPODYM works, and how it has been applied to provide preliminary assessments of the vulnerability of skipjack and bigeye tuna in the tropical Pacific to climate change.

8.6.1 Ecosystem-tuna simulations

8.6.1.1 SEAPODYM model

SEAPODYM describes the spatial dynamics of tuna and tuna-like species at basin and global scales, under the influence of both fishing and environmental effects. This model is being improved continuously to provide a general framework that allows integration of the biological and ecological knowledge of tuna species, and other large oceanic predators, within a comprehensive description of the pelagic ecosystem[7,29,56,116–119]. Together, the mechanisms included in SEAPODYM describe most of the recognised interactions between tuna and the oceanic environment. However, the impact of ocean acidification is not yet included in the model.

8.6.1.2 Projected effects on skipjack and bigeye tuna in 2035 and 2100 under B1 and A2 emissions scenarios

Preliminary simulations of the potential impact of global warming on tuna populations using SEAPODYM are presently available only for skipjack and bigeye tuna. These simulations are based on atmospheric CO_2 concentrations reaching 850 ppm in 2100, and historical data between 1860 and 2000, which enables the effects on both species of tuna to be projected under the A2 scenario. Because the projected effects on the physical and chemical properties of the tropical Pacific Ocean are quite similar under the B1 and A2 scenarios in 2035 (Chapter 3), we also consider that our simulations for A2 in 2035 approximate those for B1 in 2035. After 2035, the two scenarios start to diverge, and the conditions projected at the end of this century for the B1 scenario are close to those of the A2 scenario in the middle of this century. Therefore, we use the results of the A2 simulation for 2050 as a surrogate for B1 in 2100[v].

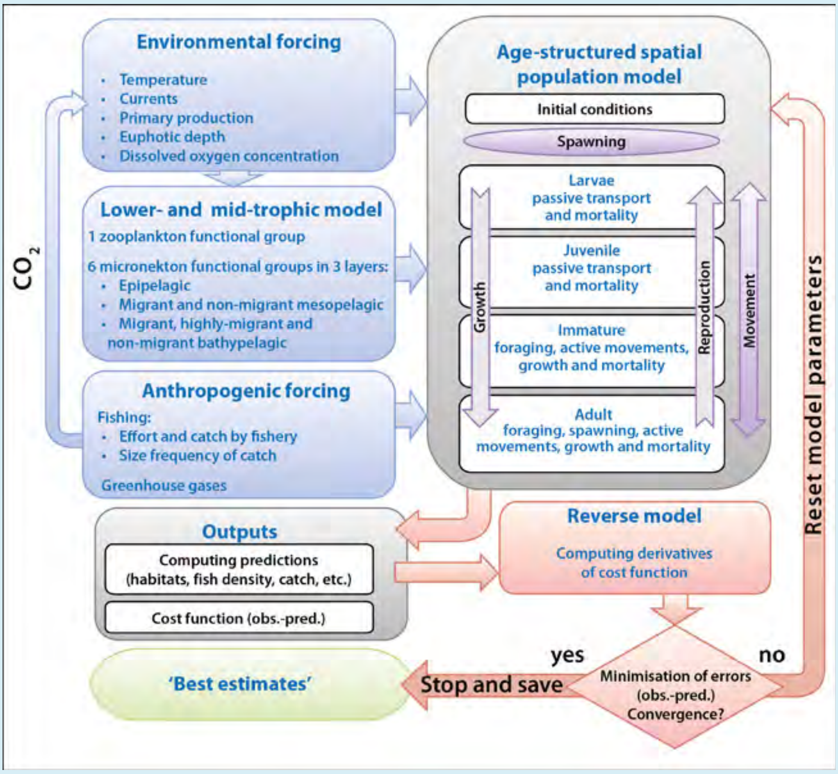
These simulations are driven by physical-biogeochemical fields obtained from a global Earth system simulation[120]. The simulations cover the Pacific basin at a geographic resolution of 2 × 2 degrees[121]. An initial optimisation of parameters for the model for bigeye and skipjack tuna was done using historical catch data for the last 50 years, and a hindcast from a coupled physical-biogeochemical model driven by the NCEP (National Centers for Environmental Prediction) atmospheric reanalysis. The

[v] It is important to note that while CO_2 emissions are similar for B1 in 2100 and A2 in 2050, the multi-model mean of sea surface temperature is 0.18 (+0.23)°C higher under B1 in 2100 than A2 in 2050 (Chapter 1).

Box 8.2 The SEAPODYM model

SEAPODYM is a tool for investigating the spatial dynamics of tuna populations under the influence of fishing and environmental effects. The key features of the model, which incorporates an optimisation approach, are illustrated below and include:

- analysis (forcing) of the effects of environmental variables, e.g. temperature, currents, primary production and dissolved oxygen concentration, on tuna populations;
- prediction of the temporal and spatial distributions of functional groups of prey[119], and age-structured predator (tuna) populations[56];
- prediction of the total catch and the size frequency of catch by fleet; and
- parameter optimisation based on fishing data assimilation techniques[29].



The mid-trophic level model describes vertical and horizontal dynamics of prey groups. Dynamics of tuna populations are estimated using habitat indices, movements, growth and mortality. The feeding habitat is based on accessibility of tuna to groups of prey. The spawning habitat combines temperature preference and coincidence of spawning with presence or absence of predators and food for larvae. Successful larval recruitment is linked to spawning biomass, and mortality during dispersal by currents. Older tuna can swim in addition to being advected by currents. A food requirement index is computed to adjust the local natural mortality of cohorts, based on food demand and accessibility to available forage.

parameterisation based on the IPSL projections from 1985 to 2000 was used for the whole climate simulation (1860–2100), to investigate the general trends of biomass and spatial distributions associated with environmental changes under the increasing forcing of atmospheric CO_2. Fishing effort and catch for the historical period (1960–2000) were used for the optimisation of parameters and the validation. For future projected effort, we used the average fishing effort for the 20 years from 1980 to 2000.

8.6.1.3 Skipjack tuna

To put the preliminary projections for the effects of climate change on skipjack tuna into context, it is important to remember that, based on observations of larval abundance[80], the present spawning grounds of this species are mainly in the Warm Pool and in the Philippines and Indonesia. However, spawning activity and larvae have been observed in the eastern Pacific Ocean[80,122]. Also, the average distribution of spawning fish is influenced by ENSO. During El Niño episodes, skipjack favour spawning grounds in the central and eastern equatorial Pacific. Conversely, the core habitat of the entire population in the WCPO is the Warm Pool but the fish extend into the mid latitudes (40°N–40°S) in summer when the water warms. There are also substantial longitudinal displacements of skipjack associated with ENSO events (Section 8.3).

Under the B1 and A2 scenarios in 2035, the average density of skipjack larvae is projected to increase slightly in the present-day spawning grounds, and more spawning is expected to occur in the central Pacific (**Figure 8.13**). For the entire population of skipjack tuna, the projections are that density will decrease in the waters of PNG and Solomon Islands, and increase in the eastern equatorial Pacific. A clear long-term trend in total biomass for the entire WCPO under B1 and A2 in 2035 is difficult to differentiate from the natural long-term variability (**Figure 8.14**).

In 2100 under the B1 scenario, more significant changes in the location of spawning areas for skipjack tuna are projected, with the favoured spawning grounds extending to higher latitudes, and also to the central Pacific (**Figure 8.13**). For the skipjack tuna population as a whole, the western equatorial Pacific is expected to become much less suitable on average, and the highest biomass of fish is projected to occur in the central Pacific instead (**Figure 8.13**). The change in total biomass of skipjack tuna over time becomes conspicuous under B1 in 2100 (and under A2 in 2050) in the WCPO, especially in light of the opposite trend occurring in the eastern Pacific (**Figure 8.14**).

In 2100 under the A2 scenario, the greatest density of skipjack is projected to move further to the east and the biomass of adults to decrease significantly in the WCPO (**Figure 8.13**). This is due to projected higher natural mortality associated with less suitable habitat conditions (less food and higher temperatures), and to displacement of fish to the more favourable central and eastern regions. Under A2, the present-day dominance of the WCPO over the eastern Pacific Ocean as habitat for skipjack is reversed (**Figure 8.14**).

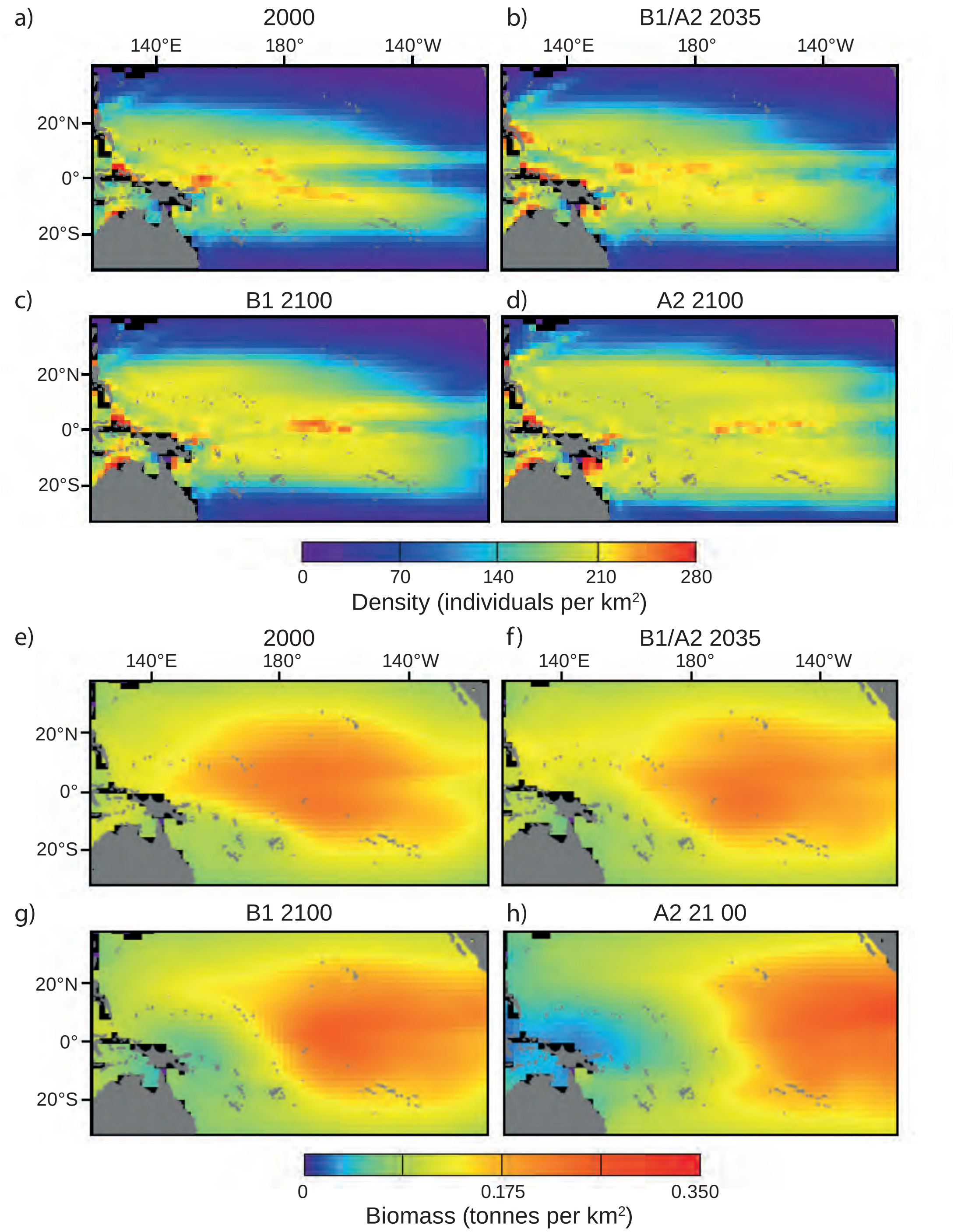


Figure 8.13 Projected distributions (density) for skipjack tuna larvae recruits from the SEAPODYM model (a) in 2000; (b) under the B1/A2 emissions scenario in 2035; (c) under B1 in 2100; and (d) under A2 in 2100. Also shown are estimates of total biomass (tonnes per km^2) of skipjack tuna populations based on average (1980–2000) fishing effort in (e) 2000; (f) under B1/A2 in 2035; (g) under B1 in 2100; and (h) under A2 in 2100.

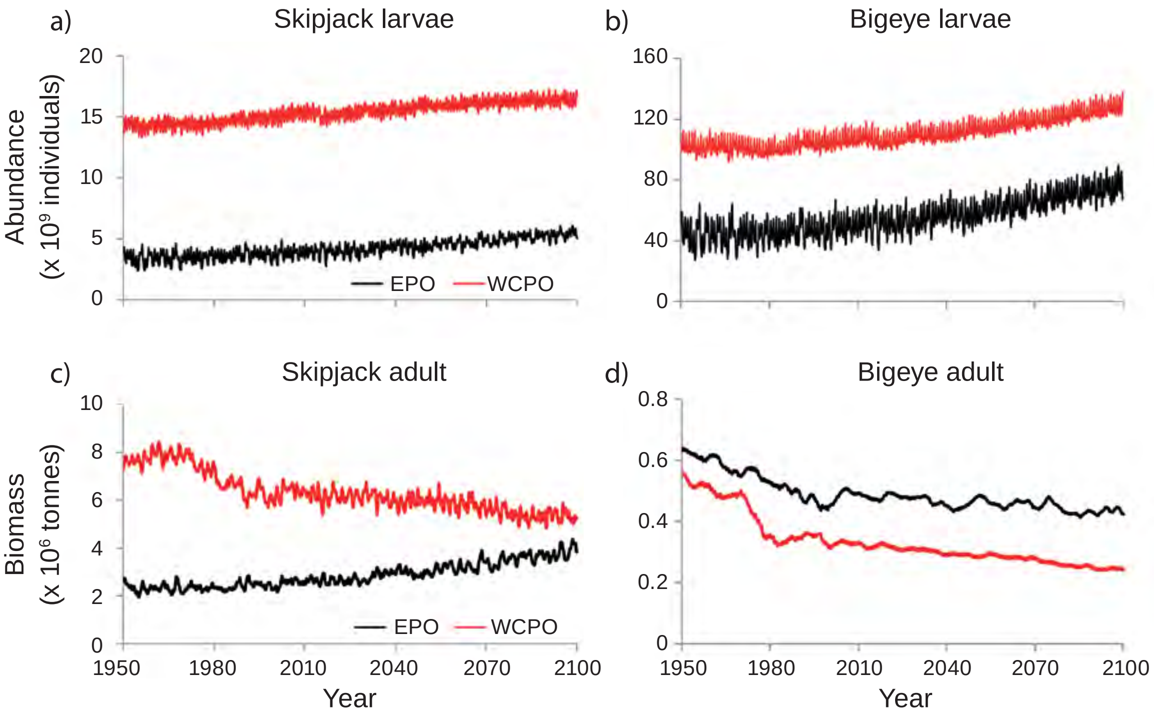


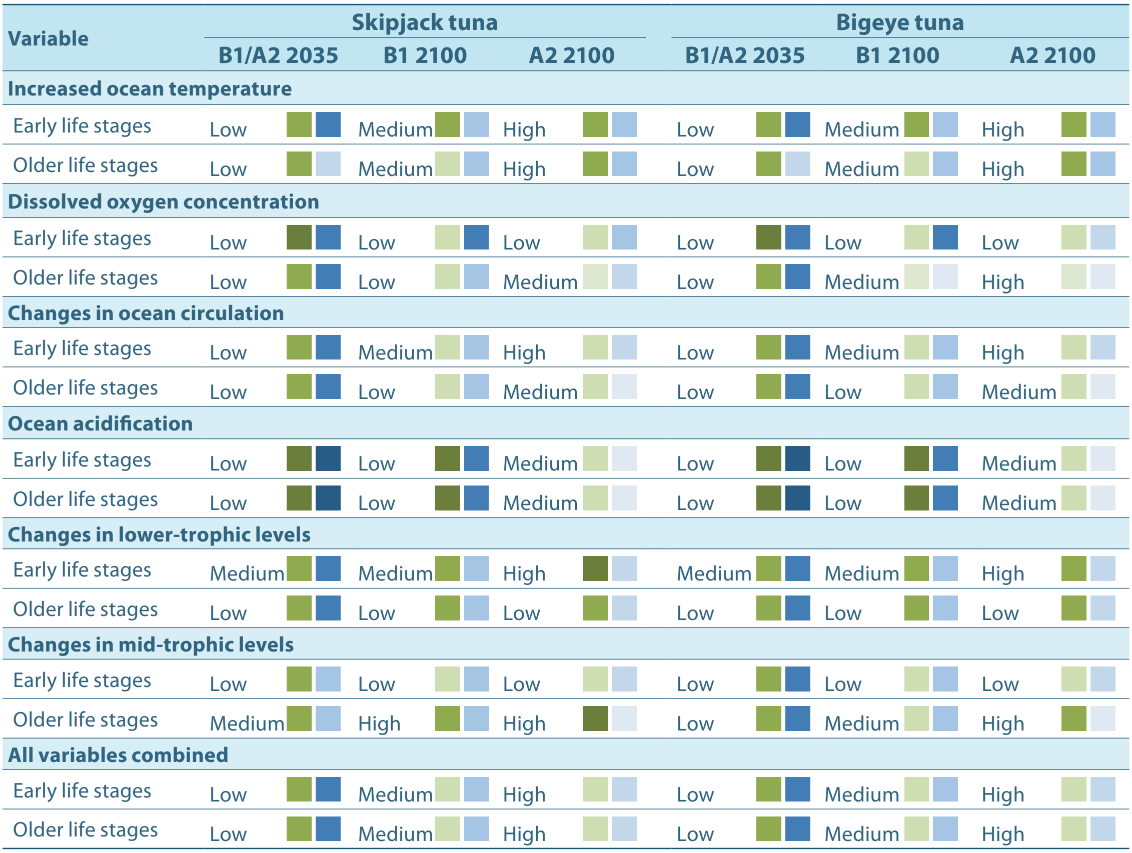
Figure 8.14 Projected changes in the biomass and abundance of larval and adult skipjack and bigeye tuna in the Eastern Pacific Ocean (EPO) and Western and Central Pacific Ocean (WCPO) under the A2 emissions scenario until 2100. Abundance of tuna larvae (total number of larvae recruited in the juvenile cohort) of (a) skipjack; and (b) bigeye tuna, and total biomass of adults of (c) skipjack; and (d) bigeye tuna. Note that the A2 scenario in 2050 can be used as a proxy for the B1 scenario in 2100. Simulations are based on average fishing effort for the period 1980–2000.

Summary of vulnerability of skipjack tuna

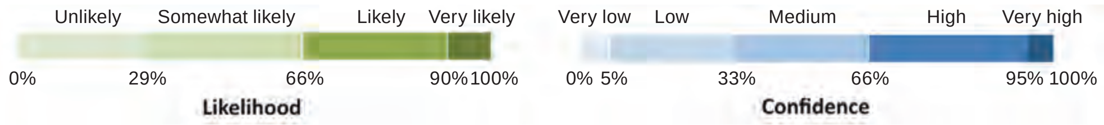
Based on this preliminary simulation, and the anticipated responses of skipjack tuna to the direct and indirect effects of climate change described in Sections 8.4 and 8.5, the overall vulnerability of skipjack to the projected changes in the physical and chemical properties of the tropical Pacific Ocean (Chapter 3) and the oceanic food web (Chapter 4) under the B1 and A2 scenarios by 2035 is considered to be low (**Table 8.3**). Indeed, any changes by 2035 will be difficult to differentiate from natural variability, particularly the effects of ENSO.

By 2100, the population of skipjack tuna in the WCPO is likely to have a moderate vulnerability to climate change under the B1 scenario, increasing to a high vulnerability under the A2 scenario (**Table 8.3**) due to expected major changes in temperature, productivity at lower- and mid-trophic levels, and currents. Note, however, that the projections for A2 in 2100 have a lower confidence due to the large uncertainty of projected changes in dissolved O_2 concentration, and the impact of circulation and ocean acidification. Assuming a level of fishing effort equivalent to the average during 1980–2000, the SEAPODYM model estimates that the biomass of skipjack is likely to decrease by 32% between 2000 and 2100 in the WCPO under the A2 scenario, and increase by 50% in the Eastern Pacific Ocean (EPO).

Table 8.3 Projected vulnerability of skipjack and bigeye tuna to expected changes in various features of the tropical Western and Central Pacific Ocean, and to all variables combined, under the B1 and A2 scenarios for 2035 and 2100. Estimates of likelihood and confidence are provided for these assessments, based on the key below.



Variable	Skipjack tuna			Bigeye tuna		
	B1/A2 2035	B1 2100	A2 2100	B1/A2 2035	B1 2100	A2 2100
Increased ocean temperature						
Early life stages	Low 🟩🟦	Medium 🟩🟦	High 🟩🟦	Low 🟩🟦	Medium 🟩🟦	High 🟩🟦
Older life stages	Low 🟩🟦	Medium 🟩🟦	High 🟩🟦	Low 🟩🟦	Medium 🟩🟦	High 🟩🟦
Dissolved oxygen concentration						
Early life stages	Low 🟩🟦	Low 🟩🟦	Low 🟩🟦	Low 🟩🟦	Low 🟩🟦	Low 🟩🟦
Older life stages	Low 🟩🟦	Low 🟩🟦	Medium 🟩🟦	Low 🟩🟦	Medium 🟩🟦	High 🟩🟦
Changes in ocean circulation						
Early life stages	Low 🟩🟦	Medium 🟩🟦	High 🟩🟦	Low 🟩🟦	Medium 🟩🟦	High 🟩🟦
Older life stages	Low 🟩🟦	Low 🟩🟦	Medium 🟩🟦	Low 🟩🟦	Low 🟩🟦	Medium 🟩🟦
Ocean acidification						
Early life stages	Low 🟩🟦	Low 🟩🟦	Medium 🟩🟦	Low 🟩🟦	Low 🟩🟦	Medium 🟩🟦
Older life stages	Low 🟩🟦	Low 🟩🟦	Medium 🟩🟦	Low 🟩🟦	Low 🟩🟦	Medium 🟩🟦
Changes in lower-trophic levels						
Early life stages	Medium 🟩🟦	Medium 🟩🟦	High 🟩🟦	Medium 🟩🟦	Medium 🟩🟦	High 🟩🟦
Older life stages	Low 🟩🟦	Low 🟩🟦	Low 🟩🟦	Low 🟩🟦	Low 🟩🟦	Low 🟩🟦
Changes in mid-trophic levels						
Early life stages	Low 🟩🟦	Low 🟩🟦	Low 🟩🟦	Low 🟩🟦	Low 🟩🟦	Low 🟩🟦
Older life stages	Medium 🟩🟦	High 🟩🟦	High 🟩🟦	Low 🟩🟦	Medium 🟩🟦	High 🟩🟦
All variables combined						
Early life stages	Low 🟩🟦	Medium 🟩🟦	High 🟩🟦	Low 🟩🟦	Medium 🟩🟦	High 🟩🟦
Older life stages	Low 🟩🟦	Medium 🟩🟦	High 🟩🟦	Low 🟩🟦	Medium 🟩🟦	High 🟩🟦



8.6.1.4 Bigeye tuna

The present-day distribution of bigeye tuna in the Pacific extends from the equator to mid-latitudes. Although the larvae and juveniles of bigeye have a similar distribution to those of skipjack tuna, i.e. mainly in the tropical surface waters (20°N–20°S) of the WCPO, the adults have a markedly different distribution both to their own juveniles and to skipjack (**Figure 8.15**). Adult bigeye tuna are concentrated in the central and eastern Pacific, where they occur mainly in the subsurface zone in the equatorial region. However, there are also seasonal concentrations of fish in the subtropical Pacific (35°–40°S and 35°–40°N) during summer and autumn.

Under the B1 and A2 emissions scenarios by 2035, both the spawning of bigeye tuna, and the density of their larvae, are projected to increase slightly in the eastern equatorial region (**Figure 8.15**). There is no obvious difference in the projected distribution and biomass of adult bigeye, relative to 2000 (**Figures 8.14** and **8.15**).

The relative importance of the WCPO and the EPO for spawning and as feeding habitat for larvae and juveniles is maintained under the B1 scenario in 2100 (and A2 in 2050) (**Figures 8.14** and **8.15**). However, spawning fish and the resulting distribution of larvae of bigeye tuna are projected to extend their ranges slightly towards higher latitudes due to the general warming of the ocean.

Under the A2 scenario in 2100, a larger increase in the density of larvae in the EPO, compared with the WCPO, is projected (**Figures 8.14** and **8.15**). This change is correlated with the expected increase in water temperature, although variations in productivity and circulation also interact through the larval prey-predator trade-off mechanism in the model. In the western equatorial Pacific, the temperature is expected to become too warm for bigeye tuna to spawn. This potential loss of spawning habitat is compensated for by the expected increase in survival of larvae in subtropical regions. However, there is a projected increase in mortality of older stages due to poorer habitat resulting from increased SST, lower O_2 concentrations in subsurface waters, and a reduction of prey.

Conversely, in the eastern Pacific Ocean, SST is expected to become optimal for the spawning of bigeye tuna by 2100 under the A2 scenario. The feeding habitat for adult bigeye also improves strongly under the IPSL-CM4 simulations because higher O_2 concentrations would provide adults with access to prey at greater depths. Enhanced adult habitat should lead, in turn, to an increase in adult biomass, with a direct effect on spawning through the stock-recruitment relationship.

Summary of vulnerability of bigeye tuna

The preliminary simulation for bigeye tuna, and its expected responses to the direct and indirect effects of climate change described in Sections 8.4 and 8.5, indicates that the overall vulnerability of this species to projected changes in the physical and chemical properties of the tropical Pacific Ocean and the oceanic food web under both emissions scenarios by 2035 is likely to be low (**Table 8.3**). However, significant decreases in abundance are projected for the WCPO. Overall, vulnerability in the WCPO increases to moderate for the B1 scenario in 2100 (and A2 in 2050), and to high for the A2 scenario in 2100, albeit at a lower level of confidence.

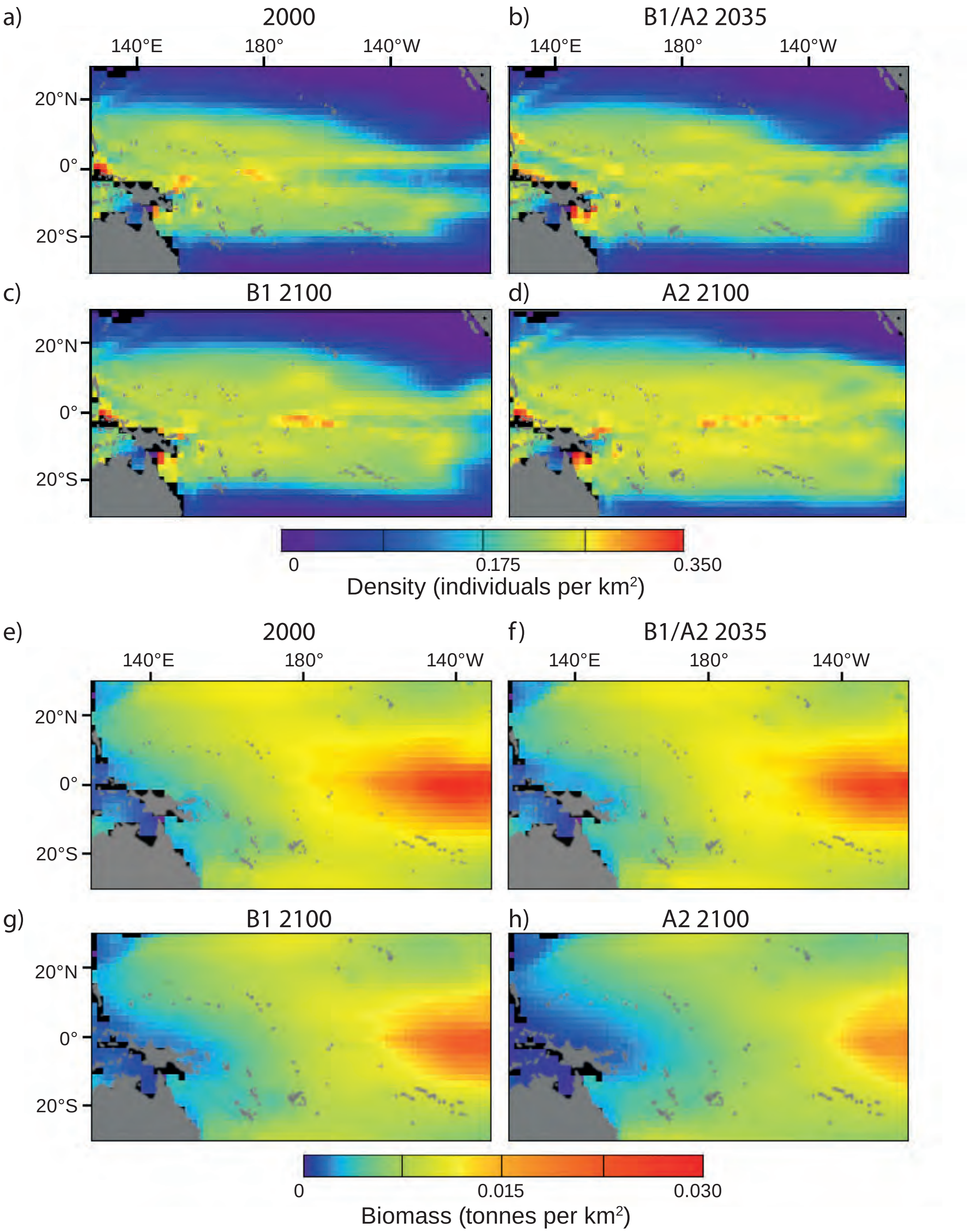


Figure 8.15 Projected distributions (density) for bigeye tuna larvae recruits from the SEAPODYM model in (a) 2000; (b) under the B1/A2 emissions scenario in 2035; (c) under B1 in 2100; and (d) under A2 in 2100. Also shown are estimates of total biomass (tonnes per km^2) of bigeye tuna populations based on average (1980–2000) fishing effort in (e) 2000; (f) under B1/A2 in 2035; (g) under B1 in 2100; and (h) under A2 in 2100.

8.6.1.5 Potential impact on yellowfin tuna and albacore

The biology and ecology of yellowfin tuna can be considered to lie between those of skipjack and bigeye tuna. Therefore, the effects of climate change on yellowfin tuna should be similar to those already described for these two species. In particular, there is expected to be a progressive extension of spawning grounds towards mid-latitudes and the central equatorial Pacific, and deterioration of foraging habitat in the WCPO. These changes are projected to result in a decrease in total biomass of yellowfin tuna in the WCPO, and an increase in the EPO. However, such projections depend strongly on the future concentrations of dissolved O_2. Given the general decrease in primary productivity projected for the tropical Pacific Ocean, the overall abundance of yellowfin tuna in the entire Pacific basin is also expected to decrease.

The situation is different for albacore in the southern Pacific Ocean, which spawn in tropical waters and then move seasonally to the subtropical convergence zones to feed. Because albacore are particularly sensitive to low levels of dissolved O_2, the main projected effects of climate change are expected to be a poleward shift in distribution as fish avoid the decreasing O_2 concentrations in the equatorial subsurface waters of the western Pacific. The projected increases in primary production at mid-latitudes in the southern Pacific Ocean are also expected to improve the feeding habitat of albacore that migrate there, leading to a higher biomass of this species at the edges of the South Pacific Subtropical Gyre province.

8.7 Projected changes in the catch of skipjack and bigeye tuna

The SEAPODYM model was used to make preliminary assessments for projected percentage changes in catches of skipjack and bigeye tuna within the EEZs of PICTs, relative to the 20-year average catch for 1980 to 2000, for the B1 and A2 emissions scenarios by 2035 and 2100.

For skipjack tuna, this preliminary modelling indicates that catches are likely to increase across the region in 2035, although the increases are expected to be greater for PICTs in the eastern than in the western Pacific (**Table 8.4**). By 2100 under the B1 scenario, catches for the western Pacific are then projected to decrease and return to the average levels for this region in 1980 to 2000, although catches in Solomon Islands and PNG are actually projected to decrease by 5% and 10%, respectively. In contrast, catches in the eastern Pacific are projected to increase on average by > 40% (**Table 8.4**).

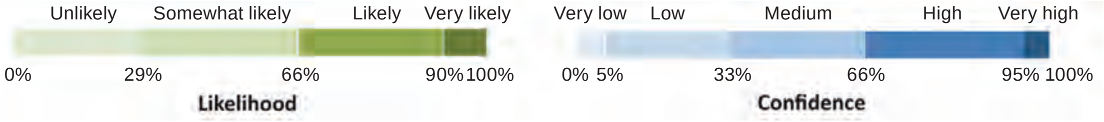
Under the A2 scenario in 2100, catches of skipjack tuna for the western Pacific are estimated to decline further, by an average of > 20%, and by as much as 30% for PNG (**Table 8.4**). Although catches in the eastern Pacific are still substantially greater compared to 1980 to 2000 levels, they are expected to decrease relative to the projections for the B1 scenario. Across the entire region, total catch is projected to decrease by 7.5% under the A2 scenario by 2100 (**Table 8.4**).

For bigeye tuna, small decreases in catch (usually < 5%) are projected to occur in 17 of the 22 PICTs by 2035 (**Table 8.4**). The magnitude of the reduced catches is projected to increase to 5–10% in most PICTs under the B1 scenario by 2100, and 10–30% for many PICTs under the A2 scenario in 2100 (**Table 8.4**).

Table 8.4 Projected percentage changes in catches of skipjack and bigeye tuna, relative to recent catches (20-year average 1980–2000), under the B1 and A2 emissions scenarios in 2035 and 2100, derived from the SEAPODYM model. Likelihood and confidence values for all estimates for each scenario are also provided.

PICT	Skipjack tuna			Bigeye tuna		
	B1/A2 2035	B1 2100*	A2 2100	B1/A2 2035	B1 2100*	A2 2100
Melanesia						
Fiji	25.8	24.0	33.1	0.8	0.7	-1.4
New Caledonia	22.5	18.7	39.4	1.1	1.2	6.0
PNG	3.1	-10.6	-30.2	-4.5	-13	-27.9
Solomon Islands	3.2	-5.5	-15.4	0.1	-2.9	-7.3
Vanuatu	18.4	15.1	26.1	-3.0	-6.1	-9.7
Micronesia						
FSM	14.0	4.8	-15.8	-3.5	-11.5	-32.5
Guam	15.8	10.5	-7.7	-6.7	-12.7	-32.7
Kiribati	36.8	43.1	24.1	-0.7	-5.4	-16.6
Marshall Islands	24.0	24.2	9.8	-3.1	-9.6	-26.9
Nauru	25.1	19.7	-1.2	-1.4	-6.6	-19.5
CNMI	23.0	21.7	13.2	-0.3	-4.9	-22.6
Palau	10.2	1.7	-26.9	-3.9	-11.2	-45.2
Polynesia						
American Samoa	41.1	47.8	57.8	-4.7	-7.9	-17.9
Cook Islands	40.4	50.2	47.4	-3.0	-7.8	-15.5
French Polynesia	40.8	48.9	76.9	-1.6	-7.7	-12.5
Niue	nea	nea	nea	-5.4	-7.8	-14.7
Pitcairn Islands	nea	nea	nea	-2.3	-4.5	-4.1
Samoa	44.0	49.2	54.9	1.4	1.4	-4.2
Tokelau	60.8	69.0	63.2	-3.1	-6.5	-16.1
Tonga	47.0	50.2	58.5	-4.0	-5.1	-10.3
Tuvalu	36.8	40.9	25.0	2.9	2.2	-6.2
Wallis and Futuna	44.2	48.7	46.4	0.4	-0.4	-6.9
Regional						
Total fishery	18.9	12.4	-7.5	0.33	-8.8	-26.7
Western fishery**	10.7	-0.2	-21.5	-2.03	-12.3	-33.8
Eastern fishery***	36.9	43.2	26.8	3.3	-4.53	-17.8
	🟩🟦	🟩🟦	🟩🟦	🟩🟦	🟩🟦	🟩🟦

* Equivalent to A2 2050; ** 15°N–20°S and 130°–170°E; *** 15°N–15°S and 170°E–150°W; nea = no estimate available.



We emphasise that the preliminary nature of the modelling for skipjack and bigeye tuna means that the projected changes in catch for PICTs should be regarded as indicative only, although we have higher confidence in the general trend that catches in the western Pacific will decrease and those in the eastern Pacific will increase. It is also likely that the effects on catches estimated in this analysis are likely to be amplified by future changes in fishing effort because, as catch per unit effort (CPUE) in an area changes, the relative profitability of fishing also changes (Chapter 12). As a result, fishing effort increases in areas where CPUE improves, and decreases where CPUE declines. However, the model can be run to separate the effects of climate change and fishing where this information is required.

8.8 Uncertainty and gaps in knowledge

As indicated above, the projected effects of climate change on the oceanic environment and ecosystems that support tuna (Chapters 3 and 4), and on the population dynamics of tuna, are highly uncertain. The main sources of uncertainty are (1) the modelling of the global climate system, the coarse resolution of physical models and the lack of clear understanding of future ENSO patterns (Chapters 1–3); (2) the gaps in knowledge on the physiology, biology and ecology of tuna species; (3) the modelling of the food webs in the tropical Pacific Ocean, and the spatial distribution of tuna in relation to changes in their environment; and (4) the quality of fishing data.

The global climate models simulate changes in the Earth's climate by coupling the atmosphere, ocean, land surface and ice regions, with the exchanges and interactions between them, based on physical laws (Chapter 1). The domain of a global climate model is divided into small spatial cells, with multiple layers from the top of the atmosphere to the bottom of the ocean. The reductions in the resolutions of global climate models required to enable them to run on the present generations of computers result in some biases (Chapter 1). These biases do not seriously impede the simulations of surface climate and changes to the physical and chemical nature of the tropical Pacific Ocean due to increased emissions of greenhouse gases. However, they do have larger consequences for assessing the effects on ecosystems and the biology of key species. For example, an error in projecting water temperature of 1°C or 2°C could significantly misrepresent the location of suitable spawning habitat for a tuna species. One method of compensating for such biases is to recalibrate the model parameters for environmental variables that are thought to be biased by the climate model simulations.

For the lower levels of the food webs in the ocean, such problems can be overcome by coupling biogeochemical models to global climate models, to project the carbon cycle and the interactions between physics and the biology of the organisms. These particular coupled models are known as 'Earth's climate models'. Progress in the development of these models has been substantial, and their main projections (e.g. simulations for decreasing biological production in the tropical regions due to higher stratification) are considered to be quite robust. However, a crucial gap in knowledge is the uncertainty about projected dissolved O_2 concentrations in the ocean associated with the C/N ratio of organic matter.

Much still also needs to be learned about the physiological responses of tuna to the changes in the major physical and chemical properties of the tropical Pacific Ocean summarised in this chapter. In particular, the responses of the fish to temperature and dissolved O_2 are still only partially understood, and they are virtually unknown for pH. Our understanding of the basic energy requirements of the four species of tuna, and the different life stages of each species, is also limited. Furthermore, knowledge on the potential non-linear interactions, feedbacks and thresholds for the different effects of climate change on the energetic balance of tuna species is almost completely lacking.

Substantial improvements to the modelling of marine ecosystems and the spatial population dynamics of tuna are also required. At present, the uncertainties in physical and biogeochemical models are simply transferred to the simulations of the mid-trophic levels of the food webs that support tuna, and the simulations of tuna population dynamics. To limit this uncertainty, the SEAPODYM model uses relative rather than absolute parameterisation as much as possible. For example, all projected movements of fish are based on habitat gradients and habitat index values. Likewise, the parameterisation of spawning habitat uses the ratio between primary production and mid-trophic levels to represent the trade-off between density of prey and predators of larvae. The feeding habitat index combines accessibility to mid-trophic level components and their biomass, but does not depend on absolute consumption.

This approach reduces the impacts of biases in primary production estimates and mid-trophic levels considerably. On the other hand, parameterisation leading to absolute biomass of tuna populations is achieved with a rigorous mathematical approach based on assimilation of all historical fishing data (effort, catch and size of catch) in the model (Box 8.2).

8.9 Future research

The gaps in knowledge outlined above frame the priorities for research on the effects of climate change on tuna in the tropical Pacific. Given the great importance of tuna to the economies of PICTs (Chapters 1 and 12), urgent priorities for research are more robust projections of catches of the main species of tuna within the EEZs of PICTs. This analysis will depend on the development of global climate models at higher resolutions, combined with dynamical or statistical downscaling techniques[123] at the scale of national EEZs[vi], to improve the environmental forcing of ecosystem models.

Much research is also needed to improve the biogeochemical ecosystem models, and the estimates of future fishing effort, which need to be coupled to the global

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[vi] This work is now being done for the tropical Pacific by the Australian Bureau of Meteorology, CSIRO and partners, under the Pacific Climate Change Science Programme; see www.cawcr.gov.au/projects/PCCSP

climate models to estimate catches of the four species of tuna under various climate change scenarios. The main research required to further develop and parameterise the biogeochemical models is summarised below.

- Assessment of the effects of higher atmospheric concentrations of CO_2 on the C/N ratio of organic matter in the ocean through laboratory experiments and networks of *in situ* observations.
- Definition of the optimal range and thresholds of temperature and dissolved O_2 concentrations for the four species of tuna, and for their different life history stages. This will require both laboratory experiments and the use of internal and external electronic tags with multiple sensors.
- Evaluation of the potential impacts of increased acidification of the tropical Pacific Ocean on the production of gametes, fertilisation, embryonic development, hatching and larval behaviour and ecology of tuna. Experiments would be restricted to yellowfin tuna in the first instance because this is presently the only species of tropical tuna from the region that can be propagated in captivity.
- Investigation of other important physiological mechanisms in tuna that may also be affected by elevated levels of CO_2/ocean acidification, including interactions with variability in water temperature and dissolved O_2, and the effects of altered acoustics.
- Estimation of (1) the energy transfer efficiency between all levels of the food web, but particularly from the lower levels to the mid-trophic level (micronekton), which constitutes the prey of tuna; and (2) the spatial and temporal variation in the diversity, distribution and abundance of micronekton across the region. Such research is needed to help define the carrying capacity of the pelagic ecosystem in the tropical Pacific Ocean for tuna more realistically. It is also needed to assess whether productivity of tuna stocks is controlled directly by food abundance, or if there are non-linear relationships such as changes in food assimilation rates in relation to prey density or threshold limits. The research will require investment in extensive sampling programmes, including development and validation of new acoustic methods for quantifying micronekton, and routine use of these methods by merchant vessels of opportunity (see Chapter 4 for details).
- Ongoing tagging programmes, both with conventional and electronic tags, for all four species of tuna to verify whether the projected changes in their distributions, in response to altered water temperatures, currents and O_2 levels, occur.
- Description of the diets of the four species of tuna in more detail to evaluate competition between these species more accurately.
- Identification of the socio-economic scenarios likely to drive future fishing effort in the region[3], taking into account, for example, the increasing demand for tuna, the changing demography of the region, the likelihood of spatial changes in fishing effort, and increasing fuel costs.

8.10 Management implications and recommendations

As described in Section 8.1, overall management of tuna fisheries in the western and central Pacific is the responsibility of the WCPFC. Its primary role is to ensure that stock-wide exploitation of tuna and related species in its convention area is undertaken in a responsible and sustainable way. Within these overall constraints, PICTs are seeking opportunities to maximise the economic benefits from tuna fisheries in their EEZs arising from onshore handling and processing of the catch, and local support industries. For many PICTs, these objectives and the strategies to achieve them are laid down in their 'National Tuna Management and Development Plan'. These plans have a high level of political support. Members of the Pacific Islands Forum also pursue coordinated policy approaches to maximise the benefits from tuna through the Forum Fisheries Agency. Increasingly, however, hands-on management is being pursued through subregional groupings of PICTs, such as the PNA in the case of the tropical surface fishery for tuna, and the members of the Te Vaka Moana Arrangement focusing on longline fisheries targeting albacore and swordfish in southern subtropical waters.

Within this overall management framework, the implications of the projected effects of climate change on tuna need to be integrated into strategies that will mitigate negative effects and take advantage of increased abundances of fish where they are projected to occur. Clearly, this process will need to evolve over time as the uncertainties and knowledge gaps outlined in Section 8.8 are addressed. However, based on the information presented in this chapter, management authorities can begin to position themselves to deal with the potential future changes. The main management implications and measures that need to be considered are outlined below.

- The WCPFC should explicitly consider the implications of climate change as it develops its management objectives and strategies over the coming years. With the eventual possibility of reduced overall abundance of skipjack, yellowfin and bigeye tuna in the WCPO, the WCPFC will need to continue to (1) strengthen the mechanisms to manage overall fishing effort or catches (or both) in its convention area; and (2) develop the necessary tools to monitor and enforce its conservation and management measures, in order to anticipate any large change in the fundamental biological parameters of exploited stocks.
- The eastern boundary of the WCPFC convention area is 150°W north of 4°S and 130°W south of 4°S, while the western boundary of the organisation charged with tuna fisheries management in the EPO, the Inter-American Tropical Tuna Commission (IATTC), is 150°W. These boundaries neatly separate the historical high-volume purse-seine catches into their western and eastern components (**Figure 8.16**). However, the projections described in Section 8.6.1 indicate that the distributions of skipjack and bigeye tuna (and by extension yellowfin tuna) are likely to shift progressively towards the central and eastern Pacific during the

21st century. Because both the surface and longline fisheries are likely to respond to these shifts, a much more even distribution of catch across the tropical Pacific (than historically) is plausible. This would require cooperation in all aspects of tuna fisheries management between the WCPFC and the IATTC. A merger of these organisations, creating a pan-Pacific tuna fisheries management body, is something that may eventually require serious consideration, on the proviso that the present relative levels of effort in the WCPO and EPO are maintained.

- A major re-distribution of tuna fishing activity towards the central Pacific would clearly alter the current distribution of the fisheries among the EEZs of PICTs, and associated economic benefits (Chapter 12). This would create challenges for some PICTs and opportunities for others. It will be important that the various layers of management, but particularly the PNA in whose EEZs a significant portion of the regional tuna catch occurs, further develop their management systems to ensure flexibility to cope with a potentially changing spatial distribution of fishing effort.

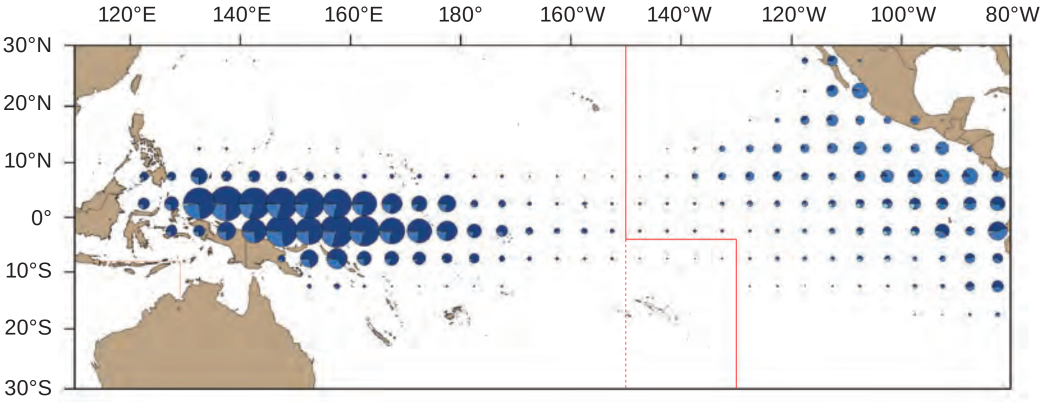

Figure 8.16 Distribution of purse-seine catches of skipjack (dark blue), yellowfin (blue) and bigeye tuna (light blue) in the tropical Pacific Ocean from 1980 to 2009. The convention area of the Western and Central Pacific Fisheries Commission lies to the west of the solid orange line. The Inter-American Tropical Tuna Commission convention area lies to the east of the solid line north of 4°S and the dashed line south of 4°S. Circles indicate relative differences in the sizes of aggregated catches of all species.

- Notwithstanding the results from the preliminary modelling, indicating an eastward re-distribution of tropical tuna stocks, there may well be subregional effects that run counter to this trend. For example, projections of a 10–20% increase in rainfall for the Sepik-Ramu and other large river systems under the A2 emissions scenario by 2100 could increase nutrient flows into the Bismarck Sea and more generally through the Indonesia-PNG archipelagos, retaining concentrations of tuna in these areas. Any such persistent subregional concentrations of tuna would heighten the need for regionally-responsible, spatially-explicit management in these archipelagic areas, which are currently beyond the mandate of WCPFC because of the sovereign status of archipelagic waters.

- PNA has implemented a vessel day scheme (VDS)[vii] for the purse-seine fishery in the EEZs of its members, and recently taken steps to develop a similar scheme for the longline fishery. Essentially, these schemes allocate fishing effort among the EEZs according to agreed criteria and allow for transferability of these rights among members. The transferability aspect of the VDS has recently come into effect, and will need to be implemented and adjusted in the future if changing distributions of fishing effort are to be managed in an orderly fashion.

  The VDS has the potential to operate in a similar way to the 'cap and trade' systems being considered by many countries worldwide to limit their emissions of CO_2[124]. Indeed, a key advantage of the VDS is that it can hold total fishing effort for PNA members constant, yet allow them to trade fishing days when the fish are concentrated either in the west or east due to ENSO events. For the VDS to work efficiently, however, PNA members will need to ensure that fishing effort conforms to the levels specified. The allocation of effort among members will also need to be adjusted periodically as the stocks of tuna move progressively east. Periodic adjustment will still allow the transfer of effort during ENSO events but avoid the need for PNA members further to the east to continually purchase vessel days from those in the west, based on present-day catches.

- Eastward re-distribution of tuna and their associated fisheries could have major consequences for the vulnerability of stocks to exploitation, particularly bigeye tuna. In recent years, the purse-seine catch of bigeye tuna has been concentrated in the western Pacific (**Figure 8.17a**), in line with the distribution of effort by purse-seine vessels. However, catch per unit effort of bigeye tuna by purse-seine is much higher in the central and eastern Pacific (**Figure 8.17b**), possibly as a result of greater abundance or greater vulnerability of this species to purse-seining in the region due to the shallower depth of the mixed layer there[23]. Thus, any large-scale shift of the purse-seine fishery towards the central Pacific is likely to increase the exploitation rates of bigeye tuna and place the stock under even greater pressure than is currently the case. Management authorities would, therefore, need to give high priority to developing further measures to mitigate the capture of bigeye tuna by purse-seine.

- Albacore in southern subtropical areas are caught mainly by longline, with considerable fishing activity based out of PICTs located in this part of the region. The initial interpretations from the modelling discussed in Section 8.6.1 are that increases in productivity at the edges of the South Pacific Subtropical Gyre province may have a positive impact on the abundance of albacore, although some poleward displacement in the distribution of the stock is also possible. Such potential changes in distribution of the fish and the fleet may create a need for spatial management arrangements for albacore similar to the VDS for the tropical species of tuna. Strategies to develop the fishery for albacore may also need to

[vii] For a description of the vessel day scheme, see Attachment C of WCPFC Conservation and Management Measure for Bigeye and Yellowfin Tuna in the Western and Central Pacific Ocean (CMM 2008-01) www.wcpfc.int/doc/cmm-2008-01/conservation-and-management-measure-bigeye-and-yellowfin-tuna-western-and-central-pa

consider appropriate vessel size, fuel economy and onboard storage facilities, in the event that vessels need to travel further to effectively exploit a more southerly-based resource.

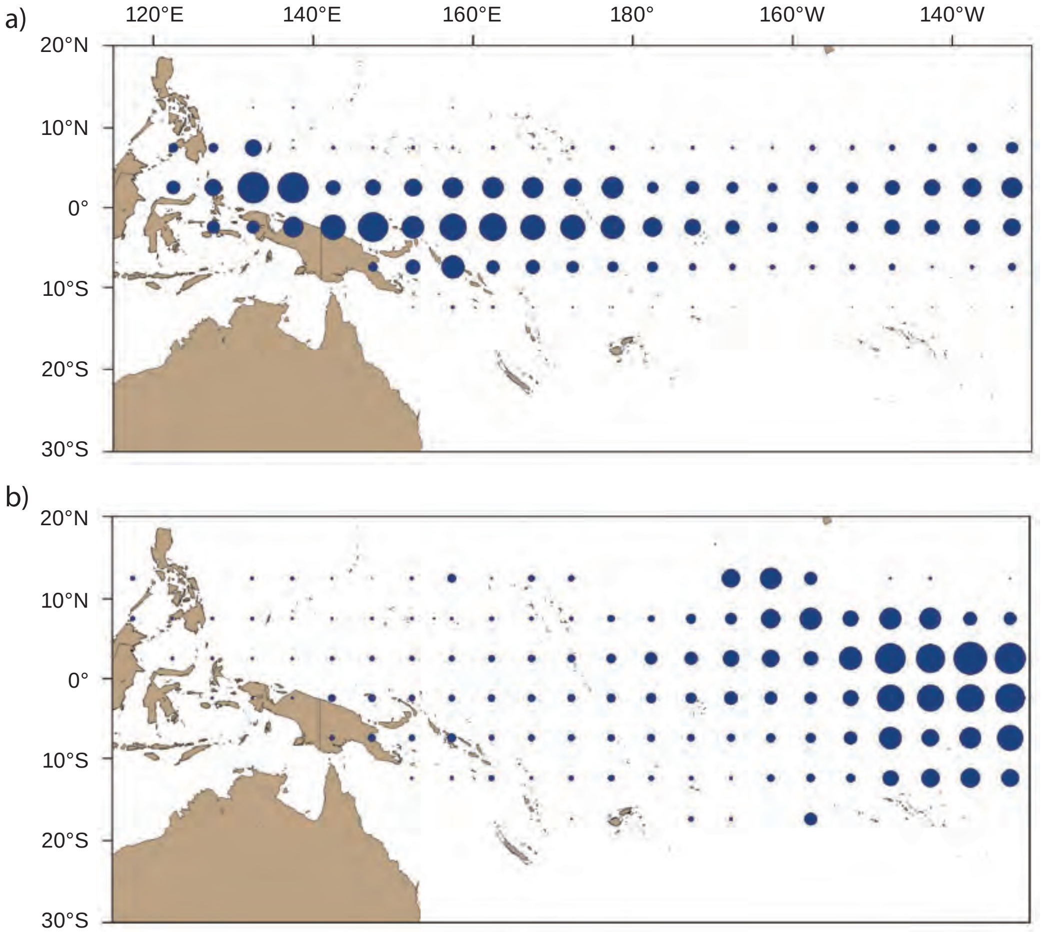

Figure 8.17 Distribution of (a) average bigeye tuna catch, and (b) average catch per unit effort for bigeye tuna by purse-seine vessels, in the tropical Pacific Ocean from 1996 to 2009. Circles indicate relative differences in the sizes of the aggregated catches.

- Signatories to the 'Convention on the Conservation and Management of High Migratory Fish Stocks in the Western and Central Pacific Ocean' are required to assess the effects of fishing, other human activities and environmental factors on target stocks, non-target species and species belonging to the same ecosystem, or dependent upon, or associated with target stocks. In addition to the effects on tuna described in this chapter, climate change is expected to affect the distribution and abundance of non-target species. It is possible that the interaction between target and non-target species and fishing activities will vary in response to the altered distributions and abundances of fish. If so, this may result in different impacts of fishing on non-target species, and species dependent on tuna. Many markets are now adopting certification schemes that require the impacts of tuna fishing on non-target and dependent species to be minimised. The potential for such impacts under a changing climate need to be evaluated, and fishing practices modified if necessary, to ensure that the demands of the market are satisfied.

Although there are still several uncertainties associated with the projected future distributions of tuna in the tropical Pacific, the likely trends in distribution and catches reported here have a reasonable basis. Pacific Island countries and territories, and the tuna management institutions acting in their interests, would be wise to begin deciding how to adapt to these trends. They should also commission the science needed to improve confidence in these projections so that the necessary adaptations can be progressively fine-tuned.

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Chapter 9

Vulnerability of coastal fisheries in the tropical Pacific to climate change

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> *'Reef fish fisheries have long sustained coastal communities throughout the tropics as an important, sometimes sole, source of protein and livelihood.'* (Sadovy 2005)[i]

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Contents Page

9.1 Introduction

Although the coastal fisheries of the Pacific Island countries and territories (PICTs) differ considerably from the industrial tuna fisheries of the region (Chapter 8), the importance of coastal fisheries cannot be overstated. Throughout the tropical Pacific, coastal fisheries contribute significantly to the food security, livelihoods, and culture of both rural communities and urban populations[1–5]. In the majority of PICTs, fish consumption by coastal communities exceeds 50 kg per person per year, and is > 90 kg per person per year in six PICTs[4]. In comparison, average global fish consumption per person is 16–18 kg per year[6,7].

Not surprisingly, therefore, coastal fisheries in the tropical Pacific are based mainly on subsistence activities to provide fish and invertebrates for household food[1,4,8,9]. Nevertheless, an average of 47% of households in fishing communities also earn their first or second income from selling surplus fish and invertebrates caught from coastal and nearshore waters[10]. Specialised fisheries for coastal invertebrates (e.g. sea cucumbers and trochus) and fish (e.g. groupers and snappers) for export commodities, have also contributed substantially to national income and local livelihoods over the years. The only parts of the tropical Pacific where coastal fisheries do not help underpin food security and livelihoods are the inland areas of Papua New Guinea (PNG), Solomon Islands and Fiji (Chapter 10). The significance of coastal fisheries is demonstrated by the total contributions of subsistence and commercial catches to gross domestic product (GDP) across the region; together, they are estimated to be worth USD 272 million. This is considerably higher than the USD 200 million derived from locally-based industrial tuna fleets[5].

The benefits of coastal fisheries depend on the coral reefs, mangroves, seagrasses and intertidal sand and mud flats that support the many fish and invertebrate species harvested. Taken together, these habitats constitute the littoral and sublittoral areas surrounding PICTs (Chapters 5 and 6), and provide shelter and/or feeding areas for various life history stages of the hundreds of species of fish and invertebrates caught regularly by coastal communities in the tropical Pacific[1,10].

In some areas, the benefits to PICTs from coastal fisheries have been undermined by habitat degradation or loss, resulting from coastal development, pollution, sedimentation from careless land use within catchments, reclamation or excavation of reef areas, and destructive fishing practices[11–14], as well as over-exploitation of coastal fish and invertebrates[8,15–17]. In coral reef habitats, the increasing range of anthropogenic effects is compounding the disturbances caused by natural events, such as cyclones and outbreaks of the coral feeding crown-of-thorns starfish *Acanthaster planci*[18–19]. Crown-of-thorns starfish, for example, have contributed greatly to loss of coral in Fiji and French Polynesia over the last 40 years and remain the major cause of reef degradation in much of the Pacific[20–21]. Together with reduction of seagrass and mangrove habitats (Chapter 6), damage to complex coral reef ecosystems significantly reduces biological productivity in tropical coastal waters[22].

Overfishing in the tropical Pacific has been driven mainly by rapid growth of human populations (Chapter 1), the need for coastal communities to earn cash in increasingly 'Westernised' societies, greater demand for export commodities, and a lack of alternative livelihoods[2,23–25]. Exploitation of fisheries resources is strongly linked to economic development at the national level, and availability of alternative income opportunities at the community level[9,26]. Coastal communities with limited access to alternative livelihoods are most vulnerable because of their high dependence on coastal fisheries resources. This dependence is demonstrated by the direct relationship between small-scale artisanal invertebrate catches and daily cash expenditure[26].

Projected changes to the surface climate of the region and the tropical Pacific Ocean (Chapters 2 and 3) have the potential to affect the productivity of coastal fisheries, and the success of management measures to improve sustainability of these essential resources. Recent and rapid changes in the global climate (Chapter 2) are having major impacts on physical and biological processes across a wide range of ecosystems[27–29]. Periodic large-scale climatic events, such as the El Niño-Southern Oscillation, are known to have significant effects on the distribution or productivity of exploited fish populations[30–33], leading to widespread concern about the future impact of global climate change[34] (Chapters 1 and 8). Variations in water temperature, current regimes, availability of nutrients and the pH of the ocean can be expected to have a direct influence on the physiology, growth and replenishment of many fisheries species, leading to marked changes in their size, abundance and/or distribution[35–37]. Changes to water temperature, ocean acidity, severity of storms and cyclones, sea level, sedimentation, and rainfall are also likely to affect coastal fisheries indirectly by altering the extent and structure of the coral reefs, mangroves, seagrasses and intertidal areas that support them (Chapters 5 and 6).

The purpose of this chapter is to assess the vulnerability of coastal fisheries in the tropical Pacific to projected climate change. As a prelude to this assessment, we summarise the nature and status of coastal fisheries by describing the main species of fish and invertebrates harvested, together with their uses, recent catch levels, status and estimated sustainable production. We then use the vulnerability framework outlined in Chapter 1 to assess (1) the exposure and sensitivity of the major groups of fish and invertebrates to projected changes in surface climate (Chapter 2), oceanic conditions (Chapter 3) and the habitats that support them (Chapters 5 and 6); and (2) the adaptive capacity of these species to reduce the potential impact stemming from their exposure and sensitivities. Changes in fisheries production by 2035 and 2100 are projected for representative low (B1) and high emissions (A2) scenarios[38] (Chapter 1).

We conclude with the gaps in knowledge that currently limit confidence in vulnerability assessments for coastal fisheries, the research needed to fill these gaps, and the management actions required to reduce the vulnerability of coastal fisheries in the tropical Pacific to climate change.

9.2 Nature and status of coastal fisheries

9.2.1 Main fisheries and their uses

For the purposes of this chapter, coastal fisheries are defined as the harvesting of wild demersal fish and invertebrates from inshore coastal habitats to a depth of 50 m, as well as pelagic fish caught in nearshore waters within 10 km of the coast. We give only limited consideration to finfish and invertebrates that spend either part or all of their lives in brackish water because these species are covered in Chapter 10. Marine and estuarine ecosystems are, however, strongly interconnected and it is difficult to attribute some fisheries activities (e.g. trawl-based fisheries for penaeid shrimp in PNG) to a single ecosystem.

We do not consider the deep slope fisheries for snappers, groupers and other species[1] because these deeper-water environments are likely to be buffered against the main effects of climate change, particularly increasing temperature, during the timeframes (25–90 years) considered in this chapter. Deepwater fish species may be affected by changes in productivity and food supply due to changes in current patterns and eddies (Chapter 3). Information on the biology of these fish is very limited, however, preventing effective assessment of their vulnerability to climate change.

This assessment does not include sharks, rays, reptiles or mammals. The effects of climate change on sharks and rays are generally unknown but assumed to be similar to those for finfish occupying equivalent habitat types. For example, reef sharks such as *Carcharhinus amblyrhynchos* and *Triaenodon obesus* are highly dependent on coral reefs and are likely to be affected negatively by extensive habitat degradation[39]. Although turtles, crocodiles, dolphins and dugongs are culturally important and clearly vulnerable to climate change[40], they are not assessed here. With some exceptions[41], these species generally make a limited contribution to subsistence or commercial fisheries in PICTs and are increasingly subject to environmental protection or regulations based on customary use.

The coastal fisheries of the tropical Pacific, as we define them, are based on wild capture of a wide range of fish and invertebrate species and are best thought of as low-investment, small-scale, multi-gear, multi-species fisheries. Even so, there are marked differences in catch composition among PICTs[1,10]. In particular, the number of species caught declines from west to east, corresponding with known gradients in the biodiversity of marine species[42] (Chapter 1). Further differences in catch composition arise from the use of different fishing methods, variation in available fish habitats (Chapters 5 and 6), and regional differences in dietary preferences and cultural practices of Pacific Island people[1].

Considering both target species and their key supporting habitats, the coastal fisheries of the region fall into four distinct categories (1) demersal (bottom-dwelling) fish; (2) nearshore pelagic fish; (3) targeted commercial invertebrates; and (4) shallow subtidal and intertidal invertebrates. Importantly, these four categories of fisheries may be affected in different ways by climate change.

The main species caught by these fisheries, the habitats that support them, the main fishing methods, and the uses of the resources (subsistence and income generation) are summarised below. This review of the main groups of fish and invertebrates comprising coastal fisheries, and the present range of coastal fishing activities, is based largely on comprehensive sampling conducted by the Pacific Regional Oceanic and Coastal Fisheries (PROCFish) Development Project, implemented by the Secretariat of the Pacific Community (SPC)[10] (Appendix 9.1).

9.2.1.1 Demersal fish

A diverse range of demersal fish are caught from the coastal waters of PICTs, spanning specialist species associated mainly with coral reefs to generalist species that occur across a range of different habitats (**Figure 9.1**). The greatest abundance and diversity of fish are caught around coral habitats[1,9,10,17]. However, fishing also occurs close to mangroves, in seagrass meadows and over inter-reefal habitats with little biological structure (Chapters 6 and 10).

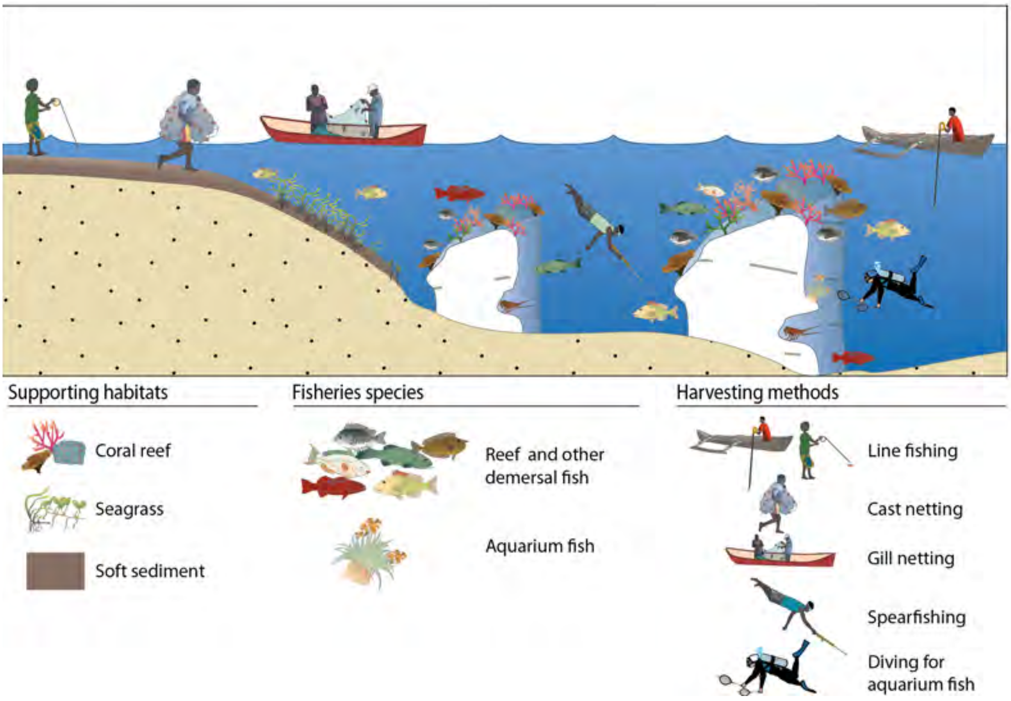


Figure 9.1 Main habitats where demersal fish are caught in the tropical Pacific, and the most common methods used to catch these fish.

The main families of demersal coral reef fish caught for subsistence and livelihoods are fairly consistent across the tropical Pacific (**Figure 9.2**, **Table 9.1**), i.e. catches are dominated by carnivorous emperors (Lethrinidae), snappers (Lutjanidae) and groupers (Serranidae), as well as herbivorous parrotfish (Scaridae), surgeonfish (Acanthuridae) and rabbitfish (Siganidae). In Melanesia, catches of demersal fish are comprised mainly of emperors, whereas the composition of catches in Micronesia and Polynesia varies depending on the country or territory (**Table 9.1**). Across these two regions, carnivorous species dominated catches in Kiribati, Marshall Islands, Palau, Niue and Tonga, whereas herbivorous surgeonfish, parrotfish, rabbitfish, or drummers (Kyphosidae) were caught more often in Federated States of Micronesia (FSM), Nauru, Cook Islands, French Polynesia and Samoa (**Table 9.1**).

Table 9.1 Proportional catches of major families of demersal fish in 17 Pacific Island countries and territories (PICTs). Information based on extrapolated catches from socio-economic surveys conducted in 4–5 coastal fishing communities in each PICT between 2002 and 2008. The trophic group of each family is designated as carnivore (C) or herbivore (H), based on the predominant role of species in each family (source: SPC PROCFish Project).

PICT	Family (trophic group)											
	Lethrinidae (C)	Acanthuridae (H)	Scaridae (H)	Serranidae (C)	Lutjanidae (C)	Siganidae (H)	Holocentridae (C)	Mullidae (C)	Kyphosidae (H)	Labridae (C)	Balistidae (C)	Others* (C + H)
Melanesia	**20.4**	**7.2**	**8.4**	**8.5**	**8.9**	**6.4**	**1.3**	**3.6**	**1.2**	**0.9**	**2.4**	**30.7**
Fiji	37.4	7.7	2.8	9.4	8.0	1.4	1.8	2.1	0.0	0.0	1.8	27.6
New Caledonia	21.5	10.7	11.5	12.7	3.1	10.3	0.0	4.4	0.0	0.1	0.0	26.0
PNG	14.5	1.9	5.8	5.2	16.0	4.2	0.7	2.1	1.8	0.7	2.1	44.9
Solomon Islands	10.5	5.5	9.2	13.1	18.1	2.0	3.3	1.8	0.1	3.9	4.0	28.5
Vanuatu	17.8	9.0	12.1	1.3	0.9	13.3	1.2	7.6	4.4	0.0	4.5	27.8
Micronesia	**12.8**	**14.0**	**11.4**	**14.3**	**10.9**	**9.1**	**2.1**	**3.1**	**1.7**	**0.7**	**0.3**	**19.7**
FSM	7.8	29.3	26.4	8.1	1.2	14.0	0.1	2.9	0.0	1.0	0.0	9.2
Kiribati	9.2	2.5	2.0	10.8	11.0	0.4	2.0	3.6	0.3	1.0	0.1	57.2
Marshall Islands	10.5	9.5	4.5	28.8	17.2	12.2	3.0	3.7	5.6	0.2	0.3	4.6
Nauru	0.0	34.1	8.3	6.6	10.4	0.0	10.9	0.0	4.5	0.0	4.0	21.2
Palau	26.8	9.5	13.5	11.4	14.4	12.1	0.9	3.1	0.4	0.6	0.1	7.1
Polynesia	**13.2**	**16.8**	**15.4**	**8.4**	**7.2**	**3.1**	**6.1**	**2.8**	**5.7**	**1.3**	**0.2**	**19.8**
Cook Islands	2.6	10.4	36.8	9.7	2.3	4.6	4.9	4.1	14.5	2.3	0.0	7.9
French Polynesia	4.6	19.4	18.1	9.4	4.3	3.3	10.0	4.0	2.0	1.0	0.0	23.8
Niue	0.3	2.4	2.2	6.4	1.3	0.0	22.3	1.2	25.0	4.7	0.3	34.0
Samoa	13.6	22.9	18.7	5.0	5.4	5.1	8.1	3.7	0.7	1.9	0.8	14.0
Tonga	40.3	12.9	11.0	10.9	9.4	4.7	0.8	1.4	1.5	1.3	0.2	5.5
Tuvalu	9.4	17.4	3.1	10.9	14.7	0.8	4.1	0.8	8.7	0.1	0.0	29.9
Wallis and Futuna	14.5	21.8	4.9	3.7	9.7	0.0	3.1	2.7	2.0	0.0	0.1	37.6

* Includes a wide range of species, such as trevallies (Carangidae) and mullet (Mugilidae).

Regional differences in catch composition do not reflect the availability of fish. Rather, comparisons of the relative importance of the main fish families in catches, with estimates of their average biomass from underwater visual census, show that emperors, groupers, parrotfish and surgeonfish are differentially selected among PICTs (**Figure 9.2**, **Table 9.2**). This selection is presumably due to regional variation in fishing techniques, and preferences for different fish as food.

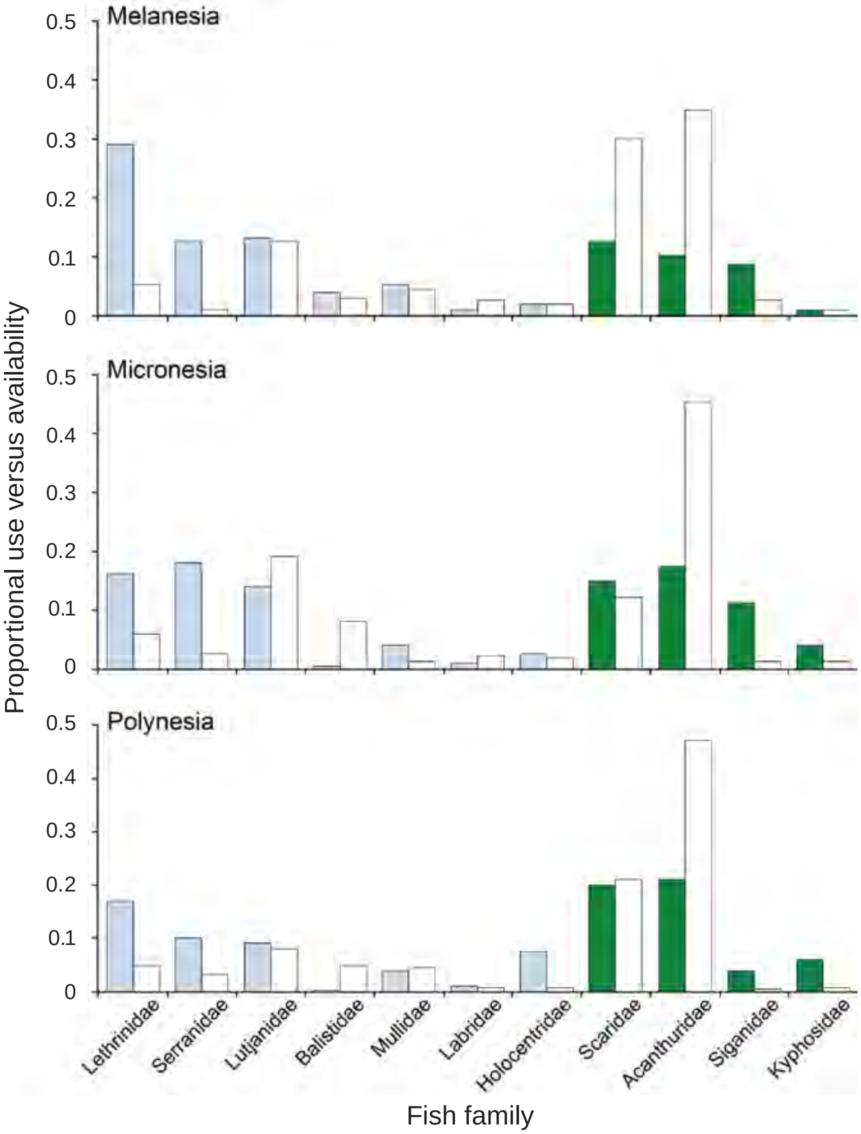


Figure 9.2 Proportional use versus availability of the 11 most harvested families of demersal fish. Proportional use (solid column) was estimated from extrapolated catches from socio-economic surveys conducted in 4–5 coastal fishing communities within each Pacific Island country and territory (PICT) between 2002 and 2008. Availability of each family (blank column) was assessed based on average biomass (tonnes per km^2) estimated using visual census at 1–4 coral reef habitats at 4–5 sites within each of 17 PICTs, between 2002 and 2008. The primary trophic group of each family is designated as carnivore (blue) or herbivore (green) (source: SPC PROCFish Project).

The fishing methods used to catch demersal fish in the tropical Pacific are diverse (**Figure 9.1**). They include handlines, gill nets, spearguns and handheld spears, cast and scoop nets, and mobile and permanent artisanal and commercial fish traps. The traps are made from stones, sticks and/or wire mesh and concentrate fish as they retreat from shallow habitats during tidal exposure, or pass through passages to atoll lagoons. Traditionally, fish are also chased into 'drive-in' nets and corrals[1]. Handlines are used more frequently in Melanesia, than in Micronesia and Polynesia, whereas handspears, spearguns and gill nets are widespread[43]. The fishing method influences the range of species caught[44], as well as the impact of fishing on the habitat. Highly destructive fishing practices (e.g. dynamite, derris root and cyanide) rapidly deplete both target and non-target species, and also contribute to habitat degradation, further increasing the likelihood of overfishing.

Table 9.2 Average biomass (tonnes per km^2) of commonly harvested demersal fish families associated with coral reef habitats. Information derived from underwater visual census at 1–4 coral reef habitats at 4–5 sites within each of 17 Pacific Island countries and territories (PICTs) between 2002 and 2008. The trophic group of each family is designated as carnivore (C) or herbivore (H), based on the predominant role of species within each family (source: SPC PROCFish Project).

PICT	Family (trophic group)										
	Acanthuridae (H)	Scaridae (H)	Lutjanidae (C)	Lethrinidae (C)	Balistidae (C)	Mullidae (C)	Serranidae (C)	Labridae (C)	Holocentridae (C)	Siganidae (H)	Kyphosidae (H)
Melanesia	**40.9**	**35.0**	**15.0**	**6.6**	**2.9**	**4.5**	**2.3**	**3.0**	**2.2**	**3.5**	**1.3**
Fiji	27.2	30.6	10.2	4.4	1.1	3.2	1.4	3.5	0.7	4.8	0.2
New Caledonia	26.3	41.3	3.3	3.1	0.3	3.8	2.4	2.1	0.4	3.4	0.1
PNG	54.5	29.3	20.2	6.5	2.8	4.1	1.9	2.5	3.6	1.9	1.9
Solomon Islands	44.7	22.4	21.8	13.1	7.5	7.9	3.2	2.8	4.0	4.3	0.2
Vanuatu	51.8	51.7	19.4	5.8	2.7	3.4	2.8	4.3	2.1	3.2	4.3
Micronesia	**62.3**	**16.6**	**25.7**	**8.9**	**12.5**	**2.1**	**4.1**	**3.4**	**2.0**	**0.9**	**1.3**
FSM	28.3	25.9	10.2	9.1	1.7	1.6	0.7	1.3	1.7	0.8	1.3
Kiribati	72.9	18.5	88.4	18.4	24.2	2.7	12.6	12.2	2.7	0.2	3.6
Marshall Islands	22.0	17.3	10.8	8.4	1.3	3.3	3.8	0.9	2.0	1.1	0.0
Nauru	153.4	6.9	4.3	4.5	34.2	0.2	2.1	0.1	1.5	0.1	21.2
Palau	34.8	14.5	14.6	4.2	1.2	2.9	1.3	2.3	2.2	2.2	0.4
Polynesia	**40.4**	**17.8**	**7.3**	**4.8**	**3.9**	**3.6**	**2.7**	**1.5**	**1.1**	**0.8**	**1.6**
Cook Islands	59.3	13.8	1.2	3.0	1.7	12.3	3.9	1.8	0.6	0.3	0.7
French Polynesia	23.2	25.4	2.7	4.7	5.4	4.0	1.7	1.2	0.5	0.7	0.0
Niue	35.0	11.2	1.6	0.8	3.5	1.5	2.2	0.8	0.3	0.0	2.4
Samoa	43.7	24.3	7.8	3.0	4.6	2.4	0.8	1.0	1.4	1.2	0.3
Tonga	12.3	8.6	0.9	0.7	0.2	1.7	0.6	1.3	1.0	0.5	0.0
Tuvalu	77.7	32.4	26.7	14.6	10.7	0.8	7.7	3.6	1.3	1.6	6.8
Wallis and Futuna	31.8	8.8	10.5	6.8	1.4	2.2	1.8	0.9	2.8	0.5	0.7

In all but the most remote locations, demersal fish contribute to both food security (subsistence) and livelihoods (to earn income through sales at markets) in rural and urban areas. In general, however, catches for subsistence far exceed those made for sale, often by several-fold[5,45] (Section 9.2.2). Small-scale commercial (artisanal) fisheries for demersal fish are most important in PICTs where urban populations are large relative to the total population (e.g. Fiji, French Polynesia, Kiribati, New Caledonia and Tonga), or where the large urban areas or national or provincial capitals allow for market opportunities (e.g. PNG and Solomon Islands). In these PICTs, demersal fish are caught across a wide range of locations, including increasingly remote and outlying areas, to supply central markets[46].

Other ways in which coastal demersal fish have been used to earn income are through the capture of fish for the live fish food trade and the market for tropical marine ornamental products[47,48]. Several species of groupers, and the large wrasse, *Cheilinus undulatus* (Labridae), have been caught in some countries in the western Pacific to supply the export trade in live food fish. It is estimated that as much as 30,000 tonnes of live reef fish are caught per year within the Asia-Pacific region to supply this trade[49], although official figures are 13,000–14,000 tonnes per year, with an annual value of USD 350 million[50]. These highly valuable species are targeted by specialised operations[5,51]. However, catches from the Pacific have usually comprised < 10% of the trade and have recently ceased due to environmental concerns, and ciguatera poisoning from fish caught in Kiribati.

Smaller species associated with coral reefs, such as damselfish (Pomacentridae), butterflyfish (Chaetodontidae), wrasses (Labridae), triggerfish (Balistidae), cardinalfish (Apogonidae) and gobies (Gobiidae) are caught for export to the ornamental (aquarium) market in the United States, Asia and Europe[48,52–54]. This trade is estimated to be worth at least USD 300 million per year worldwide[55,56], and makes an important contribution to the national economies of several PICTs. For example, > 600 people are employed in the marine aquarium trade in Fiji. In Kiribati, coral reef aquarium fish account for 78% of export earnings. The trade is also significant in Vanuatu, which exports 180,000 aquarium fish each year[10]. Active fisheries for ornamental specimens also exist in Cook Islands, French Polynesia, Marshall Islands, Palau, Solomon Islands and Tonga[10,48].

9.2.1.2 Nearshore pelagic fish

Although the vast majority of the region's rich tuna resources are caught offshore by industrial fleets (Chapter 8), skipjack tuna *Katsuwonus pelamis*, yellowfin tuna *Thunnus albacares* and bigeye tuna *Thunnus obesus*, and a range of other large pelagic fish species, are also caught in nearshore waters (**Figure 9.3**). Together, these fish contribute significantly to coastal fisheries production and are used for both subsistence and earning income through sales to rural and urban markets. The large pelagic species are caught mostly by trolling along reef edges and within several kilometres of the coast. Increasingly, however, they are also being targeted using mid-water fishing techniques, such as vertical longlines, drop-stone and palu-ahi (mid-water handlines) around low-cost, anchored rafts or fish aggregating devices (FADs) deployed close to shore in depths < 1000 m[7,57].

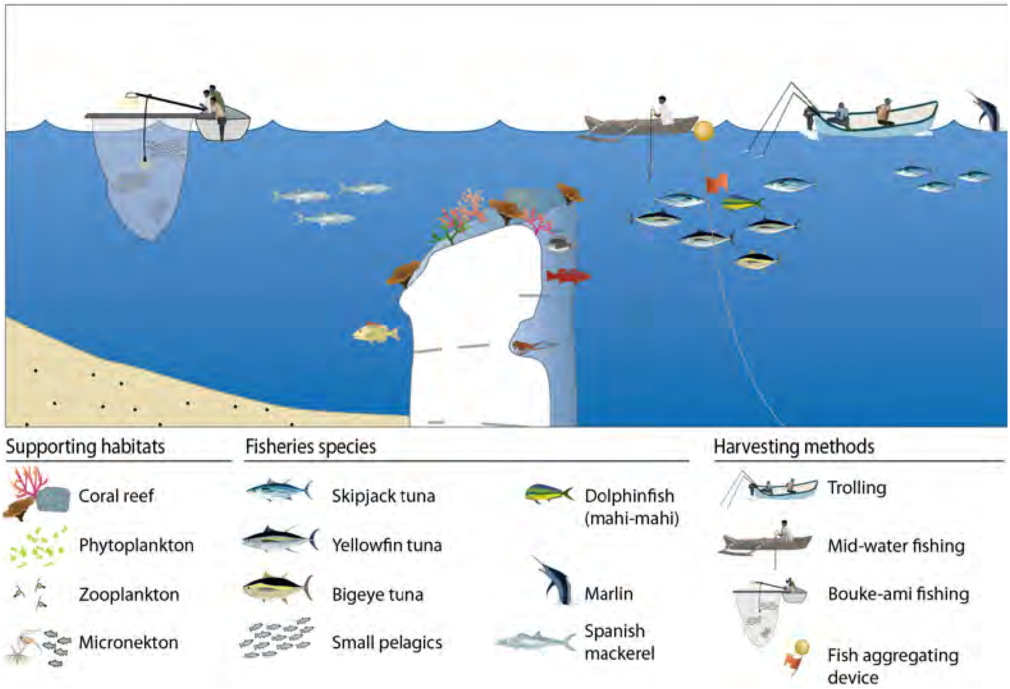


Figure 9.3 Habitats where large and small pelagic fish are caught by the nearshore fishery and the methods used to catch them, including fish aggregating devices (FADs).

Large pelagic fish other than tuna caught by the nearshore fishery include Spanish mackerel *Scomberomorus commerson*, barracuda *Sphyraena* spp., rainbow runner *Elagatis bipinnulata*, wahoo *Acanthocybium solandri*, mahi-mahi *Coryphaena hippurus*, sailfish *Istiophorus platypterus*, marlin *Makaira* spp. and *Tetrapturus* spp.[1]. Spanish mackerel is particularly important in PNG, Solomon Islands, Fiji and New Caledonia, because of the occurrence there of suitable nursery habitats – shallow lagoons fringed with mangroves[1].

Nearshore catches of large pelagic fish can be seasonal, with some of the more sought-after species (e.g. yellowfin tuna and mahi-mahi) caught mainly during cooler months[1]. Accurate information on the relative contribution of tuna and non-tuna species to the nearshore pelagic fishery is not available for many PICTs. This contribution varies among PICTs, however, for example in Niue the non-tuna species comprise more than two thirds of the catch, whereas in Cook Islands two thirds of the landings are tuna[10]. In most PICTs, non-tuna species are currently thought to dominate the nearshore pelagic fishery, because of the fishing methods used.

Small pelagic fish (< 500 g), comprising mackerel (Scombridae), scads (Carangidae), flying fish (Exocoetidae), pilchards and sardines (Clupeidae) and anchovies (Engraulidae), are also caught in nearshore waters throughout the tropical Pacific. They can represent an important part of production for subsistence catches, especially in PICTs with a limited reef area[1], and are one of the resources that could be harvested more widely for food security. Schools of small mackerel *Rastrelliger* spp., bigeye scad *Selar* spp. and mackerel scad *Decapterus* spp. are seasonally abundant and are exploited opportunistically using a combination of seine nets, gill nets, cast nets and scoop nets. Some artisanal fisheries target small pelagics to supply bait for industrial pole-and-line tuna fleets, for example, in Solomon Islands and Fiji[58,59].

In contrast to demersal fish, several species targeted by the nearshore pelagic fishery (tuna, mahi-mahi, wahoo, marlin and small pelagic species) are not highly dependent on coastal habitats. Thus, although these species associate closely with nearshore habitats for feeding and shelter, they are likely to be relatively insensitive to changes in coral cover and composition of coral species.

9.2.1.3 Targeted invertebrates

Fisheries for high-value invertebrates (**Figure 9.4**) have a long history throughout the tropical Pacific[1,60]. In fact, harvesting of sea cucumbers for processing into bêche-de-mer (or trepang) was the first intensive commercial fishery in the region, established in Fiji during the early 1800s[61]. Artisanal fisheries for sea cucumbers have brought considerable benefits to remote communities, and supported export enterprises in PICTs such as PNG, Solomon Islands, New Caledonia and Fiji. These benefits have accrued because the harvesting, processing and storage of sea cucumbers is relatively easy and requires no specialised equipment[62]. Exports of up to 1000 tonnes of bêche-de-mer per year were made from PNG and Fiji during peak production in the late 1980s[63] and have remained significant. For example, exports from PNG alone supplied up to 10% of bêche-de-mer caught from the wild worldwide[64] before PNG's recent moratorium on harvesting of sea cucumbers under a national management plan. When exports of bêche-de-mer are converted to wet weight of sea cucumbers, the fisheries in Fiji, Solomon Islands and New Caledonia have landed between 19% and 32% of the weight of tuna caught by national tuna fleets from their exclusive economic zones (EEZs)[10]. The export value of bêche-de-mer from New Caledonia in 2007 (USD 5.3 million) was twice that of tuna[65].

Sea cucumbers have traditionally been collected from coral reef habitats by gleaning (opportunistic gathering) and snorkelling, but also commonly from seagrass meadows and soft substrata near mangroves. However, in some PICTs, the high value of sea cucumbers has induced fishers to invest in larger boats, SCUBA or hookah diving gear, and drag nets. Use of this equipment exacerbates the current overfishing of these valuable resources[66] (Section 9.2.3).

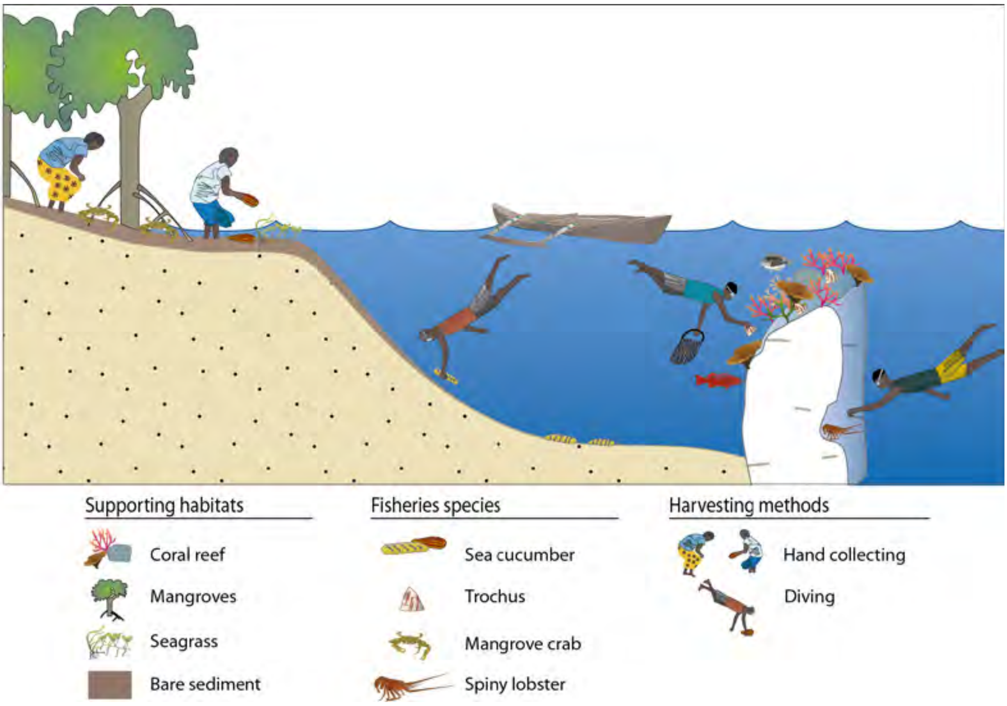


Figure 9.4 Habitats where invertebrates for export and sale to local markets are collected, and the methods used to catch them.

Several species of molluscs are harvested as export commodities in the tropical Pacific. The most important of these is the topshell *Trochus niloticus*, a herbivorous gastropod collected by diving on shallow coral reefs. The nacre of topshell (also known as trochus) has been in demand for buttons since the early 1900s[67], and this species has been extensively introduced beyond its normal geographic range to expand the economic benefits to other PICTs[1,68]. Trochus has contributed substantially to fishery exports for Cook Islands, Fiji, FSM, New Caledonia, PNG, Solomon Islands, Vanuatu and Wallis and Futuna. Over the past century, the combined harvests of topshell from Fiji, PNG and Solomon Islands exceeded 50,000 tonnes, with a present-day value of USD 200 million[10]. Green snail *Turbo marmoratus* has also been harvested and translocated in the tropical Pacific for its nacre, although the quantities involved are low compared with topshell[69]. Before the development of large-scale black pearl farming around 1980 (Chapter 11), ~ 450 tonnes of black-lipped pearl oysters *Pinctada margaritifera* collected from the wild were exported each year from French Polynesia and Cook Islands[70].

Commercial fisheries for crustaceans (spiny lobsters, mangrove crabs and coconut crabs) for sale at local and export markets also occur in many PICTs. Spiny lobsters were caught traditionally by skin divers for local markets, but are now the target of export fisheries in some PICTs, increasing the likelihood of overfishing. Mangrove crabs are caught mainly by being removed from their burrows at low tide, often by women, and are common at central markets in Fiji, FSM, New Caledonia, Palau, PNG, Solomon Islands and Vanuatu. Penaeid shrimp are the basis of a commercial trawl fishery in PNG. Most of the fleet operates in the Gulf of Papua and catches have been as high as 1000 to 1300 tonnes per year, while smaller trawl fisheries have been established at several other locations in PNG[71,72].

9.2.1.4 Shallow subtidal and intertidal invertebrates

Invertebrates inhabiting shallow reeftops and reef platforms, mangrove areas, seagrass meadows, and sand or mud flats exposed or accessible at low tide, are regularly gleaned by people in the tropical Pacific (**Figure 9.5**) (Chapter 6). A large variety of sessile or sedentary invertebrates are harvested in this way (**Table 9.3**). Gleaning is mainly a subsistence activity, although some gastropods are collected for their shells which are made into handicrafts and sold at markets. Several species of sea cucumbers are also collected, processed and sold as bêche-de-mer (see above). Importantly, gleaning is a fall-back fishery for times when adverse weather prevents sea-based fishing activities. The diversity of animals harvested may often be much greater than indicated in **Table 9.3**. For example, at least 50 species of molluscs alone are routinely harvested from shallow coral reefs and mangrove forests in Fiji, Guam, Palau, PNG and Tonga[1].

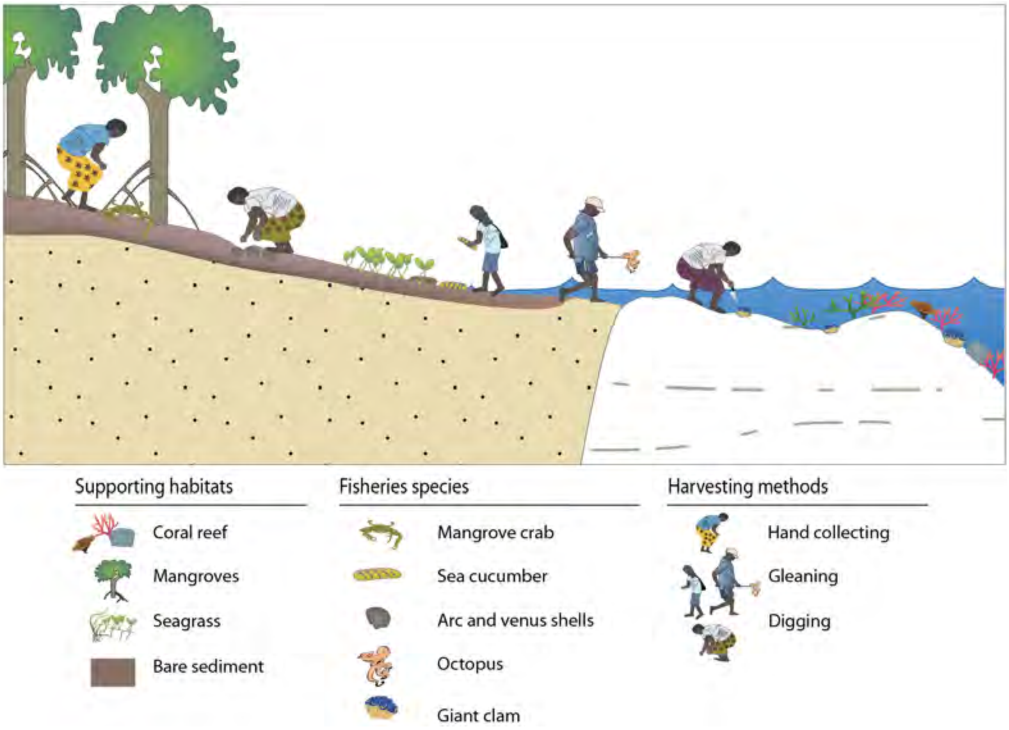


Figure 9.5 Shallow subtidal and intertidal habitats where invertebrates are collected by gleaning, together with a selection of the key species harvested.

Densities of invertebrate species on shallow intertidal reefs and in other coastal habitats can be high (**Table 9.4**). As a result, production from gleaning in subtidal and intertidal areas can be substantial. For example, annual harvests of arc shells *Anadara holoserica* were estimated to be 1800 tonnes for Tarawa Atoll and 3286 tonnes for the Gilbert Islands in the 1980s. Regrettably, potential harvesting of arc shells from Tarawa Lagoon is now threatened by the health risks associated with eating shellfish contaminated by deteriorating water quality, because of dense human populations. In general, harvests of intertidal invertebrates are dominated by bivalves (giant clams, arc and venus shells), echinoderms (sea cucumbers and sea urchins) and gastropods (turban shells, spider shells and trochus) (**Figure 9.6**).

Table 9.3 Average catch composition (percentage wet weight) of the major groups of invertebrates used for food and livelihoods in 17 Pacific Island countries and territories (PICTs). Information based on extrapolated catches from socio-economic surveys conducted in 4–5 coastal fishing communities within each PICT between 2002 and 2008 (source: SPC PROCFish Project).

PICT	Invertebrate groups								
	Giant clams	Sea cucumbers	Gastropods	Spiny lobsters	Crustaceans	Octopus	Bivalves	Trochus	Others
Melanesia									
Fiji	5.1	69.1	2.5	2.6	4.6	4.3	8.3	2.7	0.8
New Caledonia	10.2	5.5	8.1	18.3	28.4	6.5	7.1	15.9	0.0
PNG	13.8	52.1	15.8	3.2	3.6	6.2	4.6	0.8	0.0
Solomon Islands	49.8	0.7	12.7	5.5	12.9	0.8	6.6	9.1	2.0
Vanuatu	5.2	19.9	36.5	0.1	14.0	4.2	18.1	0.8	1.2
Micronesia									
FSM	34.4	13.9	2.1	31.9	3.5	5.9	0.7	7.6	0.0
Kiribati	60.7	3.6	1.5	12.4	2.0	1.1	2.2	0.0	16.5
Marshall Islands	33.4	0.0	39.4	8.7	10.1	7.2	1.2	0.0	0.0
Nauru	0.0	12.3	28.6	10.5	33.5	13.4	0.8	0.7	0.0
Palau	28.5	68.9	0.0	0.7	1.9	0.0	0.0	0.0	0.0
Polynesia									
Cook Islands	30.8	24.4	15.4	15.3	4.3	2.3	2.7	0.8	4.0
French Polynesia	69.1	0.0	3.6	24.1	1.6	0.0	0.1	0.0	1.5
Niue	5.0	3.9	72.1	10.6	5.8	1.2	1.3	0.0	0.0
Samoa	34.4	45.0	2.4	2.1	7.4	3.9	3.1	1.1	0.6
Tonga	24.7	17.4	14.3	8.5	0.0	28.4	0.9	0.0	5.8
Tuvalu	7.5	0.0	46.1	27.5	3.3	2.8	12.7	0.0	0.0
Wallis and Futuna	15.4	1.9	7.7	30.8	9.0	2.2	3.1	29.9	0.0

The species composition and relative abundance of invertebrate catches from coral reefs, and other coastal habitats has been documented across the tropical Pacific (**Table 9.3**), but the total contribution of gleaning to coastal fisheries production for food security is largely unknown. The importance of intertidal gleaning to historical and contemporary seafood consumption is often overlooked, mostly because the entire catch is consumed almost immediately and is highly variable and difficult to characterise. Catches of the larger and more conspicuous invertebrates (e.g. octopus) have often been incorporated in estimates of subsistence reef fisheries[45], but such species may represent only a small percentage of the total fisheries production from gleaning[1] (**Figure 9.6**).

Table 9.4 Mean densities (individuals per ha) of commonly harvested groups of invertebrates caught mainly for export commodities (in light blue), or gleaned from shallow subtidal and intertidal habitats for food security and livelihoods (in darker blue). Information derived from surveys at 4–6 sites in 17 Pacific Island countries and territories (PICTs) between 2002 and 2008 (source: SPC PROCFish Project).

	Invertebrate group														
	Sea cucumbers				**Mother-of-pearl**			**Gastropods**		**Bivalves**				**Others**	
PICT	*Holothuria whitmaei*	*Holothuria scabra*	*Bohadschia argus*	*Holothuria atra*	*Trochus niloticus*	*Pinctada margaritifera*	*Tectus pyramis*	*Turbo* spp.	*Lambis lambis*	*Tridacna maxima*	*Tridacna squamosa*	*Tridacna gigas*	*Anadara* spp. (per m^2)	*Tripneustes gratilla*	*Panulirus* spp.
Melanesia															
Fiji	0.1	72	3.7	174	52	1.8	77	69	8.3	769	8.2	0.0	5.8	16.1	0.2
New Caledonia	5.3	418	22.1	59	252	3.2	226	123	13.5	462	2.8	0.0	1.3	0.2	0.7
PNG	0.8	63	1.8	3	40	2.5	93	18	11.8	244	8.3	0.5	0.1	52.9	1.3
Solomon Islands	0.2	4	1.0	6	20	2.5	141	59	17.1	105	2.9	> 0.1	0.6	0.7	1.5
Vanuatu	1.1	428	5.3	88	188	1.7	23	35	10.3	80	4.0	0.0	2.3	0.5	0.4
Micronesia															
FSM	1.6	0	5.6	70	336	0.9	23	68	8.1	79	0.7	0.0	0.0	> 0.1	0.2
Kiribati	0.2	0	3.5	988	0	3.5	1	0	0.0	5665	1.0	> 0.1	25.8	0.0	0.5
Marshall Islands	0.2	0	2.4	302	16	2.2	3	10	9.3	1024	6.7	0.4	0.0	0.0	0.1
Nauru	0.0	0	0.0	2	0	0.0	0	50	0.0	0	0.0	0.0	0.0	0.0	0.0
Palau	8.4	281	15.7	116	299	2.8	129	32	29.5	240	14.1	0.8	0.0	0.0	0.6
Polynesia															
Cook Islands	0.1	0	0.4	4350	608	0.2	0	1	0.0	635	0.0	0.0	0.0	23.5	0.0
French Polynesia	0.0	0	33.2	1306	1387	2.4	0	35	0.0	5657	0.0	0.0	0.0	0.4	> 0.1
Niue	0.3	0	0.3	0	0	0.0	0	0	0.0	215	0.0	0.0	0.0	0.0	0.0
Samoa	1.1	0	16.2	2231	0	0.0	8	0	0.3	6	< 0.1	0.0	0.0	0.0	0.0
Tonga	3.9	0	19.3	670	195	2.1	65	26	1.3	61	1.0	0.0	0.1	0.5	0.1
Tuvalu	0.7	0	2.7	3	0	0.0	36	3	0.0	78	5.0	0.0	0.0	0.0	> 0.1
Wallis and Futuna	4.3	1.1	17.2	603	91	0.0	15	7	0.0	51	0.0	0.0	0.3	0.0	0.1

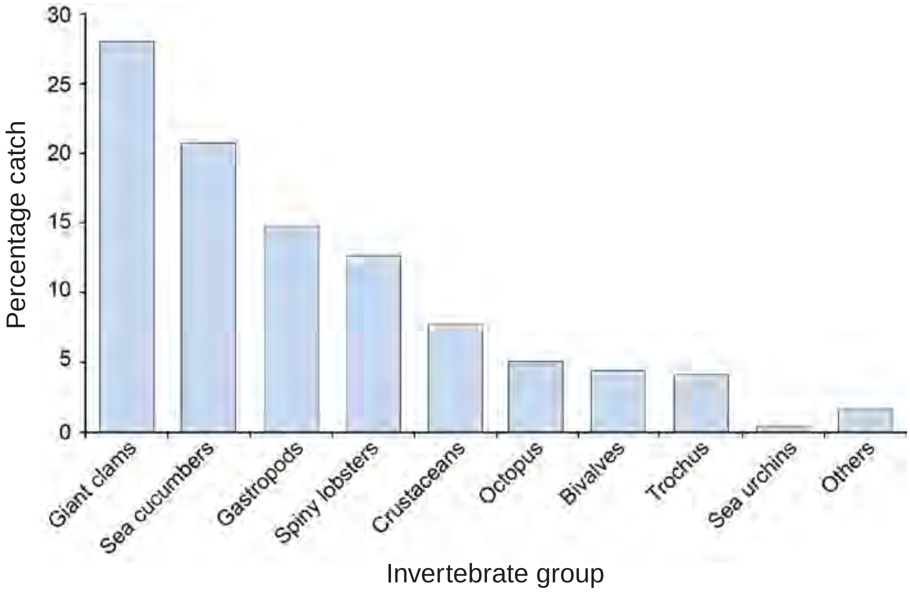


Figure 9.6 The main groups of invertebrates harvested by gleaning and free-diving from shallow subtidal and intertidal habitats in Pacific Island countries and territories (PICTs). Values are percentages of total reported catch (wet weight). Information based on socio-economic surveys conducted in 4–5 coastal fishing communities within 17 PICTs between 2002 and 2008 (source: SPC PROCFish Project).

9.2.2 Recent harvest levels, stock status and estimated sustainable yields

The existing level of harvesting in coastal fisheries throughout much of the world is generally regarded as unsustainable, and in many cases the resources are already over-exploited[73,74]. Despite some notable errors[75], Newton et al.[17] suggested that inshore fisheries, and specifically coral reef fisheries, have collapsed in 18% of tropical island countries worldwide, and are fully- or over-exploited in a further 17% of countries. The sustainability of coastal fisheries depends on the area and quality of critical coastal habitats, relative to the level of exploitation. Many coastal fish and invertebrates are associated with specific habitat types (e.g. coral reefs, seagrasses and mangroves) (Chapters 5 and 6), and decline in abundance after the degradation or loss of these habitats[76]. Major causes of habitat degradation (Section 9.1) generally increase with human population densities, further compounding the ecological impacts of overfishing. However, fisheries exploitation is relatively low within most PICTs compared with other parts of the world, due to relatively small human populations[75].

Estimates of coastal fisheries production in the tropical Pacific in 2007[5] indicate that production totalled ~ 155,000 tonnes across the 22 PICTs, of which 110,000 tonnes resulted from subsistence fishing and ~ 45,000 tonnes from commercial (artisanal) activities (**Table 9.5**). Although subsistence catches exceeded commercial catches in 19 of 22 PICTs (**Table 9.5**), many studies have suggested that subsistence catches are likely to be grossly under-estimated[4,5,8]. Despite the overwhelming importance of subsistence and small-scale artisanal fisheries, there is no uniform system to measure the composition and volume of national fish consumption, or sales of seafood at local markets[4,5]. Therefore, national estimates of coastal fisheries production are often based largely on extrapolation of fish consumption per person derived from household income and expenditure surveys (HIES)[5,7,17].

Table 9.5 Estimated area of coastal habitat and subsistence and commercial coastal fisheries production for all Pacific Island countries and territories (PICTs). Standardised estimates of total fisheries production per area of coastal habitat, and human population density in 2010, are also shown.

PICT	Coastal habitat		Coastal fisheries production (tonnes per year)[c]			Standardised fisheries production (tonnes per km^2 per year)	Population density (no. people per km^2 coastal habitat)[d]
	Area (km^2)[a]	Coral reef (%)[b]	Subsistence	Commercial	Total		
Melanesia							
Fiji*	10,020	?	17,400	9500	26,900	2.68	85
New Caledonia	35,930	12.7	3500	1350	4850	0.13	7
PNG*	22,178	?	30,000	5700	35,700	1.61	135
Solomon Islands	12,635	56.0	15,000	3250	18,250	1.44	43
Vanuatu	1250	56.8	2830	538	3368	2.69	196
Micronesia							
FSM	15,070	21.0	9800	2800	12,600	0.84	7
Guam	240	77.1	70	44	114	0.48	780
Kiribati	4160	47.4	13,700	7000	20,700	4.98	24
Marshall Islands	13,570	14.7	2800	950	3750	0.28	4
Nauru	5	100.0	450	200	650	130.00	2000
CNMI	250	40.0	220	231	451	1.80	82
Palau	2975	23.9	1250	865	2115	0.71	21
Polynesia							
American Samoa	365	17.8	120	35	155	0.42	181
Cook Islands	665	31.6	267	133	400	0.60	24
French Polynesia	15,130	19.8	2880	4002	6882	0.45	18
Niue	55	54.5	140	10	150	2.73	27
Pitcairn Islands	50	80.0	7	5	12	0.24	1
Samoa	465	43.0	4495	4129	8624	18.50[e]	394
Tokelau	210	47.6	375	0	375	1.79	6
Tonga	6160	58.3	2800	3700	6500	1.06	17
Tuvalu	3170	27.4	989	226	1215	0.38	4
Wallis and Futuna	930	45.7	840	121	961	1.03	15
Total	**145,483**	**19.9**	**109,933**	**44,789**	**154,722**	**1.06**	**42**

* Preliminary estimates only; a = information derived from Dalzell et al. (1996)[1] and Institut de Recherche pour le Développement; b = Chapter 5; c = Gillett (2009)[5]; d = SPC Statistics for Development Programme; e = reduces to 16.40 when deep-slope species are removed.

Catches from distinct fisheries sectors, such as the four categories of resources described in Section 9.2.1, are almost never differentiated in national fisheries statistics or household income and expenditure surveys. At best, estimates of volume and value of coastal fisheries are divided into subsistence versus commercial catches[5]. This classification is a major impediment to understanding the contribution of demersal fish, nearshore pelagic fish, targeted invertebrates and shallow subtidal and intertidal invertebrates to food security and livelihoods, and to measuring the success of management to optimise the benefits from these resources. For example, tuna and other pelagic species clearly make a significant but unquantified contribution to coastal fisheries production in Nauru, as well as Samoa and Kiribati[5], and greatly affect estimates of standardised fisheries production for these PICTs (**Table 9.5**).

To address this problem, we used the results from the socio-economic surveys conducted during the SPC PROCFish Project[10] (Appendix 9.1) to disaggregate estimates of national subsistence and commercial catches in 2007[5] into the four categories of coastal fisheries (**Table 9.6**, Appendices 9.1 and Supplementary **Table 9.1** at www.spc.int/climate-change/fisheries/assessment/chapters/12-supp-tables.pdf). The surveys conducted by the SPC PROCFish project also provide information on the status of important families of demersal fish, and the two groups of invertebrates, across a subset of 17 PICTs.

9.2.2.1 Fisheries for demersal fish

Demersal fish dominate the catch from coastal fisheries in the tropical Pacific – they are estimated to yield 86,000 tonnes per year and account for an average of 56% of the total coastal fisheries production, ranging from ~ 30% to 80% among PICTs (**Table 9.6**). As highlighted above, the majority of demersal fish are caught by subsistence fishing.

The status of demersal fish stocks throughout much of the tropical Pacific is poorly known, because of the lack of long-term catch records. However, two broad measures indicate that demersal fish populations are not as over-exploited as in many other developing countries. First, recent estimates of national-level fish catches[5], converted to production per area, show that the majority of PICTs are harvesting < 2 tonnes of seafood per km^2 per year from coastal habitats (**Table 9.5**). Given that only a portion (at most ~ 80%) of the catch comprises demersal fish, such harvests appear to be sustainable (see estimated sustainable yields below). Second, underwater visual surveys of coral reef fish at 4 to 5 sites in each of 17 PICTs show that the biomass of commonly caught species is often in the range of 50 to 250 tonnes per km^2 (**Figure 9.7**), suggesting that stocks of coral reef fish have the potential to sustain substantial harvests in many locations across the region.

These broad indicators need to be interpreted with caution, however. As mentioned earlier, the extent to which estimates of subsistence catches may have been underestimated is unknown[4,5]. Also, low standardised catches for PICTs with large areas of coastal habitat relative to their human populations (**Table 9.5**) do not account for significant spatial variation in exploitation (Box 9.1). In most PICTs, dense human populations occur around provincial centres and urban areas, where intense fishing is likely to lead to localised over-exploitation. Fish stocks may also be over-exploited in areas of low development and low human population densities, if efficient transportation exists that enables increased sale of fish in urban centres.

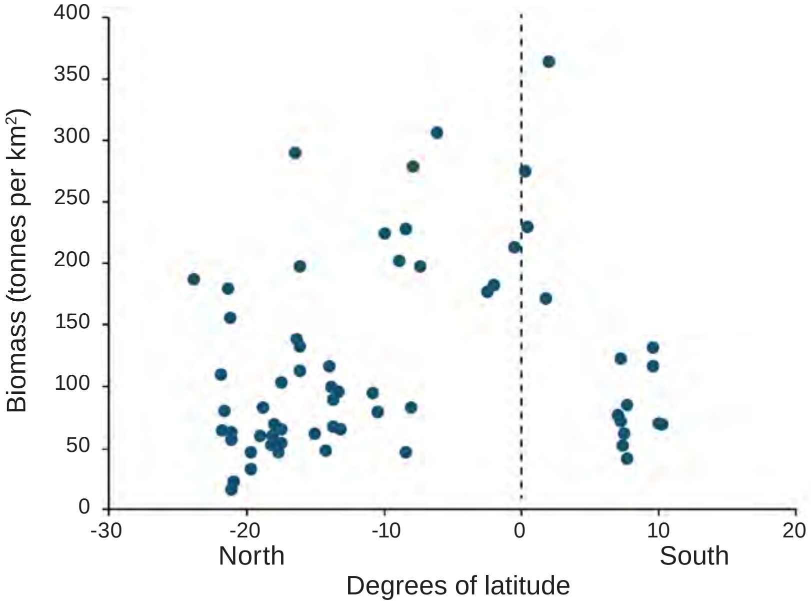


Figure 9.7 Mean biomass (tonnes per km^2) of commonly harvested demersal fish associated with coral reefs at 63 sites from 17 Pacific Island countries and territories (PICTs). Sites are plotted by distance from the equator (degrees of latitude N and S). Information derived from underwater visual census within each PICT between 2002 and 2008 (source: SPC PROCFish Project).

Another important consideration in assessing the status of fisheries for demersal fish is the extent to which fishing is concentrated on different species, especially those considered to play an important role in maintaining the resilience of coral reefs. Foremost among functionally important reef fish, are the herbivorous species that keep reefs relatively free of macroalgae, thereby facilitating the settlement and growth of habitat-forming corals[19]. The role of these fish is especially important given the increasing incidence of coral loss due to climate change[18]. Over-exploitation of herbivorous fish may ultimately lead to a 'phase-shift', where reef habitats become dominated by macroalgae[77,78]. Such phase shifts threaten the status of other reef-associated fish, which is a cause for concern because herbivorous fish (parrotfish, surgeonfish and rabbitfish) comprise a large proportion of the catch in several PICTs (**Table 9.1**). Furthermore, the proportions of parrotfish and rabbitfish in catches are greater than those occurring on reefs (**Figure 9.2**).

A comparison of the recent status of commonly-caught demersal fish with the catch rates of these fish at 63 sites across 17 PICTs, using an approach that integrates many of the key factors outlined above[79], is shown in **Figure 9.8**. The status of demersal fish at 38% of sites was estimated to be poor to medium even though current fishing pressure is low. Such sites appear to have limited potential to produce fish, or productivity may have already been compromised by historical overfishing and/or habitat degradation. Another 25% of sites were in more serious trouble – the status of demersal fish resources was poor to medium and they were subject to high fishing pressure. Demersal fish resources at another 17% of sites had medium to good status but fishing pressure was high and probably unsustainable. Only 19% of sites had medium to good resource status and low fishing pressure.

Table 9.6 Preliminary annual estimated catches in tonnes, and as a percentage of total catch, for the four categories of coastal fisheries in all Pacific Island countries and territories (PICTs). See Appendices 9.2 and Supplementary Table 9.1 (www.spc.int/climate-change/fisheries/assessment/chapters/12-supp-tables.pdf) for the derivation of these estimates.

PICT	Demersal fish		Nearshore pelagic fish		Targeted invertebrates		Sub/intertidal invertebrates		Total catch (tonnes)
	tonnes	%	tonnes	%	tonnes	%	tonnes	%	
Melanesia									
Fiji	17,450[d]	64.9	5270[a]	19.6	630	2.3	3550	13.2	26,900
New Caledonia	2670	55.1	560[a]	11.5	300[e]	6.2	1320	27.2	4850
PNG	14,520	40.7	13,760[a]	38.6	1300[f]	3.6	6120	17.1	35,700
Solomon Islands	8925	48.9	5750[a,g]	31.5	950	5.2	2625	14.4	18,250
Vanuatu	1730	51.3	753[a]	22.4	70	2.1	815	24.2	3368
Micronesia									
FSM	6290	49.9	3560[b]	28.3	30	0.2	2720	21.6	12,600
Guam	33	28.9	77[b]	67.6	0	0.0	4	3.5	114
Kiribati	15,075	72.8	4250[c]	20.5	60	0.3	1315	6.4	20,700
Marshall Islands	2417	64.4	1080[a]	28.8	3	0.1	250	6.7	3750
Nauru	310	47.7	310[c]	47.7	0	0.0	30	4.6	650
CNMI	260	57.6	161[a]	35.7	0	0.0	30	6.7	451
Palau	950	44.9	680[a]	32.2	100	4.7	385	18.2	2115
Polynesia									
American Samoa	92	59.4	47[a]	30.3	0	0.0	16	10.3	155
Cook Islands	146	36.5	240[c]	60.0	0	0.0	14	3.5	400
French Polynesia	3666	53.3	2582[c]	37.5	104	1.5	530	7.7	6882
Niue	62	41.3	75[a]	50.0	0	0.0	13	8.7	150
Pitcairn Islands	10	83.4	1[a]	8.3	0	0.0	1	8.3	12
Samoa	4419	51.2	2550[b]	29.6	0	0.0	1655	19.2	8624
Tokelau	182	48.5	150[c]	40.0	0	0.0	43	11.5	375
Tonga	5245[h]	80.7	650[b]	10.0	0	0.0	605	9.3	6500
Tuvalu	837	68.9	326[b]	26.8	0	0.0	52	4.3	1215
Wallis and Futuna	718	74.7	106[a]	11.0	17	1.8	120	12.5	961
Total	**86,007**	**55.6**	**42,938**	**27.8**	**3564**	**2.3**	**22,213**	**14.4**	**154,722**

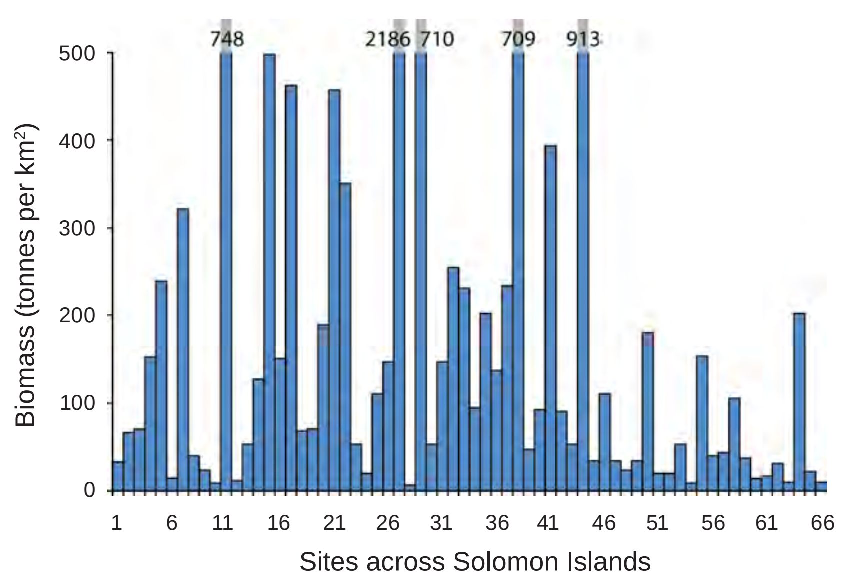
a = Nearshore pelagic fishery dominated by non-tuna species; b = nearshore pelagic fishery comprised equally of non-tuna and tuna species; c = nearshore pelagic fishery dominated by tuna; d = includes deepwater snappers; e = includes mangrove crabs and spiny lobsters sold on local market; f = includes hundreds of tonnes of penaeid shrimp; g = includes 800 tonnes of baitfish; h = includes 700 tonnes of deepwater snappers.

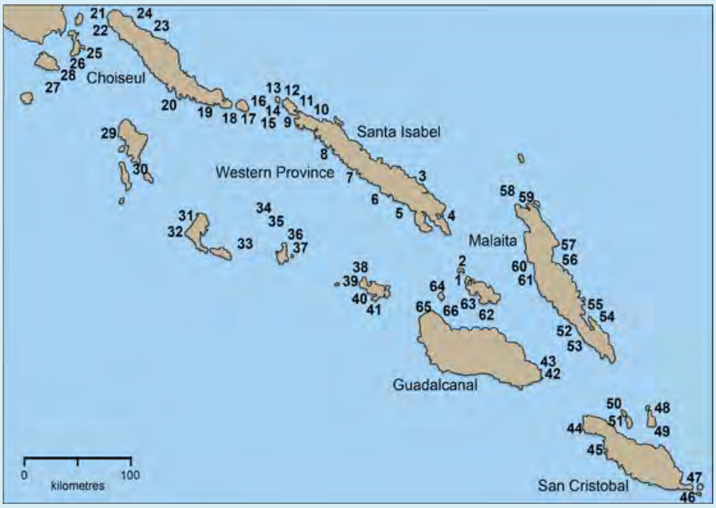
Box 9.1 Within country variation in fisheries resources and exploitation: Case study from Solomon Islands

For much of the tropical Pacific, the fine-scale patterns in the abundance and distribution of coastal fisheries species, and variation in the nature and extent of fisheries activities, are poorly understood. Yet the factors that contribute to fisheries depletion often operate at local scales. For example, the supply of larvae to replenish fished stocks varies at the scale of islands or reefs[259–261]. The size of coastal communities, and the extent of their impacts on coastal fish habitats and stocks, e.g. through sedimentation from poor coastal development (Chapters 5–7), destructive fishing and over-harvesting, also vary at localised scales[81].

How these factors and impacts interact to affect multi-species coastal fisheries within PICTs is still not well understood. Depletion of resources is more likely to be exacerbated where these effects coincide. Without adequate understanding of the factors that affect the status of resources, the incidence of localised stock depletion is likely to increase, leading to reduced resilience of coral reef ecosystems[19].

The information on the abundance of coastal fisheries species at 66 sites across Solomon Islands[262] illustrated here shows the variability in the status of local resources within a country. The highly variable abundance of demersal fish in Solomon Islands is attributable to differences in habitat quality, levels of exploitation, resource management practices, and accessibility to markets[46]. This variation calls for a better understanding of coastal fisheries, including local abundance of key species, quality of fish habitats, socio-economic conditions and cultural practices.





Coral reef habitats are generally expected to yield 3 tonnes of demersal fish per km^2 of reef habitat per year[17]. This yield is the median value for estimates of maximum sustainable production from diverse multispecies coral reef fisheries and, provided that relative species composition remains stable, consistent harvests at this level are likely to be possible. This value is consistent with estimates of long-term (20 years) sustained harvests of 2.9 to 3.7 tonnes per km^2 from Fiji[80]. However, as indicated in **Figures 9.7** and **9.8**, sustainable harvests from coral reefs will vary considerably depending on their condition and productivity. For example, reefs in Fiji with low impacts from land-based activities have been estimated to provide sustained yields of at least 10 tonnes per km^2 per year[81]. Documented yields in 43 locations in the tropical Pacific range from 0.3 to 64 tonnes per km^2 per year[82], and earlier surplus production yield curves suggested a maximum sustainable yield for reef fish in the region of 6 to 20 tonnes per km^2 per year[1].

Although coral reefs are the most significant habitat for coastal fisheries across the region (**Table 9.5**), mangroves, seagrasses, intertidal sand and mud flats also play an important role, both in enhancing productivity of nearby coral reef habitats, and sustaining fisheries production in their own right[83] (Chapter 6). Many of the fish that occupy coral reef habitats as adults reside in other habitats as juveniles[84], although the extent to which these habitats actually contribute to fisheries production on coral reefs is still unknown. The important question is how much of coastal demersal fish production would be lost if there was widespread degradation of mangroves, seagrasses and intertidal flats? To address this issue, catches of demersal fish from distinct habitat types need to be assessed.

If national fisheries production is standardised according to the area of coral reef habitats (rather than all coastal habitats), it exceeds 3 tonnes of seafood per km^2 of reef habitat per year for 10 out of 22 PICTs. Harvest levels of demersal fish are presently

< 3 tonnes per km^2 of reef per year in American Samoa, Cook Islands, French Polynesia, Guam, Marshall Islands, New Caledonia, Palau, Pitcairn Islands, Solomon Islands, Tonga, Tuvalu and Wallis and Futuna.

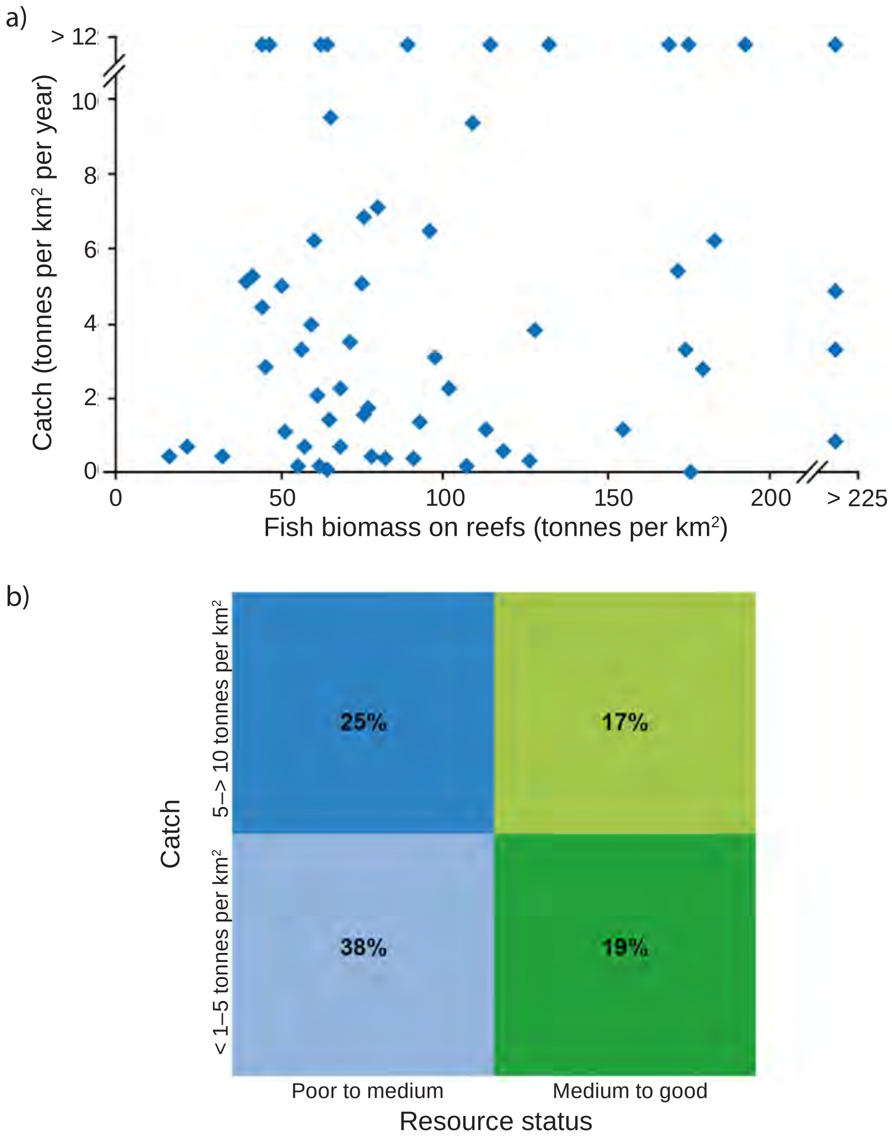


Figure 9.8 Relationships between the status and catches of demersal fish at 63 sites in 17 Pacific Island countries and territories, for the 11 families of fish listed in Table 9.1, based on (a) estimates of fish biomass from underwater visual surveys and socio-economic surveys of adjacent fishing communities; and (b) a more integrated approach to assessing resource status, which combines features of the fish community (size composition from size spectra slopes, differences between cumulative biomass and density dominance curves, relative density of large species, relative biomass of small fish and piscivores, and the ratio of herbivores to carnivores) and site quality (distance from centre of biodiversity, number of reef types, and proportion of the outer-reef surface area) (source: Kronen et al. 2010, Pinca et al. 2011, SPC PROCFish Project)[79,271].

9.2.2.2 Fisheries for nearshore pelagic fish

Large and small pelagic fish also make a significant contribution to the production of coastal fisheries in many PICTs. They are estimated to yield 43,000 tonnes annually, and to make up an average of 28% of total coastal fisheries production, ranging from ~ 10 to 70% among PICTs (**Table 9.6**). In 12 of the 22 PICTs, species other than tuna are estimated to collectively dominate the catch of nearshore pelagic fish (**Table 9.6**). In the remainder of PICTs, tuna (especially skipjack and yellowfin tuna) make up 50% or more of this component of coastal fisheries.

The status of the main species of tuna caught in the nearshore pelagic fishery is monitored closely by the SPC Oceanic Fisheries Programme[85] (Chapter 8). The biomass of the most abundant species in tropical waters, skipjack tuna, remains high and fishing mortality is low. The status of yellowfin tuna is also considered reasonable, with fishing mortality still below the level recommended to achieve maximum sustainable yield, although the impacts of fishing are apparent in the tropical western Pacific (Chapter 8). On the other hand, the present catch rate of bigeye tuna throughout the Western and Central Pacific Ocean is now considered to be unsustainable (Chapter 8). There are few concerns about the status of the other truly oceanic fish species caught by coastal fisheries (mahi-mahi, wahoo, rainbow runner, sailfish and marlin).

The status of pelagic species more closely associated with coastal habitats, such as Spanish mackerel and barracuda, is largely unknown because catch data and knowledge of the population biology and regional abundance of these species are limited. However, Spanish mackerel populations have very low levels of connectivity[86] and there is, therefore, considerable risk of localised depletion.

There is little concern about the status of the small pelagic species used for subsistence and bait. The target species have regular rates of replenishment due to their multiple-spawning reproductive strategy, rapid growth and early recruitment[87]. Even when the pole-and-line tuna fleet in Solomon Islands was operating at its maximum capacity, annual catches of baitfish of around 2000 tonnes per year were considered to be sustainable[59].

The nearshore fisheries take only a tiny fraction of the regional harvests of skipjack and yellowfin tuna, and catches of these two species by the coastal fisheries sector could be increased greatly. The need to do so to provide food security for coastal communities is being actively promoted[4,88]. Ultimately, this increase will involve more of the recommended national sustainable catches of tuna being allocated for this purpose. Such allocations are likely to be in the range of 5–10% of total recommended catches by 2035 (Chapter 12). Increasing fisheries production from nearshore pelagic resources may be used to offset increasing fishing pressure on demersal fish. The fact that tuna and other pelagic species already contribute significantly to coastal fisheries in many PICTs[1,5,10] (**Table 9.6**) suggests that the rates at which demersal fish are being harvested may not be as great as the standardised production figures in **Table 9.5** indicate.

9.2.2.3 Fisheries for targeted invertebrates

Disaggregating the total regional catch from coastal fisheries shows that invertebrates targeted for export commodities make up only about 2% (~ 3500 tonnes) of the total harvest (**Table 9.6**). However, the relatively low catches of targeted invertebrates belie the importance of this fishery, which can contribute significantly to export income in some PICTs[5]. Sea cucumbers often dominate this component of the catch, and the fact that exports of these species comprise processed bêche-de-mer, which typically weighs < 10% of the harvested animals, also masks the importance of this fishery. National records indicate that around 1500 tonnes of bêche-de-mer were exported from the region in 2007. When this catch is converted to live weight, an additional ~ 13,500 tonnes needs to be added to the total harvests[64].

Underwater visual surveys of the densities of sea cucumbers and trochus by the SPC PROCFish Project show that these important resources have been severely overfished in many PICTs[10]. In general, densities of sea cucumbers of high and medium value in fished areas have been greatly reduced, compared with densities in protected and unfished sites in the region, or sites in PICTs where a moratorium has been in place on fishing for these species for at least 10 years[64]. These trends are illustrated by the densities of black teatfish across the Pacific (**Figure 9.9**). Similarly, analyses of the proportion of replicate counts made during surveys of sea cucumber abundance above or below a 'high status' threshold level, show that sea cucumbers have been overfished across most of the region (**Figure 9.10**). The potential yields of sea cucumbers remain low in many parts of the region due to this chronic overfishing. In an effort to restore stocks, some countries (e.g. Palau, PNG, Marshall Islands, Samoa, Solomon Islands and Tonga) have implemented long-term bans on the export of bêche-de-mer at various times. Such measures need to be maintained until densities well exceed the threshold needed for regular replenishment, and appropriate management plans to sustain increased catches are developed[66,89].

Most trochus stocks across the Pacific are also now at very low densities, and experiencing limited recruitment[10]. Only 12 of the 63 shallow water sites surveyed by the SPC PROCFish Project had densities of trochus great enough to support commercial operations (500–600 individuals per ha) (**Figure 9.11**). Interestingly, despite the large number of depleted sites, 44% of sites had 500–600 trochus per ha for at least one of the replicate counts during recent surveys[10]. This density indicates that many areas have potential for recovery provided effective management controls can be implemented to protect the number of adults required for successful reproduction. The potential for rapid recovery is also evident from the fact that viable fisheries for trochus have been established at several places in the Pacific after the introduction of relatively low numbers of adults[68,90,91].

9.2.2.4 Fisheries for shallow subtidal and intertidal invertebrates

The estimated catches of intertidal and subtidal invertebrates of ~ 22,000 tonnes per year, comprising 14% of all coastal fisheries production (**Table 9.6**), may well be underestimates because of the difficulties in effectively capturing the contribution of intertidal gleaning to subsistence catches. Moreover, the use of shallow subtidal and intertidal invertebrates increases when alternative fisheries are inaccessible, or collapse.

There are few reliable indicators of the status of invertebrates gleaned from shallow subtidal and intertidal coastal habitats. However, the densities of the giant clam *Tridacna maxima*, recorded during surveys by the SPC PROCFish Project in 17 PICTs from 2002 to 2008 is a useful one, particularly because giant clams are the invertebrates collected most frequently for food (**Figure 9.6**). Average densities of *T. maxima* were very high (> 5000 clams per ha) in Kiribati and French Polynesia (**Figure 9.12**), due to the suitability of habitats there[92] and low human population density. Elsewhere, however, their average density was < 1000 individuals per ha, and was especially low in PICTs with dense human populations, such as Nauru and Samoa (**Figure 9.12**, **Table 9.4**).

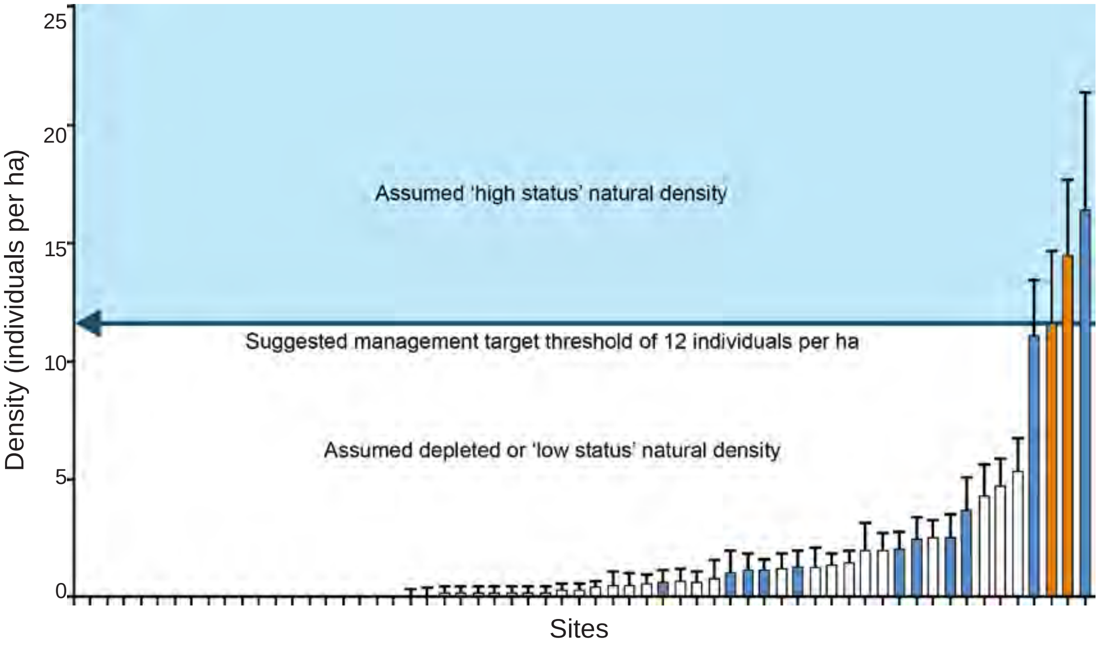


Figure 9.9 Mean density (individuals per ha, +SE) of the high-value black teatfish sea cucumber (*Holothuria whitmaei*) at a range of sites in the tropical Pacific where fishing has occurred (white bars), where fishing has been halted for a decade or more (blue bars), and where fishing has not been recorded in recent history (orange bars) (source: SPC PROCFish Project and, for a single site, S. Purcell, the WorldFish Center).

Whereas some species of spiny lobsters and crabs have proved to be vulnerable to over-exploitation[93], gleaning of infaunal bivalves such as arc and venus shells from soft substrata has remained productive even under heavy fishing pressure[94]. The opportunistic nature of subtidal and intertidal invertebrate fisheries suggests the presence of an element of self-regulation, which prevents localised depletion of most species. Large, rare or highly prized species will still be vulnerable, however.

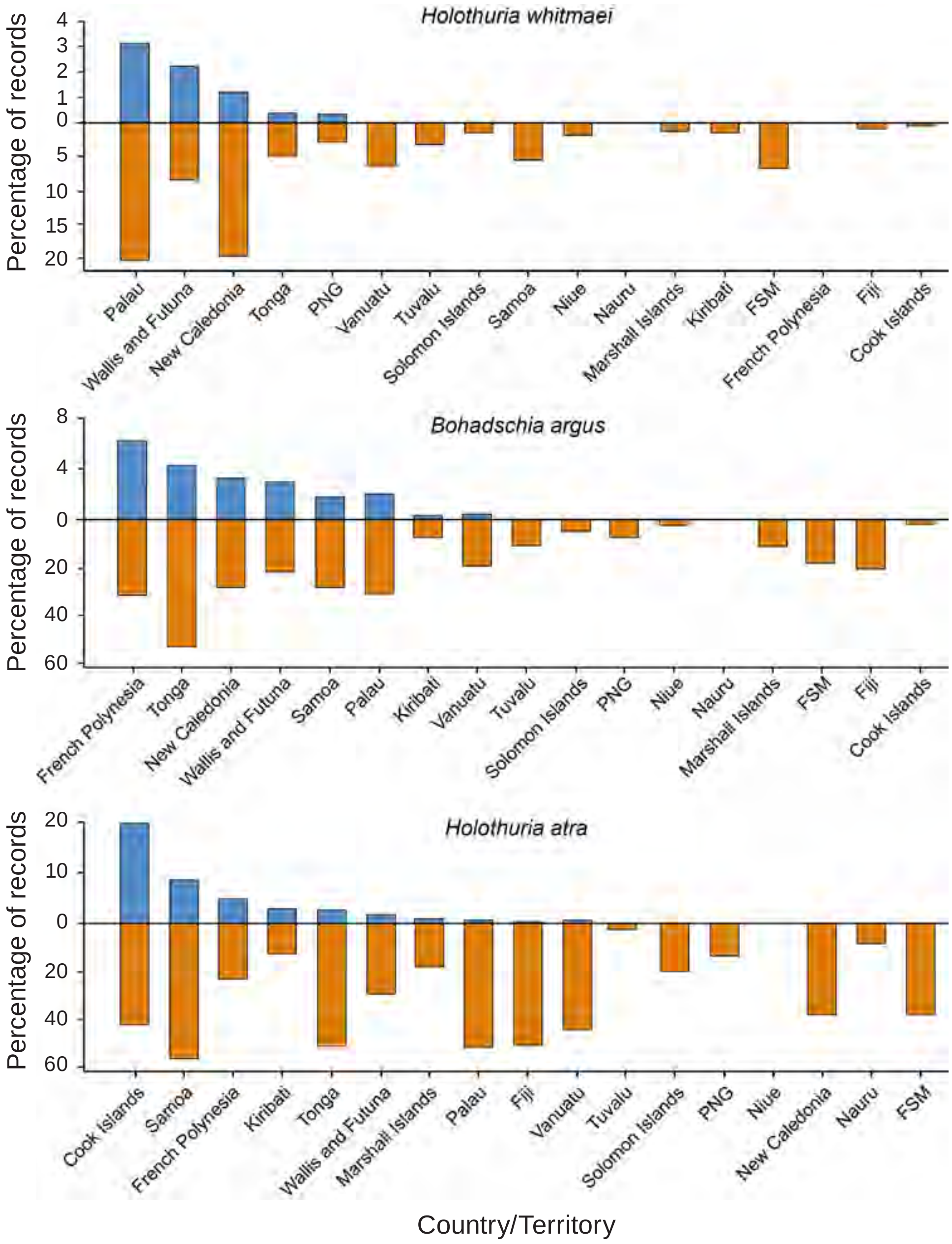


Figure 9.10 Relative status of populations of three 'indicator' species of sea cucumbers across 17 Pacific Island countries and territories (PICTs). The sum of the percentages of the blue and orange portions of each bar gives the total percentage of survey transects where the species was recorded for each PICT. Blue represents abundance at or above a 'high' status threshold and orange reflects a density below this threshold. The threshold is the average of the transects with the 25% highest abundances across 17 PICTs. *Holothuria whitmaei* is a low-density/high-value species, *Bohadschia argus* is a medium-density/mid-value species and *Holothuria atra* is a high-density/low-value species (source: SPC PROCFish Project).

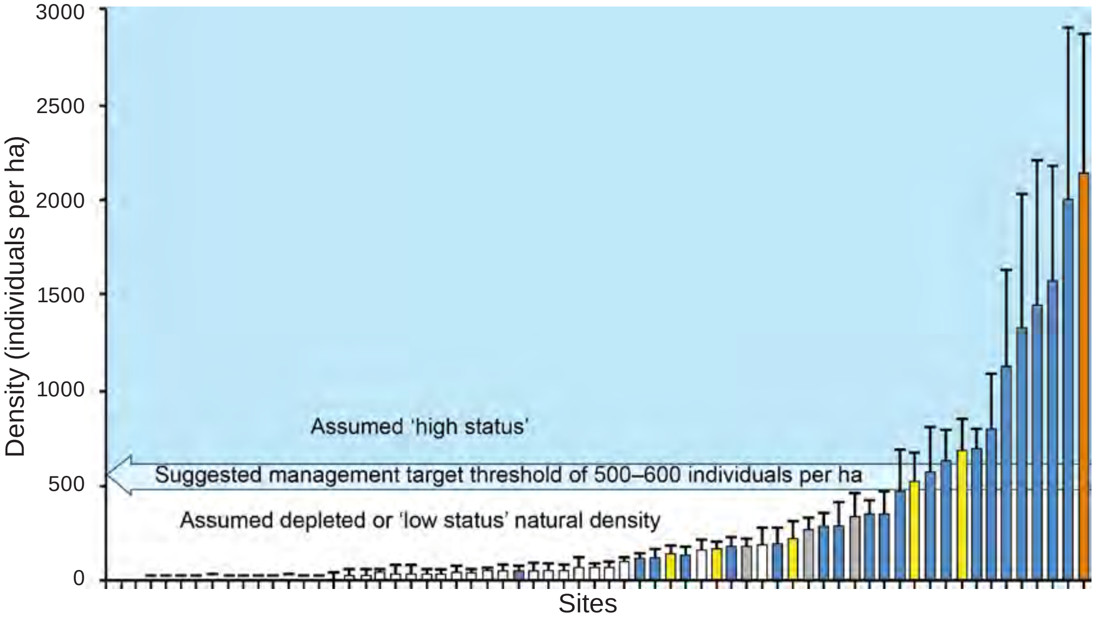


Figure 9.11 Mean density (individuals per ha, +SE) of trochus at a range of sites in the tropical Pacific where fishing has occurred (white bars), fishing is strongly regulated through government and traditional community controls (blue bars), fishing is strongly regulated through community controls alone (yellow bars), trochus have recently been introduced and are subject to national regulations (grey bars), and fishing has not occurred (orange bar). Information derived from underwater visual census in 17 Pacific Island countries and territories between 2002 and 2008 (source: SPC PROCFish Project).

9.3 Vulnerability to climate change

Recent harvests from coastal fisheries are generally within estimated sustainable limits across much of the region (**Table 9.5**) except for some targeted invertebrates. However, there is evidence that catches are not distributed equitably among areas within PICTs and potential target species (Section 9.2.2), and several sites have a poor to medium resource status and high fishing pressure (**Figure 9.8**). The real challenge to sustainability of coastal fisheries will arise as the food requirements of rapidly growing human populations increase by 20–60% over the next two decades[4], and more people seek to fulfil their aspirations to derive livelihoods from fisheries resources[25]. These problems will be particularly acute in Melanesia (Chapters 1 and 12). The difficulties involved in establishing levels of fishing that maximise benefits for people engaged in small-scale fisheries are considerable[24], due largely to the lack of necessary data and understanding of coastal fisheries in the region (Chapter 13). These problems can be expected to increase under the added effects of climate change.

Climate change is expected to alter the potential productivity of coastal fisheries directly, by changing the 'milieu' in which fish and invertebrates live[36,94–96] (Chapters 2 and 3), and indirectly by altering the habitats (Chapters 5 and 6) that provide them with shelter and food[96–99]. The most important direct effects are likely to be due to the projected increases in sea surface temperature and ocean acidification, and changes in ocean currents[36,100] (Chapter 3). The most significant indirect effects will be the projected degradation, fragmentation and loss of coral reefs, mangroves, seagrasses and intertidal flats (Chapters 5 and 6).

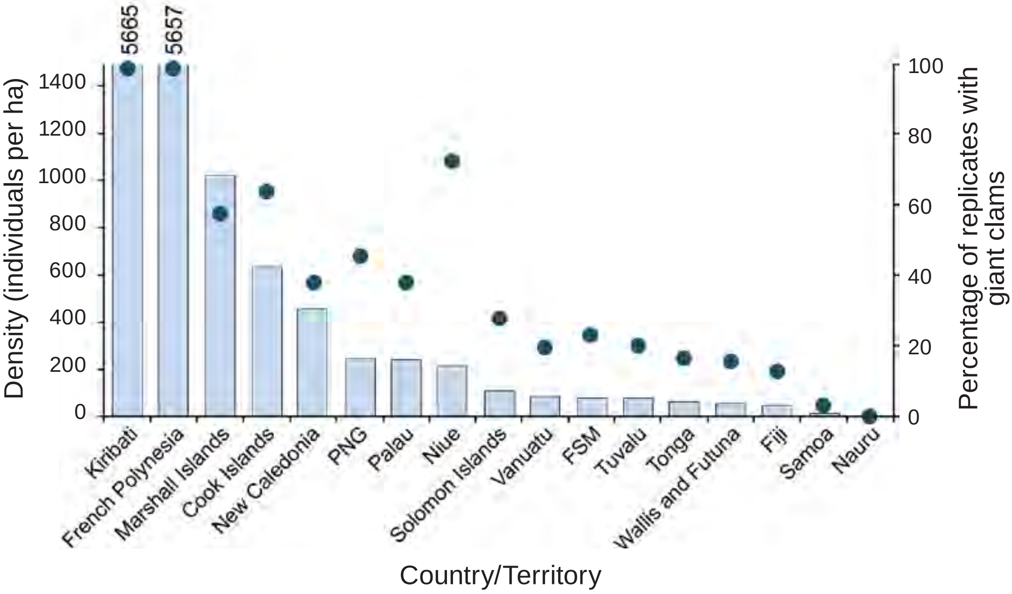


Figure 9.12 Average density (individuals per ha) of the giant clam *Tridacna maxima* for 17 Pacific Island countries and territories (PICTs), and its frequency in the total number of replicate visual underwater survey transects for each PICT (average n = 420). Information collected between 2002 and 2008 (source: SPC PROCFish Project).

Additional environmental changes and severe climatic events, such as increased severity of tropical cyclones, more extreme rainfall events and sea-level rise, could have further direct and indirect effects for some species or life stages[36,37]. For example, tropical cyclones are expected to become more intense in a warmer world[101] (Chapter 2) and cause greater damage to key habitat-forming species, such as corals[102] and seagrasses (Chapters 5 and 6). The effects of cyclones are expected to compound damage to coral reefs caused by bleaching and acidification. Indeed, cyclones are known to reduce abundance of fish due to loss of critical habitat[76,103]. Overall, the indirect influence of cyclones on the physical and biological complexity of fish habitats is expected to have greater effects on coastal fisheries than the direct effects of more intense cyclones, and increases in rainfall and sea-level rise.

The direct and indirect effects of climate change on coastal fish and invertebrate species will vary depending on their biology and ecology[36]. For example, recent effects of climate-induced coral loss on reef fish vary depending on their reliance on live corals for food, shelter and/or recruitment[104]. Butterflyfish, and certain species of damselfish, cardinalfish and coral-dwelling gobies have the greatest dependence on live coral and are directly at risk from loss of corals[104]. Other fish may also be particularly susceptible to climate change owing to their sensitivity to changes in temperature or ocean chemistry[106]. However, specific tests of sensitivity of reef fish to projected environmental changes are restricted to a few species and mostly one to two families[105–107]. It is unclear how the results from these limited experiments will relate to species targeted by fisheries, which are often larger and more mobile.

The vulnerability of key fisheries species to changes in environmental conditions (temperature, ocean acidification, ocean circulation and nutrient supply) and habitats depends on their exposure, sensitivity, and capacity to modify the potential impact (Chapter 1). Exposure is the magnitude and extent of projected changes in environmental variables and/or habitats relative to the existing conditions, whereas sensitivity refers to the likely responses of the species to the projected changes, in terms of local abundance, size or productivity (Chapter 1). The potential impact of projected changes on species is moderated by the species ability to alter its physiology, behaviour and/or distribution to cope with change. Species with a high sensitivity to changes in environmental conditions and habitats, which are unable to adapt, for example by switching to other prey, living in slightly different habitats, or evolving increased tolerances, are most vulnerable and potentially at risk of local extinction due to climate change[108,109].

Changes in the distribution and abundance of coastal fisheries resources are also expected to the social and economic fabric of Pacific Island nations, depending on their willingness and capacity of communities to alter and/or diversify fisheries activities, their access to alternative sources of food, and alternative opportunities to earn income[26,110,111]. However, with the exception of possible risks to changes in the incidence of ciguatera fish poisoning, this chapter focuses on the vulnerability of coastal fisheries resources to climate change, not the socio-economic effects. The risks to food security and livelihoods of coastal communities in the region are assessed in Chapter 12.

9.3.1 Vulnerability to the direct effects of climate change

9.3.1.1 Water temperature

Changes in water temperature have a major influence on most coastal fish and invertebrates because they have limited capacity to maintain an independent body temperature. Indeed, variation in temperature tolerances[112–114] has a major bearing on the geographic ranges[115–116] and general biology[117] of fish and invertebrates. As sea surface temperature (SST) increases due to global warming, populations of thermally-sensitive marine organisms are expected to shift towards higher latitudes, whereas populations that can endure warmer waters may exhibit changes in their life history traits, such as growth rates and longevity[36]. Global warming is likely, therefore, to have significant consequences for the distribution and abundance of key fish and invertebrate species, as well as productivity and composition of coastal fisheries throughout the region.

Exposure and sensitivity

Average global atmospheric temperatures have increased by > 0.7°C over the past 100 years (Chapter 2), with the current rate of warming far greater than at any time during the last 1000 years[27]. In the tropical Pacific Ocean, mean SST is expected to increase substantially by the end of this century (Chapters 2 and 3). Even under a low (B1) emissions scenario, average SST in the region is likely to increase by 0.7°C by 2035, and 1.0–1.5°C by 2100 relative to 1980 to 1999. However, if recent increases in global CO_2 emissions continue unabated (represented by the A2 scenario), average SST for the tropical Pacific may increase by as much as 2.5–3.0°C. The projected surface warming also has a spatial pattern, with greater warming in the eastern than western equatorial Pacific and less warming in the southeast Pacific (Chapters 2 and 3).

Many marine species can withstand a considerable range in water temperature, as apparent from their large geographic and latitudinal distributions[118,119]. Even within their limited home ranges, tropical and subtropical organisms are regularly exposed to a range of temperatures due to diurnal and seasonal cycles of warming and cooling. Diurnal variation in water temperatures is particularly apparent in shallow coastal habitats, where it can fluctuate by > 14°C throughout the day[120].

In contrast, water temperature typically varies less than 1°C per day for deep subtidal habitats[121] and the average daily SST range in the ocean is only about 0.2–0.3°C[122]. Seasonal variation in SST in the tropical Pacific Ocean is generally < 7°C (Chapter 3), but marked increases in solar radiation can heat shallow water bodies rapidly during summer. These habitats also cool quickly during cold winter nights. Seasonal variations in SST can also be amplified by large-scale climatic events on decadal cycles (Chapter 2). For example, in the eastern tropical Pacific, the El Niño-Southern Oscillation can increase SST by up to 2.0–3.0°C during El Niño events and cause similar reductions during La Niña episodes[123,124] (Chapter 3).

Tropical marine fish and invertebrates are sensitive to variations in SST because temperature regulates metabolism and development, and limits activity and distribution. Many of these species are relatively tolerant of short-term changes in ambient temperature, and tend to live well within their critical thermal limits[125,126]. However, virtually all organisms have a 'hump-shaped' temperature-performance curve, which shows how growth, reproduction or movement increases with SST elevations, until the optimal temperature is reached, after which performance declines[117,127] (**Figure 9.13**). The rate of change in performance with increasing SST is often more pronounced beyond the optimal temperature, up until the point at which it becomes lethal. Therefore, small increases in SST above the thermal optimum can have important consequences.

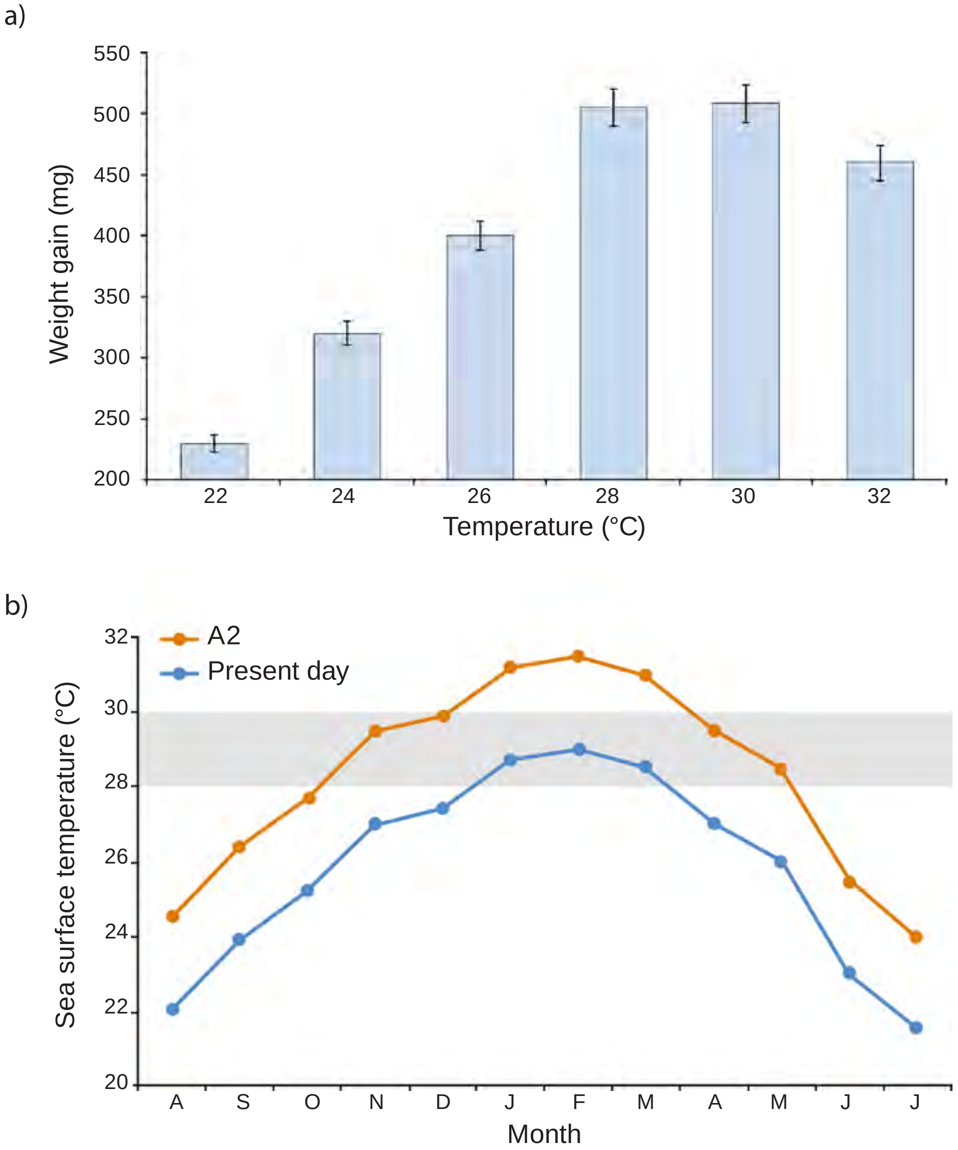


Figure 9.13 (a) Mean weight gains (mg ±SE) for larval damselfish *Acanthochromis polyacanthus* reared in captivity at 29°C, and then maintained at different temperatures for 6 weeks from one week-post hatching (Liao, Coker and Pratchett, unpublished data). The thermal optima (at which weight gains were maximised) appear to be 28–30°C; (b) present-day and increased mean monthly sea surface temperatures (SSTs) expected to occur by 2100 under a high (A2) emissions scenario – the shaded area represents the current thermal optima (28–30°C) for *A. polyacanthus* at Orpheus Island, central Great Barrier Reef, which corresponds with the present-day mean summer maximum SST (source: Munday et al. 2008)[105].

The extent to which increasing SST will have positive or negative effects on individual species depends on whether water temperatures are moving towards or away from the thermal optima for a particular population[128]. Increases in overall SST may increase growth and production during months and seasons where temperatures are presently well below the optimum (**Figure 9.13**). However, there are likely to be increased risks to fish populations in seasons where SSTs begin to exceed thermal optima[129]. Indeed, projected increases in SST of 1–3°C will take summer maximum temperatures beyond the range at which growth, reproduction and metabolic rate are maximised for some populations[105,130,131].

The main effect of rising water temperatures on fish relates to increases in their metabolic processes, and limitations in meeting the associated higher demands for oxygen (O_2)[117]. The metabolic rate of an individual reflects the total energy expended for ingestion and digestion of food, growth, maintenance and activity[113]. Metabolic activity for fish increases in direct proportion to moderate increases in ambient temperature[119,132–134]. However, with increasing SST, there is a decrease in available dissolved O_2, whereas a fish's demand for O_2 is increasing[116,135]. Consequently, oxygen becomes a limiting factor in cardiovascular performance[136]. Decreased capacity of the ventilatory system to keep pace with increased oxygen demands at higher temperatures is therefore the key physiological mechanism controlling an organism's thermal tolerance, and determines its response to increasing SST[116,117].

The sensitivity of the aerobic system to increased SST is unknown for most tropical marine species. However, sensitivity to increasing temperature has been shown to differ greatly among five species of coral reef fish[130]. In two cardinalfish, the maximum oxygen uptake for aerobic activity (aerobic scope) declined dramatically with an increase of 2–4°C. Aerobic scope was reduced by nearly half at 31°C compared with 29°C and virtually all capacity for additional oxygen uptake was exhausted at 33°C. In contrast, three species of damselfish were relatively tolerant of the same increase in temperature and retained over half their aerobic scope at 33°C. These results suggest that adults of some species are highly sensitive to small increases in temperature, whereas other species may be quite tolerant to the increases of 2.5–3.0°C in SST projected to occur under the A2 emissions scenario by the end of the century.

Potential impact and adaptive capacity

Projected increases in SST within shallow coastal environments of up to 2.5–3°C by 2100 are expected to have limited direct effects on survival of adults for most fisheries species, but may still interfere with reproduction, recruitment and juvenile growth[131,137,138]. Even temperature increases of 1–2°C can affect the reproductive performance of some reef fish[131,138] and are likely to lead to shifts in the timing of spawning, and possibly falling egg production, in some populations. Where reproductive development and spawning synchrony are cued to temperature, seasonal changes in SST may lead to alterations in the timing of breeding[36]. Increases in average SST could also lead to more protracted or more irregular opportunities for successful reproduction, depending on how close present-day SSTs are to the optimum temperatures[36]. Species that use photoperiod as the major cue for spawning[137] are less likely to adjust the timing of reproduction to suit the thermal environment. For these species, reproductive success may be compromised if higher water temperatures cause egg production to be impaired[139], increase embryonic mortality[138], or lead to a mismatch between the timing of spawning (set by photoperiod) and the optimal conditions in the plankton for survival and dispersal of larvae (set by temperature)[140].

Increases in ambient temperature, and corresponding increases in food demands, are also expected to affect the survival of offspring, especially during pelagic dispersive phases. Larval fish grow and develop more rapidly at higher temperatures[37], meaning that they may experience lower rates of mortality[141]. However, under higher SSTs, entire cohorts of larval fish may not be able to obtain sufficient food to sustain their rapid growth and development, leading to more frequent recruitment failure[37,142].

Increases in SST above the thermal optima are also expected to reduce individual performance, leading to declines in growth and reproduction. For example, a 3°C increase in SST would mean that optimal temperatures for growth of the damselfish *Acanthochromis polyacanthus* would be exceeded for at least half the year (**Figure 9.13**). If such effects are also typical of harvested species, decreases in fisheries production can be expected. A decline in summer performance of fish species may, however, be offset by increased growth during cooler months. Ambient temperatures may be below the local optima at such times, except where the warming causes mean monthly SST to exceed normal summer optima for extended periods. Thus, unless species can acclimatise or adapt to such temperature increases, an overall reduction in biomass may occur. The capacity of most tropical marine fish and invertebrates to acclimatise or adapt to rapid temperature change is unknown[143]. This serious gap in our knowledge must be filled before projections about the consequences of future increases in SST on demersal fish and invertebrates associated with coral reefs can be made with confidence.

Many tropical marine fish have large latitudinal ranges that extend across temperature gradients greater than the expected increases in SST due to global warming. Life history traits of some species covary in a predictable way with these latitudinal and temperature gradients[144,145]. Although there are many exceptions, reef fish species tend to be shorter-lived and reach smaller maximum sizes in equatorial areas compared with the subtropics[36]. Juveniles are also expected to reach their asymptotic size at a faster rate at higher temperatures. Consequently, we might expect that as SST increases, life history traits of populations in the subtropics will become more like those exhibited in populations already living at higher temperatures (e.g. shorter-lived and smaller maximum sizes), with knock-on effects on fisheries production. However, life history traits are also influenced by food supply, and population density and structure, which vary at a range of spatial scales, and might themselves be influenced by increased SST. Thus, projecting the likely effects of elevated temperature on life history traits is extremely difficult[36].

The main way that fish and invertebrates are likely to respond to altered environmental regimes is to shift their geographic (especially latitudinal) ranges[115,146,147]. Poleward shifts in geographic ranges have been observed for many marine organisms[115,148–150]. However, the ability of species associated with coral reefs to establish permanent populations at subtropical latitudes will depend on their specific requirements for food, shelter and reproduction, their tolerance to lower minimum temperatures in winter, and competition from established subtropical species[36].

Vulnerability

The net effects of increasing SST on growth, abundance and productivity of coastal fisheries species are uncertain[100], but moderate increases in temperature are likely to affect reproductive output as well as the development and survival of larval stages. As a result, fished stocks may become more vulnerable to periodic collapse due to greater inconsistency in the supply and survival of larvae. This threat would be compounded by changes in population connectivity caused by more rapid larval development; in particular, the opportunity for larval replenishment from distant stocks in cases of local overfishing is likely to be reduced[37]. Productivity of coastal fisheries is also likely to be reduced as a result of the effects of higher SST on metabolic rates. Fish and invertebrates are expected to need more food, given their higher rate of metabolism in warmer waters, under circumstances where changes in climate are projected to reduce nutrient inputs (Chapters 3 and 4) and degrade benthic habitats (Chapters 5 and 6) (as discussed below). Overall fisheries production is expected to decline with increasing SST, except in locations of local nutrient enrichment[99] (Section 9.3.3).

Checking a fish trap in Polynesia

Photo : Hemis.fr/SuperStock

An independent global analysis has also concluded that the redistribution of fisheries species associated with increasing SST and shifts in climate is expected to have significant impacts on fisheries production of tropical countries[147]. Geographical shifts in the distribution and abundance of major fisheries species, combined with projected changes in primary production, are expected to cause a decline of up to 40% in fisheries production in the tropical Pacific under high emissions scenarios[147]. However, these estimates fail to take account of habitat requirements that will limit latitudinal shifts of many reef species; only generalist species that are loosely associated with coral and reef habitats are expected to move poleward to escape rising SST in the tropics.

9.3.1.2 Ocean acidification

Ocean acidification, caused by the uptake of carbon dioxide (CO_2) emissions by the ocean (Chapter 3), is a serious threat to marine ecosystems[151,152] and fisheries[153]. Additional CO_2 dissolved in the ocean reacts with sea water to form weak carbonic acid, causing pH to decline and reducing the availability of dissolved carbonate ions required by many marine calcifying organisms (particularly corals, other invertebrates and coralline algae) to build their shells or skeletons[154] (Chapter 3). Ongoing ocean acidification will reduce growth and survival of many calcifying organisms and affect the food webs that depend on them[152,155] (Chapters 4 and 5). The reduction in ocean pH could also have a range of direct effects on coastal fish, from increased metabolic demands to developmental problems[156].

Exposure and sensitivity

Atmospheric CO_2 concentrations have increased from ~ 280 ppm in pre-industrial times to ~ 390 ppm today, causing the average pH of the ocean to decline from 8.2 to 8.1[157]. Depending on emissions scenarios, CO_2 concentrations are projected to reach 540–800 ppm by the end of the century[157] (Chapter 1), resulting in a further decline in average ocean pH of 0.3 to 0.4 units[158] (Chapter 3). The projected emissions of CO_2 are expected to make the ocean more acidic than at any time in the past 800,000 years[159]. Changes in global ocean pH will be most apparent in open ocean waters, where pH naturally varies by only 0.1–0.2 units depending on biological production and nutrient inputs. In contrast, pH is naturally variable in coastal habitats. For example, pH ranges up to 0.8 units throughout the day in shallow coral reef habitats due to diurnal patterns of respiration, photosynthesis and calcification[160]. The potential for dissolution of carbonate within extensive coral reef frameworks to partly buffer the effects of ocean acidification is also unknown, but this effect may limit declines in pH of near shore, shallow carbonate systems.

Many coastal invertebrates (including molluscs, echinoderms and crustaceans) are expected to be sensitive to any changes in the pH of nearshore waters because their exoskeletons, shells or skeletal elements are composed of aragonite or high-magnesium calcite[161], both of which have low saturation states in sea water. Levels of acidification that could occur in the world's oceans within the next 50 years are below the levels that have been shown (in controlled experiments) to reduce calcification rates for a wide range of species[162–167]. Calcifying molluscs that have been subject to reduced pH, either under experimental conditions or in marine habitats with naturally low pH, usually have much thinner shells, reduced growth and lower survival rates[166,168]. For commercially important invertebrates in the tropical Pacific that are harvested for their shell (e.g. trochus), these weaknesses may simultaneously affect the size of populations as well as the individual value of each animal.

Reduced calcification rates could also possibly affect spicule formation in sea cucumbers[64], thereby reducing growth or increasing susceptibility to predation. In contrast, decapod crustaceans (spiny lobsters, crabs and shrimp) may be capable of higher rates of calcification in acidified conditions. These animals have an external organic layer (epicuticle), which separates their carapace from sea water and can effectively regulate internal pH at the site of calcification[161]. Growth and survival of some decapods declines at low pH[169], however, which may reflect the increased physiological costs associated with adverse environmental conditions.

The internal bony skeletons of fish are unlikely to be affected to the same degree as the external skeletons of invertebrates. Fish bones are composed of calcium phosphate, not calcium carbonate, and the skeletons of fish may be protected from external pH changes by the fish's own internal acid-base regulation[170]. Fish otoliths (ear bones) are more likely to be susceptible because they are composed of aragonite. However, otoliths may also be protected by active acid-base regulation of the endolymph. Indeed, one recent study found that otolith calcification increased in larvae kept at low pH, possibly as a result of increased carbonate concentrations in the endolymph caused by acid-base regulation[171]. Whether acidification affects otolith growth or development in other species is unknown, but any effects could be significant because otoliths are important for individual orientation and hearing, especially during the dispersive larval stage[37].

Increased CO_2 not only acidifies the ocean, it also decreases the pH of animal tissue[156,170,172]. Fish compensate for this acidification with bicarbonate accumulation and counter-exchange of ions across the gills[173,174]. Consequently, most fish tolerate a wide range of dissolved CO_2 and pH levels[156,172,175]. Although compensation of acidosis is not detrimental in the short-term, ultimately, it might have some physiological costs, especially for species or life stages with high metabolic demands[156] or when compounded by higher metabolic demands at elevated temperatures[117].

Enzymatic changes consistent with a shift from aerobic to anaerobic metabolic pathways have been observed in a temperate marine fish exposed to CO_2 levels ~ 4.5 times above average[176]. Also, significant declines in aerobic scope have been detected for two species of coral reef fish exposed to CO_2 levels ~ 2.5 times above ambient[177]. In the latter study, the effect on aerobic scope of 1000 ppm CO_2 was similar to that caused by a 3°C increase in water temperature above the summer average. This effect indicates that ocean acidification could have consequences for the aerobic performance of coral reef fish in addition to those expected to occur as a result of increasing SST[130]. Limited research on marine invertebrates suggests that there is considerable variation in the extent to which species can regulate internal pH to withstand short-term changes in ambient conditions[161,178]. It is not clear whether this regulation will enable species to withstand projected changes in ocean chemistry.

Potential impact and adaptive capacity

Direct effects of elevated CO_2 are likely to be greatest during the early life history phases of marine fish and invertebrates[156,179]. Indeed, fertilisation of eggs[180] and development of larvae[168] of some invertebrates is influenced significantly at the range of CO_2 concentrations that are projected to occur by 2100. Even moderate increases in CO_2 concentrations (560 ppm leading to a decline in pH to ~ 7.9) reduce the growth of adult gastropods and sea urchins due to reduced calcification[168]. In contrast, a study of reef fish, using CO_2 levels relevant to climate change projections (up to 1000 ppm), did not detect any negative effects on the growth or development of clownfish larvae[106]. Clearly, more research is needed to test the effect of elevated CO_2 on the early life stages of coastal fish across a broader range of species, and to examine possible synergistic effects of elevated temperature and CO_2.

A greater concern for coastal fisheries in the tropical Pacific is the effect that elevated CO_2 levels could have on the sensory ability of larvae. Clownfish larvae exposed to CO_2-acidified water lose their ability to distinguish olfactory cues from preferred settlement habitat[106], or to detect and avoid the smell of predators[181], at the end of their larval phase. When reared in water treated with 1000 ppm CO_2, the larvae became strongly attracted to chemical cues they normally avoided. The larvae of many marine fish use chemical cues for a wide range of important behaviour decisions, including navigation to reefs and selection of settlement sites[182–184]. Impairment of this process by ocean acidification could have serious implications for the replenishment of adult populations and patterns of population connectivity in coral reef ecosystems.

Despite the fact that acclimatisation or adaptation are important considerations when assessing the vulnerability of fish and invertebrates to projected climate change[18,152,185], the potential for most marine organisms to adapt to a rapid reduction in ocean pH has rarely been tested. Ocean pH has changed very little over the past 800,000 years[159], and so it might be expected that marine organisms lack genetic variation necessary for rapid adaptation to changes in seawater chemistry[151].

Vulnerability

Declines in global ocean pH and associated decreases in the availability of carbonate ions will cause reduced calcification, growth and survival of calcifying organisms in the absence of rapid and effective adaptation. Key fisheries species that are likely to be directly affected include bivalves (giant clams), gastropods (trochus), sea cucumbers and sea urchins. If greenhouse gas emissions continue unabated, as projected by the A2 scenario, these calcifying organisms are unlikely to be able to sustain significant commercial and subsistence fisheries into the future.

Ocean acidification is also expected to compound the negative effects of increasing SST for fish and invertebrates. Impaired larval behaviour caused by elevated CO_2 could also affect the replenishment of populations, increasing the risks of decline in the stocks that support coastal fisheries.

9.3.1.3 Ocean currents

Changes to ocean circulation and current patterns throughout the tropical Pacific, expected to occur as a consequence of climate change (Chapter 3), could affect the production of coastal fisheries in two main ways. Firstly, currents, eddies, and other hydrodynamic features play an important role in the retention and dispersal of pelagic larvae[186–188]. Any changes to circulation patterns as a result of climate change could have fundamental effects on the spatial and temporal patterns of larval settlement, and the degree of connectivity among meta-populations[37]. Secondly, currents play an important role in providing nutrients and food to coastal habitats that are often limiting. In the waters surrounding PICTs, nutrient supply influences the production and distribution of phytoplankton and zooplankton[189,190] (Chapter 4), which are integral parts of the food webs supporting both larval fish and planktivorous adult fish residing on reefs. Changes to primary and secondary productivity caused by altered ocean circulation are expected to affect the growth and survival of these two categories of fish[191–193] and biological production throughout the entire ecosystem[99].

Exposure and sensitivity

The South Equatorial Current (SEC), which flows westward just south of the equator, is a major oceanographic feature of the tropical Pacific Ocean. The SEC generates significant surface currents and eddies, and drives vertical mixing and upwelling of nutrient-rich waters (Chapter 3). The transport volume of the SEC is expected to decrease in strength by 3–5% under the B1 and A2 emissions scenarios by 2035, by ~ 10% under B1 by 2100, and ~ 20% under A2 by 2100 (Chapter 3). The eastward-flowing South Equatorial Counter Current (SECC) is also expected to decrease in velocity and change direction. These changes are expected to take time to appear – flow of the SECC is projected to decrease by < 5% under the B1 and A2 scenarios by 2035. However, flow is expected to decrease by ~ 30% under B1 by 2100, and by 60% under A2 by 2100. The surface flow is also likely to turn towards the south, reducing the penetration of the SECC to the east (Chapter 3). Consequently, associated eddies and upwellings are expected to decline. The projected increases in SST are also likely to enhance stratification and reduce vertical mixing[35,194] (Chapters 3 and 4).

Such large-scale changes to circulation patterns have potential to influence dispersal and survival patterns of marine fish larvae (**Figure 9.14**), while reductions in vertical mixing and supply of nutrients to shallow coastal habitats could reduce the productivity of coastal ecosystems. In nearshore environments, diminished supplies of nutrients from the ocean may be compensated by increased inputs from runoff, which are expected to increase with climate change (Chapters 2 and 7).

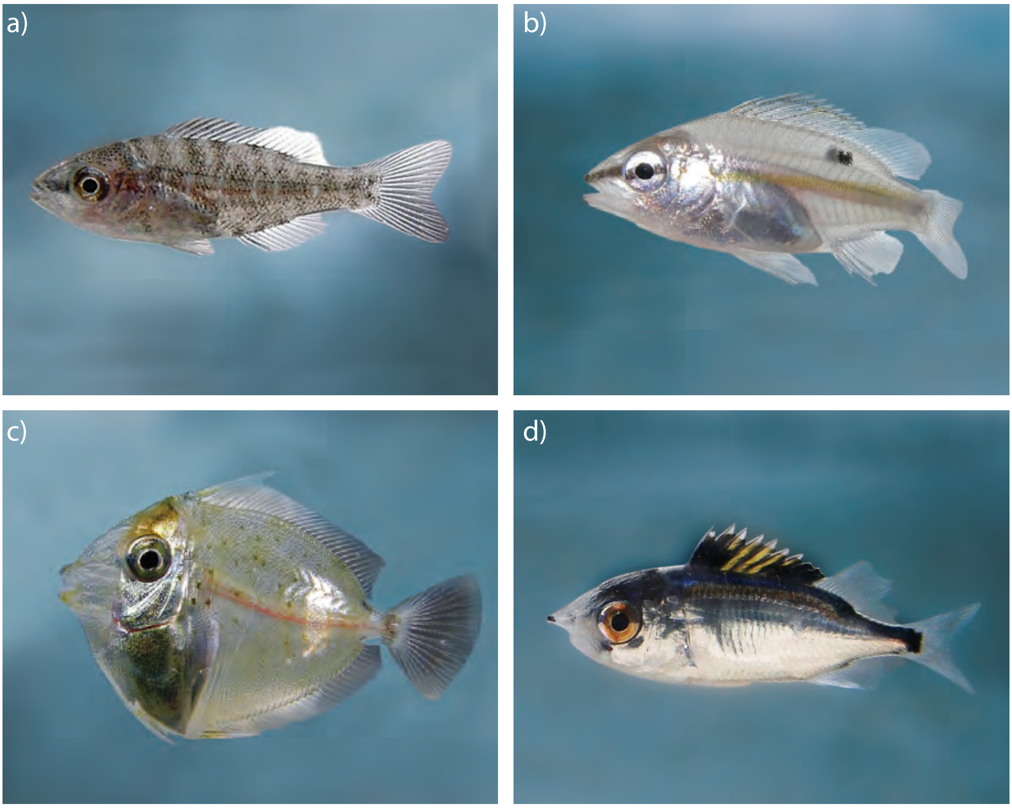


Figure 9.14 Postlarvae of demersal fish families from the tropical Pacific (a) Lethrinidae, (b) Lutjanidae, (c) Acanthuridae, and (d) Holocentridae (photos: Colin Wen).

Fisheries production is sensitive to changes in ocean circulation, and especially the strength and persistence of upwellings. Approximately 25% of total global marine fish catches are concentrated in areas where the strong vertical mixing of ocean layers brings nutrients to the surface[99]. Increased thermal stratification of the ocean layers reduces the delivery of nutrients from the deeper, cooler waters to coastal habitats[35,194,195] (Chapter 3). This reduction in supply of nutrients decreases the productivity of the plankton communities that provide an important food source for many coastal fish and invertebrates, and which underpin the food webs sustaining large pelagic fish species (Chapter 4). In the Western Pacific Warm Pool and the Archipelagic Deep Basins provinces of the region[196], where the larger PICTs are situated, phytoplankton production is estimated to decline by 5–8% under the B1 and A2 emissions scenarios in 2035, by 9–20% under B1 in 2100, and by 9–33% under A2 in 2100 as a result of reduced vertical mixing[197] (Chapter 4). The productivity of planktonic communities can also be reduced at higher temperatures[190] (Chapter 4). Reduced availability of food, combined with increased metabolic rates at higher temperatures[36], may lead to starvation of fish and invertebrates, especially among early life history stages.

Impact and adaptive capacity

Changes to major ocean currents and wind-driven surface currents, upwelling, eddies, and other hydrodynamic features of the tropical Pacific Ocean could have important effects on the dispersal and survival of coral reef fish larvae[37]. Connectivity among distant reefs and islands is likely to be compromised, so that stocks are expected to be more reliant on local reproduction to replenish populations. Projected declines in the strength of surface currents (of up to 50%) will reduce the transport of pelagic larvae among disparate islands and reefs and declines in the strength of eddies may reduce the retention and accumulation of larvae within the vicinity of appropriate settlement habitats. Connectivity is likely to be reduced further by increased fragmentation of coastal habitats (Chapters 5 and 6), and declines in the pelagic duration for larvae (as discussed previously). Management to avoid localised depletion of fisheries stocks will be essential, as replenishment of depleted populations from distant spawning adults becomes less likely.

At this time, the projections of how ocean currents are expected to change lack sufficient confidence and resolution, at scales relevant to the ecology of coastal fish and invertebrate species, to enable meaningful estimates of the likely impact on individual coastal fisheries species[36,37]. Also, little is known about the present levels of connectivity within meta-populations among reefs, islands and nations for any of the target species in the tropical Pacific. However, vertical stratification of the water column and associated declines in the delivery of nutrients to surface waters are likely to cause a general decline in productivity of coastal marine assemblages. Declining nutrient availability imposes fundamental limitations on available energy and productivity. Although some changes in community structure and energy dynamics within coastal ecosystems may occur, the adaptive capacity to withstand a fall in nutrient availability is limited. Nutrient limitation may also compound the increased metabolic demands of marine organisms coping with higher SST and reduced pH and lead to a significant decline in biological production.

Vulnerability

The productivity of all coastal fisheries is expected to be vulnerable to changes in the delivery of nutrients to coastal habitats, which are generally expected to decrease in the tropical Pacific as a result of weakening of the SEC and SECC, and increases in stratification of the water column. Local increases in productivity may occur in some locations, however, as currents change in velocity and direction (Chapter 3), and as freshwater runoff increases around high islands due to the projected higher rainfall intensity in the tropics (Chapter 2). In general, the stocks of predatory demersal fish, and the large nearshore pelagic fish that depend on the food chains supported by nutrient-rich waters[198], are expected to be negatively affected as the occurrence and intensity of the vertical mixing of the water column decline.

Any changes in the supply and settlement of larvae caused by changing currents and eddies are likely to have major effects on coastal fish and invertebrates. Locations that consistently receive a disproportionate number of settlers (recruitment 'hotspots') may be very important in supplying recruits to surrounding locations. Vulnerability to changing hydrodynamics is likely, therefore, to be localised. The capacity to downscale changes in ocean circulation to project these effects is presently limited. At the scales of islands and reefs, the weakening of the SEC and SECC is likely to reduce both the transport of pelagic larvae among distant islands and reefs, as well as the retention and accumulation of larvae within eddies formed adjacent to islands and reefs by currents.

9.3.2 Vulnerability to the indirect effects of climate change

Coastal habitats are particularly susceptible to a wide range of natural and anthropogenic disturbances[22,76]. The diversity, frequency and intensity of the anthropogenic influences on coastal habitats have been increasing worldwide over the past 100 years, leading to strong shifts in the structure of coral reefs[18,19], seagrass meadows[199,200] and mangroves[201–203]. Although the causes and the extent of coral loss vary regionally, mean coral cover throughout the Indo-Pacific decreased from 42.5% in the early 1980s to 22.1% in 2003[20]. Climate change threatens to compound the natural and direct anthropogenic disturbances, accelerating the degradation and loss of coral reefs (Chapter 5). Similarly, 35% of the global area of mangrove forests has disappeared since 1980, mostly due to intensified use and destruction[203]. These losses are also expected to be exacerbated by climate change, especially sea-level rise (Chapter 6). These structurally complex, yet highly vulnerable, coastal habitats are fundamental to sustaining coastal fisheries through their roles as nursery, feeding and shelter areas[83,204,205]. Climate-induced degradation of these habitats also poses a major threat to the great marine biodiversity of the tropical Pacific.

Exposure and sensitivity

The fish and invertebrates associated with coral reefs, seagrasses and mangroves are exposed to great changes in the quality and extent of the habitats that support them, due to climate change[27,104,206–208] (Chapters 5 and 6).

Based on the rate of coral loss reported over the last 20 years[20], and the projected effects of more frequent coral bleaching and ocean acidification, average coral cover throughout the Pacific is expected to decline to 15% by 2035. Moreover, coral reefs will become increasingly dominated by relatively robust coral genera (e.g. *Porites* and *Favia*), rather than the branching coral species (*Acropora* and *Stylophora*) prevalent today. By 2100 under the B1 emissions scenario, coral cover is likely to decrease to < 5% with weak management, and to < 2% under the A2 scenario (Chapter 5).

Extensive death of corals leads to profound changes in the biological and physical structure of reef habitats (**Figure 9.15**) (Chapter 5). Over time, coral skeletons of dead branching corals (e.g. *Acropora* and *Pocillopora*) break down into coral rubble[97,209], and the more robust skeletons of massive corals (e.g. *Porites*) become dislodged or gradually eroded *in situ*[209]. These processes contribute to long-term declines in structural complexity, and ultimately result in low-profile reef landscapes[209,210]. The bioeroding algae, which contribute to physical collapse of dead coral skeletons, also grow faster under elevated CO_2 conditions[211], further contributing to degradation of coral reefs with ongoing climate change.

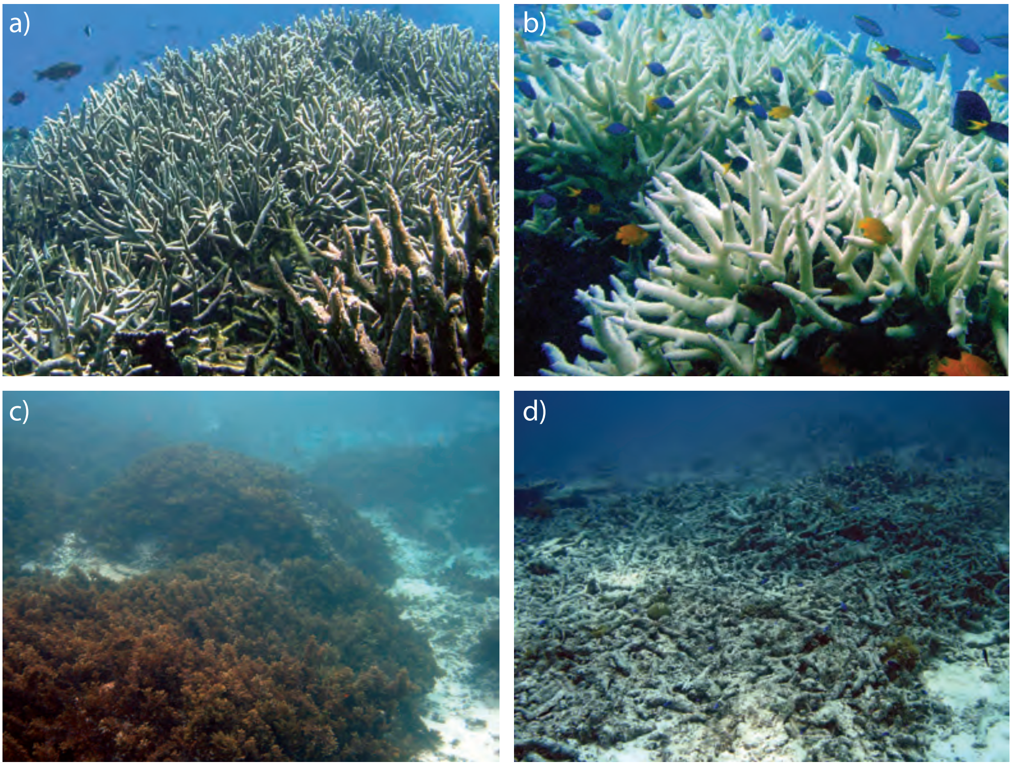


Figure 9.15 Changes in the state of coral reef ecosystems caused by climate-induced coral bleaching. Coral-dominated and structurally complex coral reef habitats (a) once bleached (b) can become overgrown with algae (c) and then collapse to form rubble banks (d) [Photos: Morgan Pratchett (a); Darren Coker (b); Shaun Wilson (c and d)].

In some instances, coral reef habitats become dominated by macroalgae[78] or other sessile fauna[212], fundamentally altering the nature of these ecosystems. Macroalgae are expected to proliferate on reefs under climate change for the following reasons (1) the reduced abundance of corals increases space for colonisation of algae; (2) the lack of physical structure (formerly provided by reef-building corals) leads to declines in abundance of herbivorous fish that typically control the growth of macroalgae; and (3) increasing temperatures and higher rainfall/runoff will favour the growth and productivity of macroalgae. The onset of such degradation is expected to occur even earlier in places where overfishing has already reduced the abundance and diversity of herbivores[18,19,77].

As mentioned above, the demise of coral reefs is not the only way in which coastal fisheries are exposed to degradation and loss of habitat. Depending on the location of PICTs, projected increases in water temperature, sea level, cyclone intensity and turbidity of coastal waters caused by higher rainfall, can be expected to affect the growth and survival of mangroves, seagrasses, non-reefal algal habitats, and the nature of intertidal flats. While data are scarce on recent and projected effects of climate change within non-reefal habitats of the tropical Pacific, data from elsewhere (e.g. Australia) indicate the likelihood of major effects[35]. The response of mangroves to such impacts is typically manifested as a change in their zonation, structure and species composition (Chapter 6). Similarly, for seagrasses, changes in local patterns of abundance and species composition are likely, but reductions in the overall extent of seagrass habitats may or may not occur (Chapter 6).

The fish and invertebrates that depend on coral reefs for food and/or shelter are highly sensitive to degradation and loss of these important habitats[213–215]. The frameworks provided by living and intact corals are also important for sustaining a great diversity and abundance of species that do not feed or live on corals directly[216–218]. As habitat diversity and topographic complexity decline, there are fewer places for reef-associated species to shelter from potential predators or competitors[219,220], with the result that degraded reef environments support fewer individuals and fewer species[76,97,210,218] (**Figure 9.16**). Loss of habitat complexity is especially detrimental for small-bodied fish (including both small species and juvenile phases of larger-bodied species) because such individuals are more exposed to predatory fish associated with coral reef environments[221].

The projected decline in abundance of juvenile stages of fishery target species due to degradation and loss of coral reefs is of particular concern. Small to medium size classes (up to 30 cm total length) of target species can decline substantially after the collapse of the reef structure, which is likely to lead to failure of recruitment to adult stocks, and declines in fisheries catch[222]. These declines have been profound for herbivorous fish stocks, for example parrotfish, and a decline in medium size classes of piscivorous species can result due to the absence of their prey[222]. An estimated 56%

of fisheries species targeted by subsistence fisheries in PNG are strongly associated with coral reefs[9] and likely to be affected by degradation or loss of coral-dominated habitats.

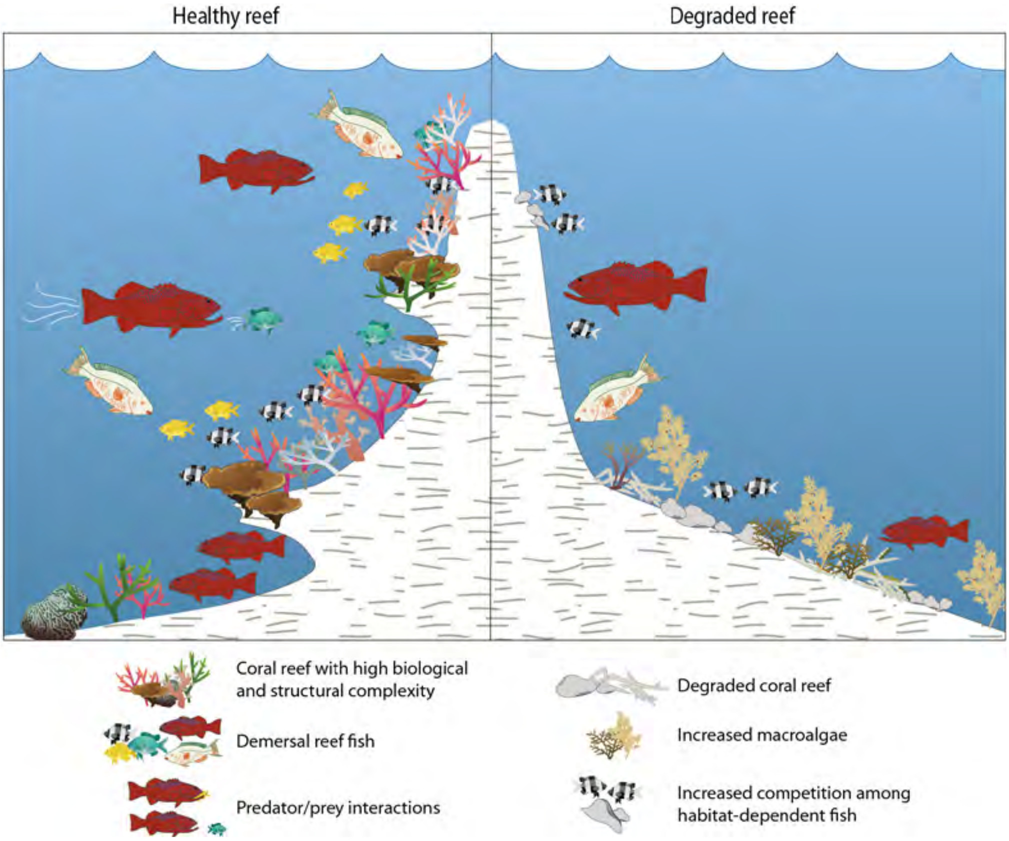


Figure 9.16 Degradation of coral reef habitats (declines in live coral cover and loss of structural complexity) has implications for the abundance and diversity of reef-associated fish and invertebrates. Prey are expected to decline in abundance due to lack of suitable habitat, ultimately leading to declines in abundance of predatory fish. Generalist benthic feeding fish (e.g. herbivores) may have access to more food on degraded reefs because of the increase in macroalgae, and become more abundant. However, the projected changes in habitat structure, and the expected alterations in sea surface temperature and oceanic currents, may simultaneously reduce recruitment success of such generalist species.

The role played by seagrasses, mangroves and intertidal flats in supporting fisheries production in the tropical Pacific is poorly understood. However, vegetated areas may provide important nurseries and feeding habitats for a wide range of coastal fish species[223–225]. Reduced coverage and structural complexity of the vegetated habitats caused by more severe disturbance from cyclones, increased stress from higher temperatures, reduced light levels from more turbid conditions and sea-level rise[226–229], can be expected to reduce recruitment success for many species of fish and invertebrates in the absence of other shelter[230]. Erosion of intertidal flats, and changes to the associated microalgae that drive the high productivity of these areas[224], are also likely to occur as a result of more intense cyclones and sea-level rise (Chapter 6). Such changes can be expected to alter the function and productivity of intertidal flats, which represent feeding areas for roving fish and are in themselves an important source of food for subsistence fishers (e.g. the fishery for arc shells in Kiribati).

Potential impact and adaptive capacity

The loss of the structural and biological complexity of coral reefs is expected to profoundly affect the types of fish and invertebrates associated with them. Species that depend on live coral for food, and on the variety of shelter created by structurally complex reefs for their survival, are likely to disappear[76,97,104]. These coral-dependent and highly specialist reef fish may be replaced by herbivorous and generalist species, leading to changes in community composition rather than net losses of biodiversity[231]. However, simplification of reef habitats will involve the loss of many existing energy pathways, making these ecosystems much more sensitive to future disturbances, including overfishing[232]. As such, effects of climate change on coastal fisheries associated with coral reefs may not be immediately apparent, but may result in slow, long-term (decadal) declines in yields as resilience and productivity are gradually eroded.

Increasing loss and degradation of non-reefal habitats (e.g. mangroves and seagrasses) will also affect coastal fisheries, though the effect this will have on overall fisheries production is not clear. It remains to be determined what proportion of target fisheries species are specifically reliant on mangrove and seagrass habitats, either as juveniles or throughout their life, and whether these fish can use alternative areas in the absence of preferred habitats. In the Caribbean, some coral reef fish (e.g. parrotfish) depend heavily on mangroves as nursery areas, and have become locally extinct where mangroves have been removed[84]. However, some fish that use mangroves as nurseries were able to use alternative habitat types, and were no less abundant on islands without mangroves[84]. Similar studies conducted in the tropical Pacific have revealed relatively little overlap in fish assemblages from coral reef habitats versus mangroves or seagrass beds[83,233], but some of the fish found in mangroves have important functional roles on coral reefs[83]. Widespread loss or degradation of non-reefal habitats is likely to lead to loss of some species, causing local declines in biodiversity, which may or may not affect overall fisheries production.

The extent to which species may be able to adapt to changes in resource availability and habitat structure depends on their ecological versatility. Highly specialised species, such as the coral feeding butterflyfish *Chaetodon trifascialis* are completely dependent on specific types of corals and will die without access to them[234,235]. On the other hand, other species of butterflyfish, such as *C. lunulatus*, are capable of switching their diets to feed on whatever coral prey is available[236]. Highly specialist species are, therefore, extremely vulnerable to habitat loss and degradation, and likely to become locally extinct if catastrophic changes in reef habitats occur[104,213], whereas more generalist species capable of using a range of prey and habitat types are likely to persist[231]. Thus, species vary along a continuum from highly specialised to highly generalist, with the most specialised species likely to be affected first and worst by environmental disturbances[113]. The extent to which other more generalist species are affected will depend upon the severity and extent of the habitat degradation and associated resource depletion.

Vulnerability

Reef-associated fish and invertebrates are likely to become less abundant following extensive degradation and loss of the coastal habitats on which they depend, especially coral reefs. The demersal fish commonly associated with coral reefs that are expected to be affected include emperors, snappers, groupers, surgeonfish, parrotfish and rabbitfish[9]. These fish currently account for 35–80% (by weight) of the estimated total catch of demersal fish in PICTs (**Table 9.2**).

If water temperatures increase by 3°C, and CO_2 exceeds 550 ppm, as projected under the A2 emissions scenario by 2100, coral cover and habitat complexity will be greatly reduced (Chapter 5). This is likely to result in substantial reductions in the abundance of 62–75% of coral reef species, and similar proportions of reef-associated fish and invertebrates[76,210,215,218], including many species presently caught by subsistence and artisanal fishers[9]. Some of these species could persist in areas with remnant coral growth, but these areas will be small and poorly connected and unlikely to support diverse assemblages of fish and invertebrates. There may also be some replacement of specialist reef-associated species with more generalist species (e.g. Mugilidae). However, the loss of coral reefs and other critical coastal habitats is expected to progressively reduce production of demersal fish throughout the tropical Pacific.

9.4 Vulnerability of the four categories of coastal fisheries

Vulnerability to the combined effects of changes in SST, the pH of the ocean, currents and habitats, is expected to differ among the four categories of coastal fisheries. The direct effects of altered atmospheric and oceanic conditions are likely to vary among the key species within each category due to differences in their ontogeny and physiology. The indirect effects due to changes in habitats are also expected to differ among the four categories because the key species depend on coral reefs and the other coastal habitats in different ways. Integrating the effects of climate change on coastal fisheries involves combining the vulnerability of all four categories of coastal fisheries to both the direct and indirect effects.

Here we provide preliminary estimates of how each coastal fisheries category may be expected to respond to the projected changes in the atmosphere and ocean, and the habitats that support them, under the B1 and A2 emissions scenarios by 2035 and 2100. These vulnerability estimates are based on our expert opinion of how the various types of species in each category might be affected by climate change.

9.4.1 Fisheries for demersal fish

The dominance of demersal fish in the catches of coastal fisheries (**Table 9.6**) means that any negative effects of climate change on these fish will lead to major declines in fisheries production and/or marked changes in the structure of coastal fisheries. The most immediate and apparent threat of climate change to demersal fish is the loss and degradation of critical coastal habitats, particularly coral reefs. The demersal fish likely to be affected first and most severely are the small, strongly coral-dependent species, such as butterflyfish, wrasses and damselfish[104], which are the basis of fisheries for aquarium specimens. However, many large reef-associated fish species could also become locally extinct given the extent of habitat loss and reef degradation projected to occur if SST increases by more than 2.0°C (Chapter 5).

Alternatively, there may be corresponding increases in abundance of highly generalist species (e.g. herbivores) that do not rely on live coral substrates[231,237–239]. Some studies have documented increases in the local abundance of herbivorous fish immediately after extensive coral bleaching, possibly due to the greater abundance of algae caused by coral loss[104]. On longer time-frames, however, most reef-associated fish are expected to be less abundant in habitats with low coral cover because negative effects associated with declines in the structural complexity of reef habitats (reduced settlement and survivorship of juvenile fish) will offset any advantage provided by increases in food availability[97,222].

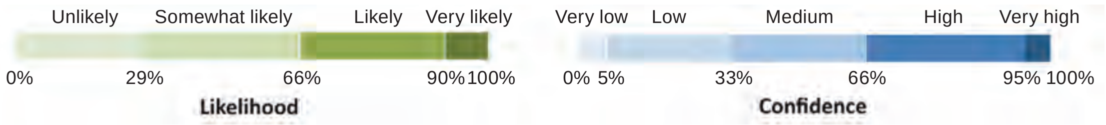
Consequently, overall declines in the abundance of demersal fish, and fisheries production, from coral reef habitats will be a combination of the responses of obligate, reef-associated and generalist species to the projected decreases in coral cover and structural complexity of coral reefs (Chapter 5 and Section 9.3.2). Major declines in species richness and the community structure of demersal fish are very likely, because of ongoing habitats loss and degradation of coastal habitats[76], but declines in fisheries production are likely to be minimal (restricted to a few strongly coral-dependent species) until 2035 (**Table 9.7**). Indeed, the vulnerability of demersal fish is expected to be low under the B1/A2 emissions scenarios in 2035 and any declines in production may be indiscernible against the backdrop of ongoing exploitation and habitat degradation. Very few locations in the Pacific are unaffected by human activities, which makes it difficult to isolate the effects of climate change[240].

By 2100 under the B1 scenario, increasing coral loss and associated degradation of coastal habitats are projected to affect a number of species. Coral reefs, for example, are expected to lose > 40% of their structural complexity, thereby reducing the number of reef-associated fish (individuals and species) that can be sustained by as much as 40%, and all demersal fish by 20%. Under A2 in 2100, coastal fish habitats are expected to be severely degraded (Chapters 5 and 6), leading to extensive loss of reef-associated and other habitat-dependent fish and a 20–50% reduction in all demersal fish (**Table 9.7**). Therefore, demersal fish are expected to have a moderate vulnerability to climate change under B1 in 2100 and a high vulnerability under A2 in 2100.

Projected declines in demersal fish by 2100 will result not only from the anticipated degradation of coral reefs, but also by progressive increases in recruitment limitation, due to decreases in strength of the SEC and SECC, and the effects of higher water temperatures on development and survival of fish larvae. Making projections about likely changes in recruitment is challenging, because of the complexity of the interacting factors that could be affected by climate change, but declines of up to 40% may possibly occur (based on the present inputs of larvae from distant sources). Such effects would lead to reduced and more localised replenishment of populations.

Table 9.7 Projected changes in productivity of the demersal fish component of coastal fisheries under low (B1) and high (A2) emissions scenarios in 2035 and 2100. The estimated responses of broad types of demersal fish are also shown. The likelihood of these responses (especially for A2 in 2100) is low to medium.

Type of species	Emissions scenarios		
	B1/A2 2035	B1 2100	A2 2100
Coral-dependent	-50%	-90%	-100%
Reef-associated	0%	-20 to -40%	-20 to -80%
Generalist	0%	0%	-10 to -20%
All demersal fish	**-2 to -5%**	**-20%**	**-20 to -50%**
	🟩 🟦	🟩 🟦	🟩 🟦



Alterations in the relative abundance of carnivorous and herbivorous fish, and changes in SST and the quality of coral reefs, have possible implications for the incidence of ciguatera fish poisoning in demersal fish, as well as the nearshore pelagic fish (e.g. Spanish mackerel and barracuda) that prey on them (Box 9.2). Chronic incidences of ciguatera are already limiting potential fish consumption in some parts of Cook Islands and French Polynesia[241], leading to significant decreases in the amount of fresh fish consumed. In the past, high incidences of ciguatera may have instigated the movement of Pacific settlements[242].

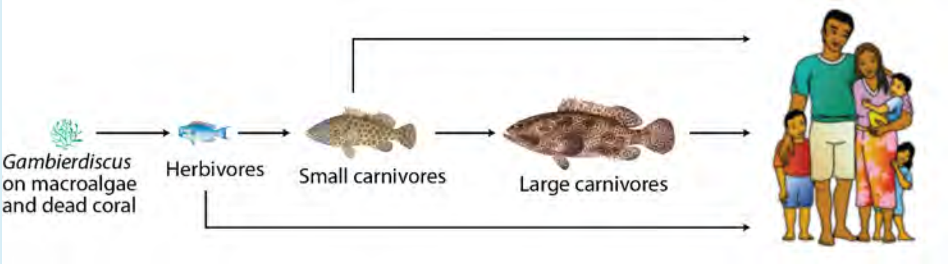
Data on the biology and ecology of fish associated with mangroves, seagrasses and intertidal flats are insufficient to assess additional consequences of declines in the quality and/or quantity of non-reefal habitats. For example, whether larval fish that settle in mangrove and seagrass habitats fail to do so successfully if the structure of these habitats is degraded or lost, or whether they will simply settle in other less optimal areas[84,230], is unknown. It is somewhat likely, however, that habitat loss and degradation of other coastal habitats will compound declines in fisheries production caused by expected changes in the structure of coral reef habitats. Changes in the

Box 9.2 Ciguatera fish poisoning

Ciguatera poisoning has been known for centuries in regions where people eat fish associated with coral reef environments – during his second expedition to the Pacific in the late 1790s, Captain Cook related how two red fish (possibly *Lutjanus bohar*) poisoned his officers. Ciguatera is the most common illness arising from eating fish, with 3400–4700 cases recorded from Pacific Island countries and Territories each year[263]. Because of inaccurate reporting, however, the records are considered to represent only 10–20% of the actual number of cases[264].

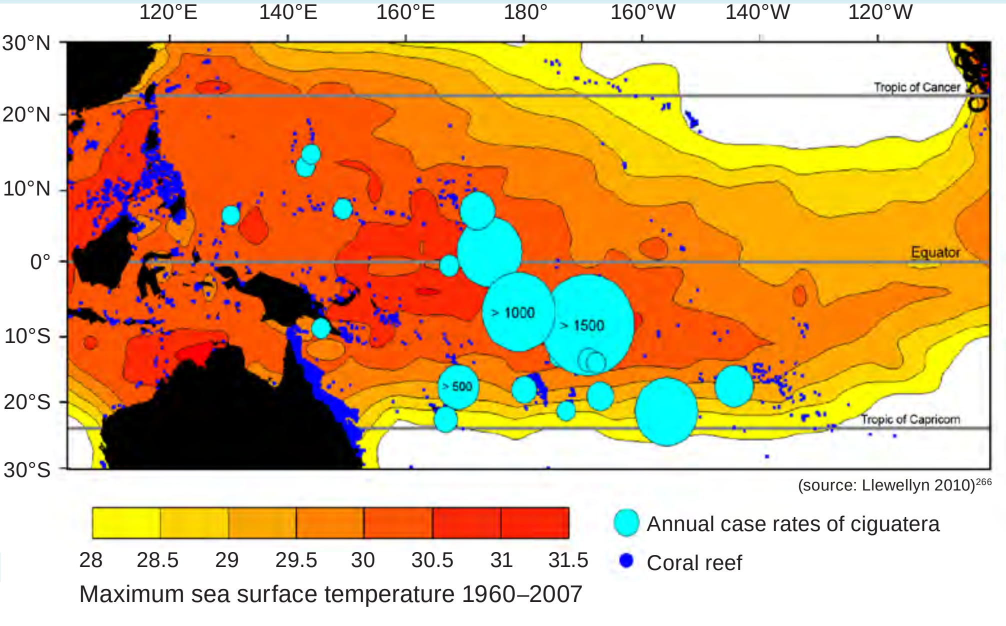
The organisms responsible for ciguatera fish poisoning are dinoflagellate microalgae in the genus *Gambierdiscus*. These microalgae live as epiphytes on the surface of macroalgae, or on dead coral, and are ingested by herbivorous fish when they graze the larger plants or substrate[263].

Gambierdiscus spp. produce toxins that are biotransformed into ciguatoxins by the fish that eat them[264]. The ciguatoxins reside in the muscle tissue of fish, and at much higher levels in the liver and viscera, and 'bioaccumulate' through the food chain. Consequently, the toxins may be found at highest concentrations in large or old carnivorous fish. Where *Gambierdiscus* bloom, however, herbivorous parrotfish and surgeonfish can also be poisonous[241]. Ciguatera-related toxins are resistant to cooking and freezing, so that people who eat ciguatoxic fish are exposed, regardless of how they prepare these fish.



It is difficult to tell whether a fish is ciguatoxic, but the symptoms of ciguatera, and the range of possible symptomatic remedies, are well known[246,263,264]. In general, the symptoms include numbness, tingling of the lips, tongue and throat, joint, muscle and abdominal pain, nausea, vomiting and severe diarrhoea. The classic symptom is the reversal of hot and cold sensations. The prognosis is usually benign, although severe cases of poisoning, which are the exception, can lead to paralysis, coma and even death.

Although this form of fish poisoning has been reported from coral reef habitats worldwide, both the incidence and toxicity of ciguatera are greatest in the Pacific. Within the region, ciguatera is more prevalent where corals have been damaged, allowing macroalgae to grow more profusely[263]. The disturbances to reefs that can promote ciguatera include rises in sea surface temperature (SST)[265]. Interestingly, ciguatera poisoning does not occur throughout the tropical Pacific, for example, it has not been observed in much of Solomon Islands, or in Pitcairn Islands – see map below showing relative abundance of ciguatera cases (blue circles) in the tropical and subtropical Pacific relative to maximum SST[266].



(source: Llewellyn 2010)[266]

Positive correlations have been observed between the annual incidence of fish poisoning and local increases in SST in PICTs that experience warming during El Niño conditions[267]. However, subsequent analysis indicates that any relationship between ciguatera and climate change needs to take account of more complex effects of temperature on the abundance of *Gambierdiscus*, the production of the toxin by the dinoflagellates, and the metabolism of the ciguatoxin by fish[266]. In particular, it appears that (1) SST needs to be above a lower threshold long enough to generate enough toxin in the ecosystem for ciguatera to be widely observed in a human population; and (2) if SST exceeds an upper limit long enough, occurrence of ciguatera decreases. Thus, increases in SST may have both a positive and negative effect on ciguatera case rates. If this hypothesis is correct, the zone in which ciguatera is prevalent may move poleward with climate change.

Regardless of the temperature range that favours ciguatera, the risk of higher incidences of this type of fish poisoning could increase in the future as a result of the projected degradation of coral reefs (Chapter 5). The consequence of such degradation is that, as corals die and macroalgae proliferate, reefs are likely to have more substrate for *Gambierdiscus*. Increases in ciguatera pose problems for many PICTs because both rural and urban communities depend heavily on fish associated with coral reefs for food[4].

strength and/or direction of major surface currents would also be expected to affect connectivity among different habitats, causing direct effects on recruitment by demersal fish that depend on links between habitats during ontogeny.

9.4.2 Fisheries for nearshore pelagic fish

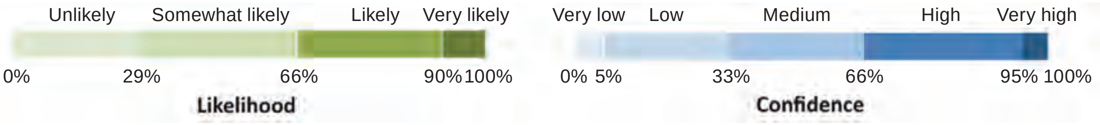
The potential to expand the catches of many of the small and large pelagic species involved in this fishery, particularly skipjack and yellowfin tuna, will be determined by changes to the production of the phytoplankton and zooplankton that underpin the food webs on which these species depend (Chapter 4). The wide-ranging nature of these species also means that they are likely to respond to future changes in environmental conditions by moving to more suitable regions and habitats[30,243] (Chapter 8).

Preliminary estimates of the future changes in the availability of nearshore pelagic species (**Table 9.8**) can be made by using the modelling for skipjack tuna (Chapter 8), and the projections of zooplankton production near the base of the food web (Chapter 4) that also supports the non-tuna species. When the large projected differences in abundance of tuna between the west and the east, and the greater projected decreases in productivity of zooplankton in the west (**Table 9.8**), are combined with the average proportions of tuna and non-tuna species in the catch, there are substantial differences in projected abundances of nearshore pelagic fish in the two parts of the region. In the west, the overall catch is projected to decrease by 2100, whereas it is likely to increase in the east by 15–20% in 2035 and 10–20% in 2100 (**Table 9.8**).

Table 9.8 Projected changes in productivity of the nearshore pelagic fish component of coastal fisheries for the eastern and western areas of the tropical Pacific region under low (B1) and high (A2) emissions scenarios in 2035 and 2100.

Type of species	West*			East**		
	B1/A2 2035	B1 2100	A2 2100	B1/A2 2035	B1 2100	A2 2100
Tuna[a]	+10%	0%	-20%	+35 to +40%	+40 to +45%	+25 to +30%
Non-tuna[b]	-4%	-10 to-15 %	-10 to -25%	-3%	-4%	-8%
Total[c]	**0%**	**-10%**	**-15 to -20%**	**+15 to +20%**	**+20%**	**+10%**
	🟩 🟦	🟩 🟦	🟩 🟦	🟩 🟦	🟩 🟦	🟩 🟦

* 15°N–20°S and 130°–170°E; ** 15°N–15°S and 170°E–150°W; a = approximations based on preliminary modelling for skipjack tuna (Chapter 8); b = approximations based on estimated average percentage change in the production of zooplankton in the Warm Pool, Archipelagic Deep Basins and North Pacific Tropical Gyre Provinces for the western part of the region; and for the Pacific Equatorial Divergence and South Pacific Subtropical Gyre Provinces in the east (Chapter 4); c = based on approximate weighted average for tuna and non-tuna species, where non-tuna species usually dominate the catch of nearshore pelagic fish from Pacific Island countries and territories (PICTs) in the west, and tuna and non-tuna species make approximately equal contributions on average to catches for PICTs in the east (derived from Table 9.6).



Overall, the nearshore pelagic fishery in the west is expected to have little vulnerability to climate change in 2035, a low to moderate vulnerability under B1 in 2100 and a moderate vulnerability under A2 in 2100. In the east, vulnerability is likely to be low because tuna are projected to be more abundant there under all scenarios (**Table 9.8**).

Notwithstanding the projected decreases in availability of nearshore pelagic fish in the west, all PICTs there should be in a position to substantially increase catches of tuna by nearshore pelagic fisheries in the years ahead because there should still be ample tuna for allocation to the coastal fishery (Chapter 8).

It is possible that the increased runoff from major rivers (Chapter 7) may increase the productivity of phytoplankton and zooplankton in coastal areas within the archipelagic waters of PNG, improving the environmental conditions for some species of small pelagic fish. However, we are not in a position to project the extent of potential increases in this component of the coastal fisheries catch.

9.4.3 Fisheries for targeted invertebrates

Climate change is expected to affect the targeted invertebrate species mainly through the loss and degradation of critical habitats (e.g. coral reefs, seagrasses and mangroves). In general, the greatest effects are likely to occur for highly specialist species with particular habitat requirements, e.g. the sea cucumbers *Holothuria fuscogilva* and *H. scabra*, which settle only in shallow seagrass meadows[244,245]. By 2035, the vulnerability of targeted invertebrates to climate change is expected to be low, with the projected changes to habitats estimated to result in a 2–5% decrease in production of the fishery. During the next 2–3 decades, however, overfishing will remain a much greater threat to stocks than climate change, especially for sea cucumbers[64,66]. Thereafter, depending on the extent to which fisheries management can prevent widespread over-exploitation, the effects of climate change may become apparent.

Continued degradation of the supporting habitats and increases in acidification of the ocean are likely to have significant effects on many target invertebrate species, with reduced calcification leading to higher rates of predation on juvenile molluscs. By 2100, vulnerability is expected to be low to moderate under B1 scenario, resulting in a 10% decrease in production. Under A2 in 2100, targeted invertebrate fisheries are likely to have a moderate vulnerability and a possible 20% decrease in production. The quality of many high-value invertebrates harvested for their shell (e.g. trochus, green snail and pearl oysters) is also expected to decrease progressively due to the projected increases in acidification of the ocean[153] (Chapter 11).

9.4.4 Fisheries for shallow subtidal and intertidal invertebrates

Climate change is expected to affect subtidal and intertidal habitats in several ways. First, projected increases in surface air temperatures (Chapter 2) will lead to marked increases in water temperatures in shallow environments. The higher temperatures are expected to reduce the number of species that can use intertidal areas. Second, the projected declines in pH and carbonate ion saturation are likely to affect growth and survival of bivalves (e.g. giant clams, arc and venus shells) and gastropods (e.g. trochus, turban and spider shells), which typically dominate catches from this fishery. Third, sea-level rise will reduce the area of the mangrove forests and intertidal flats (Chapter 6) favoured by some species, especially where land barriers constrain the shoreward migration of those habitats.

The extent to which these changes affect potential harvests requires estimates of the productivity of invertebrates from subtidal and intertidal habitats, which are unknown for the tropical Pacific. It is also very likely that there will be changes in abundance of different invertebrate species. Some species are expected to be favoured and others disadvantaged by the changing environmental conditions and alterations to the areas of mangrove, seagrass and intertidal flats. For example, predation on invertebrates by demersal fish would be expected to increase where intertidal areas become subtidal. Increased ocean acidification poses another grave risk to the potential production of the many molluscs that comprise this coastal fisheries category (**Figure 9.6**). Such effects are expected to be generally negative across these species.

Given the opportunistic nature of the species that underpin existing subtidal and intertidal invertebrate fisheries, the future potential production of this coastal fisheries category is very uncertain. Mainly on the basis of ocean acidification, we estimate that this fishery would have little or no vulnerability to climate change by 2035. By 2100, vulnerability could be low (a 5% decrease in production) under the B1 scenario, and low to moderate (a 10% decrease in production) under A2. These estimates would need to be revised considerably in the event of catastrophic sea-level rise, where sea level increases by up to 2 m by 2100 due to the breakup of the Greenland and West Antarctic ice sheets (Chapter 3), effectively drowning many highly productive intertidal habitats.

9.5 Integrated vulnerability assessment

Vulnerability of coastal fisheries in the tropical Pacific to climate change is expected to vary among PICTs, and be driven by a wide range of factors. These include the extent of the various coastal habitats, local biodiversity, the relative contributions of the four categories of coastal fisheries to the total catch, regional variation in projected changes to atmospheric and oceanic conditions and habitats, past levels of exploitation of stocks, and the extent of habitat degradation. Relative changes to atmospheric climate and features of the ocean are likely to be most pronounced in subtropical areas, although highest overall air temperatures and SST will be experienced in equatorial regions (Chapters 2 and 3). The consequences of local species extinctions are likely to be greatest for PICTs with naturally depauperate coastal fauna and flora[247], i.e. those in the southern and eastern parts of the tropical Pacific (Chapter 1). Fisheries for demersal fish and the two categories of invertebrate fisheries are expected to be more vulnerable in PICTs where stocks have been chronically overexploited, and where the supporting habitats have been severely degraded.

In this section, we summarise the projected changes to SST, ocean acidification, currents and habitats for the tropical Pacific under the B1 and A2 emissions scenarios in 2035, B1 in 2100 and A2 in 2100. We then integrate the projected changes in vulnerability and production for each coastal fisheries category, based on the relative contribution of each category to total catches (**Table 9.6**), to produce overall projected changes in total coastal fisheries production in 2035 and 2100 under B1 and A2.

9.5.1 Low and high emissions scenarios in 2035

Changes in environmental conditions in the tropical Pacific are expected to be fairly moderate until 2035 under both the B1 and A2 emissions scenarios (Chapters 2 and 3). By 2035, surface air temperatures are expected to be 0.5–1.0°C higher, increasing average SST in the tropical Pacific Ocean to 28.0°C whereas ocean pH is projected to decline by < 0.1 (Chapter 3) (**Table 9.9**). As described in Sections 9.3 and 9.4, the direct effects of these changes on all categories of coastal fisheries are likely to be fairly limited by 2035. Small increases in ocean temperatures of < 1°C may actually be beneficial for some key fish and invertebrate species, increasing reproductive success through more rapid development and increased survival of larvae[248].

The ongoing effects of climate-induced changes to nutrient supply (Chapter 4) and habitat degradation (Chapters 5 and 6) expected to occur by 2035 (**Table 9.9**) are likely to be more important. The projected declines in coral cover to around 15%, resulting in losses to the structural complexity of coral reefs (Chapter 5), and changes to mangroves and seagrasses are expected to reduce the diversity and abundance of demersal fish species progressively. Nevertheless, the dominance of coastal fisheries by demersal fish and nearshore pelagic species, some of which are likely to cope with the changes projected to occur by 2035, or even increase, means that reductions in total coastal fisheries production are expected to be negligible over the next two to three decades (**Table 9.10**).

When the projected vulnerability of all four categories of coastal fisheries are integrated, the overall vulnerability of coastal fisheries production is expected to be low in 2035 under the B1/A2 emissions scenarios across the region (**Table 9.10**).

Some variations in these overall conclusions are expected to occur, however. In the more eastern PICTs, the availability of nearshore pelagic fish is projected to increase (**Table 9.10**). In places where overfishing and/or anthropogenic habitat degradation (e.g. destructive fishing, sedimentation and pollution) have already reduced the diversity of key functional groups (e.g. herbivores), the effects of climate change may be more apparent by 2035 because the resources are expected to have greatly reduced resilience. In such places, effects of climate change in the coming decades may be indistinguishable from, and compounded by, the effects of increasing fishing pressure due to the rising local and global demand for fish.

Table 9.9 Projected changes to environmental conditions and habitats that underpin coastal fisheries for 2035 and 2100 under the low (B1) and high (A2) emissions scenarios. Information derived from Chapters 3–5.

Variable	**Present**	**Emissions scenario**		
		B1/A2 2035	**B1 2100**	**A2 2100**
Environmental Conditions				
Carbon dioxide (CO_2) (ppm)	> 380	> 400	500–600	750–800
Ocean				
Sea surface temperature (°C)	27.3	28.0	28.7	29.8
pH	8.1	7.9	7.9	< 7.7
Aragonite saturation	3.5–4.0	< 3.0	< 3.0	< 2.5
Surface currents				
- SEC (transport)	n/a	-3 to -5%	-9%	-18%
- SECC (strength)	n/a	-8 to -18%	-28%	-60%
Net primary production[a]	n/a	-4%	-8%	-13%
Habitats				
Coral cover (%)	30–40			
- Strong management		15–30	10–20	< 2
- Poor management		15	< 5	< 2
Dominant corals	Acroporidae	Poritidae, Faviidae	Poritidae, Faviidae	None
Reef structural complexity (% decrease)	n/a	20–30	> 50	> 90

a = Average for all five provinces listed in footnote to Table 9.8 (derived from Chapter 4); SEC = South Equatorial Current; SECC = South Equatorial Counter Current; n/a = non applicable.

At national levels, the 'health' of coral reefs and the productivity of the fisheries they support are broadly correlated with human population density[17,249,250] and the lack of alternative opportunities to earn income[43]. Well-designed monitoring programmes will be needed to separate the effects of climate changes on coastal fisheries from other stressors (Chapter 13).

9.5.2 Low emissions scenario in 2100

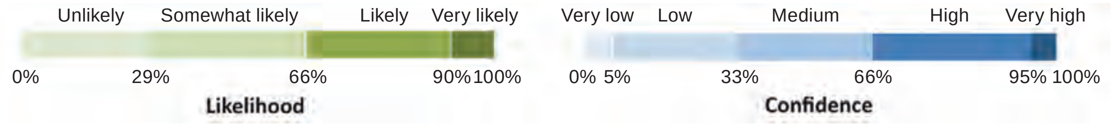
By 2100 under B1, surface air temperatures are expected to increase by 1.0–1.5°C (Chapter 2) and atmospheric concentrations of CO_2 are likely to exceed 500 ppm (**Table 9.9**). In the tropical Pacific, average SST is projected to increase by > 1.4°C to

28.7°C and pH will decline to ~ 7.9. These changes in SST and seawater chemistry are expected to have noticeable effects on the growth and survival of coastal fisheries species. In addition, major impacts on coastal fisheries production are expected to arise from projected loss and degradation of coral reefs, mangroves, seagrasses and intertidal flats (Chapters 5 and 6). Redistribution of species from equatorial to subtropical locations in response to the direct effects of climate change is also expected to occur – fish and invertebrate species not constrained to living on coral reefs or in other tropical coastal habitats are expected to move poleward, reducing

Table 9.10 Vulnerability (V) and projected changes in production (P) of the four categories of coastal fisheries and total coastal fisheries production in 2035 and 2100 for the B1 and A2 emissions scenarios. Note that the availability of nearshore pelagic fish is expected to increase in the eastern part of the region (Chapter 8). The main potential impacts of climate change projected to cause future variations in production of coastal fisheries are also summarised here.

Variable			**Coastal fisheries category**					**Total coastal fisheries*** **	
			Demersal fish	**Nearshore pelagic fish**		**Targeted invertebrates**	**Shallow subtidal and intertidal invertebrates**		
Present contribution to coastal fisheries production			56%	28%		2%	14%		
				West*	East**			West*	East**
Vulnera-bility and projected change in production	B1/A2 2035	**V**	L	nil	L	L	nil[a]	nil[a]	nil[a]
		P	-2 to -5%	nil	+15 to +20%	-2 to -5%	nil	Negligible	Negligible
			🟩 🟦	🟩 🟦	🟩 🟦	🟩 🟦	🟩 🟦	🟩 🟦	🟩 🟦
	B1 2100	**V**	M	L-M	L	L-M	L	M	L
		P	-20%	-10%	+20%	-10%	-5%	-10 to -20%	-5 to -10%
			🟩 🟦	🟩 🟦	🟩 🟦	🟩 🟦	🟩 🟦	🟩 🟦	🟩 🟦
	A2 2100	**V**	H	M	L	M	L-M	M-H	M
		P	-20 to -50%	-15 to -20%	+10%	-20%	-10%	-20 to -35%	-10 to -30%
			🟩 🟦	🟩 🟦	🟩 🟦	🟩 🟦	🟩 🟦	🟩 🟦	🟩 🟦
Major impacts			Habitat loss, and reduced recruitment due to ⇧SST and ⇩currents	Reduced production of zooplankton in food webs for non-tuna species and changes in distribution of tuna		Habitat degradation, and declines in aragonite saturation due to ocean acidification	Declines in aragonite saturation due to ocean acidification		

* 15°N–20°S and 130°–170°E; ** 15°N–15°S and 170°E–150°W; *** assumes that the proportions of the four coastal fisheries categories remain constant; a = nil or very low vulnerability; ⇧ = increasing sea surface temperature; ⇩ = reduced currents; L = low; M = moderate; H = high.



the abundance and diversity of fisheries species in equatorial regions. Independent analyses also project that, without any compensatory increases in growth and abundance of local species, the estimated redistribution of tropical fisheries species could contribute to declines in coastal fisheries production[147].

On coral reefs, increased temperatures and ocean acidification are expected to effectively eliminate branching corals and other sensitive habitat-forming species, thereby reducing coral cover to < 5% under poor management, which will reduce habitat complexity by > 50% (**Table 9.9**). Extensive coral depletion will have a disproportionate effect on many smaller, coral-dependent demersal reef fish (**Table 9.7**) not targeted by coastal fisheries[76,104] (except for aquarium fisheries). However, there are also likely to be knock-on effects for overall production of carnivorous reef-associated demersal fish (**Table 9.7**), caused by declines in the abundance of potential prey fish. When the effects of degradation of other coastal habitats are included, the abundance and diversity of all demersal fish in coastal habitats is expected to decrease by 20%[76] (**Table 9.10**).

The availability of nearshore pelagic fish is expected to decrease by 10% in the western part of the region, but increase by 20% in the east (**Table 9.8**). Targeted invertebrates and those gleaned from subtidal and intertidal areas are projected to decrease by 10% and 5%, respectively.

Taken together, declines in the local production of fish and invertebrates from critical coastal habitats, and movement of some generalist species, are somewhat likely to cause a decline in total coastal fisheries production of 10–20% in the west and 5–10% in the east (**Table 9.10**). The integrated vulnerability for all coastal fisheries is estimated to be moderate in the west and low in the east by 2100 under the B1 emissions scenario (**Table 9.10**). This assessment is based on the assumption that movement of demersal fish is likely to be highly constrained, even though the potential of corals to acclimatise and adapt to moderate long-term temperatures may increase[18] (Chapter 5).

9.5.3 High emissions scenario in 2100

Under the A2 emissions scenario, drastic changes in environmental conditions for the tropical Pacific are expected to occur by 2100 (**Table 9.9**). Surface air temperatures are projected to increase by up to 3.0°C and CO_2 concentrations are likely to be 750–800 ppm. These changes are expected to raise average SST to 29.8°C, reduce pH by 0.3–0.4 units and take aragonite saturation below 2.5. The major consequences are likely to be increased coral bleaching and declines in calcification by corals and coralline algae, molluscs and echinoderms (Chapter 5) (Section 9.4.3). This is expected to reduce habitat for demersal fish, food for nearshore pelagic fish, and the abundance of sea cucumbers, gastropods and bivalves that comprise the fisheries for targeted invertebrates and those gleaned for subsistence.

The drastic loss of structural and biological complexity of coral reefs, and their subsequent domination by macroalgae (Chapter 5) under this scenario, is likely to have profound effects on local abundance and diversity of fish and invertebrates associated with coral reefs. Production of demersal fish is expected to be severely affected. Indeed, heavy mortality of corals, and corresponding decline in habitat complexity, have been calculated to reduce coral reef fish abundance by up to 65%[97,210,218,251]. In addition, reduced oceanic transport associated with weakening of the SEC and SECC is expected to affect replenishment of demersal fish and decrease the supply of nutrients to coastal areas in the western Pacific (**Table 9.9**) (Chapter 4). Even among herbivorous fish, negative effects associated with declines in habitat structure and reduced replenishment could more than offset any benefit from increased availability of food resources (macroalgae).

The combination of these expected effects is likely to reduce the production of demersal fish by 20–50% under the A2 scenario by 2100 through strong effects on coral-dependent and reef-associated species (**Table 9.7**). A 15–20% reduction in the productivity of nearshore pelagic fish is also expected in the western Pacific, and a 10% increase in the east (**Table 9.8**). The productivity of targeted invertebrates is likely to decrease by 20% and those collected from shallow subtidal and intertidal areas by 10% (**Table 9.10**). Taken together, these changes are expected to reduce the overall production from coastal fisheries by 20–35% in the west and 10–30% in the east under the A2 scenario by 2100 (**Table 9.10**), with negative impacts likely to be apparent across most species, except the tuna taken by the nearshore pelagic fishery in PICTs in the east. Thus, the vulnerability of all coastal fisheries categories combined to climate change under the A2 scenario in 2100 is expected to be moderate to high in the west and moderate in the east (**Table 9.10**).

9.6 Uncertainty, gaps in knowledge and future research

The expected effects of climate change on the productivity of the four categories of coastal fisheries outlined above are surrounded by various levels of uncertainty (**Table 9.10**). While climate change is expected to have significant direct and indirect effects on coastal fisheries, our knowledge of such effects is extremely limited. For example, the effects of increasing temperature and declining pH on tropical marine fish have only been tested for relatively small and strongly site-attached species, mostly damselfish[143]. The extent to which these findings are relevant to important fisheries species (e.g. emperors, snappers, groupers, parrotfish, surgeonfish and rabbitfish) is unknown, which reduces the confidence with which we can project changes in coastal fisheries production due to expected alterations in environmental conditions and the structural complexity and biological diversity of supporting habitats.

Improving our understanding of the vulnerability of coastal fisheries to climate change, and identifying effective management actions, will depend to a large extent on doing the following research, outlined in Chapters 2 to 6.

- Obtaining high-quality observations of surface climate and oceanographic conditions throughout the tropical Pacific and identifying their links to coastal ecosystems.
- Downscaling the models for surface climate and oceanographic conditions to the scale of islands[ii] to allow more rigorous assessment of local sensitivity and vulnerability of coastal fish and invertebrates to changes in SST, nearshore currents and ocean acidification.
- Producing an inventory of vegetated coastal habitats, including mangroves and seagrasses, their connectivity to coral reefs, and their environmental thresholds for growth and survival.

Filling important gaps in knowledge also depends on the specific research on coastal fish and invertebrates listed below, so that we can understand better the likely responses of key species to changes in environmental conditions and habitats.

1. Assessing the role of coral reefs, and variation in their structural complexity and biological diversity, in moderating the distribution and abundance of reef-associated fish and invertebrate species harvested by commercial and subsistence fisheries, especially during larval settlement and recruitment. This research needs to be combined with studies of comparative resilience of different reef-building corals, to assess likely changes in composition and structure of reef habitats.
2. Improving our knowledge of the role of mangroves, seagrasses and intertidal flats in supporting the fish and invertebrates caught by coastal fisheries. In particular, we need to know how these habitats function as nursery and feeding areas, their links with coral reefs, and whether fish and invertebrates use the different habitats sequentially during ontogeny, or whether the configuration of the habitat mosaic affects the ecosystem services provided by mangroves, seagrasses and intertidal flats.
3. Testing the sensitivity and adaptive capacity of fish and invertebrate species important for existing and future fisheries production to the effects of rising SST and declining pH, including effects on early life history stages. This research should include (i) testing the combined effects of these variables and their interactions with other anthropogenic stressors, and (ii) assessing the ability of target fisheries species to adapt to these environmental changes.

[ii] This work is now being done for the tropical Pacific by the Australian Bureau of Meteorology and CSIRO, and partners, under the Pacific Climate Change Science Programme; see www.cawcr.gov.au/projects/PCCSP

4. Determining whether there is a link between ciguatera fish poisoning, which can render demersal fish and some nearshore pelagic fish inedible, and climate change. In particular, research is needed to determine whether (i) populations of the microalgae *Gambierdiscus* spp., from which ciguatera originates, are affected by deterioration of coral reefs due to climate change; and (ii) projected changes in SST are likely to alter the areas in which ciguatera occurs, and its virulence.
5. Determining the risks to coastal fisheries, and the communities that rely on them for food, that climate change may alter the incidence of toxic marine algae other than *Gambierdiscus* spp.
6. Evaluating the likely effects of higher levels of nutrients from the projected increases in runoff around high islands in tropical Melanesia (Chapter 7) on the productivity of small pelagic fish species.
7. Assessing the vulnerability to climate change of deepwater species taken by coastal fisheries not considered in this chapter, especially snappers and groupers.

In addition, monitoring the size and composition of catches for all four categories of coastal fisheries must be established across the region. In particular, practical, well-designed sampling programmes are needed to (1) build up more reliable information on the contribution of the four categories of coastal fisheries to food security and livelihoods in each PICT, and the success of adaptations to retain the benefits of coastal fisheries, using household income and expenditure surveys[252]; (2) distinguish the catches for each category of coastal fisheries derived from different habitats; and (3) separate the effects of climate change from other impacts on coastal fisheries.

Photo: Joshua Cinner

Harvesting demersal fish, Papua New Guinea

9.7 Management implications and recommendations

Coastal fisheries have immense nutritional, social, cultural and economic value to the people of the Pacific[1,4,5,23,253] (Chapters 1 and 12). Improving the management of coastal fisheries to meet the needs and aspirations of growing populations is an imperative for PICTs, particularly given their heavy reliance on subsistence fisheries for food security, the limited opportunities to earn income in many rural areas, and a broad range of other drivers affecting the sector[25,26]. This challenge is made all the more demanding by the likely effects of climate change on the production of all four categories of coastal fisheries, but especially demersal fish.

Apart from urgent actions to keep atmospheric CO_2 concentrations below levels expected to damage coral reefs[254] (Chapter 5), a number of management recommendations can be made to optimise benefits from coastal fisheries in the face of ongoing changes to the climate. These measures centre on nurturing the habitats that support coastal fisheries, and avoiding overfishing, which is likely to make some species more sensitive to the effects of climate change[34]. Most of these measures have long been proposed for the toolbox for managing coastal fisheries in the Pacific[1,66,255], but now take on added importance to build resilience to climate change. These measures are outlined briefly below.

- Prohibit local activities that reduce the structural complexity and biological diversity of coral reefs, mangroves and seagrasses to assist these important coastal fisheries habitats to maximise their potential to adapt to climate change (Chapters 5 and 6). The high value of fish habitats needs to be emphasised in coastal zone management plans, and the principles of integrated coastal zone management[256,257] need to be applied. Such efforts will help avoid or minimise impacts from runoff of nutrients and sediments from land use in adjacent catchments, destructive fishing, coral extraction, removal of mangroves, dredging of seagrasses and pollution.
- Keep production of demersal fish and invertebrates within sustainable bounds by ensuring that sufficient spawning adults are safeguarded for regular replenishment of stocks. This constraint requires diagnosis of the internal and external factors affecting fishing by coastal communities, and the implementation of durable, practical and adaptive management to address these various drivers[24] (Chapter 13). Important management measures include (1) creating alternative livelihoods through development of enterprises outside the fisheries sector and through sustainable aquaculture to prevent fishing effort that cannot be supported by stocks[24,26]; (2) strengthening simple community-based management[255]; (3) implementing national fishery regulations (e.g. size limits, closed seasons and areas, gear restrictions and export bans) to underpin community-based management in a way that prevents overfishing; and (4) promoting awareness of the inter-dependence of fishing communities, based on the connectivity between habitats in the life cycles of target species and the need for all stakeholders to manage their resources cooperatively[258].

It is especially important to protect stocks against localised depletion to avoid the situation where replenishment of populations relies on sporadic recruitment from distant sources within a meta-population. Such replenishment is increasingly unlikely where increased SST and altered current patterns reduce the availability of juveniles derived from remote areas (Section 9.3.1.3).

- Raise awareness among fishing communities of the likely changes in species composition of demersal fish under climate change, for example, greater relative abundance of herbivorous fish. Assist communities to switch effort to these species and develop methods to harvest them within sustainable bounds, and in ways that do not adversely affect the important role played by herbivores on coral reefs.

- Rebuild populations of targeted invertebrate species to densities above the thresholds identified for regular replenishment, in order to restore the benefits of these resources on a sustained basis. Sea cucumber fisheries are particularly susceptible to recruitment overfishing[64,66,91]. Strict controls on the export of the smaller size classes and conservative management thresholds based on indicators should be established. Populations of trochus need to be restored in many areas to at least 500–600 individuals per ha, with a wide spread of size classes, before fishing is considered. Restricting future catches to 180 shells per ha per year, preferably with 3- to 5-year moratorium periods between fishing events, should then provide sustainable harvests[10].

- Diversify and increase fishing activities for nearshore pelagic fish through (1) use of low-cost, inshore anchored FADs to improve the catches of skipjack and yellowfin tuna by subsistence and small-scale commercial fishers; and (2) development of fisheries for small pelagic species (fusiliers, anchovies, mackerel, pilchards, sardines, scads and squid)[4,10]. Inshore, anchored FADs, in particular, promise to provide access to the greater quantities of fish that will be needed for food security by many PICTs as their human populations continue to grow (Chapter 12). However, care needs to be taken to position such FADs where they provide access to tuna, so that the FADs do not increase the fishing mortality of large nearshore pelagic species associated with coral reef habitats (e.g. Spanish mackerel).

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Appendix 9.1 Overview of the SPC PROCFish Project

The Pacific Regional Oceanic and Coastal Fisheries (PROCFish) Development Project was initiated in March 2002, and conducted by the Coastal Fisheries Programme and Oceanic Fisheries Programme at the Secretariat of the Pacific Community. The coastal component of PROCFish combined socio-economic surveys and local ecological assessments to gauge the importance and condition of reef and lagoon fisheries throughout the region. Research was undertaken at 4–5 sites in each of 17 Pacific Island countries and territories (PICTs) (**Table 9.1**). Sites represented distinct fishing grounds with active reef fisheries by a discrete human population (i.e. a relatively closed system of local exploitation). As such, the data from the PROCFish Project do not encompass the full range of variation within each PICT. Most importantly, relatively little information was collected close to large urban centres.

Socio-economic surveys were conducted at each site, using a 'snapshot approach'[268], involving analyses of 25 households and a corresponding number of people catching fish and invertebrates. Random sampling was used to provide an average and representative picture of fishing in each community, including people who do not fish, those engaged in fishing for fish and/or invertebrates for subsistence, and those engaged in fishing activities for livelihoods (income) on a small-scale, artisanal basis. The main aims of the household surveys were to (1) collect recent demographic information (needed to calculate seafood consumption); (2) determine the number of fishers per household by gender and type of fishing activity (needed to assess the total fishing impact of a community); and (3) assess the relative dependency of the community on coastal resources.

Ecological assessments were conducted separately for fish and invertebrates. Fish resources and associated habitats were sampled using distance-based underwater visual census (D-UVC). At each site, surveys were conducted along 24 transects, with six transects in each of the four main coral reef structures: sheltered coastal reefs, intermediate reefs, back-reefs and outer reefs. Only coral reef fish of interest for consumption or sale, and species that could potentially serve as indicators of coral reef health (e.g. butterflyfish), were surveyed. Low percentage occurrence could either be due to scarcity (which is of interest) or low detectability (representing a methodological bias). Therefore, analyses were restricted to the 15 most frequently observed families of fish for which D-UVC is an efficient resource assessment method. Substrate characteristics were recorded within ten, 5 m × 5 m quadrats located on each side of a 50 m transect (n = 20 quadrats per transect), using a standard method[269].

Various survey methods were used to compare the status of commonly targeted invertebrates across PICTs and the region. A general assessment of large sedentary invertebrates and habitats was made at spatial scales relevant to species (or species groups), using a tow-board technique[270]. Broad-scale surveys were used to record a range of invertebrates caught for subsistence across sites, whereas invertebrate species targeted by commercial fisheries for export were assessed using more detailed surveys of specific habitats. At each site, surveys were made at multiple 'stations'. At each station, epibenthic invertebrate resources, and some sea star and urchin species (potential indicators of habitat condition), were counted within six, 40 m × 1 m transects. Dedicated night searches were made for sea cucumbers at each station for predominantly nocturnal species. Sea cucumbers were also sampled by collecting all individuals present during three, 5-minute searches by two divers.

Appendix 9.2 Method used to estimate catches for the four categories of coastal fisheries

The following method was used to produce the estimates of catches for the four categories of coastal fisheries (demersal fish, nearshore pelagic fish, targeted invertebrates and subtidal and intertidal invertebrates) for each Pacific Island country and territory (PICT) in **Table 9.6** and Supplementary **Table 9.1** (www.spc.int/climate-change/fisheries/assessment/chapters/12-supp-tables.pdf).

Subsistence catches

Subsistence catches for demersal fish, nearshore pelagic fish, and subtidal and intertidal invertebrates were derived from the total coastal subsistence catches for each PICT in 2007, as reported by Gillett (2009)[5]. Expert opinion from national and regional fisheries agencies familiar with coastal subsistence fisheries in each PICT was used to estimate the average proportion of nearshore pelagic species (as defined in Section 9.2.1.2) in total national subsistence catches (see first data column in the table below). The total subsistence catch was then divided by this proportion to estimate the catch of nearshore pelagic species used for subsistence.

The remainder of the subsistence catch was assumed to be a combination of demersal fish and subtidal and intertidal invertebrates. To divide the remaining catch between these two categories, we used the proportions of fish and invertebrates recorded in the catches from coral reefs used by households for consumption from the SPC PROCFish Project socio-economic surveys at 4–5 sites in 17 PICTs (see third and fourth data columns in the table below). For those PICTs where surveys were not done, we used the average from other PICTs with communities of the same ethnic origin.

Commercial catches

The total catch of targeted invertebrates was derived from national records (or estimates) of exports for sea cucumbers (bêche-de-mer) and trochus for 2007, and anecdotal descriptions of catches for other species, such as mangrove crabs and spiny lobsters, and shrimp in the case of PNG, from Gillett (2009)[5], and occasionally expert opinion (e.g. for mangrove crabs in the case of New Caledonia).

When catches of targeted invertebrates occurred for a PICT, these were deducted from the total commercial catch. The remainder was then partitioned into the estimated proportion of nearshore pelagic fish in coastal commercial catches, based on the expert opinion of national and regional fisheries staff (see second data column in table below, and note that the estimated proportion of nearshore pelagic fish in total commercial fish catches differs from the proportion for subsistence fisheries in some PICTs). The remainder represented demersal fish.

Example for Fiji

In 2007, the total annual subsistence catch was estimated to be 17,400 tonnes[5]. The percentage of total subsistence catch comprised of nearshore pelagic fish was estimated to be 15% (2610 tonnes).

The reminder of the subsistence catch of 14,790 tonnes (17,400 tonnes - 2610 tonnes) was comprised of 76% (11,240 tonnes) demersal fish and 24% (3550 tonnes) subtidal and intertidal invertebrates.

PICT	% nearshore pelagic fish		% demersal fish in remainder subsistence catch	% subtidal and intertidal invertebrates in remainder subsistence catch	Source of estimate for nearshore pelagic fish
	Subsistence	Commercial			
Melanesia					
Fiji	15	30	76	24	A Vunesia, SPC
New Caledonia	10	20	58	42	J Bell, SPC
PNG	40	40	66	34	J Manieva, SPC
Solomon Islands	30	30	76	24	C Oengpepa, WorldFish
Vanuatu	20	35	64	36	L Chapman, SPC
Micronesia					
FSM	25*	40**	63	37	* Gillett (2009)[5]; ** A Vunisea, SPC
Guam	67	67	82[a]	18[a]	'Dominate' commercial landings, Gillett (2009)[5]
Kiribati	20**	22***	88	12	** A Vunisea, SPC; *** 1500 tonnes, Gillett (2009)[5]
Marshall Islands	25*	40**	88	12	* Gillett (2009)[5]; ** A Vunisea, SPC
Nauru	50	50	95	5	T Adams, Nauru Fisheries
CNMI	20	50	82[a]	18[a]	L Chapman, SPC
Palau	35	40	56	44	A Vunisea, SPC
Polynesia					
American Samoa	30	30	81[b]	19[b]	Gillett (2009)[5]
Cook Islands	60	60	87	13	I Bertram, SPC
French Polynesia	9	58	80	20	2332 tonnes commercial catch, Gillett (2009)[5]
Niue	50	50	81[b]	19[b]	Gillett (2009)[5]
Pitcairn Islands	15	n/a	81[b]	19[b]	Gillett (2009)[5]
Samoa	20	40	54	46	A Vunisea, SPC
Tokelau	40	n/a	81[b]	19[b]	K Passfield, IUCN; A Vunisea, SPC
Tonga	10	10	76	24	L Chapman, SPC
Tuvalu	25	35	93	7	A Vunisea, SPC
Wallis and Futuna	10	10	84	16	L Chapman, SPC

a = Average for surveys in Micronesia; b = average for surveys in Polynesia; n/a = not applicable.

National records show that the total catch of targeted invertebrates was 630 tonnes. When the catch of targeted invertebrates is deducted from the total commercial catch of 9500 tonnes[5], the remainder of the commercial catch was 8870 tonnes. This remainder is comprised only of nearshore pelagic fish and demersal fish because subtidal and intertidal invertebrates are used for subsistence. Nearshore pelagic fish comprised 30% (2260 tonnes) of the remainder and the rest (6210 tonnes) was demersal fish.

Sources of error

Considerable caution is needed in interpreting these estimated catches. The estimates are provided as a first attempt to quantify the relative importance of the four categories of coastal fisheries, and will need to be amended as more thorough methods are developed by PICTs to measure the catches within these categories of coastal fisheries. It is particularly important to note that:

- any errors in the catch estimates assembled by Gillett (2009)[5] are transferred here;
- estimates of the proportions of nearshore pelagic fish are seldom based on national catch records and represent expert opinion for most PICTs;
- the socio-economic surveys by the SPC PROCFish Project may not represent national trends, particularly in the larger PICTs, because they were conducted at only 4–5 sites and were targeted at coastal communities heavily engaged in fishing;
- the weights of invertebrates recorded in the SPC PROCFish Project socio-economic surveys represent whole animal weights but for several species the amount eaten is often a minor proportion of total weight; and
- the total catch of targeted invertebrates was often dominated by exports of bêche-de-mer, which usually represent < 10% of the live weight of sea cucumbers. Thus, the relative importance of targeted invertebrate catches is grossly underestimated.

Photo: Hemis.fr/SuperStock

Chapter 10

Vulnerability of freshwater and estuarine fisheries in the tropical Pacific to climate change

Peter C Gehrke, Marcus J Sheaves, David Boseto, Boga S Figa and Jacob Wani

> *'Currently, the magnitude of global climate change is such that most of its effects on freshwater fisheries could be easily masked by or attributed to other anthropogenic influences, such as deforestation, overexploitation and land use change.'* (Ficke et al. 2007)[i]

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[i] Ficke et al. (2007) Potential impacts of global climate change on freshwater fisheries. *Reviews in Fish Biology and Fisheries* 17, 581–613.

Contents

10.1 Introduction

The freshwater and estuarine fisheries in the tropical Pacific are poorly understood compared to the oceanic and coastal fisheries of the region (Chapters 8 and 9). Yet freshwater and estuarine fisheries are more important than most people realise – catches from freshwater habitats alone contribute 4% of regional gross domestic product (GDP) derived from all fisheries resources[1]. This contribution is remarkable, given that freshwater fish habitats account for such a small proportion of the land area of Pacific Island countries and territories (PICTs), and that the land itself represents only 1.8% of the total area of the territorial waters and exclusive economic zones of PICTs (Chapter 1). Because of the predominance of high islands in Melanesia (Chapter 1), most of the freshwater fish production comes from Papua New Guinea (PNG), with significant harvests also being made in Fiji and Solomon Islands[1].

Recent preliminary estimates indicate that the total production of freshwater fish from the region is ~ 24,000 tonnes per year[1]. The significance of this production is apparent when it is compared with the total catch of freshwater fish in Australia, which is estimated to average about 300 tonnes per year for commercial fisheries[2], and around 4000 tonnes per year for recreational fisheries[3].

The estimates of freshwater and estuarine fish catches for the region are preliminary, but these catches undoubtedly form an important part of the diet for people in inland rural areas[4–6]. Indeed, freshwater fish are the most common source of animal protein for communities with access to freshwater and estuarine habitats in PNG[7]. For example, villagers along parts of the Fly River eat as much as 2 kg of fish per person each week[8]. This compares with the highest levels of per capita fish consumption (> 100 kg per person per year) by coastal communities in the region (Chapter 1)[1,9]. Clearly, any alteration in freshwater and estuarine fish production as a result of climate change has potential to affect the food security and livelihoods of people in the inland areas of the region.

In this chapter, we assess how the projected changes to surface climate (Chapter 2) and sea level (Chapter 3), and the anticipated alterations to fish habitats (Chapter 7), are likely to affect freshwater and estuarine fisheries. Because of the limited information available, and the inherent uncertainty that stems from the complex ways in which freshwater and estuarine fish interact with their habitats and other species, this chapter represents a starting point for more detailed investigation rather than a definitive analysis of vulnerability.

We begin by describing the main species of fish and invertebrates harvested from freshwater and estuarine habitats in the tropical Pacific and the ways in which they are used, and then summarise recent catch levels, status of stocks and estimates of sustainable production. To assess the vulnerability of the resources, we use the framework described in Chapter 1 to outline how the main groups of fish species are directly exposed to projected changes in surface climate and sea level, and how they are indirectly exposed through changes to the habitats on which they depend for food, shelter and reproduction. We also evaluate their sensitivity to these changes, and their capacity to adapt. These assessments are made for a low (B1) and a high (A2) emissions scenario[10] for 2035 and 2100.

We conclude by examining the gaps in knowledge and the research required to address them, and by identifying the management measures needed to reduce the negative impacts and harness the possible opportunities for freshwater and estuarine fisheries likely to be associated with climate change.

10.2 Nature and status of freshwater and estuarine fisheries

10.2.1 Main species and their uses

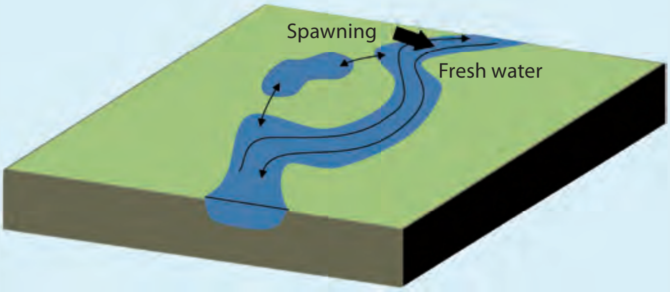
The wide variety of freshwater and estuarine habitats in the tropical Pacific (Chapter 7) supports a diverse range of fish and invertebrate species (Appendix 10.1). Several taxonomic surveys have shown that the greatest diversity and abundance of species occur on the high islands in Melanesia[4–6,11–20]. However, information on the biology of freshwater and estuarine fish and invertebrates in the tropical Pacific is limited. The best available knowledge is for barramundi *Lates calcarifer* in southern PNG[21]. The general migration patterns of various species are also reasonably well understood (Box 10.1). The most complex of these patterns occurs for the amphidromous gobies, some of which rely on transoceanic migration between islands during the larval stage to maintain distributions in rivers over wide areas of the tropical Pacific[22–25].

Surveys also reveal the prevalence of fish introduced to supplement catches of native species, or introduced illicitly or carelessly. Tilapia *Oreochromis* spp. and common carp *Cyprinus carpio* are the most widespread of the species introduced to augment production across the region and have become valued highly as food[26,27]. In PNG, a much broader range of species has become established, however (Appendix 10.2)[28–32]. In contrast to native species, the biology of the introduced species is well known, albeit from other regions.

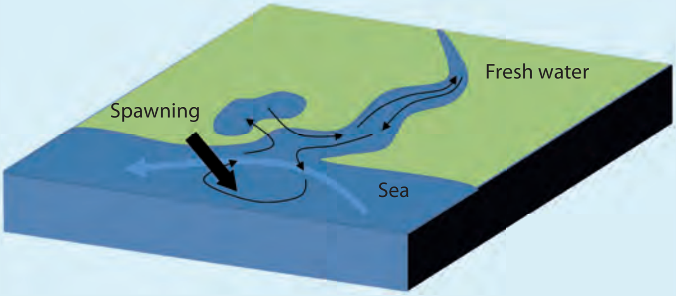
Reliable information on freshwater and estuarine fisheries in the tropical Pacific is also often lacking, and the estimates that are available (**Table 10.1**) involve a considerable amount of guesswork[1]. Nevertheless, it is evident that many of the species caught are used mainly for subsistence, and that women play an important role in these fisheries[30,33–35]. Artisanal fisheries based on the sale of catches surplus to household needs to generate income are, however, also relatively common.

Box 10.1 Migration patterns of freshwater fish in the tropical Pacific

Potamodromous species migrate wholly within fresh water and complete their life cycle without having to enter the sea. Examples in the tropical Pacific region include freshwater mullet *Cestraeus plicatilis*, which produce pelagic eggs and migrate upstream to counter the downstream drift of eggs and larvae[19]. River herring *Nematalosa papuensis* in PNG are also thought to migrate only within fresh water.



Catadromous species live in fresh water as adults and migrate to the sea to spawn. Larvae and juveniles then migrate upstream to enter fresh water. Examples of such species include barramundi *Lates calcarifer*, jungle perch *Kuhlia rupestris* and eels of the family Anguillidae.



Amphidromous species live in fresh water as adults, and spawn in fresh water. Larvae are carried to sea where they feed and grow, returning to fresh water as juveniles. The best known examples from the tropical Pacific region include gobies such as *Sicyopterus lagocephalus*, and the freshwater prawn *Macrobrachium lar*.

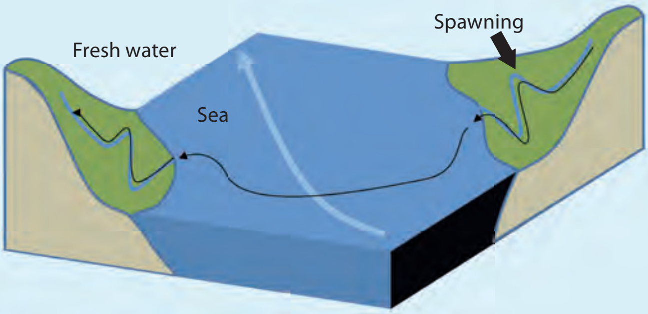


Table 10.1 Recent estimates of annual catches from freshwater fisheries in Pacific Island countries and territories (PICTs), and the estimated combined value of subsistence and commercial catches in 2007. Estimates should be considered as indicative only (source: Gillett 2009)[1].

PICT	Catch (tonnes)	Value (USD)
Melanesia		
Fiji	4146	4,287,500
New Caledonia	10	45,885
PNG	17,500	16,554,054
Solomon Islands	2000	1,464,052
Vanuatu	80	173,077
Micronesia		
FSM	1	8000
Guam	3	10,000
Kiribati	-	-
Marshall Islands	-	-
Nauru	-	-
CNMI	-	-
Palau	1	8000
Polynesia		
American Samoa	1	4000
Cook Islands	5	36,765
French Polynesia	100	488,506
Niue	-	-
Pitcairn Islands	-	-
Samoa	10	33,206
Tonga	1	1980
Tokelau	-	-
Tuvalu	-	-
Wallis and Futuna	-	-
Total	**23,858**	**23,115,025**

- Indicates that freshwater fisheries do not occur in the country or territory.

The enterprises established for commercial fisheries are limited. The most significant commercial fisheries are for barramundi in the southern rivers of PNG, and kai clams *Batissa violacea* and freshwater prawns *Macrobrachium* spp. in Fiji. In general, however, commercial fisheries for freshwater species are poorly developed in most of the tropical Pacific because the rivers are too small to sustain economically viable catches. Other fisheries based on freshwater and estuarine resources in the region are the guided recreational fishing operations for tourists in PNG, and the (often illegal and unpoliced) collection of ornamental species for the international aquarium trade[6,36].

The methods used to catch freshwater and estuarine fish and invertebrates in the tropical Pacific are usually traditional and simple. They include an assortment of woven baskets and traps, hoop nets, cast nets, gill nets, seines, hook-and-line, spears and spearguns, bow and arrow, and hand collection (Appendix 10.1) (**Figure 10.1**). Villagers in parts of PNG also divert streams to trap fish in isolated pools where they can be netted or speared[18]. Derris roots containing rotenone are crushed and applied to pools or slow-flowing waters to stupefy fish in some PICTs. Women are also skilled at catching fish, eels, prawns and freshwater clams using their hands and feet[18,37].

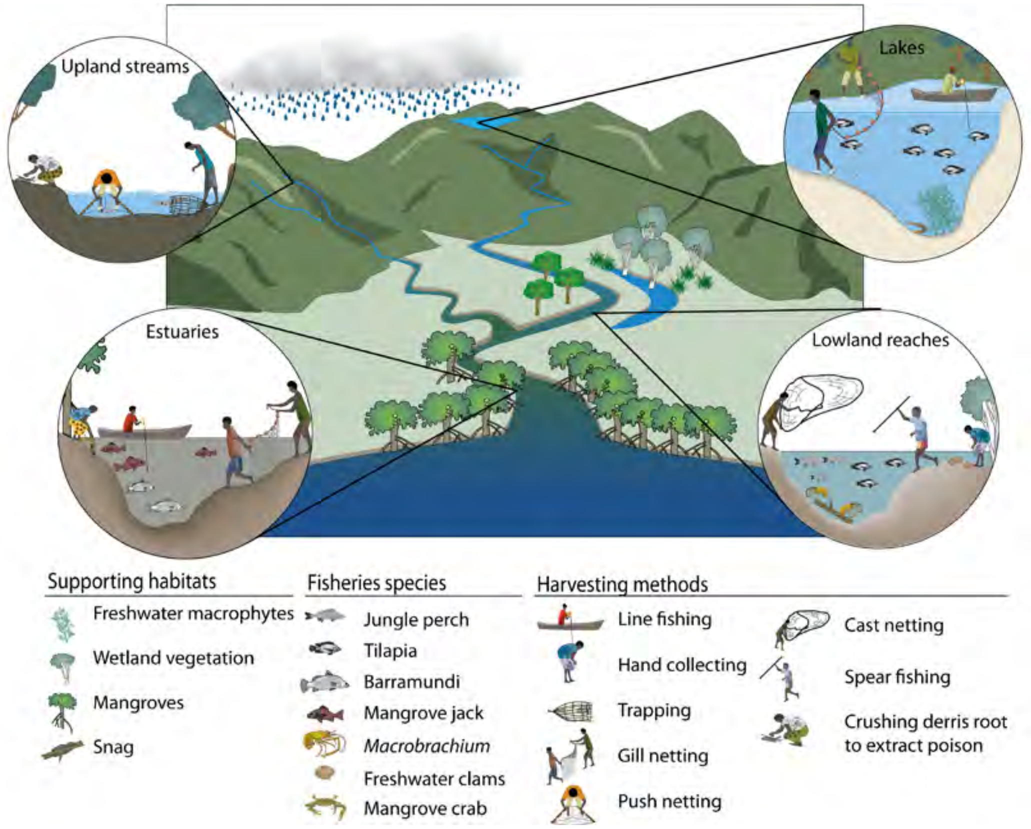


Figure 10.1 Examples of methods used to catch fish and invertebrates in freshwater and estuarine habitats in the tropical Pacific.

The most detailed accounts of freshwater fisheries come from the Fly River system of PNG[8,31,38–42]. The Sepik-Ramu River system in PNG has also been investigated for the purpose of stocking introduced species to increase production[7,28,30,33,43–45]. Yields and stock dynamics for freshwater clams (kai) in Fiji have also been documented[46]. Other fisheries, such as those for amphidromous gobies ('whitebait') returning to fresh water after their ocean migration (Box 10.1), are poorly described[47]. Overall, the most recent estimates of freshwater fish production across the region are acknowledged as crude and require validation[1]. The main native and introduced species of fish and invertebrates supporting freshwater and estuarine fisheries in the Pacific are described briefly below.

10.2.1.1 Native species

- **Barramundi** *Lates calcarifer* is the dominant species in the Fly River system in PNG, accounting for more than 30% of the total fish biomass in the river[39]. The commercial fishery began exporting barramundi caught with gill nets near the mouth and in the middle of the Fly River around Lake Murray in the 1960s[48]. Barramundi are the major predatory fish in the ecosystem and have a complex life cycle, starting as males and changing sex to become females at around seven years of age[49]. They migrate to sea to spawn in the coastal waters of southwestern PNG, and return to fresh water. Juveniles use shallow floodplain wetlands as nursery habitats.

- **River herring** *Nematalosa papuensis* make up 66% of fish numbers in the floodplain habitats of the Fly River, PNG. They are highly fecund and grow rapidly, feeding predominantly on phytoplankton and zooplankton. They are not commonly eaten, but efforts are underway to allow the fishery to expand to supply cannery and fishmeal facilities.

- **Fork-tailed catfish** *Arius* spp. are the main species caught in the Fly River subsistence fishery and are preferred by villagers over barramundi and Papuan black bass *Lutjanus goldei*[40]. The combined subsistence, artisanal and commercial yield is ~ 600 tonnes per year[40]. Fork-tailed catfish are also caught in the Sepik-Ramu River system, PNG[50].

River fisherman, Papua New Guinea

Photo: Kent St John

- **Freshwater eels** *Anguilla* spp. (six species) occur in the southwest Pacific. In Fiji, eels are caught with baited lines, spears, a variety of traditional woven traps, hollow poles and cane knives, but there is no organised fishery. A small commercial eel fishery has operated in the past on Mitiaro Island in the Cook Islands[51], with catches of between 4680 and 10,400 eels per year[52].

- **Mullet** are caught in estuaries and rivers, and from reef flats and coastal waters, for subsistence and sale throughout the Pacific islands. Several species are captured, including warty-lipped mullet *Crenimugil crenilabris*, diamond-scale mullet *Liza vaigiensis*, striped mullet *Mugil cephalus*, blue-spot mullet *Valamugi seheli* and acute-jawed mullet *Crenimugil leuciscus*, using gear such as gill nets and spears. In Fiji, gill nets were banned in 1989, and have been replaced by spears as the main fishing method[26]. Mullet are exported dried, and sold fresh or salted at local markets. Mullet are highly prized in Tonga. In Vanuatu, mullet provide a significant source of protein for local communities and surplus catches are sold for income[27].

- **Goby-fry,** known as 'whitebait' – a general term applied to juvenile fish that swarm near the mouths of rivers as they re-enter fresh water – support fisheries on many islands, e.g. Tahiti and Moorea in French Polynesia. The amphidromous species of gobies harvested in these fisheries include the genera *Awaous*, *Stenigobius*, *Rhinogobius*, *Sicyopus*, *Lentipes*, *Stiphodon*, *Sicyopterus*, and *Sicydium*[23,47]. Traditional methods for catching whitebait include a variety of woven traps and baskets. Data on goby-fry fisheries are difficult to find because catches are episodic, and most of the product is eaten locally[47].

- **Flagtails**, also known as jungle perch, *Kuhlia rupestris* and *K. munda* are a highly valued food fish in Vanuatu and provide a significant source of animal protein for local communities[27]. They are also widespread in Fiji, New Caledonia and Solomon Islands, and have value as a recreational species.

- **Tropical freshwater snappers** are highly prized for food and have economic value through recreational fisheries. Prominent species include mangrove jack *Lutjanus argentimaculatus*, Papuan black bass *L. goldiei*, spot-tail bass *L. fuscescens* and Moses snapper *L. russellii*. These fish are principally marine species that visit fresh water during their juvenile and immature adult stages, although Papuan black bass are thought to live entirely in fresh water[15].

- **Freshwater clams,** known as kai, are prolific in some rivers in Fiji[53]. Kai live in sandy and muddy sediments between the upper tidal limit down to the upstream extent of saltwater penetration. They attain average densities of > 680 g per m^2 [46]. Women collect the clams with their hands and feet by wading, or occasionally, by diving[37]. In the Ba River, the commercial catch accounts for ~ 25% of the total harvest, with the remainder used for subsistence[46]. Kai are kept alive in moistened baskets and sold in markets. The meat is marinated in lime juice and eaten raw[54] or cooked in salted water, coconut cream, curried, deep fried or added to soup[26]. Commercial catches fluctuated between 1000 and 1800 tonnes per year from 1982 to 1992[26,55], suggesting a total harvest of up to 4000 to 7000 tonnes per year. In 2004, the commercial catch was ~ 2500 tonnes[1]. Meat yield is about 20% of harvested weight.

- **Freshwater prawns** *Macrobrachium* spp. and *Palaemon* spp. occur widely in the Pacific islands. The most popular native species is *Macrobrachium lar* which grows to 300 g. In Fiji, the fishery operates exclusively at an artisanal or subsistence level, with freshwater prawns usually collected by women using push nets, fine spears, traps or their hands[53]. Between 1986 and 1992, combined sales of *Macrobrachium* and *Palaemon* prawns in Fiji fluctuated between 22 and 105 tonnes per year, with *Macrobrachium* accounting for ~ 70% of the catch. In Vanuatu, up to six species of *Macrobrachium* are harvested for subsistence and by artisanal fisheries as a source of income.

Photo: Timothy Pickering

Woman selling freshwater clams in Suva, Fiji

- **Shrimp** *Penaeus merguiensis* use estuaries in southern PNG as nursery areas. The adults are caught mainly in the Gulf of Papua, where catches as high as 1000–1300 tonnes per year have been made (Chapter 9).
- **Other species** are harvested opportunistically for subsistence fisheries and occasional sale to local markets. Such species include bull sharks (Carcharhinidae), oxeye herring (Megalopidae), grunters (Haemulidae), trevallies (Carangidae), silver biddies (Gerreidae), silver moon-fish (Monodactylidae), spotted scats (Scatophagidae) and larger species of gudgeons (Eleotridae) and gobies (Gobiidae).

10.2.1.2 Introduced species

Introduced species make an important contribution to fisheries production in many PICTs. This contribution is greatest in PNG, where > 25 species have been introduced since 1949 to provide additional sources of animal protein for local people[56] (Appendix 10.2). Introduced species such as tilapia, carp and golden mahseer *Tor putitora* support important fisheries, but the environmental consequences of these introductions, including the effects on native fish stocks, have received limited attention and remain controversial[57,58].

Observed adverse effects of some stockings include declines in production of native species, damage to vegetated habitats and wetland hydrology, toxic effects from eating the eggs of snowtrout *Schizothorax richardsonii*, and bite injuries to people swimming in rivers from pacu *Piaractus brachypomus*[56]. There are also reports that pacu and an unidentified introduced species known as 'rubber-mouth' have greatly reduced the tilapia fishery in the Sepik River[56].

Walking catfish *Clarias batrachus*, climbing perch *Anabas testudineus* and striped snakehead *Channa striata* are of particular concern in PNG because of their effects on valuable fisheries species[32,38]. The catfish and climbing perch are increasing in abundance[32], and in places have largely replaced native species[42]. Climbing perch are extending their distribution southward, and have recently been recorded on Australian islands in Torres Strait[59–61]. In the Sepik-Ramu floodplains, local people attribute a decline in native fish to consumption of aquatic vegetation by pacu and Java carp *Barbonymus gonionotus*.

The main introduced species presently contributing to fisheries production and food security are tilapia and carp although many other introduced species are also used for subsistence in PNG (Appendix 10.2). Brief summaries of the contributions made by tilapia and carp are provided below.

- **Tilapia** have been introduced widely throughout the Pacific. The most common species are Mozambique tilapia *Oreochromis mossambicus* and Nile tilapia *O. niloticus*. Redbreast tilapia *Tilapia rendalli* were also stocked into the Sepik-Ramu River system in PNG. Subsistence catches of tilapia from the Sepik region have been estimated at 1500–4000 tonnes per year[44,62], accounting for 50% of the total freshwater fish catch[50]. Traditionally, most of the fishing was done by women using woven cane traps, but by the 1970s gill nets were common. Tilapia are also sold in roadside markets by women and generate a significant source of income[63]. On Bougainville Island, tilapia make up 45% of freshwater fish numbers[64], but total fish yields are low (7–12 tonnes per year) so people rarely fish for them. About 60 to 70 tonnes of tilapia were marketed each year in Fiji in the early 1990s, with additional catch consumed by subsistence fishers[26]. However, the marketed catches include fish produced by aquaculture (see Chapter 11 for recent estimates).
- **Common carp** *Cyprinus carpio* have been introduced in many freshwater systems throughout the region, both intentionally, and following escape from aquaculture facilities. In the Sepik-Ramu River system in PNG, parts of Vanuatu and Fiji, carp provide a significant subsistence fishery[7,26,27,65].

10.2.2 Recent harvest levels

Estimates of freshwater fish catches throughout the tropical Pacific (**Table 10.1**) need to be interpreted with caution. PNG is clearly the leading producer – estimates for 2007 of 17,500 tonnes per year[1] are similar to earlier figures for total annual production of 14,500 to 18,500 tonnes[66]. Catches of freshwater fish from PNG in the past are estimated to have consisted of 2.5% barramundi, 3.5% river herring, ~ 80% other freshwater fish and 14% marine fish entering fresh water (**Table 10.2**). Harvesting of river herring has strong potential, however (Section 10.2.4.2).

Fiji is the next-largest producer, with catches ranging from 1263–5921 tonnes between 2001 and 2003[1,2]. In 2007 average production was estimated to be 4146 tonnes per year (**Table 10.1**). Freshwater fisheries harvests from Fiji are remarkable because they are dominated by invertebrates – the catch consists of 85% kai, 11% *Macrobrachium* spp. and *Palaemon* spp., and 4% freshwater fish (**Table 10.2**).

Without much factual basis, the catch of freshwater fish and invertebrates from Solomon Islands has been estimated to be around 2000 tonnes per year[1]. In French Polynesia, estimates of freshwater catches vary from 50 to 100 tonnes per year[1,2], mostly freshwater fish with a small percentage of crustaceans. Estimated catches of freshwater fish from FSM and Samoa are 5 tonnes and 1 tonne per year, respectively (**Table 10.2**).

Table 10.2 Recent estimated annual catches (tonnes) of representative groups of freshwater fish and invertebrates from some Pacific Island countries and territories (PICTs)[2]. Values should be considered as indicative only of average catches.

PICT*	Group					
	Barramundi	River herring	Other freshwater fish	Marine visitors	Crustaceans	Molluscs
Fiji	-	-	124	nea	396	3024
French Polynesia	-	-	50	nea	2	nea
FSM	-	-	5	nea	nea	nea
PNG	350	480	10,814	1850	6	nea
Samoa	-	-	1	nea	nea	nea
Total	**350**	**480**	**10,994**	**1850**	**404**	**3024**

* No estimates available for Solomon Islands; - indicates that species does not occur; nea = no estimate available.

10.2.3 Status of stocks

Concern has been expressed about increasing fishing pressure on freshwater fish stocks, and the threats to production and biodiversity from mining, forestry, agriculture and invasive alien species[16,18,19,32]. Changes in estuarine environments are also thought to be affecting species that migrate between fresh water and the sea (Box 10.1)[25]. In PNG, fishery-independent surveys in the Fly River system found that mining and increased fishing effort contributed to a decrease in fish biomass of 57% to 92% upstream of the confluence of the Fly and Strickland Rivers, and that the number of fish species has been reduced by 6% to 80% since 1983[42].

Here, we summarise present knowledge of the status of the main freshwater fish and invertebrate species in the tropical Pacific. The data are patchy, however, and most reports are not recent and do not necessarily provide a reliable indicator of current trends in stocks. Based on the available data, we have categorised the status of species as 'likely overfished', 'likely fully exploited', 'likely underfished' or 'status uncertain'.

- **Barramundi:** Production in PNG peaked at 330 tonnes per year in the 1970s, but the commercial fishery in the coastal reaches of the Fly River ceased in the early 1990s when the total annual catch plummeted to 4 tonnes[67]. The decline is attributed to the combined effects of mining, overfishing and El Niño droughts[21,42,67]. After the late 1990s, catches increased again and the fishery was managed to yield more sustainable harvests of ~ 40 tonnes per year from the coastal fishery, and 170 tonnes per year from the middle Fly River system (likely fully exploited).
- **River herring:** Abundance of this species in the Fly River system has shown no consistent changes over time[42], and river herring make up ~ 40% of fish numbers and ~ 5% of biomass in riverine habitats, and > 60% of the fish caught in floodplain habitats[38,39] (likely underfished).
- **Fork-tailed catfish:** The giant catfish *Arius dioctes* is an important species in the subsistence, artisanal and commercial fisheries in the larger river systems of southern and central PNG[15]. Numbers of other fork-tailed catfish species have declined at some sites in the Fly River, with several species not recorded during recent sampling[42]. The abundance of fork-tailed catfish in the Sepik-Ramu River system has also declined, from ~ 25% of the total fish catch in the 1980s[44] to < 12% in more recent surveys[33] (likely overfished).
- **Eels:** Little is known about the status of eel populations in the region, although they are still thought to be in robust condition, given the lack of targeted commercial fisheries for the relatively modest stocks[26] and the extended seasons over which elvers enter rivers. Large upstream runs of returning elvers and glass eels, typical of temperate waters, do not occur in Fiji[53], but have not been investigated elsewhere (likely underfished).
- **Mullet:** Declining mullet catches in Fiji and Tonga have prompted changes in permitted fishing gear to allow stocks to rebuild[26,68]. Mullet harvests appear to be stable at most locations in the Fly River system, although catches of *Liza alata* have declined significantly in the middle section of the river[42] (status uncertain).
- **Whitebait:** Catches of goby postlarvae returning to freshwater habitats in French Polynesia are highly variable, ranging from 1 to 100 tonnes per year. With such large variability, the ability to detect changes in stocks is limited. However, concerns have been expressed about the decline of goby-fry fisheries as a result of habitat alteration and over exploitation throughout their range[12,25,47] (status uncertain).
- **Tropical freshwater snappers:** Stocks of Papuan black bass appear to have declined in parts of the middle Fly River system[42], but no data are available for populations elsewhere. Freshwater snappers are still regarded as common in many rivers in the Solomon Islands[18,19] and Vanuatu[27] (likely underfished).

- **Tilapia:** Stocks generally appear to be stable, or increasing in locations where they have spread only recently. In Fiji, catches increased from 6 tonnes per year prior to 1989 to 63 tonnes per year in 1993[26], but there is no recent information on tilapia stocks in the nation's rivers and lakes. In the Sepik-Ramu River system, stocks of redbreast tilapia increased soon after their introduction in the early 1990s[33] but, as mentioned earlier, populations are now being reduced as a result of predation from larger introduced species[56]. In Lake Tegano, on the island of Rennell in Solomon Islands, tilapia has yielded harvests of ~ 16 tonnes per year for many years[69,70]. Large fish are not as common as they used to be, much to the disappointment of local people. Decreasing fish size has been attributed to recent establishment of a large cormorant population, and to overfishing[71] after the introduction of gill nets (status uncertain).

- **Carp:** In the catchment of the Sepik-Ramu River system, PNG, concerns have been expressed that carp populations may become stunted unless they are fished heavily, and that red-breasted tilapia may reduce carp numbers through competition[33] (likely underfished).

- **Freshwater clams:** Catches of kai at the rate of ~ 25% of the standing stock in the Ba River, Fiji, appear to be sustainable. The traditional fishing method of wading means that kai in deeper water are not accessible to the fishery, and provide a source of unfished spawners to help maintain the population. Catches are also limited in years with high rainfall because women are unable to wade during floods[46] (likely underfished).

- **Freshwater prawns:** Catches of *Macrobrachium* spp. and *Palaemon* spp. in Fiji increased by a factor of five from 1988 to 1991, and then fell sharply in 1992, suggesting that stocks near major urban areas may have been severely overfished[26] (likely overfished in Fiji, but underfished in other PICTs).

10.2.4 Estimated sustainable production

Freshwater fish populations commonly exhibit boom-and-bust cycles linked to river flows, floods and droughts, leading to great variation in catches. Peak recruitment often occurs following major floods[72,73], whereas recruitment may fail during drought. Consequently, the large catches that can be taken after wet years are likely to be unsustainable in dry years. Nevertheless, it should be possible to manage species that do not exhibit boom-and-bust population cycles in relation to river flow, such as kai, to achieve more consistent levels of harvest.

Estimates presented here should be considered as representing sustainable production in average years, although large (sometimes an order of magnitude) increases might be quite normal for some species after wet years. A failure to reduce catches during drought when many species are most vulnerable to capture may severely inhibit population recovery after a return to normal flow conditions.

Fishing in a small stream, Papua New Guinea

Photo: Arne Hodalic/Corbis

10.2.4.1 Estimates of sustainable production

Potential fisheries yields from tropical rivers and lakes in other parts of the world have been estimated using empirical relationships between harvests and catchment area, floodplain area and surface area[74,75].

For example, fisheries production (tonnes per year) for African rivers has been estimated as:

$$\text{Yield} = 0.048 \times \text{catchment area } (\text{km}^2)^{0.93} \qquad (r^2 = 0.95)$$

In lakes and reservoirs, fisheries production in these terms has been estimated as:

$$\text{Yield} = 8.32 \times \text{lake surface area } (\text{km}^2)^{0.92} \qquad (r^2 = 0.93)$$

Freshwater habitats in the tropical Pacific tend to be much smaller, with steeper catchment gradients than those in Africa (Chapter 7), so that equations based on African rivers are unlikely to provide reliable estimates of freshwater fisheries production for the region. These equations can indicate possible yields, however, and simple measurements of catchment area and lake surface area can be used to compare potential yields among systems (**Tables 10.3** and **10.4**).

Apart from the yields from the larger rivers of PNG, sustainable catches of freshwater fish from tropical Pacific rivers are quite small. Estimates of sustainable production from five lakes and one reservoir in PNG, Solomon Islands and Vanuatu (**Table 10.4**) suggest that lakes may potentially provide larger catches than rivers. Because Lake Murray in PNG swells to > 2000 km^2 in the wet season, its potential yield may approach 9000 tonnes per year, depending on the duration of inflows.

Table 10.3 Estimated annual sustainable yield (tonnes) of freshwater fish and invertebrates from selected river systems in Pacific Island countries and territories (PICTs), based on the pooled equations for African rivers and floodplains[75]. See Chapter 7 for details of rivers.

PICT	Island	Largest river	Catchment area (km^2)	Annual sustainable yield (tonnes)
Melanesia				
Fiji	Viti Levu	Rewa	2918	80
	Vanua Levu	Dreketi	317	10
New Caledonia	Grande Terre	Le Diahot	589	18
PNG	Mainland	Sepik-Ramu	96,000	2064
	Mainland	Fly	76,000	1661
Solomon Islands	Malaita	Wairaha	486	15
	Guadalcanal	Lungga	394	12
Vanuatu	Espiritu Santo	Jourdain	369	12
	Efate	Teouma	91	3
Micronesia				
FSM	Pohnpei	Nanpil Kiepw	7.8	< 1
Guam	Guam	Talofofo	60	2
Palau	Babeldaob	Ngerdorch	39	1
Polynesia				
American Samoa	Tau	Laufuti	8	< 1
Cook Islands	Rarotonga	Avatiu	5.5	< 1
French Polynesia	Tahiti	Papenoo	91	3
Samoa	Savai'i	Sili	51	2
	Upolu	Vaisigano	33	1
Tonga	'Eua	Fern Gully	2.3	< 1

10.2.4.2 Fly River region, Papua New Guinea

The most reliable estimates of sustainable fish production from freshwater habitats are for barramundi in the Fly River[76], where a total allowable catch has been set at 260 tonnes per year for the combined coastal and inland fishery. Recent assessments suggest that the effective spawning population is large, and that recorded catches of > 170 tonnes per year from the middle Fly River system, and 50 tonnes per year from the coastal fishery, appear to be sustainable.

Sustainable yields for river herring in the Fly River system have been estimated at 18,000 to 33,000 tonnes per year[77] and 5000 to 18,000 tonnes per year[41]. These assessments included habitats that are inaccessible to fisheries, so that estimates of

5000 tonnes per year for this species may be more reasonable. Even so, this represents a significant increase in potential production compared with recent catches of < 500 tonnes per year[2]. For all species combined, potential fisheries yield for the middle Fly River system has been estimated at between 5000 and 10,000 tonnes per year[8,78].

Table 10.4 Estimated annual sustainable yields (tonnes) of freshwater fish from selected lakes in Pacific Island countries and territories (PICTs), based on the pooled equations for African lakes and reservoirs[75].

PICT	Lake	Surface area (km²)	Annual sustainable yield (tonnes)
PNG	Murray	647	3207
	Chambri	260	1386
	Kutubu	50	304
	Yonki Reservoir	22	143
Solomon Islands	Tegano	155	861
Vanuatu	Letas	19	125

10.2.4.3 Other regions

Following the filling of Yonki Reservoir in PNG, catches of carp, Mozambique tilapia and redbreast tilapia increased by more than 50% from 40.2 tonnes per year in 1992 to 60.8 tonnes per year[30]. People living near Yonki Reservoir had no history of fishing, so that the catches may reflect both improved fishing experience and increasing stocks. Catches may approach the empirical estimate of 143 tonnes per year (**Table 10.4**).

Estimates of sustainable fisheries production from the Sepik-Ramu River system in PNG vary considerably. Initial estimates from the floodplain ranged from 3000 to 5000 tonnes per year[44], whereas subsequent estimates suggested a sustainable production of > 8000 tonnes per year[33,79]. The latter estimates are about four times greater than the empirical estimate in **Table 10.3**, and may reflect the introduction of redbreast tilapia *Tilapia rendalli*, giant gourami *Osphronemus goramy*, Java carp *Barbonymus gonionotus*, golden mahseer *Tor putitora*, chocolate mahseer *Neolissochilus hexagonolepis*, snowtrout *Schizothorax richardsonii*, Emily's fish *Prochilodus argenteus*, pacu *Piaractus brachypomus*, and other species into the Sepik-Ramu River system. The program is considered to have been successful in increasing fish catches for food production and income[57], but the environmental and social sustainability of these fisheries have not been assessed. The estimated sustainable yields of > 8000 tonnes per year may change if the introduced species ultimately have significant adverse effects on habitats, on native species, or on each other.

Sustainable production in Fiji can be estimated from catch records[26]. Mullet catches declined after a peak of > 1000 tonnes in 1988 and appeared to stabilise at a more sustainable 300 to 500 tonnes per year. Most of this catch comes from coastal waters but rivers play an important role in the life cycle of most mullet species. Decreases in freshwater prawn production after a peak of > 100 tonnes in 1991, suggests that sustainable production is likely to be 20 to 50 tonnes per year. However, fluctuations in the Southern Oscillation Index (SOI) (Chapter 2) and river flows[80] may affect natural production of freshwater prawns in any given year. Kai harvests appear to be relatively constant and sustainable at the levels described above[1,26,55].

10.3 Vulnerability of freshwater and estuarine fisheries to the direct effects of climate change

The vulnerability of freshwater and estuarine fish and invertebrates to climate change is expected to arise from the combination of (1) direct effects of changes in physical and chemical quality of the water on the survival, growth, recruitment and distribution of species, and (2) indirect effects caused by alterations to structure and complexity of the habitats that species depend on for food, shelter and reproduction (Chapter 7).

Direct effects result from projected changes in water temperature, river flow rates, salinity, dissolved oxygen and turbidity, driven by alterations in surface air temperatures, rainfall and cyclone intensity (Chapter 2), and increases in sea level (Chapter 3). These changes are expected to affect the physiology and behaviour of freshwater and estuarine fish and invertebrates, and alter the normal cues for spawning and migration.

Here we apply the framework outlined in Chapter 1 to assess the exposure of freshwater and estuarine fish and invertebrate species in the tropical Pacific to the main direct physical and chemical changes to water quality and sea level expected to occur under the B1 and A2 emissions scenarios in 2035 and 2100. We also evaluate the sensitivity of these species to these projected changes, the potential impact on these species, their adaptive capacity to reduce these impacts, and, ultimately, the vulnerability of the fish and invertebrate resources to climate change.

10.3.1 Water temperature

Exposure and sensitivity

Exposure of freshwater fish and invertebrates to projected increases in surface temperature, of 0.5–1.0°C under B1 and A2 in 2035, 1.0–1.5°C for B1 in 2100 and 2.5–3.0°C under A2 in 2100 (Chapter 2), needs to be set against the tolerance of the species to prevailing conditions, and other factors that interact with global warming to increase exposure.

Most freshwater fish and invertebrates cannot regulate their body temperature other than by selecting thermal refuges within their habitat. Increased water temperatures affect their metabolic rate, digestion, growth and muscle performance[81–84].

Freshwater fish and invertebrates that use shallow floodplain habitats in tropical regions often have upper temperature tolerances above 35°C, and some species may tolerate water temperatures > 40°C. In contrast, species that inhabit only river channels tend to occur in waters with temperature < 35°C[85,86].

Prevailing water temperatures in freshwater habitats in the tropical Pacific are typically within the range tolerated by tropical fish described above, although extreme high temperatures in floodplain habitats can kill fish. Water temperatures in the Fly River system vary between 24.8°C and 28.1°C (±3.3 SD) in channel habitats[39], and from 27.7°C (±1.4) to 33.1°C (±1.8) in floodplain habitats[38]. In Fiji, freshwater creeks have temperatures between 20°C and 26.5°C[87], whereas the range for the Rewa River is 24°C to 31°C[88]. River temperatures in Solomon Islands usually range between 24°C and 29°C, but can increase to 31°C in open pools[6] and vary between 23.5°C and 26°C[89] in forested catchments.

Increases in water temperatures of 2.5–3.0°C in flowing waters by 2100 under the A2 emissions scenario are unlikely to expose fish to lethal conditions, although sub-lethal responses may occur. Exposure to high temperatures is likely to occur more frequently in floodplain and supratidal habitats.

Exposure to the expected high temperatures could increase significantly where riparian vegetation has been cleared for other land uses (Chapter 7). For example, on the island of Babeldaob in Palau, deforestation reduced shading of the water surface by 87% and increased water temperature by 0.4°C[90]. In a more extreme case, harvesting riparian forests in British Columbia increased water temperature by up to 8°C[91].

Freshwater and estuarine fish and invertebrates in the tropical Pacific are expected to be sensitive to projected changes in water temperature in their early stages of development. Embryonic development and growth of larval fish are typically more rapid at higher temperatures[92]. Barramundi larvae reared at 31°C develop larger muscle fibres than those incubated at 26°C or 29°C, and may have enhanced swimming ability[93]. Optimal growth of postlarval barramundi occurs over a wide range of temperatures from 27°C to 36°C[94], suggesting that increases of up to 3°C may enhance survival and recruitment. However, accelerated development may mean that larvae have increased likelihood of starvation[95] before they reach their nursery habitats, resulting in lower recruitment. Elevated metabolic rates in *Macrobrachium* spp. at higher temperatures and variable salinities may alter the distribution and migratory behaviour[96] of these species.

Sex ratios may change significantly in populations exposed to elevated water temperatures – Nile tilapia exposed to 36°C resulted in subsequent generations consisting of as few as 19% females[97].

Temperature tolerances may be reduced where fish are exposed to pollutants. In Australia, temperature tolerances of silver perch *Bidyanus bidyanus*, eastern rainbowfish *Melanotaenia duboulayi* and western carp gudgeon *Hyseleotris klunzingeri* were reduced by 2.5°C to 4.3°C following chronic exposure to endosulfan and chlorpyrifos[98]. Dissolved metals also reduce the temperature tolerance of fish[99–102] and crustaceans[103,104].

Clearly, there are serious concerns that exposure of freshwater fish and invertebrates to contaminants from mine wastes, forestry and intensive agriculture may increase sensitivity to rising water temperatures.

Floodplain, Sepik River, Papua New Guinea

Photo: Robert Harding Picture Library/SuperStock

Potential impact and adaptive capacity

Mortality of fish typically increases with rising temperatures, presumably due to the greater demands for energy[105]. In general, fish with a constant weight and growth coefficient have a natural mortality of 0.57 at 25°C[105]. The projected increases of 0.5–1.0°C by 2035 are not expected to affect this estimate. Even the projected increases of up to 1.5°C under the B1 emissions scenario, and up to 3.0°C under A2 by 2100 are only likely to alter the general mortality rate marginally, increasing it to 0.58 and 0.60, respectively. Therefore, the potential impact of direct projected increases in temperature on adult freshwater and estuarine fish and invertebrates is considered to be small.

Fish eggs and larvae, which are more susceptible to the effects of heat stress, are expected to experience higher mortality more frequently in shallow habitats under both climate change scenarios, but especially under A2 in 2100. Reduced reproductive performance may also affect recruitment through changes in sex ratios[97,108].

Potential impacts due to the direct effects of higher temperatures are expected to be greatest where elevated contaminant loads and deforestation occur together. These effects should be reduced by planting riparian vegetation to increase shading of the water surface, and by improving the interception of runoff to prevent contaminants entering freshwater habitats (**Figure 10.2**).

Effects of rising temperatures are expected to be greater in freshwater lakes than in rivers, where they are likely to influence fisheries production by altering primary productivity[106]. Warmer waters can result in greater primary production in lakes and, in turn, increased harvests from fisheries[107]. For example, total estuarine and coastal fisheries landings in the Burdekin-Dry Tropics region in northern Australia are estimated to increase by 40% to 60% in the next 50 years under the A2 scenario due to the effects of temperature on primary production[107]. Nevertheless, the impact of increasing temperatures on fisheries harvests is also likely to depend on the balance between bottom-up effects (primary production), driven by nutrient availability, and the top-down effects of predation.

The distributions of species currently limited by their lower temperature tolerances are expected to expand as waters warm, especially for those species that migrate through the sea. For example, the distribution of barramundi is likely to increase southward by 800 km under the A2 scenario[109].

Potential negative impacts of higher temperatures will be ameliorated to a degree by the adaptive capacity of species. In addition to high temperature tolerances, which extend to 38.5°C to 39.0°C in barramundi, bony herring *Nematalosa erebi* and Nile tilapia[110], most species have a physiological ability to acclimate to increasing temperatures[86]. For example, zebrafish *Danio rerio* embryos reared at 33°C produce more heat shock protein to cope with thermal stress than embryos incubated at lower temperatures[111]. Carp also develop increased temperature tolerance after acclimation to temperatures of 30°C to 35°C [112]. However, the capacity of fish to adapt to increased temperature will be reduced by exposure to pollutants.

Vulnerability

The vulnerability of fish in lowland rivers and estuarine habitats to projected increases in water temperatures under the B1 and A2 emissions scenarios is expected to be low (**Table 10.5**). This assessment is based on the ability of most species to withstand fluctuating, elevated temperatures under existing conditions, combined with their capacity to adapt physiologically to projected increases in water temperature.

In contrast, fish in shallow floodplain or supratidal habitats that heat rapidly, and where prevailing temperatures are closer to their upper thermal limits, are more vulnerable to damaging warmer temperatures (**Figure 10.2**). Recruitment of species with wetland-dependent juvenile stages may be affected if cooler temperature refuges

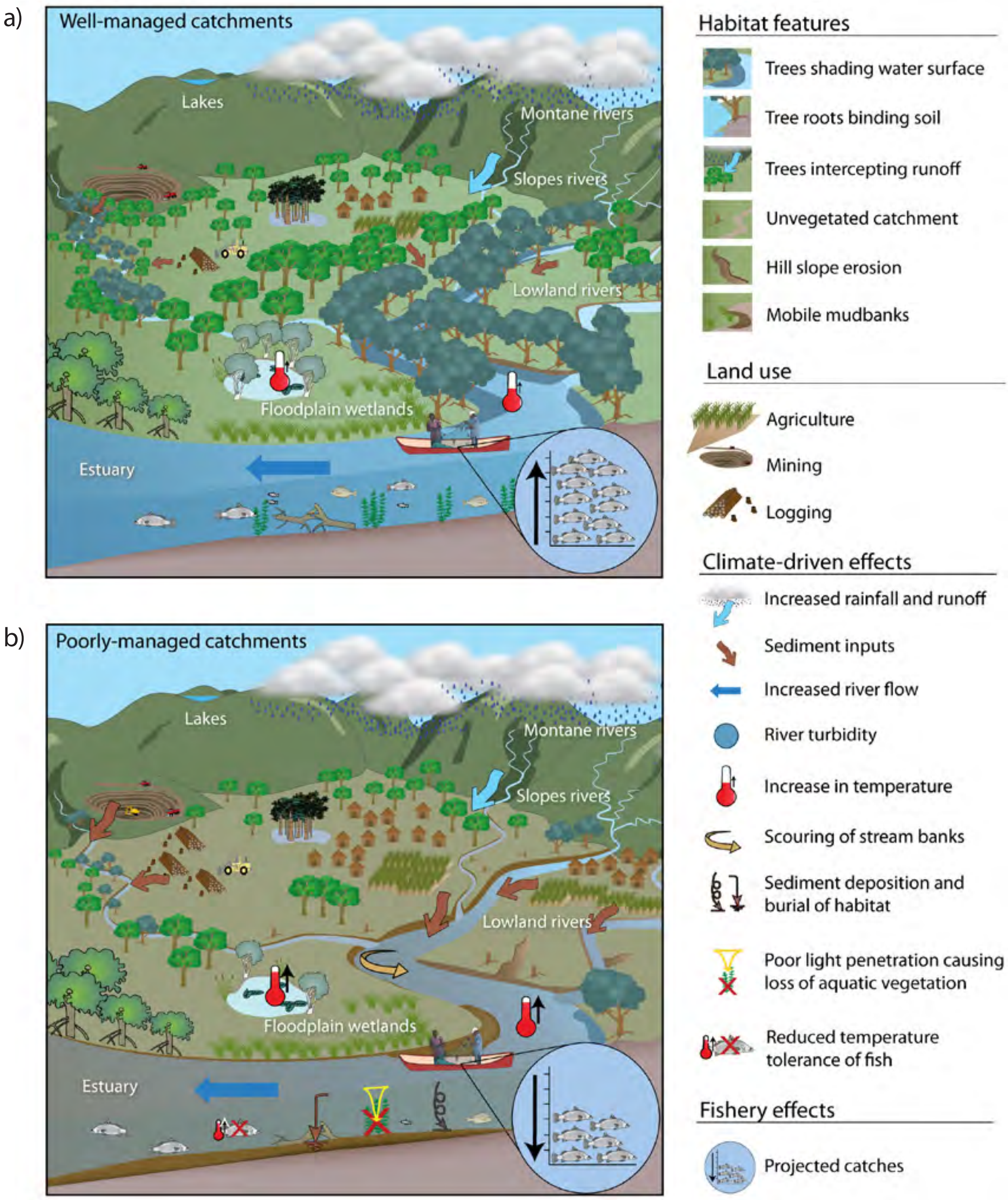


Figure 10.2 Principal effects of climate change on freshwater and estuarine fisheries in (a) well-managed and (b) poorly-managed catchments. In well-managed catchments the increase in habitat availability as a result of climate change is expected to result in increased fish catches. In poorly-managed catchments, where vegetation cover has been reduced, exposure of fish to warming and turbidity will be greater. Contaminants washed from poorly managed catchments would increase sensitivity to higher temperatures further leading to reductions in fish catches.

are not available. At high elevations in PNG, coldwater fish such as rainbow trout, snowtrout and mahseer, are vulnerable to upstream habitat contraction as temperature increases. Fisheries production is also expected to become more vulnerable to thermal stress in catchments that have been partially or completely cleared of forest, or where mining operations, intensive agriculture and forestry lead to elevated contaminant loads in rivers.

Table 10.5 Expected vulnerability, and direction of response (⇧ = higher, ⇩ = lower), of various groups (and representative species) of fish and invertebrates in Pacific Island countries and territories to the direct effects of climate change. Assessments are based on projected changes in water temperature, river flow, salinity, dissolved oxygen (O_2) and turbidity. Note that vulnerability is often projected to be different for disturbed catchments.

Group	Water temperature	River flow	Salinity	O_2	Turbidity
Catadromous species Barramundi, eels, jungle perch, mullet, oxeye herring	➢ L ⇧ ➢ H ⇩ in disturbed catchments	➢ L ⇧	➢ L ⇩	➢ L ⇩ ➢ M ⇩ in floodplain and lake habitats	➢ L ⇩ ➢ M ⇩ in disturbed catchments
Amphidromous species Gobies, gudgeons, *Macrobrachium* spp.	➢ L ⇧, ➢ L ⇩ at high elevation ➢ H ⇩ in disturbed catchments	➢ L ⇧	➢ L ⇩	➢ L ⇩ ➢ M ⇩ in floodplain and lake habitats	➢ L ⇩ ➢ M ⇩ in disturbed catchments
Marine visitors Snappers	➢ L ⇧ ➢ H ⇩ in disturbed catchments	➢ L ⇧	➢ L ⇧	➢ L ⇩	➢ L ⇩ ➢ M ⇩ in disturbed catchments
Potamodromous species River herring, kai, carp*	➢ L ⇧ ➢ H ⇩ in disturbed catchments	➢ L ⇧	➢ L ⇩ ➢ M ⇩ where upstream retreat is blocked	➢ L ⇩ ➢ M ⇩ in floodplain and lake habitats	➢ L ⇩ ➢ M ⇩ in disturbed catchments
High-elevation species Rainbow trout*, snowtrout*	➢ M ⇩ ➢ H ⇩ in disturbed catchments	➢ L ⇧	➢ na	➢ L ⇩	➢ M ⇩ ➢ H ⇩ in disturbed catchments
Substrate spawners Eel-tailed catfish, large gudgeons	➢ L ⇧ ➢ H ⇩ in disturbed catchments	➢ L ⇧ ➢ H ⇩ in disturbed catchments	➢ L ⇩	➢ L ⇩ ➢ M ⇩ in floodplain and lake habitats	➢ M ⇩ ➢ H ⇩ in disturbed catchments
Mouth brooders Fork-tailed catfish, saratoga	➢ L ⇧ ➢ H ⇩ in disturbed catchments	➢ L ⇧	➢ M ⇩ ➢ H ⇩ where upstream retreat is blocked	➢ L ⇩ ➢ M ⇩ in floodplain and lake habitats	➢ L ⇩ ➢ M ⇩ in disturbed catchments
Tilapia*	➢ L ⇧ ➢ H ⇩ in disturbed catchments	➢ L ⇧	➢ L ⇩	➢ L ⇩ ➢ M ⇩ in floodplain and lake habitats	➢ L ⇩ ➢ M ⇩ in disturbed catchments

* Introduced species; H = high vulnerability; M = moderate vulnerability; L = low vulnerability; na = not applicable.

10.3.2 River flow

Exposure and sensitivity

Projected changes in rainfall, and increased intensity and variability of rainfall (Chapter 2), are expected to expose freshwater fish and invertebrates to complex changes in river flows (Chapter 7). The projected trend under the A2 scenario is for a wetter climate and increased river flows in both wet and dry seasons, producing an estimated -5% to +20% change in mean annual discharge in the western Pacific (Chapter 7). For PICTs in the east, projections under the A2 scenario are for a slight reduction in wet season flows, and increased dry season flows, changing mean annual discharge by -10% to > +20%. In contrast, for New Caledonia, wet season flows are expected to increase, with a decrease in dry season flows, producing an overall change in mean annual discharge of -20% to +20% (Chapters 2 and 7). These projections under A2 are more pronounced in 2100 than in 2035. Projected flow regimes under the B1 scenario are largely intermediate between existing conditions and the A2 scenario.

Superimposed on changes in river flow is the likelihood that more extreme flow events could become even more extreme if tropical cyclones become more intense. Although there is still no consensus about the changes to the frequency and intensity of El Niño-Southern Oscillation (ENSO) events, they will remain a feature of the tropical Pacific climate and will continue to have profound effects on river flow through droughts (Chapter 2).

Cyclones and droughts affect river flows on different spatial and temporal scales. Cyclones usually affect spatial scales of the order of ~ 100 km, whereas droughts can influence entire climatic regions at scales of 1000 km. In contrast to the short-term floods associated with cyclones, low flow conditions caused by drought often last for several years, with ecological recovery requiring even longer[113–115]. Despite the widespread expectation for higher rainfall, periods of reduced river flow may also increase under the influence of higher air temperatures and increased evaporation.

Fish in rivers and estuaries are particularly sensitive to changes in river flow, such as the magnitude, timing, frequency and duration of flow events, the rate of change in flow, and the seasonality, variability and predictability of flows[116]. Four types of river flow that affect fish are described in Chapter 7 and summarised briefly below.

- **Population maintenance flows** influence fish biomass through changing the area of available channel and floodplain habitats[117], and are related to flow magnitude measured as volume, depth or area of inundation.
- **Critical flows** trigger life history events such as migration or spawning, and are characterised by velocity and seasonal timing.

- **Habitat flows** maintain environmental quality, such as temperature, dissolved oxygen, sediment transport and substratum characteristics, and plant growth, and operate directly by scouring sediments from gravel spawning beds, or indirectly by increasing productivity of the food web. Habitat flows are characterised by volume, velocity and inundated area.
- **Stress flows** occur during extreme high or low flows, commonly associated with cyclones and El Niño drought events, and may damage fish and their habitats through high velocities, or cause habitat contraction.

Consequently, river flows affect fish directly, and indirectly through modification of habitats (Section 10.4).

Barramundi in northern Australia provide a good example of the effects of changes in river flow on riverine and estuarine fisheries, and the relationships between flow, habitat and aquatic production (Box 10.2). Populations of barramundi are expected to be sensitive to changes in river flows in PNG because the timing and magnitude of flow has a strong influence on downstream migration and spawning.

The strong relationship between river flows and abundance and catches has been well documented for many species[72,117,128,129]. It is based on interactions between seasonal habitat availability, nutrient transport, algal production, food web processes leading to increased recruitment, and cues for fish migration[74,116,130,131].

Kai clams within the lower reaches of rivers in Fiji appear to be resilient to strong flows because they burrow in sediments. However, excessively fine sediments may limit the distribution of kai by inhibiting the ability of the clams to feed using their siphons[46]. Feeding and growth of kai are presumably influenced by freshwater flows, with moderate increases in flow providing improved access to suitable habitat and food. Existing catch data are inadequate to determine whether production of kai is sensitive to changes in river flow, however.

Amphidromous species, such as *Macrobrachium* spp., reproduce in fresh water and larvae are carried by flow downstream to the estuary[132] (Box 10.1). After a larval period of 50 to 110 days, postlarvae migrate upstream[133,134] in response to freshwater flow[135–137]. Dispersal of larvae through the sea is an important life history feature for maintaining *Macrobrachium* distributions[138]. Strong flows can cause downstream displacement, but this can be balanced by increased upstream migration opportunities during high flows[139].

Larvae of amphidromous gobies may survive in fresh water for only a few days if they consume their yolk supply before reaching salt water[25]. During normal and low flow conditions, most larvae may starve to death before reaching the sea[140]. Spawning, downstream migration to the sea, and upstream return migration are cued by seasonal flow events[141], so that even small changes in flow magnitude or timing may affect survival of larvae and recruitment. Because of the long duration of the larval period,

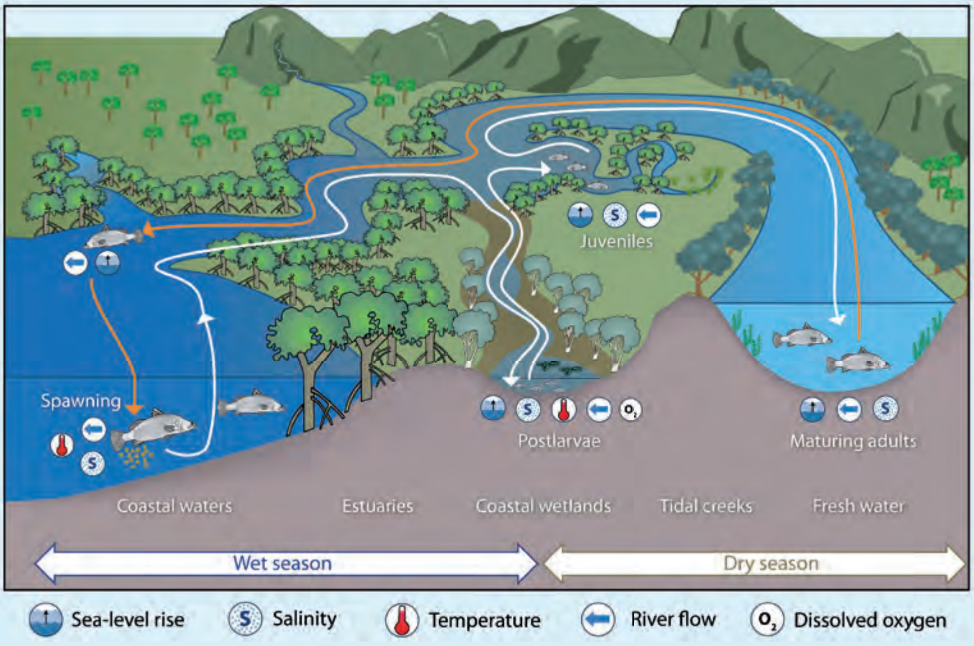
Box 10.2 Life cycle of barramundi *Lates calcarifer*

Barramundi live in coastal waters, estuaries, tidal creeks and lagoons, saltpans, floodplain wetlands and rivers with temperatures ranging from 15°C to 39°C and salinity from 0 to 40 practical salinity units (PSU). Their distribution is limited by lower temperatures and presence of permanent flowing rivers. The eggs survive salinities of 22 to 40 PSU, and early juveniles live in hypersaline flats with temperatures up to 36°C[118–122].

River flows allow adult barramundi to migrate from freshwater to coastal habitats to spawn. Early wet season flows then allow the resulting juveniles to migrate from coastal nurseries into freshwater habitats[109,118,120,123]. Towards the end of the wet season, juveniles move into permanent freshwater habitats where they mature. Growth is fastest in wet seasons with high freshwater flows and warm temperatures[124,125].

Recruitment is strongest in years with high freshwater flows during the spawning and nursery periods[126], translating into increased catches in subsequent years[75,109,125,127]. However, stress flows from severe cyclones reduce barramundi recruitment through reduced egg survival, increased predation in nursery habitats, and downstream displacement of juveniles[73], leading to lower catches in subsequent years.

Lack of flow during prolonged droughts also affects barramundi. Catches in the Fly River in PNG declined dramatically in the early 1990s when floodplain wetlands dried during an El Niño drought[38,67].



most amphidromous species are assumed to disperse widely before re-entering fresh water, but the incidence of fish returning to their natal river or island, is unknown. Goby larvae and *Macrobrachium* spp. are assisted in reaching the sea if spawning coincides with flow events. Return migrations are also assisted by flows that improve habitat continuity through cascades and pool-riffle sequences (Chapter 7).

Potamodromous species that migrate within river channels, or between channel and floodplain habitats, also fluctuate in abundance according to the magnitude and timing of freshwater flows. For example, the abundance and recruitment of bony herring *Nematalosa erebi* in Australia is reduced in rivers affected by flow regulation[142,143].

A decrease in abundance of invertebrates by > 50% occurred in the Port Curtis estuary in Queensland during the 1997–1998 El Niño drought[144]. El Niño drought elsewhere in Queensland has also caused reduced catches of fish, e.g. striped mullet *Mugil cephalus* and flathead *Platycephalus* spp.[127].

Potential impact and adaptive capacity

Modest changes in river flow may have significant effects on fish populations and catches in rivers and estuaries in the tropical Pacific. Flow accounts for 30% to 80% of variation in estuarine fishery catches in Queensland[127], and similar dependence on flow has been demonstrated in tropical riverine fisheries elsewhere[117].

Anecdotal evidence from the tropical Pacific largely supports this generalisation. Projected changes in rainfall for most PICTs are expected to enhance population maintenance flows, critical flows, and habitat maintenance flows. Provided that rainfall coincides with the timing of critical spawning, recruitment and migration behaviour, these changes are likely to result in increased populations of freshwater and estuarine fish. For barramundi, for example, increased rainfall during the low flow season is expected to provide moderate increases in habitat availability, and elevated wet season flows should increase access to shallow nursery habitats, leading to increased recruitment (Box 10.2). Stocks of other catadromous species, including striped mullet, eels, flagtails and oxeye herring are also expected to increase in response to higher rainfall and river discharge.

In contrast, elevated wet season flows in New Caledonia are likely to trigger migration and spawning of the common freshwater fish species found there, which may then be negated by reduced population maintenance and habitat flows in the dry season.

In rivers where water resource development alters seasonal flow regimes, fish typically show limited capacity to adapt to changes in flow seasonality, and decline in abundance. However, in tropical Pacific rivers where seasonal temperatures are relatively stable, fish may have a greater capacity to adapt to changes in seasonal flows as a result of climate change.

Impacts of stress flows from cyclones on riverine and estuarine fisheries are expected to be largely transient, but nonetheless may be severe in affected areas. Fish in montane habitats are adapted to cope with spate flows, and recolonisation after downstream displacement tends to be rapid[137,139]. Stress flows from cyclones are also expected to have relatively low impacts on catadromous species, amphidromous gobies and *Macrobrachium* spp., and on potamodromous species that have extensive distributions in large river systems. For such species, populations in unaffected reaches should recolonise damaged areas relatively rapidly.

Fishing with spears in a coastal river, Papua New Guinea

Photo: Jay Dickman/Corbis

Harvests of kai clams may be interrupted for longer periods during the stronger flows from more extreme rainfall events and cyclones. This outcome is expected mainly through the reduced ability of women to collect kai during high flows[46]. Indeed, most freshwater fishing operations in PICTs within the cyclone belt are expected to be disrupted for longer periods after cyclones until flood flows, debris and water quality return to normal.

The frequency and intensity of El Niño events is also expected to be important in determining the long-term population size of tropical freshwater fish species. Changes to river ecosystems[131] by ENSO and similar extreme events are likely to continue to cause variation in fishery yields from freshwater and estuarine habitats.

Vulnerability

Vulnerability of freshwater and estuarine fisheries to changes in river flow under the B1 and A2 emissions scenarios is expected to be low in the tropical western Pacific (**Table 10.5**), where fish production is projected to increase because of enhanced population maintenance flows, critical flows and habitat flows. In the eastern Pacific, annual flows are expected to increase and to become more uniform, largely through an increase in dry season flows. Rivers in this region are likely to provide increased population maintenance flows and habitat flows, but may experience a reduction in critical flows in dry years. These changes may enhance fish populations through increased habitat availability and quality, but with potentially limited recruitment.

In contrast, vulnerability of freshwater and estuarine fisheries in New Caledonia to changes in river flow is likely to be moderate to high because of lower flows and reduced habitat availability during dry seasons, with some possibility of compensation by increased critical flows during the wet season.

PICTs within the cyclone belt are expected to be more vulnerable to damaging variations in river flow because of the episodic occurrence of severe stress flows.

The anticipated positive and negative changes are projected to be less pronounced under the B1 scenario in 2035 and greatest in 2100 under the A2 scenario. In the absence of detailed studies and downscaled climate modelling, changes in fish stocks and potential yields are estimated to be approximately proportional to changes in rainfall.

10.3.3 Salinity

Exposure and sensitivity

Projected rises in sea level of 20–30 cm by 2035 under the B1 and A2 scenarios, and up to 70–110 cm and 90–140 cm by 2100 under the B1 and A2 scenarios, respectively (Chapter 3), are likely to not affect the salinity of existing freshwater and estuarine habitats uniformly. Some of the larger islands with well-developed floodplains have the highest sediment deposition rates in the world at 3.2 to 4.0 cm per year (Chapter 7), and accretion may outstrip the effects of sea-level rise so that salinity regimes do not alter significantly. Conversely, estuaries on islands that are subsiding will experience greater upstream penetration of salt water. Large river systems such as the Fly and Sepik-Ramu, are expected to have increased freshwater discharge (Chapter 7), which should counter saline intrusion to some extent. Exposure of fish to increasing salinity will, therefore, be determined by a combination of the magnitude of sea-level rise, subsidence and uplift at the island scale, and by freshwater discharge and sediment deposition at the local river scale. These processes would be affected by more severe cyclones, and by droughts associated with El Niño events.

Species likely to be exposed to increased salinity are mainly estuarine residents, marine visitors, catadromous fish such as barramundi, and amphidromous animals such as *Macrobrachium* spp. and gobies. Most of these species are expected to have little sensitivity to increased salinity, however, because of their occurrence in estuarine or salt water for at least part of their life cycle, and their ability to tolerate a wide range of salinities.

In lowland reaches of small rivers, freshwater species that are unable to retreat upstream because of steep cascades, waterfalls, or man-made barriers are expected to be exposed to higher salinities as sea level rises. Species such as sooty grunter *Hephaestus fuliginosus*, saratoga *Scleropages jardinii*, and sleepy cod *Oxyeleotris herwedenii* in these reaches have low tolerance to increased salinities. Large numbers of saratoga died in the Torassi River in western PNG during a severe El Niño event in 1997–1998, when reduced freshwater flow allowed salt water to penetrate 100 km upstream[36]. The combination of environmental stress, increased fishing pressure, and increased catchability in restricted habitats, can result in dramatic reductions of local saratoga populations. Other species, like barramundi, oxeye herring, and mullet have well-developed osmoregulatory abilities to tolerate increasing salinity.

Photo: Nicolas Petit

Fishing for *Macrobrachium* in New Caledonia

Potential impact and adaptive capacity

Variation in salinity tolerances among species produces distinct assemblages along salinity gradients in estuaries[145–148]. Changes in species composition can be expected at fixed locations in estuaries and the lower reaches of rivers as marine species penetrate further inland, and species with low salinity tolerance move upstream. For example, kai clams in Fiji live in brackish to fresh water at the upper tidal limit, and are likely to be forced to move upstream as sea level rises. Tilapia and carp, which are noted for their tolerance of low salinities, are unlikely to be affected by saline intrusion except at the downstream limit of their distributions, where they are expected to adapt by retreating upstream.

Salinity tolerances and acclimation may also be temperature dependent[149], so that interactions between altered rainfall, increased temperature, and saline intrusion may produce unexpected results for some species and locations. One possibility is that extreme cyclones may create freshwater plumes extending for large distances along the coast or to other islands to allow increased dispersal of freshwater species.

Vulnerability

Where no barriers to upstream migration occur, populations of freshwater and estuarine fish and invertebrates are likely to have low vulnerability to increased salinity stemming from sea-level rise (**Table 10.5**), although they can be expected to move upstream. Vulnerability to increased salinity is likely to be moderate in catchments where upstream migration of sensitive species is blocked. In these rivers, reduced stocks of sensitive species can be expected, but species that tolerate a wide range of salinities should remain.

10.3.4 Dissolved oxygen

Exposure and sensitivity

The availability of oxygen (O_2) in water is determined by diffusion from the atmosphere, production of O_2 by photosynthesis and consumption of O_2 by aerobic respiration. Dissolved oxygen in aquatic habitats typically peaks around dusk as a result of photosynthesis during the day, and declines overnight to minimum values in the early morning. Diel fluctuations in O_2 availability in flowing waters tend to be small because movement of the water surface promotes O_2 diffusion from the atmosphere, and mixing in the water column. In standing waters, however, large diel fluctuations in O_2 availability near the surface, and the depletion of O_2 in water layers near the bottom, can constrain fish movements, even within well-oxygenated habitats.

Oxygen solubility in water varies according to temperature, salinity and atmospheric pressure. At sea level, O_2-saturated fresh water at 20°C contains 9.09 mg O_2 per litre, but at 35°C contains only 6.95 mg O_2 per litre[150]. Respiration of most aquatic organisms increases with increasing temperature, so that an increase in temperature simultaneously increases biological O_2 demand and reduces the availability of O_2. As temperature increases, fish expend more energy in ventilating their gills[151] until the decreased O_2 availability is insufficient to meet the increased metabolic demand.

Projected reductions in O_2 availability as a result of temperature increases range from 0.08 to 0.12 mg per litre by 2035 under the B1 and A2 scenarios, equivalent to a change of 1% to 1.5% of saturation, to 0.15 to 0.23 mg per litre (1.8–2.8%) in 2100 under the B1 scenario, and 0.37 to 0.44 mg per litre (4.5–5.3%) in 2100 under the A2 scenario. These projected reductions are small compared with the changes in dissolved O_2 that occur over daily cycles as a result of photosynthesis and respiration by primary producers, or changes with depth in wetlands and lakes.

Actual changes in O_2 availability as a result of climate change can be difficult to project, and will vary greatly among habitats. For example, the rate of O_2 diffusion from the atmosphere into water is influenced by wind and wave action. Where wind turbulence increases mixing of the water column in shallow lakes, O_2 availability is expected to increase. However, in deep, stratified lakes, increased wind action under projected climate regimes (Chapter 2) is expected to bring hypoxic water from below the thermocline to the surface, resulting in reduced O_2 availability and declining fisheries production[152].

Under scenarios of higher temperatures and increased biological oxygen demand, O_2 availability is likely to decrease in some floodplain habitats. For example, growth of floating plants can form a barrier to diffusion of O_2 from the atmosphere, resulting in deoxygenation of the water column. Such declines will be offset in rivers where increased flow can be expected to maintain O_2 availability at or near saturated levels. In wetlands, fish and invertebrates are most likely to be exposed to reduced O_2 availability in water bodies with high organic loads that experience increased temperatures and drying. Fish in lakes may also experience reduced O_2 availability, depending on stratification patterns.

Species that live in flowing, well-aerated rivers typically have low tolerance to low O_2 concentrations. For example, jungle perch are rarely found in water containing less than 6.8 mg O_2 per litre[153]. In contrast, species such as snakeheads have accessory air-breathing organs that enable them to survive in wetlands when O_2 availability becomes too low to support aquatic respiration. Sensitivity of fish and invertebrate species to changes in O_2 availability as a result of climate change is therefore expected to differ depending on their preferred habitats and their tolerance to oxygen depletion.

Potential impact and adaptive capacity

Under normal conditions, the projected changes in O_2 would have negligible effects for most fish species, except for those in marginal habitats where O_2 is already limited. The effects of reduced O_2 availability may be more widespread, however, than suggested by the distribution of exposed habitats. Where shallow wetlands provide nursery habitats for species such as barramundi in PNG, reduced O_2 availability may limit recruitment. This situation may be exacerbated if predators of juvenile fish in wetland nurseries have greater tolerance of hypoxia than species valued for food. In PNG, for example, invasive alien species such as snakeheads may become significant predators of juvenile barramundi[32].

Despite their tolerance of extreme environmental conditions, barramundi in PNG are sensitive to climate effects when wetlands dry during a drought[38]. Potential for reduced O_2 availability in wetlands may then also reduce survival and recruitment in the subsequent wet season, reducing the resilience of the barramundi population to other disturbances.

Tropical fish species in habitats prone to low O_2 availability tend to be tolerant of hypoxia[151], and may have physiological adaptations such as increased blood-oxygen affinity[154], accessory air-breathing organs, and behaviours such as avoidance of hypoxic habitats or the ability to respire from the air-water interface[155]. Increased frequency of hypoxia may therefore result in fish communities dominated by hypoxia-tolerant species.

Sleepy cod *Oxyeleotris herwedenii*, Fly River, Papua New Guinea

Photo: Boga Figa

Vulnerability

Vulnerability of fish to reduced O_2 availability in riverine and estuarine habitats as a result of climate change is likely to be low under both B1 and A2 emissions scenarios in 2035 and 2100 because flowing habitats are actively aerated (**Table 10.5**). Species in habitats prone to low O_2 availability, such as floodplain and supratidal habitats, are naturally vulnerable to hypoxia (**Figure 10.2**), as is evident from fish kills following episodic O_2 depletion. However, vulnerability to hypoxia in floodplain and supratidal habitats as a result of climate change is likely to remain low under both emissions scenarios in 2035 because changes in water temperature and rainfall are relatively modest. Vulnerability of fish to hypoxia in floodplain and supratidal habitats may increase to moderate (**Table 10.5**) by 2100 under the A2 emissions scenario due to the increased likelihood of hypoxic events under conditions of more variable rainfall and increased temperature.

10.3.5 Turbidity

Exposure and sensitivity

Turbidity is caused by suspension of fine sediments in the water column. Turbid water is derived from an upstream source of fine sediment, such as the river bed or banks, or eroding hill slopes. Turbidity is also influenced by the level of catchment disturbance due to mining, forestry and agriculture, which all increase the amount of fine sediments entering rivers (Chapter 7). Catchments with intact vegetation are likely to experience little change in water turbidity as the climate changes because potential increases in sediment transport with increasing rainfall will be offset by increased growth of catchment vegetation. Catchments in which vegetation has been cleared are exposed to increased soil erosion and elevated water turbidity as rainfall increases.

In catchments with relatively intact vegetation and stable soils, transient increases in turbidity are likely to be minor under both the B1 and A2 scenarios in 2035, with potential for small increases in turbidity towards 2100 because of the increase in rainfall and runoff. However, in catchments that have been extensively cleared, the loss of soil stability and increased rainfall is expected to lead to prolonged increases in turbidity, which are likely to be more pronounced towards 2100, especially under the A2 scenario.

Most freshwater fish are relatively tolerant of the direct effects of turbidity – field evidence for direct sensitivity of fish to turbidity is rare. However, extreme suspended sediment loads > 40 g per litre can damage the gill epithelium of fish and affect respiration[156]. Also, fish species that inhabit clear waters in montane and slopes reaches of rivers, and other high-elevation habitats (Chapter 7), tend to be more sensitive to turbidity than species from lowland rivers or floodplain habitats. Lower turbidity levels that reduce light penetration may affect feeding ability of visual predators, although this is less of a problem for planktivorous fish than for piscivores[157]. Indeed, many fish species thrive in naturally turbid rivers such as the Fly River in PNG.

The fine sediments associated with turbidity can affect the availability of spawning sites[158]. However, fish species that produce pelagic eggs (e.g. barramundi, tropical snappers, carp and mullet), or which incubate eggs in their mouths (fork-tailed catfish and tilapia), are less affected by settlement of fine sediments than species with adhesive demersal eggs, such as eel-tailed catfish and gudgeons.

Fish and invertebrates are also expected to be sensitive to turbidity because it can change the habitats and food webs on which they depend (Section 10.4). Benthic primary producers are important in food webs in montane and slopes reaches of rivers, as well as lowland river channels and floodplain wetlands (Chapter 7). Highly turbid rivers typically deposit fine sediments which cover existing habitats, reducing the availability of feeding surfaces[158]. Turbidity also reduces light penetration for photosynthesis by macrophytes, phytoplankton and benthic algae.

Potential impact and adaptive capacity

Impaired feeding ability and spawning success resulting from higher levels of turbidity may reduce the abundance and growth rates of some freshwater fish species. Effects are more likely, however, via changes in primary production that drive a shift from food webs dominated by macroinvertebrate pathways to those based on zooplankton.

Such effects may result in changes in the species composition of fish communities[159]. For example, where elevated turbidity limits benthic production, species such as river herring, mullet and *Macrobrachium* spp. may be forced to rely on other food sources such as zooplankton and detritus. If alternative food sources are not available, or are in limited supply, these important species may decline in abundance, subsequently affecting predators like barramundi and spot-tail bass.

Turbid water can be expected to affect the success of visual fishing methods, such as spears, but should favour non-visual methods like gill nets and derris poisoning.

Photo: Kent St John

Cleaning fish beside a river in Papua New Guinea

Vulnerability

Vulnerability of freshwater and estuarine fish to changes in turbidity as a result of changing patterns of rainfall is expected to be low for both the B1 and A2 scenarios in 2035 and 2100 in well-vegetated catchments (**Table 10.5**). However, clearing of catchment vegetation predisposes aquatic habitats to increased turbidity with increasing rainfall intensity. Accordingly, in disturbed catchments, vulnerability of fish to elevated turbidity will be moderate under the B1 and A2 emissions scenarios in 2035 and the B1 scenario in 2100, and high under the A2 scenario by 2100. Species with demersal eggs are more vulnerable to settlement of fine sediments than species with pelagic eggs.

10.4 Vulnerability of freshwater and estuarine fisheries to the indirect effects of climate change

In addition to the direct physical and chemical changes affecting freshwater and estuarine fish and invertebrates, the projected effects of climate change on the functional process zones of rivers described in Chapter 7 are also expected to affect species that depend on the habitats in these zones for shelter, feeding and reproduction (**Figure 10.2**). Alterations to the biological components of habitats (e.g. aquatic plants and food webs) are expected as a result of increased temperatures, more variable and extreme river flows, new salinity regimes, altered oxygen availability and changes in turbidity, driven by global warming, changes in rainfall, sea-level rise, the intensity of cyclones and the continuation of El Niño events. Variations in river flow will also change the sedimentary and geomorphological characteristics of some habitats.

The scarce information on abundance and status for most freshwater and estuarine fisheries in the tropical Pacific, and the limited knowledge of the biology of these species, makes it difficult to assess the indirect effects of climate change on freshwater fisheries[160]. Overall, the projected increases in availability of shelter, feeding and spawning habitats (Chapter 7), as a result of increased flows stemming from climate change, are expected to enhance freshwater fish populations in many PICTs.

10.4.1 Vulnerability of fish and invertebrates to changes in functional process zones and freshwater habitats

10.4.1.1 Montane rivers

Exposure and sensitivity

The main fisheries species in montane habitats are introduced rainbow trout, carp and tilapia, which have been stocked in the highlands of PNG. These fish are likely to be exposed to reductions in the amount of coldwater habitat available, higher production rates of benthic algae and riparian vegetation, and increased supplies of organic material to food webs (Chapter 7). Changes in water temperature and sediment inputs are expected to be more pronounced in cleared catchments.

Sensitivity to increased water temperature and flows will be influenced by a combination of opposing effects. Coldwater species such as rainbow trout and snowtrout are expected to be affected negatively by these changes, but tilapia and carp may benefit through increased habitat availability, increased food production and faster growth. Higher rainfall may lead to increased frequency of stressful high-flow velocities, increasing the downstream displacement of fish, but prolonging connectivity to facilitate recolonisation of upstream habitats.

Potential impact and adaptive capacity

The effects of changes to the montane sections of rivers on the resident fish species are most likely to be beneficial because the projected impacts will shift habitats closer to the preferences of tilapia and carp. Production of these species is likely to increase, potentially improving the value of the fishery to local people to compensate for reduced production of coldwater species. The exception to these projections is in the montane rivers of New Caledonia, where projected habitat changes are expected to reduce fish abundance.

Vulnerability

Vulnerability of fish production in montane rivers is expected to be low (**Table 10.6**). Indeed, fish production is likely to increase slightly under the B1 and A2 scenarios in 2035 and under B1 in 2100. The increase will be more pronounced under the A2 scenario in 2100 as a result of greater warming and increased rainfall in most of the region.

In PNG, coldwater species, such as rainbow and snowtrout, are expected to decrease in abundance due to increasing temperature under the B1 and A2 scenarios in 2035 and under B1 in 2100. This vulnerability is projected to increase to moderate under the A2 scenario in 2100.

10.4.1.2 Slopes rivers

Exposure and sensitivity

The slopes reaches of rivers are projected to provide more habitats for fish and invertebrates as a result of increased rainfall and river flows (Chapter 7). Production rates of benthic algae and riparian vegetation are expected to increase, resulting in improved food availability for herbivorous fish species. Fish and invertebrates in slopes reaches, such as eels, jungle perch, tilapia, carp, gudgeons, gobies and *Macrobrachium* spp. are likely to respond positively to increased habitat area and food availability, and their production may increase. Subtle differences in physiological tolerances and species ecology are expected to allow some species to respond to environmental change more strongly than others, resulting in a change in the composition of fish communities and catches.

In New Caledonia, the fish fauna is expected to be sensitive to the projected reduction in river flow and habitat area in slopes rivers, and increased exposure to warm temperatures.

Potential impact and adaptive capacity

The low level of clearing in many PICTs will buffer slopes habitats from the effects of increasing temperatures and sediment loads from increased runoff[161]. However, intensive clearing on some islands will increase the effects of warming and erosion associated with increased rainfall. Habitats in catchments with intact vegetation will have a level of protection from the more severe effects of cyclones, and many slopes species are expected to experience only relatively modest changes in their environments. Elevated atmospheric CO_2 concentrations (Chapter 2) are likely to promote growth of riparian vegetation and benthic algae[162,163], enhancing adaptive capacity in regions with increased rainfall by increasing the stabilising effect of catchment vegetation, and providing a higher biomass of algae and detritus for consumers.

Table 10.6 Expected vulnerability, and direction of response (⇧ = higher, ⇩ = lower), of various groups (and representative species) of fish and invertebrates in Pacific Island countries and territories to the indirect effects of climate change. Assessments are based on projected changes in the quality and quantity of fish habitats. Note that vulnerability is often projected to be different in disturbed catchments.

Group	Montane rivers	Slopes rivers	Lowland rivers	Lakes	Floodplain habitats	Estuarine habitats
Catadromous species Barramundi, eels, jungle perch, mullet, oxeye herring	➢ n/a	➢ n/a	➢ L ⇧ ➢ M-H ⇩ in cleared catchments and NC	➢ L ⇧ ➢ M-H ⇩ in cleared catchments and NC	➢ L ⇧ ➢ M ⇩ in cleared catchments and NC	➢ L ⇧ L-M ⇩ in constrained estuaries ➢ H ⇩ in NC
Amphidromous species Gobies, gudgeons, *Macrobrachium*	➢ n/a	➢ L ⇧ ➢ M-H ⇩ in cleared catchments and NC	➢ L ⇧ ➢ M-H ⇩ in cleared catchments and NC	➢ L ⇧ ➢ M-H ⇩ in cleared catchments and NC	➢ L ⇧ ➢ M ⇩ in cleared catchments and NC	➢ n/a
Marine visitors Snappers	➢ n/a	➢ n/a	➢ L ⇧ ➢ M-H ⇩ in cleared catchments and NC	➢ L ⇧ in coastal lakes ➢ M-H ⇩ in NC	➢ n/a	➢ L ⇧ ➢ L-M ⇩ in constrained estuaries ➢ H ⇩ in NC
Potamodromous species River herring, kai, carp*	➢ n/a	➢ L ⇧ ➢ M-H ⇩ in cleared catchments and NC	➢ L ⇧ ➢ M-H ⇩ in cleared catchments and NC	➢ L ⇧ ➢ M-H ⇩ in cleared catchments and NC	➢ L ⇧ ➢ M ⇩ in cleared catchments and NC	➢ n/a
High-elevation species Rainbow trout*, snowtrout*, golden mahseer*	➢ M ⇩ ➢ H ⇩ in disturbed catchments	➢ n/a	➢ n/a	➢ n/a	➢ n/a	➢ n/a
Substrate spawners Eel-tailed catfish, gudgeons	➢ n/a	➢ L ⇧ ➢ M ⇩ in cleared catchments and NC	➢ L ⇧ ➢ M ⇩ in cleared catchments and NC	➢ L ⇧ ➢ M ⇩ in cleared catchments and NC	➢ L ⇧ ➢ M ⇩ in cleared catchments and NC	➢ n/a
Mouth brooders Fork-tailed catfish, saratoga	➢ n/a	➢ n/a	➢ L ⇧ ➢ M ⇩ in cleared catchments	➢ L ⇧ ➢ M ⇩ in cleared catchments	➢ L ⇧ ➢ M ⇩ in cleared catchments	➢ n/a
Tilapia*	➢ L ⇧ H ⇩ in disturbed catchments	➢ L ⇧ ➢ M-H ⇩ in cleared catchments and NC	➢ L ⇧ ➢ M-H ⇩ in cleared catchments and NC	➢ L ⇧ ➢ M-H ⇩ in cleared catchments and NC	➢ L ⇧ ➢ M-H ⇩ in cleared catchments and NC	➢ n/a

* Introduced species; NC = New Caledonia; H = high vulnerability; M = moderate vulnerability; M-H = moderate-high vulnerability; L = low vulnerability; L-M = low-moderate vulnerability; n/a = not applicable.

Towards the upper elevation limit of slopes reaches, where the water is cooler, increasing temperatures are expected to approach the thermal preferences of species such as tilapia and carp, whereas near the downstream limit, temperatures are likely to remain within the preferred range. Fish production in slopes reaches is expected to increase due to increased food availability, and the increased metabolic rates and growth rates of fish exposed to higher temperatures.

Sampling small fish and *Macrobrachium* in Solomon Islands

Photo: David Boseto

Vulnerability

Vulnerability of fish production in slopes river habitats is expected to be low (**Table 10.6**). Indeed, production is expected to increase slightly under the B1 and A2 scenarios in 2035 and B1 in 2100, becoming even higher under the A2 scenario in 2100 as a result of greater warming and increased rainfall in most of the region. However, vulnerability to drought may increase as habitats adjust to a wetter long-term climate regime, so that when droughts do occur, impacts on fish stocks may be more pronounced.

In cleared catchments, and in New Caledonia, vulnerability of fish in slopes rivers will be low to moderate because of the increased negative effects associated with exposure to reduced rainfall under the B1 and A2 scenarios in 2035, and B1 in 2100. Vulnerability will increase to moderate to high in the drier regime under the A2 scenario in 2100.

10.4.1.3 Lowland rivers

Exposure and sensitivity

Fish in lowland rivers are expected to have greater access to suitable habitat due to higher projected rainfall, accompanied by greater growth of macrophytes, benthic algae and phytoplankton, driven by elevated temperatures and concentrations of atmospheric CO_2 (Chapter 7). Higher flows should also increase the extent of aquatic vegetation as the area of wetted habitat enlarges through channel expansion. These changes should provide juvenile fish with increased shelter from predators, and greater primary production at the base of benthic food webs. However, such effects may be balanced by a reduction in vegetated channel habitats through increased sedimentation and turbidity due to the expected increases in rainfall and the possibility of more intense cyclones (Chapter 7).

Downstream lowland reaches are likely to be exposed progressively to higher salinities from rising sea levels and storm surges, causing an upstream retreat of freshwater habitats and fish species. The present suite of fish and invertebrate species is expected to be replaced by more salt-tolerant estuarine fish species.

In New Caledonia, the projections are that fish will be exposed to narrower and shallower lowland rivers as a result of reduced winter flow and episodic sediment delivery following heavy rainfall. Sensitivity to reduced habitat availability and quality is likely to result in reduced fish abundance.

Potential impact and adaptive capacity

In general, rivers with higher discharges provide more complex habitats and support a wider diversity of fish species[164]. Increased flows also promote elevated production in aquatic food webs, resulting in enhanced recruitment and fisheries production. The higher rainfall projected for the region is expected to increase discharge in the Fly River by 9%, and in the Sepik River by 33% by 2050 under the A2 scenario[165], and these changes are likely to increase further by 2100. The increased flows and resulting increases in habitat availability and primary productivity are expected to lead to greater fish abundance.

In drier regions where river flows diminish, smaller lowland river habitats will become more exposed to increasing temperatures, and salt water may penetrate further upstream because of sea-level rise and reduced freshwater flushing. Fish in these rivers are likely to have reduced ability to adapt to the combined environmental challenges compared with fish in rivers with increased flows.

The presence of invasive alien fish species creates greater uncertainty in the projections for fish production due to their potential to tolerate environmental changes more successfully than many native species. There is the possibility that native fish, and those species introduced to increase production, may decrease in abundance under climate change if they are forced into marginal habitats because of their inability to compete with invasive alien species[166], resulting in a reduction in the value of local fisheries.

Vulnerability

Vulnerability of fish in lowland rivers is expected to be low under the B1 and A2 scenarios in 2035 and B1 in 2100. In fact, the main changes are expected to be an increase in fish production as a result of greater river flow. As temperatures and river flows increase under the A2 scenario towards 2100, fish production is projected to increase further (**Table 10.6**).

Fish in lowland rivers where flows are projected to diminish, e.g. in New Caledonia, are expected to be more vulnerable to habitat reduction. In such locations, vulnerability is expected to be low in 2035 under both B1 and A2 scenarios, increasing by 2100 to low to moderate under the B1 scenario, and moderate to high for the A2 scenario.

10.4.1.4 Lakes

Exposure and sensitivity

High-elevation lakes are expected to receive increased inflows, with a reduction in residence time, that should improve water quality (Chapter 7). The projected higher temperatures are also likely to accelerate nutrient cycling and primary production in the pelagic zone. However, coldwater species in high-elevation lakes in PNG, such as rainbow trout, are expected to experience a reduction in habitat area.

Lowland lakes are also likely to receive elevated inflows, extending wet season conditions (Chapter 7), and increasing connectivity with the sea. Fish such as barramundi, river herring, mullet, tilapia and carp should have increased access to lakes and the aquatic macrophytes and food resources they provide. In New Caledonia, lakes are expected to receive reduced inflows and increased evaporation, resulting in a reduction in area and drying of exposed macrophytes.

Coastal lakes may experience increased saline intrusion from rising sea levels and storm surges, leading to replacement of freshwater vegetation with salt-tolerant species, such as mangroves (Chapter 6). This change may be balanced by increased freshwater inflows. Some freshwater fish species in coastal lakes, such as saratoga, are sensitive to saline intrusion, so that exposure to oscillations in salinity may result in these species being replaced by migratory salt-tolerant species, such as mullet and milkfish *Chanos chanos*.

Potential impact and adaptive capacity

The effects of climate change on fish in lakes are likely to vary with altitude, depth, proximity to saline habitats, wind exposure and bathymetry. In high-elevation lakes, warmwater fish species are expected to replace coldwater species, whereas in low-elevation coastal lakes, euryhaline fish species are likely to replace freshwater stenohaline species. Interactions between native fish species and introduced species may result in additional changes that are difficult to forecast, based on factors such as tolerance of hypoxia, changes in temperature and salinity, and drying of habitats. Tolerance of adverse conditions by some invasive alien species may result in them replacing native species and reducing the value of local fisheries, given that long-established introduced fish species are now valued for food. The main invasive alien species of concern occur in PNG, and include snakehead, climbing perch, walking catfish, pacu and Java carp.

Some of the species introduced to increase food supplies, such as tilapia and carp, are tolerant of more extreme environmental conditions, and are prolific breeders. The combination of elevated temperature, food availability, growth rates and habitat availability are likely to translate into increased production of these tolerant species.

Vulnerability

Vulnerability of fish production in lakes is expected to be low, with probable minor changes in species composition. Overall, small increases in fish production are expected from lakes under the B1 and A2 scenarios in 2035 and B1 in 2100. Changes in species composition and fish production should be more pronounced under the A2 scenario in 2100 as a result of greater warming, increased rainfall in most of the region, and increased saline intrusion in coastal lakes (**Table 10.6**).

In drier regions, particularly New Caledonia, fish in freshwater lakes are likely to be increasingly vulnerable to reduced inflows, and increases in temperature and evaporation, resulting in a decrease in fish production. Increased salinisation of coastal lakes is also expected. Vulnerability in such locations is projected to be low by 2035 for the B1 and A2 scenarios, increasing to low to moderate under the B1 scenario in 2100, and moderate to high under the A2 scenario in 2100.

10.4.1.5 Floodplain habitats

Exposure and sensitivity

Fish using floodplains across the region are likely to be exposed to increased inundation of floodplain habitat (Chapter 7), resulting in more productive food webs, and increases in spawning and nursery areas. Increased evaporation due to higher temperatures is likely to be offset by the greater extent and duration of inundation, and increased rainfall. Warmer temperatures, and elevated atmospheric CO_2, should also increase rates of plant growth and decomposition, leading to increases in productivity. Sensitive plant species are likely to be affected by the increased water depth and duration of inundation, and to retreat into shallower habitats. Accordingly, fish in floodplain habitats are expected to respond positively to increases in habitat area, accessibility, and productivity. These gains may be offset by sensitivity to elevated temperatures in marginal habitats and reduced O_2 availability through decomposition of organic material.

Increased deposition of sediments is likely to cause continual alteration in the spatial arrangement of floodplain habitats as aquatic vegetation disappears from some locations, and recolonises others (Chapter 7). At lower floodplain extremities, intrusion of saline water is also expected to change the distribution of aquatic vegetation. Where rising sea levels force freshwater flows onto the floodplain, exposure of floodplain fish species to changes in salinity is likely to be less severe.

In New Caledonia, the rate of sedimentation on floodplains may increase more than elsewhere because of a decline in catchment vegetation as the climate becomes drier, combined with increased erosion during more severe cyclones. Fish are expected to be exposed to reduced permanency and increased temperature in refuge habitats, reduced benthic productivity and increased sedimentation of spawning sites. Sensitivity to these changes may result in reduced fish distributions among habitats, and reduced recruitment and abundance of fish.

Potential impact and adaptive capacity

Floodplain inundation is a powerful driver of fisheries production in large rivers[130], and fish catches in the large floodplain rivers of southern PNG are expected to expand with increasing flow and water temperatures. In particular, increased discharge in the Fly River system[166] is expected to improve the availability of floodplain habitats, and increase production of barramundi, river herring and ariid catfish[38,39,109] by up to ~ 10%. Similar increases in fish production are expected in other rivers.

The magnitude of increased fish production may be influenced by the geological history of individual rivers. The Sepik-Ramu River system in PNG provides a useful case study. The vast floodplains in this system today were formed only 6000 years ago[167]. Fish species that lived in these rivers at that time lacked the adaptations common in typical floodplain species to use the newly-available habitat[44]. As a result, fish production in the Sepik-Ramu River system is substantially lower than the habitats can potentially support. Therefore, increased habitat availability stemming from the elevated river discharge in the Sepik-Ramu might produce only relatively modest increases in fish production, except for introduced species such as carp and tilapia[28,168]. The total increase in production in the Sepik-Ramu River system is, therefore, anticipated to be lower than the 33% increase in river discharge. On smaller islands with limited floodplain areas, fisheries production is still expected to increase in response to increased flows and habitat availability.

The exception to the projections for increased floodplain inundation and fish production is New Caledonia, where reduced connectivity of floodplain habitats in winter is expected to cause a decline in fish production in line with the projections made for other regions experiencing a drier climate[86,161,164].

Vulnerability

Vulnerability of fisheries on floodplain habitats to climate impacts varies among species, river systems and islands, depending on the species composition of the fishery and geological history of the location (**Table 10.6**).

Floodplain fisheries in southern PNG have low vulnerability to all the likely changes to floodplains, and are expected to provide increasing yields under the B1 and A2 scenarios, with the greatest increases in production occurring under the A2 scenario in 2100. On islands where floodplains have developed only recently, vulnerability of fish production will also be low, with the greatest benefits projected to be increased catches of introduced species, such as tilapia and carp. On steep islands with limited floodplain development, vulnerability will also be low but increases in fish production will be modest due to the limited amount of habitat available.

In New Caledonia, vulnerability of fish production associated with floodplain habitats is expected to be low in 2035 for both B1 and A2 scenarios, increasing to low to moderate under the B1 scenario, and to moderate for the A2 scenario in 2100.

10.4.2 Vulnerability of fish and invertebrates to changes in estuarine habitats

Exposure and sensitivity

Estuarine fish and invertebrates are potentially exposed to a greater range of climate change effects than species in freshwater or coastal habitats. These potential changes include the processes of water circulation and sediment transport, and rearrangement of habitats, as well as alterations to nutrient supply, food webs and connectivity between habitats[169]. Species distributions and abundances are likely to be affected by modifications in refuge habitats, feeding areas and spawning sites. Interactions between species are expected to be different, as large predators gain access to formerly shallow habitats as water depth increases.

Most estuaries are projected to extend further upstream as sea level rises, and larger projected freshwater inflows increase flushing of estuaries, resulting in greater discharge of fine sediments and variability in turbidity (Chapter 7). The combination of increased deposition and scouring is expected to produce a more dynamic habitat for fish and invertebrates. The ability of macrophytes, such as seagrasses and mangroves, to stabilise sediment deposits and provide fish habitat will be determined by the rate of sediment delivery, rate of scouring, and rate of plant growth. Greater variability in production of benthic and planktonic algae, and the occurrence and extent of seagrass and mangrove habitats, is likely to occur (Chapter 6). The adaptive capacity of estuarine vegetation is expected to allow estuarine habitats to migrate landward at a similar rate to rising sea levels[170]. Where plant communities are unable to retreat because of local topography, estuarine fish and invertebrates will experience a reduction in habitat area.

Estuarine fish and invertebrates will be sensitive to the projected positive and negative changes in habitat area, depending on local topography. Increased freshwater inflows may strengthen recruitment of many estuarine species that depend on flow cues for breeding and migration, or flow-related increases in primary production.

The sensitivity of estuarine species to expected habitat changes is likely to be greater in New Caledonia, where estuaries may experience greater variability in salinity and sediment deposition during floods associated with stronger cyclones, interspersed with periods of reduced flow and increased salinity.

Photo: Erin Michelle Smith

Children fishing in an estuary in Papua New Guinea

Potential impact and adaptive capacity

The effects of climate change on the production of estuarine fisheries will be driven by local factors that determine the relative impacts of increased river discharge and rising sea level. Sea-level rise is expected to be a persistent change with superimposed tidal oscillations, whereas changes in river flow are likely to be more episodic. The outcome of these interactions will determine whether there is an increase or decrease in the mangroves, seagrasses, intertidal flats, supratidal saltmarshes and wetlands that support estuarine fish production (Chapter 6).

Increasing river discharge is likely to increase nutrient delivery to estuaries which is expected to enhance biological productivity when combined with increasing temperature and CO_2. However, rising sea levels are projected to alter the location of salinity gradients, resulting in substantial losses of mangroves in many places, but allowing them to migrate upstream or landward in other locations (Chapter 6). Where both salinity gradients and mangroves migrate landward, increases in estuarine fish production are likely, albeit with a change in the locations where fish species with specific salinity or habitat preferences occur. Small increases in nutrient delivery are unlikely to drive changes in species composition, but catchments that deliver large increases in nutrient loads may favour the food webs of fisheries dominated by microalgae and epiphytic algae (Chapters 4 and 6). In such situations, fish catches may shift towards small-bodied, short-lived species that achieve high biomass[171].

Extreme climatic events are likely to cause transient inputs of sediments and nutrients during floods, with potential for nutrient depletion during droughts. Provided that these events are not so severe that they eliminate fish nursery habitats (Chapter 6), the effects on production of local fisheries are expected to be transient[38,72,76,109,172].

The geological record provides evidence that estuarine habitats have adapted to past shifts in climate and sea level, and display remarkable resilience to changes in the physical environment (Chapters 6 and 7). However, small estuaries that experience catastrophic habitat damage during cyclones may be severely affected. Such events are likely to cause major losses of mangroves and seagrasses through physical damage, burial by sediments or scouring during floods (Chapter 6).

The wide environmental tolerances of estuarine fish and invertebrates suggest that they will also adapt to habitat changes, and that fisheries production may increase in some areas. Nevertheless, recovery of fish habitats and stocks may be prolonged if there are no nearby sources of recruits to re-establish damaged populations. In general, barramundi are well adapted to changing environments[169]. However, there are differences in migratory behaviour and use of nursery habitats among stocks, so that future impacts on this species in PNG may differ among river systems.

Vulnerability

Vulnerability of estuarine habitats to climate change (Chapter 7), and the resulting vulnerability of estuarine fish and invertebrates, is considered to be low in most PICTs. Rather, effects on fisheries production in estuaries may be positive (**Table 10.6**). Exceptions to this trend are likely in constrained estuaries that become flooded by rising sea levels. Such locations are expected to have low to moderate vulnerability under the B1 and A2 scenarios in 2035 and under the B1 scenario in 2100, increasing to moderate vulnerability under the A2 scenario in 2100.

Other exceptions occur in estuaries with disturbed catchments that deliver elevated contaminant loads (Chapter 7). Where changes to habitats occur, and estuarine fish are exposed to contaminants, fish production is likely to be moderately vulnerable. In New Caledonia, where river discharge and habitat availability is expected to decrease, estuarine fish production may be highly vulnerable.

10.5 Integrated vulnerability assessment

10.5.1 Dominant effects

The direct and indirect effects of climate change on freshwater and estuarine fish and invertebrates (Sections 10.3 and 10.4) are expected to have differing impacts on fisheries production. Increases in average annual river flow are estimated to have by far the greatest influence because fisheries production in freshwater and estuarine habitats is linked strongly to the extent and quality of habitats[75,106,117]. The magnitude, timing, frequency, duration, variability and rate of change in river flows all influence the availability of fish habitat (Chapter 7). River flows also provide cues for fish migration, reproduction and recruitment. Therefore, altered flow regimes are expected to dominate the climate responses that drive changes in freshwater and estuarine fisheries production.

Even so, the benefits of projected increases in river flow are likely to be tempered by the other changes in surface climate and the ocean, especially where these effects interact with human activities in catchments. For example, increasing temperatures could cause modest increases in the growth rates of fish and fisheries production under adequate flow rates, but result in heat stress and lower oxygen levels in shallow habitats isolated from flows, resulting in loss of fish. The probability that higher temperature may adversely affect, rather than foster, growth of fish in slow-flowing or stagnant waters, will be increased where riparian vegetation has been removed.

The expected benefits to fish production from increased flow rates are difficult to quantify because of uncertainties in the underlying climate models and their limited ability to project changes at scales relevant to individual river systems (Chapters 1 and 2). The benefits are expected to be substantial in the tropics and negligible in New Caledonia, and to increase in proportion to projected rainfall under the B1 and A2 scenarios in 2035 and 2100. Interactions among climate change effects and human activities in catchments can also be expected to amplify or negate some of the likely benefits of increased rainfall and river flows.

The effects of climate change on the production of freshwater and estuarine fish are expected to increase in proportion to the perturbations projected under the B1 and A2 scenarios in 2035 and 2100. Primarily, changes in habitat quality, due to increased flushing, warmer temperatures, dissolved oxygen levels and turbidity, are likely to vary among habitats, and may have either positive or negative influences on the growth and abundance of fish and invertebrates. Increases in salinity associated with sea-level rise will be minor in most rivers compared with the range of salinities typically experienced by estuarine fish across the full tidal cycle.

Nevertheless, the production of freshwater and estuarine fisheries is expected to increase in most areas of the tropical Pacific because of the influence of river flow under the B1 and A2 scenarios, both in 2035 and 2100. The magnitude of changes in production will be a function of variation in rainfall, and the frequency of habitat damage by cyclones and drought. Increasing temperature could also produce a small increase in the growth rates of fish and fisheries production, which may, however, be offset in some shallow habitats by increased mortality. The vulnerability of most species groups targeted by freshwater and estuarine fisheries is projected to be low, with a realistic prospect of increased production under both scenarios by 2100, except in New Caledonia.

Fisheries for species that migrate between fresh water and the sea, such as *Macrobrachium* spp. and barramundi, may also be influenced by changes in coastal currents as a result of interactions between oceanic processes (Chapter 3) and changes to freshwater and estuarine habitats. The effects of these changes on the abundance of migratory species are difficult to estimate.

10.5.2 Projected changes in fisheries yields

Available catch estimates and projected changes to fish habitats allow only simple linear projections of fisheries yield under different climate scenarios. Averages of the upper and lower estimates for the projected changes in habitat area under each scenario (Chapter 7) indicate that production of freshwater fish and invertebrates in most PICTs may increase by up to 2.5% in 2035, by 2.5–7.5% under B1 in 2100, and by 7.5% under A2 in 2100 (**Figure 10.3**, **Table 10.7**). These estimates do not take into account changes in fishing effort or the effects of catchment alteration. The uncertainty associated with these estimates is reflected in the range of expected changes in fish production (**Figure 10.3**), which are based largely on expected variation in habitat availability (Chapter 2).

On the basis of recent catch estimates (**Table 10.1**), projected increases in production due to increased habitat availability translate into additional catches of about 1000 to 1500 tonnes per year under the B1 scenario, and about 1500 to 2000 tonnes per year under the A2 scenario, in 2100. These figures must be interpreted with caution because of the uncertainty in catch estimates[1], and the assumptions used to estimate relationships between changes in habitat availability and fisheries production.

Data on fine-scale habitat changes and habitat use are insufficient to attempt projections for individual species. However, differences in environmental tolerances and habitat requirements among species, and trophic interactions, are likely to lead to some unexpected outcomes[107].

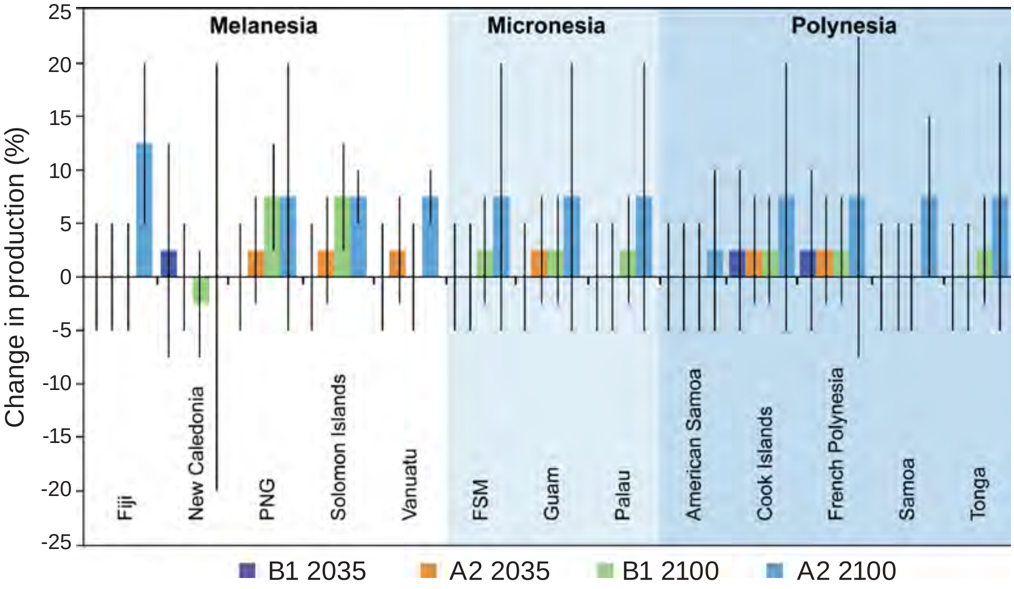


Figure 10.3 Expected changes in freshwater and estuarine fisheries production in the tropical Pacific, based on projected changes associated with rainfall and river flows. Changes in production resulting from variation in habitat quality associated with alterations in temperature, dissolved oxygen and turbidity are also expected to lie within the indicated ranges. Coloured bars indicate median expectation for each climate scenario. Vertical black bars indicate projected range of changes. These projections do not account for interactions between climate features and catchment disturbance and contaminants.

10.5.3 Projected effects on introduced and invasive alien species

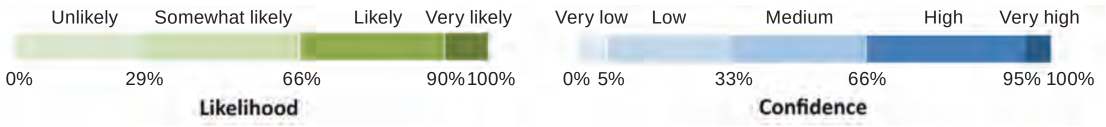
Successful introduced and invasive alien species typically have life history characteristics that allow them to thrive in disturbed environments[166]. Projected changes in habitats associated with climate change may, therefore, promote the spread of invasive alien species, and increase interactions with native species. In particular, increased river discharge may create opportunities for saltwater-tolerant invasive alien species to spread between rivers and nearby islands, leading to changes in the species composition of freshwater fisheries. Increased floodplain inundation is also likely to facilitate the spread of invasive alien species in habitats with low dissolved oxygen levels.

Carp, tilapia, snakehead, walking catfish and climbing perch are less sensitive to drought than many native species because of their ability to survive poor water quality in drying waterholes. For this reason, drying of floodplain habitats during drought, which reduces fish diversity and productivity[38,109], may create opportunities for a greater range of invasive alien species to become established in PNG.

A recent study in Australia found that a 26–34 kg reduction in carp biomass per ha resulted in a short-term increase in biomass of native fish of more than 90 kg per ha[173]. This indicates that introduced fish can sometimes reduce the total biomass available to fisheries. Greater abundance of invasive alien species as a result of climate change may therefore elevate the risk of changes in the species composition of catches, and reduced catches of target species.

Table 10.7 Projected percentage changes in annual freshwater fisheries production relative to estimated recent production[1], assessed from projected changes in habitat availability based on expected future variation in rainfall under the B1 and A2 emissions scenarios in 2035 and 2100 (Chapter 7). Likelihood and confidence values associated with the estimated changes in fisheries production are also shown.

PICT	Recent production estimates (tonnes)	Projected change (%)			
		2035		2100	
		B1	A2	B1	A2
Melanesia					
Fiji	4146	0	0	0	12.5
New Caledonia	10	2.5	0.0	-2.5	0
PNG	17,500	0	2.5	7.5	7.5
Solomon Islands	2000	0	2.5	7.5	7.5
Vanuatu	80	0	2.5	0	7.5
Micronesia					
FSM	1	0	0	0	7.5
Guam	3	0	2.5	2.5	7.5
Palau	1	0	0	2.5	7.5
Polynesia					
American Samoa	1	0	0	0	2.5
Cook Islands	5	2.5	2.5	2.5	7.5
French Polynesia	100	2.5	2.5	2.5	7.5
Samoa	10	0	0	0	2.5
Tonga	1	0	0	2.5	7.5
		🟩🟦	🟩🟦	🟩🟦	🟩🟦



10.6 Uncertainty, gaps in knowledge and future research

The main source of uncertainty associated with this assessment is the extremely limited information on freshwater and estuarine fisheries resources. The sparse data on fisheries catches make it difficult to develop quantitative estimates of the likely impacts of any threat to fisheries production.

The second most important source of uncertainty is the low resolution of the global climate models used to project changes in temperature, rainfall and intensity of cyclones (Chapters 1 and 2). Downscaling of climate models to the scales of islands or catchments is needed to allow more rigorous assessment of changes in habitat availability and quality, and exposure and vulnerability of fisheries production in individual PICTs. In particular, projected changes in the quantity, intensity and seasonality of rainfall are required[ii] to estimate river flow and habitat availability.

In addition, high-quality observation networks of surface weather (Chapter 2) and river flow are needed for catchments of major rivers. This information will enable the projected changes in climate, and subsequent effects on freshwater and estuarine habitats, to be evaluated.

Because of the local importance of freshwater fisheries in PNG, fisheries production models for the Fly and Sepik-Ramu River systems are needed, based on (1) better data for catch and fishing effort, especially for subsistence fisheries; (2) improved projections of flow rates, nutrient loads, water temperature and dissolved oxygen from the downscaled global climate models described above; (3) inventories of the habitats described in Chapter 7; and (4) elevation mapping to quantify the projected changes in areas of estuaries and floodplains as sea level rises. These models will need to go beyond simple extrapolations based on habitat availability[106]. Models developed for the large rivers in PNG can then be used to inform assessments for the smaller rivers elsewhere in the region.

Empirical assessments for individual species would also help to improve the reliability of vulnerability projections extrapolated from other species or regions. Effective adaptations to maintain the production of freshwater and estuarine fisheries will also require better knowledge of the use of habitats by fish species, responses by fish to changes in habitat availability and quality, and interactions among fish species. Research on species that migrate between fresh water and the sea, which are exposed to a wider range of climate change effects than non-migratory species, is a high priority.

The benefits of species introduced for food production need to be comprehensively assessed against the potential disadvantages (Chapter 11). This assessment should identify options to increase the ways in which introduced (and invasive) species are used, and to reduce interactions with native species that are likely to be more vulnerable to climate change. Opportunities to control invasive alien species, or under-utilised introduced species, by harvesting them for use as processed or unprocessed feed for pond aquaculture, also require investigation.

10.7 Management implications and recommendations

Freshwater and estuarine fisheries production is strongly influenced by human activities in catchments that affect the quality and quantity of aquatic habitats, such as agriculture, forestry and mining. Therefore, a cross-sectoral approach to ecosystem-

[ii] This work is now being done for the tropical Pacific by the Australian Bureau of Meteorology and CSIRO, and partners, under the Pacific Climate Change Science Programme (www.cawcr.gov.au/projects/PCSSP)

based management of freshwater and estuarine fisheries is urgently needed to maximise the opportunities, and minimise the adverse effects on production, expected to occur as a result of climate change[86].

Key challenges for cross-sectoral management are to protect undisturbed habitats to prevent further damage, and to restore degraded habitats where practical. Improved fisheries management of freshwater and estuarine resources is also essential to take advantage of the opportunities presented by climate change, and to oversee sustainable harvesting practices as demand grows to prevent overexploitation. Innovative strategies will be needed to maintain ecosystem function so that fish and invertebrates can exercise their natural capacity to adapt to climate change[86,174,175], and to manage fishing effort and gear.

Estimating future production under climate change with confidence is difficult, because of the limited information on fish catches, the meagre knowledge of the biology of most freshwater and estuarine species in the region and the habitats that support them, and the uncertainty of climate projections at the scale of islands and catchments. Nevertheless, managers need to initiate responses to projected impacts on the basis of knowledge available now, and call for support for the additional information required to improve decision-making.

In general terms, increasing the value and production of freshwater and estuarine fisheries in a sustainable way in the face of climate change will depend on (1) improving habitat management to reduce exposure and sensitivity to the changing environment; (2) building the capacity of local communities to manage habitats and fisheries resources; (3) adopting more efficient fishing and processing methods (e.g. smoking and drying), and limiting fishing effort; (4) managing threats from unwanted invasive alien species and seeking ways to benefit from those that are already established; and (5) monitoring catches and measuring the success of management interventions.

Because relatively little has been published on the management of freshwater fisheries in the region, the five categories of recommendations below are designed not only to assist PICTs to capitalise on the opportunities expected to arise from climate change, and minimise the threats, but also to identify other ways to increase production in a sustainable way.

10.7.1 Improving habitat management to reduce exposure and sensitivity to climate change

- ➢ Maximise capacity for increased fishery production by allowing freshwater habitats to expand with increasing rainfall. Options include allowing increased inundation of floodplain habitats to support fish production, and ensuring that future development does not constrain inundation patterns. This recommendation acknowledges the need for existing infrastructure to be protected from inundation where this can be justified on economic or social grounds.

- Remove or modify man-made barriers that prevent freshwater fish and invertebrates from retreating upstream as salt water penetrates into rivers with rising sea level. A survey of barriers to fish migration is needed to identify high-priority structures and cost-effective solutions. Low-cost fishways constructed with local materials may improve access to upstream habitats in places where it is impractical to remove barriers such as causeways, culverts and weirs.

- Minimise exposure of fish in disturbed catchments to increasing temperatures and sediment inputs by revegetating cleared riparian habitats to increase shading of the water surface. Revegetating cleared areas will increase the resilience of local fisheries to climate change, including cyclones, storm surges and droughts. Improved cross-sectoral governance is required to implement applicable forestry legislation where it exists, and to engage with relevant industries and local communities to encourage their participation in revegetation programs. Revegetation could provide employment for local communities. Cross-sectoral cooperation will also be required to minimise future clearing of riparian land and other important catchment areas.

- Reduce the sensitivity of fish to warmer conditions by revegetating land cleared for mining. This will help trap contaminants that reduce the tolerance of fish to higher temperatures, and reduce bioaccumulation of toxic material in fish. The cost-effectiveness of revegetation can be maximised by targeting areas that contribute most to contaminant loads in surface runoff[176]. Cross-sectoral interaction with non-fisheries agencies and relevant industries will be required to implement this recommendation.

- Engage with mining, forestry and agricultural industries to (1) identify operations that degrade freshwater and estuarine habitats, and practical, cost-effective ways to minimise these impacts; and (2) rehabilitate disturbed areas to reduce the vulnerability of freshwater and estuarine fisheries to climate change.

10.7.2 Building capacity of local communities to manage habitats and fisheries resources

- Promote innovative cross-sectoral approaches to manage small-scale fisheries[177] (Chapter 13). Local fisheries resources are often owned by communities under customary tenure, creating opportunities for villagers to manage fisheries through gear or effort restrictions, seasonal or area closures, and habitat protection or enhancement. Ownership by communities provides incentives for local-scale climate change adaptation, such as habitat protection and restoration, creating temperature refuges, or limiting catches during drought. Building local skills through co-management and community-based management to minimise vulnerability is particularly practical in communities with customary tenure of natural resources[178].

10.7.3 Adopting more efficient fishing methods and limiting fishing effort

- Regulate access to inappropriate fishing gear to avoid unforeseen interactions between increasing fishing pressure and climate change. Increasing use of monofilament gill nets, aluminium boats and outboard engines is allowing fishers to target larger areas and previously inaccessible habitats, increasing the risk of overexploitation.
- Adapt fishing methods and locations to harness the greater abundance of valuable species tolerant to the direct and indirect effects of climate change in the habitats where they occur. This approach may be particularly applicable to invasive alien species with potential fisheries value, such as snakeheads, where other forms of control are not available.
- Diversify fisheries over a wider range of species and habitats where possible. The larger rivers in PNG offer significant scope to develop fisheries for species at low trophic levels (e.g. river herring[179]), and to develop fishing methods for those floodplain habitats currently considered inaccessible. Opportunities to diversify freshwater and estuarine fisheries in many other PICTs will be limited, however, because of the small sizes of rivers and local fish stocks.
- Promote simple post-harvest methods, such as smoke curing, to increase the shelf-life of fish and fish products. Modified storage methods may also be needed to overcome the increased risk of spoilage of unprocessed fish products due to higher temperatures.

Photo: Jocelyn Carlin

Smoked freshwater fish, Papua New Guinea

10.7.4 Managing threats from invasive alien species

- Investigate ways to manage populations of low-value invasive alien species that may be favoured by climate change, to reduce negative interactions with more valuable food species. Examples may include harvesting species like climbing perch for use as fishmeal for pond aquaculture, or fish silage.
- Identify additional sources of fish to meet the need for animal protein among growing inland populations in Melanesia, particularly PNG[180]. Opportunities to develop additional freshwater fisheries are likely to be restricted to stocking new impoundments. However, responsible pond aquaculture (Chapter 11) holds promise to increase freshwater fish production for food security and livelihoods in both rural and peri-urban areas.

10.7.5 Monitoring catches and measuring the success of management interventions

- Design and implement novel and simple systems for collecting basic information on catch and effort in freshwater and estuarine fisheries to assess the effectiveness of adaptations to climate change and the sustainability of harvests. Household income and expenditure surveys or agriculture surveys, modified to include questions on freshwater fisheries, fish consumption surveys, GIS techniques and habitat classification approaches are promising tools[1,180,181].

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Appendix 10.1 Freshwater and estuarine fisheries of Pacific Islands countries and territories (PICTs)

PICT	Principal species	Main habitats	Methods of capture	Nature of fishery (and use)
Melanesia				
Fiji	Kai (freshwater clams)	Lowland rivers and upper estuaries	Hand collection	Commercial, artisanal and subsistence (sold fresh, cooked, marinated, eaten raw)
	Freshwater prawns (*Macrobrachium* and *Palaemon*)	Rivers and lakes	Push nets, hand collection, spears and traps	Artisanal and subsistence
	Eels	Lowland rivers and swamps	Hook-and-line, spears, traps	Limited subsistence
	Tilapia, carp, flagtails	Lowland rivers and lakes	Gill nets, hook-and-line, traps	Limited subsistence
	Gobies	Rivers and lakes	Whitebait traps	Limited subsistence
New Caledonia	Eels, small fish, *Macrobrachium*	Lowland rivers and lakes	Spears, traps, hook-and-line	Subsistence
PNG	Barramundi	Southern lowland rivers, floodplains, estuaries	Gill nets, traps, hook-and-line	Commercial, artisanal, subsistence and recreational
	Papuan black bass	Southern rivers and estuaries	Hook-and-line	Subsistence and recreational
	Fork-tailed catfish	Lowland rivers, floodplains, estuaries	Gill nets, traps, hook-and-line, spears	Subsistence (dried, smoked)
	River herring	Southern lowland rivers, floodplains	Gill nets, traps, cast nets	Subsistence and commercial (exploratory cannery, fish meal)
	Saratoga	Western lowland rivers, lakes and floodplains	Gill nets, hook-and-line, traps	Illegal aquarium trade and subsistence
	Tilapia and carp	Sepik-Ramu River system, lakes, reservoirs and floodplains	Gill nets, hook-and-line, traps	Subsistence and artisanal (roadside sales)
	Rainbow trout and other mountain species	High-elevation rivers and lakes	Gill nets, hook-and-line, traps	Subsistence
	Macrobrachium	Lowland rivers and lakes	Traps, cast nets, seine nets, skin diving, spears	Commercial, artisanal and subsistence
Solomon Islands	Mullet, flagtails, tropical snappers, eels, gobies and other fish	Lowland rivers and lakes	Hook-and-line, traps, gill nets	Subsistence and artisanal (local sale)
	Whitebait	Lowland rivers and lakes	Basket traps	Subsistence and artisanal (local sale)
	Tilapia	Lowland rivers and lakes	Hook-and-line, diving, gill nets	Subsistence and artisanal (local sale)
	Macrobrachium	Lowland rivers and lakes	Traps, spears	Subsistence and artisanal (local sale)

Appendix 10.1 Freshwater and estuarine fisheries of Pacific Islands countries and territories (PICTs) (*cont.*)

PICT	Principal species	Main habitats	Methods of capture	Nature of fishery (and use)
Melanesia (*cont.*)				
Vanuatu	Flagtails, grunters, snappers, silver biddies, silver moonfish, scats, mullet, eels, tilapia	Lowland rivers and lakes	Traps, hook-and-line, gill nets	Subsistence and small-scale commercial
	Macrobrachium	Lowland rivers and lakes	Traps, spears	Subsistence
Micronesia				
FSM	Eels, tilapia, *Macrobrachium*	Rivers and lakes	Hook-and-line, traps, spears	Limited subsistence
Guam	Eels, tilapia, milkfish, *Macrobrachium*	Rivers and stocked lagoons	Hook-and-line, spears, gill nets, traps	Subsistence
Kiribati	Milkfish	Stocked brackish lagoons	Gill nets	Subsistence and commercial (live bait)
Nauru	Tilapia	Ponds	Nets	Subsistence aquaculture
Palau	*Macrobrachium*	Rivers	Hook-and-line, traps, spears,	Subsistence
Polynesia				
American Samoa	Eels, gobies, flagtails, *Macrobrachium*	Lowland rivers	Traps, nets	Subsistence
Cook Islands	Eels	Lakes	Gaff, hook-and-line	Subsistence
	Tilapia	Brackish lagoons	Nets	Subsistence
	Milkfish	Stocked brackish lagoons	Nets	Subsistence
French Polynesia	Gobies (whitebait)	Lowland rivers and brackish estuaries	Basket traps	Subsistence
	Flagtails, tilapia, eels, *Macrobrachium*	Lowland rivers and brackish estuaries	Traps, hook-and-line, gill nets	Subsistence
Samoa	Tilapia, eels, *Macrobrachium*	Rivers and lakes	Traps, nets, hand collection	Subsistence and artisanal (local sale)
Tonga	Tilapia, mullet, *Macrobrachium*	Stocked lakes	Traps, nets	Subsistence
Wallis and Futuna	*Macrobrachium*	Rivers	Hand collection	Subsistence

(source: Gillet 2009, FAO 2009, Richards 1994, Amos 2007)[1,2,26,27]

Appendix 10.2 Native and introduced fish and invertebrate species harvested from freshwater and estuarine habitats in PNG

Common name	**Scientific name**	**Habitat**	**Use**
Fish – native			
Archerfish	*Toxotes chatareus*	L, F	S
Barramundi	*Lates calcarifer*	L, E, CW, La	S, A, C
Bream	*Acanthopagrus berda*	L, E	S
Bull shark	*Carcharhinus leucas*	L, E	S
Eels	*Anguilla* spp.	M, S, L	S
Eel-tailed catfish (5 species)	*Neosilurus* spp.	L, F	S
Fork-tailed catfish (9 species)	*Arius* spp.	L, F	S, A
Giant glassfish	*Parambassis gulliveri*	L, F	S
Gudgeons	*Mogurnda, Ophieleotris* spp.	L, F	S
Javelin grunter	*Pomadasys kaakan*	L, E	S
Long tom	*Strongylura krefftii*	L, E	S
Mangrove jack	*Lutjanus argentimaculatus*	L, E	S, A
Milkfish	*Chanos chanos*	La, L, E	S
Mullet (4 species)	*Liza* spp.	L, E, CW	S, A
Northern whiting	*Sillago sihama*	L, E	S
Oxeye herring	*Megalops cyprinoides*	L, E	S
Papuan black bass	*Lutjanus goldiei*	L, E	S, A
River herring	*Nematalosa papuensis*	L, F	S, C*
Saratoga	*Scleropages jardinii*	L	S, Aq
Sawfish	*Pristis microdon*	L, E	S
Sleepy cod (2 species)	*Oxyeleotris* spp.	L, F	S
Sooty grunter	*Hephaestus fuliginosus*	S, L	S
Spot-tail bass	*Lutjanus fuscescens*	L, E	S
Threadfin	*Polydactylus macrochir*	L, E	S
Trevally	*Caranx sexfasciatus*	L, E	S
Fish – introduced			
Brown trout	*Salmo trutta*	M	S
Common carp	*Cyprinus carpio*	L, S, F, La	S
Chocolate mahseer	*Neolissochilus hexagonolepis*	M	Sa
Climbing perch	*Anabas testudineus*	L, F, E, La	Sa
Emily's fish	*Prochilodus argenteus*	L, F	S
Giant gourami	*Osphronemus goramy*	La, F	S**
Golden mahseer	*Tor putitora*	M	S**
Goldfish	*Carassius auratus*	L, S, F	S**
Java carp	*Barbonymus gonionotus*	L, F	S
Mozambique tilapia	*Oreochromis mossambicus*	La, S, L, F	S
Nile tilapia	*Oreochromis niloticus*	La, S, L, F	S
Pacu	*Piaractus brachypomus*	L, F	S
Rainbow trout	*Oncorhynchus mykiss*	M	S
Redbreast tilapia	*Tilapia rendalli*	La, S, L, F	S
Snakehead	*Channa striata*	L, F, E	S
Snakeskin gourami	*Trichogaster pectoralis*	La, F	S**
Snowtrout	*Schizothorax richardsonii*	M	S
Walking catfish	*Clarias batrachus*	L, F, E	S
Invertebrates – native			
Giant freshwater prawn	*Macrobrachium rosenbergii*	L, F	S, A
Red claw	*Cherax quadricarinatus*	L, F	S

Habitat categories are: M = montane and high-elevation rivers; S = slopes rivers; La = lakes; L = lowland rivers; F = floodplains; E = estuaries; CW = coastal waters. Use categories are: S = subsistence; A = artisanal for sale at local markets; C = commercial; C* = potential commercial; Aq = aquarium trade; S** = of limited use for subsistence.

Photo: Ben Ponia

Chapter 11

Vulnerability of aquaculture in the tropical Pacific to climate change

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> *'Pacific Islands have many attributes that favour the development of aquaculture.'*
> (Adams et al. 2001)[i]

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[i] Adams et al. (2001) Current status of aquaculture in the Pacific Islands. In: RP Subasinghe, P Bueno, MJ Phillips, C Hough, SE McGladdery and JR Arthur (eds) *Aquaculture in the Third Millennium. Technical Proceedings of the Conference on Aquaculture in the Third Millennium, Bangkok, Thailand, 20–25 February 2000*. Network of Aquaculture Centres in Asia-Pacific, Bangkok, Thailand, and Food and Agriculture Organization of the United Nations, Rome, Italy, pp. 295–305.

Contents Page

11.1 Introduction

In addition to supporting a diverse range of fisheries, several of the coastal, freshwater and estuarine habitats in the tropical Pacific described in Chapters 5–7, and the species of fish and invertebrates they support (Chapters 9 and 10), are used for aquaculture. These activities all involve farming aquatic organisms, by intervening in the processes of reproduction and/or rearing to enhance production. They also involve individual or corporate ownership of the cultivated stock[1].

The rapid growth of freshwater and coastal aquaculture worldwide[2] has helped Pacific Island countries and territories (PICTs) to recognise that this type of farming is an important way of fostering economic development, food security and sustainable livelihoods for current and future generations[ii]. In particular, there is greater awareness that freshwater pond aquaculture can help supply the nutritious food needed by the growing populations of the region[3–5]. When planned well, this simple form of aquaculture has helped reduce poverty in Asia[6] and represents a promising way of providing fresh fish for the large inland populations of Papua New Guinea (PNG)[7]. Pond aquaculture enterprises in peri-urban areas also have potential to supply fish at a reasonable cost for the rapidly increasing urban populations of Melanesia, where poverty is increasing because of the growing number of people who no longer have access to land to produce food[8,9]. Rural communities have also identified aquaculture as a potential source of income to meet essential needs, and as a supplement or alternative to revenues from coastal and freshwater fisheries[10].

Nevertheless, development of aquaculture in the region has been limited compared with other areas of the world, partly because the governments of many PICTs lack a strategic framework for the sector. Policies, legislation and strategic planning to overcome technical, logistical and socio-economic constraints typical of aquaculture activities in the region[11,12] have often not been addressed adequately[13]. Such failures by government or the private sector[11,14] have been attributed to poor economic and financial planning, which has led to non-profitable investments or reliance on subsidies from governments or donors[13,15].

The exceptions are French Polynesia, New Caledonia and PNG (**Table 11.1**). In French Polynesia, the value of cultured black pearls was USD 173 million in 2007[24]. Pearl farming in French Polynesia employs 5000 people and represents 66% of the combined value of fisheries and aquaculture production[24]. Due to the large size of the economy, however, the value-added from pearl farming contributed < 1% to gross domestic product (GDP)[15]. In New Caledonia, shrimp farming was valued at USD 29 million in 2007[24] and contributed 33% to the combined value of production from fisheries and aquaculture[15]. Like French Polynesia, however, the value-added from fisheries and aquaculture is also < 1% of GDP.

[ii] Pacific Islands Forum, Vava'u Declaration, Forum Communiqué, Thirty-eighth Pacific Islands Forum, Nuku'alofa, Tonga, 16–17 October 2007. Annex B: The Vava'u Declaration on Pacific Fisheries Resources: 'Our Fish, Our Future'.

Despite the various constraints associated with aquaculture in the region, a wide range of aquaculture activities are currently underway in 16 of 22 PICTs (**Figure 11.1**, **Table 11.2**). In general, aquaculture activities in the tropical Pacific intended to produce commodities for food security are focused on freshwater habitats, whereas those developed to provide livelihoods are concentrated in coastal waters (**Table 11.2**). The number of households involved in growing freshwater fish for food security in the region is now thought to exceed those involved in culturing products intended for sale (**Table 11.3**). This is due mainly to the spread of small-scale freshwater aquaculture in PNG, where a conservatively estimated 10,000 (and possibly up to 50,000) small ponds have been constructed[7,iii].

Table 11.1 The production and value of aquaculture from Pacific Island countries and territories (PICTs) in 2007 (source: Ponia 2010)[24].

PICT	Production (tonnes)	Value (USD million)
French Polynesia	2464[a]	173
New Caledonia	1843	29
Others	993	8
Total	**5300**	**210**

a = Production comprised of 12 tonnes of black pearls with the remainder being mainly mother-of-pearl shell.

The recent regional Aquaculture Development Plan[10], and a series of national aquaculture development plans[16–21], promise to put aquaculture in PICTs on a new footing. However, the aspirations to develop both freshwater and coastal aquaculture in the region may be affected by the changes to surface climate and many of the features of the tropical Pacific Ocean described in Chapters 2 and 3. Because some forms of aquaculture rely on the collection of wild juveniles for grow-out, they may also be influenced by changes in the abundance of fish and invertebrates associated with coral reefs, seagrasses and mangroves (Chapter 9), and freshwater and estuarine habitats (Chapter 10).

In this chapter, we assess the vulnerability of aquaculture in the tropical Pacific to climate change. We begin by summarising recent and potential aquaculture production to set the scene for the sector, and then use the framework outlined in Chapter 1, based on exposure, sensitivity, potential impact and adaptive capacity, to evaluate the vulnerability of the main commodities for food security and livelihoods listed in **Table 11.2**. We also look at the risks posed by climate change to increased incidence of diseases. We then integrate all projected effects of climate change to assess the vulnerability of the sector as a whole. We conclude by examining the remaining uncertainty and the research needed to fill the gaps, and by identifying the management measures required to capitalise on the opportunities, and to minimise the adverse effects, expected to result from climate change.

[iii] Personal communication, Peter Minimulu, National Fisheries Authority, Papua New Guinea.

In assessing the vulnerability of aquaculture to climate change, we have not focused simply on existing activities and locations, but also considered the plans to expand the production of aquaculture in the region.

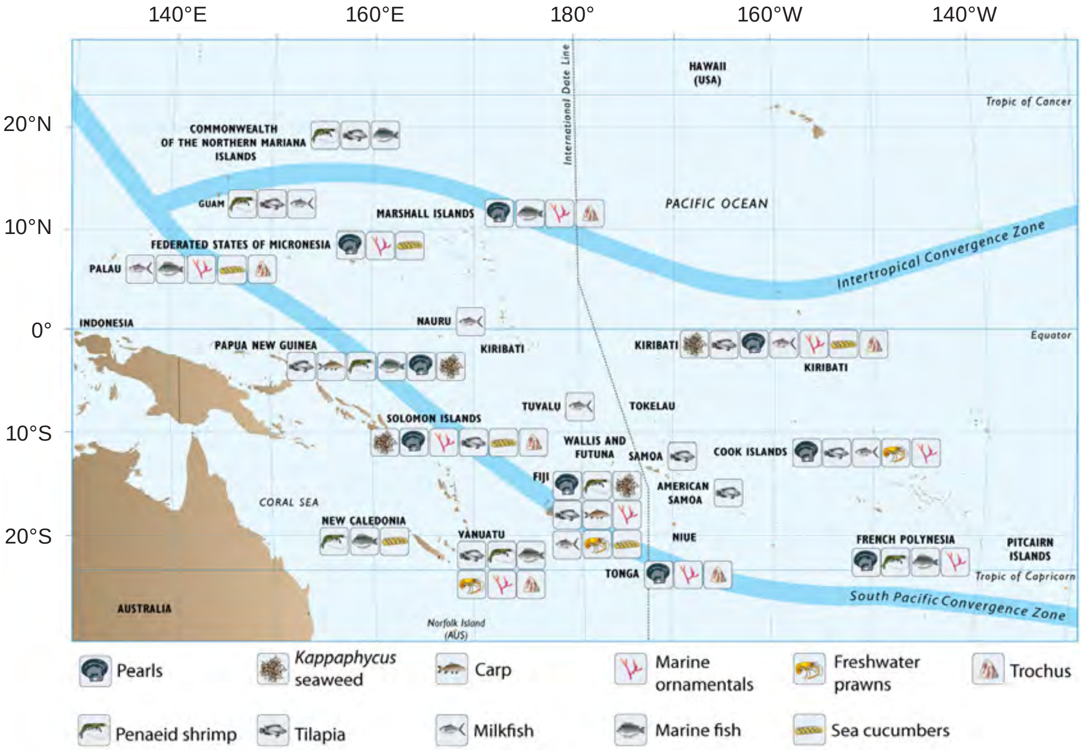


Figure 11.1 The main aquaculture activities underway in Pacific Island countries and territories.

11.2 Recent and potential aquaculture production

11.2.1 Commodities for food security

Pond aquaculture has been identified as a strategy to help meet two of the shortfalls in the fish needed for food security in PICTs. The first involves the very low rates of fish consumption among the large inland communities in PNG, where more people live than in the other 21 PICTs combined[4]. The second is the need to address the emerging gap in supply of fish for food security among urban and coastal communities in several PICTs, particularly in Melanesia, as population growth reduces the availability of fish per person below the levels recommended for good nutrition[3,4] (Chapters 1 and 12). The species of fish most likely to be produced efficiently in ponds to provide the commodities needed for food security, and the recent and potential production of these species in the region, are described below.

Table 11.2 The main aquaculture commodities produced to improve food security and create livelihoods in Pacific Island countries and territories (PICTs), together with the culture system(s) used to produce them, the environment(s) where they are grown, and the PICTs in which each aquaculture activity is established or under investigation.

Commodity	Culture system(s)	Environment(s)	PICTs involved*
Food security			
Tilapia	Earthen ponds	Terrestrial	American Samoa, Cook Islands, Fiji, Guam, Kiribati, CNMI, PNG, Samoa, Solomon Islands, Vanuatu
Carp	Earthen ponds, river releases	Terrestrial	Fiji, PNG
Milkfish	Earthen ponds, stone-walled sea pens	Terrestrial, shallow lagoons	Cook Islands, Fiji, Guam, Kiribati, Nauru, Palau, Tuvalu
Livelihoods			
Pearls	Submerged or surface longlines	Deep lagoons, sheltered bays	Cook Islands, Fiji, French Polynesia, FSM, Kiribati, Marshall Islands, PNG, Solomon Islands, Tonga
Shrimp	Earthen ponds, cement tanks	Terrestrial, adjacent to brackish or marine water source	French Polynesia, Fiji, Guam, New Caledonia, CNMI, PNG, Vanuatu
Seaweed	Off-bottom longlines, floating longlines	Shallow sandy back-reef areas of lagoons	Fiji, Kiribati, PNG, Solomon Islands
Marine ornamentals**	Seabed racks, floating cages	Lagoons	Cook Islands, Fiji, French Polynesia, FSM, Kiribati, Marshall Islands, Palau, Solomon Islands, Tonga, Vanuatu
Freshwater prawns	Earthen ponds	Terrestrial	Cook Islands, Fiji, Vanuatu
Marine fish	Floating sea cages, land-based raceways	Lagoons, sheltered bays	French Polynesia, New Caledonia, Palau, Marshall Islands, CNMI, PNG, Vanuatu
Sea cucumber	Released in the wild, pen grow-out, pond grow-out	Seagrass beds	Fiji, FSM, Kiribati, New Caledonia, Palau, Solomon Islands
Trochus	Land-based tanks, released in the wild	Coral reefs	Kiribati, Marshall Islands, Palau, Solomon Islands, Tonga, Vanuatu

* Includes past activities; ** includes giant clams propagated in hatcheries, fragments of wild corals and 'live rock', and collection of wild postlarvae.

11.2.1.1 Tilapia and carp

Mozambique tilapia *Oreochromis mossambicus* has become widely established in the region as a result of the intentional introduction of the species into lowland freshwater habitats in the 1950s and 1960s (Chapter 10) to increase the supply of fish for food[22,23].

Although it is now readily available in many PICTs, Mozambique tilapia has little potential for aquaculture because of its propensity for uncontrolled breeding, overcrowding and stunting[25,26]. More recently, some countries have introduced Nile tilapia *Oreochromis niloticus* to grow in ponds because of its suitability for aquaculture and its popularity as a food fish[27–29]. The particular attributes of Nile tilapia for farming are its adaptability to a wide variety of pond conditions, ease of reproduction, fast growth, lack of major diseases in semi-intensive production systems, tolerance to live transport to markets, availability of selectively-bred varieties, good market demand, and potential for export in value-added forms to Pacific-rim markets[25,30,32]. In addition, Nile tilapia is amenable to a variety of production systems, from extensive culture in small household ponds for subsistence to intensive industrial farms supplying urban markets[30,31].

Table 11.3 The estimated number of aquaculture farms dedicated mainly to producing commodities for food security (F) and livelihoods (L) in Pacific Island countries and territories (PICTs), and the number of people involved on a full-time, part-time or self-employed basis. Information covers the period 2007–2010 (source: SPC Division of Fisheries, Aquaculture and Marine Environment; Ponia 2010)[24].

PICT	Farming units			People employed		
	F	L	Total	F	L	Total
Melanesia						
Fiji	150	200	35 0	300	250	550
New Caledonia	-	40	40	-	560	560
PNG	> 10,000*	> 60	> 10,000*	> 10,000*	> 60	> 10,000*
Solomon Islands	8	353	361	10	600	610
Vanuatu	-	21	21	-	30	30
Micronesia						
FSM	-	5	5	-	20	20
Guam	-	5	5	-	20	20
Kiribati	1	1	2	5	5	10
Marshall Islands	-	1	1	-	5	5
CNMI	-	9	9	-	12	12
Palau	-	1	1	-	5	5
Polynesia						
American Samoa	-	11	11	-	15	15
Cook Islands	-	80	80	-	450	450
French Polynesia	-	530	530	-	5000	5000
Samoa	-	8	8	-	16	16
Tonga	10	5	15	10	10	20
Total	**13,169**	**1330**	**14,439**	**13,325**	**7058**	**20,323**

* Estimate provided by the National Fisheries Authority, Papua New Guinea, for the number of households involved in small-pond farming activities in inland areas in 2010; - indicates no aquaculture activity.

Nile tilapia is already becoming an aquaculture commodity that is helping to ensure food security in Fiji and PNG. In Fiji, the number of active household-level farms fluctuates between ~ 100 and 500, depending on the availability of inputs, such as fingerlings and feeds, and production is up to 300 tonnes per year. Although most of these farms produce for subsistence or local sales, some farmers produce several tonnes of fish per week for sale live at municipal markets. PNG apparently had an order of magnitude more small-scale tilapia farmers than Fiji[7] in 2007, with more recent estimates indicating that > 10,000 households are now engaged in small pond aquaculture in PNG (**Table 11.3**). However, because most farms in PNG are in remote highland locations, and also produce fish mainly for subsistence, collecting accurate production figures is difficult.

Demand for tilapia is growing in several PICTs due to shortages of coastal fish (Chapter 9). For example, a commercial tilapia farm in Vanuatu has no trouble selling its annual production of 80 tonnes at the central market in Vila, especially when rough seas reduce the supply of reef fish. The preference of people in the Pacific for whole fish of 200 to 400 g (plate size) increases the appeal of tilapia farming because the fish can be harvested after a relatively short (5–7 months) grow-out period.

The potential benefits of Nile tilapia for meeting the projected demand for fish for food security[4] need to be balanced with possible effects on biodiversity[5,33]. In combination with adverse effects on rivers of land degradation caused by agriculture and forestry (Chapter 7), Mozambique tilapia (commonly regarded as more invasive and ecologically damaging than Nile tilapia) may have contributed to the local loss of some native freshwater fish, such as gobies and gudgeons traditionally eaten in Fiji[34]. Feral Mozambique tilapia have reportedly been regarded as a pest by communities in Nauru and parts of Kiribati[28,35] but are widely valued for food in Melanesia. Careful assessments of the costs and benefits of Nile tilapia aquaculture for food production are needed to reconcile the important agendas for food security and biodiversity in this region[5,33]. Tilapia have been introduced and cultured widely in Asia for > 70 years as an important source of food and a base for livelihoods, but no clearly negative effects on biodiversity have been reported[29,36,37].

Asian carp have also been introduced to the cooler waters of PNG, where they are grown quite commonly, particularly at higher elevations. These fish have not proved to be as popular as Nile tilapia, however, which are easier to breed and reach market size more quickly[7]. The species of Asian carp introduced to the region include: common carp *Cyprinus carpio*, Chinese carp (silver carp) *Hypophthalmichthys molitrix*, bighead carp *Aristichthys nobilis*, grass carp *Ctenopharyngodon idella*, Indian carps (rohu *Labeo rohita*, catla *Catla catla* and mrigal *Cirrhina mrigala*), silver barb *Barbonymus gonionotus* and some other species of cyprinids[28]. Potential effects on biodiversity also need to be considered in further development of carp aquaculture[38]. However, because many carp species are already well established in the wild in PNG (Chapter 10), the potential benefits of expanding carp farming in river catchments where they already occur may outweigh any adverse effects on freshwater biodiversity.

11.2.1.2 Milkfish

The milkfish *Chanos chanos* is a large tropical species farmed widely in Asia[9,39]. It is the basis of a substantial industry in many countries with total production in the Philippines, for example, of 350,000 tonnes in 2008[40]. This species is popular for aquaculture because it is herbivorous/planktivorous and, although the adults live in the sea, the juveniles can be grown simply in coastal enclosures flushed by the tide, and in brackish and freshwater ponds[39,42]. Milkfish can be spawned and reared in captivity[43,44], but much of the industry in Asia is based on the capture and culture of juveniles caught from shallow coastal habitats[45,46]. Given the high costs of maintaining the broodstock for milkfish, much of the further development of milkfish farming in PICTs is also likely to be based on the capture of wild juveniles. Farming practices in Asia also include careful pond management to promote growth of 'lab-lab', a turf of flora and fauna that milkfish graze on, reducing the need for supplementary feeding[39,49].

Milkfish are important traditionally for food in Nauru and Kiribati, and aquaculture of this species has been launched there and in several other PICTs. For example, between 5 and 15 tonnes of milkfish per year have been produced in Kiribati, and 30 to 80 tonnes per year in Guam since 2000[40]. Palau has investigated production of small quantities of cultured juveniles for bait for tuna longlining operations[41] and is now growing-out fry imported from the Philippines for both food and bait. These enterprises based on hatchery production or collection of wild juveniles have had mixed success. The market price and scale of production have often not been sufficient to cover costs without subsidy.

If reliable sources of wild juveniles can be identified, and feed based on local inputs can be formulated, there may be scope to produce hundreds of tonnes of milkfish per year in the region. There is continued interest in developing this potential, for example village-level capture and culture operations are under consideration in Fiji[50], and the grow-out of wild-caught juveniles for tuna bait is being evaluated at Penrhyn Atoll, Cook Islands.

11.2.2 Commodities for livelihoods

The high diversity of coastal fish and invertebrate species in the Western and Central Pacific Ocean (Chapter 9), and the large number of sheltered, pristine lagoon sites for aquaculture operations, provide several PICTs with opportunities to develop commodities for niche markets. Such coastal aquaculture activities can provide coastal communities with a source of income[10,12,51]. Commodities such as cultured pearls, shrimp, seaweed and marine ornamentals are already helping fulfil the aspirations for economic development and livelihoods based on aquaculture in a few PICTs. The range of commodities capable of supporting livelihoods, for which the region may have a comparative advantage, are listed in **Table 11.2** and described in more detail below.

11.2.2.1 Pearls

Pearls produced from pearl oysters (Pteriidae) are the region's most valuable aquaculture commodity[24], driven by international demand for round pearls and mother-of-pearl products. Pearl farming has proved to be viable in the region because (1) the oysters are available either from harvesting wild shells[52,53], collection of wild spat[54,55], or production of spat in hatcheries[53,56]; (2) grow-out methods for pearl oysters are simple – no feed inputs are needed[53]; (3) there are many protected and pristine lagoon environments for holding the oysters while the pearls are formed; (4) the technicians needed to operate on adult oysters to produce cultured pearls have been willing to visit even the remotest parts of the region[54]; and (5) the high-value products are non-perishable and have negligible shipping costs[57].

Almost all production is for 'black' pearls produced by the black-lipped pearl oyster *Pinctada margaritifera*[24]. Limited enterprises are underway for white pearls produced from the silver- or gold-lipped pearl oyster *Pinctada maxima* in PNG, and the winged pearl oyster *Pteria penguin* in Tonga, currently farmed for mabè (half pearls). There is also a market for the shells of cultured pearl oysters, and the handicrafts made from them[58].

Black-lipped pearl oysters, Fiji

Photo: Leanne Hunter

Although production of black pearls is currently dominated by French Polynesia (**Table 11.1**) where production of raw pearls has been between 10 and 13 tonnes per year over the past 10 years (**Figure 11.2a**), the technological advances in hatchery techniques and widespread knowledge of pearl farming could promote the culture of black pearls in many other PICTs. Viable black pearl farms have been established in Cook Islands, Fiji, Federated States of Micronesia (FSM) and Marshall Islands, and pilot projects have been launched in Kiribati and Solomon Islands[59,60]. In practice, however, there is a high risk of failure at many potential locations due to the nature of financial investments, uncertainty of long-term access rights where customary marine tenure exists, lack of infrastructure and likelihood of cyclones. In PNG and Solomon Islands, investors are more inclined to consider enterprises based on silver-lipped pearl oysters because the generally larger pearls they produce usually attain higher prices than black pearls.

In 2007, the value of pearl production from the region, including unreported sales, domestic sales, and exports of matched pearls, is estimated to have been USD 190 million. This represents about 25% of the total annual global value of marine pearl production[60]. The scale of this production, and competition from other regions, is forcing pearl farms to achieve economies of scale by increasing the number of cultured oysters to > 200,000. Producers are also expected to supply two market segments – the higher-value market for quality round pearls, and the lower end demand for baroque, keshi and 'circle' pearls, and half pearls, where there is strong competition from Chinese freshwater pearls. Because the demand for high-value round pearls is considered to be inflexible, it has been suggested that the region should reduce supply[57]. However, an alternative strategy to maintain or further increase revenue among the PICTs already producing pearls, and to allow more PICTs to engage in pearl farming, is to increase the percentage of top-quality pearls produced through better seeding and husbandry practices.

11.2.2.2 Shrimp

Shrimp (Penaeidae) are the basis for the second-largest aquaculture industry in the region, after black pearls. The industry in New Caledonia dominates production. It was launched in 1978, with the total harvest increasing to ~ 2000 tonnes per year by 1999, where it has remained for the past 10 years[24] (**Figure 11.2b**). Although significant regionally, New Caledonia is still a small producer of shrimp compared with countries in Asia[13]. Other PICTs currently involved in shrimp farming are Fiji, French Polynesia, Guam, Commonwealth of the Northern Mariana Islands (CNMI), PNG and Vanuatu. In New Caledonia, shrimp farming is the leading agro-food export (worth ~ USD 29 million per year) and provides valued employment opportunities in remote rural areas (~ 560 jobs). The availability of possible future sites suitable for this activity on the west and north coasts of New Caledonia would enable the original plans to produce around 4000–5000 tonnes per year to be fulfilled, if local socio-economic conditions and international market opportunities permit.

Although about 10 species of penaeid shrimp occur naturally in the region, including the black tiger shrimp *Penaeus monodon* cultured in Australia, the industry in New Caledonia is based on the blue shrimp *Litopenaeus stylirostris* from Central America. This species commands an excellent price when exported to niche markets, and was introduced because of its suitability to the cooler climate in New Caledonia[61–63]. In contrast, *P. monodon*, the species that has been farmed in PNG and Fiji, has a marked reduction in growth in New Caledonia during winter[64].

The main viral pathogens affecting penaeid shrimp farming around the world have not generally posed problems for PICTs; however, aquaculture of *L. stylirostris* in New Caledonia is affected by seasonal outbreaks of vibrio bacteria[65,66]. This pathogen, which appears to be triggered by unstable pond temperatures during the short spring and autumn seasons, can cause heavy losses of shrimp, and limits the New Caledonia industry to a single crop cycle per year[67].

The development of penaeid shrimp farming in other PICTs has been slow due to the lack of local technical capacity in aquaculture, capital, infrastructure, and research and development support from governments.

11.2.2.3 Seaweed

Farming seaweed is conceptually appealing to coastal communities in several PICTs because it is a low-technology operation suitable for both men and women with a quick return on labour. The seaweed species in demand, *Kappaphycus alvarezii*, can be harvested from cuttings within 6 weeks[68]. Until recently, seaweed farming was a mainstay of the economy in Kiribati; production began in the mid-1980s and peaked at 1400 tonnes dry weight in 1999, but has decreased markedly in recent years[24] (**Figure 11.2c**). The culture of *Kappaphycus* also varied between 0 and 300 tonnes per year in Fiji over a similar period. More recently, the seaweed has also been grown in Solomon Islands, with harvests reaching 400 tonnes in 2009[69], and 800 tonnes in 2010. Based on estimates of the area of lagoons suitable for seaweed farming in Solomon Islands and Fiji, production levels at least 2000 tonnes per year could be possible for each country.

Photo: Georges Steinmetz

Seaweed farm, Tabiteuea Atoll, Kiribati

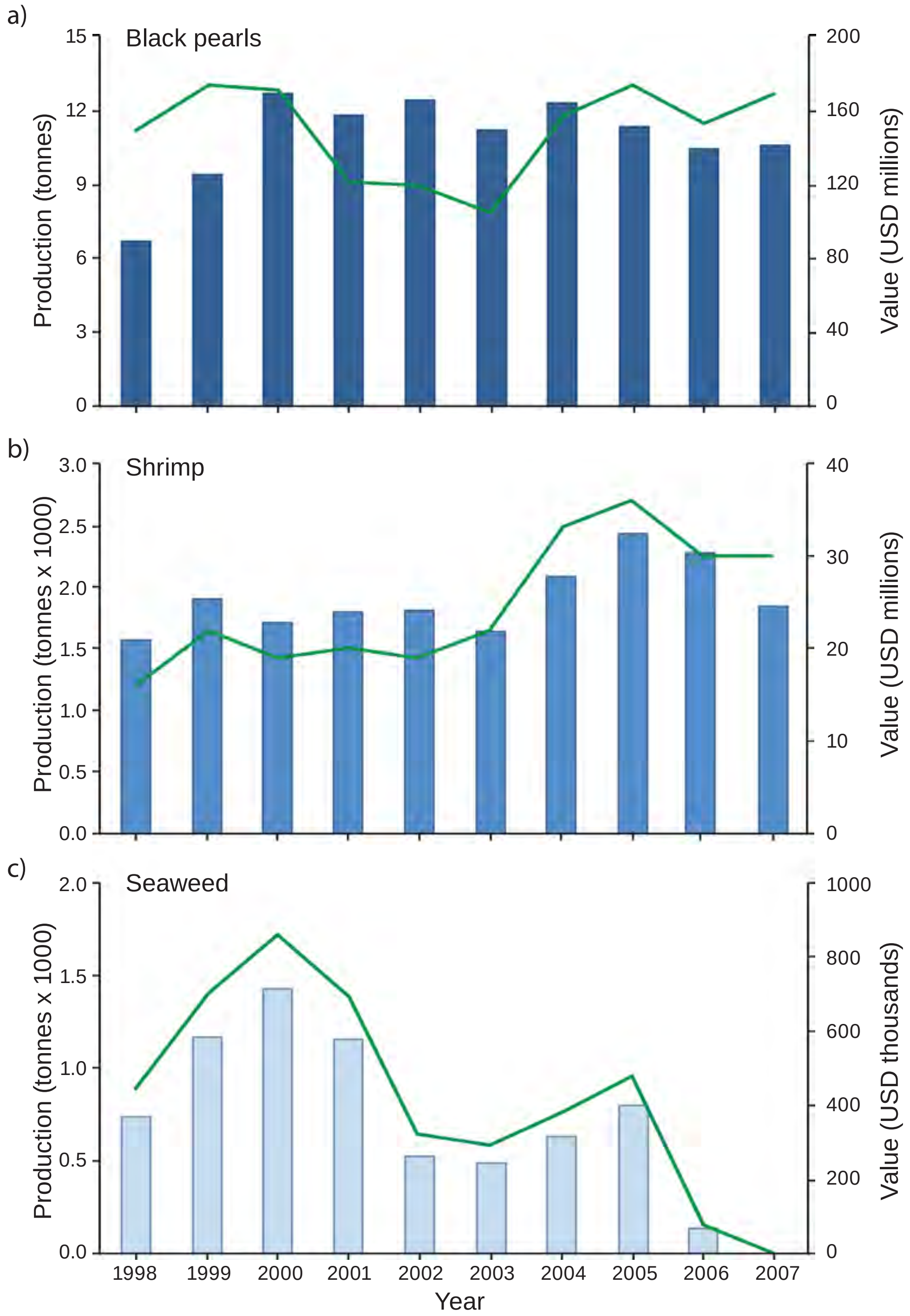


Figure 11.2 Production of (a) all black pearl products in French Polynesia, (b) shrimp in New Caledonia, and (c) seaweed in Kiribati between 1998 and 2008; the green line represents the value of production (source: Ponia 2010)[24].

There are constraints to farming *Kappaphycus*, however. Dried seaweed is a low-value bulk commodity so seaweed aquaculture has difficulty competing with alternative livelihood options (e.g. fishing for sea cucumbers) except in very remote areas where there are few alternative opportunities to earn income. However, transport costs from such areas to shipment points and centralised export operations can be prohibitive. There can also be seasonal or site-specific losses due to grazing by herbivorous reef fish (such as siganids); epiphytic filamentous algae, which colonise the seaweed thalli and stunt growth; or rough sea conditions. Such problems need to be addressed through appropriate site selection. In a few communities, the availability of space and building materials to construct seaweed drying platforms is a limitation. In these places, cost-effective and sustainable alternatives to cutting mangroves for timber to build platforms need to be found[69].

Potential for culture of other species of seaweed is based mainly on *Cladosiphon* sp., which has been commercially harvested in Tonga for the Japanese domestic food market[21].

11.2.2.4 Marine ornamentals

Although a variety of live marine ornamental fish and invertebrates are exported from PICTs for the aquarium market (Chapter 9), aquaculture currently contributes substantively to only two of these products: corals and giant clams. However, culture of 'live rock' (decorative, small coral boulders covered in encrusting organisms and crustose coralline algae which act as biological filters in aquaria) is now moving to a pilot commercial scale in Fiji and Tonga. There is no hatchery-based production of marine ornamental fish in PICTs, although juvenile fish, cleaner shrimp and spiny lobsters caught from the wild and reared for several weeks in 'postlarval capture and culture' operations[46–48] are under development in French Polynesia and Solomon Islands.

Coral farming is based on the collection and grow-out of fragments from wild colonies[70]. The technology is simple, low cost, and suitable for small-scale operations and for self-employment of rural women and youth. In 2007, more than 77,000 pieces of cultured coral were produced in Fiji, FSM, Marshall Islands, Solomon Islands and Vanuatu combined[71]. In addition to supplying the aquarium market, cultured corals can be used for coral reef restoration, enhancement of snorkeling trails at tourism sites, and sale to the curio trade, where higher prices are paid for cultured corals than for wild specimens.

Six of the eight species of giant clams in the Pacific (*Tridacna crocea*, *T. derasa*, *T. gigas*, *T. maxima*, *T. squamosa*, and *Hippopus hippopus*) (**Figure 11.3**) have been produced in hatcheries, grown-out in cages in 'village farms' or in land-based facilities, and sold to the aquarium trade by PICTs[72–75]. Cultured giant clams have also been placed in the wild in limited restocking operations[76]. The hatchery and grow-out methods are straightforward[72,77,78] and had been applied in 11 PICTs by the late 1990s[79], and in 17 PICTs by 2007[80]. The combined exports of cultured giant clams from Cook Islands, FSM, Kiribati, Marshall Islands, Palau, Solomon Islands, Vanuatu and Tonga totalled 75,000 pieces in 2007[81].

Figure 11.3 The six species of giant clams that have been cultured in the tropical Pacific: *Tridacna maxima* (top left), *T. gigas* (bottom left), *Hippopus hippopus* (top centre), *T. derasa* (bottom centre), *T. squamosa* (top right) and *T. crocea* (bottom right) (photo: Mike McCoy).

11.2.2.5 Freshwater prawns

Techniques for farming freshwater prawns in the genus *Macrobrachium* have been developed in many countries[82]. These prawns are not a global commodity on the same scale as penaeid shrimp, but their importance is steadily growing and in 2008 their global value was 66% of that of tilapia[83]. Worldwide, most of the production is based on *Macrobrachium rosenbergii*[82] but this species does not occur naturally in PICTs except in PNG. It has been introduced to several parts of the region for aquaculture trials (e.g. Fiji, French Polynesia and Solomon Islands), although there are no reports of it becoming established in the wild. However, captive stocks of *M. rosenbergii* in the region are currently limited to one population maintained by hatchery production in Fiji. This stock forms the basis of an emerging aquaculture industry, with production of ~ 25 tonnes per year, mainly from one medium-sized farm (8 ha). Other PICTs are interested in engaging or re-engaging in farming *M. rosenbergii* and, considering the strengthening demand for freshwater prawns, there is potential for producing several hundred tonnes per year across the region.

The local market for freshwater prawns is supplied mainly by the capture of the indigenous *Macrobrachium lar* (Chapter 10). The prospects for hatchery-based aquaculture of this species do not look good, however, because it has a long and complicated larval stage[84]. Farming of *M. lar* will need to be based on capture and grow-out of juveniles caught from the wild. Preliminary trials suggest that this may be possible on a small (household-level) scale[85].

11.2.2.6 Marine fish

High-value tropical marine food fish of potential interest for aquaculture in PICTs are mainly groupers (Serranidae), which form the basis for the international live reef fish trade. Due to a rapid increase in demand from China, and limited stocks in the wild[86,87], culture techniques have been developed in Asia and Australia to supply these highly-prized fish[88]. However, these methods require considerable investment in sophisticated hatcheries and the infrastructure for growing fish to market size. They also depend on large quantities of fresh fish as feed or expensive imported high-protein, formulated diets. The high costs of operating such facilities in PICTs, and the competitive advantage of marine fish farming operations in Asia (with lower labour costs and better proximity to markets), argue against development of enterprises in PICTs to supply the live reef fish trade[89].

The only hatchery-based marine fish farming operations in the region are modest enterprises for barramundi *Lates calcarifer* in PNG, CNMI (Saipan) and Vanuatu, batfish *Platax orbicularis* in French Polynesia, rabbitfish *Siganus lineatus* in New Caledonia, and milkfish *C. chanos*, rabbitfish *Siganus* spp. and the coral trout *Plectropomus areolatus* in Palau.

The often high but variable availability of juvenile rabbitfish (Siganidae)[90] in many PICTs provides the potential for grow-out operations for this species and some research on the best methods and feeds for such aquaculture has been done[91,92]. Although rabbitfish are a popular food fish in the western Pacific, it remains to be seen whether the reliability of capture and culture operations, and local market demand, are good enough to make aquaculture viable.

11.2.2.7 Sea cucumbers

There has been considerable investment within the region in the development of methods for producing the sandfish *Holothuria scabra* in hatcheries, and releasing the juveniles in the wild. The work was pioneered by the WorldFish Center in Solomon Islands[93–98] and in New Caledonia[99–103]. The focus has been on sandfish because it has proved to be the easiest of the tropical sea cucumbers to rear in captivity, and commands one of the highest prices per kilogram when processed into bêche-de-mer[104,105]. Another of the highly valuable sea cucumbers, the white teatfish *Holothuria fuscogilva*, has also been reared in Kiribati, and released in limited quantities in nearby coastal habitats[106,107]. However, the techniques for propagation and release of *H. scabra* are far more advanced.

The ability to produce juvenile sandfish in hatcheries creates the opportunity to grow-out this species in earthen ponds in much the same way as sea cucumber are cultured in China[104]. Whether this can be done competitively in New Caledonia, with its relatively high labour costs and slow rates of growth, remains to be seen[102]. More emphasis is being placed on the use of cultured juveniles for restocking overfished populations, and for sea ranching initiatives[108]. Building on recent work in New Caledonia[103], sea ranching trials for sandfish are now underway in Fiji[109].

PICTs in Melanesia meet many of the pre-requisites for restocking and sea ranching sandfish including (1) extensive areas of seagrass (Chapter 6), which provide essential habitat for this species[110]; (2) severely overfished populations (Chapter 9), which provide few options for replenishment apart from restocking[105,111,112], and vacant habitat for sea ranching; and (3) local tenure arrangements that enable coastal communities to benefit from releases of hatchery-reared juveniles. Whether survival rates of cultured juveniles in the wild will justify the costs of producing and releasing them still needs to be determined.

11.2.2.8 Trochus

The topshell *Trochus niloticus*, also commonly known as trochus, provides an important source of income for coastal fishing communities in many PICTs[113], but stocks have now been fished to chronically low levels in many parts of the region (Chapter 9). Overfished stocks can be restored and new fisheries can be established simply by translocating adults and imposing a moratorium on fishing until the populations are robust enough to sustain harvests[76]. However, methods have also been developed to produce trochus in hatcheries for release in the wild[114,115]. Where hatchery-based release programmes are deemed to be necessary, combining the culture of giant clams and trochus has been proposed as a way of reducing the cost of rearing trochus to a size where they have reasonable chances of survival in the wild[116]. There is also a limited market for trochus in the ornamental trade. In 2007, Marshall Islands produced 5000 pieces of trochus for this market.

11.3 Vulnerability of aquaculture to the effects of climate change

Aquaculture is vulnerable to climate change in more ways than fisheries. The vulnerability of fisheries is due mainly to the direct and indirect effects of climate change on the abundance and distribution of species that provide the harvests (Chapter 1). Although more severe weather may mean that catches must be postponed until it is safe to fish again, the effects of climate on fishing operations are usually likely to be less important than the response of the target species, and the habitats they depend on, to the changing environment (Chapters 5–10).

For aquaculture, however, both the organisms that are produced in hatcheries or collected from the wild as 'seed' and grown to market size, and the farming operations and infrastructure themselves, are subject to the direct and indirect effects of climate change[117]. Changes to temperature and rainfall, and their effects on salinity and oxygen, can be expected to affect the reproduction, growth and survival of the organisms selected for aquaculture. Similarly, for those species collected as juveniles from the wild, changes to the habitats on which the adults depend may affect the economic viability of relying on the collection of wild juveniles for grow-out.

The fact that much of the infrastructure for aquaculture (e.g. ponds) cannot usually be moved to prevent damage from severe weather conditions means that aquaculture is more exposed to the direct effects of climate change than fishing fleets, which can be relocated to secure harbours. Other examples of the indirect effects of climate on the viability of aquaculture operations include (1) the reduced availability and higher cost of feed ingredients due to the effects of the El Niño-Southern Oscillation (ENSO) on the supplies of fishmeal and the impacts of drought on crops, and (2) the failure of energy supplies due to natural disasters.

Here we apply the vulnerability framework described in Chapter 1 to these two main components of aquaculture – the species that underpin production, and the farming operations themselves. We consider the direct and indirect potential impacts of climate change on both components of aquaculture for each of the main commodities produced in the region for food security and livelihoods.

11.3.1 Vulnerability of commodities for food security

11.3.1.1 Tilapia and carp

Exposure and sensitivity

- **Temperature:** Tilapia and carp are typically cultured in earthen ponds where prevailing rainfall patterns provide sufficient surface or ground water to keep the ponds filled. Water temperatures in these farming systems in the tropical Pacific are projected to increase in line with those for surface air temperature, i.e. by 0.5–1.0°C under the B1 and A2 emissions scenarios in 2035, by 1.0–1.5°C for B1 in 2100 and by 2.5–3.0°C under A2 in 2100, relative to 1980–1999 (Chapter 2).

  Tilapia and carp farming are expected to be sensitive to the projected increase in temperature because the distribution of these operations in Melanesia is currently limited by the effects of cooler conditions on reproduction and growth of these species at higher altitudes. In particular, feeding of tilapia is reduced sharply at temperatures < 20°C and spawning is not possible below 22°C[118]. Mortality of tilapia occurs if there is prolonged exposure to temperatures < 12°C[119–121], with fingerlings being more sensitive than adults[122]. Among tilapia, *Oreochromis mossambicus* is the most cold-sensitive species[123]. At the other end of the scale, tilapia can tolerate temperatures up to 42°C[118], although exposure to high temperatures results in more deformities in early larval stages, and sex ratios skewed towards males[118]. Even within the optimal temperature range for reproduction, development and growth of tilapia (25–30°C)[118–120,124,125], maintaining water temperatures closer to the upper end of this range can make a big difference to the productivity of tilapia aquaculture[118].

The optimum temperature range for growth of common carp is similar to tilapia, at 23–30°C. Carp are much more cold-tolerant than tilapia, however. For example, bighead and silver carp can tolerate temperature extremes typical of cold temperate to tropical regions, and have similar optima for growth to common carp[126].

The ecosystems in tilapia and carp ponds are also sensitive to changes in water temperature. Higher temperatures can cause stratification, leading to algal blooms and reduced levels of dissolved oxygen (**Figure 11.4**). Tilapia can tolerate dissolved oxygen concentrations as low as 0.1–0.5 mg/l, but only for limited periods[127]. Fish can avoid potentially lethal areas in stratified ponds but this reduces the volume of available habitat and increases the stress on fish congregated in non-lethal areas. Heat stress can also occur due to elevated temperatures and is exacerbated in shallow-water ponds (< 50 cm deep) compared with deeper-water ponds (100–200 cm deep), where fish can 'escape' by staying lower in the water column during summer and moving towards the surface in winter[118].

Overall, tilapia and carp are considered to be relatively hardy fish for aquaculture but repeated or prolonged exposure to extreme temperatures and low dissolved oxygen levels, especially at high stocking densities, can be expected to increase stress and the susceptibility of the fish to disease (Section 11.3.4).

- **Rainfall:** In tropical Melanesia, where most pond farming for tilapia and carp is expected to occur, rainfall is projected to increase by 5–15% under the B1 emissions scenario in 2035, by 5–20% under A2 in 2035, and by 10–20% under B1 and A2 in 2100, relative to 1980–1999 (Chapter 2). Also, wet and dry periods are expected to become more extreme (Chapter 2).

  Growing tilapia in small ponds at a low stocking density (2 fish per m^2) without exchanging the water, which is a common form of subsistence aquaculture in inland PNG[7], is expected to be favoured by the projected increases in rainfall because this farming system depends on rainfall exceeding pond evaporation[128].

In general, the projected increases in rainfall are likely to expand the distribution of the areas where tilapia farming based on low or zero water exchange occurs.

- **Sea-level rise:** The rates of sea-level rise projected in the Fourth Assessment Report of the Intergovernmental Panel on Climate Change are acknowledged to be conservative – more recent estimates are that sea level will rise by 20–30 cm under the B1 and A2 emissions scenarios in 2035, by 70–110 cm under B1 in 2100 and by 90–140 cm under A2 in 2100 (Chapter 3). The penetration of saline water further inland is expected to render some of the existing ponds near the coast unsuitable for Nile tilapia and carp because reproduction and growth of these species is greatest at salinities < 5 practical salinity units (PSU)[129,130]. Salination of ponds in areas subject to sea-level rise may be mediated by the projected increases in rainfall.
- **Cyclones:** Although cyclones are not projected to become more frequent, they may become more intense (Chapter 2). Floods caused by cyclones and more extreme rainfall events are expected to be a threat to tilapia ponds constructed in low-lying areas or close to rivers. Flooding could result in damage to ponds and other farm infrastructure, and the escape of fish through 'over-topping' of pond dykes by rising waters.

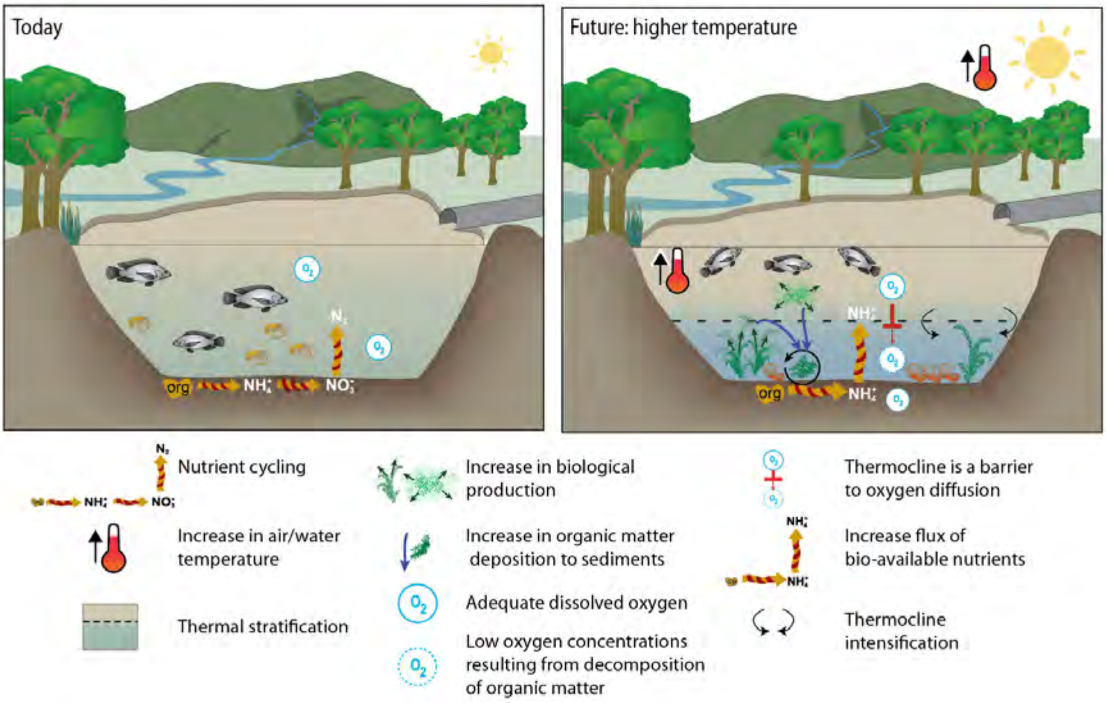


Figure 11.4 Effects of projected higher water temperatures on stratification in freshwater aquaculture ponds and the consequences for levels of dissolved oxygen.

Potential impact and adaptive capacity

The direct effects of projected increases in temperature are not expected to affect the suitability of lowland habitats in the region for tilapia or carp farming. In fact, production is likely to increase in lowland areas above the influence of rising sea levels and floods due to enhanced growth rates at higher temperatures and greater availability of fresh water for pond aquaculture. Increased deformities may affect production if prolonged periods of high temperatures occur in the low-lying equatorial areas. However, any effects on sex ratio may not affect production adversely because tilapia farmers often strive to produce male fingerlings for grow-out[131].

The warmer and wetter conditions are also expected to enable tilapia and carp to be grown at higher altitudes and at more locations at these altitudes, increasing the potential area where tilapia and carp can be produced. Expansion of suitable areas for farming tilapia would benefit inland communities in PNG, which have limited access to animal protein (Chapters 1 and 10)[4].

On the negative side, higher temperatures are likely to increase stratification in ponds with low water exchange, reducing production and increasing the risk of disease (Section 11.3.4) (**Figure 11.4**). The occurrence of stratification is, however, expected to be reduced by the benefits of the projected increases in rainfall on pond mixing and turnover. In other places, flooding from more intense cyclones and more frequent extreme rainfall events could damage ponds and cause loss of fish.

Adaptations to reduce any eventual adverse effects of warmer pond temperatures have focused on locating and constructing ponds to increase the mixing of water, either by mechanical means or by increased turnover. Increased turnover should be balanced against the need to maintain plankton blooms to provide natural food, and minimise the cost of supplementary feeding. Where possible, ponds should be placed at sites not exposed to floods, that receive an abundant supply of water through gravity-flow. This will allow lengthwise laminar flow of inlet water at the surface, and drainage through outlets placed at the bottom of the pond. In locations without access to strong flows, or where water has to be pumped, paddle-wheel aerators can be used to reduce stratification. However, the cost involved in such adaptations is likely to eliminate small-holders from farming tilapia where stratification is a problem.

Because intensive tilapia farming enterprises growing fish for urban markets depend heavily on formulated diets with ~ 20% protein, changes in the availability of fishmeal may indirectly affect tilapia production. Formulated feeds comprise 30% of costs for tilapia farming in Fiji, and increases in the price of fishmeal may affect the viability of these enterprises. The risks are due to the broader effects of climate change on (1) the abundance of the small pelagic fish in South America used to produce the fishmeal; and (2) the supply of tuna to processing plants in the region that make fishmeal as a by-product.

Tilapia and carp farming have a high capacity to adapt to a changing climate – both species can be produced simply and reared cost-effectively under a broad range of warm-water temperatures, and stocked at a wide range of densities and water exchange rates. Enterprises based on intensive culture systems have a lower adaptive capacity than small ponds used for subsistence, where stocking densities can simply be altered to suit the prevailing conditions and availability of fish feeds. Ultimately, the capacity for tilapia and carp farmers to take up any opportunities created by a changing climate will depend on the measures that PICTs implement to promote small pond aquaculture, within the context of reconciling plans to promote food security and maintain biodiversity[33].

Vulnerability

The farming of tilapia and carp in the tropical Pacific has little or no vulnerability to climate change. Indeed, if PICTs decide that tilapia and carp farming is a responsible way to increase the availability of fish for food security, climate change is likely to have a low, positive effect on production by 2035 under the B1 and A2 emissions scenarios. In particular, the higher temperatures and increased availability of fresh water are expected to favour pond aquaculture in tropical Melanesia. Low to medium positive effects on production are likely to occur under B1 by 2100, increasing to medium positive effects under A2 by 2100.

11.3.1.2 Milkfish

Exposure and sensitivity

- **Temperature:** The life cycle of the milkfish, and all aspects of its farming in brackish or fresh water, are also expected to be exposed to the increases in sea surface temperature (SST) described in Section 11.3.2.1, and Chapters 2 and 3.

  Warmer SST is expected to lead to an expansion of the range of adult milkfish and the seasonal availability of fry. Milkfish occur where SST exceeds 20°C, and fry are common in coastal habitats once SST reaches 27°C[39,132]. Also, the length of the season for collecting fry is positively correlated with SST[133]. Warmer temperatures in ponds are projected to increase growth rates, and improve the efficiency of food conversion ratios[134].

- **Rainfall:** The projected increases in rainfall (Section 11.3.2.1, Chapter 2), which are expected to result in increases in precipitation of 5–20% in the tropics under the B1 and A2 emissions scenarios by 2100, are likely to increase the number of locations where milkfish can be farmed in freshwater ponds. However, reductions in salinity due to increased rainfall may change the distributions of postlarvae recruiting to coastal habitats.

- **Ocean acidification:** Postlarval milkfish are projected to be exposed to progressive acidification of the ocean (Chapter 3). The effects of acidification on the recruitment success of milkfish larvae have not been studied. However, experiments involving the postlarvae of some coral reef fish indicate that survival is likely to be reduced at lower pH due to the adverse effects of ocean acidification on behaviour (Chapter 9).

- **Sea-level rise:** Milkfish should not be sensitive to the projected changes in sea level outlined in Section 11.3.2.1 and Chapter 3 because they can be grown in a wide range of salinities. However, sea-level rise may require ponds to be moved further inland to prevent damage from wave surge and loss of fish from inundation.
- **Cyclones:** Milkfish farming is expected to be more exposed to the physical damage caused by the projected intensification of cyclones (Chapter 2) than tilapia and carp aquaculture because most milkfish ponds and cages are located close to the coast.
- **Habitat alteration:** Milkfish farming enterprises in PICTs may be exposed to changes in the availability of milkfish fry, due to the effects of climate change on coastal habitats. Increased variation in the supply of juveniles is likely to stem from changes to the location and suitability of inshore habitats for collection of fry, caused by changes in the areas of mangroves, seagrasses and intertidal flats[135–137] (Chapter 6). Alterations to these habitats are expected to be driven by increasing temperatures, sea-level rise, and variation in coastal currents and salinity regimes (Chapters 3 and 6).

Photo: Timothy Pickering

Milkfish ponds, Vitawa Village, Fiji

Potential impact and adaptive capacity

The direct effects of the projected increases in water temperature are likely to be beneficial to milkfish farming in the tropical Pacific. In particular, they are expected to (1) lengthen the season in which wild fry are available for stocking ponds; (2) extend the geographical range of milkfish spawning to higher latitudes; and

(3) reduce the time to harvest. Increased rainfall is also likely to provide more options for growing milkfish in freshwater ponds. The potential impact of any changes in the location and availability of wild juveniles for stocking ponds is difficult to estimate because the industry has yet to develop. However, sufficient quantities of juveniles are expected to be available in some PICTs – it just remains to be seen where these locations will be. Milkfish farming could be affected indirectly by increases in the availability and cost of fishmeal. The relatively low value of milkfish would make it difficult for enterprises to operate economically in the face of increased prices for feed, which is often the major aspect of production costs[39].

In the event that milkfish farming based on the collection of wild fry is affected by increased variability in the supply of juveniles, the industry may be able to adapt by producing juveniles in hatcheries. This is an expensive option, however, and only likely to be viable if the industry grows to a large size and has comparative advantages that enable other production costs to be reduced. The herbivorous/planktivorous diet of milkfish allows farmers to adapt to shortages of fishmeal in formulated diets by applying lab-lab pond management techniques, and replacing much of the fishmeal in formulated diets with plant protein[138].

Vulnerability

Milkfish farming in the tropical Pacific appears to have little or no vulnerability to climate change. Indeed, plans to develop milkfish farming in the region are expected to benefit from a low, positive effect of climate change on production under the B1 and A2 emissions scenarios by 2035. The potential benefits stem from the expected extension of the geographical area suitable for collection of fry and pond culture due to increasing water temperatures and rainfall, and increased rates of production within the present-day distribution of the species in the tropical Pacific. The level of potential benefits in 2100 is uncertain due to the possible increased adverse effects from continuing acidification of the ocean and habitat alteration on the supply of juveniles. Until these effects are better understood, any benefits for milkfish farming in 2100 should be considered to remain low.

11.3.2 Vulnerability of commodities for livelihoods

11.3.2.1 Pearls

Exposure and sensitivity

- **Temperature:** The significant pearl farming enterprises in French Polynesia, Cook Islands and Fiji, those underway in FSM, Marshall Islands, PNG and Tonga, and those planned for Kiribati and Solomon Islands, are projected to be exposed to increases in SST within the range of 0.5–1.0°C by 2035 under the B1 and A2 scenarios, and 1.0–1.5°C and 2.5–3.0°C under B1 and A2 in 2100, respectively (Chapters 2 and 3).

These important regional aquaculture activities are expected to be sensitive to increases in SST because temperatures > 28–32°C increase the susceptibility of pearl oysters in general to pathogens and parasites[139,140]. For example, harmful algal blooms can form when high temperatures increase stratification of coastal waters (Chapter 3) and/or when runoff from land during heavy rainfall increases nutrient loads (Chapter 7). 'Red tides' (*Heterocapsa* sp.) caused by such conditions have led to mass mortalities of Akoya pearl oysters in Japan, and large economic losses[141]. Water temperatures > 29°C have also been linked to mass mortalities (70%) of Akoya pearl oysters[142].

The thickness and deposition rate of nacre laid down by pearl oysters, and therefore pearl quality[143,144], is also likely to be sensitive to increases in SST. It is generally accepted that higher-quality nacre with superior lustre is deposited when water temperatures are cooler[145]. The rate of nacre secretion increases at warmer temperatures[146] and, although this allows production of larger pearls over a fixed period or earlier harvest of pearls of minimum market size, it could result in reduced pearl quality.

- **Rainfall:** The pearl industry in the tropical Pacific would have a varied exposure to projected changes in rainfall. Rainfall is generally expected to increase in equatorial areas, and decrease in the subtropics, by 5–20% in 2035 and 10–20% in 2100 (Chapter 2).

  The more extreme rainfall events likely to occur in the future would cause abrupt decreases in salinity of coastal waters, increased sediment loading and rapid changes in the productivity of coastal waters. These changes can lead to mass mortality of oysters[147–149], for example, when the excessive filtration of suspended solids by oysters in turbid water exceeds their energy budget[149–151].

  The sensitivity of pearl farming to higher rainfall is expected to depend on the location of operations. Farms in French Polynesia and Cook Islands, where most production occurs, will not be exposed to reduced salinities because rainfall is projected to decrease in subtropical areas. Even if extreme rainfall events do occur occasionally, there is little scope for runoff from atolls where farms are situated. Those pearl farms in FSM, Kiribati and Marshall Islands that have the benefit of being in atolls are not expected to be sensitive to the projected increase in rainfall. Farms established in lagoons in FSM, PNG, Solomon Islands and Fiji under the influence of runoff from high islands would be at increased risk of losing oysters due to reduced salinity and increased nutrient loads. Throughout Melanesia, increased rainfall could interact with warming SST to increase stratification and the incidence of harmful algal blooms (Chapters 2 and 3).

- **Ocean acidification:** The pH of the tropical Pacific Ocean is projected to decrease by 0.1 units by 2035 under the B1 and A2 emissions scenarios, and by 0.2–0.3 units by 2100, relative to the 1980–1999 average (Chapter 3). Little is known about the sensitivity of pearl oysters to this exposure, but the information available for other marine invertebrates, and for other species of oysters that construct shells and skeletons from calcium carbonate (Chapters 3 and 5), indicates that pearl oysters are likely to be badly affected by long-term declines in pH. Like many other marine invertebrates, acidification of the ocean is expected to limit the development of larvae and increase the percentage of individuals with abnormal shells[152,153,157–159]. These deficiencies would be expected to result in greater rates of predation and mortality, leading to reduced availability of oyster spat on collectors.

The fitness of surviving adults is also expected to be affected. Calcification rates of both the Pacific oyster *Crassostrea gigas* and the Atlantic oyster *C. virginica* are projected to decrease with declining aragonite saturation[160,161]. Decreases in calcification can reduce growth rates and lead to thinner or more fragile shells, causing oysters to be more susceptible to boring pathogens and mechanical disturbance, which ultimately results in increased mortality[162]. Shells of the pearl oyster *Pinctada fucata* exposed to acidified sea water (pH 7.8 to 7.6) for 28 days showed a 26% reduction in strength compared to controls, presumably as a result of dissolution[163]. Furthermore, adult *P. fucata* secreted fewer and thinner byssal threads under acidified conditions, indicating impaired physiological function, greater susceptibility to mechanical disturbance and loss from culture equipment[163].

There are also concerns that ocean acidification will reduce the quality of pearls. Although the shell of adult pearl oysters is dominated by calcite, the less soluble of the two forms of calcium carbonate used by marine invertebrates to construct their skeletons and shells (Chapter 3), the nacre of pearl oysters is composed mainly of the more soluble aragonite. Exposure of live *P. fucata* to acidified conditions (pH 7.8 to 7.6) resulted in malformation and/or dissolution of nacre at its growing edge[163]. Ocean acidification could affect the quality of half pearls (mabè) grown on the inner surface of pearl oyster shells, but its potential impact on round pearl quality is less clear. Round pearls develop within an oyster's tissues and are not in direct contact with ambient conditions. However, impaired physiological function under acidified conditions[163] could influence the rate at which nacre is deposited onto pearls as they form, and nacre quality.

- **Sea-level rise:** The projected rises in sea level (Section 11.3.2.2, Chapter 3) are likely to result in more frequent over-topping of atoll reefs by ocean swells, leading to increased current velocity and reduced residence time of sea water in enclosed lagoons. Pearl farming operations are expected to be sensitive to these changes because currents are essential for delivery of food (suspended organic particles) to the sessile oysters[164]. Greater supplies of food result in faster rates of nacre secretion, although the nacre deposited under such conditions is usually of lower quality[165]. Larvae may be washed out of the lagoons faster, thereby reducing pearl oyster recruitment rates.

- **Cyclones:** Pearl farming is expected to be highly susceptible to the projected increases in the intensity of cyclones (Chapter 2). In addition to the increased mechanical disturbance of the water column causing greater stress and mortality of oysters, more severe storms would be expected to inflict greater damage to farm infrastructure. The heavy seas and high winds caused by Cyclone Tomas in Fiji in March 2010 provide a recent example of the adverse effects of cyclones on pearl farming. Cyclone Tomas destroyed pearl seeding platforms, inundated a hatchery and swept away seawater intake pipes. Cyclones may also cause oligotrophic conditions leading to mass mortalities of pearl oysters due to the favourable conditions created for pathogens[166].

Potential impact and adaptive capacity

The projected increases in SST by 2035 are likely to have little effect on the growth and survival of *P. margaritifera*, which produces black pearls in Polynesia. However, the higher SSTs projected for 2100, particularly under the A2 scenario, may stress *P. margaritifera* in the warmer months of the year. The silver-lipped pearl oyster *P. maxima* farmed in PNG is also likely to reach upper thermal limits for optimal growth during warmer months by 2100.

Ocean acidification is expected to progressively reduce the rates of spat collection due to increased susceptibility of spat with weaker shells to predation. Growth of oysters to adult size in atolls may not be affected if the benefits of faster growth stemming from stronger currents due to sea-level rise cancel out the effects of ocean acidification on shell growth. In lagoons around high islands, increased nutrient loads would be expected to drive the locations for collection of spat further offshore[54].

Perhaps the greatest potential impact on pearl farming in the region, however, will be the combined effects of higher water temperatures, increased current regimes and ocean acidification on pearl quality. The profitability of pearl farming operations is closely linked to the percentage of high-quality pearls produced[167] (**Figure 11.5**), and any significant decrease in pearl quality will have consequences for the economic viability of enterprises.

The pearl industry is in a reasonable position to adapt to some of the projected effects of climate change. Any effects of higher SSTs, ocean acidification and high nutrient loads on the collection of spat can probably be overcome by increasing the proportion of spat produced in hatcheries under controlled temperature and pH conditions, albeit at increased cost. It may also be possible to counter the effects of rising SST on pearl quality to some extent by placing the oysters at a greater depth, and harvesting the pearls during the cooler months of the year.

Combating the likely effects of ocean acidification on pearl quality will be difficult because pearl oysters cannot be maintained economically under controlled conditions for the time it takes to produce pearls – the oysters need to be held in sheltered marine areas. However, there may be scope for identifying areas that remain buffered against lower aragonite saturation states. Such places can be found near well-flushed, carbonate-rich coral reefs, and in close proximity to areas with a good cover of seagrass and macrophytes[168] (Chapter 6).

The design of the entire infrastructure of pearl farms needs to be assessed to increase durability under more intense cyclones. Placing pearl oysters in deeper water to reduce the adverse effects of higher SST on nacre quality should also reduce damage by storms.

Vulnerability

The production of pearls is expected to have a low vulnerability to the effects of global warming and ocean acidification under the B1 and A2 emissions scenarios in 2035. However, vulnerability is expected to increase to moderate towards 2100, particularly in the equatorial western Pacific. This assessment may well need to be revised 'downwards', however, once the results of research on the effects of reduced aragonite saturation on the larvae and adults of pearl oysters, and on pearl quality, are examined in detail.

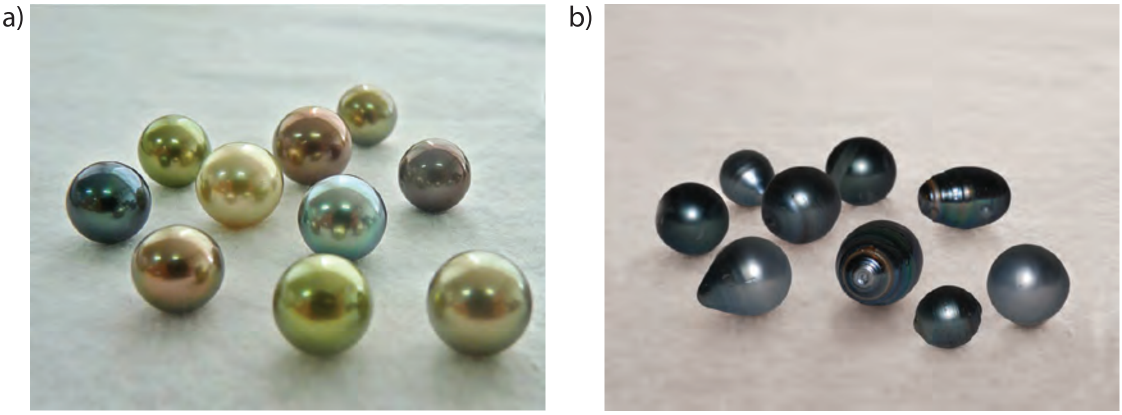


Figure 11.5 (a) High-quality pearls from black-lipped pearl oysters (photo: Leanne Hunter); and (b) low-quality pearls with poor lustre and surface defects (photo: Emily Naidike).

11.3.2.2 Shrimp

Exposure and sensitivity

- **Temperature:** The species of shrimp used in the region for aquaculture, *Litopenaeus stylirostris* in New Caledonia and Vanuatu, *Penaeus monodon* in Fiji and PNG, and *L. vannamei* in CNMI and Guam, are expected to respond to the changes in surface air temperatures projected to occur under the B1 and A2 emissions scenarios in 2035 and 2100 (Section 11.3.2.1, Chapter 2). The first two species are presently grown at the lower limits of their temperature ranges. In CNMI and Guam, *L. vannamei* is reared in intensive, closed, recirculating systems where temperature is easier to control.

The ideal temperatures for growth of *L. stylirostris* are between 24°C and 30°C[61]. Below 24°C, growth rates fall rapidly (up to 75% decrease at 20°C), and food consumption is reduced at temperatures > 30°C. Despite slower growth at lower temperatures, *L. stylirostris* was selected as the basis for the shrimp industry in New Caledonia because it had potential for year-round farming. However, fluctuations in pond temperatures during the relatively short autumn and spring transitions between the longer, more stable summers and winters, have caused chronic mortalities due to two vibriosis diseases, known as 'Syndrome 93' and 'Summer Syndrome'[169,170] (**Figure 11.6a**). The syndromes are linked to the stresses caused to shrimp by pond temperature variations of several degrees in only a matter of days.

The normal expectation for survival of *L. stylirostris* to harvest size in production cycles initiated in summer in New Caledonia is 60% if the effects of autumn and spring temperature transitions are weak. If the transitions are severe, however, vibriosis-induced mortality reduces survival to 35–40%[65]. Warming would be expected to lead to an improvement in survival in ponds seeded in the autumn (April–May) and winter (June–August). On the other hand, the success of the summer shrimp farming cycle for *L. stylirostris* depends on moderate summer temperatures because survival is correlated to the temperature during the first month of growth[62]. Thus, the summer production cycle may be adversely affected by the higher projected surface air temperatures. Male broodstock of *L. stylirostris* are also likely to be sensitive to increased temperatures – adult male shrimp held in earthen ponds already have problems producing viable sperm during the hottest months of the year (January–March)[171–173].

Penaeus monodon is more sensitive to cool water temperatures than *L. stylirostris*; growth of *P. monodon* slows once temperatures fall much below 28°C[174]. Variations in pond temperature also have pronounced effects on production of *P. monodon*, with maximal growth rates occurring during sustained warm periods[175]. In Fiji, poor growth and increased mortality of *P. monodon* have been associated with winter temperatures of 22–25°C.

- **Rainfall:** New Caledonia is expected to be exposed to reductions in rainfall of up to 20% by 2100 under the A2 scenario, with the drying occurring predominantly during winter (Chapter 2). Fiji, PNG and Vanuatu on the other hand, are projected to receive up to 20% more rain by 2100. Throughout the region, extremes in wet and dry periods are expected to become more extreme.

The shrimp industry within the tropical Pacific is likely to be sensitive to changes in rainfall patterns. The severe drought in New Caledonia from 1991 to 1995

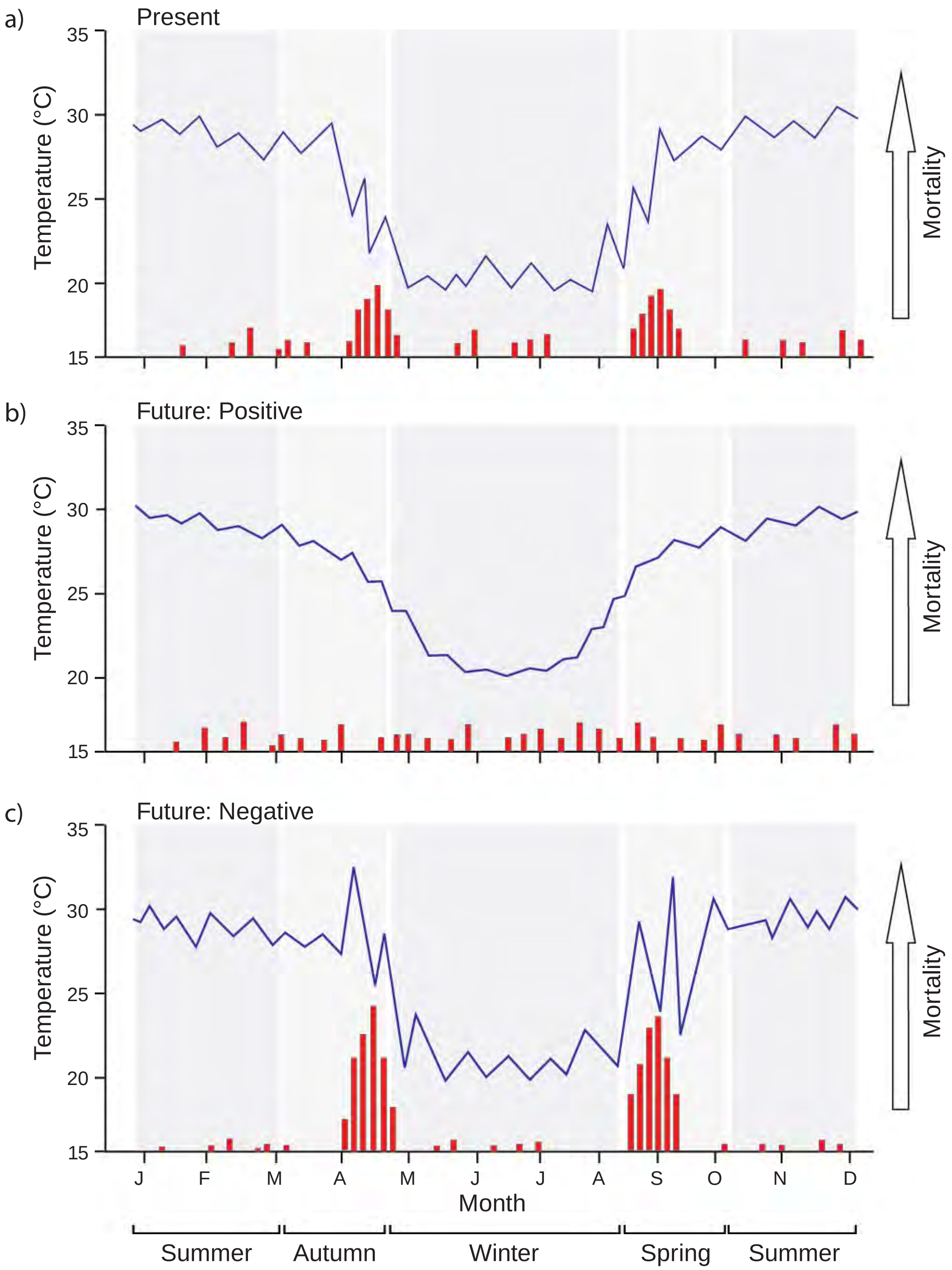


Figure 11.6 (a) Generalised rates of mortality (red columns) of the blue shrimp *Litopenaeus stylirostris* in ponds in New Caledonia throughout the year due to outbreaks of 'Summer Syndrome' and 'Syndrome 93' in autumn and spring; (b) expected decreases in mortality of shrimp if global warming reduces temperature variation in autumn and spring; and (c) projected increases in shrimp mortality if warming increases variation in temperature.

resulted in a significant increase in salinity and a decrease in mean temperature of ponds[176]. Sustained hypersaline conditions reduce the growth rate of *L. stylirostris*, and salinities > 55 PSU lead to high mortalities[61]. The largest shrimp farming company in New Caledonia recorded a 20% decrease in net yields from 1991 to 1995, attributed partly to the effect of the drought.

Extreme rainfall events can transport high quantities of minerals and organic nutrients into ponds through leaching from surrounding areas, depending on land use. Such events result in poor water quality in ponds (e.g. low dissolved oxygen levels) and unfavourable conditions for shrimp farming.

The increase in rainfall projected for Fiji is expected to hinder drying of ponds between production cycles – ponds must be thoroughly dried and the soil tilled to re-oxygenate it, before re-filling for the next culture cycle. Failure to do this stresses shrimp because of the toxic effects of inorganic nitrogen, resulting in greater risks of disease and catastrophically low harvests.

- **Ocean acidification:** Like some other crustaceans, penaeid shrimp typically exert high biological control over calcification by gradually accumulating intracellular stocks of carbonate ions to harden their chitin and protein exoskeletons, usually in the less soluble form of calcite. Therefore, formation of the exoskeleton in shrimp is not highly sensitive to the projected reductions in calcium carbonate ($CaCO_3$) expected to result from acidification of the ocean (Chapter 3).

  Litopenaeus stylirostris may be more sensitive to acidification of sea water than other species of penaeid shrimp, however, because of its thinner shell. Given the detrimental effects of marks such as 'black spot' on the price received for shrimp by farmers in New Caledonia, any deformities due to the effects of ocean acidification on thin shells would be expected to reduce profits. On the other hand, some crustaceans actually increase calcification when concentrations of carbon dioxide (CO_2) in sea water are high[177]. Research is required to determine if this is the case for *L. stylirostris* and *P. monodon*.

- **Sea-level rise:** The projected rises in sea level, described in Section 11.3.2.2 and in Chapter 3, are expected to cause major problems for the shrimp industry because farming operations depend on the ability to drain ponds quickly and effectively.

  Sea-level rise threatens the drainage of ponds because (1) the height differential between the pond floor and nearby coastal waters is reduced; and (2) mangroves and other aquatic vegetation are projected to migrate landward (Chapter 6), increasing the retention of sediment 'downstream' from shrimp farms and reducing the height differential further (**Figure 11.7**). Greater intrusion of salt water is also likely to promote colonisation of the channels that drain shrimp ponds by *Rhizophora* spp. (red mangrove), retarding flow.

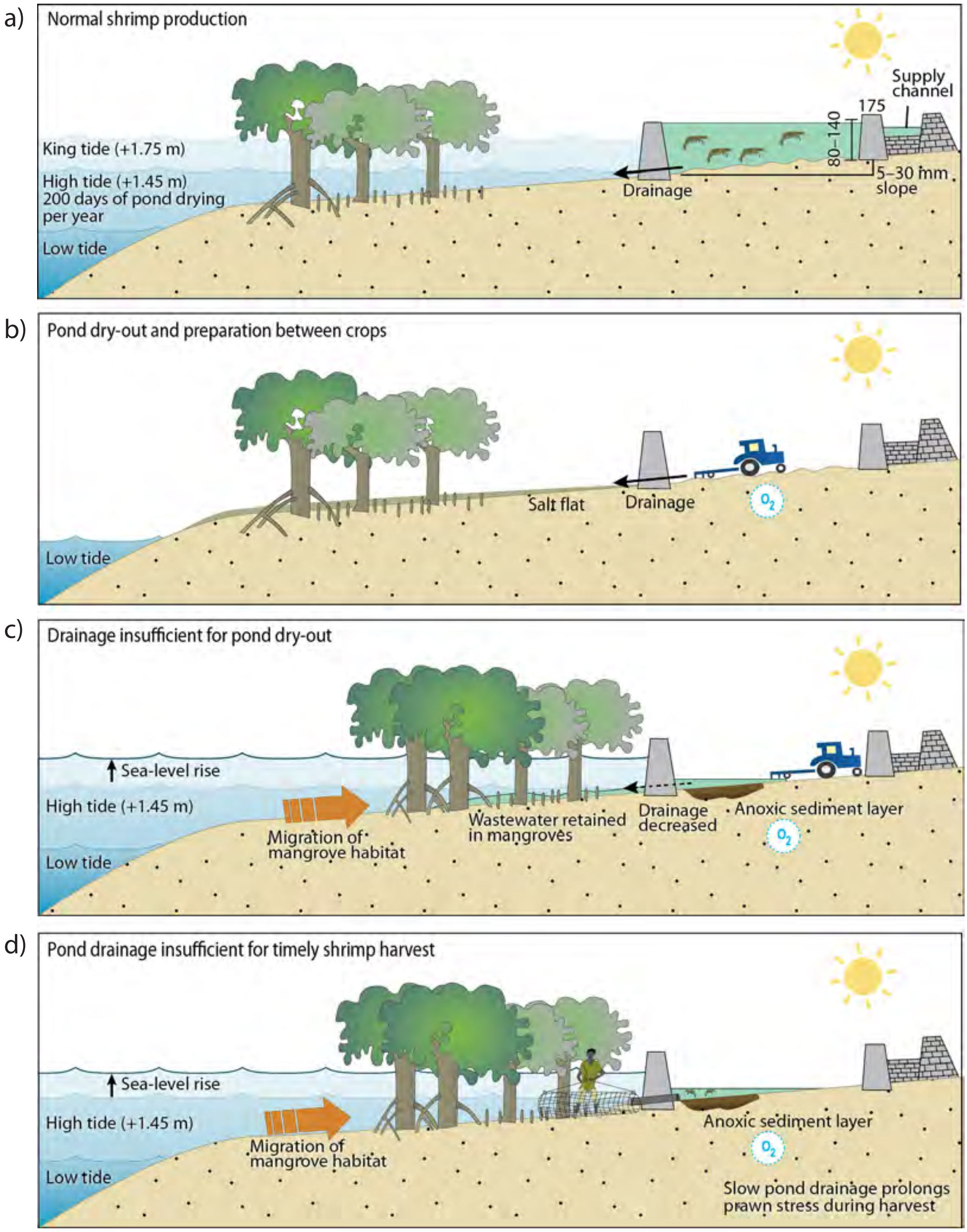


Figure 11.7 Present-day relationships of shrimp ponds in New Caledonia to the existing tidal levels when (a) shrimp are being grown throughout a normal production cycle, and (b) ponds are drained at low tide after harvest and dried between crops; and the adverse effects of sea-level rise and migration of mangroves on (c) drainage and drying of ponds between crops, and (d) the multiple partial-harvest system.

- **Cyclones:** If cyclones become more intense, greater levels of damage to shrimp ponds would be expected due to more powerful storm surges, and the scope for the waves to penetrate further inland due to sea-level rise. Shrimp farms in Fiji are likely to be the most susceptible to increased damage from stronger cyclones.

Potential impact and adaptive capacity

There are two main possible impacts of the projected rises in surface air temperature and SST on the shrimp industry in New Caledonia, depending on whether the autumn and spring seasonal temperature transitions become smoother, or more variable. Increases in pond temperatures, combined with reduced variation in temperature, during April and May (similar to the present-day conditions in Vanuatu) would benefit the production of *L. stylirostris* (**Figure 11.6b**). In particular, the growing season would be extended, perhaps enabling two production cycles per year, if conditions during summer do not become too hot. On the other hand, if climate change exacerbates variations in temperature during autumn and spring, which might occur if the land mass of New Caledonia has a 'continental effect', high losses due to vibriosis would be expected to continue (**Figure 11.6c**).

On balance, we expect the projected warming to reduce the effects of cold seasons on shrimp in New Caledonia, resulting in greater yields per hectare in 2035 compared with 2100. In particular, *L. stylirostris* would be expected to have faster growth rates under adequate management if climate change increases primary and secondary production levels in the semi-intensive ponds[178].

The warming conditions are also expected to increase the efficiency of farming *P. monodon* in Fiji. However, by 2100 the warming expected around New Caledonia and Vanuatu is likely to reduce growth rates of *L. stylirostris* during summer, particularly in Vanuatu. The projected warming could also preclude the option of stocking ponds with postlarvae at that time of year.

For *L. stylirostris* broodstock held in earthen ponds, there is also the possibility that the warmer conditions will increase the percentage of males with unviable sperm. To provide the postlarvae needed to capitalise on any opportunities for greater pond production resulting from the warmer conditions, shrimp farming enterprises may need to invest in indoor temperature-controlled facilities for maintaining broodstock.

If pond temperatures become untenable for producing *L. stylirostris*, the warming climate itself may provide the shrimp industry with an adaptation – producers in New Caledonia and Vanuatu may be able to diversify into warmer-water species, such as *P. monodon*. In Fiji, yields of *P. monodon* would be expected to increase under the warmer conditions but farmers there may also be able to consider growing the indigenous *P. semisulcatus* and *P. merguiensis*, provided that production methods are competitive with imported shrimp.

An increase in the frequency and intensity of drought events is expected to have a negative impact on yields from shrimp aquaculture in New Caledonia.

The effects of sea-level rise on the drainage of shrimp ponds is expected to have an adverse effect on the farming of *L. stylirostris* in New Caledonia and *P. monodon* in Fiji. However, in Fiji, ponds for the more-intensive culture of *P. monodon* are generally smaller and constructed at higher elevations than in New Caledonia, so that the impact of sea-level rise is expected to be lower.

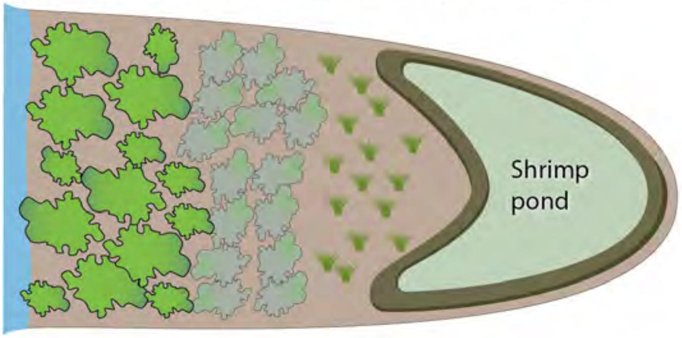
The three main effects of sea-level rise on shrimp ponds (inhibiting outflow of wastewater, inability to lower pond levels quickly for harvesting, and loss of capacity to prepare emptied ponds before restocking) (**Figure 11.7**) could potentially have a powerful impact on the profitability of shrimp farming. Reduced ability to lower pond level quickly would also put at risk the current multiple partial-harvest system of pond management, by prolonging stressful crowded harvest conditions and leading to shrimp mortality or loss of product quality. Where farms are located in confined bays, poor drainage will increase the risk that effluents from ponds contaminate the water pumped to fill ponds. The potential problems are expected to be particularly severe in New Caledonia, where the ponds are typically built at the rear of mangrove areas in the intertidal zone (**Figure 11.8**). The problems are likely to affect the 8–12 ha ponds used for semi-intensive farming (stocked with 15–20 postlarvae per m^2), the 3–5 ha ponds farmed intensively (30–40 postlarvae per m^2), and the 0.2–0.4 ha ponds used to keep broodstock.

In New Caledonia, shrimp farmers will eventually face the expense of constructing new ponds at higher elevation or modifying existing ponds to improve drainage. Construction of new ponds will involve more intensive farming methods (higher stocking density, higher inputs) to compensate for the fact that fewer areas are expected to be suitable for shrimp farming. New approaches to shrimp farming will be needed. There are strong messages here for other PICTs considering the development of shrimp farming – farm layout and farming methods should be based on smaller ponds stocked at higher densities, built in more landward locations (**Figure 11.8**).

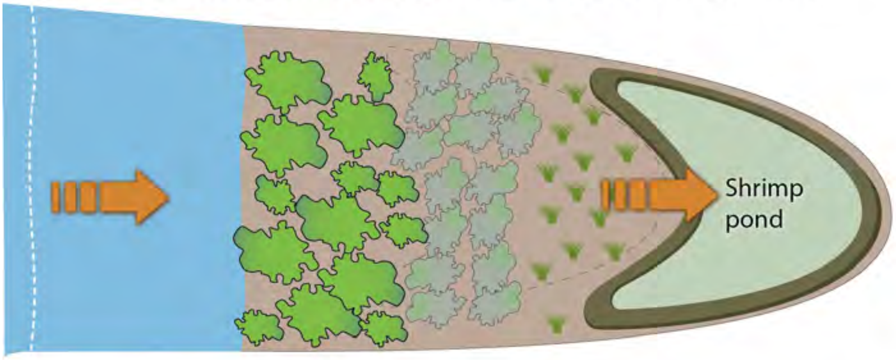
Adaptation based on modifying existing ponds will need to focus on heightening walls and raising the floor level of ponds to maintain water depth and the necessary height differential for rapid drainage[179]. The rate of sea-level rise is expected to be sufficiently slow to allow work on the heightening of walls to be done at the same time as routine maintenance.

Care will be needed in selecting the appropriate substrate for raising the floor level of ponds. Organisms associated with pond sediments comprise an important part of the diet of cultured shrimp[180–182], even when postlarvae are stocked at densities > 30 per m^2. Typically, the abundance of benthic meiofauna (copepods, nematodes, foraminiferans) in ponds falls by 85% during the first month after stocking shrimp[183]. However, rapid turnover of meiofauna ensures that they continue to contribute to

a) Present-day situation for semi-intensive shrimp culture methods



b) Future conditions for semi-intensive shrimp culture methods with new ponds constructed landward in anticipation of sea-level rise (increases pumping costs due to higher lift in the shorter term)



c) Future conditions where ponds cannot be relocated landward. This requires intensive or super intensive shrimp culture methods in smaller elevated ponds.

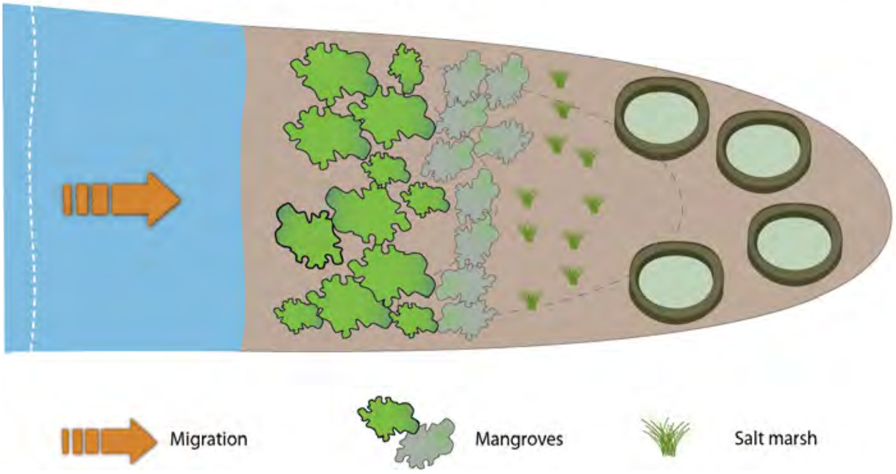


Figure 11.8 (a) Present-day relationships between intertidal coastal vegetation and semi-intensive shrimp ponds in New Caledonia; (b) relocation of semi-intensive shrimp ponds landward as sea level rises and coastal vegetation migrates; and (c) conversion of semi-intensive shrimp ponds to elevated, smaller intensive ponds as sea level rises where landward extension of ponds is blocked.

the nutrition and health of farmed shrimp. Boosting production of meiofauna by fertilisation can lead to significant gains in shrimp growth[183]. To retain these benefits, sediments suitable for colonisation by meiofauna should be used to raise pond floors.

Any adverse effects of seawater acidification on farmed shrimp can be partially addressed by application of agricultural lime during the preparation of ponds, although this will further increase production costs.

Shrimp farming in the tropical Pacific also needs to position itself to adapt to the effects of global warming on two of the key ingredients in the diet of cultured shrimp: *Artemia* and fishmeal. The larval rearing and acclimatisation of *L. stylirostris* in New Caledonia depends on large quantities of *Artemia* cysts (15 kg per million postlarvae), almost all of which (90%) are produced in Great Salt Lake, Utah, USA. However, *Artemia* cyst production in Utah drops significantly during El Niño events, which cause reductions in salinity and increases in temperature, as happened between 1993 and 1997[184,185]. Future supplies of *Artemia* can also be expected to be vulnerable to climate change. The shrimp industry in the region will need to switch to formulated micro-particles as soon as the promising research and development to produce this specialised food is complete.

Exposure to potential shortages of fishmeal is discussed in Section 11.3.2.1. Formulated diets fed to shrimp in ponds have a high fishmeal content (38–40% crude protein)[186] and can account for 35–40% of production costs[62]. Keeping pace with international trends in re-formulation of shrimp feeds to incorporate alternative sources of protein will be an important adaptation. Another key adaptation is to make better use of the natural productivity of ponds by rotating the farm through extensive or hyper-intensive modes, such as by development and application of biofloc technologies[187].

Subject to adaptive strategies being successful and cost-effective, it appears that the goal to double the production of the shrimp industry in New Caledonia to ~ 4000 tonnes per year, involving 1000 livelihoods, could still be met, assuming the industry can rise to existing socio-economic challenges to expansion and find appropriate niche markets for its product. Also, based on the likely future climatic conditions and amount of available space for shrimp farms, both Fiji and PNG should be able to retain their medium-term potential to produce 1000 and 2000 tonnes per year, respectively, employing about 500 people.

Vulnerability

The shrimp industries in New Caledonia and Fiji are estimated to have a low vulnerability under the B1 and A2 emissions scenarios in 2035. Indeed, climate change is expected to have a low, positive effect on production. In particular, the conditions for farming *P. monodon* in Fiji are likely to improve due to warmer pond temperatures. The prospect of increased temperatures resulting in improved yields of *L. stylirostris* in New Caledonia will depend on whether there is also reduction in the often rapid variation in temperature during autumn and spring, which can cause major losses of shrimp due to vibriosis.

By 2100, however, the outlook may not be as positive. Furthermore, the complexities of shrimp farming mean that the various aspects of the industry are likely to have differing vulnerabilities to climate change. For example, the survival and growth of the shrimp themselves are expected to be most vulnerable to changes in water temperature, whereas the profitability of farming operations has added vulnerabilities related to changes in rainfall patterns and sea-level rise. Any benefits due to faster growth rates of *L. stylirostris* in New Caledonia are likely to be eroded by (1) the costs involved in adapting the location or structure of shrimp ponds to overcome the effects of sea-level rise on the drainage of ponds; and (2) more extreme dry periods. Overall, shrimp production in New Caledonia is estimated to have low vulnerability to climate change under the B1 scenario in 2100, and low to moderate vulnerability under A2 in 2100.

11.3.2.3 Seaweed

Exposure and sensitivity

- **Temperature:** The projected increases in SST described in Section 11.3.3.1 represent considerable exposure for the seaweed *Kappaphycus alvarezii* farmed in the tropical Pacific. It is already at the upper limits of its temperature tolerance in the lagoons where it is grown in Kiribati, Fiji and Solomon Islands[188]. Indeed, recent increases in temperature that caused bleaching and mortality of corals (Chapter 5) were also detrimental for seaweed cultivation[68,189]. In particular, SST > 30°C inhibits growth, causes stress of *K. alvarezii*[68,190] and makes the seaweed susceptible to outbreaks of epiphytic filamentous algae, e.g. *Neosiphonia*, and tissue necrosis ('ice-ice'), resulting in stunting of plants and high mortalities (**Figure 11.9**). Seasonally rapid increases and decreases in temperature and salinity are also known to trigger such outbreaks[191].

  The species of harvested seaweed in Tonga, *Cladosiphon* sp. (mozuku), is also expected to be sensitive to increased SST because it relies upon marked seasonal changes in temperature for annual sporulation and completion of its life cycle. Warmer SSTs are likely to inhibit reproduction and growth of this species.

- **Rainfall:** Seaweed farming operations in tropical areas are expected to be exposed to significant increases in rainfall (Section 11.3.2.1, Chapter 2). *Kappaphycus* is sensitive to reduced salinities and the farming of this seaweed is already limited to areas well away from the influence of runoff[68].

- **Ocean acidification:** The higher projected concentrations of dissolved CO_2 driving the expected decreases in the pH of the ocean (Chapter 3) are likely to stimulate the growth of seaweed. Like all plants, *K. alvarezii* depends on CO_2 for photosynthesis and might be expected to have a faster growth rate as the concentrations of CO_2 in the ocean increase, if other variables remain constant. As described above, however, other features of the environment are likely to retard growth, so any potential benefit to seaweed farming from the higher levels of dissolved CO_2 is questionable unless farming operations can be moved to better locations.

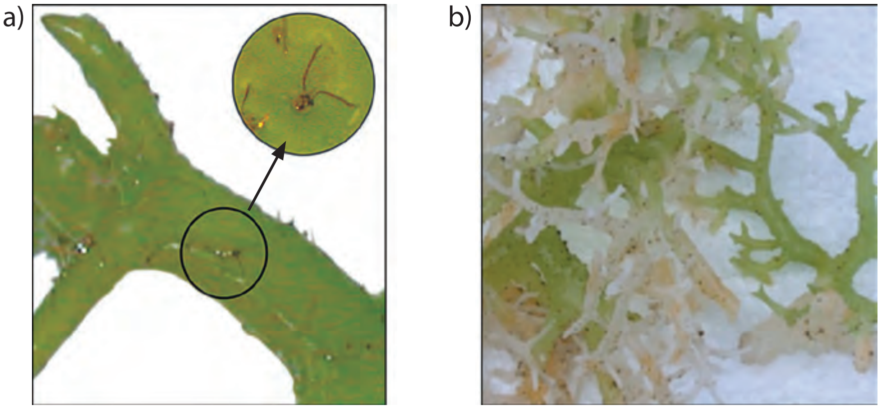


Figure 11.9 Farmed seaweed *Kappaphycus alvarezii* affected by (a) epiphytic filamentous algae, and (b) tissue necrosis (photos: Reuben Sulu).

- **Sea-level rise:** Seaweed farming is also heavily exposed to the projected increases in sea level described in Section 11.3.3.1 and Chapter 3 because the activities occur in shallow subtidal areas. While this may result in some locations no longer being suitable for seaweed farming due to an increase in depth, the increase in local currents associated with sea-level rise is expected to benefit seaweed farming. Indeed, successful production of *K. alvarezii* depends on water movement[189,192].

  The main advantage of stronger currents is that they help overcome shortages of nitrogen, caused by low rates of water exchange in combination with other stresses, such as higher temperatures or lower salinities, which result in outbreaks of ice-ice and epiphytic filamentous algae. However, good growth can be achieved in oligotrophic conditions where strong water movement increases nutrient flux. For this reason, *K. alvarezii* is farmed most often on the back-reef coralline-sand flats of high island lagoons, or on coralline-sand flats adjacent to inhabited islets in the lagoons of atolls, where there is sufficient water exchange to support 'off-bottom' (wooden-stake) culture.

- **Cyclones and ENSO events:** In Fiji, seaweed farming may possibly be exposed to more intense cyclones. However, because seaweed farming is sensitive to the effects of waves generated by winds of much lower velocity than those typical of cyclones, it is no more sensitive to more intense cyclones than it is to present-day cyclones – both can be expected to destroy stocks of plants and infrastructure. The sensitivity of seaweed farming to wind strength and direction is demonstrated by responses to ENSO events. In Kiribati, the reversal in wind direction that occurs during El Niño episodes sets up harmful wave action in seaweed farming sites that are normally sheltered (**Figure 11.10**), requiring shifts in farm locations. Such changes in wind direction are expected to continue, although there is no consensus on future changes to the frequency or intensity of ENSO events (Chapter 2).

Potential impact and adaptive capacity

The projected increases in SST pose a significant threat to seaweed farming in Solomon Islands and Kiribati. By 2100, the areas for growing seaweed in these countries are expected to be above the upper thermal limit for present varieties of *K. alvarezii* for most of the year, reducing production substantially and increasing susceptibility to disease. Under the A2 scenario, many sites where production of seaweed is underway today may become unsuitable for farming. This applies less to Fiji, where coastal waters are cooler than in Solomon Islands. However, even there, SST is expected to be above the upper thermal limits for part of the year by 2100, threatening the viability of seaweed farming.

The impact of higher SST may be reduced in locations where rising sea level causes increased over-topping of reefs by ocean swells, leading to increased current velocity, shorter residence times of sea water in enclosed lagoons and lower water temperatures. Such changes would be expected to help maintain seaweed production unless the stronger tidal currents and wave action resulted in loss of plants or damage to equipment. The projected degradation of coral reefs due to climate change (Chapter 5) may increase the locations where currents can penetrate to seaweed growing areas.

At sites where currents remain within acceptable limits, the problems caused by higher SST are likely to be compounded by increased rainfall, leading to more regular losses of seaweed from ice-ice and epiphytic filamentous algae. These incidents will have a strong local impact because production cannot recommence until farms can be restocked by propagating seaweed cuttings delivered from unaffected localities.

There is limited scope for adaptation of seaweed farming at the regional level by shifting production to higher latitudes – it is an activity suited only to remote coastal communities in countries with low expectations of return on labour, and where there are few alternative opportunities to earn income. In principle, it could be expanded to Vanuatu as temperatures warm, but considerable research would be needed to assess the suitability of sites and the social need for, and acceptance of, seaweed farming.

There is no scope for selection of temperature-tolerant strains unless new varieties of *K. alvarezii* are imported, because all seaweed cuttings in the region are vegetatively-propagated clones derived from small founder stocks imported from Southeast Asia.

In the absence of new, more temperature-tolerant varieties, strategies for growing the existing stock will need to be devised to reduce the effects of climate change on production, and to increase the speed of recovery of yields after disruptions.

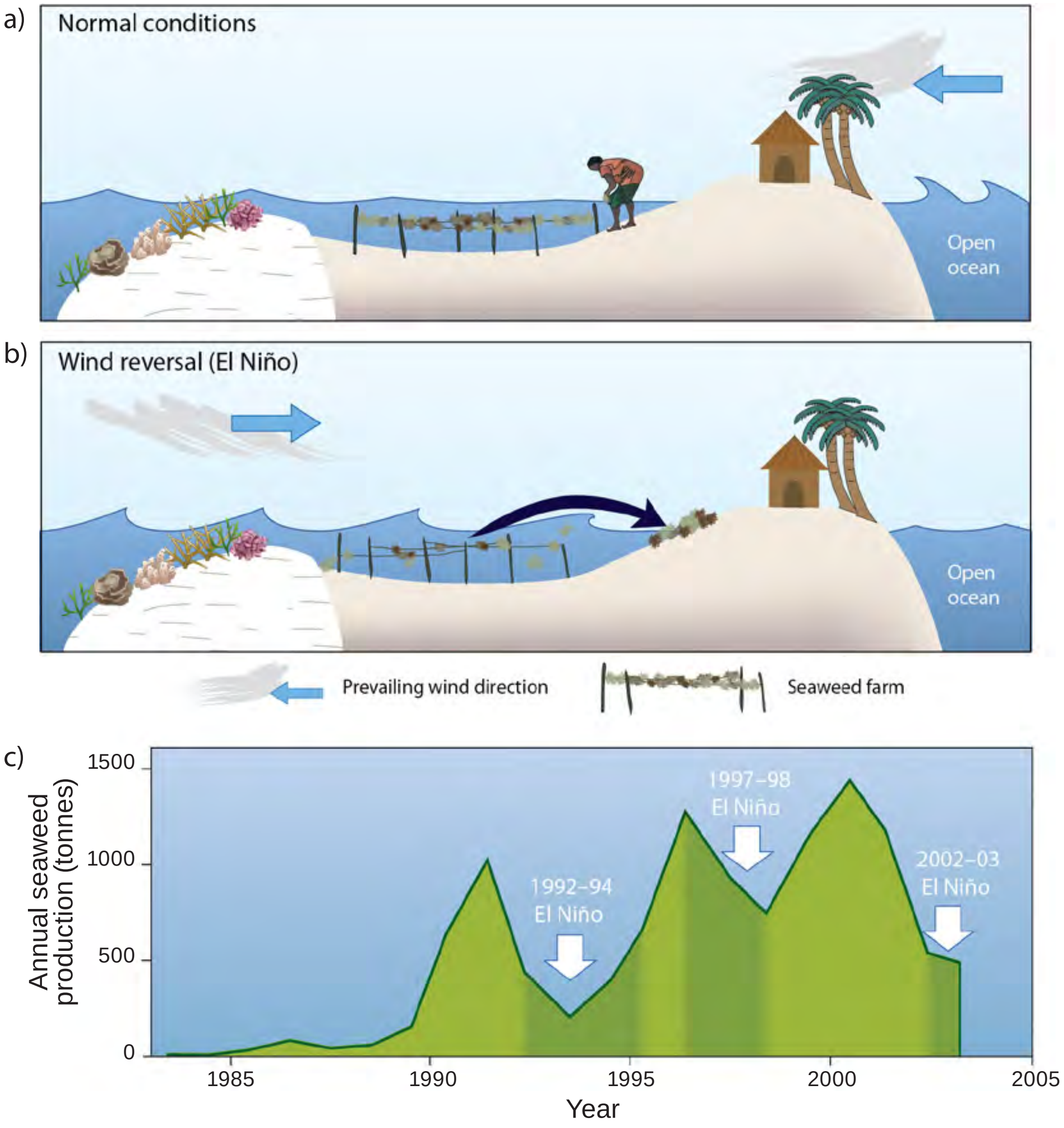


Figure 11.10 (a) Average conditions for farming seaweed in Kiribati, (b) effects of altered wind conditions associated with El Niño events on seaweed farming in Kiribati, and (c) consequences of El Niño events for total annual seaweed production in Kiribati.

Sites where temperatures and salinities are likely to be suitable for growing seaweed need to be identified for existing production areas in Kiribati, Solomon Islands and Fiji, with a view to re-location of operations away from sites where conditions deteriorate. The key to this will be finding locations where currents regularly flush prospective farming areas. In the shorter term, seaweed at such sites may benefit from the increasing concentrations of CO_2 in the ocean. However, restrictions are expected on the length of time seaweed can be grown at any site due to the increasingly adverse effects of higher SST and rainfall. Thus, seaweed farming should be regarded as a shorter-term investment opportunity. As harvests of seaweed become more unreliable, due to regular outbreaks of ice-ice and epiphytic filamentous algae, seaweed farmers will need assistance to diversify into other livelihoods.

Increases in SST are expected to reduce the viability of *Cladosiphon* aquaculture because farming systems are dependent on availability of natural sporefall.

Vulnerability

Farming of *Kappaphycus* seaweed in the tropical Pacific is estimated to have a moderate vulnerability to climate change by 2035 under the B1 and A2 emissions scenarios. By 2100, this form of aquaculture is likely to have moderate to high vulnerability under B1, increasing to high vulnerability under A2. Continued selection of more suitable farming sites and introduction of a more suitable seaweed variety will be required to reduce the vulnerability of seaweed culture. Production targets of 1000–2000 tonnes per year for both Fiji and Solomon Islands should still be achievable until 2035, but not necessarily in the same places or using the existing methods of management.

11.3.2.4 Marine ornamentals

Exposure and sensitivity

- **Temperature:** Because coral fragments cultured for the aquarium trade are grown in shallow, sheltered coastal areas (**Figure 11.11**), their exposure to increasing SST is expected to be as high as, or higher than, the exposure of coral reefs described in Chapter 5. The major response of corals to increased SST is expulsion of their zooxanthellae, which affects their energy production, potentially reducing growth and ultimately resulting in the death of colonies after protracted bleaching[193–195] (Chapter 5).

  The projected steady increase in SST under the B1 and A2 emissions scenarios of 0.5–1.0°C by 2035, is expected to cause coral fragments to bleach twice as frequently as today (Chapter 5). The increased levels of temperature stress by 2035 are likely to result in a 25% increase in loss of coral fragments relative to 2007, particularly in the case of branching species such as *Acropora* and *Stylophora* (Chapter 5). Under the B1 scenario by 2100, coral bleaching is projected to occur every 1–2 years and most branching species are expected to be too difficult to grow, although it may still be possible to culture fragments of massive species such as *Porites*, and encrusting corals like *Favia* and *Favites* (Chapter 5). Under A2 by 2100, SST is expected to be hostile to most species of corals, except very robust extremophiles.

The giant clams cultured for the ornamental trade also rely on zooxanthellae within their mantle tissue to supply organic compounds needed for growth[78,196]. The zooxanthellae are expelled from the mantle during periods of unusually warm SST[200,201]. Prolonged periods of bleaching can result in mortality of giant clams because, although they obtain a proportion of their food by filter feeding[196], they do not survive when deprived of sunlight and the products of photosynthesis by zooxanthellae. Lethal temperatures for giant clams are ~ 34–35°C[77,197]. Below the temperature threshold that induces bleaching, growth of giant clams is correlated positively with SST[75].

Increasing SST is also expected to alter the abundance and distribution of postlarval fish and crustaceans through changes in spawning location and duration, and the effects of higher temperatures on larval dispersal and survival[198] (Chapter 9). However, little is known about the sensitivity of the species presently collected in 'capture and culture' operations to changes in SST.

Figure 11.11 Coral fragments grown on trellises in sheltered, shallow coral reef habitats in Solomon Islands (photo: Jamie Oliver).

- **Rainfall:** The projected increases in rainfall in tropical areas (Section 11.3.2.1, Chapter 2) are expected to have advantages and disadvantages for enterprises culturing corals and giant clams in sheltered coastal waters. In locations where there are modest increases in runoff, the additional nutrients are likely to boost the growth rates of corals and giant clams, provided any associated increase in turbidity does not unduly inhibit photosynthesis by zooxanthellae[199,204]. Where salinities drop to 25–30 PSU for short periods, the growth of corals[202] and giant clams is unlikely to be affected. However, where the volume and duration of runoff increases significantly due to more extreme rainfall, conditions are expected to be unsuitable more often for culturing corals and giant clams due to (1) the adverse effects of prolonged reductions in salinity and light; and (2) the effects of increases in sedimentation and fouling by epiphytic algae and macroalgae[202–204](Chapter 5).

Cultured corals and giant clams are unlikely to be sensitive to any reduction in nutrients in coastal waters due to increased stratification resulting from projected changes in salinity and SST (Chapter 3) because they receive much of their nutrition from the organic products of photosynthesis by zooxanthellae.

- **Ocean acidification:** Corals farmed for the ornamental market will be exposed to the effects of ocean acidification on aragonite saturation levels in the same way as natural coral reefs (Chapter 5). By 2035, calcification of coral colonies is likely to be 50% less than that seen in the early 1990s. In 2100 under the B1 scenario, reef calcification is expected to be reduced by ~ 80%, and physical and biological erosion is likely to exceed calcification. The situation is likely to deteriorate further under A2 in 2100, when atmospheric CO_2 is expected to surpass 750 ppm, driving ocean pH below 7.7 and carbonate ion concentrations far below the levels needed for coral growth (Chapter 5).

  Ocean acidification is also likely to affect the culture of giant clams and the crustose coralline algae components of live rock. Acidification is expected to result in reduced growth and weaker valves in giant clams because their shells are made of aragonite[177]. Crustose coralline algae are likely to be susceptible to the effects of acidification earlier than corals because these algae secrete high levels of magnesium calcite, which is more soluble than the aragonite of coral skeletons[205]. Thus, crustose coralline algae are also expected to be in danger of dissolution rates exceeding calcification rates by the end of this century[206]. Enterprises producing live rock depend on their products being ready to sell within 6 to 12 months. Even then, operations are only marginally profitable and recent research aims to reduce production times[207]. These enterprises are expected to be susceptible to any delays in production of live rock due to slower calcification rates.

  Ocean acidification is also expected to alter the recruitment success of postlarval fish and invertebrates, through changes to their fitness and behaviour[153–156] (Chapter 9), and the marine food webs that support them[208,209] (Chapter 4).

- **Sea-level rise:** The projected rises in sea level (Section 11.3.2.1) are expected to increase rates of water exchange in atoll lagoons, and some inshore habitats around high islands, through increased over-topping of reefs by ocean swells. Village-based enterprises producing cultured coral fragments and giant clams for the aquarium trade are expected to have access to more potential grow-out sites as water circulation and nutrient supply at previously oligotrophic areas increase, along with sea level.

- **Cyclones:** The possibility that cyclones may become more intense, but less frequent (Chapter 2), may not necessarily increase the sensitivity of farmed marine ornamental products or the infrastructure required – any cyclone is likely to destroy equipment and stock left in shallow water. A reduction in frequency of cyclones would be expected to reduce such losses.

- **Habitat alteration:** As described above and in Chapter 5, global warming and ocean acidification are expected to degrade coral reefs progressively. Consequently, there are expected to be fewer sources of coral fragments for grow-out, particularly for branching coral species. It remains to be seen whether degradation of coral reefs reduces the supply of giant clam broodstock – the two most popular species in the ornamental trade, *Tridacna maxima* and *T. crocea*, also occur in dead, massive corals.

Potential impact and adaptive capacity

The combined effects of projected changes to SST, rainfall, ocean acidification, sea-level rise, cyclones and coral reef habitats in 2035 are expected to have a low potential impact on enterprises farming corals and giant clams in the shallow coastal waters of the tropical Pacific. In fact, although more bleaching is predicted to occur, the time required to grow these products to market size is expected to be reduced under the warmer and more nutrient-rich conditions in countries such as Vanuatu and Tonga. By 2035, warming is also likely to benefit flow-through giant clam hatcheries in Vanuatu, by making spawning and larval rearing possible year-round. Farm sites can be chosen in areas where the occurrence of bleaching is low, such as resilient areas of lagoons, or simply by moving the farms deeper.

Coral bleaching

Photo: Ove Hoegh-Guldberg

By 2100, medium to high negative effects on farm production caused by regular bleaching are likely. Similarly, corals and giant clams are expected to have difficulty forming their skeletons and shells due to increased acidification of the ocean and the detrimental effects of increased runoff. These problems are projected to emerge earlier for the branching corals that dominate the trade in coral fragments. Production of live rock is expected to become unprofitable in many areas during the second half of the 21st century.

It is difficult to see how enterprises producing corals and giant clams in equatorial areas will be able to adapt, because transferring operations from the sea to recirculating tanks on land, where they could control water temperature and pH, requires seawater pumping and acquisition of land-based sites. Such costs would place these enterprises at a competitive disadvantage to those in subtropical areas. Growth rates of giant clams in re-circulation systems can, however, be maximised by fine-tuning the addition of nutrients[199], and shading to enhance mantle colour[210], assisting growers to obtain higher prices.

As coral reefs degrade, coral farmers who depend on collection of fragments from the wild will need to progressively transfer production from branching species, to massive and encrusting species, and develop markets for these products. Fragments of branching corals will probably need to be supplied from source colonies held under controlled conditions in land-based facilities.

Where it is still possible to produce corals, giant clams and live rock in the sea, e.g. micro-sites at higher latitudes with suitable levels of aragonite saturation (Section 11.3.3.1), provision will need to be made to move stock ashore, or to much deeper water, before the onset of cyclones and storms.

The potential impacts of the projected environmental changes on the capture and culture of postlarvae is difficult to identify – the industry is based on a broad range of species but focuses on those that cannot be collected easily as adults. It is possible that a different but equally valuable 'scarce' suite of postlarvae may be available to harvest and grow under a changing climate.

Vulnerability

The broad range of marine ornamental products is expected to have differing vulnerabilities to climate change and acidification of the ocean. The changing environment is likely to have low, negative effects on the production of cultured corals and giant clams under the B1 and A2 emissions scenarios in 2035. However, enterprises growing these two products in shallow coastal habitats are likely to have moderate to high vulnerability to the changes projected to occur by 2100 unless they can find economical ways of developing land-based systems that ease the stress likely to be caused by higher SST and ocean acidification. The vulnerability of live rock producers is also expected to be moderate in 2035, increasing to high by 2100. It is not possible to determine the vulnerability of postlarval capture and culture operations, but it may be low.

11.3.2.5 Freshwater prawns

Exposure and sensitivity

- **Temperature:** Aquaculture of the introduced *Macrobrachium rosenbergii* occurs in the same general type of earthen freshwater ponds used for tilapia (Section 11.3.2.1) and is exposed to the same projected increases in water temperature relative to 1980–1999: 0.5–1.0°C for B1 and A2 in 2035, 1.0–1.5°C for B1 in 2100 and 2.5–3.0°C for A2 in 2100. The optimum temperature range for *M. rosenbergii* is 26–32°C and they become stressed below 22°C or above 34°C[82,211,212]. Freshwater prawns are less tolerant of temperature stresses than tilapia but more resilient than penaeid shrimp. Little is known about the temperature tolerances of the indigenous freshwaters prawns *M. lar*, apart from some observations reported by hobbyists which indicate a preferred range of 23–28°C. Occurrence of *M. lar* in montane river habitats (Chapter 7) indicates that this species may indeed have a lower preferred temperature range than *M. rosenbergii*.
- **Rainfall:** Projected increases in rainfall mean that freshwater prawn farming enterprises are likely to be exposed to greater risk of flooding, and more extreme rainfall events (Section 11.3.2.1, Chapter 2). Farming operations are sensitive to flooding because prawns escape when rising waters over-top or damage pond walls.
- **Sea-level rise:** Intrusion of saline water further inland (Chapter 3) is not expected to have a major impact on grow-out of *M. rosenbergii*, because it grows well in water of 5 PSU although survival decreases if salinity exceeds 10 PSU[213].
- **Cyclones:** Floods caused by more intense cyclones have the potential to damage ponds constructed for freshwater prawns. Such floods would also increase the risk of prawns escaping from ponds.
- **Habitat alteration:** The projected increased rainfall is expected to expand freshwater habitats in the tropical Pacific by up to 10% in 2035 and 20% in 2100 (Chapter 7). In turn, the greater availability of habitat is expected to augment production of freshwater fish and invertebrates in most PICTs by up to 2.5% in 2035, by 2.5–7.5% for B1 in 2100, and by 2.5–12.5% for A2 in 2100 (Chapter 10), where catchments are well managed. Because *M. lar* is a conspicuous part of the freshwater fauna in lowland areas, the abundance of wild juveniles is also likely to increase in line with these estimates.

Potential impact and adaptive capacity

The warming projected to occur by 2035 is not likely to adversely affect aquaculture of freshwater prawns in the tropical Pacific. Rather, the expected range of temperatures is likely to increase their rates of growth and survival. However, by 2100 warming in equatorial regions could result in pond temperatures in excess of 34°C at some times of year, and losses of production through increased stratification and heat stress. A more positive possible outcome by 2100 is that the warming temperatures could make culture of *M. rosenbergii* practical in subtropical areas.

The projected increases in rainfall should increase availability of fresh water and provide opportunities to farm *Macrobrachium* spp. in a greater range of locations. The possibility of a greater abundance of *M. lar* would make it easier to collect wild juveniles for grow-out operations. *Macrobrachium lar* also has the advantage that it is hardier than *M. rosenbergii*, and expected to be more resilient to stressful environmental conditions.

Adaptations to reduce the eventual adverse effects of warmer pond temperatures centre around locating and constructing ponds to create high rates of water turnover in the way described for tilapia and carp in Section 11.3.2.1, particularly as freshwater prawns do not directly rely on plankton blooms.

Future developments to capitalise on the potential of this commodity should be based on semi-intensive production to avoid creating the kind of host-pathogen-environment interactions that lead to disease and production losses (Section 11.3.4).

Although the protein requirements of *Macrobrachium* spp. are less than for penaeid shrimp, commercial enterprises will still depend on some fishmeal to formulate suitable diets. Thus, any effects of climate change on the global supply of fishmeal are likely to increase production costs. Freshwater prawn farmers could adapt by using fishmeal from the increased number of tuna canneries in the region (Chapter 12). Alternatively, any freshwater prawn farming enterprises established near major rivers in PNG could arrange with local fishers to use the unwanted introduced species common there (Chapter 10) to make local supplies of fishmeal. *Macrobrachium lar* appears to have lower dietary protein requirements than *M. rosenbergii*, although this needs to be confirmed by more research.

Vulnerability

Freshwater prawn aquaculture does not appear to be particularly vulnerable to climate change because it is currently a fledgling industry. However, any development of freshwater prawn farming in PICTs with sufficient domestic market demand to support commercial enterprises is expected to benefit from a low, positive effect on production under the B1 and A2 emissions scenarios in 2035. This assessment changes for 2100, when freshwater prawn farming is expected to have a low vulnerability to climate change.

11.3.2.6 Marine fish

Exposure and sensitivity

- **Temperature:** The exposure and sensitivity of the limited number of hatchery-based marine fish aquaculture operations in the region (Section 11.2.2.6) to the projected changes in SST (Chapters 2 and 3) are expected to be low in 2035. These operations rely on captive broodstock and often use environmentally controlled facilities to mature them, and rear the progeny, to the point where the juveniles are ready to stock into sea cages. The exposure and sensitivity of marine fish held in sea cages to the projected increase in SST is likely to be similar to the responses of demersal fish associated with coastal habitats, i.e. metabolic rates are expected to increase (Chapter 9). Depending on the species and location of operations, growth could be inhibited under the A2 emissions scenario by 2100.

Collection of wild juvenile rabbitfish (**Figure 11.12**) for grow-out to supply local markets is expected to be sensitive to increases in SST. The timing of spawning, and the survival and distribution of larvae of rabbitfish, can be expected to respond to changes in water temperature to some extent, although how this may affect existing distribution patterns of postlarvae remains to be determined. Whatever the distribution, the already great interannual variation in abundance of juvenile rabbitfish[90] is projected to increase due to the effects of higher SST on larval development (Chapter 9).

Figure 11.12 Juvenile rabbitfish (Siganidae) which settle in coastal habitats in the western Pacific in high but variable numbers each year (photo: Antoine Teitelbaum).

- **Rainfall:** Marine fish farming operations are expected to have only minor sensitivity to the projected reduction in the salinity of coastal waters stemming from increases in rainfall (Chapter 2). Although both hatchery and grow-out sites require sheltered areas with salinities of ~ 35 PSU, and the number of such sites will be reduced in the future, there should still be sufficient suitable areas in those PICTs that decide to engage in marine fish farming.
- **Ocean acidification:** Hatchery-based marine fish aquaculture operations growing fish in sea cages are not expected to be adversely affected by the projected acidification of the ocean (Chapter 3) because the survival and growth of demersal fish do not appear to be affected by reductions in pH of 0.1–0.3 units (Chapter 9).

On the other hand, there is the possibility that enterprises based on the collection of wild juveniles may be jeopardised by increasing variability in the supply of juveniles if ocean acidification has an adverse effect on the behaviour of larvae[154–156] (Chapter 9).

- **Sea-level rise:** Development of marine fish farming is likely to have only minor exposure to the effects of increases in sea level. However, some of the protection presently offered by coastal habitats, e.g. coral reefs and mangroves, that help create the sheltered sites needed for sea cages, may be reduced as sea level rises.
- **Cyclones:** Sea cages, hatcheries and other infrastructure involved in marine fish farming are already exposed to severe damage by storm surges and strong winds in PICTs where cyclones occur. The degree of additional potential damage likely to occur during stronger cyclones is difficult to assess – any cyclone near a marine fish farming enterprise is likely to cause major problems.
- **Habitat alteration:** Because the broodstock for prospective species for hatchery-based fish farming are likely to survive, even if widespread degradation of coral reefs occurs (Chapter 9), few adverse affects are expected for this type of aquaculture through habitat alteration. As warmer SSTs and increased ocean acidification degrade coral reefs (Chapter 5), macroalgae, which form a major part of the diet of rabbitfish[214], are expected to proliferate. This food source may boost the supply of wild-caught juveniles for rabbitfish farming.

Potential impact and adaptive capacity

Climate change and ocean acidification are expected to have relatively minor impacts on any development of marine fish farming in the region. Such enterprises would need to make comprehensive assessments of the suitability of local environmental conditions for establishment of hatcheries and sea cages, and markets, before investment occurs. Thus, any effects of projected climate changes on prospective marine fish species, or the infrastructure needed to produce them, can be taken into account during that process. A possible longer-term effect is that once sites are selected, fish may need to be fed a greater daily ration due to their higher rates of metabolism in warmer waters.

With the exception of siganids, optimum diets for cultured marine fish have a high fishmeal content[215]. The same concerns about the broader global effects of climate change on supply of fishmeal, and the possible adaptations to cope with periodic shortfalls in supply described for tilapia farming (Section 11.3.2.1), also apply to marine fish but would be more pronounced.

Vulnerability

The vulnerability of existing and future marine fish aquaculture in the tropical Pacific to climate change and ocean acidification is expected to be low under the B1 and A2 emissions scenarios in 2035, and under B1 in 2100, possibly increasing to low to moderate in 2100 under A2.

11.3.2.7 Sea cucumbers

Exposure and sensitivity

- **Temperature:** Projected increases in surface air temperature and SST (Chapters 2 and 3) are expected to cause changes in the reproduction and growth of *H. scabra* (sandfish), which may influence the efficiency of farming this species in ponds, and release of cultured juveniles in restocking and sea ranching initiatives. Growth rates in ponds in Vietnam[96] are much faster than those in New Caledonia[102], indicating that greater rates of production from ponds should be possible for *H. scabra* in areas away from the equator as these regions warm. In equatorial areas, however, rising temperatures may result in longer periods near the upper thermal limit for sandfish and higher mortality during warm months. Survival of small juvenile sandfish is lower at temperatures > 32°C[103].

  Possible upper lethal temperature limits of larger sandfish are indicated by total mortality of adults in ponds exposed to water temperatures of 35°C during trials in northern Australia. However, stratification of the water column due to freshwater influx is likely to have contributed to the mortality, and low dissolved oxygen levels probably exacerbated the temperature effects.

  Reproduction of *H. scabra* is linked to temperature because spawning can be induced year round within 10–12°N/S of the equator, but only for 3–4 months in New Caledonia (22°S). Culture of larval sandfish and grow-out of juveniles is recommended when temperatures are between 26°C and 30°C[99,216,217]. Thus warmer conditions should assist hatchery production in Fiji, Vanuatu and New Caledonia.

  Cultured sandfish released into shallow seagrass beds in sea ranching projects are likely to be adversely affected by increasing SST. Sandfish > 40 mm reduce burying activity at 29°C[218,219], increasing the time they are at risk of predation[220].

- **Rainfall:** Although sandfish are tolerant of salinities as low as 20 PSU[110], the culture of sandfish in ponds is likely to be affected negatively by the projected increases in rainfall in the tropics (Chapter 2) because reduced salinities are likely to increase the risk of stratification, resulting in potentially lethal low levels of dissolved oxygen. Plans to produce sandfish in ponds in New Caledonia may not be threatened in this way because rainfall is projected to decrease in the subtropics (Chapter 2). Sea cucumber larvae appear to be less tolerant of low salinities than adults[221], although this is not expected to be a problem because salinities can be managed in hatcheries.

- **Ocean acidification:** There has been no research on the effects of projected ocean acidification (Chapter 3) on sandfish. However, research on other sea cucumbers, and related sea urchins and starfish, suggest that sandfish may have some sensitivity to reduced concentrations of carbonate ions in sea water. In particular, the size and strength of the calcareous spicules in the outer layer of their skin is likely to be reduced as acidification of the ocean increases. Developing larvae are also known to be sensitive to changes in pH, for reasons yet to be explained[221,222].

- **Sea-level rise:** Where sandfish are grown in existing shrimp ponds, the projected increases in sea level (Section 11.3.2.2, Chapter 3) are expected to create difficulties in draining ponds (Section 11.3.3.3). However, where ponds are dedicated to producing sandfish, complete drying of ponds between production cycles may not pose the same problems as for shrimp farming because few nitrogenous feeds are used to grow sandfish and the harvest does not depend on rapid drainage of ponds.
- **Cyclones:** Sea ranching operations, which involve releases of juvenile cultured sandfish into seagrass beds[103], are likely to be highly sensitive to the effects of cyclones. Occurrence of a cyclone between release of juveniles and harvest is likely to reduce yields significantly because the resulting turbidity and wave action would inhibit burying[218]. Storm surges could also displace sandfish to unsuitable habitats and cause abrasion of sandfish, increasing the risk of disease and mortality.
- **Habitat alteration:** The projected changes in the area and leaf density of seagrass beds, due to the expected increases in SST, runoff and possibly storm surge (Chapter 6), would alter the quality and extent of suitable sites for releasing sandfish in sea ranching projects. Survival of juvenile sandfish released in the wild is strongly related to the quality of the site[103] (**Figure 11.13**).

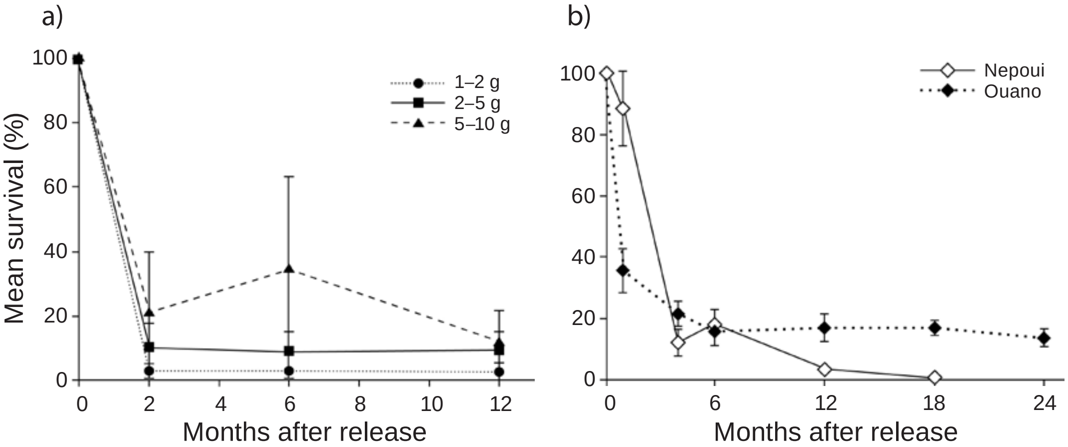


Figure 11.13 (a) Mean percentage survival of released juvenile cultured sandfish of different sizes after 12 months at two sites combined in New Caledonia; and (b) mean average survival of released juvenile cultured sandfish, weighing between 1 g and 20 g, after 24 months at two sites in New Caledonia; vertical bars are standard errors (source: Purcell and Simutoga 2008)[103].

Potential impact and adaptive capacity

The possible effects of climate change are expected to vary for the two most promising uses of hatchery-reared sandfish – sea ranching and farming in ponds. The warmer conditions are likely to enable juveniles to be produced in hatcheries year-round in more PICTs. On the other hand, hatchery production may be impeded by warmer conditions in equatorial areas. Similar considerations apply to growth and survival in ponds, and in sea ranching projects. Enterprises farming sandfish in ponds in subtropical areas are expected to benefit from faster growth rates with only modest risk of increased stratification of ponds. Conversely, without specialised management of ponds, sandfish in ponds in the tropics are likely to suffer high mortality due to the increased likelihood of stratification caused by higher rainfall and reduced salinity.

Higher water temperatures, reduced salinities and ocean acidification are expected to affect the success of sea ranching operations. In the tropics, higher SSTs and increased levels of runoff are projected to affect both the survival of sandfish and the quality of their seagrass habitats. In the subtropics, cyclones and storms will continue to pose the main climate-related direct and indirect risks to the profitability of sea ranching due to loss of juveniles and their seagrass habitats. Ocean acidification may reduce the fitness of released juveniles in both the tropics and subtropics, although further research is needed to assess the likelihood of this potential impact.

Adaptations can be made within hatcheries to control water quality, including temperature, salinity and pH, so no problems are anticipated in producing juvenile sandfish in the future. Methods have also been developed in Vietnam to avoid low salinities in ponds during the wet season. These methods include ensuring that pond stratification is avoided by mixing the water column during heavy rainfall, and maximising the turnover of sea water.

For sea ranching projects, careful selection of sites likely to maximise the survival of released juveniles will be an essential way of adapting to the changing environmental conditions. However, it may also be possible to select broodstock with progeny that are more tolerant to changing environmental conditions. If so, managers would either need to (1) limit sea ranching to the areas where such populations occur in order to preserve the existing differences in the genetic structure of sandfish populations[223,224]; or (2) permit releases anywhere to increase production and accept that sandfish resources would become more genetically homogeneous.

Adaptations to reduce the potential impact of ocean acidification on the growth and survival of sandfish will be difficult. If increased mortality due to acidification jeopardises the viability of sea ranching operations, production of sandfish may be limited to ponds, where 'liming' of pond substrate can help maintain pH at desired levels. However, substantial prices would need to be received for bêche-de-mer from pond-reared sandfish to adapt all sandfish production to pond farming systems. Most PICTs do not presently have an infrastructure of ponds and it is debatable whether purpose-built ponds would be profitable.

Vulnerability

The vulnerability of proposed sea ranching projects for sandfish in Fiji and New Caledonia to climate change and ocean acidification is projected to be low under the B1 and A2 emissions scenarios in 2035, and under B1 in 2100. The vulnerability of investments in sandfish farming and sea ranching in more tropical areas is expected to increase to low to moderate under A2 in 2100.

Sea cucumber pen damaged by a cyclone, Fiji

Photo: Cathy Hair

11.3.2.8 Trochus

Exposure and sensitivity

- **Temperature:** The projected changes in SST (Chapters 2 and 3) are not expected to cause any problems for hatchery-reared trochus released in restocking projects – laboratory experiments show that juvenile trochus recover quickly from heat stress when exposed to temperatures as high as 40°C[225].
- **Rainfall:** Trochus are distributed naturally in intertidal and shallow subtidal coral reef habitats[113] and can be expected to have similar salinity preferences as corals. Therefore, the projected increases in runoff from high islands in the tropical Pacific (Chapters 2 and 7) are expected to make some inshore reefs unsuitable for releasing trochus.
- **Ocean acidification:** There is uncertainty about how trochus acquire the calcium carbonate they use to construct their aragonite shells. There is some circumstantial evidence that they obtain some of it by scraping algae from the surface of dead coral with their toothed radula while feeding. This evidence comes from observations that trochus reared in tanks where coral rubble was added to

the substrate developed heavier shells than those in tanks without coral rubble. However, the improvements in shell strength may have been due to the greater abundance of diatoms on the increased surface area provided by the rubble. Even though shell strength can be improved by addition of coral rubble, shells of hatchery-reared trochus are still weaker than those of wild individuals[116], and have a different shape[226] (**Figure 11.14**). As a result of these shell deformations, projects releasing hatchery-reared trochus into the wild are already susceptible to high mortality rates[76,116]. If scraping dead coral surfaces does not help provide calcium for trochus to build their shells, ocean acidification can be expected to increase this mortality further.

- **Sea-level rise:** The projected changes in sea level (Chapter 3) are expected to affect the availability of the structurally complex intertidal and shallow subtidal habitats required by juvenile trochus[227], especially in locations where a greater depth of water makes the existing habitats unsuitable and steep terrain prevents the formation of new intertidal areas.

- **Cyclones:** Powerful waves have caused heavy mortality of transplanted trochus[228]. Therefore, the success of projects releasing trochus can be expected to be susceptible to cyclones. While the more intense cyclones projected to occur in the future are likely to kill many of the trochus on reefs, mortality may be proportional to the size of the shells and the time after release – as trochus grow they move into deeper water where both their size and the depth should increase their resilience to the effects of storms.

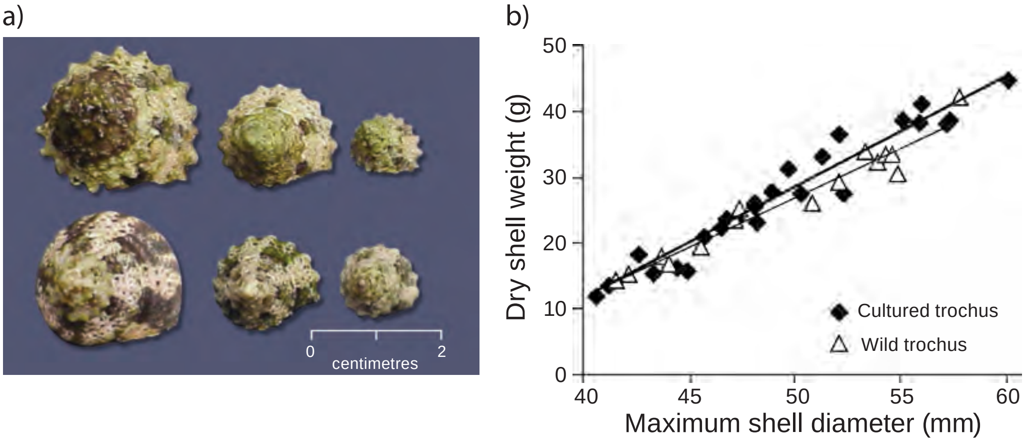


Figure 11.14 (a) Differences in shell shape of wild (upper) and hatchery-reared (lower) juvenile trochus (photo: Steven Purcell), and (b) variation in the relationship between basal shell diameter and shell weight for cultured and wild trochus (source: Clarke et al. 2003)[116].

- **Habitat alteration:** The projected effects of higher water temperatures, increased runoff and ocean acidification on coral reefs and other coastal habitats (Chapter 5) are not expected to have many adverse effects on the habitat for trochus. For example, juveniles often use 'rock pool' habitats with boulders and crevices in the intertidal zone, whereas adults graze algae from the surface of coralline rock and dead massive corals in subtidal areas[113]. Indeed, the degradation of coral reefs may provide more suitable habitat for trochus.

Potential impact and adaptive capacity

The projected changes to the salinity of coastal waters surrounding high islands in the tropics are expected to make some of the reefs previously occupied by trochus unsuitable for this species. On the other hand, degradation of coral reefs may well provide increased areas for colonisation of the algae grazed by trochus. Nevertheless, the projected combined direct and indirect effects of climate change on survival and growth of trochus are expected to have a minor, negative impact on the usefulness of restocking as a management measure for trochus fisheries. The reduced fitness of hatchery-reared animals for survival in the wild due to weakness of their shells remains a major obstacle. If this deficit is exacerbated by ocean acidification following release, the increased rates of predation expected to occur may mean that the benefits of releasing cultured juveniles rarely exceed the costs of producing them. Release of hatchery-reared juveniles is already considered to be less effective than re-distribution of adults as a method for replenishing severely overfished populations of trochus[76] and any additional effects of ocean acidification on released cultured juveniles may remove it as an option altogether.

An adaptation to improve the survival of cultured trochus released in the wild is to reduce the effects of shell deformities resulting from the hatchery process. Juveniles should also be released at sizes > 40 mm in areas that not only provide them with protection from predators but also with access to the coralline substrata they seem to need to construct the strongest shells possible[76,116]. Such areas are expected to increase as a result of the projected degradation of coral reefs (Chapter 5).

Vulnerability

Where the release of cultured juveniles provides the only option for restoring local stocks of trochus, restocking initiatives are expected to have low vulnerability to climate change and ocean acidification under the B1 and A2 emissions scenarios in 2035. Until the uncertainty about how trochus acquire calcium carbonate to construct their shells, and the possible effects of ocean acidification on this process, are resolved, vulnerability is also estimated to remain low in 2100 under both emissions scenarios.

11.3.3 Climate change, aquaculture and aquatic diseases

Plans to increase production of the commodities listed above through farming systems, or the release of cultured juveniles into the wild, are already exposed to an additional risk – the threat of disease. Disease is a greater consideration for aquaculture than for the capture fisheries described in Chapters 8, 9 and 10 because diseases can proliferate when aquatic animals and plants are reared in close proximity[229]. Some of the main diseases which threaten aquaculture in the tropical Pacific and worldwide are listed in **Table 11.4**. Climate change may increase the risk posed by disease through alterations in the distribution, prevalence and virulence of pathogens (bacteria, viruses, fungi and parasites), and changes in the susceptibility of the host species used to produce the commodities[230].

Ideally, the projected changes to disease risk should be added to the list of indirect threats which aquaculture is likely to be exposed to in the tropical Pacific as a result of climate change. However, this is not yet possible because the likely responses of existing diseases in the tropical Pacific, and those with the potential to spread here, are not well understood. Instead, we outline the main factors expected to cause changes in the distribution, prevalence and virulence of aquaculture diseases in the region to raise awareness of this potentially severe problem.

Table 11.4 Examples of common diseases of aquaculture commodities worldwide, and in the tropical Pacific.

Disease	Commodity
Epizootic ulcerative syndrome (EUS)[254]	Freshwater fish
Viral nervous necrosis (VNN)[255]	Marine fish
Koi herpes virus (KHV)[256]	Koi and common carp
White spot syndrome virus (WSSV)[237]	Shrimp (Penaeidae)
Taura syndrome virus (TSV)[237]	Shrimp *Litopenaeus vannamei*
Infectious hypodermal and hematopoietic necrosis virus (IHHNV)[237]	Shrimp *Litopenaeus vannamei, L. stylirostris*
White tail disease (WTD)[257]	Freshwater prawn *Macrobrachium rosenbergii*
Syndrome 93 vibriosis[65]	Shrimp *Litopenaeus stylirostris*
Syndrome 85[258]	Pearl oyster *Pinctada margaritifera* (French Polynesia)
Bacterial infection *Vibrio harveyi*[259]	Pearl oyster *Pinctada margaritifera* (Cook Islands)

11.3.3.1 Factors likely to increase the risk of diseases in the future

Globalisation

The increasing volume of international trade in live aquatic animals and their products has created new mechanisms for transboundary spread of pathogens. As a result, there is more potential for both known and unknown disease problems to arise quickly in any country's aquaculture sector, often with serious economic, social and ecological consequences[231]. Such diseases are often difficult or impossible to eliminate once established. The continued expansion of global trade can be expected to exacerbate these problems and the onus is on PICTs to improve biosecurity in line with international protocols[232,233]. All countries have a responsibility to guard against the intensification of aquaculture in a way that promotes the transfer of diseases. The concern is that unless aquaculture operations are well designed and managed, they can provide a platform for the emergence of serious pathogens[234], with consequences for neighbours and trading partners.

Environmental change

A delicate balance exists between the host, the pathogen and the environment; disturbing this balance can create opportunities for pathogens to proliferate. In particular, temperature fluctuations, salinity changes, low pH, low dissolved oxygen, habitat alterations and harmful algal blooms can stress the host and suppress its immune system[235]. Stress disturbs the normal functions of the host and promotes a series of 'stress responses' designed to restore homeostasis, which are not always effective. For example, an animal may increase production of stress hormones (corticosteroids) to help mobilise additional energy, but these stress hormones suppress the immune system, rendering the host more susceptible to disease. As a result, the incidence of disease outbreaks and rates of disease transmission often increase during changes to the environment. The host also becomes more susceptible to opportunistic infections. Particularly severe problems can occur when the environmental change not only stresses the host, but also favours the pathogen[117].

Many environmentally-induced disease problems are caused by obligate pathogens, which are an integral part of the ecosystem and normally exist in a biological cycle that involves association with one or more hosts. New diseases usually emerge as a consequence of a major shift in the environment of the pathogen due to anthropogenic influences – increases in temperature due to climate change are of particular concern in this regard.

The sequence of disease development also depends to a large extent on environmental factors. Virulence of the pathogen, disease resistance mechanisms of the host and the prevailing environmental factors determine the pathology in the host and the outcome of the disease development process[235]. Environmental perturbations can modulate this process significantly and lead to increased disease outbreaks and spread of diseases to new geographical areas.

11.3.3.2 Possible effects of climate change and ocean acidification on diseases

Climate change and ocean acidification have the potential to alter the host-disease relationships outlined above. In a recent survey, the World Animal Health Organisation found that 71 of its 126 member-states were 'extremely concerned' about the expected impact of climate change on animal disease. In fact, 58% of the members had already identified at least one disease associated with climate change that was new to their territory or had returned to their territory recently[236].

Warming of the climate and ocean acidification can be expected to alter the incidence of diseases of aquatic organisms directly by affecting the pathogens themselves, and indirectly by altering the biology of the hosts[238]. The modes of transmission and virulence of pathogens can also be influenced by climate change[239]. Under a changing climate, PICTs are likely to witness alterations in development and survival rates of pathogens, transmission of diseases and susceptibility of hosts.

11.4 Integrated vulnerability of the aquaculture sector

When the direct effects of the projected changes to water temperature, rainfall, ocean acidification, sea-level rise, cyclone intensity, and the expected indirect effects of alterations to habitats, are integrated it is evident that:

1. existing and planned aquaculture activities to produce tilapia, carp and milkfish in freshwater ponds for food security are likely to benefit from the anticipated changes to surface climate; and
2. aquaculture enterprises producing commodities for livelihoods in coastal waters are likely to encounter production problems due to changes projected to occur in the tropical Pacific Ocean (**Table 11.5**).

Aquaculture operations for tilapia, carp and milkfish are expected to benefit strongly from projected increases in temperature and rainfall, and to cope with other changes to the environment even though some are negative (**Table 11.5**). These projected benefits are expected to be apparent by 2035, and well established by 2100, especially under the A2 emissions scenario, when surface temperatures are expected to be 2.5–3.0°C higher, and rainfall 10–20% greater, in tropical areas relative to 1980–1999 (Chapter 2). A proviso is that the changing climate does not limit access to the ingredients needed to formulate appropriate diets for tilapia, carp and milkfish, particularly fishmeal.

The expected boost to freshwater pond aquaculture as a result of climate change by 2035 should also apply to freshwater prawns. However, this trend may be reversed by 2100 due mainly to the temperature sensitivity of freshwater prawns and the effects of higher temperatures on stratification of ponds.

Although some commodities for livelihoods are likely to benefit from the projected changes in specific environmental variables, when the effects of all variables are integrated most commodities dependent on coastal waters for hatchery production and/or grow-out are expected to incur production losses, albeit at a low vulnerability rating (**Table 11.5**). The exceptions are shrimp farming and seaweed culture. For shrimp farming in 2035, the expected benefits from the projected increases in water temperatures may well improve yields. For seaweed farming, the expected increases in SST and rainfall by 2035 are likely to mean that the industry has a moderate rather than low vulnerability to crop losses due to increased incidence of outbreaks of epiphytic filamentous algae and tissue necrosis.

By 2100, the effects of climate change and ocean acidification on all livelihood commodities are expected to be negative and their vulnerability increases (**Table 11.5**). Under the A2 emissions scenario, seaweed farming and production of marine ornamentals are likely to have a high vulnerability, and the culture of pearls a moderate vulnerability. Shrimp farming, marine fish farming and sea ranching/pond farming of sea cucumbers are expected to have a low to moderate vulnerability, while the vulnerability of trochus is rated as low until further research elucidates the mechanisms by which they acquire calcium carbonate to construct their shells.

Vulnerability does not necessarily imply that there will be overall reductions in productivity of these commodities in the future. Rather, it indicates that the efficiency of enterprises producing the commodity will be affected. Total production could still increase if the operations remain viable, albeit with reduced profit margins, and more enterprises are launched. For example, seaweed production targets that have been set for the next decade of 1000–2000 tonnes per year (engaging several hundred households) in both Fiji and Solomon Islands should still be achievable, but not necessarily in the same places or with the methods now in use.

11.5 Opportunities

11.5.1 New commodities

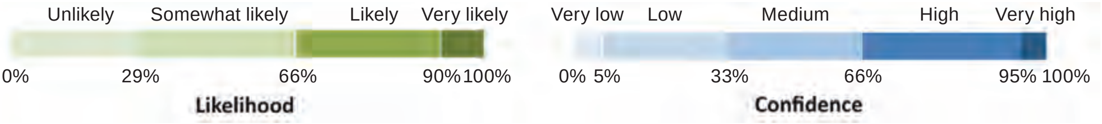
Pacific Island countries and territories are likely to have limited opportunities to produce new aquaculture commodities as a result of climate change, and other major drivers influencing the sector[240]. The development of markets for biodiesels as a renewable source of energy to replace fossil fuels is perhaps a possibility[241]. Marine algae have many advantages over land-based crops for producing biodiesel, including fast growth rates, high yields and no requirement for freshwater resources. Governments and enterprises around the world are now investing in research and development to reduce the operating and capital costs involved in large-scale culture of marine microalgae required to make production of biodiesel commercially viable.

Several PICTs, particularly those with atolls that have consistently high water temperatures and sunshine hours, and access to fertilisers (e.g. phosphate), may be in a position to convert part of their lagoons into the pond infrastructure needed to culture marine algae for biodiesel. Such operations are likely to be less affected by the projected increases in temperature because appropriate strains of microalgae can be selected or developed to suit the conditions.

Table 11.5 Projected direct effects of various features of climate change, and indirect effects due to habitat alteration, on the productivity of the main aquaculture commodities in Pacific Island countries and territories. Also shown is the overall vulnerability of these commodities, based on the integration of these effects, under the B1 and A2 emissions scenarios in 2035 and 2100. Note that specific and integrated effects can be negative (-) or positive (+). Likelihood and confidence estimates have been provided for each assessment.

Commodity	Specific effects						Vulnerability		
	Temp.	Rain-fall	Ocean acid.	Sea-level rise	Cyclones	Habitat alteration	B1/A2 2035	B1 2100	A2 2100
Food security									
Tilapia and carp	(+) 🟩🟦	(+) 🟩🟦	n/a	(-) 🟩🟦	(-) 🟩🟦	n/a	L (+) 🟩🟦	L (+) 🟩🟦	L (+) 🟩🟦
Milkfish	(+) 🟩🟦	(+) 🟩🟦	(-) 🟩🟦	(+/-) 🟩🟦	(-) 🟩🟦	(-) 🟩🟦	L (+) 🟩🟦	L (+) 🟩🟦	L (+) 🟩🟦
Livelihoods									
Pearls	(-) 🟩🟦	(-) 🟩🟦	(-) 🟩🟦	(+/-) 🟩🟦	(-) 🟩🟦	n/a	L (-) 🟩🟦	L (-) 🟩🟦	M (-) 🟩🟦
Seaweed	(-) 🟩🟦	(-) 🟩🟦	(+) 🟩🟦	(+) 🟩🟦	(-) 🟩🟦	n/a	M (-) 🟩🟦	M-H(-) 🟩🟦	H (-) 🟩🟦
Shrimp	(+/-) 🟩🟦	(-) 🟩🟦	nil 🟩🟦	(-) 🟩🟦	(-) 🟩🟦	n/a	L (+) 🟩🟦	L (-) 🟩🟦	L–M (-) 🟩🟦
Marine ornamentals	(-) 🟩🟦	(-) 🟩🟦	(-) 🟩🟦	(-) 🟩🟦	(-) 🟩🟦	(-) 🟩🟦	L (-) 🟩🟦	M (-) 🟩🟦	H (-) 🟩🟦
Freshwater prawn	(+) 🟩🟦	(+/-) 🟩🟦	n/a	(-) 🟩🟦	(-) 🟩🟦	(+) 🟩🟦	L (+) 🟩🟦	L (-) 🟩🟦	L (-) 🟩🟦
Marine fish	(-) 🟩🟦	(-) 🟩🟦	(-) 🟩🟦	(-) 🟩🟦	(-) 🟩🟦	(+/-) 🟩🟦	L (-) 🟩🟦	L (-) 🟩🟦	L-M (-) 🟩🟦
Sea cucumbers	(+/-) 🟩🟦	(-) 🟩🟦	(-) 🟩🟦	(-) 🟩🟦	(-) 🟩🟦	(-) 🟩🟦	L (-) 🟩🟦	L (-) 🟩🟦	L-M (-) 🟩🟦
Trochus	nil 🟩🟦	(-) 🟩🟦	? 🟩🟦	(-) 🟩🟦	(-) 🟩🟦	(+) 🟩🟦	L (-) 🟩🟦	L (-) 🟩🟦	L (-) 🟩🟦

Temp. = Temperature; Ocean acid. = ocean acidification; L = low; M = moderate; H = high; nil = no projected effect; ? = undetermined; n/a = non applicable.



Care will be needed in evaluating (1) the potential for rainfall to reduce salinities of ponds below acceptable limits in tropical areas; and (2) the effects of large-scale ponds on lagoon environments, noting that modification to such atolls to increase productivity have been suggested in the past[242]. Comprehensive assessments of the opportunity cost of these farming operations, for example loss of fishing areas and other social services normally provided by lagoons, will also be required.

New Caledonia plans to develop biosaline agriculture of halophytes like *Sarcocornia quinqueflora* on available salt pans as a source of food for people, and as a replacement for fishmeal in shrimp feeds. This initiative may also provide a potential source of biomass for biodiesel.

11.5.2 Harnessing new opportunities to expand production

Making the most of the potential benefits of the changing climate to increase production of freshwater commodities for food security will not only mean adapting production techniques, it will involve positioning producers to take advantage of local market opportunities. For example, enterprises growing tilapia in peri-urban areas will need incentives and strategies to market their product, so that they can help fill the expected shortfall in the supply of coastal fisheries for growing urban populations caused by progressive degradation of coral reefs (Chapters 5, 9 and 12).

Other opportunities to expand the production of existing aquaculture commodities are likely to emerge for small-holders, and also at the industry level. For example, small-holders could diversify ways of growing-out wild juvenile freshwater prawns *M. lar*, which are likely to be more abundant in the future (Section 11.3.3.5), by combining culture of these prawns with taro as freshwater habitats expand under the projected higher levels of rainfall (Chapter 7). The potential to diversify industrial shrimp farming to produce *P. monodon*, and perhaps other species, as coastal waters warm is described in Section 11.3.3.3.

11.5.3 Market instruments and climate change

Adaptations to make the most of the opportunities expected to be provided by climate change will need to go beyond the tasks of investing in production of promising new commodities, and expanding production of commodities favoured by the changing environmental conditions and local market place. Effective adaptations will also need to respond to international market forces, and related issues and actions arising from global concerns about climate change. Increased understanding of climate change in many of the larger developed countries importing aquaculture products is creating new marketing challenges. Below, we highlight some of the key factors that will need to be considered when developing plans to maintain and expand the benefits of aquaculture for PICTs in the face of climate change.

11.5.3.1 Carbon labelling

There is increasing interest in Europe and the USA in 'labelling' products with information on the amount of carbon dioxide released during manufacturing processes, and transport to markets, to indicate the 'carbon footprint' associated with the item[iv]. Products from aquaculture are unlikely to be exempt from this scrutiny – increasingly consumers can be expected to seek information on carbon to reduce the footprint of their purchases.

Of particular interest are the direct use of fossil fuels for production and transport, and the indirect use of fossil fuels associated with conversion of natural ecosystems (which may influence natural greenhouse gas sinks and reservoirs), construction, services, stock respiration and waste decomposition[243]. Intensive and semi-intensive farming systems have the highest energy consumption[244]. Small-scale, extensive systems producing seaweed and molluscs have the lowest energy consumption and carbon footprints, and may be net absorbers of CO_2.

The challenge for aquaculture enterprises will be to adapt, either through regulation or voluntary approaches, to meet the demands of the market. However, there will be limited scope to reduce carbon emissions associated with the long distances that commodities such as shrimp need to be shipped to international markets. This is likely to affect the competitiveness of products from PICTs. The concern over 'food miles' to date has not, however, taken into account the social and economic benefits of trade for poorer countries and communities[245]. Careful monitoring and attention to all dimensions of carbon labelling are needed to negotiate such market barriers, even for small producers[243]. Novel schemes of energy conservation and carbon offset through improved efficiency along the supply chain, marketing strategies, and better management of natural resources are required to develop new business models for the sector[246].

The issues described above are likely to compound the existing problems of low competitiveness due to distance from markets, and the relatively high labour costs and low economies of scale compared with Asian producers, already faced by aquaculture enterprises in the tropical Pacific. Although the implications of carbon labelling are expected to take some time to have an impact on the market place, because of the processes involved in standardising carbon auditing and applying labelling schemes equitably[247], PICTs should act now to integrate the effects of a changing global market place in their strategies to expand aquaculture.

11.5.3.2 Green labelling

The benefits of producing aquaculture products in an environmentally sensitive and sustainable way are already apparent to PICTs and various schemes have been promoted, e.g. certification by the Marine Aquarium Council[248,249], in the hope that

[iv] Carbon Trust (www.rpm-solutions.ca/CSR/CarbonFootprint_methodology_full.pdf)

conforming producers will receive more market share and/or premium prices. There is some doubt, however, about how certified production methods will influence the willingness of consumers to pay higher prices. For example, the higher rates of survival of captive-reared aquarium specimens compared with those taken from the wild appears to be an equally strong, if not stronger, factor influencing the purchases of some marine ornamental fish by hobbyists[48]. Nevertheless, innovative farming systems supplying products from well-maintained healthy ecosystems might be expected to attract higher prices in the future, especially if they also reduce carbon footprints. Where products must still be transported long distances, other features of the production system that are environmentally friendly may also attract consumers. Organically-produced tilapia and milkfish products, which have potential markets in Australia, New Zealand and United States of America, are in this category.

11.5.4 Financing options for future development

The aquaculture sector in PICTs could be assisted by the emerging opportunities for international financing to assist developing countries adapt to climate change (Chapter 13). There is also the possibility that some of the habitats that help underpin coastal aquaculture could be maintained by carbon offset schemes. Such opportunities may emerge because seafood is traded internationally in large volumes and has a significant carbon footprint compared with many other products from primary industry. Recent FAO/WorldFish estimates show that 3.7 teragrams (Tg) of CO_2 are released from air freight of seafood each year and 300–340 Tg of CO_2 from sea and land freight[250]. The offset of these CO_2 emissions may have substantial value in carbon trading markets. Estimates of actual values are now needed, together with an understanding of supply chain dynamics, efficiencies and opportunities for improvements. Seafood traders and larger buyers can then evaluate the potential for future reduction in carbon footprints through purchase of offsets in carbon sinks in coastal habitats, such as mangrove planting (if eligible).

Other schemes to remove carbon from the atmosphere, or prevent release of carbon, that become eligible under the international carbon trading system should also be evaluated to determine whether they provide opportunities to support aquaculture activities, and the ecosystems on which they depend.

11.6 Uncertainty, gaps in knowledge and future research

11.6.1 Commodities for food security

Given the potential importance of freshwater pond aquaculture in helping to provide the animal protein needed in the diets of inland communities in PNG, Solomon Islands and Fiji[4] (Chapters 1 and 12), there is a need to reduce the uncertainty about surface temperature and rainfall patterns at spatial scales relevant to this activity. In particular, information from the most recent set of global climate models needs to be downscaled to the level of river catchments, so that planners, managers and stakeholders can make the best possible assessments of projected conditions for efficient farming of tilapia, carp and milkfish.

Such research will not only enable PICTs to capitalise on the expected opportunities to increase production of freshwater fish commodities for food security (Section 11.3.1), it will also indicate which areas within countries and territories may not be suitable for this form of aquaculture.

Tilapia farming, Vanuatu

Photo: Paul Christian Ryan

Although downscaled information on surface climate and rainfall will identify the locations where pond aquaculture will be technically feasible in the future, PICTs also need reliable information to assess any potential impacts of fish introduced for farming on freshwater biodiversity. Such information will enable PICTs to weigh up the advantages and disadvantages of promoting pond aquaculture as a way of supplying animal protein to inland communities[5]. The design of research to provide this information will need to ensure that any effects of escaped fish on freshwater biodiversity are not confounded with changes to freshwater habitats caused by poor management of vegetation in catchments (Chapter 7). It will also be important to identify whether Nile tilapia has any effects on freshwater biodiversity over and above any impact attributed to *O. mossambicus*. This may be unlikely because the Mozambique tilapia *Oreochromis mossambicus* has long been established throughout many of the freshwater habitats in the region, and is potentially more invasive than the Nile tilapia *O. niloticus* because of its broader salinity tolerances[118].

11.6.2 Commodities for livelihoods

Downscaled projections for SST and rainfall will also be needed to plan how best to manage shrimp farming in the future. A key research question for the shrimp industry in New Caledonia, and of interest to other commodities, is how variability in temperature is likely to alter with global warming. In particular, downscaling to determine whether temperature fluctuations during the short 'spring' and 'autumn' seasons, which presently create stresses that lead to chronic shrimp mortality (Section 11.3.2.2) (**Figure 11.6**), are likely to be reduced over time or get worse. This information will be instrumental in decision-making about investment to develop the industry further.

Downscaled projections for SST and rainfall should also help identify the locations and timeframes where farming of the seaweed *Kappaphycus alvarezii* is likely to remain viable. These projections should help determine whether seaweed farming can be expanded to Vanuatu as temperatures warm. If so, gender-based, socio-economic research will be needed to find out if the relatively low incomes available from growing seaweed are likely to (1) meet the expectations of coastal communities; and (2) enable sufficient and regular production over the long term to facilitate establishment of enterprises to export the products.

Much uncertainty also surrounds the potential effects of ocean acidification on the aquaculture commodities produced in coastal waters to support livelihoods. Although there is medium to high confidence in the assessments that the survival and growth of pearl oysters, corals and giant clams are likely to be adversely affected by ocean acidification, it remains to be seen whether micro-sites can be located where the aragonite saturation levels stay within acceptable limits due to the buffering effects of nearby reefs and macrophytes. Locating such sites is also likely to be needed to maintain the quality of pearls. Given the great significance of pearl farming in the region, the experiments on the effects of ocean acidification on pearl quality are a priority. Possible effects of ocean acidification on the production of shrimp should also be investigated, although they are not expected to be particularly detrimental.

Experiments on the effects of ocean acidification are needed to determine if this process changes (1) the behaviour of postlarval milkfish and their recruitment success; and (2) the size and strength of spicules in sandfish. It would also be interesting to know whether the feeding behaviour of trochus confers some resistance to the projected decline in aragonite saturation levels.

11.6.3 Other important considerations

As outlined in Section 11.3.4, there are many reasons to be concerned that the abundance and virulence of the viruses, bacteria, fungi and parasites that routinely cause production losses in aquaculture may alter with the changing climate. Research should focus on determining the possible responses of known pathogens to global warming in the high-value pearl and shrimp industries, and identifying scenarios and developing mitigation strategies to manage any projected consequences.

A key gap in information across the region is the lack of accurate statistics needed to track and forecast the development of the sector. A uniform system is needed for collecting data on the quantities or volumes of commodities produced for commercial sale or subsistence, number of farm units, number and gender-balance of people employed part and full time, and export value. This system should be based on standardised methods, and is essential not only for planning development of the sector, but also for monitoring the effectiveness of adaptations to assist producers to capitalise on the opportunities presented by climate change, and to minimise the adverse effects. The system for data collection on production from aquaculture and sea ranching should also be designed in line with international protocols to provide the information required by FAO[251]. Strategies for collecting these data need to be assessed carefully. Where it is not practical to organise regular dedicated surveys, censuses and household income and expenditure surveys can be used to gather basic information[252].

The fledgling nature of many aquaculture commodities in the tropical Pacific means that the research required to reduce uncertainty should not be limited to investigating the effects of changes in environmental variables on production. In many cases, the primary need is to make the basic production methods more efficient and reliable. The knowledge available for optimising the survival of hatchery-reared sandfish released in the wild is a case in point. Although estimates of survival have been made for four sites in New Caledonia[103], reliable information is needed for other PICTs where governments wish to investigate the possible benefits of sea ranching sandfish. Allied to this is the need to produce better maps of the extent and quality of seagrass beds (Chapter 6), to assess the locations of suitable release habitats.

11.7 Management implications and recommendations

The onus is on the managers and stakeholders of aquaculture sectors across the region to adapt future activities to optimise the benefits and minimise the losses expected to occur under the changing climate – some commodities are expected to be easier to produce, and others more difficult. The aim should not be just to maintain the present level of activities, but to pave the way for the sector to continue to grow. The challenge is to re-align investment to harness the full potential of the more promising commodities, while assisting disadvantaged producers to adapt, either by changing their methods or diversifying into those commodities favoured by the changing climate. Failure to do so has a large opportunity cost.

In making judgements about where and how to invest in future development, priority should not be given only to potentially lucrative export commodities. Promoting and supporting the commodities for food security, and assisting small-holders to maintain viable operations for seaweed and marine ornamentals for as long as possible, will have great social benefits. Both activities aid marginalised communities with few other opportunities to earn income.

Collecting farmed *Kappaphycus* seaweed, Solomon Islands

Photo: Gideon Tiroba

In addition to forming alliances with regional technical agencies to undertake the activities described in Section 11.6 to reduce uncertainty and fill gaps in knowledge, there are a number of actions that PICTs can make to fulfil these goals. These actions are outlined below.

- Promote the benefits of freshwater aquaculture as a vehicle for supplying fish to growing human populations in (1) rural areas where it is not practical to provide better access to tuna and other large pelagic fish (Chapter 9), and (2) peri-urban areas where low-value tuna and bycatch are not landed by industrial fleets (Chapter 8). Until the research on the possible effects of Nile tilapia on freshwater biodiversity is complete, applying this method to help provide food security for rural communities and the urban poor should be limited to catchments where Mozambique tilapia is well established. Similar recommendations apply for carp farming in PNG. There is no need to promote pond aquaculture of tilapia in PICTs where supplies of coastal fish are expected to meet recommended consumption levels well into the future (Chapter 12).

- Support the development of pond aquaculture by (1) seeking expert advice and resources to design and construct the types of hatchery systems and networks that will allow fingerlings with fast growth characteristics to be distributed effectively, even to remote areas; (2) formulating cost-effective feeds for semi-intensive and intensive farming systems based on locally available ingredients wherever possible; and (3) increasing the knowledge and capacity of fisheries staff and extension officers for providing training in all forms of freshwater pond aquaculture, and post-harvest methods.

- Ensure that any ponds constructed for freshwater aquaculture near rivers, or in lowland areas, are situated where they will not be affected by the higher floods expected to eventuate as a result of projected changes to rainfall.

- Anticipate saltwater intrusion into freshwater ponds used to grow tilapia or *Macrobrachium* spp. located close to the coast and make provision to convert such ponds for milkfish farming or salt-tolerant tilapia where these fish already occur in the catchment and are well accepted as food fish.

- Identify micro-sites (close to existing coral reefs and seagrass meadows) where aragonite saturation levels are likely to remain high enough for good growth and survival of pearl oysters, and formation of high-quality nacre.

- Identify which existing shrimp ponds can be modified by elevating the walls and floor to continue to function under rising sea levels, and which ones will need to be abandoned in favour of new ponds further landward at higher elevations. Assess which alternative commodities could be produced in ponds that are no longer suitable for shrimp in ways that do not impede landward migration of mangroves and seagrasses.

- Reduce exposure of all commodities dependent on fishmeal (tilapia, carp, milkfish, shrimp, freshwater prawns, marine fish) to shortages in global supplies due to climate change and worldwide demand by (1) ensuring that processing plants for tuna in the region use the waste products to produce fishmeal with a high-protein content in efficient ways; (2) lobbying for priority access to local supplies of fishmeal; (3) using undesirable introduced freshwater fish species (e.g. walking catfish *Clarias batrachus*, climbing perch *Anabas testudineus*) in PNG to produce fishmeal; (4) progressively replacing fishmeal with alternative sources of protein; and (5) promoting Best Management Practice (BMP) for feeding farmed fish to increase feed efficiency.

- Fast track the completion of research needed to develop micro-particle feeds for shrimp to reduce dependence on *Artemia*.

- Map the location of all aquaculture activities and supporting infrastructure to identify any risks to operations posed by expected changes in environmental variables, increased storm surge, sea-level rise or pathogens. Valuable lessons can be learned here from the mapping of pearl oyster farms in Manihiki Atoll, Cook Islands[253].

- Assess designs of equipment and infrastructure for aquaculture and improve the resistance of these components to the effects of stronger cyclones.
- Strengthen national capacity and regional networks to adopt and implement aquatic biosecurity measures, including capacity for monitoring, detecting and reporting aquatic animal diseases, using international protocols[237], to prevent introduction of new pathogens. This will require cross-sectoral approaches involving fisheries, quarantine and environmental agencies[13].
- Maintain a watching brief on advances in aquaculture technologies in other regions to identify opportunities to diversify the sector in ways with potential to perform well under the changing climate. Consider transfer of such technologies, with the necessary biosecurity precautions, to increase the resilience of the sector.

A shrimp farm, New Caledonia

Photo: Yves Harache

- Ensure that any application of 'carbon labelling' initiatives for regional seafood products is treated equitably, and takes into account the special vulnerabilities of the economies of small and remote PICTs within the global market place. This may require assistance from regional trade organisations.
- Analyse the carbon footprints of aquaculture systems in the region, and investigate better ways to conserve energy, and market products, through improved efficiency along the supply chain, innovative strategies, and better management of natural resources. Use regional trade and preferential access agreements to facilitate this process.
- Promote mangrove replanting and wetland conservation programmes in suitable habitats (Chapter 6) to capture carbon and enhance the coastal habitats on which some aquaculture based on collection of wild-caught juveniles ultimately depends.

- Strengthen national capacity to manage the environmental issues related to development of aquaculture, such as application of Environmental Impact Assessment procedures that consider both present and future risks associated with specific proposals.

Development of independent capacity in these areas will be beyond the capability of some PICTs. For those countries and territories with an aquaculture sector, or the potential to develop one, it will be important to identify the alliances and partnerships that can help provide the necessary support. Collaboration with regional technical agencies will be a key strategy for effective implementation of the recommendations listed above.

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Chapter 12

Implications of climate change for contributions by fisheries and aquaculture to Pacific Island economies and communities

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> *'Climate change impacts could change resource access 'winners' and 'losers', at both the community and national level.'* (FAO 2008)[i]

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[i] FAO (2008) *Climate Change, Energy and Food*. High-level Conference on Food Security: Challenges of Climate Change and Bioenergy, 3–5 June 2008, Food and Agriculture Organization of the United Nations, Rome, Italy.

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12.1 Introduction

Throughout Pacific Island countries and territories (PICTs) there is broad recognition that fisheries and aquaculture make vital contributions to economic development, government revenue, food security and livelihoods[1–5] (Chapters 8–11). Indeed, the Pacific Plan[6] recognises that development of the region is linked to the effective management of fish, and the habitats that support them – *'development and implementation of national and regional conservation and management measures for the sustainable use of fisheries resources'* is a priority of the Plan. The Pacific Island Forum Leaders' Vava'u Declaration[ii] reinforces the need for responsible and effective stewardship of the region's fisheries resources. The objectives and strategies of fisheries agencies throughout the region also repeat the desire to use fish for the benefit of people within the context of sustainable development.

'The Future of Pacific Islands Fisheries' study[7] now provides a roadmap for harnessing the potential economic and social benefits of fisheries and aquaculture in the face of the many drivers influencing the sector. These drivers include population growth, urbanisation, globalisation of markets, international trade policies, the world food crisis and economic constraints.

It is also clear that the plans to optimise the benefits of fisheries and aquaculture for the region are likely to be affected by climate change (Chapters 2–11). Here, we assess the vulnerability of economic development, government revenue, food supplies and livelihoods derived from fisheries and aquaculture to climate change, and the implications for PICTs.

We begin by summarising the recent contributions of oceanic, coastal and freshwater fisheries, and aquaculture, to the region. We then explain the plans PICTs have to optimise these benefits and conclude by assessing the vulnerability of these plans to the main projected changes in production of fisheries resources and aquaculture due to climate change for 2035 and 2100 under a low (B1) and high (A2) emissions scenarios (Chapters 8–11).

To provide assessments for the medium term, we have used the projections for B1 in 2100 as a surrogate for A2 in 2050 (Chapter 1). In assessing the vulnerability of economic development and government revenue, we have focused mainly on the projected changes to skipjack tuna because this species dominates the catches of industrial fleets[8] (Chapter 8). For food security, we concentrate on the projected changes to coastal fisheries because they currently provide most of the fish eaten by people in Pacific communities[3] (Chapter 9). The projected effects of climate change on all fisheries resources and aquaculture (Chapters 8–11) have been considered in assessing the vulnerability of livelihoods.

[ii] www.forumsec.org.fj/pages.cfm/documents/forum-resolutions

12.2 Contributions to economic development and government revenue

12.2.1 Contributions from industrial tuna fishing

The tuna industry in the Western and Central Pacific Ocean (WCPO) is based on the four species of tuna described in Chapter 8 (skipjack, yellowfin, bigeye and albacore) and is characterised by large vessels owned by major fishing companies from distant water fishing nations (DWFNs) and from PICTs. Much of the catch is marketed by multinational fish trading corporations.

The amount of tuna caught in the WCPO has doubled over the past 20 years, from 1.2 million tonnes in 1988 to ~ 2.5 million tonnes in 2009. This growth is due mainly to an increase in the catches of skipjack tuna[8]. Although the fishery has always been dominated by fleets from DWFNs, the percentage of the total catch taken by domestic and locally-based vessels has increased substantially in the last couple of decades (**Figure 12.1**). In 2009, the total landed value of catches of the four main species of tuna from the WCPO was estimated at ~ USD 4.2 billion. Of this, 395,000 tonnes, worth USD 593 million (14.2%), were caught by fishing fleets from PICTs. In 2007, the volume of fish processed within PICTs was 300,000 tonnes, representing 12.5% of the catch from the WCPO.

The total catch of tuna in the WCPO comes from two separate fisheries (1) a surface fishery targeting schools of skipjack and juvenile yellowfin tuna using purse-seine and pole-and-line fishing methods to supply canneries in the Pacific, Asia and Europe; and (2) a longline fishery, which targets mature bigeye and yellowfin tuna for the Japanese sashimi trade and other high-value markets, and albacore for canning in American Samoa and Fiji. Much of the fishing occurs within the exclusive economic zones (EEZs) of PICTs, but also on the high seas (international waters) (Chapter 1).

The catches made by the surface fishery in the WCPO are around 10 times greater than those made by the longline fishery[8]. This trend has also occurred for catches within the EEZs of several PICTs in Melanesia and Micronesia (**Figure 12.2**), because these countries are located in the tropical waters preferred by the abundant skipjack tuna. Total catches by both fisheries in Melanesia and Micronesia are an order of magnitude higher than those in the cooler waters of Polynesia, where a greater percentage of the fish are caught by longlining (**Figure 12.2**).

12.2.1.1 Surface tuna fishery

Volume and value

Catches made by the surface fishery in the WCPO are based heavily on purse-seining – more than 85% of the catch is now landed by this fishing method. Skipjack tuna make up ~ 75% of the purse-seine catch and > 90% of the pole-and-line catch. Yellowfin tuna is the other important component of the purse-seine fishery, making up ~ 20% of the catch. Relatively small quantities of bigeye tuna are caught in the surface fishery, although catches have been increasing in recent years due to the widespread use of drifting fish aggregating devices (FADs) by purse-seine fleets (Chapter 8). The relative importance of skipjack, yellowfin and bigeye tuna in the total catch from the EEZs of PICTs[iii] reflects the proportions from the WCPO described above[iv].

Between 1999 and 2008, the overwhelming majority of the surface catch was taken in the EEZs of the Parties to the Nauru Agreement (PNA)[v] (**Table 12.1**). The average volumes and values of fish landed over this 10-year period are a reasonably good indication of the relative importance of the catches in each EEZ because they even out some of the El Niño and La Niña conditions that influence the distribution of skipjack tuna and fishing effort across the region (Chapter 8). Nevertheless, it should be noted that the average total catch and value for this 10-year period is now considerably lower than the more recent annual catches due to the increase in purse-seining operations (**Figure 12.3**).

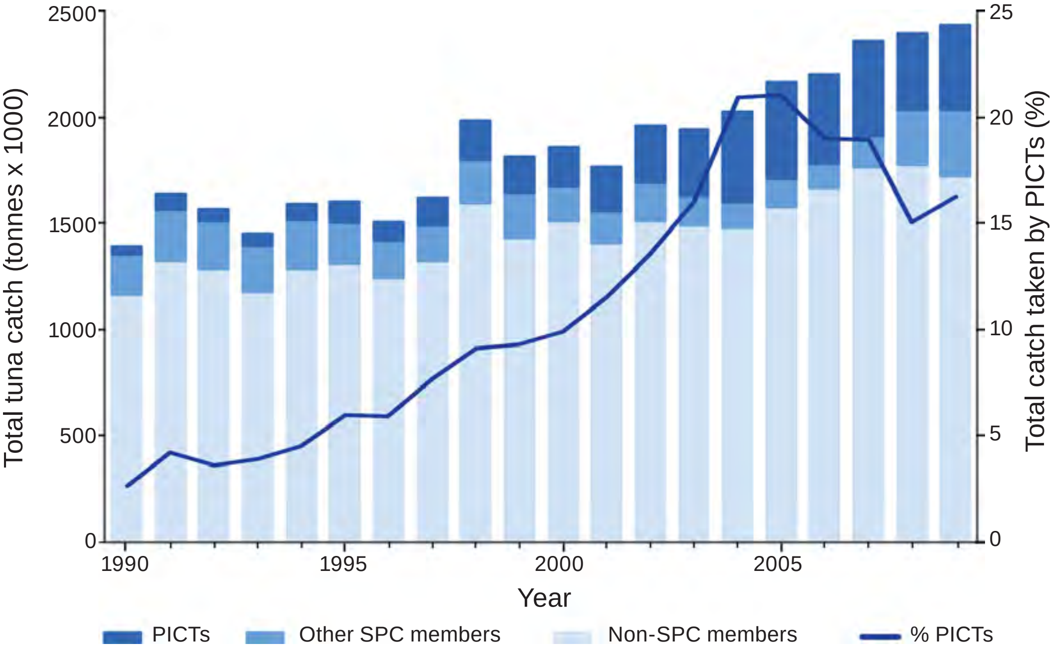

Figure 12.1 Catches of the four main species of tuna combined from the Western and Central Pacific Ocean between 1990 and 2009 taken by fleets operating from Pacific Island countries and territories (PICTs); other SPC members (mainly USA, but also Australia and New Zealand); and non-SPC members (mainly Indonesia, Philippines, and distant water fishing nations, notably Japan, Korea, China and Taiwan/ROC). The percentage of catch taken by PICTs each year is also shown.

[iii] The area approximating 25°N to 25°S and 130°E to 130°W (see **Figure 1.1** in Chapter 1).

[iv] See Supplementary Table 12.1, www.spc.int/climate-change/fisheries/assessment/chapters/12-supp-tables.pdf

[v] PNA members are: Federated States of Micronesia, Kiribati, Marshall Islands, Nauru, Palau, Papua New Guinea, Solomon Islands and Tuvalu (www.pnatuna.com).

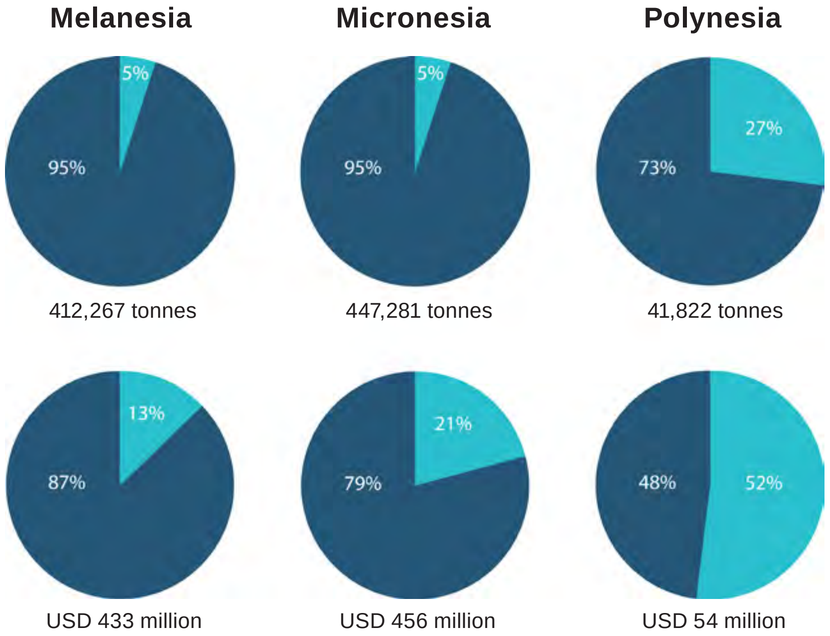

Figure 12.2 Average volume (tonnes), and average value (USD), of the total tuna catch from the exclusive economic zones of Pacific Island countries and territories in Melanesia, Micronesia and Polynesia taken by the surface (■) and longline (🟦) tuna fisheries over the period 1999–2008.

Striking trends within the surface fishery are that (1) catches by DWFNs within the EEZs of PICTs where the abundances of skipjack and yellowfin make industrial fishing economically viable usually far exceed those by domestic fleets; and (2) fleets flagged in the Federated States of Micronesia (FSM), Kiribati, Marshall Islands and Vanuatu catch far more tuna outside their EEZ (**Table 12.1**). In reality, however, some of these national fleets do not represent true domestication of the industry because vessels are registered in PICTs but are effectively owned and controlled by companies based elsewhere. Indeed, the recent decline in the percentage of the catch taken by PICTs (**Figure 12.1**) reflects re-flagging of some purse-seine vessels to other countries.

It is also important to note that, except for American Samoa and PNG, and to some extent Solomon Islands, the indicative port landings (**Table 12.1**) represent transshipments by vessels transporting fish to canneries outside the region.

The average annual value of tuna caught in the surface fishery by the national fleet in PNG exceeded USD 100 million between 1999 and 2008, and ~ USD 20 million in Solomon Islands (**Table 12.1**). However, these long-term averages mask recent trends[8]. The total value of tuna catches remained relatively static between 1999 and 2005 because oversupply of the global market depressed prices, but then increased substantially over the following three years when the price for canning tuna improved. For example, the average value of catches from the purse-seine fishery in PNG between 1999 and 2005 was USD 206 million, increasing to an average of USD 657 million from 2006–2008.

Table 12.1 The average annual catch and value of the surface tuna fishery for national fleets and foreign fleets in the exclusive economic zones (EEZs) of Pacific Island countries and territories (PICTs) where the fishery operated between 1999 and 2008. The average total volume and value of the catch made by national fleets across the Western and Central Pacific Ocean as a whole is also shown, together with average annual landings by national and foreign fleets at ports within PICTs. Note that New Caledonia, Commonwealth of the Northern Mariana Islands, Niue, Pitcairn Islands, Tonga and Wallis and Futuna are not included in this analysis because no catch was made in the EEZs of these PICTs by the surface fishery during this period. See Supplementary Table 12.1 for catch by species (www.spc.int/climate-change/fisheries/assessment/chapters/12-supp-tables.pdf).

PICT	Average annual catch (tonnes)			Average annual catch value (USD million)**			Average port landings (tonnes)***	
	National fleet		Foreign fleet	National fleet		Foreign fleet	National fleet	Foreign fleet
	EEZ	Region	EEZ	EEZ	Region	EEZ		
Melanesia								
Fiji	465	465	248	1.44	1.44	0.77	0	3939
PNG*	97,933	158,594	221,792	105	170.4	203	55,762	88,627
Solomon Islands*	20,829	22,369	13,446	19.7	21.1	46.7	8766	57,578
Vanuatu	0	43,523	77	0	43.5	0.06	0	193
Micronesia								
FSM*	3227	19,247	152,349	2.67	15.9	126	9796	196,053
Guam	0	0	17	0	0	0	0	0
Kiribati*	335	5332	180,851	0.28	4.52	153	132	61,068
Marshall Islands*	2756	35,777	22,530	2.44	31.7	20.0	32,511	121,524
Nauru*	0	0	63,063	0	0	52.4	0	2115
Palau*	0	0	1815	0	0	1.83	0	203
Polynesia								
American Samoa	0	0	49	0	0	0.04	0	107,620
Cook Islands	0	0	650	0	0	0.44	0	0
French Polynesia	623	636	80	0.52	0.53	0.07	172	87
Samoa	0	0	60	0	0	0.03	0	363
Tokelau	0	0	2664	0	0	2.00	0	0
Tuvalu*	0	0	26,379	0	0	22.6	0	0

* Parties to the Nauru Agreement; ** represents ex-vessel value calculated using the approach taken by Gillett (2009)[4], where prices provided by FFA (2009)[69] are discounted by 15% to account for transshipping costs with the exception of the locally-based fleet in PNG where no product is transshipped and therefore no discount is applied; *** representative values only, derived from logsheet, port sampling and landings data.

Contributions to gross domestic product and government revenue

Although large catches are made by the surface fishery in the EEZs of several PICTs, contributions to gross domestic product (GDP) are affected by whether the catches are landed in the country and, if they are landed, by the size of the national economy.

In PNG, where the national economy is large in regional terms, the significant surface fishery in the EEZ (which dominates catches from the western Pacific) averaged only 1.5% of GDP from 1999–2008, although it was 2.8% at the end of this period (**Table 12.2**). For the economies of Solomon Islands and FSM, the surface fishery made up 2.3% and 3.3% of GDP over the 10-year period, respectively, and increased to 3% for Solomon Islands in 2007 (**Table 12.2**).

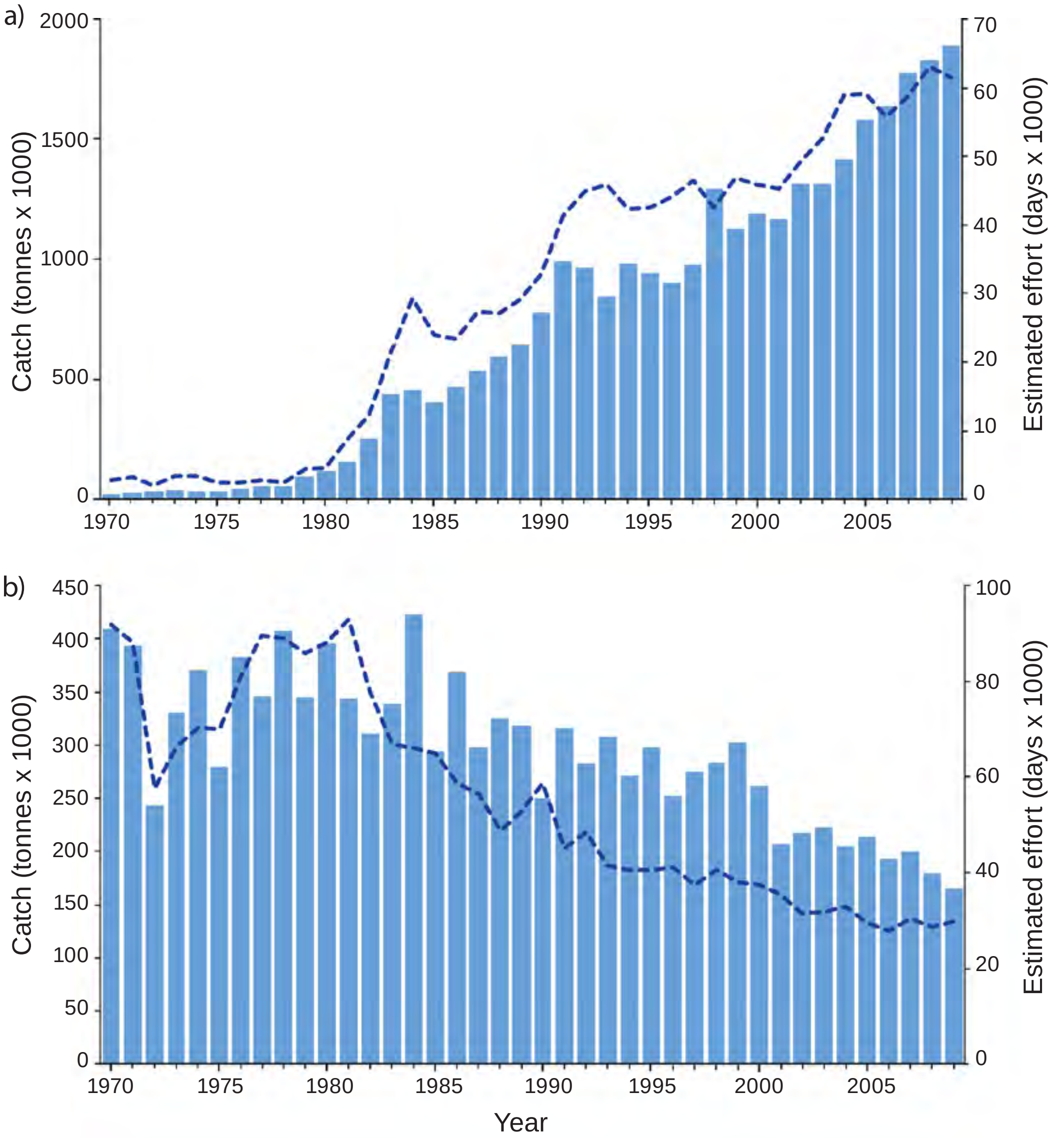

Figure 12.3 Changes in catch (columns) and effort (dashed line) by (a) the purse-seine fleet, and (b) the pole-and-line fleet, in the surface fishery for tuna in the Western and Central Pacific Ocean between 1970 and 2009 (source: Williams and Terawasi 2010)[8].

Contributions of the surface fishery to GDP have been greatest in the Marshall Islands, where they averaged > 10% over the 10-year period and were 21% in 2007 (**Table 12.2**). These substantial contributions are due to the large size of the local purse-seine fleet, and the limited opportunities for other economic activities in this small atoll nation. Despite the fact that purse-seine vessels flagged in Kiribati and Vanuatu make substantial catches within the region, the boats are not locally based and, according to international guidelines for calculating GDP, make no contribution to national GDP[4]. Similarly, vessels that offload to the cannery in American Samoa are not considered to be locally based – they come to Pago Pago primarily to discharge their catch[4].

It is important to note that the contributions from the surface fishery to GDP described above relate to fishing operations only and do not include any post-harvest activities. However, processing can be a significant part of GDP in some PICTs. American Samoa provides the best example, where the recent value of manufacturing outputs was 22.3% of GDP[9], worth around USD 100 million. When the value of post-harvesting of tuna is added to the fishing operations in Solomon Islands, the combined contribution to GDP increases to 4.6%, worth USD 22 million[10].

Whereas the surface fishery contributed to the GDP of relatively few PICTs, 15 countries and territories received fees from DWFNs for their purse-seine and pole-and-line fleets to fish within national EEZs[4,11] (**Table 12.2**). The payment of access fees by DWFNs is not captured in GDP calculations as it is a transfer of funds from outside the domestic economy. In 2007, access fees ranged from USD 132,000 for Tonga to USD 21.4 million for Kiribati (**Table 12.2**)[vi].

Foreign access fees are of great importance to many PICTs – they contributed between 3% and 42% of total government revenue for seven countries and territories in 2007 (**Table 12.2**). They are particularly important to the smaller economies within the PNA (Kiribati, Nauru and Tuvalu), and to FSM. Indeed, in some of these PICTs, government revenue exceeds GDP (**Table 12.2**). The level of access fees reflects both the distribution of fishing effort and catches – fees are normally negotiated as a percentage of the value of catches in the EEZ – as well as national policies. In certain PICTs, e.g. Tonga, some fees are received as a result of being part of the multilateral treaty between the US and members of the Forum Fisheries Agency[vii], even though no or very little catch is taken in their EEZ. Several other PICTs, including the French territories, do not generally favour access agreements and reserve part or all of the fishery for locally-based vessels.

Some governments also gain revenues from a variety of sources associated with purse-seine and pole-and-line fishing activity, including transshipment revenues and

[vi] See Supplementary Table 12.2 for access fees paid in other years, www.spc.int/climate-change/fisheries/assessment/chapters/12-supp-tables.pdf

[vii] Members of FFA are: Cook Islands, Federated States of Micronesia, Fiji, Kiribati, Marshall Islands, Nauru, Niue, Palau, Papua New Guinea, Samoa, Solomon Islands, Tokelau, Tonga, Tuvalu, Vanuatu, together with Australia and New Zealand.

licence fees paid by operators of domestic tuna vessels[4]. These revenues vary among countries but are usually less than access fees from DWFNs as a percentage of catch value.

Table 12.2 Contributions of the surface tuna fishery to gross domestic product (GDP), and total government revenue (GR) through payment of access fees by distant water fishing nations, to Pacific Island countries and territories (PICTs) in USD, and in percentage terms. Contributions to GDP relate only to fishing operations and do not include post-harvest activities. See Supplementary Table 12.2 for sources of estimates for GDP and GR and contributions to GDP and foreign access fees for other periods (www.spc.int/climate-change/fisheries/assessment/chapters/12-supp-tables.pdf).

PICT	GDP	Contribution to GDP				Total government revenue	Foreign access fee revenue 2007*[a]	
		Locally based purse-seine and pole-and-line fleets						
		Estimate based on 1999–2008 average		2007*				
	USD million	USD million	% GDP	USD million	% GDP	USD million	USD million	% GR
Melanesia								
Fiji	3290	0.7	0.02	0	0	920	0.26[b]	< 0.1
New Caledonia	8829	0	0	0	0	996	0	0
PNG	5708	85.2	1.49	161	2.82	2599	14.97[b]	0.6
Solomon Islands	457	10.5	2.31	14	3.07	267	11.76[b]	4.4
Vanuatu	500	0	0	0	0	79	1.36	1.7
Micronesia								
FSM	237	7.9	3.35	7.8	3.28	145	14.76	10.2
Guam	3679	0	0	0	0	428	0	0
Kiribati	71	0	0	0	0	51	21.36	41.9
Marshall Islands	156	15.8	10.16	32.7	20.95	93	1.95	2.1
Nauru	22	0	0	0	0	30	6.13[b]	20.4
CNMI	633	0	0	0	0	193	0	0
Palau	157	0	0	0	0	36	1.12	3.2
Polynesia								
American Samoa	462	0	0	0	0	155	0	0
Cook Islands	211	0	0	0	0	86	0.26[b]	0.3
French Polynesia	5478	0.3	< 0.01	nea	nea	865	0	0
Niue	10	0	0	0	0	12	0.26[b]	2.2
Pitcairn Islands	nea	0	0	0	0	7	0	0
Samoa	524	0	0	0	0	168	0.26[b]	0.1
Tokelau	nea	0	0	0	0	13	1.48[b]	11.4
Tonga	238	0	0	0	0	76	0.13[b]	0.2
Tuvalu	15	0	0	0	0	31	3.45	11.1
Wallis and Futuna	188	0	0	0	0	nea	0	0

* Derived from Gillett (2009)[4]; a = estimates are for aggregate access fee revenues for foreign pole-and-line, purse-seine and longline fleets as provided by Gillett (2009)[4]; b = PICTs which did not receive access fee revenues from foreign longline fleets between 2006 and 2008 or which usually receive > 90% of their total access fee revenue from foreign fleets operating in the surface fishery; nea = no estimate available.

12.2.1.2 The longline fishery

Volume and value

Longline vessels operate more widely across the WCPO than the purse-seiners in the surface fishery, and much of the catch from this lower volume/higher value fishery is taken outside the EEZs of PICTs in international waters[8]. Nevertheless, national longline fleets from 15 PICTs operate within their own EEZs, and relatively large catches (1400–6600 tonnes per year) are made by Cook Islands, Fiji, French Polynesia, New Caledonia, PNG and Samoa (**Table 12.3**). Longline fleets from several PICTs also fish elsewhere in the region. For example, vessels from the six PICTs listed immediately above take > 50% of their total catches outside their EEZs, and the fleet from Vanuatu takes > 85% of its landings in this way (**Table 12.3**).

Longline fishing by fleets from DWFNs spans an even greater number of PICTs. Longline vessels from DWFNs have operated at some stage in the EEZs of most of the 22 countries and territories, although catches from the waters of six PICTs are < 10 tonnes per year (**Table 12.3**). Catches by DWFNs are lower than the national fleet within the EEZs of nine PICTs and greater than those by the national fleet in 13 PICTs. Catches by DWFNs relative to the national fleet are particularly high in FSM, Kiribati, Marshall Islands, Palau, Solomon Islands and Vanuatu (**Table 12.3**). The most significant longline catches by DWFNs are made in Kiribati, where they averaged 8800 tonnes per year between 1999 and 2008.

Several PICTs land the majority of their longline catch at their own ports, although the Samoan vessels land much of their fish in American Samoa. Fleets from DWFNs mainly offload their catch in Fiji and American Samoa, although Palau, Marshall Islands, FSM and French Polynesia are also used to land large catches (**Table 12.3**). Albacore and yellowfin tuna dominate the catch in Melanesia, whereas bigeye and yellowfin tuna are caught most commonly in Micronesia, and albacore in Polynesia[viii].

Contributions to gross domestic product and government revenue

The lower volumes and values of fish caught by the longline fishery compared to the surface fishery (**Figure 12.2**) result in much more limited contributions to GDP and government revenue from longlining in most PICTs[ix]. In 2007, contributions to GDP from locally-based longline fleets ranged from 0.05–0.7% for 10 PICTs, however, they were significant for Niue (3.7%), Palau (3.4%) and Marshall Islands (2.0%)[4].

The contributions to government revenue from access fees paid by DWFN longline fleets are hard to estimate because they are often tied together with the fees for the surface fishery (**Table 12.2**). Access fees from longlining appear to have contributed ~ 6% of annual government revenue in Kiribati and > 1% in Cook Islands, FSM and Marshall Islands[11].

[viii] See Supplementary Table 12.3 (www.spc.int/climate-change/fisheries/assessment/chapters/12-supp-tables.pdf).

[ix] See Supplementary Table 12.4 (www.spc.int/climate-change/fisheries/assessment/chapters/12-supp-tables.pdf).

Table 12.3 The average annual catch and value of the longline tuna fishery for national and foreign fleets in the exclusive economic zones (EEZs) of Pacific Island countries and territories (PICTs) where the fishery operated between 1999 and 2008. The average total volume and value of the catch made by national fleets across the Western and Central Pacific Ocean as a whole is also shown, together with average annual landings by national and foreign fleets at ports within PICTs. See Supplementary Table 12.3 for catch by species (www.spc.int/climate-change/fisheries/assessment/chapters/12-supp-tables.pdf).

PICT	Average annual catch (tonnes)			Average annual catch value (USD million)*			Average port landings (tonnes)**	
	National fleet		Foreign fleet	National fleet		Foreign fleet	National fleet	Foreign fleet
	EEZ	Region	EEZ	EEZ	Region	EEZ		
Melanesia								
Fiji	6641	10,785	196	17.75	28.56	0.5	9995	11,274
New Caledonia	1840	1879	8	0	5.41	0	1673	16
PNG	2763	2769	134	10.65	10.68	0.44	2178	107
Solomon Islands	519	529	4186	2.33	2.37	12.54	496	140
Vanuatu	953	7156	4237	2.46	18.11	10.02	8	36
Micronesia								
FSM	592	978	5553	3.15	5.19	26.05	567	1281
Guam	0	0	0.3	0	0	0	0	56
Kiribati	0.6	5.9	8808	0.04	0.04	37.82	0	44
Marshall Islands	50	49	2921	0.3	0.3	14.4	54	2293
Nauru	5.2	5.2	1.4	0.02	0.02	0.01	0	0
CNMI	0	0	0.1	0	0	0	0	0
Palau	26	26.1	2380	0.14	0.13	12	19	3299
Polynesia								
American Samoa	0	0	407	0	0	0.95	2630	10,284
Cook Islands	1432	1567	72	3.56	3.95	0.16	176	31
French Polynesia	4355	4626	294	12.17	12.26	1.03	3639	1078
Niue	55	55	18.3	0.15	0.16	0.04	46	16
Pitcairn Islands	0	0	0.5	0	0	0	0	0
Samoa	2867	3531	3	6.45	7.99	0	843	109
Tokelau	0	0	5.5	0	0	0.02	0	0
Tonga	852	981	137	0.26	2.83	0.31	725	19
Tuvalu	0	0	651	0	0	2.32	0	2

* Represents ex-vessel value calculated using the approach taken by Gillett (2009)[4], where prices provided by FFA (2009)[69] are discounted by 30% to account for transportation costs and increased by 10% to account for bycatch sales. Cook Islands is the exception due to the atypical marketing channels for the fish caught there; ** information provided by SPC Oceanic Fisheries Programme.

12.2.2 Plans to increase contributions from industrial tuna fishing

For decades, PICTs have identified the region's tuna resources as one of their major assets – in the case of some countries it would seem to be the only renewable natural resource which can support economic development[12].

From the 1950s to the 1970s, operational bases for US and Japanese fishing and processing companies were established in American Samoa, Fiji and Solomon Islands. Despite some changes of ownership, these facilities are still important centres for processing tuna. In the 1980s and 1990s, several other PICTs set up national tuna fishing companies, however, none of these government-owned operations proved to be profitable on a sustained basis due to a range of operational and management problems. Locally-owned longline fishing operations were also established by the private sector in a number of PICTs in the 1990s, mainly in the south of the region. These operations enjoyed greater success but have faced difficult economic conditions in recent years and only well-managed companies in favourable locations have survived[13].

Since the 1980s, however, the tuna industry in the WCPO has been dominated by two trends (1) the growth of the purse-seine fishery, using large capital-intensive vessels which can range throughout the region and transship their frozen catches for transport to markets anywhere in the world (**Figure 12.3**); and (2) the development of large efficient tuna processing hubs in countries like Thailand and the Philippines, with plentiful low-cost labour. Many Pacific Island countries facilitated this development through their willingness to sell access to their EEZs in exchange for much-needed government revenue. As a result, the majority of the catch is still taken by foreign vessels and shipped outside the region for processing.

In the last decade there has been renewed interest by a number of PICTs in capturing wider economic benefits from tuna resources, particularly employment, by attracting foreign investment into locally-based fishing and processing operations. This has been encouraged recently by the 'DevFish' project[x] funded by the European Union (EU), which has demonstrated that the economic gains for PICTs from a tonne of tuna caught in the region are much greater from locally-based longlining or purse-seining operations when the catches are landed for processing onshore[14,15]. In the last three years alone, > USD 60 million has been invested in new tuna processing plants in the region[16] and several new facilities are proposed – mainly in PNG and Solomon Islands.

Although the opportunities to increase total catches are limited, it is now apparent that each additional 100,000 tonnes of tuna retained from the surface fishery for processing in the region can create ~ 7000 new jobs[17]. This is an important consideration in PICTs where population growth has outpaced the rate at which jobs are created. However, the tuna industry is a globalised business and responds quickly to opportunities created by changes in the economic environment, as well as to technological advances. Therefore, investments in the region are sensitive to the prevailing economic conditions. Recent examples include the Interim Economic Partnership Agreement (IEPA) between PNG and the EU, which has promoted increased investment, and the mandated minimum wage rates in American Samoa, which threaten the future of both the long-established canneries there[18].

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[x] www.ffa.int/devfish

The eight PNA countries are currently exploring collective ways to promote development of domestic tuna industries, including a possible tuna corporation or cartel[19]. This grouping, which has often led regional fisheries initiatives, established an independent office in Marshall Islands in 2010 to further the interests of its members. It must be recognised, however, that large-scale onshore processing is only viable in those few PICTs with adequate land and fresh water, and low labour costs. Other mechanisms, such as transferring the nominal ownership of fishing vessels to Pacific Island governments, have yet to demonstrate economic benefits and may prove to be less advantageous than access agreements in some cases.

12.2.3 Contributions from coastal fisheries

Coastal fisheries include a range of fishing methods that catch demersal fish (bottom-dwelling fish associated with coral reef, mangrove and seagrass habitats), nearshore pelagic fish, and a wide variety of invertebrates (Chapter 9). Although much of the fishing effort is by subsistence fisheries (Section 12.3), several species of demersal fish, nearshore pelagic fish and a limited range of invertebrates are also caught for sale at local markets and, in some cases, for export (e.g. sea cucumbers, trochus, aquarium fish and deepwater snappers). Fishing operations are typically artisanal and small-scale, with boats and other assets often owned by the fishers themselves.

Volume and value

In 2007, the total catch of commercial coastal fish and invertebrates from the region was estimated to be almost 45,000 tonnes, with a landed value of USD 165 million[4] (**Table 12.4**). Demersal fish are estimated to make up ~ 60%, nearshore pelagic fish 32% and invertebrates 8% of the total commercial catch (Chapter 9). However, these calculations underestimate the importance of sea cucumbers (exported as processed bêche-de- mer) because the weight of bêche-de-mer is usually < 10% of live weight[20]. In 2007, ~ 1500 tonnes of bêche-de-mer were exported from the region (Chapter 9) and so another ~ 13,500 tonnes needs to be added to the live weight of invertebrates caught. When the total catches from the three categories of coastal fisheries in **Table 12.4** are adjusted for the live weight of sea cucumbers, the invertebrates make up ~ 30% of the total catch. Based on the overall landed values of coastal commercial and subsistence catches for the region in 2007[4], the important contribution of high-value bêche-de-mer to commercial catches makes the average landed value of commercial coastal fisheries products (~ USD 3.70 per kg), twice that of fish and invertebrates caught for subsistence (~ USD 1.80 per kg).

Contributions to gross domestic product and government revenue

Due to the relatively high value-added ratio for small-scale fishing operations, coastal fisheries are estimated to have contributed ~ USD 105 million to the combined GDP of PICTs in 2007[4] (**Table 12.4**). Although the contributions to GDP from coastal fisheries are dwarfed by those from the surface tuna fishery in Marshall Islands, PNG and Solomon Islands, and are somewhat lower for FSM, they exceed those from the surface tuna fishery in the other 18 PICTs (**Tables 12.2** and **12.4**). In the case of some of the latter PICTs, this is because the catch from the surface fishery by DWFNs does not

Table 12.4 Estimated annual catches of the main components of commercial coastal fisheries (demersal fish, nearshore pelagic fish, targeted invertebrates) in 2007, together with the total volume and value of the catch. Contribution of the total commercial catch to GDP for Pacific Island countries and territories (PICTs), calculated by the value added ratio used by Gillett (2009)[4], is also shown. See Chapter 9 for the method used to estimate the catches of commercial demersal fish, nearshore pelagic fish and invertebrates. See Supplementary Table 12.2 for source of GDP estimates at each PICT (www.spc.int/climate-change/fisheries/assessment/chapters/12-supp-tables.pdf).

PICT	GDP (USD million)	Commercial coastal fisheries catch						
		Demersal fish (tonnes)	Nearshore pelagic fish (tonnes)	Inverte-brates (tonnes)	Total catch (tonnes)	Total value (USD million)	GDP con-tribution (USD million)	% GDP
Melanesia								
Fiji	3290	6210[a]	2660	630	9500	33.75	18.56	0.56
New Caledonia	8829	840	210	300[b]	1350	8.69	5.65	0.06
PNG	5708	2640	1760	1300[c]	5700	27.03	16.99	0.30
Solomon Islands	457	1050[e]	1250[d]	950	3250	3.31	2.19	0.48
Vanuatu	500	280[e]	188	70	538	2.18	1.52	0.30
Micronesia								
FSM	237	1660	1110	30	2800	7.56	5.67	2.39
Guam	3679	14	30	0	44	0.19	0.12	0.00
Kiribati	71	5430[e]	1510	60	7000	18.49	12.02	16.93
Marshall Islands	156	567[e]	380	3	950	2.90	2.17	1.39
Nauru	22	100	100	0	200	0.84	0.50	2.29
CNMI	633	115[e]	116	0	231	0.95	0.60	0.09
Palau	157	460	305	100	865	2.84	1.99	1.27
Polynesia								
American Samoa	462	24	11	0	35	0.17	0.11	0.02
Cook Islands	211	53[e]	80	0	133	1.03	0.67	0.32
French Polynesia	5478	1566[e]	2332	104	4002	23.00	12.65	0.23
Niue	10	5	5	0	10	0.06	0.03	0.30
Pitcairn Islands	nea	5	0	0	5	0.04	0.02	nea
Samoa	524	2479	1650	0	4129	19.56	15.65	2.99
Tokelau	nea	0	0	0	0	0	0	nea
Tonga	238	3330[f]	370	0	3700	11.29	6.98	2.93
Tuvalu	15	147	79	0	226	0.62	0.28	1.87
Wallis and Futuna	188	83	21	17	121	1.21	0.78	0.42
Total		**27,058**	**14,167**	**3564**	**44,789**	**165.69**	**105.15**	

a = Includes deepwater snappers and aquarium fish; b = includes mud crabs and spiny lobsters sold on local market; c = includes hundreds of tonnes of penaeid shrimp; d = includes 800 tonnes of baitfish, and aquarium fish; e = includes aquarium fish; f = includes 700 tonnes of deepwater snappers, and aquarium fish; nea = no estimate available.

come ashore and therefore makes no contribution to GDP. In comparison, commercial coastal fisheries account for ~ 17% of GDP in Kiribati and 1.3–3% of GDP in another seven PICTs (**Table 12.4**). The contribution of commercial coastal fisheries to GDP also exceeds that from the tuna longline fishery in all PICTs except American Samoa, Niue and Palau. Coastal fisheries make little contribution to government revenue because the artisanal, small-scale nature of fishing operations is not licensed in most PICTs. A few PICTs (e.g. Fiji, Kiribati and Solomon Islands) have from time to time collected modest export duties or other taxes on the export of bêche-de-mer and trochus.

Photo: Louise Goggin

Sea cucumbers, Solomon Islands

12.2.4 Plans to increase contributions from coastal fisheries

The opportunities to increase production from commercial coastal demersal fisheries are limited. Many demersal fisheries for cash income in the region are considered to be fully exploited or overexploited[21,22] (Chapter 9). Where stocks of demersal fish are still in good condition, increasing human populations and difficult economic conditions are likely to drive coastal communities in several PICTs to use these resources directly for subsistence, unless increased access can be provided to the fish needed for food security through development of fisheries for nearshore pelagic fish (tuna) and pond aquaculture[3] (Section 12.3). In remote, sparsely populated areas of some PICTs, e.g. French Polynesia, Kiribati and Marshall Islands, there are still abundant stocks of commercially-valuable coastal fish and invertebrates. However, the costs of transporting catches from such areas to distant local markets can be prohibitive and there is little prospect of them contributing to economic development. Also, there is increasing interest in conserving these areas for non-extractive use. The recently established Phoenix Islands protected area in Kiribati is a case in point.

The situation for the invertebrates targeted by commercial coastal fisheries, particularly sea cucumbers and trochus, is even more serious for many PICTs. Populations of these valuable species have been overfished to the point where the adult spawning biomass is well below the threshold levels needed to provide regular substantial harvests[20,23–25] (Chapter 9). In recognition of the need to rebuild the spawning stocks to more productive levels, several PICTs (e.g. Marshall Islands, Palau, PNG, Samoa, Solomon Islands, Tonga) have, at various times, implemented moratoriums on fishing for sea cucumbers. With the exception of a few PICTs where stocks of trochus and sea cucumbers are still healthy (e.g. New Caledonia), effective management measures are needed to rebuild populations before greater and sustainable economic benefits can be expected from invertebrate fisheries for export commodities (Chapters 9 and 13). In most cases, this will involve a reduction in contributions to GDP in the short- to medium-term while stocks are rebuilt.

There are, however, options to increase production of resources currently harvested by coastal commercial fisheries. These options, which promise to deliver greater economic benefits under sustainable management, are outlined below.

- **Increase the catch of tuna from nearshore waters:** Skipjack and yellowfin tuna, together with a range of other large pelagic oceanic species, are already caught regularly by coastal fisheries in many PICTs (Chapter 9), either by trolling near the surface, or by handlining in deeper water. Stocks of skipjack tuna are robust (Chapter 8) and increased catches by small-scale fishers are likely to have a negligible impact on the resource compared to the industrial harvest. Even greatly increased catches of yellowfin tuna by artisanal coastal fisheries are likely to be minor compared to the current harvests made by the industrial fisheries (Section 12.2.1). Nevertheless, catches by coastal fisheries should be taken into account in assessing and monitoring regional stocks of skipjack and yellowfin tuna.

  The production and profitability of small-scale coastal fisheries for tuna can be increased by (1) improved handling of the catch; (2) investment by governments in the infrastructure needed to access higher-value markets; (3) deployment of low-cost, anchored FADs in coastal waters in depths < 1000 m; and (4) training programmes to improve the fishing skills for fishers who have focused previously on demersal fish. Investments in inshore, anchored FADs promise to increase catches greatly[2] (Chapter 13), however, care needs to be taken to position these FADs where they will attract mainly tuna and other oceanic fish. Otherwise, inshore FADs may increase the fishing mortality of Spanish mackerel, and other pelagic fish species dependent on coastal habitats, to unsustainable levels (Chapter 9).

- **Make greater use of small pelagic fish:** The wide range of small pelagic species (e.g. anchovies, pilchards, scads and flyingfish) that occur in nearshore waters throughout much of the tropical Pacific (Chapter 9) are not widely used for food. They are popular food fish elsewhere in the world and, as the demand for fish grows in many PICTs as a result of rapidly growing human populations

(Section 12.3), these species could help supply the fish required through sales at local markets. Fusiliers (*Caesio* spp.), which occur in the mid water above coral reefs, are also abundant in many PICTs (Chapter 9) and are a popular food fish in Okinawa, Japan. In some PICTs, fishers will require training in how to catch small pelagic fish using methods such as 'bouke-ami' and 'bagan', which do not damage coastal fish habitats or result in significant bycatch (Chapter 9).

- **Expand the marine aquarium trade:** The collection of fish, corals and other invertebrates for export to aquarium enthusiasts overseas has become a multi-million dollar business in PICTs over the last 20 years[25,26]. The trade is attractive because it provides an income from species which are not used for food, and can be managed sustainably through controls on a small number of exporters (especially important in the case of corals, which could otherwise be overexploited). Resource surveys indicate that there is potential to develop enterprises to export tropical marine ornamental products in several PICTs[27]. Elsewhere, transport costs and communications are a constraint.
- **Non-extractive uses:** Developing sustainable ways to harvest a greater range and quantity of fish and invertebrates is not the only way to increase economic returns from coastal fisheries resources. Non-extractive uses of coastal fish habitats and fish stocks, such as dive-based tourism in marine protected areas[28–30], may offer opportunities for economic development that also help protect spawning biomass and replenish stocks in surrounding areas open to fishing[31,32]. Sportfishing based on coastal fish can also provide employment and income in a way that has minimal impact on the resource.

12.2.5 Contributions from aquaculture

Development of aquaculture in the region has been limited compared to other parts of the world[4,33] (Chapter 11). The exceptions are French Polynesia and New Caledonia. The value of cultured black pearls from French Polynesia was USD 173 million in 2007[33], although pearl farming contributed < 1% to GDP because the economy is large[4]. In New Caledonia, shrimp farming produced ~ 1850 tonnes of high-quality shrimp valued at USD 29 million in 2007[33]. The value added from fisheries and aquaculture combined is also < 1% of GDP in New Caledonia due to the large size of the economy. Most of the other aquaculture industries in the region, except for pearl farming in Cook Islands, are at a fledgling stage, and the combined value of the various commodities was estimated to be USD 8 million in 2007[33].

12.2.6 Plans to increase contributions from aquaculture

Slow development of many aquaculture commodities in PICTs has been attributed to the lack of policy and legislation frameworks and planning to overcome technical, logistical and socio-economic constraints (Chapter 11). However, the past is not necessarily a guide to the future of aquaculture in the tropical Pacific. The regional

'Aquaculture Development Plan'[34], and a series of national aquaculture development plans[35–39], promise to put aquaculture in PICTs on a new footing – there is potential to increase production of several of the existing commodities in the region, and scope to produce new products.

The main prospects are thought to be (1) increasing the value of pearl production in Cook Islands, Fiji, FSM, Marshall Islands and PNG, and launching commercial pearl farming in Kiribati and Solomon Islands; (2) doubling the production of shrimp in New Caledonia and developing enterprises to help meet local demand in Fiji and PNG; (3) scaling-up the production of seaweed in Solomon Islands; (4) establishing intensive pond aquaculture for tilapia in peri-urban areas in Fiji, PNG, Solomon Islands and Vanuatu to provide fish for rapidly growing urban populations; (5) growing-out wild-caught juvenile milkfish, rabbitfish and freshwater prawns for local markets; (6) using the region's pristine image and environmentally friendly farming methods to increase the market share of cultured tropical marine fish and invertebrates for the ornamental trade; (7) forging stronger links between tourism and local aquaculture products; and (8) possible production of marine algae for biofuels (Chapter 11).

12.3 Food security

12.3.1 Current fish consumption

Most PICTs have an extraordinary dependence on fish[xi] for food security due to limited access to other sources of animal protein, particularly in rural areas[3,4,40] (**Table 12.5**). Although comprehensive data are not available for the entire region, recent national annual consumption per person by rural communities exceeds 50 kg in many PICTs, and is 60–145 kg in coastal communities in 11 PICTs (**Table 12.5**). Fish provides 51–94% of animal protein in the diet in rural areas, and 27–83% in urban areas, across the region. PNG is the exception, where the large inland population generally has much less access to fish, except for communities living near rivers (Chapter 10). Importantly, the great majority of fish for food security in the region is derived from coastal subsistence fishing – in 14 PICTs, 52–91% of the fish eaten in rural areas is caught by the household from coral reefs and other coastal habitats (**Table 12.5**) (Chapter 9). High levels of subsistence fishing are also common in urban areas in many of the smaller PICTs. The high dependence on fish by Pacific communities is a stark contrast with average global fish consumption of fish per person, which is 16–18 kg per year[41,42].

Due to the high dependence on fish for animal protein, and the widespread participation of households in fisheries (Section 12.4), subsistence fishing in coastal and freshwater habitats produced three times as much fish as commercial fishing in coastal waters in 2007[4]. Even when the production of bêche-de-mer is converted

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[xi] Fish is used here in the broad sense to include fish and invertebrates.

to live weight, subsistence fishing produced 2.25 times the volume of fish taken in small-scale commercial fisheries in 2007.

Fish is a cornerstone of food security for many Pacific communities[43]. Due to the lack of agricultural systems capable of producing large quantities of animal protein in the region, fisheries resources must continue to be allocated for this purpose in the future[44]. The problem is that more fish is required by the rapidly growing human populations in the tropical Pacific, particularly in Melanesia (Chapter 1). By 2035, ~ 320,000 tonnes of fish will be needed across the region to provide the fish recommended for good nutrition[40], or to maintain traditional patterns of fish consumption (**Table 12.5**). This represents an increase of more than 80% in the fish required for food security in 2010.

12.3.2 Plans to maintain fish consumption

The vital role that fish plays in food security in many PICTs has led to plans to provide the fish required in the future. These plans are based on identifying how much fish people should be eating for good nutrition, assessing how much they eat now, forecasting how much fish will be needed as human populations increase, and identifying how to provide access to more fish where shortfalls in the productivity of coastal fisheries are projected to occur[3].

Based on the recommendation from the SPC Public Health Programme that people in the region should eat 35 kg of fish per year to ensure they obtain the protein needed for good health, or to maintain the traditionally greater rates of fish consumption in several PICTs, substantial quantities of fish will be needed across the region in the coming decades, particularly in Melanesia[3,40] (**Table 12.5**). In nine of the 22 PICTs, coastal fisheries are not expected to be able to meet this future demand for fish and the gap between the fish required and the fish expected to be available from coastal fisheries (and freshwater fisheries in some cases) will be substantial. In another seven PICTs, it may not be economical to transport fish to urban centers from remote, productive coral reefs. If so, future demand for fish in the rapidly growing urban centres in these PICTs may not be fulfilled. The PICTs in each of these two categories are listed in Section 12.8.

Fortunately, the rich tuna resources of the region, and the high levels of rainfall in tropical Melanesia, provide the potential to fill this gap through (1) increasing access to tuna by the coastal nearshore pelagic fishery through the use of low-cost, anchored FADs; (2) using small tuna formerly discarded at sea to provide fish at low prices for rapidly growing and often poor urban populations; and (3) developing pond aquaculture for suitable species of freshwater fish both in rural areas and on the outskirts of urban centres[3,45]. In addition, there appears to be scope to increase the harvests of small fish species in the nearshore pelagic component of coastal fisheries

(Section 12.2.4) (Chapter 9). Care will be needed in choosing appropriate options for filling the gap. For example, inshore FADs will not be effective in transferring subsistence fishing effort from demersal fish to tuna everywhere. They should be located in places where they attract mainly tuna and, preferably, where people can paddle to them. Issues involved in planning which options to use are discussed in Chapter 13.

Table 12.5 Estimates of annual fish consumption per person, percentage of animal protein in the diet derived from fish, and percentage of fish consumed caught by subsistence fishing, in Pacific Island countries and territories (PICTs). The amount of fish needed for food security in 2035 is also shown (source: Bell et al. 2009, Gillett 2009)[3,4]. Fish is used here in the broad sense to include fish and invertebrates. Blank spaces indicate that no estimate was available.

PICT	Fish consumption per person (kg)				Animal protein in diet (%)		Subsistence catch (%)		Fish needed for food by 2035 (tonnes)
	National	Rural	Urban	Coastal*	Rural	Urban	Rural	Urban	
Melanesia									
Fiji	21	25	15	113			52	7	34,200[a]
New Caledonia	26	55	11	43			91	42	11,700[a]
PNG	13	10	28	53			64		140,700[b]
Solomon Islands	33	31	45	118	94	83	73	13	33,900[a]
Vanuatu	20	21	19	30	60	43	60	17	14,800[a]
Micronesia									
Guam	27								8800[a]
FSM	69	77	67	96	80	83	77	73	7300[c]
Kiribati	62	58	67	115	89	80	79	46	9000[c]
Marshall Islands	39								2200[a]
Nauru	56			62	71	71	66	66	790[c]
CNMI									4700[a]
Palau	33	43	28	79	59	47	60	35	800[a]
Polynesia									
American Samoa		63							3100[a]
Cook Islands	35	61	25	79	51	27	76	27	600[a]
French Polynesia	70	90	52	61	71	57	78	60	23,200[c]
Niue	79			50			56	56	100[c]
Pitcairn Islands	148								10[c]
Samoa	87	98	46	94			47	21	17,600[c]
Tokelau	~ 200								250[c]
Tonga	20			85			37	37	4000[a]
Tuvalu	110	147	69	146	77	41	86	56	1400[c]
Wallis and Futuna	74			56			86	86	1000[c]

* Applies to households in coastal fishing communities at > 4 sites; a = based on recommended fish consumption of 35 kg per person per year; b = based on the recent national average of 13 kg per person per year, rather than 35 kg, to reflect the difficulties of distributing fish to the large inland population; c = based on recent traditional levels of fish consumption (source: Bell et al. 2009)[3].

It is also important to recognise the link between food security and opportunities to earn income from catching and selling fish[3,46] (Section 12.4). Households that also earn income from selling fish have the resources to buy food to supplement the crops they grow and the fish they catch themselves. The pervasive importance of coastal fisheries as a source of income in the region (Chapter 9) should help to make coastal communities resilient to times when severe weather events damage crops and prevent fishing.

Photo: Christophe Launay

Small pelagic fish – an additional source of food

12.4 Livelihoods

12.4.1 Existing opportunities to earn income based on fisheries and aquaculture

Although there is little consistency across the region in the way information is kept on the proportions of people working full-time or part-time in fisheries and aquaculture[4], it is evident that employment in the sector is relatively important compared to many other parts of the world. For example, in American Samoa and French Polynesia, fisheries and aquaculture directly or indirectly provide > 20% of paid jobs due to the establishment of tuna canneries and black pearl farming, respectively[4].

Large numbers of formal full-time and part-time jobs have also been created through tuna processing in PNG, Solomon Islands and Fiji (**Table 12.6**), although they represent only a low percentage of total employment in these PICTs due to their relatively large populations (Chapter 1). Aquaculture has also provided large numbers of jobs in rural areas of Cook Islands and New Caledonia (**Table 12.6**). In general, however, most of the formal employment in the sector is associated with the tuna fishery and typically accounts for 1–3% of the workforce in a range of PICTs[4].

Table 12.6 Number of jobs in Pacific Island countries and territories (PICTs) on tuna vessels and in shore-based operations (e.g. canneries). Also shown is the average percentage of households in 4–5 coastal communities in each of 17 PICTs that earned their first or second income from fishing between 2002 and 2008, and the number of jobs in aquaculture (including opportunities to earn income) (source: Gillet 2009, Philipson 2007, Ponia 2010, SPC PROCFish Development Project)[4,13,33].

PICT	Local jobs on tuna vessels			Local jobs in shore-based processing of tuna			Coastal household earnings from fishing (%)			Jobs in aqua-culture
	2002	2006	2008	2002	2006	2008	First income	Second income	Both incomes	
Melanesia										
Fiji	893	330	150	1496	2200	1250	69.8	23.5	93.3	550
New Caledonia	Undetermined number of jobs						23.4	22.8	46.2	560
PNG	460	110	440	2707	4000	8550	53.3	32.5	85.8	> 10,000[a]
Solomon Islands	464	66	107	422	330	827	29.1	31.8	61.0	610
Vanuatu	54	20	30	30	30	30	21.4	39.8	61.1	30
Micronesia										
FSM	89	36	25	131	24	140	47.9	4.6	52.5	20
Guam	Undetermined number of jobs						nea	nea	nea	20
Kiribati	39	15	15	47	80	70	33.3	24.8	58.1	10
Marshall Islands*	5	0	25	457	100	116	36.0	17.6	53.6	5
Nauru	5	0	0	10	2	0	4.9	17.1	22.0	nea
CNMI	Undetermined number of jobs						nea	nea	nea	12
Palau	1	0	0	11	5	20	10.2	15.7	25.9	5
Polynesia										
American Samoa**	nea	nea	nea	nea	4757	nea	nea	nea	nea	15
Cook Islands	50	15	12	15	15	10	12.3	7.8	20.1	450
French Polynesia	Undetermined number of jobs						15.4	11.3	26.7	5000
Niue	5	0	0	0	14	18	1.4	8.7	10.1	0
Pitcairn Islands	No jobs based on tuna						nea	nea	nea	0
Samoa	674	110	255	108	90	40	24.2	26.6	50.8	16
Tokelau	No jobs based on tuna						nea	nea	nea	0
Tonga	161	75	45	85	35	35	41.5	4.7	46.2	20
Tuvalu	59	20	65	36	10	10	24.0	24.4	48.4	0
Wallis and Futuna	No jobs based on tuna						21.1	23.2	44.3	0
Total (average)	**2959**	**797**	**1169**	**5555**	**11,692**	**11,116**	**(27.6)**	**(19.8)**	**(47.4)**	**17,323**

* The loining plant in Majuro began operation after the period covered by the 2008 survey; ** number of jobs only available for 2006 but assumed to be about the same in 2002 and 2008; a = estimate by the National Fisheries Authority, Papua New Guinea, which includes > 10,000 households involved in pond aquaculture in inland areas and > 60 jobs in seaweed farming; nea = no estimate available.

The growth in employment based on tuna processing has been significant, however, the overall impact of the changes underway in the tuna industry on total earnings is uncertain because many jobs on fishing vessels have been lost in recent years (**Table 12.6**). Employment on longline vessels in particular has decreased as many of the boats owned by PICTs have stopped operating, and locally-based foreign longliners often use crew from Asian countries with lower wage expectations. In addition, most of the jobs in canneries are for low wages.

Overall, > 12,000 people in the region were employed directly on tuna fishing vessels or in processing operations in 2008[4,7] (**Table 12.6**). However, based on the number of associated jobs in government and the private sector in American Samoa[4], twice as many people could be employed indirectly as a result of tuna fishing and processing.

The contribution of coastal fisheries to livelihoods has been mainly through the informal economy, where self-employed artisanal and small-scale fishers harvest a wide range of fish species (Chapter 9) for sale at local markets, or sell fish that is surplus to household needs. But the informal nature of these activities should not be used to measure their significance – large numbers of people are engaged in coastal fisheries for their livelihoods across the region[4]. Perhaps the best measure of the significance of coastal fisheries to income earning opportunities in the region comes from the socio-economic surveys of 4–5 coastal communities in each of 17 PICTs during the SPC PROCFish Development Project[25]. Those surveys revealed that an average of 47% of households derived either their first or second source of income from fishing (**Table 12.6**). As mentioned above, this income can also be used to supplement the diet through the purchase of non-marine protein[46,47].

12.4.2 Plans to increase income earning opportunities based on fisheries and aquaculture

Predicting future employment in the tuna sector is difficult. Although plans for new canneries and loining plants in PNG and Solomon Islands have been announced, there is uncertainty over the future of tuna processing in American Samoa. However, as described in Section 12.2.2, there is potential to greatly increase direct and indirect employment based on tuna in PICTs that have suitable conditions for processing[17]. In short, if the ~ 700,000 tonnes of tuna caught from the EEZs of PICTs and shipped outside the region was processed in PICTs, another 40,000–50,000 jobs would be created. A key proviso here is that processing plants established in PICTs would need to be internationally competitive under the range of scenarios likely to be driven by trade agreements and other global factors[7]. With more vessels based in Pacific island ports, employment in service industries would also increase.

Few opportunities exist for increasing the number of livelihoods based on coastal demersal fisheries, and invertebrates targeted to produce export commodities, in most PICTs. Indeed, the hard decisions required to reduce fishing to restore the productivity of some coastal stocks (Section 12.2.4) would result in fewer jobs in the short to medium term. However, potential exists for more livelihoods to be created by the range of opportunities that exist for enhancing the production of coastal fisheries described in Section 12.2.4.

The plans to expand aquaculture in the region (Section 12.2.6) are also expected to create more opportunities to earn income, although it is still difficult to identify which commodities will drive these opportunities, or how the new jobs will be distributed among PICTs. Demand for fish in the rapidly growing urban centres of Melanesia should provide incentives for enterprises based on intense pond aquaculture. The relatively low cost of labour in Melanesia may also favour further development of pearl farming and seaweed culture. New jobs are also expected in the production of tropical marine ornamental products, although the limited size of the global market for these commodities is likely to provide relatively few additional opportunities to earn income.

12.5 Vulnerability of plans for economic development and government revenue

The substantial economic benefits derived from oceanic fisheries by PICTs, and the plans to sustain and expand those benefits, are expected to be affected by the projected changes in productivity of tuna described in Chapter 8. Here, we use the vulnerability framework outlined in Chapter 1, and applied widely to fisheries elsewhere[48–51] and throughout this book (Chapters 4–11), to identify the comparative vulnerability of future contributions of oceanic fisheries to economic development and government revenue. This framework uses the exposure of a national economy to changes in the availability of tuna and the sensitivity (dependence) of the economy to contributions from industrial fisheries to identify a potential impact, which can be offset to some extent by the adaptive capacity of the country or territory[52].

The analyses done in Chapter 8 provide estimates of the exposure of economic development and government revenue due to the effects of climate change on oceanic fisheries. The recent analysis of the contribution of tuna to the economies of PICTs[4], and the analyses in Section 12.2, allow the sensitivity of national economies to this exposure to be quantified. To assess the human and social capital that underpins the adaptive capacity of PICTs[53,54], we have relied heavily on the information collated for the region by the SPC Statistics for Development Programme[xii], and the World Bank. It is important to note, however, that the vulnerability assessment for economic development and government revenue only identifies the comparative vulnerability of PICTs; it does not identify projected losses or gains in real terms. This is done in Section 12.6 for the contributions of the surface tuna fishery.

12.5.1 Vulnerability of economies to changes in the surface tuna fishery

12.5.1.1 Calculating the vulnerability index

Assessing the vulnerability of national economies to the potential effects of climate change on the surface fishery depends mainly on the projections for the abundance of the skipjack tuna that dominate the catch[xiii]. We used the projected percentage changes in catches of skipjack tuna within the EEZ of a PICT, relative to the 20-year

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[xii] www.spc.int/prism

[xiii] See Supplementary Table 12.1 (www.spc.int/climate-change/fisheries/assessment/chapters/12-supp-tables.pdf).

average catch for 1980–2000 (Chapter 8) (**Table 12.7**), as the index of exposure of the surface fishery under the B1 and A2 scenarios in 2035, B1 in 2100 and A2 in 2100. Projected changes in catch are positive for all PICTs in 2035, however, depending on the location of the national EEZs, projected changes in catch are positive or negative by 2100 (**Table 12.7**). To construct an index of the sensitivity of a national economy to changes in projected catches by the surface fishery, we used the average percentage contributions of the fishery to GDP and government revenue (**Table 12.2**).

Potential impact (PI) was estimated by multiplying the exposure index (E) by the sensitivity index (S). Although a broad range of approaches are used to construct vulnerability indices[55], and additive approaches have been used in another broad assessment of the effects of climate change on global fisheries[50], we multiplied E x S to estimate potential impact. This recognised the vital importance of contributions to GDP and government revenue to the economies of some PICTs and suppressed high scores that would have occurred for PICTs where catches of skipjack are projected to increase substantially, but where they currently contribute little to the economy. Because the potential impact values were > 1 and varied widely, they were standardised and normalised to range from 0 to 1, with higher values representing greater potential impact.

To assess adaptive capacity, we combined four indices – health, education, governance and the size of the economy – on the assumption that PICTs with higher levels of human and economic development are in a better position to undertake planned adaptation. Health was estimated as a weighted combination of infant mortality rate (1/3) and life expectancy (2/3). Education was measured as the combination of the literacy rate for people up to 24 years of age (2/3) and the percentage of students enrolled in primary education (1/3). The World Bank governance index[56] was used to amalgamate six equally weighted aspects of governance: political stability, government effectiveness, regulatory quality, rule of law, voice and accountability, and corruption. To indicate the size of the economy and purchasing power parity we used GDP per person. The four adaptive capacity indices were standardised and normalised to range between 0 and 1, and then averaged to produce a composite adaptive capacity index (AC) (Appendix 12.1).

Vulnerability was calculated as PI multiplied by AC[xiv]. In PICTs with a surface fishery where the abundance of skipjack is projected to decrease, AC was inverted (1 - AC) so that the PICT with the greatest adaptive capacity had reduced vulnerability to lower catches of tuna. For PICTs where skipjack catches are projected to increase, the adaptive capacity index was retained as calculated to reflect the likelihood that the PICT with the greatest adaptive capacity would be more capable of maximising benefits from the increased resource.

[xiv] A limitation of the methods used to estimate vulnerability is that E changes over time because it is derived from the preliminary modelling summarised in **Table 12.7**, whereas S and AC are fixed at recent estimates.

Table 12.7 Projected percentage changes in catches of skipjack and bigeye tuna, relative to the 20-year average for 1980–2000, under the B1 and A2 emissions scenarios in 2035 and 2100, derived from the SEAPODYM model described in Chapter 8.

PICT	Skipjack			Bigeye		
	B1/A2 2035	B1 2100*	A2 2100	B1/A2 2035	B1 2100*	A2 2100
Melanesia						
Fiji	+26	+24	+33	+1	+1	-1
New Caledonia	+22	+19	+40	+1	+1	+6
PNG	+3	-11	-30	-4	-13	-28
Solomon Islands	+3	-5	-15	0	-3	-7
Vanuatu	+18	+15	+26	-3	-6	-10
Micronesia						
FSM	+14	+5	-16	-3	-11	-32
Guam	+16	+10	-8	-7	-13	-33
Kiribati	+37	+43	+24	-1	-5	-17
Marshall Islands	+24	+24	+10	-3	-10	-27
Nauru	+25	+20	-1	-1	-7	-19
CNMI	+23	+22	+13	0	-5	-23
Palau	+10	+2	-27	-4	-11	-45
Polynesia						
American Samoa	+41	+48	+58	-5	-8	-18
Cook Islands	+40	+50	+47	-3	-8	-15
French Polynesia	+41	+49	+77	-2	-8	-12
Niue	nea	nea	nea	-5	-8	-15
Pitcairn Islands	nea	nea	nea	-2	-4	-4
Samoa	+44	+49	+55	+1	+1	-4
Tokelau	+61	+69	+63	-3	-6	-16
Tonga	+47	+50	+58	-4	-5	-10
Tuvalu	+37	+41	+25	+3	+2	-6
Wallis and Futuna	+44	+49	+46	0	0	-7
Regional						
Total fishery	+19	+12	-7	+0.3	-9	-27
Western fishery**	+11	-0.2	-21	-2	-12	-34
Eastern fishery***	+37	+43	+27	+3	-4	-18

* Note that model simulations for A2 in 2050 have been used to approximate B1 in 2100; it is important to note, however, that while CO_2 emissions for these scenarios/times are similar, the multi-model mean of sea surface temperature is 0.18°C (±0.23) higher under B1 2100 than A2 2050; ** 15°N–20°S and 130°–170°E; *** 15°N–15°S and 170°E–150°W; nea = no estimate available.

Vulnerability (or potential benefit) was estimated for the B1 and A2 scenarios in 2035, in which exposure to changes in abundance of skipjack is similar (Chapter 8), for B1 in 2100, and for A2 in 2100.

We limited the vulnerability analyses to those PICTs where the surface fishery contributes at least 0.01% to either GDP and/or government revenue based on fishing operations alone (**Table 12.2**). Thus, American Samoa, Fiji, French Polynesia, Guam, Commonwealth of the Northern Mariana Islands (CNMI), New Caledonia, Niue, Pitcairn Islands and Wallis and Futuna were not considered, even though canneries make a great contribution to GDP in American Samoa (Section 12.2.1.1). Niue and Pitcairn Islands were not included either because no estimates of future changes in skipjack in their EEZs were available.

12.5.1.2 Comparative vulnerability of economies

Under the B1 and A2 scenario in 2035, the economy of Kiribati is projected to receive the greatest relative benefit from changes in the distribution and abundance of skipjack tuna (**Table 12.8**). Kiribati has a relatively high exposure to increased catches (**Table 12.7**) and is highly sensitive because access fees paid by DWFNs contribute > 40% of government revenue (**Table 12.2**). Although the potential benefit for Kiribati in 2035 is the highest for any PICT, it is somewhat constrained by a relatively low adaptive capacity[xv]. Projected changes in the surface fishery are also expected to have a relatively high positive effect on the small economy of Tokelau for similar reasons, although Tokelau has a higher exposure (**Table 12.7**) and a lower sensitivity (**Table 12.2**) than Kiribati. The economies of Nauru and Tuvalu are also likely to be quite well-placed to benefit from the increased abundance of skipjack in their EEZs by 2035, with more modest benefits flowing to Marshall Islands and FSM (**Table 12.7**).

The economies of PNG and Solomon Islands have very low positive scores relative to the PICTs listed above because (1) catches in their EEZs are projected to increase only slightly (**Table 12.7**); and, (2) despite the fact that catches are large, the tuna industry makes relatively low contributions to GDP and government revenue (**Table 12.2**). Although catches in the EEZs of Palau and Vanuatu are projected to increase by 10–20% by 2035, and those in Cook Islands, Samoa and Tonga are expected to increase by > 40%, the economies of these PICTs also have very low positive scores in relative terms due to the very limited contribution of the surface fishery to their economies (**Table 12.2**).

The relative scores for the economies of these PICTs are generally maintained under the B1 scenario in 2100 (equivalent to A2 in 2050), with the exception of PNG and Solomon Islands, which have negative scores because catches in their EEZs are projected to decrease compared to 1980–2000 levels, and FSM where benefits are projected to change from low to very low (**Table 12.8**). However, under the A2 scenario in 2100, the situation changes considerably. With the likelihood that skipjack will move further east and southeast into Polynesia (Chapter 8) (**Table 12.7**), the economies of FSM, Nauru and Palau are expected to join those of PNG and Solomon Islands in having increased vulnerability to negative economic impacts from the projected decreases in skipjack catches (**Table 12.7**). In the case of FSM and Solomon

[xv] See Supplementary Table 12.5 (www.spc.int/climate-change/fisheries/assessment/chapters/12-supp-tables.pdf).

Islands, the vulnerability is rated as low, whereas it is still very low for PNG, Nauru and Palau. On the other hand, the positive effects for Tokelau increase from high to very high (**Table 12.8**).

Although American Samoa, Cook Islands, Fiji, French Polynesia and Vanuatu do not have significant surface fisheries (**Table 12.1**), and Wallis and Futuna does not have a surface fishery for tuna within its EEZs at all, these PICTs may be in an improved position in the future to develop domestic surface fisheries or to negotiate access fees with DWFNs if they so desire. These benefits are expected as a result of (1) the expected changes in distribution of skipjack tuna (Chapter 8); (2) the projected increases in catches from their EEZs (**Table 12.7**); and (3) the relatively high (or at least moderate) adaptive capacity of these PICTs (Appendix 12.1).

Table 12.8 Relative vulnerability (-) or benefit (+) for economies of Pacific Island countries and territories (PICTs) to projected changes in the surface fishery and longline fishery for tuna under the B1/A2 emissions scenarios for 2035, B1 for 2100 and A2 for 2100. Scores have been classified as very low (0.00–0.05), low (0.06–0.10), moderate (0.11–0.20), high (0.21–0.30) or very high (> 0.30). See Supplementary Tables 12.5–12.10 (www.spc.int/climate-change/fisheries/assessment/chapters/12-supp-tables.pdf) for the exposure, sensitivity, potential impact and adaptive capacity indices used to calculate the scores.

PICT	Surface fishery			Longline fishery		
	B1/A2 2035	B1 2100	A2 2100	B1/A2 2035	B1 2100	A2 2100
Melanesia						
Fiji*				- Very low	- Very low	- Very low
New Caledonia*				+ Very low	+ Very low	+ Very low
PNG	+ Very low	- Very low	- Very low	- Very low	- Very low	- Very low
Solomon Islands	+ Very low	- Very low	- Low	- Very low	- Very low	- Very low
Vanuatu	+ Very low	+ Very low	+ Very low	- Very low	- Very low	- Very low
Micronesia						
FSM	+ Low	+ Very low	- Low	- Moderate	- High	- Moderate
Kiribati	+ Very high	+ Very high	+ Very high	- Moderate	- Very high	- Very high
Marshall Islands	+ Low	+ Low	+ Low	- High	- Very high	- Very high
Nauru**	+ Moderate	+ Moderate	- Very low			
Palau	+ Very low	+ Very low	- Very low	- High	- Very high	- Very high
Polynesia						
American Samoa*				- Low	- Low	- Very low
Cook Islands	+ Very low	+ Very low	+ Very low	- Low	- Moderate	- Very low
French Polynesia				- Very low	- Very low	- Very low
Niue*				- Very high	- High	- Moderate
Samoa	+ Very low	+ Very low	+ Very low	- Very low	- Very low	- Very low
Tokelau**	+ High	+ High	+ Very high			
Tonga	+ Very low	+ Very low	+ Very low	- Very low	- Very low	- Very low
Tuvalu	+ Moderate	+ Moderate	+ Moderate	- Low	- Low	- Very low

* PICTs where the surface fishery contributes < 0.01% of gross domestic product (GDP); ** PICTs where the longline fishery contributes < 0.01% of GDP.

12.5.2 Vulnerability of economies to changes in the longline tuna fishery

Although the contributions to GDP and government revenue from the longline fishery are usually considerably lower than those from the surface fishery, they affect economies in a greater number of PICTs (Section 12.2.1.2). The vulnerabilities of economies to projected changes in the longline fishery were calculated in the same way described for the surface fishery. In the absence of projections for yellowfin tuna and albacore, we based the exposure index on the preliminary projections for changes in abundance of bigeye tuna within the EEZs of PICTs (Chapter 8) (**Table 12.7**). These projections are only a partial indicator of exposure because bigeye tuna made up only ~ 25% of the tuna caught by the longline fishery within the EEZs of PICTs in 2007, but 42% of the value[8]. The sensitivity of economies to changes in projected catches by the longline fishery was estimated as the average of the percentage contribution of the fishery to GDP in 2007[4], and the contribution to government revenue in 1993 or 2003[xvi], whichever was greatest.

Once again, we limited the vulnerability analyses to those PICTs where the longline fishery contributed > 0.01% to either GDP and/or government revenue based on fishing operations alone (**Table 12.2**); Guam, Nauru, CNMI, Pitcairn Islands, Tokelau and Wallis and Futuna were not included.

The projected decreases in catches of bigeye tuna under the B1 and A2 scenarios in 2035 (**Table 12.7**) indicate that most PICTs are likely to be vulnerable to loss of economic benefits from this component of the longline fishery. Several PICTs in Micronesia and Polynesia have relatively moderate, high or very high vulnerabilities to economic losses from reduced bigeye catches (**Table 12.8**). The most vulnerable PICTs are Niue, Palau and Marshall Islands because the longline fishery contributes ~ 2–4% of GDP[xvi].

As the projected catches of bigeye tuna decline further under the B1 scenario in 2100 (equivalent to A2 in 2050) (**Table 12.7**), the level of vulnerability increases for all PICTs in Micronesia, and for Cook Islands in Polynesia (**Table 12.8**). Kiribati has the most significant increase in relative vulnerability under this scenario (from moderate to very high) due to the high impact of reduced catches in its EEZ and its modest adaptive capacity. This is because Kiribati receives more government revenue from the longline fishery than other PICTs[xvi]. The relative vulnerability to losses of economic benefits of Marshall Islands and Palau also increases to very high due to the rapid increase in potential impact[xvii] as a result of the large projected decreases in catches of bigeye tuna from the longline fishery in their EEZs under the B1 emissions scenario in 2100 (**Table 12.7**). The vulnerability of FSM increases from moderate to high for similar reasons. These patterns of vulnerability among PICTs are largely maintained under the A2 scenario in 2100 (**Table 12.8**), although the great decrease in projected catch of bigeye tuna for Palau (**Table 12.7**) suppresses the relative vulnerabilities of some of the PICTs compared to the B1 emissions scenario in 2100.

[xvi] See Supplementary Table 12.4 (www.spc.int/climate-change/fisheries/assessment/chapters/12-supp-tables.pdf).

[xvii] See Supplementary Tables 12.8 and 12.9 (www.spc.int/climate-change/fisheries/assessment/chapters/12-supp-tables.pdf).

Modelling needs to be done for yellowfin tuna and albacore, the two other species of tuna taken by the longline fishery, to determine whether the vulnerabilities of economies to projected decreases in the catches of bigeye tuna are representative of this fishery in general. Such modelling is needed to determine whether some of the projected benefits from the surface fishery for PICTs in Micronesia and Polynesia as skipjack tuna move east could be undermined by reduced catches from longlining. Any effects of this type may be relatively minor, however, because the potential economic benefits for PICTs from establishment of a surface fishery in their EEZs might reasonably be expected to outweigh losses from reduced longlining catches.

12.6 Potential effects on economic development and government revenue from projected changes to the surface tuna fishery

To assess the potential effects of projected changes to the surface fishery on the economies of PICTs, we estimated the lower and upper bounds of projected contributions to GDP and government revenue under the B1 and A2 scenarios in 2035, B1 in 2100 and A2 in 2100. The range was based on the variation in estimates of GDP and government revenue derived from the surface tuna fishery between 1999 and 2008. The estimates were also based on the following assumptions.

- Projected catches of skipjack tuna are a good indicator of the effects of changes to the surface fishery on national economies because landings of skipjack dominate this fishery (Section 12.2.1.1).
- Variations in catch will have similar impacts both on GDP, and on government revenues. Thus, if the contribution of the surface fishery is estimated to be 5% of GDP, and catch is projected to rise by 10%, then the increased contribution to GDP due to the greater catch is estimated to be 0.5% of GDP.
- Tuna prices, GDP, levels of taxation, and the value-added component of purse-seine and pole-and-line fishing operations, remain constant, relative to 1999–2008 levels. These assumptions are common in other future economic vulnerability analyses[57].
- The balance between catches by locally-based fleets (which contribute to GDP) and DWFNs (which do not) remain constant.
- Fishing effort remains constant. We recognise that this is unlikely because as catch per unit effort (CPUE) in an area changes, the relative profitability of fishing also changes. As a result, fishing effort increases in areas where CPUE improves, and decreases where CPUE declines. This means that the impacts estimated in this analysis are likely to be amplified. For example, if catches within an EEZ fall by 30% under current effort levels, further significant falls in fishing effort would be expected as vessels move to areas where CPUE is greater, causing declines in catch much greater than 30% within the EEZ. Without coupled biophysical and fleet dynamics models, we cannot include such complexity in our assessment.

Our analysis is restricted to PICTs where the average contribution of the surface fishery to GDP or government revenue was > 1% over the period 1999–2008, or where large quantities of skipjack tuna were transshipped or processed. These PICTs are: PNG and Solomon Islands, where tuna are caught and processed and/or transshipped; FSM, Kiribati, Marshall Islands, Nauru, Palau, Tuvalu and Tokelau, where tuna is caught within the EEZ; and American Samoa where there are significant processing operations (**Table 12.2**). The estimated impacts are based on the preliminary modelling of catch variations in the EEZ of each PICT (**Table 12.7**) (Chapter 8). However, because the post-harvest processing sector in American Samoa is supplied by fish caught throughout the fishery, the impacts on American Samoa are based on the projected catch variations for the fishery as a whole (**Table 12.7**).

The projected increases in catches of skipjack tuna by 2035 show that landings are expected to rise by ~ 20% across the fishery, driven by strong increases (> 35%) in catch in the eastern part of the region and more modest increases (~ 10%) in catches in the west (**Table 12.7**). The expected improvements in catch lead to projected increases in GDP and government revenue by 2035, particularly for those PICTs in the east (**Table 12.9**). The most significant projected increases to GDP associated with the projected changes in catch are for American Samoa (3–6%) and Marshall Islands (2–6%). The greatest expected increases in government revenue are for Kiribati (11–18%), Tuvalu (4–9%), Tokelau (1–9%) and Nauru (2–6%) (**Table 12.9**).

Under the B1 scenario in 2100 (equivalent to A2 in 2050), the catch of skipjack tuna is projected to rise by 12% overall, driven by expected increases in catch in the eastern region of the fishery of > 40%, with a marginal decline in projected catches in the western region (**Table 12.7**). For PICTs in Micronesia and Polynesia, the general level of benefits projected for 2035 are expected to continue in 2100 (**Table 12.9**). On the other hand, projected decreases in catch of 11% in PNG and 5% in Solomon Islands by 2100 under the B1 scenario (**Table 12.7**) are expected to lead to declines in GDP and government revenues. However, due to the relatively low importance of the surface fishery to the larger economies of these PICTs, GDP is estimated to decline by only 0.1–0.4% in both countries. Government revenues are also expected to fall by only 0.1% in PNG and 0.3% in Solomon Islands (**Table 12.9**).

By 2100 under the A2 scenario, catches of skipjack tuna are projected to fall for the fishery as a whole by around 7% because the modest projected increases in the east of the region (27%) are more than offset by the expected decline of 21% in the larger component of the fishery in the west (**Table 12.7**). The projected 30% decline in catches of skipjack tuna in the EEZ of PNG is particularly significant, although it is estimated to result in a reduction of only up to 1.2% in GDP, and 0.2% in government revenue, due to the large size of the economy in PNG. The projected declines in catches from Solomon Islands and FSM of ~ 15% are also expected to cause reductions of about 0.8–1% in GDP, and ~ 1–2% in government revenue in both countries. The catch in Nauru, and consequentially government revenue, is expected to fall only marginally.

Marshall Islands, Kiribati and Tuvalu are projected to continue to receive increased economic benefits under the A2 scenario in 2100, albeit at lower levels than for B1 and A2 in 2035, or under the B1 scenario in 2100 (**Table 12.9**).

Table 12.9 Changes in percentage contributions of oceanic fisheries to GDP and government revenues in Pacific Island countries and territories (PICTs), relative to 1999–2008, resulting from projected alterations in the catch of skipjack tuna in 2035 and 2100 under B1 and A2 emissions scenarios. Lower (L) and upper (U) limits for these projections are estimated for each scenario, and shown for the period 1998–2008. Only PICTs where industrial fishing or processing contributes > 1% of GDP or government revenue are included.

PICT	Change to GDP (%)								Change to government revenue (%)							
	1999–2008 (%)		B1/A2 2035		B1* 2100		A2 2100		1999–2008 (%)		B1/A2 2035		B1* 2100		A2 2100	
	L	U	L	U	L	U	L	U	L	U	L	U	L	U	L	U
Melanesia																
PNG	1.5	4	0	+0.1	-0.2	-0.4	-0.4	-1.2	0.2	0.8	0	0	0	-0.1	-0.1	-0.2
Solomon Islands	2	5	+0.1	+0.2	-0.1	-0.3	-0.3	-0.8	0.2	5	0	+0.2	0	-0.3	0	-0.8
Micronesia																
FSM	1.5	5	0	+1	0	0	0	-1	6	12	+1	+2	0	+1	-1	-2
Kiribati									30	50	+11	+18	+13	+21	+7	+12
Marshall Islands	10	25	+2	+6	+2	+6	+1	+2	2	5	0	+1	0	+1	0	0
Nauru									10	25	+2	+6	+2	+5	0	0
Palau									2.5	3.2	+0.2	+0.3	0	+0.1	-0.7	-0.9
Polynesia																
American Samoa	20	25	+3	+6	+2	+4	-1	-2	5	20	+1	+4	+1	+2	0	-1
Tokelau									2	15	+1	+9	+1	+10	+1	+9
Tuvalu									10	25	+4	+9	+4	+10	+2	+6

* Approximates the A2 emissions scenario in 2050 (**Table 12.7**).

The expected outcomes for American Samoa are mixed. Projected increases in overall catches of skipjack tuna to 2035, and under the B1 scenario in 2100, may have a positive impact. Conversely, catch declines under the A2 scenario in 2100 may have a negative effect on the economy in American Samoa.

We emphasise that the analyses presented here are preliminary, and based on some simplistic assumptions – the estimates provide only an indication of the direction and magnitude of possible economic impacts and need to be improved by matching the baselines for projected catches (1980–2000) with the baselines for the contributions to GDP and government revenue (1999–2008). More advanced modelling of future catches of skipjack tuna needs to be done, incorporating outputs from the new generation of global physical climate models linked to biological parameters (e.g. prey for tuna) and to fleet dynamics models (e.g. fishing effort changes). Modelling the effects of climate change projections on yellowfin tuna also needs to be integrated with the modelling for skipjack tuna to provide a more complete picture for the surface fishery.

12.7 Vulnerability of plans for using fish for food security

12.7.1 Differences in capacity to provide fish among PICTs

The amount of fish needed to assist PICTs to achieve food security over the coming decades has been publicised widely[2,3,7,34,40,43]. As outlined in Section 12.3.2, the quantities of fish required, and the plans to supply them, have been based on (1) identifying the consumption of fish per person needed for good nutrition or the traditionally higher levels of fish consumption typical of many PICTs; (2) forecasting the amount of fish needed by the growing populations of the region; (3) identifying the fish likely to be available to meet the projected needs; and (4) assessing how best to increase access to additional fish where required.

The amount of fish needed for food security by each PICT over the next couple of decades due to increases in population is well understood[3] (**Table 12.5**). Identifying where the 35 kg of fish per person per year recommended for good nutrition[40] will come from is not as straightforward. However, it is reasonable to assume that much of the fish used for food will continue to be supplied by coastal fisheries[4] (Chapter 9), and from freshwater fisheries in some parts of PNG, Fiji and Solomon Islands (Chapter 10). This is because these resources are on the 'doorstep' of rural communities, and within easy access for subsistence fishers.

In the absence of detailed information on the sustainable production of coastal fisheries throughout the region (Chapter 9), we have used three sets of data to estimate the quantities of fish likely to be available per person in each PICT for food security until the end of the 21st century. These data sets are (1) the area of coral reef in km^2 (Chapter 5); (2) a median estimate of sustainable fisheries production from coral reef habitats of 3 tonnes per km^2 per year[21] (Chapter 9); and (3) the predicted future population of each PICT (see Appendix 12.2 for details of how datasets (1) and (2) were used to estimate sustainable fisheries production and how they were modified for PICTs with freshwater fisheries; and Chapter 1 for predicted populations of PICTs in 2035).

In recognition of the fact that there is considerable variation in the productivity of coastal fisheries throughout the region (Chapter 9), we have also assessed the quantities of fish expected to be available per person in the future where the status of fisheries resources is poor to medium and fishing pressure is high, and where fisheries resources is medium to good and fishing pressure is low[21,22] (Chapter 9). Sustainable fish production in these situations was assumed to be 1 tonne and 5 tonnes per km^2 of coral reef per year, respectively.

When the capacity of PICTs to supply their populations with the recommended 35 kg of fish per person per year for the remainder of the 21st century is estimated as described above, PICTs fall into three groups[xviii].

[xviii] Note that the classification of PICTs here differs slightly to that of Bell et al. (2009)[4] because more information is now available on the area of coral reef in each PICT (Chapter 5).

- **Group 1** (Cook Islands, Marshall Islands, New Caledonia, Palau, Pitcairn Islands and Tokelau), where coastal fisheries are expected to meet the increased demand for fish for the foreseeable future. Planning the use of fish for food security in this group of PICTs relies mainly on good management of coral reefs so that they can continue to yield their normal harvests (Chapter 13), and ensuring that excessive catches are not made for local tourism or export.

- **Group 2** (FSM, French Polynesia, Kiribati, Niue, Tonga, Tuvalu and Wallis and Futuna), where the area of coral reef should be able to produce the fish needed in the future, but where it will be difficult to distribute the potential harvests to urban centres because of the great distances between the main population centres and the islands, atolls and reefs, where the fish occur. Regular access to the fish needed by the growing urban populations in these PICTs will depend not only on good management of coral reefs, but also on (1) installation of low-cost FADs anchored inshore to assist subsistence and artisanal fishers catch tuna; (2) improved access to tuna and bycatch caught by industrial fisheries; and (3) development of fisheries for small pelagic fish (Sections 12.2.4 and 12.3.2).

- **Group 3** (American Samoa, Fiji, Guam, Nauru, CNMI, PNG, Samoa, Solomon Islands and Vanuatu), where coral reefs and other coastal habitats do not have the potential to produce the fish needed for good nutrition of their populations. In these PICTs, the plans to supply the fish required emphasise the need to manage coastal fisheries and fish habitats as well as possible to minimise the gap between the fish needed for food security and the fish available from coral reefs and other coastal habitats[40]. These plans also depend heavily on the interventions to increase access to tuna described above, particularly facilitating the distribution of low-value fish and bycatch from industrial fleets and installing anchored inshore FADs to assist subsistence and artisanal fishers in rural areas to catch tuna. However, development of small pond aquaculture where there is adequate fresh water[3,45] (Chapter 11), and scaling-up fisheries for small pelagic fish (Chapter 9), also have potential to make substantial contributions to the fish required at the local level, and modest contributions nationally.

  In some of the more economically developed PICTs in Group 3 (e.g. American Samoa, Guam and CNMI), purchases of local and imported canned tuna can also provide much of the fish required. The relatively high GDP per person in these three PICTs (Appendix 12.1) also means that many people there will have the ability to purchase other sources of animal protein and may not always need 35 kg of fish per year for good nutrition. Nevertheless, all PICTs in Group 3 have been analysed in the same way.

To determine whether the plans described above could be derailed by climate change, we estimated the effects of the projected changes in coastal fisheries production (and freshwater fisheries production where relevant) under the B1 and A2 emissions scenarios on future availability of fish per person, over and above the effects of population growth (see Appendix 12.2 for the methods involved).

Due to the strong interest in this issue in the region[44,47,58,59] we analysed the effects of population growth and climate change on the supply of fish for food security in 2035, 2050 and 2100 to provide assessments for the near, mid and long term. Projections are provided for the B1 and A2 emissions scenarios in 2035 and for B1 in 2100 and A2 in 2100, but only for A2 in 2050, where we have used the projected effects for B1 in 2100 as a surrogate for A2 in 2050 (Chapter 1). The predicted populations of PICTs in 2035 are given in Chapter 1, and for 2050 and 2100 in Appendix 12.3. The methods used to make the predictions for 2100 are given in Appendix 12.4.

12.7.2 Vulnerability of Group 1

Based on access to coastal fisheries resources alone, availability of fish per person is not at risk of falling below the recommended 35 kg per year or the higher levels of traditional fish consumption for PICTs in Group 1, even under the A2 scenario in 2100 (Table 12.10). This is due to the large areas of coral reef relative to population size in these countries and territories, and the prediction that population growth will be stagnant or negative due to emigration in several of these PICTs.

Table 12.10 Estimates of fish available per person for the B1/A2 emissions scenarios in 2035, A2 in 2050, and B1 and A2 in 2100 for Pacific Island countries and territories (PICTs) in Group 1 (Section 12.7.1). These estimates assume sustainable fisheries production of 3 tonnes per km^2 of coral reef per year. See Appendix 12.2 for a description of methods and Supplementary Tables 12.11–12.14 (www.spc.int/climate-change/fisheries/assessment/chapters/12-supp-tables.pdf) for details of calculations.

PICT*	Reef area (km^2)**	Estimated potential fish yield per km^2 per year (tonnes)	Population***			Fish available per person per year (kg)[a]			
			2035	2050	2100	B1/A2 2035	A2 2050	B1 2100	A2 2100
Melanesia									
New Caledonia	35,925	107,775	322,500	343,000	372,000	326	268	245	215
Micronesia									
Marshall Islands	13,930	41,790	62,700	61,200	61,000	644	566	558	484
Palau	2496	7488	22,700	22,500	22,000	320	283	279	250
Polynesia									
Cook Islands	667	2000	16,900	16,900	16,000	115	101	107	92
Tokelau	204	612	12,800	1150	1150	495	451	451	388

* Pitcairn Islands not included but estimates of fish available per person per year exceed 900 kg for all scenarios; ** derived from Chapter 5; *** source: SPC Statistics for Development Programme; a = includes invertebrates.

In the unlikely event that sustainable production of fisheries from coral reefs in PICTs in Group 1 averages only 1 tonne per km^2 per year, the availability of fish per person per year, even under the A2 scenario in 2100, is still estimated to be more than twice the recommended level for good nutrition (Table 12.11). The exception is Cook Islands, where 31 kg of fish per person per year would be available.

Tuna are also caught by small-scale subsistence and artisanal fisheries in PICTs in Group 1 (Chapter 9) but are not included in the analyses because they do not depend directly on coastal habitats (Chapters 4 and 8). However, the ability of PICTs in Group 1 to provide sufficient fish for food security is strengthened further by the projections that their access to tuna is expected to increase substantially under a warmer climate (**Table 12.7**). The exception is Palau in 2100 under the A2 scenario, where catches of tuna are projected to decrease by > 25%.

Table 12.11 Relative effects of population growth (P) and climate change emissions scenarios (B1, A2) on future availability of fish in the three groups of Pacific Island countries and territories (PICTs) (Section 12.7.1). Values are estimated averages of fish available per person per year (kg) for all PICTs in the group due to population growth alone, and for the combined effects of population growth and climate change under the B1/A2 emissions scenarios in 2035, A2 in 2050, and B1 and A2 in 2100. Estimates are for three levels of fisheries production: 3 tonnes per km^2 of coral reef per year (considered to be most likely), 1 tonne per km^2 per year (to represent reefs where resource status is poor to medium and fishing pressure is high), and 5 tonnes per km^2 per year (for reefs where the status of resources is medium to good and fishing pressure is low). Note that Group 3 includes contributions from freshwater fish, which are held constant.

Group	Tonnes of fish per km^2 per year	Availability of fish per person per year (kg)						
		2035		2050		2100		
		P	B1/A2	P	A2	P	B1	A2
1*	1	130	125	130	110	130	110	95
	3	390	375	390	330	390	330	285
	5	650	625	650	550	650	550	475
2	1	90	86	85	71	75	62	54
	3	270	258	255	213	225	186	162
	5	450	430	425	355	375	310	270
3	1	5.7	5.6	5.0	4.7	3.9	3.4	3.1
	3	15.2	14.8	13.7	11.8	10.5	9.0	7.9
	5	24.8	24.1	22.2	19.0	17.1	14.7	12.8

* Average does not include Pitcairn Islands.

12.7.3 Vulnerability of Group 2

The problems encountered by most PICTs that currently have the capacity to produce the fish needed for food security, but encounter difficulties in distributing it to population centres, are not generally expected to be exacerbated by climate change. Even under the A2 scenario, most PICTs in Group 2 are still expected to have the potential to produce enough fish to meet traditional levels of fish consumption (**Table 12.12**).

The exception is Kiribati under all scenarios (**Table 12.12**). In the unlikely event that all future production of reef-associated fish could be distributed effectively from remote islands to the main population centres, reefs in Kiribati are estimated to produce only

65 kg per person per year in 2050 under the A2 scenario, 50 kg per person under B1 in 2100 and 42 kg per person under A2 in 2100. Although such production supplies the recommended 35 kg of fish per person per year it is insufficient to maintain the traditionally high levels of fish consumption in Kiribati[3]. In French Polynesia, the potential annual reef fish production available per person is estimated to be 85 kg per person under A2 in 2100, which would be sufficient to maintain the traditionally high levels of consumption (Table 12.5) provided this fish can be distributed effectively.

Table 12.12 Estimates of fish available per person for the B1/A2 emissions scenarios in 2035, A2 in 2050, and B1 and A2 in 2100 for Pacific Island countries and territories (PICTs) in Group 2 (Section 12.7.1). These estimates assume sustainable fisheries production of 3 tonnes per km^2 of coral reef per year. See Appendix 12.2 for a description of methods and Supplementary Tables 12.15–12.18 (www.spc.int/climate-change/fisheries/assessment/chapters/12-supp-tables.pdf) for details of calculations.

PICT	Reef area (km^2)*	Estimated potential fish yield per km^2 per year (tonnes)	Population**			Fish available per person per year (kg)[a]			
			2035	2050	2100	B1/A2 2035	A2 2050	B1 2100	A2 2100
Micronesia									
FSM	15,074	45,222	105,300	109,300	109,300	418	352	352	307
Kiribati	4320	12,960	144,600	163,300	211,300	86[b]	65[b]	50[b]	42[b]
Polynesia									
French Polynesia	15,126	45,378	330,800	348,800	378,900	131	109	100	85
Niue	56	168	1200	1300	1300	125	114	114	104
Tonga	5811	17,433	115,000	123,000	146,900	145	116	97	81
Tuvalu	3175	9525	12,800	13,900	18,500	711	570	428	362
Wallis and Futuna	932	2796	13,600	13,600	13,600	197	171	172	145

* Derived from Chapter 5; ** source: SPC Statistics for Development Programme (see also Appendix 12.3); a = includes invertebrates; b = PICTs where availability of reef-associated fish per person is less than current rates of traditional fish consumption.

If reef-dependent fisheries in PICTs in Group 2 turn out to be less productive than the estimated median value for coral reefs in general, and yield only 1 tonne of fish per km^2 per year, average annual fish production would still be more than the recommended level of 35 kg per person per year under all climate change scenarios (Table 12.11). Notwithstanding the difficulties in distributing the potential production, this analysis masks the fact that access to fish in Kiribati would fall below the recommended level of 35 kg per person per year for all scenarios. Similar problems would also occur in French Polynesia and Tonga in 2100. On the other hand, if production from reef-dependent fisheries is higher than the median estimate, at 5 tonnes per km^2 per year, the potential availability of fish per person for PICTs in Group 2 far exceeds traditional levels of fish consumption, except in Kiribati under A2 in 2100.

The good news for most PICTs in Group 2 is that the plans they need to make to provide better access to tuna to fill any shortfall in supply of reef-associated fish, due to difficulties in distribution of catches (Section 12.7.1), are expected to be enhanced by the projected changes in the distribution and abundance of tuna (Chapter 8). This is especially important for Kiribati and French Polynesia, where catches of skipjack tuna are projected to increase by > 35% in 2035 (**Table 12.7**). FSM is the exception in 2100 under the A2 scenario, when abundances of skipjack tuna are projected to decline by > 25% (**Table 12.7**).

12.7.4 Vulnerability of Group 3

PICTs in Group 3 are in a very different situation to those in Groups 1 and 2. Based on median estimated production of reef-associated fish and invertebrates of 3 tonnes per km^2 per year[21], and current freshwater fish production[4] (Chapter 10), many of the PICTs in Group 3 were already facing a very large gap in the fish needed for good nutrition of their populations in 2010 (**Table 12.13**). Fiji and Solomon Islands are the exceptions – their coastal and freshwater fisheries are currently likely to be producing > 35 kg of fish per person per year. Coastal fisheries in Samoa are estimated to produce close to the recommended quantities of fish. On the other hand, reefs in Nauru and Guam only provide a small fraction of the fish required. The gap in PNG only applies to coastal communities and those living close to freshwater habitats – the gap is far greater for the very large inland populations which have little access to fish[3].

Due to the complexity of the situation for PICTs in Group 3, we present their vulnerability to shortages of fish due to population growth and climate change separately, rather than together as done for Groups 1 and 2 above.

12.7.4.1 Vulnerability to shortages of fish due to population growth alone

The large predicted growth in the populations of PNG, Solomon Islands and Vanuatu causes the projected availability of fish per person to decline substantially in 2035, 2050 and 2100 (**Table 12.13**). The changes in Solomon Islands are particularly dramatic – the estimated fish surplus of 15 kg per person per year in 2010 changes to a shortfall of 7 kg in 2035, 13 kg in 2050 and 21 kg in 2100. The gap also continues to widen for all PICTs in Group 3 over time, although it does not increase substantially for Guam, Nauru and CNMI because the shortfalls in fish required for good nutrition based on coastal fisheries production of 3 tonnes per km^2 per year in these four PICTs are already very large (**Table 12.13**).

Even if sustainable fisheries production from coral reefs is considered to be 5 tonnes per km^2 per year, there would still be an average shortfall in the recommended access to 35 kg of fish per person per year of 10 kg in 2035, 13 kg in 2050 and 18 kg in 2100 for PICTs in Group 3 (**Table 12.11**). The exceptions are Fiji, Samoa and Solomon Islands, where such rates of production would meet the recommended supply of fish for good nutrition in Fiji and Samoa until 2100, and in Solomon Islands until 2050. On the other hand, if sustainable production is only 1 tonne per km^2 per year, the average gap to be filled between the fish needed for good nutrition and the fish available is projected to be ~ 30–32 kg from 2035 onwards, and ranges from 20–35 kg per person per year for all PICTs in Group 3.

Table 12.13 Gap between the recommended fish consumption of 35 kg per person per year, and the estimated annual supply of fish per person from coastal (reef-associated) and freshwater fisheries in 2010, 2035, 2050 and 2100 for each of the Pacific Island countries and territories (PICTs) in Group 3 (Section 12.7.1). Note that these projected gaps do not incorporate the impacts of climate change, and are based on sustainable fisheries production of 3 tonnes per km^2 of coral reef per year. See Appendix 12.5 for estimates of reef area, fish production and predicted populations of PICTs in 2010, 2035, 2050 and 2100 used to calculate total fish available per person and the gap in fish needed per person.

PICT	Total fish available per person per year (kg)				Gap in fish needed for good nutrition per person per year (kg)			
	2010	2035	2050	2100	2010	2035	2050	2100
Melanesia								
Fiji	40	35	32	26	+(5)	0	3	9
PNG	12	8	6	4	23	27	29	31
Solomon Islands	50	28	23	14	+(15)	7	12	21
Vanuatu	16	10	8	6	19	25	27	29
Micronesia								
Guam	4	3	3	2	31	32	32	33
Nauru	2	1	1	1	33	34	34	34
CNMI	12	10	9	9	23	25	26	26
Polynesia								
American Samoa	17	13	11	8	18	22	24	27
Samoa	33	30	29	25	2	5	6	10

+ Indicates that there is no gap (surplus fish).

12.7.4.2 Increased vulnerability due to climate change

Climate change is expected to have relatively minor effects on availability of fish per person compared to those due to population growth for PICTs in Group 3. When the projected effects of the B1 and A2 emissions scenarios in 2035, A2 in 2050, B1 in 2100 and A2 in 2100 on the abundances of coastal and freshwater fish (Chapters 9 and 10) are added to the effects of population growth, the access to fish per person decreases by only 1–2 kg under all scenarios for most PICTs in Group 3. There are two main reasons for this. First, a very large gap already exists between the amount of fish needed for good nutrition and the estimated sustainable harvests from the areas of coral reef and associated coastal habitats in many of these PICTs (**Table 12.13**). Second, the effects of population growth on availability of reef-associated fish per person are profound (**Table 12.13**), leaving little scope for climate change to increase the gap further. Varying the estimates of sustainable coastal fisheries production from 1 tonne to 5 tonnes per km^2 does not alter this basic pattern substantially (**Table 12.11**).

The exceptions are Fiji, Solomon Islands and Samoa[xix]. The effects of climate change on the supply of coastal fish, over and above those caused by population growth, for Fiji and Solomon Islands are shown in **Figure 12.4**. In both countries, the additional gap in the fish required due to climate change is expected to be relatively small initially, and becomes more noticeable in 2050 and 2100.

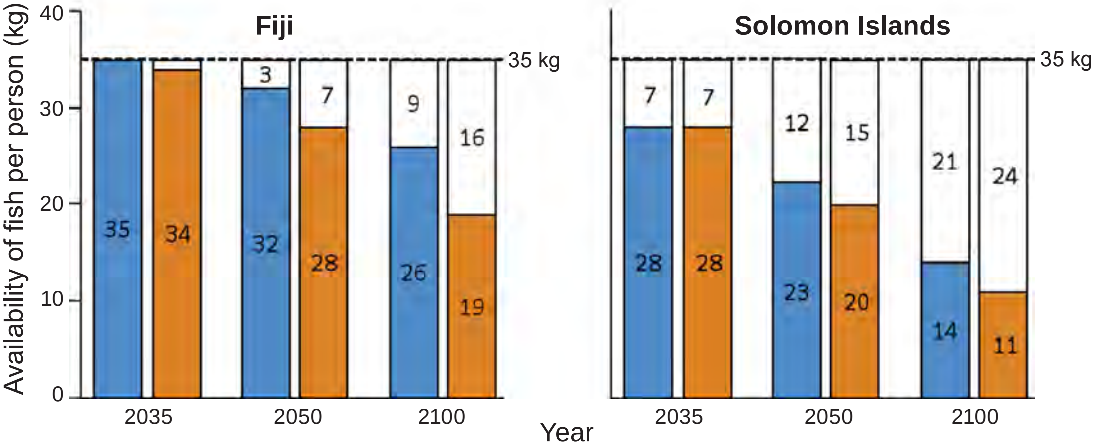

Figure 12.4 Relative effects of population growth and the A2 emissions scenario on the gap between recommended annual fish consumption of 35 kg per person, and the estimated annual supply of fish from coastal and freshwater fisheries in 2035, 2050 and 2100 for Fiji and Solomon Islands; 🟦 = availability of fish per person due to the effects of population growth alone; 🟧 = availability of fish per person remaining after the combined effects of population growth and climate change. See Appendix 12.2 and Supplementary Tables 12.19–12.22 (www.spc.int/climate-change/fisheries/assessment/chapters/12-supp-tables.pdf) for methods used to estimate the additional gap due to climate change.

12.7.4.3 Relative vulnerability of PICTs in Group 3

Estimating how climate change is likely to add to the effects of population growth on the availability of fish per person is not the only way to assess the vulnerability of PICTs in Group 3 to shortages of fish for food security. Because these PICTs vary in their traditional dependence on fish, and their capacity to adapt to changing conditions, we have also applied the vulnerability framework described in Chapter 1 and Section 12.5. This analysis assesses the relative vulnerability of PICTs in Group 3 to the use of fish for food in the face of population growth and climate change (in the absence of the plans to increase access to fish mentioned in Section 12.7.1).

We estimated exposure to shortages of fish in each PICT for the B1 and A2 scenarios in 2035, A2 in 2050, and B1 and A2 in 2100, using an index based on the availability per person (kg) of (1) demersal fish, non-tuna nearshore pelagic fish and shallow subtidal and intertidal invertebrates in proportion to their contributions to the estimated production of 3 tonnes per km^2 per year, and (2) freshwater fish based on

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[xix] Compare Supplementary Tables 12.19–12.22 (www.spc.int/climate-change/fisheries/assessment/chapters/12-supp-tables.pdf) with **Table 12.13**.

current national catches[4,xx]. Although tuna contribute to coastal fisheries in several PICTs in Group 3 (Chapter 9), we have not included them in the exposure index for the reasons outlined in Appendix 12.2. The availability of all reef-associated fish and invertebrates, and freshwater fish, was modified by the projected changes to their production under each scenario (Appendix 12.2). The resulting total availability of fish per person was then deducted from the 35 kg per person required for good nutrition to estimate the exposure (E) of each PICT.

Sensitivity (S) was estimated as the recommended level of fish consumption for good nutrition (35 kg per person per year)[3,40], or higher national levels of consumption where these occur[3,4,60]. Potential impact (PI) was estimated as E x S, and then standardised and normalised.

The capacity of PICTs in Group 3 to adapt to shortages in the supply of fish was calculated differently to the adaptive capacity index used to assess the vulnerability of economic development and government revenue (Appendix 12.1). This was done because, in the absence of plans to provide greater access to other sources of fish, purchasing power plays a greater role in allowing individuals to acquire fish. Therefore, the adaptive capacity index for food security (AC) was estimated by weighting the values for the size of the economy (purchasing power) by 0.5, and the indices for health, education and governance by 0.167 (Appendix 12.1).

Vulnerability was estimated by multiplying PI x (1 - AC), so that the potential impact on PICTs in Group 3 with the greatest adaptive capacity was reduced relative to PICTs with poor adaptive capacity.

In 2035 under the B1 and A2 scenarios, Fiji has a very low vulnerability (**Table 12.14**) to shortages of fish because estimated harvests are largely projected to provide 35 kg of fish per person per year for the increased population. Solomon Islands has a low vulnerability because the shortfall of 7 kg of reef-associated and freshwater fish per person per year projected to occur there is much lower than for most other PICTs except Samoa, which has a moderate vulnerability due to its traditionally high fish consumption (**Table 12.5**). Guam also has a moderate vulnerability but for a different reason – the potential impact of the great shortages of reef-associated fish per person expected to occur there is reduced by substantial national adaptive capacity. The vulnerability of CNMI is high rather than very high for similar reasons. American Samoa, Nauru, PNG and Vanuatu have a very high vulnerability to shortages in the recommended, or traditional, levels of fish consumption because of the projected limitations to the amount of fish available per person and weak adaptive capacity (**Table 12.14**).

As indicated in Section 12.7.4, the aspirations to provide 35 kg of fish per person for the large inland communities in PNG are unrealistic. PNG would be expected to have a somewhat reduced, but still high, vulnerability to shortages of fish in the future if

[xx] See Supplementary Tables 12.23–12.26 (www.spc.int/climate-change/fisheries/assessment/chapters/12-supp-tables.pdf).

the present-day rate of fish consumption per person (**Table 12.5**) was used to assess vulnerability.

These general patterns of vulnerability are expected to be maintained in all PICTs in Group 3 under A2 in 2050, and B1 and A2 in 2100, except Samoa, Guam, Vanuatu and Solomon Islands (**Table 12.14**). The vulnerability of Samoa increases from moderate in 2050 to high in 2100 due to substantial decreases in access to fish per person. A similar trend also occurs in American Samoa. The relatively rapid increases in vulnerability scores in Samoa, and in America Samoa[xxi], reduces the relative vulnerability of Guam, which decreases from moderate in 2050 to low in 2100, and Vanuatu, which declines from very high in 2050 to high in 2100. The relative vulnerability of Solomon Islands increases from low in 2035 to moderate to high in 2050 and 2100 (**Table 12.14**).

Table 12.14 Relative vulnerability scores of Pacific Island countries and territories (PICTs) in Group 3 to the availability of coastal (reef-associated) and freshwater fish for food security under the B1/A2 emissions scenarios for 2035, A2 for 2050, and B1 and A2 in 2100. Scores have been classified as very low (0.00–0.05), low (0.06–0.10), moderate (0.11–0.20), high (0.21–0.30) or very high (> 0.30). See Supplementary Tables 12.23–12.26 (www.spc.int/climate-change/fisheries/assessment/chapters/12-supp-tables.pdf) for exact vulnerability scores and the values of indices for exposure, sensitivity, potential impact and adaptive capacity used to calculate the scores.

PICT	Emissions scenarios			
	B1/A2 2035	A2 2050	B1 2100	A2 2100
Melanesia				
Fiji	Very low	Very Low	Very Low	Very Low
PNG	Very High	Very High	Very High	Very High
Solomon Islands	Low	Moderate	High	Moderate
Vanuatu	Very High	Very High	High	High
Micronesia				
Guam	Moderate	Moderate	Low	Low
Nauru	Very high	Very high	Very high	Very high
CNMI	High	High	High	High
Polynesia				
American Samoa	Very high	Very high	Very high	Very high
Samoa	Moderate	Moderate	High	High

12.7.4.4 Vulnerability of plans to increase access to fish in Group 3

The reality is that although reef-associated fish and invertebrates have long been the main source of food for PICTs, tuna have also provided a significant amount of the fish captured by coastal fisheries for local consumption (Chapter 9). Considering the very large gap to be filled between the amount of fish needed for good nutrition and the reduced quantities of reef-associated and freshwater fish available per person due to the combined effects of population growth and climate change (Section 12.7.4.2), PICTs in Group 3 will need to depend heavily on the plans to use tuna to meet the shortfall in supply of fish for food security (Section 12.7.1).

[xxi] See Supplementary Tables 12.23–12.26 (www.spc.int/climate-change/fisheries/assessment/chapters/12-supp-tables.pdf).

Potential contributions from pond aquaculture could help diversify local fish production but will be minor compared to the contributions that tuna can make at the national level. Assuming there is adequate investment in farming systems and progressive development, pond aquaculture has the potential to supply up to 1 kg of fish per person at the national level by 2035, 2 kg by 2050 and 4 kg by 2100 in PICTs in Group 3, except American Samoa, Guam, Nauru and CNMI where areas for construction of ponds are limited (Chapter 11). This potential rate of production may also be hard to achieve in PNG due to the predicted growth of the already large population.

Overall, however, many PICTs in Group 3 will need to provide access to an additional 20–30 kg of tuna per person per year by 2035 to supply the fish recommended for good nutrition. In PICTs where only relatively small quantities of tuna are harvested within their EEZs (American Samoa, Guam, CNMI), this access will depend heavily on local or imported canned tuna. The quantities of tuna required in Fiji, Solomon Islands and Samoa are smaller but significant nonetheless. Assuming that pond aquaculture fulfills its considerable potential in Fiji (Chapter 11), access will be needed to an additional 5 kg of tuna per person in 2050, and 10 kg in 2100. In Solomon Islands, an additional 5 kg of tuna per person will need to be made available for food security in 2035, increasing to 15 kg in 2050 and 20 kg in 2100. The corresponding quantities for Samoa are 5 kg in 2035, 7 kg in 2050 and 12 kg in 2100.

The good news is that access to tuna for all PICTs in Group 3 is expected to increase in 2035 (**Table 12.7**). Production of pond aquaculture is also expected to be aided by increased temperatures and higher rainfalls in 2035, provided ponds are built where they will not be affected by floods (Chapter 11).

The benefits of climate change for the plans to increase access to fish are expected to continue for most PICTs in Group 3 in 2050 and 2100. PNG and Solomon Islands are the main exceptions – catches of skipjack tuna in their EEZs are projected to fall by ~ 11% and 5% under A2 in 2050, and by ~ 30% and 15% under A2 in 2100, respectively (**Table 12.7**). However, PNG and Solomon Islands are still expected to continue to make relatively large catches of tuna despite the projected decreases. These catches should be sufficient to provide access to the fish needed for food security, and to support substantial industrial fisheries and processing operations (Section 12.9.3.3). Catches of skipjack tuna are also projected to fall slightly in Guam and Nauru under the A2 scenario in 2100 (**Table 12.7**).

12.8 Vulnerability of plans to create additional livelihoods

The plans to increase the number of livelihoods derived from fisheries and aquaculture in the region (Section 12.4.2) are expected to be either progressively enhanced or retarded by climate change, depending on the resource involved (**Table 12.15**).

By 2035, the changing climate is expected to make more skipjack tuna available in both the western and eastern parts of the region (but particularly in the east) (**Table 12.7**), creating more scope for jobs on fishing vessels and in processing plants, provided plans to increase the 'domestication' of these industries (Section 12.2.2) are successful. Opportunities to increase the number of livelihoods based on the capture of nearshore pelagic fish species by coastal fisheries are also expected to increase substantially in the eastern part of the region due to the higher projected abundances of skipjack and yellowfin tuna there (Chapter 8). Although good opportunities for new livelihoods based on the tuna component of nearshore pelagic fish should also exist in the west (Section 2.2.4), they will not be favoured by climate change to the same extent because the nearshore pelagic fishery is dominated by non-tuna species, such as Spanish mackerel, which are more closely associated with coral reefs (Chapter 9).

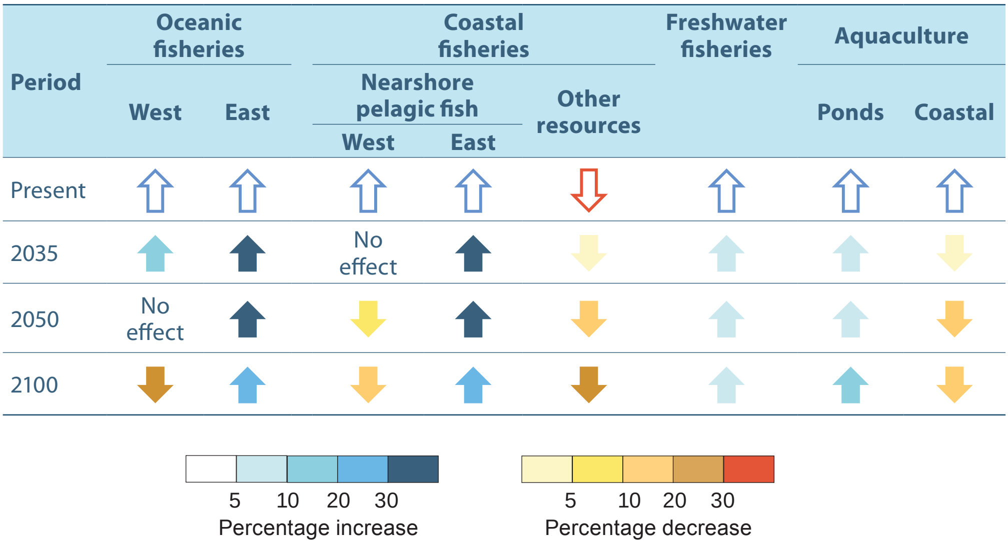
Other commercial coastal fisheries resources (demersal fish and invertebrates targeted for export) are also expected to decline slightly because of increasing CO_2 emissions by 2035 (Chapter 9), limiting opportunities to create more livelihoods, over and above the gains that could be made from effective management in the interim. The projected degradation of coastal habitats, and increase in sea surface temperatures and ocean acidification, are also expected to affect production from coastal aquaculture by 2035 (Chapter 11). This is not the case for freshwater pond aquaculture, however, which is likely to be boosted throughout much of Melanesia by the projected increases in rainfall and water temperatures. Slight increases in opportunities to earn income from freshwater fisheries in PNG are also expected for the same reasons (Chapter 10).

These patterns are likely to be maintained in 2050, except that no increases in the catch of skipjack tuna by industrial fleets, and a decrease in the catch of nearshore pelagic fish by coastal fisheries, may occur in the west (**Table 12.15**). The general patterns described for 2035, and the changing trends for 2050, are expected to strengthen by 2100 (**Table 12.15**), although there is increased uncertainty about the distribution and abundance of skipjack tuna in 2100 (Chapter 8). The exception is in the western part of the region, where catches of skipjack tuna are projected to decrease by > 20% in 2100 (**Table 12.7**), potentially resulting in fewer jobs based on fishing for tuna.

We have not done a formal analysis of the relative vulnerability among PICTs of the plans to optimise the number of livelihoods that could be created from the resources that underpin fisheries and aquaculture in the region. Such an analysis would be difficult given the problems involved in (1) constructing composite indices for exposure and sensitivity across the various oceanic and coastal fisheries and aquaculture resources involved; and (2) weighting the various components of exposure and sensitivity indices due to insufficient data on the jobs based on each resource. Instead, each PICT should be able to ascertain the general direction and magnitude of the likely impact of climate change on their plans to create livelihoods across the sector as a whole from the information in **Table 12.15**.

It is also important to note that the vulnerability of plans to maximise the number of livelihoods that can be derived from fisheries and aquaculture does not depend only on the projected future status of resources. Climate change can affect other aspects of people's lives and livelihoods directly and indirectly, for example, through inundation of coastal land, destruction of coastal infrastructure, or impacts on non-fishing features of coastal livelihood systems, including agriculture. Also, climate change is not the only large-scale driver of change in employment opportunities in fisheries and aquaculture. Other drivers include technological change (e.g. substitution of labour by technology), changing demographics (rural-urban migration, international labour migration), shifts in culture, educational attainment and lifestyle aspirations[7,61,62].

Table 12.15 Summary of the direction of present existing plans (outlined arrows) to derive more livelihoods from the various fisheries and aquaculture resources in the tropical Pacific. The projected effects of the A2 emissions scenario in 2035, 2050 and 2100 on the outcomes of these plans, in terms of percentage increases or decreases, are also shown. ⇧ = increased opportunities, ⇩ = decreased opportunities.



Period	Oceanic fisheries		Coastal fisheries			Freshwater fisheries	Aquaculture	
	West	East	Nearshore pelagic fish West	Nearshore pelagic fish East	Other resources		Ponds	Coastal
Present	⇧	⇧	⇧	⇧	⇩	⇧	⇧	⇧
2035	⬆	⬆	No effect	⬆	⬇	⬆	⬆	⬇
2050	No effect	⬆	⬇	⬆	⬇	⬆	⬆	⬇
2100	⬇	⬆	⬇	⬆	⬇	⬆	⬆	⬇

12.9 Implications

12.9.1 Economic development and government revenue

On balance, the projected changes in catches for the surface tuna fishery from the preliminary modelling – increases in the east and decreases in the west – indicate that there could be more advantages than disadvantages for the region. The possible advantages are that the significant contributions that licence fees already make to government revenue in Kiribati, Tuvalu, Tokelau and Nauru (**Table 12.2**) would be expected to increase as catch rates improve in their EEZs, giving these PICTs the opportunity to negotiate for increased revenue. These projected benefits are expected to endure until 2100 under the A2 emissions scenario for Kiribati, Tuvalu and Tokelau, but only until 2050 for Nauru (**Table 12.9**). More modest benefits to government revenue are also expected for American Samoa, FSM and Marshall Islands until 2050 under the A2 scenario.

Gross domestic product in Marshall Islands is also projected to increase until 2100 as a result of greater catches by their industrial fleet (**Table 12.9**). Similarly, canning operations in American Samoa are expected to benefit from the more eastern distribution of skipjack tuna until 2050 under A2 (**Table 12.9**). Fiji may also have better access to fish for processing in the future.

These benefits will depend on PICTs (1) continuing to develop more flexible management systems to cope with the changing spatial distribution of tuna stocks and fishing effort, and (2) limiting overall catches from the WCPO to recommended levels (Chapter 13).

The potential disadvantages are that the progressive movement of skipjack tuna, and ultimately fishing effort (Section 12.6), further to the east may eventually affect the contribution of fishing and processing operations to GDP, and licence fees to government revenue, for some PICTs in the western part of the region (FSM, Palau, PNG and Solomon Islands). In particular, the plans to expand industrial fishing and processing in PNG and Solomon Islands to domesticate more of the benefits from tuna resources could be affected. To obtain sufficient skipjack and yellowfin tuna to supply processing plants, PNG and Solomon Islands may have to (1) reduce the access of distant water fishing nations to their EEZ to provide more fish for national vessels; (2) require distant water fishing nations operating with their zone to land a proportion of catches for use by local canneries; (3) enhance existing arrangements for their national fleet to fish in other EEZs, and (4) create incentives for tuna caught in other EEZs to be landed in their ports (Chapter 13).

Clearly, the likely effects of climate change on catches of skipjack and yellowfin tuna, and the feasibility of obtaining the fish required in the future, need to be considered when planning the expansion of national fleets, construction of new canneries and loining plants, and development of any additional transshipping ports.

In the event that the four measures described above are not entirely successful in supplying the fish required, or incur costs that affect the profitability of processing operations, production from canneries would be curtailed. Any such effects would also exacerbate problems that canneries in PNG may have in the future if the present import tariff advantages conferred by the IEPA with the EU (Section 12.2.2) are eventually eroded or lost. Overall, however, the effects of any decline in industrial fishing and processing due to climate change on the GDP of PNG and Solomon Islands would be limited because industrial fishing and processing make relatively small contributions to the national economies of these PICTs (**Tables 12.2** and **12.9**).

It is also important to note that the potential opportunities for PICTs in the east arising from altered distributions of tuna due to climate change may be tempered, and the disadvantages for PICTs in the west reinforced, by (1) the prospect that increasing fuel prices will increase the costs of catching and transporting fish, especially for longline fleets[63]; (2) the costs involved in upgrading fleets operating or based in subtropical PICTs to provide acceptable standards of safety at sea[64,65] during more severe storms (Chapter 2); and (3) the projected effects of sea-level rise (Chapter 3), which are eventually expected to result in some wharfs and shore-based facilities having to be rebuilt or relocated, and 'climate proofing' of future infrastructure.

We stress that the possible implications outlined above are based on preliminary modelling of the effects of climate change on tuna stocks. The projected implications will need to be revised regularly as investments are made in models capable of simulations with greater certainty (Chapter 13).

12.9.2 Food security

12.9.2.1 Group 1

There are few implications from the projected effects of climate change on coastal fisheries for the plans to use fish for food security in Cook Islands, Marshall Islands, New Caledonia, Palau, Pitcairn Islands and Tokelau. All these PICTs will continue to have large ratios of coral reef area per person under predicted rates of population growth. Even the greatest projected decrease in production of fish associated with coral reefs under the A2 emissions scenario in 2100 (Chapter 9), is not expected to affect access to the fish needed for food security. In addition, the local abundance of skipjack and yellowfin tuna, which comprise part of the nearshore pelagic fish component of coastal fisheries in these PICTs (Chapter 9), is expected to increase under climate change (**Table 12.7**).

One possible implication is that small-scale commercial fishers supplying urban markets may have to travel greater distances to maintain harvest levels because catch per unit effort of reef-associated fish and invertebrates can be expected to decrease as coral reefs degrade (Chapter 5). A possible increase in ciguatera in PICTs outside the equatorial zone (Chapter 9), and future increases in the cost of fuel[4,7], would compound this situation. To avoid the higher costs of travelling further to fish, or transporting fish greater distances to urban centres, it may be necessary to supplement local reef-based fish production with catches of tuna around anchored inshore FADs. Such investments are expected to be favoured by the re-distribution of tuna due to the changing climate (Chapter 8). However, this intervention is unlikely to be appropriate for communities on the west coast of New Caledonia, where the distances involved in travelling to FADs outside the lagoon may be too great to make small-scale commercial tuna fishing operations economically viable.

12.9.2.2 Group 2

As mentioned in Section 12.7.3, climate change is not expected to significantly affect the potential availability of reef-associated fish per person in many of the PICTs in Group 2. However, Kiribati will need to find other ways to provide the fish needed to meet its traditionally high levels of fish consumption as the combined effects of population growth and climate change reduce the potential availability of fish. Investments in low-cost FADs anchored off Tarawa, and small-scale vessels to fish around them, may be needed to provide the urban population with access to tuna to fill the gap between the fish needed for food security and the fish available from reefs. In the event that such investments are not effective, Kiribati may need to consider negotiating with industrial vessels operating within their EEZ to land a proportion of their tuna catch on a regular basis to supply the local market. Similar considerations are also expected to apply to Papeete in French Polynesia under the A2 scenario in 2100, although there might not be the option to negotiate with industrial vessels unless the greater abundance of tuna in the EEZ leads to development of an industrial fishery (Section 12.9.1).

The combined effects of population growth and climate change can also be expected to have some implications for other PICTs in Group 2, especially Tonga. For the reason described for PICTs in Group 1, the catch per unit effort at locations from where it is cost-effective to send fish to the urban markets is likely to decrease over time, threatening the viability of small-scale fisheries based on reef-associated species. Increased costs for transporting catch to urban markets may prevent small-scale commercial fishing operations at more distant unfished locations. If so, governments will need to provide incentives for supplementing local reef-based fish production with catches from anchored FADs deployed close enough to urban centres to improve access to tuna.

Any risks associated with investing in fishing around low-cost FADs anchored inshore can be expected to reduce over time because skipjack and yellowfin tuna are projected to become more abundant in most PICTs in Group 2 under the B1 and A2 emissions scenarios (**Table 12.7**) (Chapter 8).

12.9.2.3 Group 3

The large shortfalls in the fish required for good nutrition, and the catches of fish likely to be available from reef-associated and freshwater habitats, have several profound implications for PICTs in Group 3. These implications centre around the need to make several rapid and effective decisions to provide access to the fish required for food security in the face of growing populations and climate change. These decisions are (1) improving the management of coastal and freshwater habitats, and fish stocks, to reduce the gap to be filled between the fish needed for food security and the sustainable harvests available from coastal and freshwater resources; (2) assessing how best to fill the gap with available resources (tuna) and potential fish production (pond aquaculture); (3) promoting the 'vehicles' needed to deliver the fish required; and (4) because tuna provides the greatest scope for supplementing the availability of fish for food security, allocating the appropriate proportion of the tuna catch to meet the needs for food security. The rationale for these decisions is explained below.

- **Improving management of natural resources:** Stocks of coastal and freshwater fish and invertebrates, and the habitats they depend on, will need to be managed as well as possible to minimise the gap between the amount of fish needed for good nutrition and the quantity of fish that can be harvested sustainably (**Figure 12.5**). This gap already exists in some PICTs (Section 12.7.4), and increases progressively in all PICTs in Group 3 due to population growth and the projected direct and indirect effects of climate change on stocks (**Table 12.13**). Good management will improve the opportunities for coastal and freshwater fish habitats and stocks to deliver their potential sustainable yields; it will also enable these natural resources to exercise their potential capacity to adapt to climate change (Chapters 5–7, 9 and 10). The key considerations and measures involved in optimising the management of coastal and freshwater habitats, and stocks of fish and invertebrates, are described in Chapter 13.
- **Assessing how best to fill the gap:** With the exception of Guam and Nauru, where either fresh or canned tuna is already required to provide the recommended 35 kg of fish per person per year, coastal fisheries presently have the potential to make substantial contributions to the fish needed for good nutrition (**Figure 12.6**). However, two striking patterns emerge from 2035 onwards:

    1. there is a progressive decline in the relative contribution of coastal fisheries to the fish needed for food security due to the limits on production from coral reefs, mangroves and seagrasses, and the projected direct and indirect effects of climate change on stocks (Chapter 9); and

    2. the progressive increase in the size of the gap to be filled due to population growth means that the great majority of the shortfall in fish required for food security will need to be met using tuna and the bycatch from industrial tuna purse-seine and longlining operations (**Figure 12.6**).

    The role of tuna in providing fish for PICTs in Group 3 in the future is profound – not only does the amount of fish needed increase over time; tuna has to supply an increasing percentage of the total fish required (**Figure 12.6**). It is fortunate indeed that the region has rich tuna resources, and that the preliminary modelling suggests that the most abundant species (skipjack tuna) is likely to be more abundant in the EEZs of many PICTs in Group 3 in the future (**Table 12.7**) (Chapter 8). This potentially important finding needs to be confirmed by more rigorous modelling, and complemented by modelling for yellowfin tuna. In addition, the tuna catch for local consumption should be included in the general tuna management framework of the Western and Central Pacific Fisheries Commission.

Pond aquaculture has potential to make locally important contributions, possibly amounting to ~ 10% of the total fish required nationally by 2100 in some PICTs. It is also fortunate that freshwater pond aquaculture is expected to be favoured by climate change (Chapter 11).

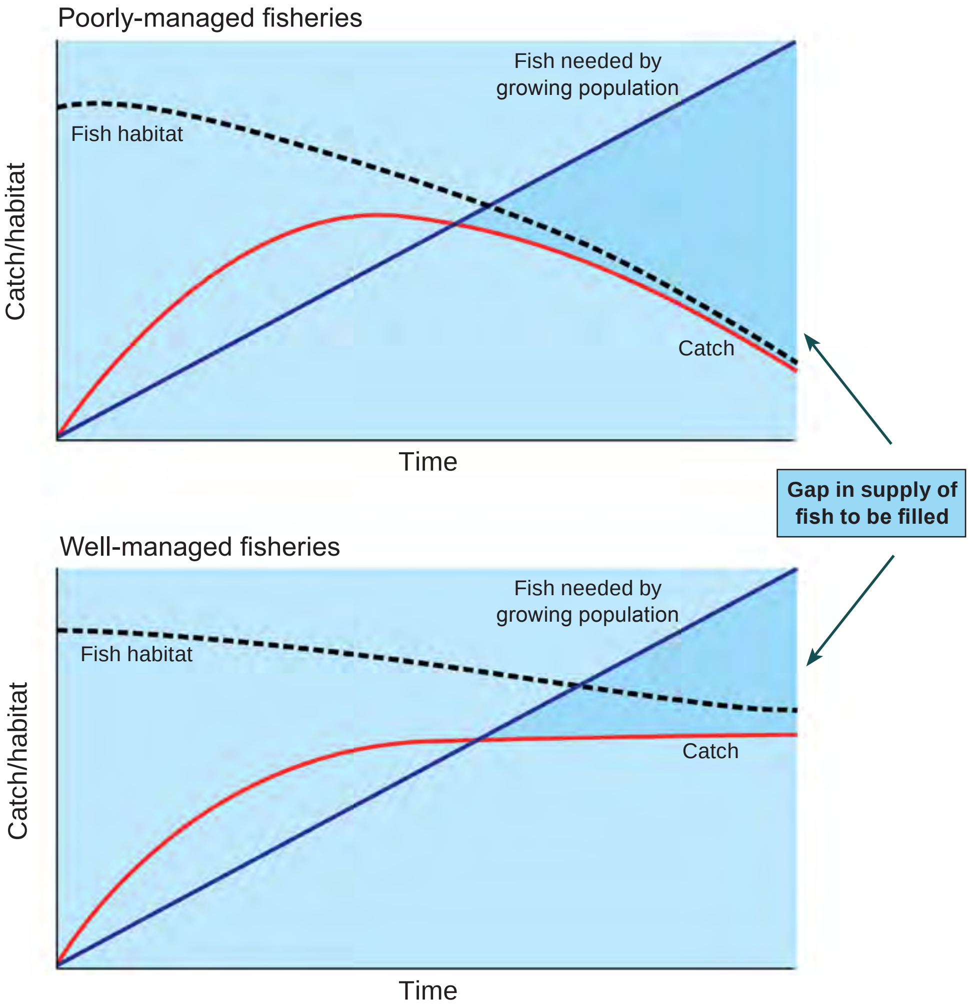
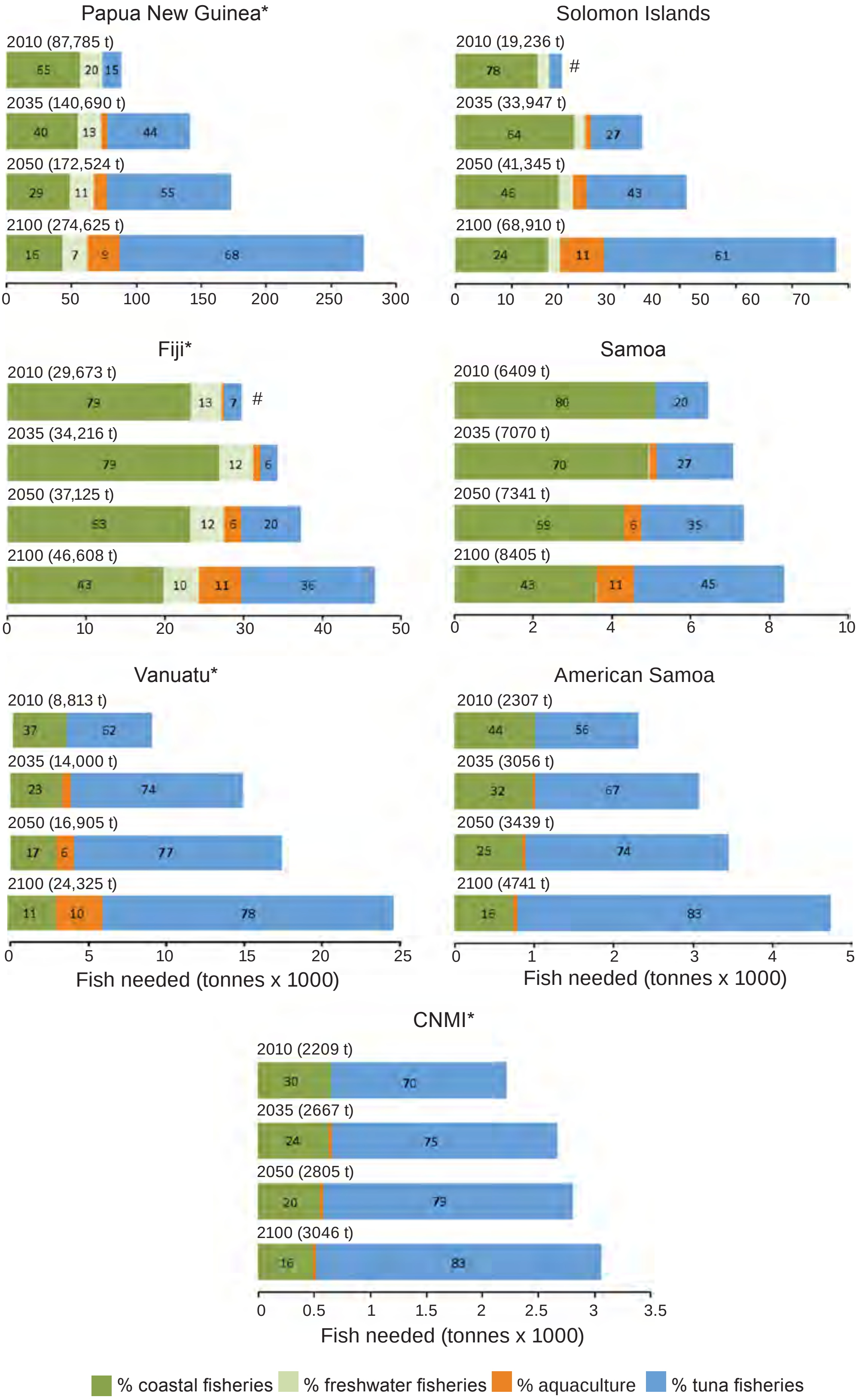


Figure 12.5 The importance of managing coastal and freshwater fish habitats and stocks well to minimise the gap between the fish required by rapidly growing populations in Pacific Island countries and territories in Group 3 for food security, and potential sustainable harvests of fish.


Papua New Guinea*
2010 (87,785 t)
65 20 15
2035 (140,690 t)
40 13 44
2050 (172,524 t)
29 11 55
2100 (274,625 t)
16 7 9 68
0 50 100 150 200 250 300
Solomon Islands
2010 (19,236 t)
78 #
2035 (33,947 t)
64 27
2050 (41,345 t)
46 43
2100 (68,910 t)
24 11 61
0 10 20 30 40 50 60 70
Fiji*
2010 (29,673 t)
79 13 7 #
2035 (34,216 t)
79 12 6
2050 (37,125 t)
53 12 6 20
2100 (46,608 t)
43 10 11 36
0 10 20 30 40 50
Samoa
2010 (6409 t)
80 20
2035 (7070 t)
70 27
2050 (7341 t)
59 6 35
2100 (8405 t)
43 11 45
0 2 4 6 8 10
Vanuatu*
2010 (8,813 t)
37 62
2035 (14,000 t)
23 74
2050 (16,905 t)
17 6 77
2100 (24,325 t)
11 10 78
0 5 10 15 20 25
Fish needed (tonnes x 1000)
American Samoa
2010 (2307 t)
44 56
2035 (3056 t)
32 67
2050 (3439 t)
25 74
2100 (4741 t)
16 83
0 1 2 3 4 5
Fish needed (tonnes x 1000)
CNMI*
2010 (2209 t)
30 70
2035 (2667 t)
24 75
2050 (2805 t)
20 79
2100 (3046 t)
16 83
0 0.5 1 1.5 2 2.5 3 3.5
Fish needed (tonnes x 1000)
% coastal fisheries
% freshwater fisheries
% aquaculture
% tuna fisheries

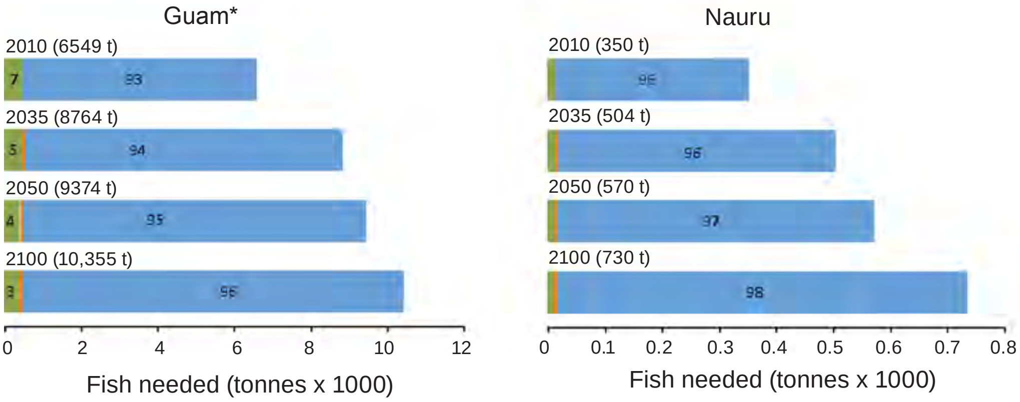


Figure 12.6 Percentage contributions of tuna (🟦), coastal fisheries (🟩), freshwater fisheries (▨) and aquaculture (🟧) required to supply 35 kg of fish per person per year for Pacific Island countries and territories (PICTs) in Group 3 in 2010, 2035, 2050 and 2100. Contributions from coastal fisheries are based on estimated sustainable production of 3 tonnes per km^2 of reef per year and have been adjusted for the projected effects of climate change (A2 emissions scenario) on the demersal fish, non-tuna nearshore pelagic fish and subtidal and intertidal invertebrates that comprise coastal fisheries (Appendix 12.2). * indicates PICTs that do not currently have national average fish consumption of ~ 35 kg per person per year; for all other PICTs estimates are limited to supplying 35 kg even though traditional rates of fish consumption may be greater (**Table 12.5**). The fish required for food security in PNG in the future is based on the estimated national average of 13 kg per person per year, rather than 35 kg, to reflect the difficulties of distributing fish to the large inland population. # indicates that coastal fisheries alone have the potential to provide 35 kg of fish per person in 2010 but estimated contributions from tuna and freshwater fisheries are also shown. 'Tuna' also includes bycatch from industrial tuna fishing vessels.

- **Promoting 'vehicles' to fill the gap:** PICTs in Group 3 will need to take active measures to promote the 'vehicles' described in Section 12.7.1 and Chapter 13 for catching and distributing tuna that allow both subsistence fishers in rural areas and urban populations to access this important resource in ways they can afford. Although, not all of the possible vehicles apply to every PICT in Group 3 (**Table 12.16**), many national governments will need to (1) establish networks of inshore FADs for the benefit of coastal communities as part of the national infrastructure for food security, and (2) provide incentives for enterprises in urban areas to store, distribute and sell lower grade (small) tuna and bycatch landed by industrial fleets (Chapter 13).

  To ensure that pond aquaculture can also fulfill its potential to help close the gap for inland communities with difficulty gaining access to tuna, governments will need to reconcile the use of pond aquaculture for food security with any possible effects on freshwater biodiversity[44,66] (Chapter 11), and implement the associated policies described in Chapter 13. The use of fish for food security in inland areas of PNG is expected to remain a problem, however, because pond aquaculture may only ever have the potential to supply 1–4 kg of fish per person per year. Transporting canned tuna produced by the expanding number of fish processing operations in PNG to inland communities is another possible way of increasing access to fish (see below). However, unless the benefits of the lucrative mining and gas industries in PNG flow to inland communities, they are unlikely to have the income to purchase more canned tuna.

Table 12.16 Possible vehicles for providing access to the additional fish needed for food security in Pacific Island countries and territories (PICTs) in Group 3.

PICT	Inshore FADs*	Landed tuna and bycatch	Local canned tuna	Imported canned tuna**	Pond aquaculture
Melanesia					
Fiji	x	Longline	x	x	x[a,e]
PNG	x	Purse-seine	x	x	x[a]
Solomon Islands	x	Purse-seine	x	x	x[b]
Vanuatu	x	Longline		x	x[a]
Micronesia					
Guam	x	Longline		x	x[c]
Nauru	x	No fish landed		x	x[d]
CNMI	x	Longline		x	x[c]
Polynesia					
American Samoa	x	Longline, purse-seine	x	x	x[c]
Samoa	x	Longline		x	x[a]

* FADs = low-cost, anchored fish aggregating devices; ** includes other fish caught and/or canned outside the region, e.g. mackerel; a = pond aquaculture established using tilapia; b = pond aquaculture using tilapia under consideration; c = limited capacity to expand pond aquaculture; d = limited capacity to expand pond aquaculture and milkfish is the preferred species; e = pond aquaculture of milkfish under development.

- **Allocating tuna for food security:** The quantities of tuna required for future food security in PNG and Solomon Islands dwarf the amounts needed by the other PICTs in Group 3 (**Figure 12.6**). Together with Nauru, PNG and Solomon Islands also stand out from the other PICTs in Group 3 as the only countries where recent catches of tuna from their national EEZs (and archipelagic waters) can directly supply the additional fish required for food security (**Table 12.17**).

  An important implication for PNG and Solomon Islands is that, due to the effects of population growth alone, an increasing proportion of annual average tuna catches will need to be allocated over time to provide the quantities of fish their populations need for good nutrition (**Table 12.17**). These proportions reach 22% and 16% for PNG and Solomon Islands, respectively, in 2050, increasing to 43% and 38% in 2100. The projected effects of the A2 emissions scenario on the distribution and abundance of skipjack tuna (**Table 12.7**) indicate that these proportions would increase marginally in 2050, and to ~ 60% for PNG and ~ 45% for Solomon Islands by 2100 (**Table 12.17**).

  Although some of this allocation will need to be given directly to coastal communities to catch tuna around inshore FADs, it is expected to have little effect on the profitability of tuna canneries in PNG and Solomon Islands because (1) the processing facilities already market substantial proportions of their products on the domestic market, and (2) canned tuna is one of the most practical vehicles for making more fish available to rapidly growing populations. Nevertheless, the implications for canneries of the relative benefits of sales to local markets versus export markets, and the costs involved in sourcing additional tuna from outside the EEZ if necessary, require formal economic cost: benefit analyses (Chapter 13).

Addressing the implications outlined in this section should not be deferred – they are urgent national priorities. Most PICTs in Group 3 are already facing major shortfalls in the fish needed for good nutrition of their populations (**Table 12.13**). Therefore, the most appropriate vehicles for filling the gap need to be identified and developed. Because such vehicles take time to establish or scale-up, even Fiji and Solomon Islands should embark on implementing them now.

Although low-cost FADs anchored in inshore waters to improve access to tuna for subsistence fishers are a large part of the solution, there is also a need to encourage small-scale commercial fishing operations around these FADs, and to develop fisheries for the smaller pelagic species. Catches made by commercial fishers not only help provide access to fish for households not engaged in harvesting, the income derived also improves food security[46].

Table 12.17 Average total tuna catch (2005–2009) taken in the EEZs of Papua New Guinea (PNG), Solomon Islands and Nauru, and the amount that would need to be allocated to provide the fish recommended for good nutrition of their populations in 2035, 2050 and 2100. Allocations are described as the percentages of average annual total tuna catch based on population growth alone (Popn) (**Table 12.7**), and on the reduced projected catch due to the effects of the A2 emissions scenario.

PICT	Average total tuna catch (tonnes)	Tuna needed for food								
		2035			2050			2100		
		Tonnes	% catch (Popn)	% catch (A2)	Tonnes	% catch (Popn)	% catch (A2)	Tonnes	% catch (Popn)	% catch (A2)
PNG	436,357	62,059	14	14	94,786	22	24	186,996	43	61
Solomon Islands	111,796	9289	8	8	17,919	16	17	42,286	38	45
Nauru	58,792	477	1	1	526	1	1	637	1	1

12.9.3 Livelihoods

The implications of the projected changes in production of oceanic, coastal and freshwater fisheries, and aquaculture, for plans to create additional sustainable livelihoods from these resources are that (1) more flexible arrangements may need to be made to ensure that tuna can be supplied cost-effectively to the existing and proposed canneries and loining enterprises in the region; and (2) livelihoods may need to be switched from one resource to another.

To ensure that the tuna processing plants in PNG and Solomon Islands obtain sufficient fish at reasonable prices as skipjack and yellowfin tuna move further east, the national governments may need to implement the measures outlined in Section 12.9.1. These measures include allocating more of the tuna within their EEZs to national fleets, negotiating access for their vessels to fish more regularly in other zones, and providing incentives for fish caught in the EEZs of neighbouring countries to be delivered to their canneries. Such measures may need to be introduced sooner rather than later if competition for canning tuna, driven by a potential global excess in processing capacity[67], limits the supply of fish to national canneries. A full Economic Partnership Agreement (EPA) with the EU should be of great assistance to PNG in this regard because it channels fish from the region destined for EU markets through PNG. Solomon Islands would also benefit from an IEPA and full EPA with the EU. The tuna canneries in Fiji, PNG and Solomon Islands provide regionally significant numbers of jobs (**Table 12.6**) and any reductions in their capacity can be expected to have substantial effects on many households in towns such as Levuka, Madang, Lae and Noro[68].

Within the coastal fisheries sector, the effort of small-scale fishers will need to be increasingly transferred from demersal fish associated with coral reefs, mangroves and seagrasses to nearshore pelagic species, particularly skipjack and yellowfin tuna. A practical way of doing this will be to invest in networks of anchored, inshore FADs, as described inSection 12.9.2. Transferring effort to nearshore pelagic species is not only expected to maintain the livelihoods of fishers as the projected declines in coastal fisheries occur (Chapter 9), it should create additional job opportunities in several PICTs because of the likely increases in the abundance of tuna (**Table 12.7**).

For aquaculture, much of the potential for growth in jobs is expected to be based on farming freshwater fish in ponds. Such enterprises are likely to be enhanced by the projected increases in rainfall and temperature. However, governments may need to provide incentives for the private sector to invest in the hatcheries and other infrastructure required to capitalise on these opportunities.

12.10 Conclusions

On balance, the Pacific Island countries and territories appear to be in a better position than nations in other regions to cope with the implications of climate change for fisheries and aquaculture. Although the changes in distribution and abundance of tuna projected from preliminary modelling are likely to require more flexible approaches for supplying existing and proposed canneries, and may eventually reduce GDP and/or government revenues slightly for a few countries in the western Pacific, the expected effects for the region as a whole are among the better possible outcomes. In particular, PICTs with the greatest dependence on tuna (e.g. Kiribati, Nauru, Tuvalu and Tokelau) are likely to receive greater benefits as the fish move east, whereas the projected decreases in production occur in those PICTs where industrial fishing and processing make only modest contributions to GDP and government revenue due to the relatively large size of their economies. The implications would have been much more severe if there was a redistribution of tuna from east to the west.

The rich tuna resources of the region also promise to provide PICTs in Groups 2 and 3 with options to deliver access to the fish recommended for good nutrition (except for populations in inland PNG) as the projected production of coastal fisheries declines due to the direct and indirect effects of climate change (Chapter 9). Even in countries like PNG and Solomon Islands, where abundances of tuna are projected to decline progessively, there should still be ample tuna to use for national food security – it is a matter of allocating the required proportion of average tuna catches for this purpose.

The increased rainfall expected to occur throughout the tropical Pacific in the future also provides several PICTs with the opportunity to increase access to fish through development of pond aquaculture. This is likely to be most important for the inland populations in Fiji, PNG and Solomon Islands, and for the rapidly growing urban populations in these countries. Higher future rainfall and water temperatures are also expected to improve the production of freshwater fisheries in Melanesia.

The various adaptations and policies needed to harness the opportunities for greater contributions from fisheries and aquaculture to economic development, food security and livelihoods expected to result from the changing climate, and the measures needed to reduce the threats, are described in detail in Chapter 13.

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Appendix 12.1 Indices used to assess the adaptive capacity of Pacific Island countries and territories

PICT	Adaptive capacity (AC)*										
	Health			Education			Governance index[c]	Size of economy		AC index Economic development[d]	AC index Food security[e]
	Infant mortality	Life expectancy	Index[a]	Literacy 15–24 years	Primary school enrolment	Index[b]		GDP per person	Index		
Melanesia											
Fiji	0.76	0.48	0.57	0.99	0.94	0.97	0.32	3175	0.09	0.49	0.35
New Caledonia	0.98	0.92	0.94	0.99	0.99	0.99	0.43	29,898	1.00	0.84	0.89
PNG	0.03	0	0.1	0.62	0.77	0.67	0.26	991	0.01	0.26	0.18
Solomon Islands	0.00	0.29	0.2	0.85	0.94	0.88	0.33	753	0.00	0.35	0.24
Vanuatu	0.67	0.56	0.6	0.87	0.93	0.89	0.59	2127	0.05	0.53	0.37
Micronesia											
FSM	0.47	0.54	0.52	0.95	1.00	0.97	0.56	2183	0.05	0.52	0.37
Guam	0.89	1	0.96	0.95	1.00	0.97	0.72	22,661	0.75	0.85	0.82
Kiribati	0.23	0.29	0.27	0.97	0.97	0.97	0.55	653	0	0.45	0.30
Marshall Islands	0.47	0.57	0.54	0.98	0.90	0.95	0.51	2851	0.08	0.52	0.37
Nauru	0.33	0.72	0.59	0.99	0.60	0.86	0.56	2807	0.07	0.52	0.37
CNMI	0.96	0.89	0.91	0.95	1.00	0.97	0.59	12,638	0.41	0.72	0.62
Palau	0.75	0.64	0.68	0.99	0.93	0.97	0.59	8423	0.27	0.63	0.51
Polynesia											
American Samoa	0.89	0.77	0.81	nea	nea	nea	0.76	6995	0.22	0.45	0.37
Cook Islands	0.83	0.71	0.75	0.99	1.00	0.99	0.38	8553	0.27	0.60	0.49
French Polynesia	0.97	0.88	0.91	0.99	0.99	0.99	0.43	22,427	0.74	0.77	0.76
Niue	0.95	0.92	0.93	0.99	1.00	0.99	0.38	5828	0.18	0.62	0.47
Samoa	0.73	0.8	0.78	0.99	0.90	0.96	0.63	2872	0.08	0.61	0.43
Tokelau	0.46	0.63	0.58	0.99	1.00	0.99	0.75	1000	0.01	0.58	0.39
Tonga	0.77	0.68	0.71	0.99	0.95	0.98	0.41	2319	0.06	0.54	0.38
Tuvalu	0.51	0.4	0.44	0.99	1.00	0.99	0.58	1831	0.04	0.51	0.36
Wallis and Futuna	1.00	0.86	0.90	0.99	0.99	0.99	0.43	14,552	0.47	0.70	0.44

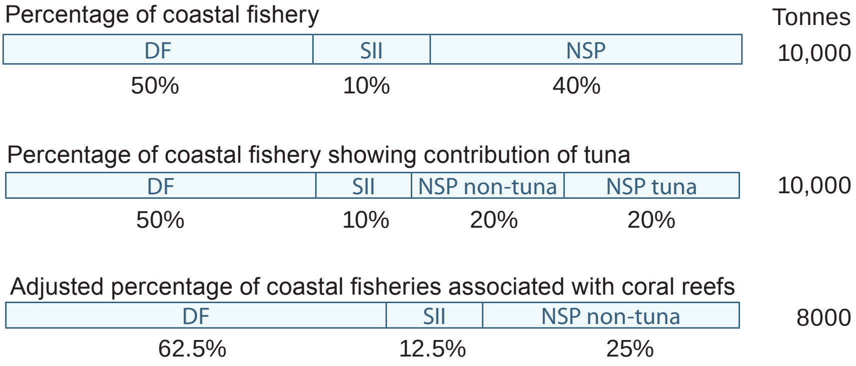
* All indices have been standardised and normalised – see text for explanation of how the indices were derived; a = 1/3 infant mortality rate and 2/3 life expectancy; b = 2/3 literacy and 1/3 primary school enrolment; c = estimates made based on the index for a PICT with similar political and cultural circumstances where a governance index was not provided by Kaufman et al. (2008)[56], e.g. the indices for French Polynesia and Wallis and Futuna have been based on the index for New Caledonia; d = average of indices for health, education, governance and size of the economy; e = based on weighted average, where size of the economy is weighted 0.5 and the indices for health, education and governance by 0.167. No indices are available for Pitcairn Islands; nea = no estimate available.

Appendix 12.2 Method for estimating changes in abundance of fish for food security due to climate change

Because most of the fish[xxii] eaten in Pacific Island countries and territories (PICTs) comes traditionally from easily accessible coastal habitats, this analysis has been limited to the effects of projected changes to the three components of coastal fisheries associated with coral reefs and other coastal habitats used for food security in the region: demersal fish (DF), nearshore pelagic fish (NSP), and shallow subtidal and intertidal invertebrates (SII) (Chapter 9). Projected changes in freshwater fisheries production (Chapter 10) have also been considered in the case of communities for some PICTs.

To estimate changes in the productivity of fish available per person from each of the three components of coastal fisheries for each PICT in 2035, 2050 and 2100 under the B1 and/or A2 emissions scenarios, we assumed that the present-day, combined sustainable harvests of DF, NSP and SII are equivalent to the median estimate for production of fish associated with coral reefs, i.e. 3 tonnes per km^2 of coral reef per year[21] (Chapter 9). In making this assumption, it is implicit that the areas of coral reef (Chapter 5) used to produce the estimates also include lagoons with seagrasses and intertidal flats (Chapter 6). The assessments also assume that there will be no change in the incidence of ciguatera fish poisoning, which effectively reduces the coastal fisheries production available for food security (Chapter 9).

Estimates of total available fish per person for each PICT in 2035, 2050 and 2100 under the B1 and/or A2 scenarios were, therefore, calculated as the area of coral reef multiplied by 3 tonnes of fisheries production per km^2 of reef per year divided by the predicted population. These estimates were then partitioned to identify the proportion contributed by DF, NSP and SII, based on the estimated proportions of DF, NSP and SII making up coastal fisheries in each PICT (Chapter 9). However, because a proportion of NSP in each PICT is derived from tuna species, which have little dependence on coastal habitats (see below), the relative contributions of DF, the non-tuna component of NSP and SII to the estimates of 3 tonnes of fish per km^2 of reef per year had to be recalculated. This was done as outlined in the hypothetical example below, where 50% of NSP is comprised of tuna.



[xxii] Used in the broad sense to include fish and invertebrates.

To estimate the effects of population growth alone on the availability of fish per person in the future, relative to the recommended 35 kg per person per year[3], estimated sustainable production (reef area x 3 tonnes per km^2 per year) was divided by the predicted population.

To estimate the effects of the projected decreases in the DF, non-tuna NSP and SII available per person for the B1 and/or A2 emissions scenarios in 2035, 2050 and 2100, the proportions of DF, non-tuna NSP and SII contributions to annual availability of coastal fisheries production per person were adjusted by the percentages derived from Chapter 9, and summarised in the table below. The projected increases in production of freshwater fish under all scenarios (Chapter 10) are also shown. Estimates were based on the midpoint of the ranges given in the table below.

Scenario	Component of coastal fisheries				Freshwater fisheries
	DF	NSP non-tuna		SII	
		West**	East***		
B1/A2 2035	-2 to -5%	-4%	-3%	0%	+2.5%
B1 2100*	-20%	-10 to -15%	-4%	-5%	+2.5 to +7.5%
A2 2100	-20 to -50%	-10 to -25%	-8%	-10%	+2.5 to +12.5%

* Approximates A2 2050; ** 15°N–20°S and 130°–170°E; *** 15°N–15°S and 170°E–150°W.

We also explored the availability of fish per person per year at production levels of 1 and 5 tonnes per km^2 per year to consider situations where production may be naturally higher, or higher due to good management, and naturally lower, or lower due to poor management[21] (Chapter 9).

Estimates of fish likely to be readily available for food security in future take into account (a) effects of population growth alone, and (b) additional effects of climate change. An example of these outputs for a hypothetical country is given below.

(a) Change in fish available per person per year in 2100 due to population growth.

Production (tonnes per km^2 per year)	Reef area (km^2)	Popn in 2010	Total fish per person in 2010 (kg)	Popn in 2100	DF (kg)	NSP non-tuna (kg)	SII (kg)	Total fish per person in 2100 (kg)
1	2000	100,000	20	150,000	8	3	2	13
3	2000	100,000	60	150,000	25	10	5	40
5	2000	100,000	100	150,000	42	17	8	67

(b) Change in fish available per person per year in 2100 due to population growth and the effects of the B1 emissions scenario in 2100.

Production (tonnes per km^2 per year)	Reef area (km^2)	Popn in 2010	Total fish per person in 2010 (kg)	Popn in 2100	DF[a] (kg)	NSP non-tuna[b] (kg)	SII[c] (kg)	Total fish per person in 2100 (kg)
1	2000	100,000	20	150,000	7	3	2	12
3	2000	100,000	60	150,000	20	9	5	34
5	2000	100,000	100	150,000	33	15	8	56

a = DF x -20%; b = NSP non-tuna x -10%; c = SII x -5%.

Tuna have not been included in the calculations because although they have been estimated to make up between 25% and 75% of NSP, depending on the PICT (Chapter 9), tuna depend mainly on the food web of the open ocean (Chapters 4 and 8). Thus, tuna are not generally considered to be supported by coastal habitats. In addition, it is not possible to estimate the likely changes in availability of tuna per person in the future because there are few data available to indicate potential present-day sustainable catches of tuna by coastal communities. Given the scale of catches made by the industrial fishery (Section 12.2), however, it is very likely that coastal communities could make substantial catches of tuna if they are provided with access and appropriate fishing methods. Tuna represent a ‘safety net’ for future supplies of fish in the tropical Pacific (Section 12.9.2.3).

Appendix 12.3 Predicted populations for Pacific Island countries and territories in 2050 and 2100

PICT	Predicted population (in thousands)					Data used to make predictions for 2100				
						Annual growth rate (period)		Rate of change of growth rate	Annual growth rate	Average annual growth rate
						2011–2015	2045–2050	2011–2015 to 2045–2050	2095–2100	2050–2100
	2011*	2015*	2045*	2050*	2100	$r_{2011–2015}$	$r_{2045–2050}$	R	$r_{2095–2100}$	$r_{2050–2100}$
Melanesia	**8797**	**9498**	**15,400**	**16,339**	**25,492**	**1.9**	**1.2**	**-1.4**		**0.9**
Fiji	852	868	1036	1061	1,332	0.5	0.5	-0.1	0.4	0.5
New Caledonia	252	266	338	343	372	1.3	0.3	-4.3	0.0	0.2
PNG	6888	7477	12,467	13,271	21,125	2.0	1.2	-1.4	0.6	0.9
Solomon Islands	553	610	1101	1181	1,969	2.4	1.4	-1.6	0.6	1.0
Vanuatu	252	278	457	483	695	2.4	1.1	-2.3	0.4	0.7
Micronesia	**546**	**579**	**707**	**720**	**808**	**1.4**	**0.4**	**-4.0**		**0.2**
FSM	102	101	108	109	109	-0.4	0.1	-	-	-
Guam	192	212	263	268	296	2.5	0.4	-5.5	0.0	0.2
Kiribati	103	110	157	163	211	1.8	0.8	-2.4	0.2	0.5
Marshall Islands	55	57	62	61	61	0.9	-0.2	-	-	-
Nauru	10	11	16	16	21	1.9	0.8	-2.6	0.2	0.5
CNMI	64	67	79	80	87	1.2	0.3	-4.1	0.0	0.2
Palau	21	21	23	22	22	0.6	-0.1	-	-	-
Polynesia	**668**	**687**	**811**	**826**	**952**	**0.7**	**0.4**	**-1.8**		**0.3**
American Samoa	67	70	94	98	135	1.2	0.8	-1.2	0.5	0.6
Cook Islands	16	16	16	16	16	0.3	-0.2	-	-	-
French Polynesia	272	284	344	349	379	1.1	0.3	-3.8	0.0	0.2
Niue	1	1	1	1	1	-2.1	0.2	-	-	-
Samoa	184	185	207	210	240	0.2	0.3	0.5	0.4	0.3
Tokelau	1	1	1	1	1	-0.2	0.0	-	-	-
Tonga	104	105	120	123	147	0.3	0.4	1.2	0.8	0.4
Tuvalu	11	11	13	14	19	0.5	0.6	0.5	0.8	0.6
Wallis and Futuna	13	13	13	14	14	-0.2	0.1	-	-	-
Total	**10,013**	**10,765**	**16,969**	**17,948**	**27,475**	**1.8**	**1.1**	**-1.4**	**0.6**	**0.9**

* Predictions made using cohort component method (source: Population data sheet, Statistics for Development Programme, SPC, www.spc.int/sdp/);
** see Appendix 12.4 for method used to make predictions for 2100. Predictions for Pitcairn Islands are not included.

Appendix 12.4 Method for predicting population size for Pacific Island countries and territories in 2100

1. Establish projected population growth rates of the period 2011–2015 ($r_{2011-2015}$) and 2045–2050 ($r_{2045-2050}$), based on projection using cohort component method[53].

$$r_{2011-2015} = \ln \left(Popn_{2015} / Popn_{2011} \right) / t$$

$$r_{2045-2050} = \ln \left(Popn_{2050} / Popn_{2045} \right) / t$$

Where:

ln = natural logarithmic function
$Popn_{2010}$ = projected population size in 2011
$Popn_{2015}$ = projected population size in 2015
$Popn_{2045}$ = projected population size in 2045
$Popn_{2050}$ = projected population size in 2050
t = time interval of population estimates (in years)

2. Calculate the average annual rate of change (R) of the population growth rate of the period 2011–2050.

$$R = \ln \left(r_{2045-2050} / r_{2011-2015} \right) / t$$

Where:

ln = natural logarithmic function
$r_{2010-2015}$ = population growth rate of the period 2011–2015
$r_{2045-2050}$ = population growth rate of the period 2045–2050
t = time interval between $r_{2011-2015}$ and $r_{2045-2050}$ (34.5 years)

3. Apply the calculated rate of change to the 2045–2050 population growth rate in order to obtain the growth rate of the period 2095–2100 ($r_{2095-2100}$).

$$r_{2095-2100} = \mathrm{Exp} \left(R \times t \right) \times \left(r_{2045-2050} \right)$$

Where:

Exp = exponential function
R = average annual rate of change of the population growth rate between period 2011–2015 and 2045–2050 (see step 2)
t = number of years to project (50 years)
$r_{2045-2050}$ = population growth rate of the period 2045–2050

4. Average the growth rates of the period 2045–2050 and 2095–2100 to obtain the average annual growth rate of the period 2050–2100 ($r_{2050-2100}$).

$$r_{2050-2100} = (r_{2045-2050} + r_{2095-2100}) \;/\; 2$$

5. Use the average annual growth rate of the period 2050–2100 to calculate the population size in 2100 ($Popn_{2100}$) by applying the formula:

$$Popn_{2100} = Exp\ (r_{2050-2100}\ x\ t)\ x\ Popn_{2050}$$

Where:

Exp = exponential function

$r_{2050-2100}$ = estimated average annual population growth rate of the period 2050–2100

t = number of years of projection (50 years)

$Popn_{2050}$ = projected population size in 2050

Exceptions

For countries with an estimated population growth rate of zero or near zero during the period 2045–2050, it is assumed that their population size in 2100 is the same as in 2050. These countries and territories are Cook Islands, Federated States of Micronesia, Marshall Islands, Niue, Palau, Tokelau and Wallis and Futuna.

For countries such as Samoa, Tonga and Tuvalu, it is assumed that the estimated population growth rate during the period 2050–2100 is the same as the average of the period 2011–2050.

Appendix 12.5 Gap in availability of fish for Group 3

Gap between the recommended fish consumption of 35 kg per person per year, and the estimated annual supply of fish per person from coastal (reef-associated) and freshwater fisheries in 2010, 2035, 2050 and 2100 for each of the Pacific Island countries and territories (PICTs) in Group 3. Note that these projected gaps do not incorporate the impacts of climate change and are based on sustainable fisheries production of 3 tonnes per km^2 of coral reef per year.

PICT	Reef area (km^2)*	Coastal fish production per year (tonnes)	Freshwater fish production (tonnes)**	Total fish production (tonnes)	Population (x 1000)***				Total fish available per person per year (kg)				Gap in fish needed for good nutrition per person per year (kg)			
					2010	2035	2050	2100	2010	2035	2050	2100	2010	2035	2050	2100
Melanesia																
Fiji	10,000	30,000	4146	34,146	848	978	1061	1332	40	35	32	26	+(5)	0	3	9
PNG	22,000	66,000	17,500	83,500	6753	10,822	13,271	21,125	12	8	6	4	23	27	29	31
Solomon Islands	8535	25,605	2000	27,605	550	970	1181	1969	50	28	23	14	+(15)	7	12	21
Vanuatu	1244	3732	80	3812	245	400	483	695	16	10	8	6	19	25	27	29
Micronesia																
Guam	238	714	3	717	187	250	268	296	4	3	3	2	31	32	32	33
Nauru	7	21	0	21	10	14	16	21	2	1	1	1	33	34	34	34
CNMI	250	750	0	750	63	76	80	87	12	10	9	9	23	25	26	26
Polynesia																
American Samoa	368	1104	1	1105	66	87	98	135	17	13	11	8	18	22	24	27
Samoa****	2000	6000	10	6100	183	202	210	240	33	30	29	25	2	5	6	10

* Derived from Chapter 5; ** based on estimates by Gillett (2009)[4]; *** source: SPC Statistics for Development Programme; **** based on total reef area to a depth of 100 m; + indicates that there is no gap.

Photo: Anders Ryman/Corbis

Chapter 13

Adapting tropical Pacific fisheries and aquaculture to climate change: Management measures, policies and investments

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> *'Fisheries policy makers should now turn their attention to the development and implementation of climate change adaptation strategies.'* (Davis 2010)[i]

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[i] Davis JC (2010) Chair's summary. In: *The Economics of Adapting Fisheries to Climate Change*. OECD Publishing, Paris, France, pp. 17–28.

Contents

13.1 Introduction

The main purpose of this book is to assess how changes projected to occur under low (B1) and high (A2) emissions scenarios in 2035 and 2100 could derail plans by the Pacific Island countries and territories (PICTs) to use the sustainable benefits of fisheries and aquaculture to foster economic development, government revenue, food security and livelihoods[1,2] (Chapters 1 and 12).

These plans already involve adaptation responses ('adaptations') and policies to address other important influences on fisheries and aquaculture, especially population growth and the associated demand for more employment. However, it is clear that the projected changes to surface climate and the tropical Pacific Ocean (Chapters 2 and 3), fish habitats (Chapters 4–7), and fisheries and aquaculture production (Chapters 8–11), could affect the plans to maximise sustainable benefits from the sector. In particular, the consequences of global warming and ocean acidification may impede some aspects of these plans, whereas other effects of climate change could bring important benefits (Chapter 12).

Fisheries managers throughout the region will need to strengthen existing and planned adaptations, and launch new interventions, to minimise threats and harness opportunities associated with the direct and indirect effects of climate change on oceanic, coastal and freshwater fisheries, and aquaculture (Chapters 8–11).

Considerations that frame the identification of practical adaptations are (1) the extraordinary reliance of PICTs on fisheries and aquaculture (Chapter 12); (2) the wide range of fisheries in the region, from globally significant industrial tuna fleets to subsistence and small-scale commercial activities with very high levels of participation; and (3) the emphasis on governance of national and regional industrial tuna fishing, but frequent neglect of small-scale fisheries crucial to food security and livelihoods[2–4] (Chapters 1 and 12).

Adaptations for fisheries and aquaculture must also complement those proposed by other sectors (e.g. agriculture and forestry) to diversify the range of options for producing food and earning income[5,6]. The greater the number of production systems available to communities, the greater the probability that some systems will not be affected, and may even be favoured, by the changing climate.

This chapter sets out the information needed by stakeholders in the fisheries and aquaculture sector at all levels to reduce the threats and capitalise on the opportunities created by climate change. In particular, we:

- outline the existing management regimes and initiatives for industrial and small-scale fisheries and aquaculture in the region to secure desired human development outcomes and maintain healthy fish stocks;

- identify an appropriate framework for selecting practical adaptations to address the key near-term drivers for fisheries and aquaculture, and the future effects of climate change;
- recommend adaptations, and suggest policy approaches, to maximise the contributions of fisheries and aquaculture to economic development, government revenue, food security and livelihoods as the climate changes;
- outline the value of modelling to examine interactions among adaptation options;
- explain the need to monitor the projected effects of climate change on the sector;
- summarise the gaps in knowledge to be filled to improve understanding of the vulnerability of fisheries and aquaculture in the tropical Pacific to climate change, and to fine-tune key adaptations;
- identify priority investments needed to apply the main adaptations, fill gaps in knowledge, strengthen partnerships, monitor the projected effects of climate change and measure the success of adaptations; and
- consider sources of funding to make the necessary investments.

We emphasise that adaptations and policies to build the resilience of the Pacific communities to climate change should not be viewed just from a scientific or technical perspective – the needs and aspirations of people must also be integrated[7,8]. Understanding how people are affected, and how their traditional knowledge, capacities and perspectives can help develop and implement adaptations is a vital part of the process. Community[ii] consultation and participation are essential to ensure that adaptations incorporate a human rights and human development approach to achieve gender equality, maintain relevant traditional customs and culture, and empower young people[9–13].

13.2 Existing management regimes and approaches

13.2.1 Oceanic fisheries

Pacific Island countries and territories are acutely aware that their aspirations to maximise the economic and social benefits of the region's rich oceanic fisheries resources[14,15] are tied to sound cooperative management of the transboundary stocks of tuna and associated large pelagic fish (Chapters 1, 8 and 12).

Cooperative management of oceanic fisheries was launched in 1979, with the formation of the Pacific Islands Forum Fisheries Agency (FFA)[iii]. FFA coordinates policy advice and technical support to assist members of the Pacific Islands Forum

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[ii] Community refers to the men, women and children who participate in catching, processing and selling fish.

[iii] www.ffa.int

manage fishing effort by distant water fishing nations (DWFNs) and domestic fleets within their exclusive economic zones (EEZs). The Forum Fisheries Agency has developed a 'Regional Tuna Fisheries Management and Development Strategy', which it implements on behalf of its member countries. This strategy is a set of shared principles for the sustainable management of oceanic fish stocks and ecosystems, and economic development based on tuna fisheries[16]. The key management measures and treaties developed by FFA for its members are summarised in **Table 13.1**.

Because ~ 25% of the world's tuna catch comes from the EEZs of the Parties to the Nauru Agreement (PNA)[iv] (Chapters 1 and 8), purse-seine fishing effort across these zones is allocated by the Director of the PNA Office through the vessel day scheme (VDS) under amendments to the Palau Arrangement (**Table 13.1**). The PNA Office in Marshall Islands also explores collective ways to increase the contributions of tuna resources to the economic development of its members[17]. In a similar move, the Polynesian countries have launched the Te Vaka Moana Arrangement (TVMA) to harmonise management approaches, exchange information and optimise the benefits from longline fishing for tuna in their EEZs.

The transboundary nature of the region's oceanic fisheries resources, which also allows them to be captured on the high seas, calls for a broader approach. In response to the need to manage tuna stocks across the entire Western and Central Pacific Ocean (WCPO), the Convention for the Conservation and Management of Highly Migratory Fish Stocks in the Western and Central Pacific Ocean was declared in 2004[v]. The Western and Central Pacific Fisheries Commission (WCPFC)[vi] was established to administer this convention. Pacific Island countries and territories engage with DWFNs, and other countries that harvest tuna in the WCPO, such as the Philippines and Indonesia, through the WCPFC to manage and conserve the region's oceanic fisheries resources.

Members of FFA, PNA and TVMA[vii] cooperate to control catch and effort within the WCPO to maintain stocks of skipjack, yellowfin, bigeye and South Pacific albacore tuna at levels that ensure conservation of these valuable resources, as well as sustainable economic benefits. Examples of management measures implemented by PNA and supported by FFA and WCPFC to address recent overfishing of bigeye tuna are provided in Chapters 1 and 12. Other measures have been suggested to improve both economic benefits and long-term conservation[18].

The management arrangements are underpinned by regular, in-depth stock assessments for all four species of tuna (Chapter 8). These stock assessments involve extensive collection of data on catch and fishing effort, sampling of catches, biological

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[iv] www.pnatuna.com

[v] www.wcpfc.int/key-documents/convention-text

[vi] www.wcpfc.int

[vii] See Chapter 1 for the members of FFA, WCPFC and PNA. The members of TVMA are Cook Islands, New Zealand, Niue, Samoa, Tokelau and Tonga.

research and tagging studies by the Oceanic Fisheries Programme at the Secretariat of the Pacific Community[viii]. Research is also underway on the open ocean food webs that support tuna[19,20] (Chapter 4), and the effects of industrial tuna fisheries on the bycatch of other large pelagic fish[21,22]. The costs of this research are justified by the significance and value of tuna catches in the WCPO, which totalled ~ 2.5 million tonnes in 2009, worth > USD 4 billion[23] (Chapters 1 and 8).

Table 13.1 The main measures developed and implemented by the Pacific Islands Forum Fisheries Agency to manage tuna fisheries for its member countries.

Measure	Key features
National tuna fishery development plans	Promotes sustainable national tuna fisheries, using the ecosystem-based approach to fisheries management[16,118,119].
Nauru Agreement	Specifies terms and conditions for tuna purse-seine fishing licences in the region. The agreement has various implementing arrangements, including the FSM Arrangement and Palau Arrangement.
FSM Arrangement*	Provides for preferential access by vessels sponsored by the Parties of the Nauru Agreement (PNA) to each others' EEZs[120].
Palau Arrangement*	Provides a suite of measures for cooperative management of the purse-seine and longline fisheries in the EEZs of PNA members, including the vessel day scheme (VDS), as well as agreed policies on licensing conditions, crewing and the operation of vessel monitoring schemes and observer programmes[63].
US Treaty	A multilateral fisheries access agreement between FFA members and the USA, which provides fishing opportunities for up to 40 US-flagged purse-seine vessels (and up to an additional five vessels under joint venture arrangements) in the treaty area, in return for funding.
Monitoring, Control and Surveillance	Agreed policies for the detection and deterrence of illegal, unregulated and unreported fishing. The tools include the Pacific Islands Regional Fishery Observer Programme, the Regional Vessel Monitoring System, the Regional Register of Fishing Vessels and the Niue Treaty for cooperation in fisheries surveillance and information sharing[121,122].

* Measures now transferred to PNA.

13.2.2 Coastal fisheries

Coastal fisheries in the tropical Pacific differ fundamentally from the industrial tuna fisheries in at least two ways. First, they are based on hundreds of species of demersal fish and invertebrates[24,25] (Chapter 9), very few of which yield sufficient economic and social benefits to justify the type of stock assessments made for tuna. Second, self-replenishing populations of most coastal species are restricted to individual PICTs, or even smaller spatial scales (Chapter 9). For this reason, stocks of coastal fish and invertebrates do not often represent transboundary resources, although some stocks are likely to be shared, for example, between PNG and Solomon Islands, PNG and Australia, and American Samoa and Samoa. These features of coastal fisheries, combined with the limited scientific capacity in the national agencies of most PICTs, have resulted in much uncertainty about the sustainable harvest levels and status of coastal fisheries (Chapter 9).

[viii] www.spc.int/oceanfish

The exceptions are (1) the easily-accessible, sedentary invertebrates, such as sea cucumbers and trochus that are harvested from shallow water and targeted for export commodities; and (2) the component of the nearshore pelagic fishery comprising skipjack and yellowfin tuna caught by subsistence and small-scale commercial fishers (Chapter 9). Dramatic declines in exports of sea cucumbers and trochus show that these valuable resources have been chronically overfished in many PICTs[25–27] (Chapter 9). The reasonably good understanding of the nearshore pelagic fish component of coastal fisheries comprised of tuna stems from the strong overlap between coastal and industrial fisheries in the region. Investments in quantitative stock assessments for tuna have produced good estimates of the status of these species (Chapter 8).

Against this backdrop, it is unlikely that PICTs will develop and implement conventional stock assessments for many species of demersal fish and invertebrates. Arguably, any attempt to do so would not be cost-effective because such approaches would not make the best use of the social capital and natural history knowledge of coastal communities. Alternative ways of assessing the status of fisheries in data-poor situations exist[28,29]. Pacific Island countries and territories have a long tradition of community-based approaches to fishery management[30] and strengthening this approach is broadly seen as offering the best hope of securing coastal fisheries resources for the future[2,31,32]. In much of Melanesia, community-based approaches to fisheries management are also favoured by long-standing customary marine tenure[33–36], which helps to ensure that benefits accrue directly to communities.

The search for innovation under the broad umbrella of community-based management is likely to remain a critical frontier for communities, national agencies, regional organisations and non-governmental organisations (NGOs)[28,37–39]. Confronting habitat degradation caused by agriculture, forestry (logging) and mining activities in catchments (Chapters 5–7), and overfishing due to population growth and other economic and social drivers[2,40–42] (Chapter 12), present the two greatest challenges.

Many PICTs need to produce more fish from their coastal waters for national food security (Chapter 12). However, management that aims to avoid further depletion of overfished stocks is likely to be more appropriate in the short term than management aimed at maximising sustainable production. Using 'primary' fisheries management[ix] to limit catches to avoid irreversible damage to stocks in the face of uncertainty[38], and investing in the social capital and institutions needed for communities and governments to manage coastal fisheries[28], are high priorities. Unfortunately, the projected increases in coral bleaching due to global warming and degradation of coral reefs from ocean acidification (Chapter 5) are expected to increase uncertainty, demanding an even more precautionary approach[29] and further reducing responsible yields from coastal fisheries (**Figure 13.1**).

[ix] Primary fisheries management recognises the need to use simple harvest controls, such as size limits, closed seasons and areas, gear restrictions and protection of spawning aggregations. Secondary and tertiary fisheries management require greater investments in stock assessments to reduce uncertainty about the economic benefits that can be gained from more accurate and precise estimates of sustainable harvests.

To equip PICTs with a practical way of managing coastal fisheries in the face of the many drivers influencing the sector, a 'community-based ecosystem approach to fisheries management' (CEAFM) is being developed for the region[32]. CEAFM merges the well-recognised need for an ecosystem approach[43,44] and primary fisheries management based on co-management through strong community involvement. Implementing CEAFM requires a legal framework and the involvement of many stakeholders to support communities and national agencies, particularly regional fisheries and environmental organisations and NGOs.

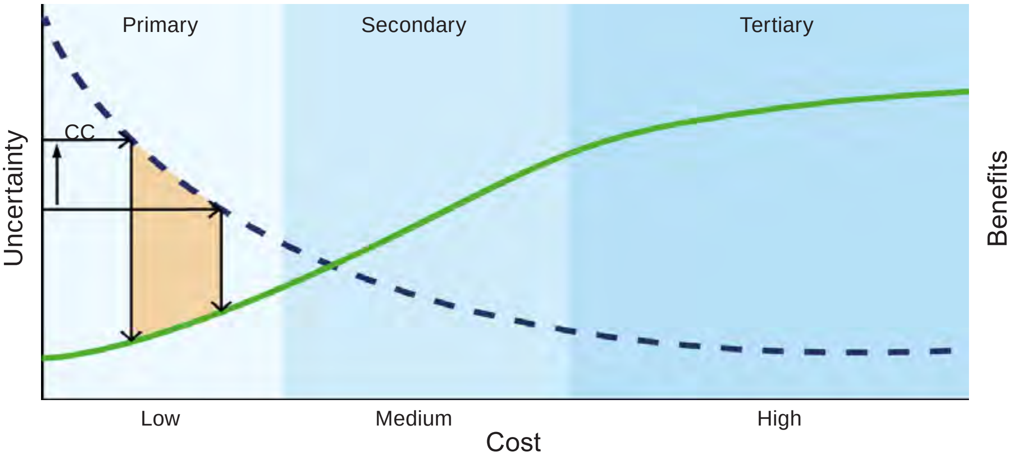

Figure 13.1 General relationship between potential benefits from fisheries for coastal demersal fish species and invertebrates (green line), and uncertainty in information for management (blue line), as functions of costs, for primary, secondary and tertiary fisheries management (source: Cochrane et al. 2010)[38] (see also footnote on page 809). The reduction in benefits under primary fisheries management as a result of the increased uncertainty caused by climate change (CC) is indicated by the orange shading.

13.2.3 Freshwater and estuarine fisheries

The freshwater and estuarine fisheries of the tropical Pacific are still poorly understood[3] (Chapter 10) and receive little or no attention from national fisheries departments and regional organisations. Primary fisheries management implemented through CEAFM, along the lines described above for coastal fisheries, is also needed to maintain the benefits of these fisheries for communities living beside rivers and lakes, mainly in Melanesia and particularly in Papua New Guinea (PNG). But the challenge is broader than that – best practice is required from agriculture, forestry and mining operations in catchments to avoid degrading freshwater fish habitats through additional sedimentation, excessive nutrients and pollution by toxic chemicals[45] (Chapter 7).

Management of freshwater fisheries in PNG must also address the risk of further invasive fish species. The freshwater fish fauna in PNG already includes a high proportion of introduced and invasive species. While many (but not all) of the introduced species are valued as food, other unwanted invasive species are reducing the availability of native fish species and the preferred introduced species (Chapter 10).

In contrast to demersal coastal fisheries, some freshwater fisheries are likely to be enhanced by climate change (Chapter 10). Projected increases in rainfall in the tropics (Chapter 2) in particular are expected to increase the area and inundation frequency of floodplain habitats (Chapter 7). Investments in primary fisheries management in freshwater and estuarine ecosystems are expected, therefore, to be operating under conditions more favourable to fisheries production, provided catchments are managed appropriately. As the areas available for catching freshwater and estuarine fish and invertebrates expand, it will be important to maintain traditional access and ownership rights, especially if the ownership of boats and fishing equipment by the growing populations in Melanesia increases.

13.2.4 Aquaculture

Pearl and penaeid shrimp farming are now mature industries (Chapter 11) in some PICTS, with private sector enterprises managed under government regulations producing high-quality exports[46]. The diverse range of exploratory and emerging aquaculture activities producing commodities for food security and livelihoods in many other parts of the region (Chapter 11) are generally operating under much looser management frameworks[3,47].

As existing activities develop and other economically viable prospects for aquaculture are identified, which is already occurring under the regional aquaculture action plan[47] and a series of national aquaculture plans (Chapter 11), PICTs will need to (1) develop national legislation to encourage investment, including licensing arrangements, guaranteed access to suitable sites, and support for pilot commercial projects; (2) implement global standards for aquatic animal health and biosecurity[48–51]; (3) set quality standards for products; (4) facilitate training in the technical and business skills needed to operate aquaculture enterprises efficiently; and (5) promote any competitive advantages they may have for aquaculture.

These measures are needed to create appropriate incentives and security for the private sector to establish substantial enterprises. They are also needed to create the large commercial operations that will be ‘vehicles’ for delivering benefits to smallholders, thereby assisting PICTs to meet their aspirations for the opportunities created by aquaculture to flow to communities. Thus, wherever appropriate, licensing conditions for large enterprises need to enable a significant proportion of production (e.g. spat collection and on-growing commodities to market size) to be out-sourced to smallholders. The main enterprise would focus on overseeing quality control and providing economies of scale for access to farm inputs needed by smallholders. Similar models have been used successfully to establish plantation agriculture and the production of chickens and eggs in the region.

13.2.5 A human rights approach

The community-based management approaches outlined in Sections 13.2.2 and 13.2.3 will be particularly effective when fishing rights closely support social, economic and human rights. Under such circumstances, small-scale coastal and freshwater fisheries can make a critical difference to food security and the broader aspirations of communities for well-being and socio-economic success[52]. People engaged in fishing who are more secure and less vulnerable can also be expected to be more effective and motivated participants in the co-management of resources. In short, treating the governance of small-scale fisheries in the region as an aspect of general human rights will encourage sustainable use of resources, and help achieve human development goals[53].

The security and well-being of coastal and freshwater fishing communities is best improved by social and political development that invokes the existing laws supporting the Universal Declaration of Human Rights[53]. In particular, the management of fisheries and aquaculture in the region should (1) secure rights to catch, process and sell fish for a broad spectrum of people from rural and urban communities; and (2) provide opportunities for equitable participation of women, children and other vulnerable groups in production and market chains in ways that remove customary and social inhibitions (i.e. rights need to be secured for the right people)[52,54]. Achieving these goals will require gender assessments and analysis.

13.3 A framework for selecting adaptations

The projected effects of climate change on the production of oceanic, coastal and freshwater fisheries and aquaculture (Chapters 8–11) are not the only likely influences on the future of the sector. Population growth and urbanisation, patterns of economic development, status of fisheries resources in other oceans, governance and political stability, markets and trade, fuel costs, technological innovation and foreign aid can all be expected to influence fisheries and aquaculture in the region[2,42,55]. Population growth and urbanisation are expected to be particularly significant, especially in Melanesia (Chapters 1 and 12).

Because most of these factors have the potential to affect fisheries and aquaculture before the projected effects of climate change become limiting, a framework is needed for planned adaptations that addresses the other drivers in the near term, and climate change in the longer term[56]. Clearly, the best investments are those that deliver short-term and long-term benefits ('win-win' adaptations) (**Figure 13.2**). Adapting to climate change will also involve some 'lose-win' adaptations – where the economic and social costs exceed the benefits in the near term, but where investments position PICTs to receive net benefits in the longer term under a changing climate. 'Win-lose' investments represent maladaptation to climate change and should be avoided, except in extreme cases where human survival may otherwise be compromised.

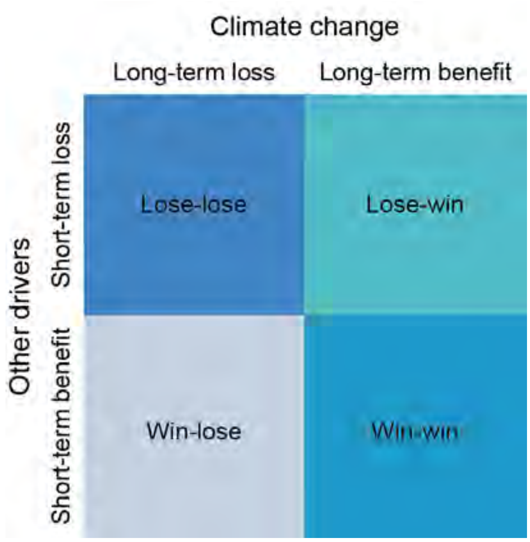

Figure 13.2 Decision framework for identifying adaptations to address climate change and other drivers (source: Grafton 2010)[56].

Identification of win-win and lose-win adaptations should not be based simply on the availability of technology and projected future responses of the resources underpinning fisheries and aquaculture. There are potential social barriers to the uptake of appropriate technology[57,58]. Examples of such barriers include the cultural norms and gender issues that may limit broad-based community participation. The probability of removing these barriers to provide communities with a wider range of strategies to adapt to climate change must also be assessed when evaluating the likely success of proposed adaptations.

Ultimately, prospective adaptations within the decision framework should be assessed using formal cost:benefit analysis, based on the best available information and economic modelling, to determine the extent to which interventions will reduce threats from short-term and long-term drivers, and effectively capitalise on the opportunities. Such analysis is also needed to assess the opportunity costs of various adaptations.

In the section below, we outline the main prospective win-win and lose-win adaptations, in the expectation that PICTs and their development partners will undertake the cost:benefit analysis needed to confirm their suitability. We also suggest policies to support these adaptations.

13.4 Recommended adaptations and suggested supporting policies

The adaptations and policies recommended here are founded on the assumptions that (1) the key objectives of national agencies responsible for managing fisheries and aquaculture are to maximise sustainable benefits for economic development, government revenue, food security and livelihoods; (2) planned adaptations are needed to improve the way that the 'vehicles' (fisheries and aquaculture activities), which deliver these benefits, are managed to reduce the threats and harness the opportunities expected to arise from climate change; and (3) the fish habitats and fish stocks that underpin these benefits are managed in ways that maximise their capacity for autonomous adaptation to the effects of climate change (**Figure 13.3**).

We also assume that adaptations will be designed and delivered in a way that is acceptable to those whom they are intended to benefit (Section 13.2.5). This important pre-requisite is expected to be relatively easy to achieve in many cases because the traditional ways that Pacific people use to respond to and cope with extreme events such as cyclones and droughts[10,59–62] should predispose them to embracing and implementing the recommended adaptations. However, improvements can be made to traditional ways of responding to extreme events, particularly by (1) increasing the participation of women in all aspects of planning and applying adaptations, and (2) ensuring that the people likely to be affected are involved in negotiations to select and implement adaptations, so that their rights are respected.

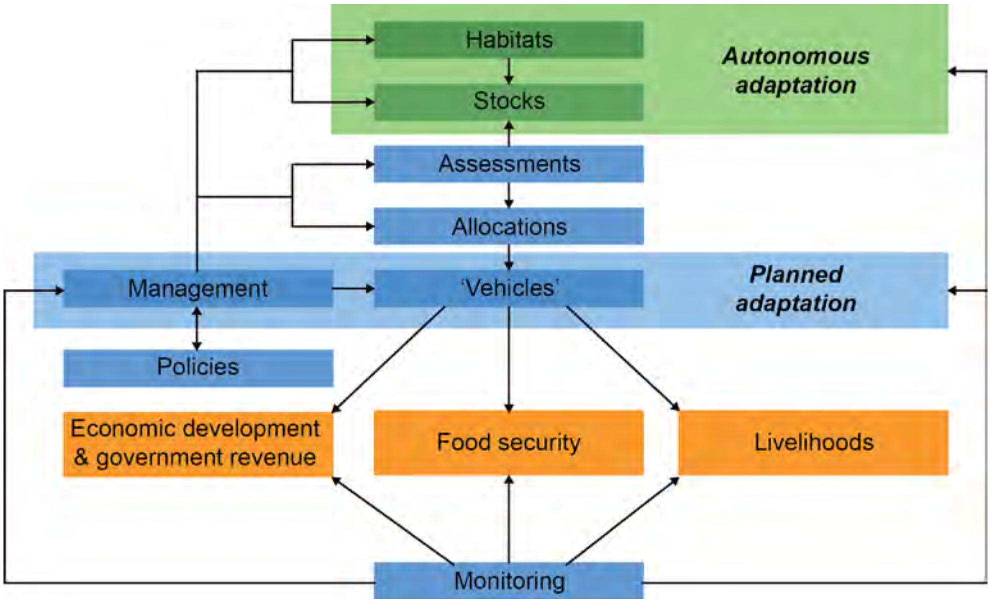

Figure 13.3 Relationships between the key objectives of fisheries management for Pacific Island countries and territories (orange), the resources on which these benefits are based (green), the actions and institutional outputs needed to deliver these benefits (blue), and the components of the system where autonomous adaptation could help limit the potential impact of climate change, and where planned adaptation should reduce the threats of climate change to economic development, government revenue, food security and livelihoods and capitalise on opportunities to increase these benefits.

Before introducing the adaptations and suggested policies, we briefly summarise the implications of climate change for the productivity of fisheries and aquaculture (Chapter 12) which these adaptations and policies are intended to address. The adaptations and suggested policies for economic development and government revenue, food security, and livelihoods are presented separately.

13.4.1 Adaptations for economic development and government revenue (E)

The projected eastward shift in the distribution of skipjack tuna (Chapter 8), and ultimately fishing effort, is expected to have two important implications for gross domestic product (GDP) and government revenue. First, it should increase the contribution of licence fees from DWFNs to those PICTs in the central Pacific (Kiribati, Nauru, Tokelau and Tuvalu) that already rely heavily on these fees for government revenue. Larger catches of tuna further east should also increase the contribution of fishing to GDP in American Samoa and Marshall Islands, and perhaps create new opportunities for economic development in Polynesia (Chapter 12). Second, it could affect plans to expand national industrial fishing and processing operations to increase benefits from tuna resources in some PICTs in the western part of the region, particularly PNG and Solomon Islands. However, while potential decreases in contributions of fishing and processing operations to GDP and government revenue from licence fees may occur for countries in the west, the implications should not be profound in PNG due to the relatively large size of its economy (Chapter 12). The effects are expected to be greater in Solomon Islands, where industrial fishing and processing presently contributes ~ 5% to GDP, and where more canneries are planned (Chapter 12).

The adaptations and suggested policies to maximise the economic benefits from oceanic fisheries for PICTs in the central and eastern Pacific, and to minimise the impacts for PICTs in the west, are outlined below. These adaptations involve (1) development of flexible management measures to allow fishing effort to shift east, while ensuring that large quantities of tuna can still be channelled through the established and proposed canneries in the west; and (2) optimising the productivity of tuna resources across the region.

➢ Adaption E1: Full implementation of sustainable fishing effort schemes (win-win)

The vessel day scheme for the purse-seine fishery, which allocates fishing effort among the EEZs of the eight PNA countries based on agreed criteria[63,64], provides an important means of accommodating the effects of El Niño-Southern Oscillation (ENSO) events on redistribution of tuna, now and in the future. The VDS for each fishery is intended to hold total fishing effort for PNA members constant, yet allow them to trade fishing days when the fish are concentrated either in the west or east due to ENSO events. The VDS is designed to operate in a similar way to the 'cap and trade' systems proposed to limit emissions of carbon dioxide (CO_2)[65] and ensures that all PNA members continue to receive some level of benefits, regardless of where tuna are concentrated. For the VDS to work efficiently, however, PNA countries will need to develop the capacity and governance to ensure that fishing effort conforms to the specified levels[63,66,67]. Allocation of effort among members will also need to be adjusted periodically, as provided for under the VDS, as tuna stocks move progressively east. Periodic adjustment will still allow the transfer of effort during ENSO events well into the future, but avoid the need for PNA members further to the east to continually purchase vessel days from those in the west, based on present-day catches.

A VDS is also being developed by PNA for the longline fishery but is likely to be more challenging to implement because of the larger number of vessels involved, the difficulties in providing observers for vessels and the lower value of the fishery. The sustainable fishing effort scheme for albacore and other species of tuna being developed by members of the Te Vaka Moana Arrangement in southern subtropical waters should also be a practical way of adapting to any changes in the distributions of these species.

➢ Adaptation E2: Diversify sources of fish for canneries (win-win)

The Interim Economic Partnership Agreements (IEPA) between PNG and the European Union (EU), and Fiji and the EU, assist these PICTs to develop their fish processing operations in the near term by paving the way for exports to Europe in the face of strong competition from canneries in Asia. The 'global sourcing provision' of the IEPA is particularly advantageous because it enables a country to acquire and export fish from any other country. Obtaining a full Economic Partnership Agreement (EPA) for the long term is of great importance to PNG so that the nation can secure supplies of fish for its canneries as tuna are redistributed further east. It is also in the strong interest of Solomon Islands to sign an IEPA with the EU, given the plans underway to build additional canneries in that country. Papua New Guinea, Fiji and Solomon Islands should continue to take an active role in the negotiations for interim and full economic partnership agreements to ensure that the global sourcing provision and other development incentives included in these agreements are available for many years.

An important proviso, however, is that any PICTs supplying fish to PNG for the European market will need to comply with (1) EU food safety requirements by establishing a fishery product food safety competent authority and the associated laboratory testing facilities; and (2) illegal, unreported and unregulated (IUU) fishing regulations[68], by setting up a system of certification and product tracking to demonstrate that fish were caught legally.

Other adaptations that should help maintain continuity in the supply of fish for canneries in PNG and Solomon Islands during El Niño episodes in the short term, and under the projected effects of climate change on tuna in the long term, include (1) reducing access for DWFNs to their EEZs to provide more fish for national vessels; (2) requiring DWFNs operating within their EEZs to land a proportion of catches for use by local canneries; (3) enhancing existing arrangements for their national fleets to fish in the EEZs of other PICTs; and (4) creating any additional incentives necessary for tuna caught in other EEZs to be landed in their ports. These adaptations would need to be integrated with the provisions of the VDS and IEPA/EPA.

➢ Adaptation E3: Immediate conservation management measures for bigeye tuna (lose-win)

Addressing the current overfishing of bigeye tuna in the WCPO (Chapter 8) by reducing fishing mortality should help rebuild the population to a level that is expected to assist this species adapt to the projected changes to the tropical Pacific Ocean (Chapters 3 and 4). The benefits of management measures to reduce fishing mortality are not expected to be fully effective for 10–20 years because bigeye tuna is a relatively long-lived species (> 12 years).

➢ Adaptation E4: Energy efficiency programmes for industrial fleets (win-win)

Energy audits to identify how to reduce the use of fuel for routine fishing operations, followed by energy efficiency programmes to implement these savings, should increase the economic efficiency of fleets in both the near and long term. These initiatives should assist industrial fleets to cope with fluctuations in oil prices, and reduce the costs for national vessels from Federated States of Micronesia (FSM), PNG and Solomon Islands of fishing further afield as the distribution of tuna shifts to the east. Although purse-seine vessels use less fuel per tonne of fish caught than longliners[69], this adaptation is still expected to result in significant reductions in operating costs for purse-seiners.

To reduce the effects of future increases in international oil prices, locally-based industrial fishing fleets in Melanesia should evaluate the economic, social and environmental benefits of coconut oil and other biofuels to ascertain whether they are a viable alternative energy source. Some coastal shipping vessels in PNG have already made the transition to locally produced biofuels and further uptake is expected once the lubrication qualities of these fuels are improved.

➢ Adaptation E5: Environmentally-friendly fishing operations (win-win)

Identifying how to reduce any effects of existing tuna fishing operations, and those projected to occur as the distribution of tuna moves to the east, on non-target and dependent species should assist PICTs to meet the requirements of certification schemes to promote responsible fishing practices. Finding ways to (1) reduce CO_2 emissions from commercial fishing fleets (outlined above) and canneries to ensure that tuna from the region is competitive in carbon labelling schemes[70]; and (2) replace steel cans with alternative forms of packaging[71], should also help maintain access to markets for tuna as global pressure to minimise the carbon footprint of fishing and processing operations increases.

Purse-seine vessel

Photo: Malo Hosken

➢ Adaptation E6: Gender-sensitive fish processing operations (win-win)

The efficiency and productivity of existing and planned tuna canneries and loining plants in PNG, Solomon Islands and elsewhere in the region rely heavily on women for their labour force. Efficiency and productivity are likely to be improved by ensuring that the rights and responsibilities of Pacific women are recognised in their employment conditions, and that they have the appropriate training and opportunities to undertake managerial roles[72]. Management that is sensitive to culture and gender provides a potential win-win adaptation because it should enhance the loyalty of staff, even when climate change imposes stresses on households.

➢ Adaptation E7: Safety at sea (win-win)

Although the weather forecasts available to tuna fleets in the region will continue to improve, safety audits should be conducted to ensure that longline vessels (and any purse-seine vessels) operating within the cyclone belt (Chapter 2) can achieve acceptable standards for safety at sea[73,74] in the event that more severe cyclones occur. This adaptation will help protect fishing crews both now and in the future.

- **Adaptation E8: Climate-proof infrastructure (lose-win)**

New infrastructure built to support fishing fleets, canneries and loining plants should be constructed in locations that will not be inundated by rising sea levels projected to occur during the expected life spans of such facilities (Chapter 3). At latitudes higher than ~ 10°S–10°N, infrastructure should also be built to withstand the possible effects of more severe cyclones (Chapter 2). Investments may also be needed to modify existing infrastructure for industrial fishing operations and processing facilities. The planning and expenditure involved in climate-proofing infrastructure for the fisheries sector may reduce profits in the shorter term, but enable operations to continue in the longer term.

- **Adaptation E9: Pan-Pacific tuna management (lose-win)**

The projected progressive shift of tuna from the WCPO to the east may eventually require cooperation in all aspects of tuna fisheries management between the WCPFC and Inter-American Tropical Tuna Commission (IATTC). A merger of these organisations to form a pan-Pacific tuna fisheries management agency is something that may eventually need to be considered (providing the relative effort by vessels from the WCPO and Eastern Pacific Ocean is maintained). The costs of any such re-organisation are likely to exceed the advantages initially, but the benefits are expected to outweigh these costs as the distributions of tuna species change.

13.4.2 Supporting policies for economic development and government revenue (E)

The suggested policies required to implement the adaptations to maintain or improve the contributions from oceanic fisheries to economic development and government revenue described in Section 13.4.1 are outlined below. The policies that apply to each adaptation are listed in **Table 13.2**.

- **Policy E1: Promote transparent access agreements** between PICTs and DWFNs so that the VDS allocations, in particular, can be easily understood by all PNA members (and non-PNA countries which purchase fishing days from PNA members under bilateral arrangements and have vessels fishing in PNA waters). Strengthen national capacity to recognise successes and failures in VDS arrangements (and other fishing effort schemes), and the governance needed to administer the VDS, so that this fishing effort scheme fulfils its potential.
- **Policy E2: Explore further approaches to collective management**[67] to see whether they can boost national capacity to implement measures that will continue to strengthen national economies and conserve tuna stocks.
- **Policy E3: Adjust national tuna management plans and marketing strategies** to provide more flexible arrangements to sell tuna, or acquire tuna needed for national processing operations. Depending on the country, this policy may

involve securing a long-term EPA with the EU, establishing a fishery product food safety competent authority and associated laboratory testing facilities or services, and demonstrating that catches comply with IUU fishing regulations. Additional markets to the EU should also be developed.

- **Policy E4: Include implications of climate change in the development of future management objectives and strategies for WCPFC**, particularly in relation to the projected eventual reduction in overall abundance of skipjack, yellowfin and bigeye tuna in the WCPO. In particular, WCPFC should consider the need to (1) strengthen the mechanisms to manage total fishing effort or catches (or both) in its convention area; and (2) develop the necessary tools to monitor and enforce its conservation and management measures to anticipate any large change in the fundamental biological parameters of exploited stocks.

- **Policy E5: Revise licensing conditions for DWFNs, as needed, to require that all vessels provide operational-level catch and effort data** from log sheets (including historical data) for fish caught both within the EEZ and on the high seas. The data should be submitted to the licensing country for subsequent use by WCPFC and SPC to improve the models for estimating tuna distributions and catches in the future (Section 13.9.2.2).

- **Policy E6: Finalise the declaration of national ocean boundaries** in compliance with the United Nations Convention on the Law of the Sea. For many countries, this involves completing the technical work to establish their baselines (terrestrial base reference points).

- **Policy E7: Apply regionally-responsible, spatially-explicit national management measures** to address the implications of climate change for subregional concentrations of tuna in national archipelagic waters beyond the mandate of WCPFC.

- **Policy E8: Develop further measures to mitigate the capture of bigeye tuna** by purse-seine as climate-driven redistribution of this species occurs to the east, where purse-seine catch per unit effort is much higher.

- **Policy E9: Use regional trade and preferential access agreements to market environmentally-friendly tuna products** based on responsible fishing methods, equitable processing operations, and distribution channels that minimise CO_2 emissions throughout the supply chain[8].

- **Policy E10: Ensure all industrial fishing operations meet accepted standards for safety at sea**, by including any changes in design or equipment needed to make longline and purse-seine vessels more seaworthy during cyclones in fishing licences.

- **Policy E11: Require all new infrastructure to be more climate-proof**, by ensuring that (1) land-based facilities are not constructed where they could be inundated by rising sea levels or exposed to any projected increase in storm surge during the expected term of the investment; and (2) wharfs and access roads continue to function as sea level rises, and if cyclones increase in intensity.

Table 13.2 Summary of adaptations and companion supporting policies to maintain or improve the contributions of oceanic fisheries to economic development and government revenue for Pacific Island countries and territories (see Sections 13.4.1 and 13.4.2 for details).

Adaptation		Type	Supporting policy*
E1	Full implementation of sustainable fishing effort schemes	W-W	E1, E2, E4–E6
E2	Diversify sources of fish for canneries	W-W	E1–E5, E7
E3	Immediate conservation management measures for bigeye tuna	L-W	E7, E8
E4	Energy efficiency programmes for industrial tuna fleets	W-W	E9
E5	Environmentally-friendly fishing operations	W-W	
E6	Gender-sensitive fish processing operations	W-W	
E7	Safety at sea	W-W	E10
E8	Climate-proof infrastructure	L-W	E11
E9	Pan-Pacific tuna management	L-W	E2

* Refers to supporting policy number in Section 13.4.2; W = win; L = lose.

13.4.3 Adaptations for maintaining the contribution of fish to food security (F)

The projected decreases in coastal fisheries production caused by the direct and indirect effects of climate change (Chapter 9) are expected to widen the gap between the quantities of fish required for good nutrition, or eaten traditionally, and the fish available from coastal (and freshwater) habitats due to population growth in nine of the 22 PICTs (Chapter 12). Decreases in coastal fisheries production are also expected to exacerbate problems in supplying fish for the large urban populations in another seven PICTs (Chapter 12).

The adaptations and suggested policies for maintaining the important role of fish for food security in the region[1,75] (Chapter 1) centre on minimising the size of this gap through (1) appropriate management of coastal (and freshwater) fish habitats and stocks (Section 13.2); (2) increasing access to tuna for rural and urban populations; and (3) boosting pond aquaculture. The recommended adaptations are set out below. Many of these interventions are not new – they have been proposed for many years as an integral part of effective coastal zone management[76–80] and ecosystem-based fisheries management[81–83], and to address the effects of population growth on the availability of fish for food security[1,75].

The CEAFM co-management framework[32], which integrates customary marine tenure and other social capital, local governance, traditional knowledge, self-interest and self-enforcement capacity, provides the most effective way to implement many of these adaptations. This is particularly the case when the adaptations are considered by cross-sectoral management advisory groups comprised of both government and non-government members.

13.4.3.1 Adaptations to safeguard fish habitats

➢ Adaptation F1: Manage and restore vegetation in catchments (win-win)

Sustaining coastal and freshwater fish production for food security in much of Melanesia begins with maintaining catchment vegetation (Chapter 12). Good vegetation cover reduces the transfer of sediments and nutrients into river networks after heavy rainfall, and greatly reduces the potential impacts on freshwater and coastal fish habitats. Poor vegetation cover results in accelerated runoff and erosion (Chapter 7), which directly damages coral reef, mangrove and seagrass habitats, and makes corals less resilient to bleaching (Chapters 5 and 6) (**Figure 13.4**). For freshwater habitats, lack of shade on riverbanks also increases exposure of fish to increasing temperatures. The main interventions needed to ensure that adequate levels of vegetation are maintained or restored in catchments are summarised below.

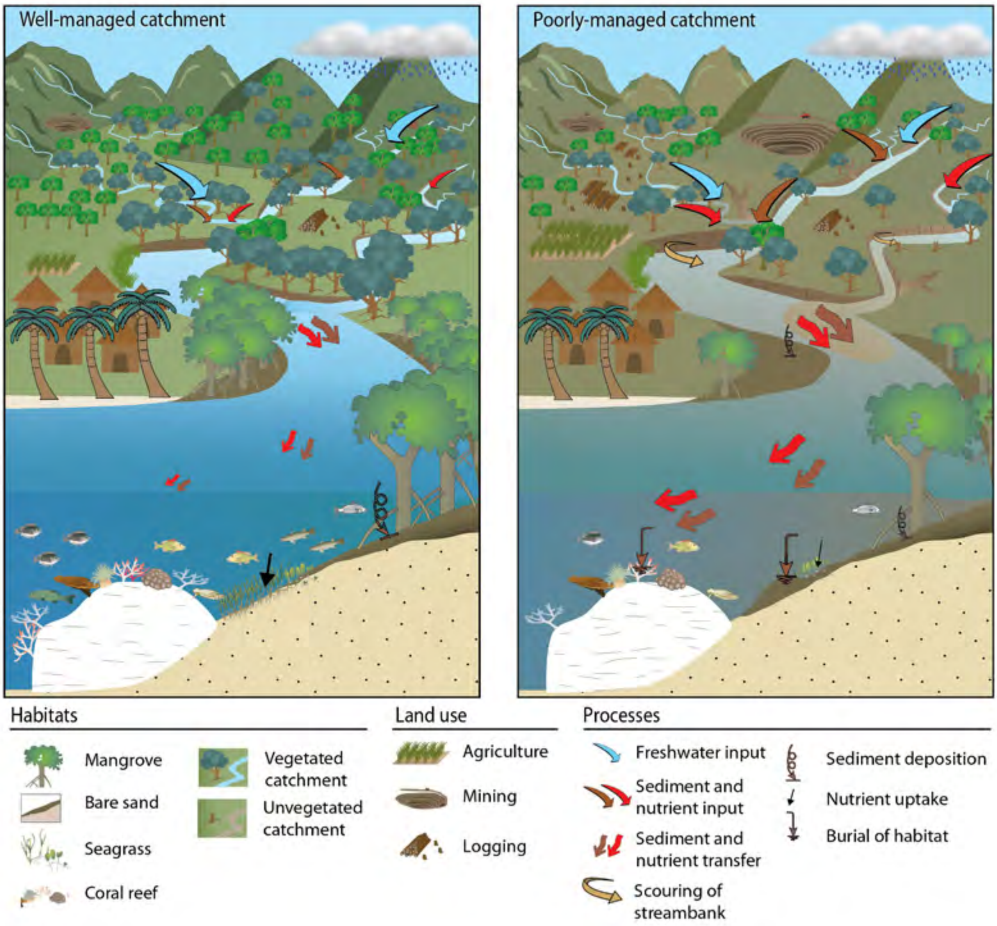

Figure 13.4 Differences in the quality of freshwater and coastal fish habitats under the influence of well-managed and poorly-managed catchments.

- Promote the importance of catchment management for fisheries at national planning meetings and obtain commitments from the agriculture, forestry and mining sectors to implement best practice to conserve vegetation and replant trees, minimise soil exposure and loss during construction of infrastructure, and prevent fertilizers and pollutants from entering watercourses.
- Encourage benign farming practices, including those built on traditional knowledge; raise awareness of the 'downstream' effects of poorly-designed agriculture and forestry operations (such as 'slash and burn'); and facilitate broad-based participation of customary owners, including men, women and youth, in the diversification of agro-forestry practices which are in harmony with the maintenance of fish habitats to build resilience to climate change[84,85].

Maintaining and restoring catchment vegetation should improve the quality of freshwater and coastal habitats in the short term. It should also help safeguard coastal habitats (Chapters 5 and 6), and allow freshwater habitats to expand and support more fish (Chapters 7 and 10), in PICTs where rainfall is projected to increase (Chapter 2).

➢ Adaptation F2: Foster the care of coastal fish habitats (win-win)

In addition to the vital importance of minimising sediment and nutrient inputs to the coastal zone from runoff, several measures are needed to improve the resilience of coastal fish habitats to climate change. These measures are listed below.

- Prevent deterioration in water quality that can arise from urban areas (e.g. sewage from humans and animal husbandry, chemical discharges, solid waste and factory effluent) by controlling pollution and managing waste. These are responsible interventions at any time, but require even greater attention in the future because the projected changes to coastal waters may reduce their capacity to attenuate waste.
- Eliminate activities that damage the three-dimensional structure of coral reefs, which provide much of the coastal fisheries production (Chapters 5 and 9). Such activities include destructive fishing methods (particularly dynamite fishing), extraction of coral for building materials; careless anchoring of boats and tourism activities; and poorly-designed coastal infrastructure and tourist facilities. Degradation of coral reefs can also promote the incidence of ciguatera fish poisoning.
- Prohibit activities that reduce mangroves, e.g. removing trees, and damage the structural complexity of seagrasses, e.g. dredging or fishing with trawl nets (Chapter 6).
- Raise awareness of communities about the dependence of fish and invertebrates on coastal habitats that may not already be part of their traditional knowledge (or has been lost); and liaise with communities to maintain connectivity among

coral reefs, mangroves, seagrasses and intertidal flats to (1) conserve the habitat mosaic needed for successful recruitment of juvenile fish and invertebrates, and (2) provide a diverse range of feeding areas for the adult demersal fish that dominate coastal fisheries (Chapters 6 and 9).

- Enlist the assistance of NGOs, coral reef task forces[x], and programmes such as Seagrass-Watch[xi] to help communities protect fish habitats, while using these habitats for firewood, tapa, building materials and medicines etc., in ways that combine traditional approaches and government regulations for sustainable use of resources.

These measures should help maintain coastal fish habitats and recruitment of coastal fish and invertebrates in the short term. They are also expected to help make coral reefs, mangroves and seagrasses more resilient to the various stressors associated with climate change in the future, such as increased water temperature, greater turbidity and nutrients loads, acidification and sea-level rise (Chapters 5 and 6).

➢ Adaptation F3: Provide for landward migration of coastal fish habitats (lose-win)

On large high islands, national planners and community leaders should avoid building infrastructure on low-lying land adjacent to mangroves, seagrasses and intertidal flats, which will eventually have to be protected from sea-level rise by erecting barriers to inundation. Instead, such low-lying areas should remain undeveloped to provide opportunities for fish habitats to migrate landward (Chapter 6), particularly where projected increases in sea level (Chapter 3) are expected to inundate large areas of land. Because land is subject to traditional ownership in much of the region, national governments should help communities identify areas that will be inundated and consider compensating resource owners who agree to forego development of their land, if necessary.

Where existing road infrastructure blocks the inundation of low-lying land suitable for the colonisation of mangroves, channels and bridges should be constructed to allow inundation to occur (**Figure 13.5**). Communities should also be encouraged and trained to plant mangroves in such places to fast-track the establishment of the trees (Chapter 6).

The short-term opportunity costs of this adaptation – loss of some uses of undeveloped low-lying land – are expected to be balanced by the benefits of maintaining fish habitats in the longer term. Some short-term benefits are also expected, however, through raising awareness among national planners of the importance of coastal fish habitats, and avoiding the construction of infrastructure on low-lying land that will be difficult to protect in the future.

[x] For example, the Coral Triangle Initiative (www.cti-secretariat.net/about-cti/plan-of-actions).

[xi] www.seagrasswatch.org/about.html

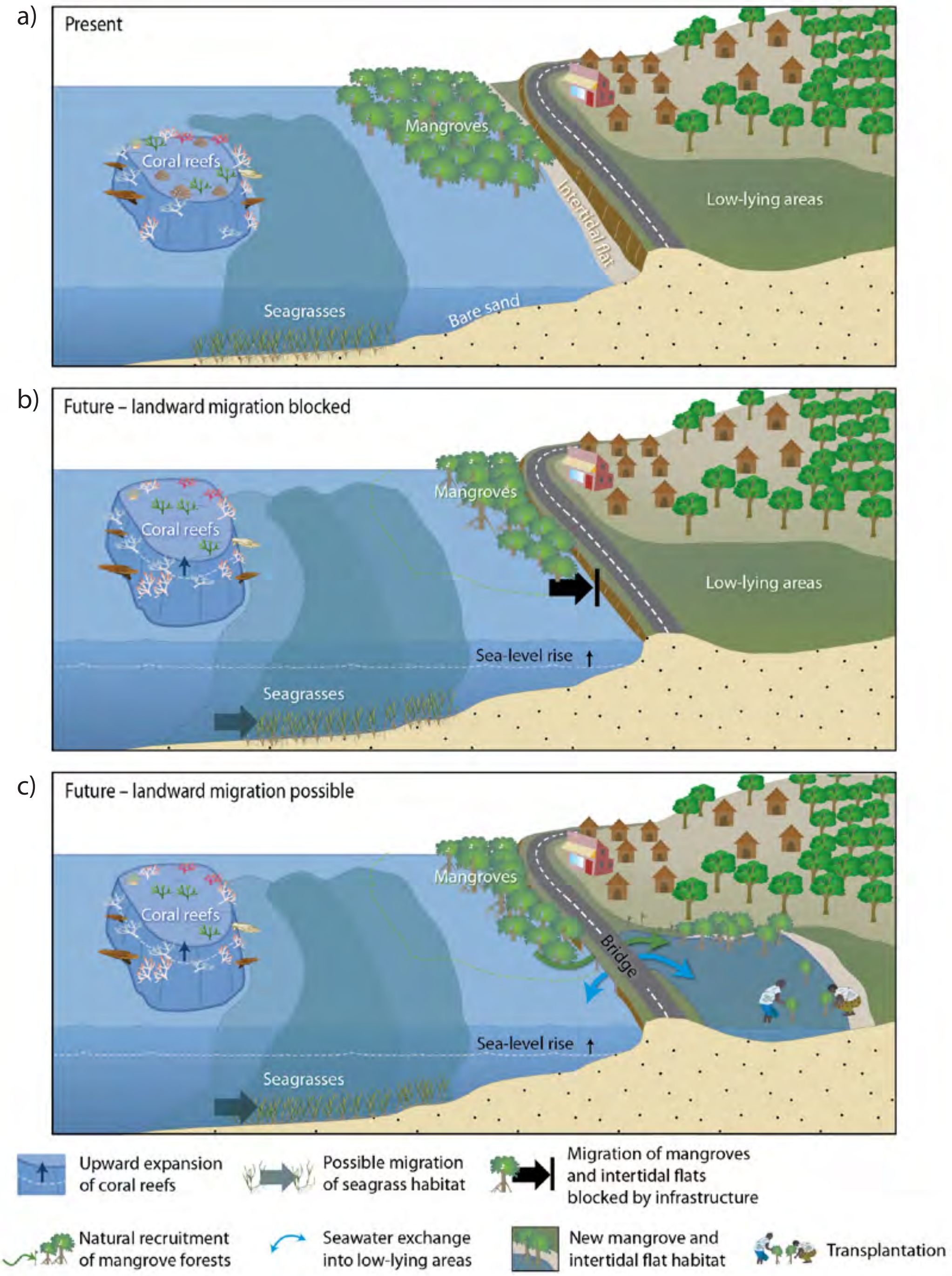

Figure 13.5 (a) Coral reef, mangrove, seagrass and intertidal habitats near low-lying undeveloped coastal land; (b) projected loss of mangrove and intertidal flat habitats because coastal infrastructure blocks their migration landward as sea level rises; and (c) modifications to road infrastructure to allow landward migration of mangroves and intertidal flat habitat, supplemented by mangrove replanting programmes.

- **Adaptation F4: Allow for expansion of freshwater habitats (lose-win)**

The following management measures are needed to maintain, and maybe increase, freshwater fish production in the region under a changing climate.

- Allow river channels to migrate naturally so that there is no permanent loss of habitat quality and area following floods (Chapter 7).
- Permit freshwater habitats to expand with increasing rainfall, by ensuring that inundation of undeveloped areas of floodplain habitats is not constrained (Chapter 7).
- Remove or modify man-made barriers that prevent freshwater fish and invertebrates from retreating upstream as salt water penetrates further into rivers as sea level rises (Chapters 7 and 10). Low-cost fishways constructed with local materials may improve access to upstream habitats in places where it is impractical to remove barriers such as causeways and weirs.

The opportunity cost for communities and governments associated with these adaptations is the alienation of land adjacent to rivers from some uses that may otherwise have been possible through engineering works to contain floods or prevent intrusion of salt water. However, the recommended measures should not only pave the way for expansion of freshwater and estuarine fish production under the projected increases in rainfall and sea-level rise (Chapters 2 and 3), they should also prevent infrastructure from being built in places where it is likely to be at risk from climate change.

13.4.3.2 Adaptations to optimise catches from coastal demersal and freshwater fish stocks

- **Adaptation F5: Sustain production of coastal demersal fish and invertebrates (lose-win)**

Community-based ecosystem approaches to fisheries management should be strengthened in all PICTs without delay. Such CEAFM approaches should be based on primary fisheries management (Section 13.2.2) intended to keep production of demersal fish and invertebrates within sustainable bounds using a range of methods to assess data-poor fisheries[28,29,86,87]. This precautionary approach will reduce the supply of demersal fish and invertebrates, but also reduce the gap between coastal fisheries production and the fish needed by rapidly growing populations by safeguarding the potential for stocks to be replenished. Conversely, poor management is likely to increase this gap[75] (Chapter 12). Understanding the dimensions of the gap will assist governments and communities to plan the adaptations needed to fill it (see below).

It is important to note, however, that CEAFM will need to be progressively more precautionary to allow for the increased uncertainty associated with climate change[29] (**Figure 13.1**). Indeed, the effects of overfishing may become increasingly difficult to reverse because replenishment of local fish stocks from distant sources is expected to become more sporadic as increased sea surface temperature (SST) and altered ocean current patterns reduce the availability of juveniles from remote areas (Chapter 9).

Fishing near a coral reef, Papua New Guinea

Photo: Jurgen Freund

➢ Adaptation F6: Diversify catches of coastal demersal fish (lose-win)

Raising awareness among fishing communities of the alterations in species composition of demersal fish likely to be caused by a changing climate will assist communities to optimise catches. Changes in species composition are expected to be driven by (1) local increases in the abundance of some species not currently harvested due to changes in distribution[88]; and (2) an increase in herbivorous species[89] as a result of the expected changes in the structure of coastal habitats (Chapters 5, 6 and 9). Diversifying fishing practices to take catches representative of the changes in relative abundance of species, within a primary fisheries management framework (Section 13.2.2), should help maximise the potential to realise gains from the increases of some fish species[90].

Nevertheless, harvesting of herbivorous fish needs to be restrained to ensure they remain plentiful enough to remove the algae that inhibit the survival and growth of corals[91,92]. An abundance of herbivorous fish is also expected to enhance the resilience of corals to increases in water temperature (Chapter 5), with positive knock-on effects on other types of reef fish (Chapter 9). Foregoing some of the catch of herbivorous species reduces potential supplies of fish in the short and long term, but should increase overall productivity of other demersal fish in the future.

➢ Adaptation F7: Manage freshwater and estuarine fisheries to harness opportunities (lose-win)

Community-based ecosystem approaches to fisheries management also needs to be introduced for PNG's extensive freshwater and estuarine fisheries, and smaller fisheries elsewhere in Melanesia. In contrast to coastal fisheries, the communities who depend on freshwater and estuarine resources can be guided to harvest more fish incrementally as production increases under greater projected rainfall and water temperatures, and sea-level rise (Chapters 7 and 10). Effective primary fisheries management (Section 13.2.3) is needed to secure these benefits. Governments and communities can use the measures described below to take advantage of the projected increases in freshwater and estuarine fisheries production.

- Diversify fisheries over a wider range of species and habitats to harness the expected increases in freshwater and estuarine fisheries production, including fisheries based on species at low trophic levels (e.g. river herring), and introduced and invasive species tolerant of the direct and indirect effects of climate change (e.g. snakehead) (Chapter 10). Fishing methods should also be developed for floodplain habitats presently considered inaccessible.
- Investigate ways to manage populations of low-value invasive species that may be favoured by climate change to reduce negative interactions with more valuable food species. For example, using walking catfish and climbing perch to produce fishmeal for pond aquaculture, or fish-silage fertiliser[93] (Chapter 11).
- Strengthen traditional mechanisms regulating access to, and use of, rivers and other freshwater habitats to conserve the projected increased benefits for rapidly growing resident communities.

Although CEAFM for freshwater and estuarine fisheries, based on primary fisheries management, limits production in the face of the great need for fish by the large inland communities in PNG, it should allow these fisheries to make greater contributions to food security as the projected increases in productivity occur due to climate change.

13.4.3.3 Adaptations to fill the gap in fish needed for food security

➢ Adaptation F8: Increase access to tuna for urban and rural populations (win-win)

The rich tuna resources of the region (Chapter 8) provide PICTs with the opportunity to fill the gap between the fish needed for good nutrition in urban and rural communities in the future, and the demersal fish expected to be available from coastal fisheries. The key adaptations for increasing access to tuna are described below.

- Promote the storage and distribution of low-value tuna and bycatch, now retained by industrial vessels transhipping their catch through capital cities in PNA countries, or landing it at other ports elsewhere in the region, to provide inexpensive fish for rapidly-growing urban populations. This adaptation should meet most of the shortfall in the fish needed for good nutrition in many of the main urban centres in the short and long term. It should be reinforced in PNG and Solomon Islands through increased landings of fish to supply the canneries being constructed there. In some other urban centres, e.g. Tarawa in Kiribati, projected changes in distribution of skipjack tuna should also make this adaptation easier to achieve (Chapter 8). This adaptation should also aim to increase the involvement of women in the distribution and selling of low-value tuna and bycatch[94,95]. In some of the smaller urban centres in the near term, care may be needed to release low-value tuna and bycatch onto the market in ways and at times that do not undermine the livelihoods of local small-scale commercial fishers.

- Transfer coastal fishing effort from demersal fish to nearshore pelagic fish, especially tuna. This can be done most effectively by installing networks of low-cost, fish aggregating devices (FADs)[96] (**Figure 13.6**) anchored close enough to the coast (usually within 1–6 km from the shore at depths of 300–1000 m) to provide better access to skipjack and yellowfin tuna for subsistence and small-scale commercial fishers.

  The technology for these anchored FADs has been developed over decades and works well, provided the FADs are placed where they attract mainly tuna and other oceanic fish, not pelagic fish closely associated with reefs (Chapter 9). Anchored fish aggregating devices now cost ~ USD 1000–2000, depending on depth. The value of tuna and other fish caught around these FADs can greatly exceed the costs of construction and deployment[96]. However, many communities will need training in the methods used to fish around FADs[97], and in post-harvest processing of catches (see below), to derive the full range of benefits. Networks of FADs should be seen as part of the national infrastructure for food security. Communities and their development partners should make plans to maintain FADs regularly, and replace them when they are lost.

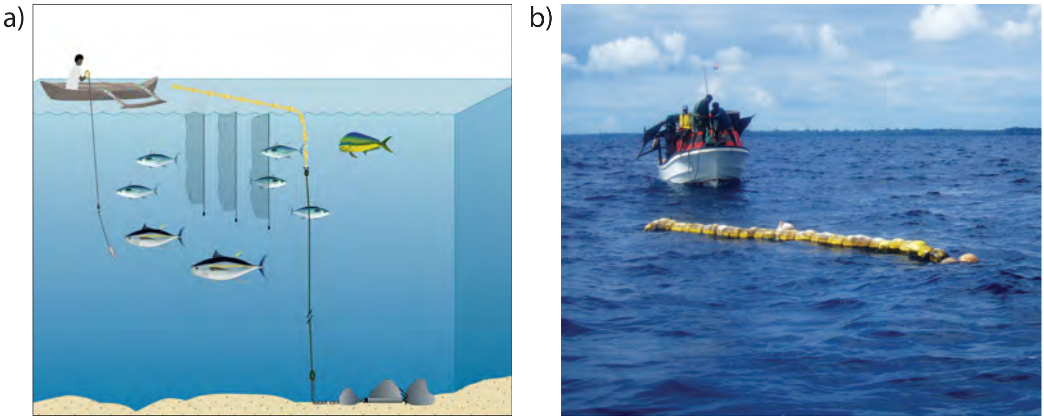

Figure 13.6 (a) Design of anchored, low-cost fish aggregating devices (FADs) suitable for placing in coastal waters (usually 300–1000 m deep) to increase access to skipjack and yellowfin tuna, and other large pelagic fish species; (b) surface buoys of a FAD in Papua New Guinea (photo: William Sokimi).

Transferring effort from demersal to nearshore pelagic fish should deliver much of the fish required for food by coastal communities (Chapter 12) in the short and long term. Increased reliance on nearshore pelagic fish should be favoured by climate change across the region until 2035, and in the east until 2100, due to projected changes in the distribution and abundance of tuna (Chapter 8). Even in PNG and Solomon Islands, where tuna catches are eventually expected to diminish, tuna should still be plentiful enough to make anchored FADs an efficient adaptation response to increasing human populations and declining demersal fisheries.

➢ Adaptation F9: Develop pond aquaculture to diversify the supply of fish (win-win)

Although there is great potential for tuna to supply PICTs with much of the additional fish they need for good nutrition of their populations (Chapter 12), providing access to tuna everywhere in the region, or at all times, will not be possible. Development of pond aquaculture (**Figure 13.7**) in peri-urban areas, and for the benefit of inland communities in PNG[98] and coastal communities with limited access to demersal fish or FADs in other PICTs, should also supply more fish (Chapters 11 and 12). Pond aquaculture has long been successful in Asia[99,100], where much of the production is based on Nile tilapia *Oreochromis niloticus*, including genetically improved, farmed tilapia (GIFT) varieties[101]. Nile tilapia are easy to reproduce and usually reach harvest size within 4–6 months in the tropics[102,103]. Carp and milkfish also have potential for pond aquaculture (Chapter 11).

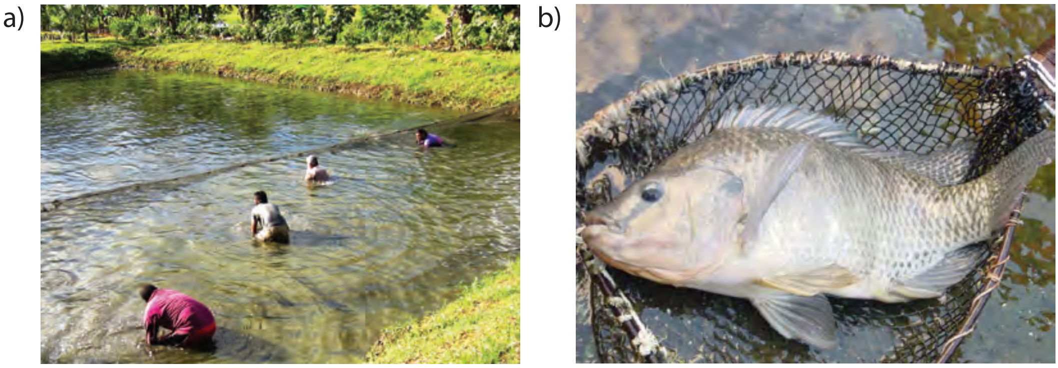

Figure 13.7 (a) Harvesting Nile tilapia from a freshwater pond in Fiji; and (b) a farmed Nile tilapia (photos: Timothy Pickering).

Key considerations involved in implementing pond aquaculture are (1) selection of appropriate species; (2) design and construction of hatchery systems and networks that allow good quality fingerlings to be distributed effectively to farmers; (3) location of ponds where they will not be affected by floods; (4) availability of cost-effective feeds for semi-intensive and intensive farming systems, based on locally-available ingredients wherever possible; (5) capacity of fisheries staff and extension officers to provide training; (6) mechanisms for distributing production to markets; (7) possible effects on freshwater biodiversity of fish escaping from ponds; (8) prevention of effluent from intensive commercial operations in peri-urban areas from entering nearby rivers and coastal habitats; and (9) the threat of greater incidence of malaria as the breeding habitat for mosquitoes is increased through pond construction.

The simple, proven technology for farming species like tilapia, carp and milkfish is expected to help meet the growing demand for fish in some locations in the short term, and is likely to be favoured by the projected increases in rainfall and temperatures in the future (Chapter 11). Availability of suitable feeds is likely to be one of the major limiting factors and could be exacerbated by increased exposure to shortfalls in global supplies of fishmeal due to climate change. Specific adaptations to secure adequate supplies of fishmeal include (1) rationalising allocation of fishmeal from tuna processing plants in the region for aquaculture and agriculture; (2) using undesirable introduced and invasive freshwater fish species in PNG to produce fish feeds at the village level; (3) replacing fishmeal with suitable local alternative sources of protein; and (4) promoting Best Management Practice (BMP) for feeding of farmed fish to increase feed efficiency.

➢ Adaptation F10: Develop coastal fisheries for small pelagic fish (win-win?)

Diversify coastal fisheries to catch small pelagic species (mackerel, anchovies, pilchards, sardines, scads, fusiliers and squid), and support communities with the training and equipment required. The generally sustainable (though variable) nature of small pelagic fish harvests (Chapter 9) should provide access to more fish in the near term. The outlook for the long term is uncertain – projected decreases in primary

A school of small pelagic fish – mackerel *Rastrelliger brachysoma*

Photo: Nathalie Behring

productivity due to increased stratification associated with higher SST (Chapter 4) may cause abundance of small pelagic fish to decline. Conversely, projected increases of nutrients in coastal waters due to greater runoff may increase their production in some locations in the long term (Chapter 9).

- **Adaptation F11: Improve post-harvest methods (win-win)**

Extend the shelf life of fish caught in coastal and inland areas by training communities, particularly women, in appropriate ways to improve traditional methods for smoke curing, salting and drying fish[104]. In this way, coastal communities could make better use of large catches of tuna and small pelagic fish in the short term and, if climate change makes catches of these species more variable, in the long term. Improved post-harvest methods could also enable households to store fish for those times when conditions are not suitable for fishing, and create opportunities to trade products with those inland communities without access to fish.

13.4.4 Supporting policies for maintaining the contribution of fish to food security (F)

The suggested policies required to implement the adaptations to maintain the contributions of fish to food security described in Section 13.4.3 are outlined below. **Table 13.3** lists the policies that apply to each adaptation.

- **Policy F1: Strengthen governance and legislation to ensure the sustainable use and protection of all coastal and freshwater fish habitats** by (1) building the capacity of management agencies to understand the threats posed by climate change; (2) amending existing legislation to empower communities to manage fish habitats; (3) establishing networks to transfer this knowledge to rural communities; (4) introducing regulations and licence conditions for forestry and mining operations to reinforce protection for catchments and coastal fish habitats; (5) strengthening traditional and national institutions and regulations for sustainable use of coastal land and aquatic habitats; and (6) assisting communities to monitor changes in habitats and comply with management decisions and regulations.
- **Policy F2: Promote ecosystem-based management measures for agriculture, forestry and mining** at all levels to prevent damage to freshwater and coastal fish habitats through soil loss, transport of sediments and nutrients to watercourses and coasts, and pollution.
- **Policy F3: Protect source and resilient coral reefs** expected to supply recruits to ‘downstream’ reefs to help these reefs recover after coral bleaching or damage by cyclones.
- **Policy F4: Minimise barriers to landward migration of coastal habitats and expansion of freshwater fish habitats** during development of strategies to assist other sectors to respond to climate change.

- **Policy F5: Promote mangrove replanting programmes** in suitable areas (Chapter 6) to meet the twin objectives of enhancing habitat for coastal fisheries, and capturing carbon.
- **Policy F6: Apply primary fisheries management** to coastal and freshwater fish stocks to maintain their potential for replenishment.
- **Policy F7: Restrict export of demersal fish** to ensure that these resources are available for national food security where necessary (this policy does not apply to deepwater snappers).
- **Policy F8: Allocate tuna from national catches for food security**, so that rural and urban communities have greater access to fish.
- **Policy F9: Revise national and regional tuna management plans to provide the fish needed for local consumption**, including the general tuna management framework of the WCPFC.
- **Policy F10: Encourage coastal fishing communities to transfer effort to nearshore pelagic species**, to supply more tuna for subsistence, and for local and urban markets.
- **Policy F11: Include FADs (anchored inshore) as part of the national infrastructure for food security**, ensure a maintenance programme is in place and make provision to replace FADs lost through wear and tear and storms.
- **Policy F12: Provide incentives for the private sector to purchase, store, process and distribute lower-value tuna** and bycatch landed by industrial fleets in major ports to increase access to fish in urban areas. Ensure that such enterprises comply with the Right to Food standards contained in the International Covenant on Economic, Social and Cultural Rights (ICESCR), and Humanitarian Law.
- **Policy F13: Dedicate a proportion of the revenue from fishing licences to improve management** of all fisheries and aquaculture, and access to fish for rural and urban populations. For example, by upgrading transport links to inland communities in PNG to enable better access to locally-canned tuna, and smoked and dried fish.
- **Policy F14: Provide incentives for the private sector** to invest in pond aquaculture, and support effective systems for producing and distributing fry to smallholders in rural areas.
- **Policy F15: Reconcile the use of introduced fish species for pond aquaculture with the potential effects on freshwater biodiversity**[105,106] by zoning pond aquaculture. Until the research recommended (Section 13.9.1.4) is completed, the introduction of Nile tilapia should be limited to (1) PICTs where coastal fisheries resources and local access to tuna are likely to be insufficient to meet the present and future recommended level of fish consumption for good nutrition (Chapter 12); and (2) catchments where Mozambique tilapia *Oreochromis mossambicus* already occurs.

- **Policy F16: Strengthen national capacity, and collaboration between national agencies, to manage environmental issues** related to aquaculture development, such as application of Environmental Impact Assessment procedures that consider present and future risks associated with aquaculture proposals.
- **Policy 17: Provide training and technical support** for coastal fishing communities to catch small pelagic fish, and for inland and coastal communities to improve post-harvest methods to extend the shelf life of catches.
- **Policy F18: Revise primary school curricula to teach children about fish and food security**, focusing on (1) the importance of fish for their health; (2) the basic management actions needed to maintain fish habitats and fish stocks; and (3) the options for increasing future supplies of fish.

Table 13.3 Summary of adaptations and companion supporting policies to maintain the contributions of fish to food security for Pacific Island countries and territories (see Sections 13.4.3 and 13.4.4 for details).

Adaptation		Type	Supporting policy*
Adaptations to safeguard habitats producing fish			
F1	Manage and restore vegetation in catchments	W-W	F1, F2, F18
F2	Foster the care of coastal fish habitats	W-W	F1–F3, F18
F3	Provide for landward migration of coastal fish habitats	L-W	F4, F5, F18
F4	Allow for expansion of freshwater habitats	L-W	F4, F18
Adaptations to optimise catches from coastal demersal and freshwater fish stocks			
F5	Sustain production of coastal demersal fish and invertebrates	L-W	F6, F7, F13, F18
F6	Diversify catches of coastal demersal fish	L-W	F6, F13, F18
F7	Manage freshwater and estuarine fisheries to harness opportunities	L-W	
Adaptations to fill the gap in fish needed for food security			
F8	Increase access to tuna for urban and rural populations	W-W	F8–F13, F18
F9	Develop pond aquaculture to diversify the supply of fish	W-W	F13–F16, F18
F10	Develop coastal fisheries for small pelagic fish	W-W?	F13, F17, F18
F11	Improve post-harvest methods	W-W	F17, F18

* Refers to supporting policy number in Section 13.4.4; W = win; L = lose.

13.4.5 Adaptations for maximising sustainable livelihoods (L)

The eventual projected shift to the east in the distributions of tuna, decreases in production of coastal fisheries and coastal aquaculture commodities, and increases in production of freshwater fisheries and pond aquaculture, are expected to alter the availability of full-time jobs, and opportunities to earn income (Chapter 12). Many of the adaptations and suggested policies required to minimise the loss of livelihoods derived from some fisheries and aquaculture activities, and to capitalise on the opportunities expected to be created for others, are the same as those described in Sections 13.4.1–13.4.4. Examples include the imperative to conserve and restore fish habitats, the need to secure the supplies of tuna required to base more tuna processing operations within PICTs, switching fishing effort from demersal fish to nearshore pelagic fish, installing inshore FADs to improve access to tuna for small-scale commercial fishers, developing pond aquaculture in peri-urban areas, and marketing environmentally-friendly products. The additional adaptations needed to optimise the number of jobs that can be sustained by the sector are outlined below.

➢ Adaptation L1: Improve technical and business skills of communities (win-win)

Increase community participation in fishing around FADs and for small pelagic species, developing pond aquaculture and applying post-harvest methods. Together, these adaptations (Section 13.4.3) provide considerable opportunities to diversify income-earning activities. Training programmes to teach community members (including women) the necessary fishing and farming techniques, and small business skills, will be required to capitalise on these opportunities. Micro-finance schemes may also be needed to assist people to diversify into the broader range of fishing operations and value-added activities involved in these adaptations. Because the technology for all these adaptations already exists, these activities are expected to deliver benefits in the short term. The projected increases in abundance of tuna (Chapter 8), and improvements in conditions for pond aquaculture (Chapter 11), in many PICTs due to climate change means that investments in these adaptations are also likely to result in benefits well into the future.

Smoking fish, Kiribati

Photo: Jocelyn Carlin

➢ Adaptation L2: Rebuild populations of sea cucumbers and trochus (lose-win)

Primary fisheries management (Section 13.2.2) is needed to reverse the declines in stocks of sea cucumbers and trochus. For sea cucumbers, this involves (1) conservative harvests based on indicators such as species composition and size-frequency to restore the densities of adults to levels above the thresholds required for regular replenishment (Chapter 9); and (2) strict controls on the size of individuals exported[87]. For trochus, densities should be restored to 500–600 individuals per ha, with a wide spread of size classes. Harvests should then be restricted to 180 shells per ha per year, preferably with 3–5 year periods of moratorium between fishing events (Chapter 9). This adaptation results in some loss of income while stocks are rebuilt, but sets the stage for greater benefits in the future. Although climate change may affect the productivity of sea cucumbers and trochus (Chapters 9 and 11), more robust populations should have a greater resilience to increased water temperatures and ocean acidification.

➢ Adaptation L3: Develop coral reef ecotourism ventures (win-win?)

Reducing the pressure on fisheries resources by providing viable alternative sources of income for local communities in the tourism sector is expected to help maintain fish stocks within sustainable limits, and make fisheries for demersal fish and invertebrates less vulnerable to climate change. However, the projected degradation of coral reefs due to increases in SST and ocean acidification may affect the long-term viability of ecotourism operations. Much care is also needed in the planning and construction of facilities for tourism to ensure that they do not affect the extent and quality of coastal fish habitats (Section 13.4.3).

➢ Adaptation L4: Diversify production of coastal aquaculture commodities (win-win)

Assess the potential to grow 'new' commodities in the region likely to (1) support profitable enterprises; and (2) be favoured by prevailing environmental, economic and social conditions in PICTs. Because the species involved in producing new commodities are most likely to be introduced from other regions, the potential risks to marine biodiversity need to be reconciled with opportunities to provide livelihoods. Otherwise, any production gains may be undermined by losses to other valued species.

➢ Adaptation L5: Modify locations and infrastructure for coastal aquaculture (lose-win)

A variety of adaptations can be made, as and when required, to reduce the expected negative effects of sea-level rise, ocean acidification and higher water temperatures on coastal aquaculture activities (Chapter 11), as described below.

- Relocate pearl farming operations to sites close to existing coral reefs and seagrass meadows, where aragonite saturation levels are likely to remain high enough for good growth and survival of pearl oysters, and formation of high-quality nacre (Chapter 11). This adaptation also applies to the small-scale village-based operations to culture giant clams and corals for the ornamental market.

- Raise the walls and floor of existing shrimp ponds so that they can continue to function under sea-level rise, and identify which ponds would need to be abandoned in favour of new structures further landward at higher elevations (Chapter 11).
- Assess which alternative commodities (perhaps sea cucumbers) could be produced in ponds no longer suitable for shrimps in ways that do not impede landward migration of mangroves and seagrasses.

Such adaptations may involve foregoing production at existing sites or facilities, or production of present commodities, in an effort to ensure that aquaculture creates jobs in the future.

13.4.6 Supporting policies for maximising sustainable livelihoods (L)

The suggested policies needed to implement adaptations recommended for maximising the contributions of fisheries and aquaculture to livelihoods described in Section 13.4.5 are outlined below. The policies that apply to each adaptation are listed in **Table 13.4**.

- **Policy L1: Provide access to the training needed to operate profitable businesses** based on small-scale coastal fisheries and aquaculture activities for rural communities.
- **Policy L2: Develop partnerships with regional technical agencies** to provide the necessary technical support to manage coastal fisheries and develop aquaculture enterprises.
- **Policy L3: Promote private sector investment in coastal tourism designed to accommodate climate change**, particularly the projected changes in sea level, storm surge and changes to coral reefs and other coastal habitats.
- **Policy L4: Inform prospective private sector investors in coastal aquaculture** about the projected horizons for economically viable operations for each commodity under climate change.
- **Policy L5: Strengthen national and regional capacity to adopt and implement aquatic animal health and biosecurity measures,** including development of a regional aquatic biosecurity framework and international protocols for monitoring, detecting and reporting aquatic animal diseases to prevent introduction of new pathogens[51]. These measures will require cross-sectoral approaches, involving fisheries, quarantine and environmental agencies.
- **Policy L6: Provide incentives for aquaculture enterprises to assess risks to infrastructure** so that farming operations and facilities can be relocated if necessary.

Table 13.4 Summary of adaptations and companion supporting policies to maximise the contributions of fisheries and aquaculture to the creation of livelihoods in Pacific Island countries and territories (see Sections 13.4.5 and 13.4.6 for details).

Adaptation		Type	Supporting policy*
L1	Improve technical and business skills of communities	W-W	L1, L2
L2	Rebuild populations of sea cucumbers and trochus	L-W	L2
L3	Develop coral reef ecotourism ventures	W-W?	L3
L4	Diversify production of coastal aquaculture commodities	W-W	L4, L5
L5	Modify locations and infrastructure for coastal aquaculture	L-W	L6

* Refers to supporting policy number in Section 13.4.6; W = win; L = lose.

13.5 Interactions among adaptations

The adaptations recommended above have been designed to fit into existing management frameworks to address the effects of population growth and habitat degradation in the short term, and climate change in the long term (Sections 13.2–13.4). However, stakeholders need to know (1) whether they are likely to succeed in the context of other processes involved in the use of resources; and (2) whether any negative interactions among these adaptations could occur. Also, some adaptations, or combinations of adaptations, may be more effective than others. Qualitative models[107,108] (Appendix 13.1) can help to answer these questions.

To demonstrate the usefulness of these tools, we have used a qualitative model to examine the relationships between the key adaptations recommended to maintain the role of fish in providing food security for coastal communities. The model considered the effects of (1) longstanding relationships among fishing effort, stocks of demersal fish and inshore pelagic fish, catch, markets and food security; (2) human population growth and habitat degradation as drivers of these relationships; (3) practical adaptations to maintain access to adequate fish for food security in the face of these drivers; and (4) the possible impact of climate change on these adaptations.

The qualitative model (**Figure 13.8**) shows the effects of subsistence and artisanal fisheries on the stocks of demersal and nearshore pelagic fish through the variables of fishing effort, catch and the market value of catch[107]. Food security is dependent on catch, which is determined by both fishing effort and stock abundance, and which suppresses the market value of the proportion of the catch sold via a supply-demand relationship. Fishing effort increases catch and reduces stock abundance, although the effect of coastal fishing on stocks of tuna is negligible compared with the effect of industrial fleets (Chapters 8 and 9) and has been omitted from the analysis. The benefits of catch support fishing effort and food security. The key drivers – human population growth and habitat degradation – shape the system in positive and negative ways. An increasing human population creates greater demand for food, leading to increased fishing effort. Population growth also contributes to degradation of the coral reefs, mangroves and seagrasses that support demersal fish stocks. Planned adaptations to maintain or increase access to fish for food security include integrated coastal zone management, management to rebuild demersal fish stocks, the use of inshore FADs to increase the catch of nearshore pelagic fish, pond aquaculture and post-harvest processing (Section 13.4).

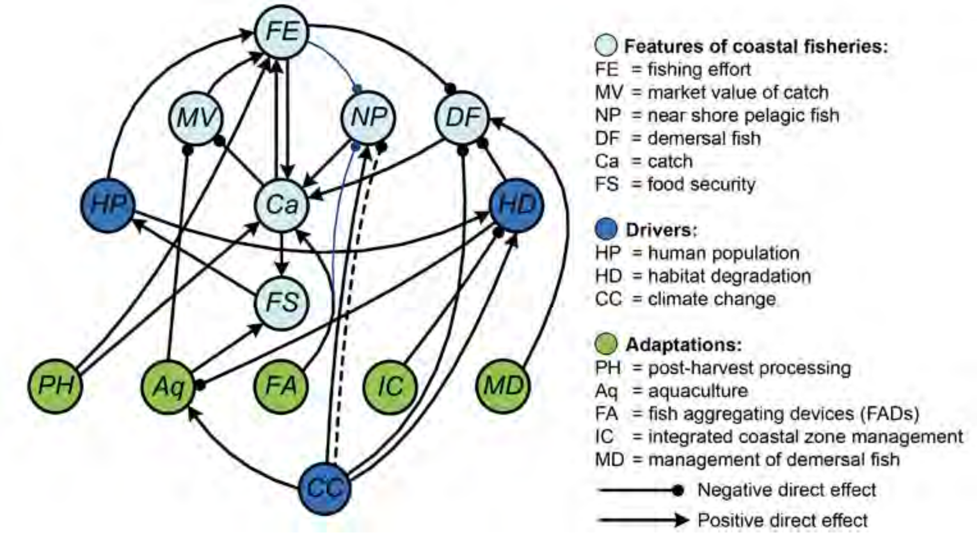

Figure 13.8 Signed digraph model of factors affecting the use of fish for food security by coastal communities in Pacific Island countries and territories under the A2 emissions scenario. Light blue circles represent major variables regulating delivery of protein from coastal fisheries; dark blue circles represent some important drivers in the system, and green circles represent possible key adaptations for food security. Links ending in an arrow represent positive direct effects and links ending in a filled circle represent negative direct effects. In 2035, the effects of climate change on catches of nearshore pelagic fish are projected to be positive across the region, but are expected to be negative in the western Pacific by 2100 (as denoted by the dashed line). The two thin-blue lined links indicate that fishing effort has a negligible effect on the tuna stocks that comprise much of the nearshore pelagic fishery. Note that in model analyses each variable was given a negative self effect (see Appendix 13.3 for further details).

The effects of climate change on the various relationships within the model are expected to:

- decrease reproduction and recruitment of demersal fish resulting from the direct effects of increased SST and ocean acidification, and the indirect effects of degradation of coral reefs, mangroves and seagrasses, exacerbated by poor coastal development (Chapters 5, 6 and 9);
- increase the abundance of nearshore pelagic fish (tuna) throughout the tropical Pacific in 2035, reduce stocks of these fish in the west by 2100, and increase them in the east until at least 2100 (Chapter 8); and

- augment aquaculture production through expansion of freshwater fish farming (Chapter 11).

The perturbations to the model (human population growth, habitat degradation and climate change) were applied differently for the eastern and western Pacific in 2035 and 2100 because human populations are predicted to increase substantially only in the west (Chapters 1 and 12), and climate change is projected to have different effects on nearshore pelagic fish in these two parts of the region (Chapter 8).

The total number of positive and negative effects on food security generated from the perturbations due to population growth and habitat degradation indicate that:

1. the contribution of catch to food security in the western Pacific is generally likely to be lower than in the eastern Pacific, demonstrating the overriding influence of increased human populations in the system – larger numbers of people have a powerful effect on reducing the fish available per person;
2. there are no adverse or unintended consequences for food security in any combination of the adaptations;
3. more adaptations result in better outcomes for food security; and
4. integrated coastal zone management, and the use of FADs combined with post-harvest processing, have the greatest positive effect on food security.

Adding climate change as another perturbation does not change the generality of these conclusions, but the projected changes in climate make it harder for these adaptations to achieve their goals in 2035, and progressively more difficult by 2100. The adaptations are also more effective in the eastern than in the western part of the region, because there is not the added pressure of large increases in human population in the east.

The qualitative nature of the model does not allow for the importance of the various adaptations to be considered precisely. This weakness is balanced, however, by the ability of qualitative models to identify variables or links that merit more in-depth investigation through other modelling approaches[108]. For example, FADs promise to provide much greater access to fish for food than aquaculture (Chapter 12). Models that weight the relative importance of these two adaptations appropriately will provide a clearer picture of their potential to enhance food security.

13.6 Planning needed to implement key adaptations

Although the technology underpinning many of the adaptations recommended here is mature, the proposed interventions will not work in all PICTs, or in all locations within a country. Additional planning will be needed to identify sites with the appropriate biological and socio-economic conditions. The use of inshore, anchored

FADs and pond aquaculture to diversify access to fish for food security are prime examples. In the case of FADs, information is needed from local communities to identify inshore areas frequented by tuna, and to identify which parts of these areas have suitable depths and bathymetry for deploying FADs to attract and temporarily hold tuna (**Figure 13.9**). Such information can be used to identify where FADs can be installed so that coastal communities can reach them easily using canoes or motor boats.

Spatial satellite imagery can also be used to identify which coastal and inland villages are close to suitable sites for pond aquaculture. Availability of flowing fresh water is not the only factor that must be considered when planning the development of pond aquaculture, however. Geographic information system (GIS) analysis of soil type, slope, rainfall and forest cover is also needed to select areas where environmental conditions are likely to be generally suitable for construction and operation of ponds[109]. At the national level, GIS analysis of population density and alternative livelihood options also needs to be considered when deciding where to encourage investors to build hatcheries to supply the juvenile fish needed by farmers. Such planning is already underway for Fiji (**Figure 13.10**).

An advantage of identifying where FADs and pond aquaculture have the potential to diversify access to fish is that the information can be combined with the area of coral reef per person for a village, to determine the extent to which these key adaptations are likely to increase local supplies of fish. Coastal communities are expected to fall into one of seven broad vulnerability categories with respect to shortages of fish, based on availability of demersal fish, and the potential to deploy FADs and build fish ponds (**Table 13.5**).

Table 13.5 Broad categories of vulnerability of coastal communities to future shortages of fish, depending on area of coral reef per person, and opportunities to install inshore fish aggregating devices (FADs) and develop pond aquaculture.

Attributes of coastal and inshore environment			Vulnerability
Coastal fisheries expected to meet future demand*	**Areas suitable for FADs**	**Areas suitable for pond aquaculture**	
Yes			Very low
No	Yes[a]	Yes	Very low – low
No	Yes[b]	Yes	Low
No	Yes[a]	No	Low – medium
No	Yes[b]	No	Medium
No	No	Yes	High
No	No	No	Very high

* Based on area of coral reef per person; a = FADs anchored in depths < 500 m and within paddling distance by canoe, i.e. within 1 km of the coast; b = boat and motor needed to reach FADs anchored in depths of up to 1000 m within 6 km of the coast.

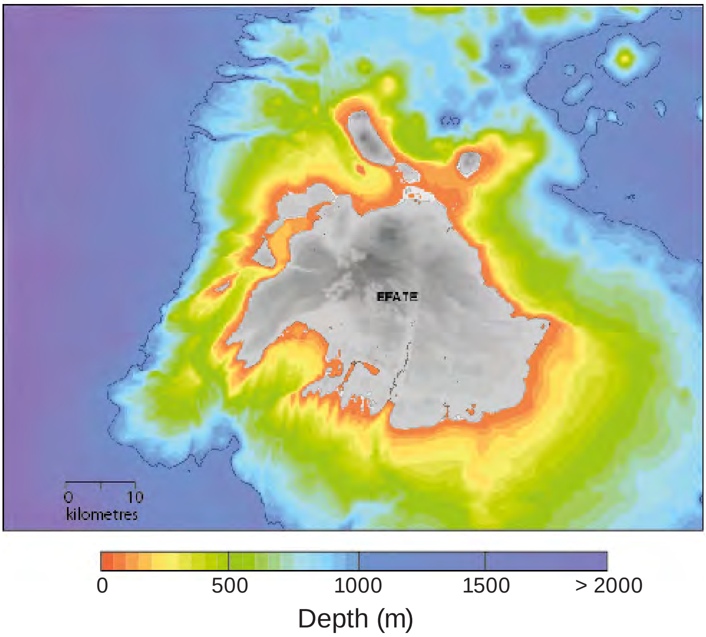

Figure 13.9 Bathymetric map of Efate Island, Vanuatu. Fish aggregating devices (FADs) could be anchored in depths of 300–1000 m to increase access to tuna for both subsistence and small-scale commercial fishers (source: Kruger et al. 2007)[123].

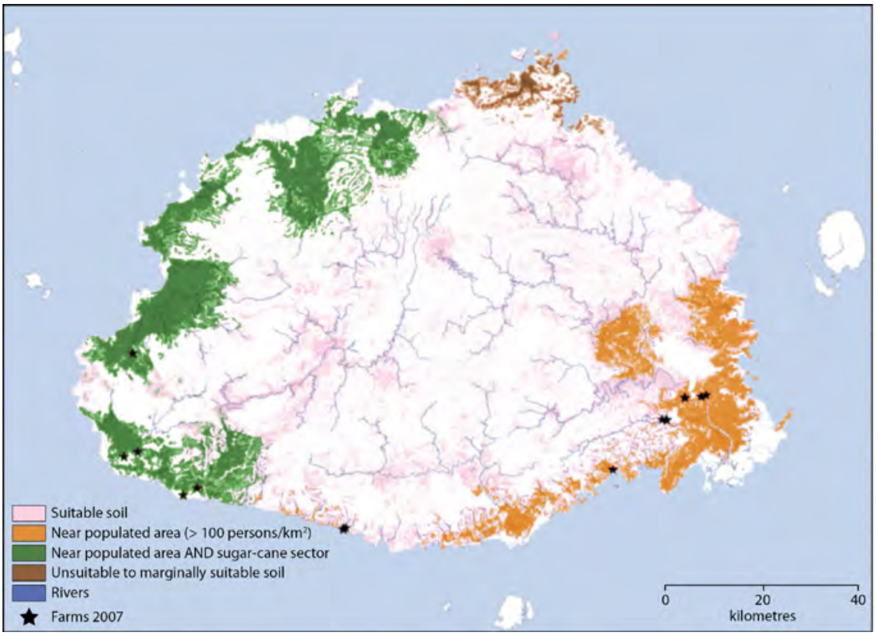

Figure 13.10 Map of Viti Levu Island, Fiji, showing areas with soils suitable for aquaculture ponds, the areas of greatest population, the location of sugar cane farming, the freshwater rivers and the locations of existing ponds for Nile tilapia. This information can be used to inform decisions about where to locate additional ponds and the hatcheries needed to supply juvenile fish (source: Chagnaud 2008)[109].

Understanding where and how the vulnerability of coastal communities to shortages of fish can be reduced by diversifying production will not only help build resilience to climate change, it could also help communities cope with non-climate related disasters, such as tsunamis. Where diversifying access to fish is not possible, communities and governments will need to place more emphasis on other ways of providing access to food and opportunities to earn income[41], for example, development of 'climate ready' crops[6,84].

13.7 The need for monitoring

The adaptations described in Section 13.4 are designed to increase the flexibility of industrial fisheries and communities to deal with projected changes in fisheries resources. However, the uncertainties associated with the projections made in Chapters 2–11 could result in other outcomes. Unexpected outcomes are likely to need alternative or modified adaptations.

To ensure that the most appropriate adaptations are applied at the right times and in the right places, PICTs will need to monitor whether changes to fish habitats and fisheries resources occur at the projected rate. Practical, well-designed programmes which can be implemented effectively by PICTs and regional organisations are required to regularly assess the status of fisheries resources and the ecosystems that support them. Monitoring is also needed to measure the success of adaptations.

The systems in place to assess variation in the distribution and abundance of tuna allow managers to monitor the effects of fishing and climate change on stocks (Chapter 8). Such monitoring is not in place for coastal fisheries in most PICTs, however, where even the basic information required to apply primary fisheries management is often missing. The three broad categories of monitoring needed for coastal fisheries are described below.

1. Assessments of the species composition and size structure of catches to provide baselines and reference points for management, against which change can be measured. This will require sampling of coastal fish catches at central markets in ways where the data can be recorded, stored and analysed easily by PICTs. Systems based on digital photography and image analysis should simplify this process.
2. Sampling to separate the effects of climate change and other stressors on coastal fish habitats, and on stocks of demersal fish and invertebrates. This will require comparisons between degraded/fished and healthy/unfished areas at representative PICTs across the region. For fish habitats, simple methods for collecting remotely-sensed data, and ground-truthing this information, have a role to play, although measures of changes in coral species composition and topographic complexity will also be needed because of their importance in

determining the abundance of demersal fish. For fisheries resources, simple indicators of abundance and size structure, which can be collected consistently by diver census over the long term, will be required.

3. Measures to assess the success of adaptations designed to maintain the benefits of fisheries and aquaculture for economic development, government revenue, food security and livelihoods. National accounts, censuses and household income and expenditure surveys (HIES) all have potential to provide the necessary data[110,111]. Assessing the success of adaptations for food security and livelihoods will also involve measuring success against a social baseline founded on human development indicators[112]. Such baselines still need to be established for many PICTs.

The imperative is to develop the necessary monitoring tools and implement long-term national and regional monitoring programmes as soon as possible – the longer the time-series, the greater the power to detect change and provide the information needed for adaptive management.

It is unlikely that the effects of climate change on aquaculture can be separated from other drivers by sampling programmes. However, there is much scope to improve the quality of production data required to measure the success of adaptations and policies in the aquaculture sector. A uniform system is needed for PICTs to record key information, such as the quantities or volumes of commodities produced for commercial sale or subsistence, number of farm units, number and gender-balance of people employed part- and full-time, and export value. This system should be designed to make it easier for countries to provide the information required by the Food and Agriculture Organization of the United Nations (FAO) for their regular 'State of World Fisheries and Aquaculture' reports.

13.8 Gaps in knowledge

Although the vulnerability assessments for fish habitats, fish stocks, and the national economies, industries and communities that rely on these resources (Chapters 4–12) were based on the best information available – the suite of global climate models from the Coupled Model Intercomparison Project, Phase 3 (CMIP3) used for the Intergovernmental Panel on Climate Change 4th Assessment Report (IPCC-AR4) – much uncertainty still surrounds these assessments. This uncertainty is due to (1) the coarse grid sizes of the CMIP3 models and their inherent biases (Chapter 1); and (2) gaps in the knowledge of the ecology of fish habitats and biology of harvested fish and invertebrates.

Here, we summarise the information needed to fill these gaps. We also consider the research needed to determine how Pacific communities are likely to accept and implement the recommended adaptations.

13.8.1 Knowledge needed to improve the understanding of vulnerability

13.8.1.1 Surface climate and tropical Pacific Ocean

More long-term, high-quality data on surface weather are needed over a wider area of the region to (1) distinguish anthropogenic effects on surface climate from natural variability; (2) link local climate to larger-scale climate observations; and (3) validate and select the best-performing climate models for each region. Such data will also establish relationships between changes in rainfall and river flow on high islands.

Increased coverage and monitoring of ocean variables are also required. In particular, the vertical distribution of nutrients, oxygen and pH needs to be measured regularly over a much more representative area of the tropical Pacific Ocean to parameterise and validate models simulating the responses of the ocean to different emissions scenarios.

To improve the next generation of global climate models, significant biases in the CMIP3 models need to be addressed. These major biases include (1) the overly zonal orientation of the South Pacific Convergence Zone, which limits confidence in projections of the rainfall and wind fields of the central-southern Pacific; and (2) the warming associated with ENSO events, which is generally situated too far to the west and often occurs too frequently. A better understanding of the physical mechanisms driving these characteristics is needed to improve the parameterisation of coupled atmosphere-ocean models.

Weather is an important consideration for coastal fishers

Photo: Franck Magron

The resolution of global climate models also needs to be increased so that they ‘see’ PICTs. Dynamical and statistical techniques to downscale global climate models are available and under continuous development to enable projections to be made for smaller areas. However, considerable further effort is needed to determine how best to implement downscaling approaches to provide robust projections of changes to surface climate and the ocean at scales meaningful to management in PICTs. This work is now underway through Australia's Pacific Climate Change Science Programme[xii].

13.8.1.2 Fish habitats

Open-ocean food webs

The extent to which climate change is likely to alter the availability of nutrients and oxygen that underpin food webs for tuna in the tropical Pacific Ocean, and the populations of phytoplankton, zooplankton and micronekton that comprise these food webs, is still poorly understood. Few reliable biogeochemical models can be linked to global climate models to project changes to these food webs and, apart from the Hawaii Ocean Time-Series station in the North Pacific Tropical Gyre (Chapter 4), no long-term observations of nutrient and oxygen levels or the abundances of phytoplankton, zooplankton and micronekton exist in the region. More long-term time-series data are a priority. Better biogeochemical models will also pave the way for improved application of ecosystem models of upper trophic levels (e.g. SEAPODYM – Spatial Ecosystem and Population Dynamics Model, and Ecopath) to project the effects of changes in components of the food web on local abundances of tuna.

The research activities required to parameterise the biogeochemical models needed to improve our confidence in simulations of tuna catches under a changing climate are outlined below.

- Assess the effects of higher atmospheric concentrations of CO_2 on the carbon-to-nitrogen ratio of organic matter in the ocean through networks of *in situ* observations and laboratory experiments.
- Identify the spatial and temporal distribution of iron in the Equatorial Undercurrent, and the future bio-availability of different forms of iron, to determine whether the present limitations on production of phytoplankton in the nutrient-rich Pacific Equatorial Divergence Province (PEQD) (Chapter 4) are likely to continue.
- Describe the variability in abundance of micronekton, and factors driving this variability. This involves validating the acoustic methods used to assess micronekton by correlating the data with micronekton sampled using nets, and from the stomach contents of tuna and other top predators[20,113].
- Evaluate the extent of lateral transport of organisms from nutrient-rich oceanic provinces such as PEQD to nutrient-poor provinces, particularly within the aphotic zone.

[xii] www.cawcr.gov.au/projects/PCCSP

Coral reefs

To reduce the uncertainty about how emissions of CO_2 and other greenhouse gases are likely to affect coral reefs, the following questions need to be answered.

- How are warming and acidification of the tropical Pacific Ocean affecting the early life history stages of corals and other key reef-building organisms? What are the knock-on effects of these processes on the wide range of species that comprise the food webs of the fish and invertebrates harvested from coral reefs?
- What is the effect of ocean acidification and warming on the relative balance between calcification and erosion? How would changes in this balance affect reef structure?
- Will synergies between projected increases in ocean acidity, SST and nutrient loads, and possibly more powerful waves from stronger tropical cyclones, damage coral reefs more severely?
- Which management strategies are likely to be most effective for coral reefs that have been bleached? Should closures to fishing and tourism be put in place until reefs have recovered?
- What are the likely consequences for coral reefs of a very rapid rise in sea level (Chapter 3)?
- Which coral reef habitats are likely to have the greatest natural resilience to bleaching, ocean acidification and other impacts of climate change?

Mangroves, seagrasses and intertidal flats

There are still major gaps in our knowledge of the distribution, diversity and coverage of mangrove and seagrass habitats, and the areas of intertidal flats, across the tropical Pacific (Chapter 6). In many cases, even the existing estimates of habitat area are likely to be gross underestimates. In addition to providing estimates of habitat area for several PICTs, and checking the accuracy of estimates already made for PICTs, the following information is needed to improve our understanding of the vulnerability of these habitats and the roles they play in supporting coastal fisheries.

- Sensitivity of mangroves and seagrasses to sea-level rise and rates of sedimentation. Mapping deep meadows will help identify the seagrass habitats most at risk.
- The locations where mangrove and seagrass habitats are likely to have greater natural resilience to thermal stress, ocean acidification and the other projected impacts of climate change.
- The contributions of epifauna and infauna to the food webs of demersal fish and invertebrates associated with mangroves, seagrasses and intertidal flats, and the vulnerability of these food webs to the projected effects of climate change on these habitats (Chapter 6).

Freshwater rivers and estuaries

Of all the fish habitats in the region, the least is known about freshwater rivers and estuaries (Chapter 7). Ecosystem models for representative river types need to be developed and validated so that managers do not have to rely on information from other parts of the world. Important first steps are to quantify and map the habitats created by rivers and estuaries, and to set benchmarks for identifying changes in habitat area and quality. This basic research will also identify places where there is strong connectivity between habitats during the life cycles of migratory fish and invertebrate species (Chapter 10). Information on the diversity, extent, function and connectivity of freshwater and estuarine habitats will help adjacent fishing communities to understand the contributions of these ecosystems to their food security and livelihoods.

13.8.1.3 Fish stocks

Oceanic fisheries

In addition to the need to downscale global climate models (Section 13.8.1.1), and parameterise biogeochemical models with better information on nutrients, iron and micronekton (Section 13.8.1.2), more knowledge about the biology of tuna is required to improve confidence in projected future catches simulated by the SEAPODYM model (Chapter 8). The main gaps in knowledge to be filled are listed below.

- Identify the likely responses of skipjack, yellowfin, bigeye and albacore tuna to variation in key environmental variables, including:
    - optimal temperature and dissolved oxygen ranges and thresholds for different life history stages;
    - potential effects of increased ocean acidification on production of gametes, fertilisation, embryonic development, hatching, larval behaviour and feeding ecology (restricted to yellowfin tuna in the first instance because this is the only species of tropical tuna propagated in captivity);
    - interactions among the effects due to temperature and ocean acidification; and
    - possible changes in vertical distribution of each species of tuna due to variation in temperature and dissolved oxygen, and the consequences for their vulnerability to capture by different gear types.
- Assess the carrying capacity of the pelagic ecosystem for tuna in the tropical Pacific, and whether the productivity of stocks is controlled directly by food abundance, or by non-linear relationships such as variation in food assimilation rates with changes in prey density. These tasks require a good understanding of:
    - energy transfer efficiency between all levels of the food web, but especially from the lower levels to the mid-trophic level (micronekton);

- spatial and temporal variation in diversity, distribution and abundance of micronekton across the region;
- diets of the four species of tuna, and the scope for competition between the species; and
- nutrient-rich coastal waters as feeding areas for tuna, and the possible retention of tuna in such areas – the archipelagic waters under the influence of increased runoff from the Sepik-Ramu river system in PNG are of particular interest (Chapter 8).

Coastal fisheries

A better understanding of the likely effects of climate change on the production of coastal fisheries depends on identifying the responses of key fish and invertebrate species to projected alterations in environmental conditions and habitats. The main research activities involved are listed below.

- ➢ Assess the role of coral reefs, and variation in their structural complexity and biological diversity, in determining the distribution and abundance of associated fish and invertebrate species, especially during larval settlement and recruitment. This research is closely linked to assessing the comparative resilience of different reef-building corals (Section 13.8.1.2).
- ➢ Investigate the role of mangroves, seagrasses and intertidal flats in supporting demersal fish and invertebrates, particularly their importance as nursery and feeding areas, and their links with coral reefs. We also need to know whether fish and invertebrates use these habitats sequentially as they grow, and whether the juxtaposition of habitats within the mosaics they form affects fisheries production.
- ➢ Assess the sensitivity and adaptive capacity of key demersal fish species and invertebrates to changes in SST and pH, including (1) the effects on early life history stages; and (2) the combined effects of these variables and their interactions with other anthropogenic stressors.
- ➢ Model the effects on larval dispersal of decreases in the strength of the South Equatorial Current and the South Equatorial Counter Current (Chapter 3).
- ➢ Determine whether a link exists between the risk of ciguatera fish poisoning and climate change. In particular, whether populations of the toxic microalgae *Gambierdiscus* spp. are affected by the deterioration of coral reefs, and whether the projected changes in SST are likely to alter the distribution, occurrence and virulence of ciguatera.
- ➢ Estimate the risks of any alteration in the incidence of other harmful marine algae caused by climate change to coastal fisheries and communities that rely on coastal fish for food.

- Evaluate the likely effects of higher levels of nutrients from the projected increases in runoff around high islands in tropical Melanesia on the productivity of small pelagic fish species.
- Assess the vulnerability to climate change of deepwater demersal species taken by coastal fisheries, especially snappers and groupers.

Tropical snappers, an important part of the coastal fish catch

Photo: SPC collection

Freshwater and estuarine fisheries

To increase confidence in the vulnerability of these poorly understood fisheries, basic research is needed on the biology of the main species, particularly the way they use various habitats at different stages of their life cycles, and their responses to changes in habitat availability and quality. It is also important to understand interactions among fish species (including introduced and invasive species) and to determine whether such interactions are likely to be affected by the projected changes to water temperature and flow rates (Chapter 10). Research on fish and invertebrates that are exposed to a wider range of climate change effects because they migrate between freshwater and the sea is a priority.

13.8.1.4 Aquaculture

Pond aquaculture

In addition to any modifications needed to adapt the well-established methods for pond aquaculture for the region (Chapter 11), other research activities are required to (1) assist PICTs to evaluate whether pond aquaculture is likely to be enhanced as a result of climate change; and (2) identify any possible disadvantages of pond aquaculture as a way of increasing access to fish. These research activities are outlined below.

- Couple global climate models to the level of river catchments so that planners, managers and stakeholders can combine this information with GIS data (Section 13.6) to identify areas most likely to be suitable for pond aquaculture in the future.
- Evaluate any potential impacts of Nile tilapia introduced for pond aquaculture on freshwater biodiversity. This research needs to be designed to ensure that any effects of escaped fish on biodiversity are not confounded with alterations to freshwater habitats caused by poor management of catchments (Chapter 7). Because Mozambique tilapia are well established throughout the region, it will also be important to determine whether Nile tilapia that escape from ponds are likely to have any impact on biodiversity over and above any effects attributed to Mozambique tilapia.
- Identify the likelihood that warmer and wetter conditions may increase the risks posed to pond aquaculture by disease (Chapter 11).
- Assess whether freshwater aquaculture ponds increase habitat for malaria mosquitoes (*Anopheles* spp.) and, if so, identify how ponds could be managed to reduce the risk.

Commodities for livelihoods

Research is needed to determine whether coastal habitats in the tropical Pacific will continue to be suitable for the production of aquaculture commodities for livelihoods in the face of climate change. The main research tasks are summarised below.

- Assess whether the temperature fluctuations during the short 'spring' and 'autumn' seasons in New Caledonia that cause mortality of shrimp are likely to be reduced or accentuated in the future.
- Evaluate the scope for extending seaweed farming to Vanuatu as temperatures warm. If it is considered technically feasible, gender-based, socio-economic research will be needed to determine whether the relatively low incomes involved are likely to (1) meet the expectations of coastal communities; and (2) result in sufficient production to warrant establishment of enterprises to export the products.
- Determine the likely effects of ocean acidification on (1) survival of pearl oysters and formation of high-quality pearls; (2) recruitment of milkfish postlarvae used to stock ponds; and (3) fitness of sea cucumbers released in sea ranching projects, due to effects on the size and strength of spicules. If acidification has significant effects on pearl quality, research will be needed to identify whether microsites

exist where the buffering effects of nearby coral reefs, macroalgae and seagrasses (Chapters 5 and 6) maintain aragonite saturation levels within the limits required by pearl oysters to produce high-quality nacre.

- Ascertain whether pathogens affecting the pearl and shrimp industries are likely to become more virulent with increasing water temperatures.

13.8.2 Knowledge needed to implement adaptations effectively

13.8.2.1 Economic analysis

The rich tuna resources of the region provide PICTs with many potential adaptations to maintain the benefits of fisheries for food security and livelihoods (Section 13.4), even under the projected redistribution of tuna to the east (Chapter 12). It is already evident that 'domesticating' the tuna industry to create jobs on fishing vessels and in processing operations adds much value to local economies compared with selling access rights to DWFNs (Chapter 12). However, economic analysis is needed to determine the relative benefits of allocating a proportion of estimated sustainable tuna catch to subsistence and small-scale commercial fishers, compared with allocating it all to DWFNs or domesticating the industry. In particular, governments need to know how the social (health) and economic benefits people receive from catching and eating fresh tuna, or selling it at a local market, compare with the benefits people receive via national revenue from licence fees, or from jobs in the tuna industry.

Provided such analysis encompasses the effects of population growth on local demand for fish, and the effects of climate change on the projected availability of tuna, it should aid PICTs to optimise future benefits from their tuna resources, and identify the best ways to provide access to the fish (or other animal protein) needed for food security (Chapter 12). The results are expected to differ among PICTs, depending on the estimated sustainable catches of tuna from their EEZs, the size of their populations, their capacity to domesticate fishing and processing operations, and other opportunities for people to earn income.

13.8.2.2 Social dimensions

Considerable gaps in knowledge still exist about how Pacific communities are likely to embrace the recommended adaptations and the need for change. Learning to catch or produce fish in new ways, and to eat different types of fish, are important adjustments for communities to make in preparation for the times ahead. Research is needed to gauge the willingness of people to make these changes, and how to assist them where necessary. The traditional social mechanisms used by Pacific people to respond to extreme events, such as tropical cyclones and droughts (Section 13.4), should predispose them to make a smooth transition to the recommended adaptations. But such responses should not be assumed. The suitability of these traditions for the projected changes in the production of fisheries and aquaculture under the A2 emissions scenario needs to be examined.

13.9 Investments required

To maintain the important contributions of fisheries and aquaculture to the region, investments by PICTs and their development partners are required at several levels. In particular, investments are needed to:

1. launch the adaptations (Section 13.4) that PICTs see as priorities for economic growth, government revenue, food security and livelihoods to address the threats and opportunities associated with climate change, and to accommodate other drivers (Section 13.3);
2. fill the gaps in knowledge required to improve our understanding of vulnerability;
3. strengthen the partnerships needed to implement adaptations effectively and fill the gaps in knowledge; and
4. monitor the projected effects of climate change on fisheries and aquaculture, and the success of adaptations.

Because this vulnerability assessment has been designed to provide guidance mainly at the national level, investments are also needed to 'localise' the results to assist communities to evaluate their vulnerability and adapt accordingly.

A community fishing over sand flats, French Polynesia

Photo: Jack Fields

13.9.1 Investments to implement adaptations

The adaptations recommended in Section 13.4 to reduce the threats posed by climate change to contributions by fisheries and aquaculture to Pacific communities, and to capitalise on the opportunities, will require the following investments.

13.9.1.1 Economic development and government revenue

- Full implementation of the vessel day scheme for the purse-seine and the longline fisheries by all PNA members, together with similar management arrangements to limit fishing effort for tuna in subtropical waters by the members of the Te Vaka Moana Arrangement.
- Development of a long-term EPA with the EU by PNG, Fiji and Solomon Islands to help secure future supplies of tuna for their canneries.
- Establishment of (1) competent authorities for fishery product food safety and the associated testing laboratories or services, and (2) systems for demonstrating compliance with IUU fishing regulations in PICTs well placed to supply canneries in those countries which have EPAs with the EU.
- Energy audits and energy efficiency programmes for national industrial tuna fleets to assist them to cope with fluctuations in oil prices, and reduce the costs of fishing further afield as the distribution of tuna shifts to the east.
- Safety audits for purse-seine and longline vessels.
- Production chain accounting of all emissions from tuna fishing and canning/processing operations, and transport to markets, for carbon labelling of tuna products from the region.
- Training of women for managerial roles in tuna canneries and loining plants.

13.9.1.2 Food security and livelihoods

- Integrated land use planning to stabilise soils and prevent high sediment loads from entering streams and reaching the coast, including (1) revegetation of areas in catchments most likely to intercept sediment, and (2) establishing well-vegetated riparian (stream side) buffer zones. Revegetation will not only reduce the vulnerability of fish habitats (Chapters 5–7), it will help mitigate CO_2 emissions by boosting carbon sequestration. Pacific leaders identified solutions to deforestation and forest degradation as a key response to climate change in their 'Call to Action on Climate Change' in 2009[xiii].
- Cross-sectoral cooperation in the development of national adaptation programmes of action (NAPAs) to (1) integrate the protection and management of coral reef, mangrove, seagrass and intertidal flat fish habitats, and freshwater and estuarine

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[xiii] Pacific Islands Forum Secretariat, Forum Communiques; www.forumsec.org.fj/pages.cfm/documents/forum-communiques

fish habitats, with other plans to assist all sectors adapt to climate change; and (2) identify the modifications to infrastructure needed to allow mangroves and other coastal fish habitats to migrate landward as sea level rises.

Photo: Christine Fung

Preventing soil loss by replanting grass, Fiji

- Capacity-building of fisheries agencies and management advisory groups in all PICTs to guide communities in (1) implementing CEAFM, incorporating primary fisheries management and ecosystem-based approaches to management of coastal and freshwater fish habitats and stocks (Section 13.2), and (2) assessing the implications of climate change and the cost and effectiveness of potential adaptation options.
- Practical business models, and incentives, for the private sector to engage in storage, processing and distribution of low-cost tuna and bycatch landed at major ports, to provide increased access to fish for rapidly growing urban populations.
- Cost:benefit analysis of producing canned tuna for local and export markets.
- Assessment of the feasibility and practicality of using a portion of licence fees from DWFNs to offset the cost of locally-canned tuna for inland populations in PNG.
- Surveys to identify the best sites for installing inshore FADs to increase access to tuna for subsistence and small-scale commercial fishers in rural areas, followed by programmes to install and maintain FADs at these sites as part of the national infrastructure for food security. This will involve maintaining stockpiles of equipment at national fisheries agencies to replace FADs as required.

- Analysis to identify the prime locations for peri-urban and rural pond aquaculture based on information on rainfall and temperature from downscaled global climate models, and other demographic and natural resources layers available for GIS.
- National and private-sector hatcheries to produce juvenile fish for pond aquaculture, supported by distribution networks to deliver high-quality juveniles to rural areas.
- Evaluation of the potential merits of micro-credit schemes and training programmes to enable coastal communities to (1) develop small-scale commercial fisheries around FADs and for small pelagic fish species; (2) expand pond aquaculture; and (3) scale-up post-harvest processing, where credit is recognised as a barrier to implementing these adaptations.
- Training and capacity building for coastal communities, especially women, to engage in (1) income-earning opportunities created by diversifying food production systems (in fisheries, aquaculture and agriculture) to build resilience to climate change; and (2) operate small businesses.
- Analysis of carbon footprints of the main aquaculture operations, and identification of better ways to conserve energy along the supply chain. Such investments should also consider innovative strategies to market environmentally-friendly products based on better management of natural resources.

13.9.1.3 Increasing participation and awareness

- Research to identify the key social mechanisms and drivers that influence participation by men, women and youth in the planning, design and implementation of adaptations to climate change.
- Educational materials to assist communities to understand (1) the contributions of fisheries and aquaculture to food security and livelihoods; (2) the fundamentals of climate change; (3) the timing of the projected effects of climate change on fisheries and aquaculture, and (4) the need to manage catchments and freshwater and coastal fish habitats well to improve the resilience of fish stocks to climate change.
- Interactive and educational computer games for children to (1) promote learning (by having fun) about vulnerability of fisheries and aquaculture (and other sectors) to climate change; (2) help them understand the consequences of adapting or not adapting; and (3) allow them to recognise other disaster risk management choices and outcomes.

13.9.2 Investments to fill gaps in knowledge

The information set out in Chapters 2–12 describes our current understanding of the natural and social processes underpinning the contributions of fisheries and aquaculture to the well-being of Pacific communities, and how these processes are likely to be affected by climate change. This knowledge is far from complete. The investments needed to improve and regularly update this vulnerability assessment are summarised below.

13.9.2.1 Surface climate and the tropical Pacific Ocean

- Building the capacity of PICTs to (1) forecast the weather and make short-term seasonal climate predictions, particularly for tropical cyclones and ENSO events; and (2) operate appropriate warning systems for severe weather events and other potential natural catastrophes (earthquakes and tsunamis).
- Constructing additional weather stations throughout the region to make long-term, high-quality surface weather observations, to assist PICTs to (1) detect the nature and significance of changing climates; (2) link relevant island-scale weather patterns to larger-scale climate observations; and (3) relate changes in rainfall to variations in local river flows and groundwater regimes.
- Developing higher-resolution physical global climate models that (1) address existing biases in the position of the South Pacific Convergence Zone and the spatial and temporal structure of ENSO, and (2) are capable of projecting changes to the frequency and intensity of ENSO events and tropical cyclones. These downscaled models are needed to provide a better understanding of the likely changes to the surface area and structure of the Warm Pool and PEQD, which are of great significance to the distribution and abundance of tuna.

13.9.2.2 Oceanic fisheries

- Expansion of the SEAPODYM model used to estimate tuna catches under different climate change scenarios to (1) link higher-resolution, physical global climate models to better biogeochemical models (see below); and (2) incorporate socio-economic scenarios likely to drive future fishing effort in the region (e.g. increasing demand for tuna from industry and from PICTs for food security, demographic changes, projected spatial changes in fishing effort, and increasing fuel costs).
- Development, parameterisation and verification of biogeochemical models, including collection of data on variability of nutrients, oxygen, pH, phytoplankton, zooplankton and micronekton throughout the water column; movements of tuna; diets of juvenile and adult tuna; and the responses of juvenile tuna to ocean acidification. This involves:
  - obtaining catch data from vessel logbooks reporting the exact locations where fish were caught in the tropical Pacific Ocean;
  - establishing long-term monitoring stations for physical and chemical variables in all provinces;

- adding biochemical and acoustic sensors to the Tropical Atmosphere Ocean (TAO) array of moorings in the Warm Pool and PEQD, and/or to the Argo floats[xiv];
- continuing the satellite remote sensing of SST and chlorophyll *a*, so that changes in the convergence zone between the Warm Pool and PEQD can be tracked easily;
- validating the accuracy of acoustic data in discerning the relative abundance of the main groups of micronekton, so that 'ships of opportunity' fitted with suitable instrumentation can build up time-series of variation in micronekton along major shipping routes[xv];
- supporting observers on industrial tuna vessels to sample micronekton from the stomachs of tuna and other top predators;
- tagging programmes for all four species of tuna, both with conventional and electronic tags, to verify projected changes in their distributions in response to altered nutrients, water temperatures, currents and oxygen levels, including movements in archipelagic waters; and
- assessing the effects of ocean acidification on recruitment success of tuna larvae.

➢ Regular assessments of the projected catches of all four species of tuna under selected climate change scenarios every 5–7 years, using the enhanced SEAPODYM model, to inform regional and national management agencies. An example of the finer spatial scale projections expected to be possible with SEAPODYM using information from downscaled physical models of the tropical Pacific Ocean and improved biogeochemical models is shown in **Figure 13.11**.

13.9.2.3 Coastal fisheries

➢ Sampling programmes to determine how (1) spatial and temporal variation in environmental stressors, such as SST, affect the three-dimensional architecture of the coral reefs that support demersal fish (Chapter 9), and (2) coral reefs respond to appropriate management measures to prevent degradation.

➢ Modification of the available satellite products to (1) provide the finer-scale measurements (< 1 km grid size) needed to manage individual reefs; and (2) integrate data on light intensity, pH and turbidity with SST.

➢ Maps of mangroves, seagrasses and intertidal flats for all PICTs to help (1) quantify the contribution of these habitats to coastal fisheries production; (2) raise awareness among coastal planners of their importance; and (3) provide a baseline for monitoring changes in the area, density and species composition of mangroves and seagrasses, and the area of intertidal flats.

[xiv] www.argo.ucsd.edu

[xv] See www.imber.info/CLIOTOP_MAAS.html for more details.

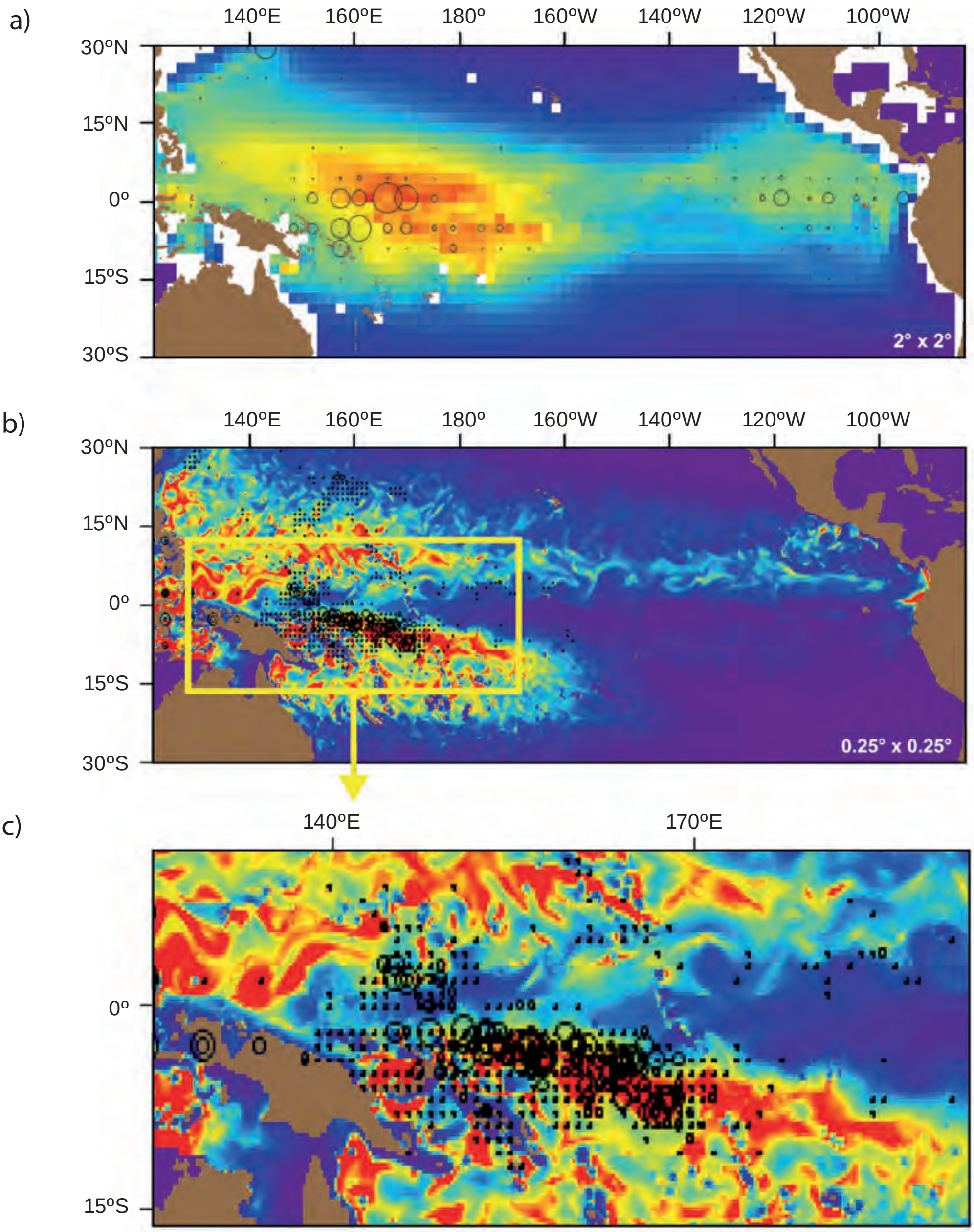

Figure 13.11 Simulations of skipjack tuna distributions in the tropical Pacific Ocean produced by the SEAPODYM model using different resolutions of environmental forcing and fisheries/ecosystem data: (a) average for the period 1980–2007 using environmental forcing at resolutions of 2 x 2 degrees, and fisheries data at a resolution of 1 x 1 degree or lower, and a monthly time interval; (b) average for the period 1998–2007 using environmental forcing and fisheries data at a resolution of 0.25 degree or lower plus primary production estimates from satellite data; and (c) an example of a weekly time interval from the period in (b). Circles indicate relative abundance of skipjack tuna (source: Patrick Lehodey).

- Continued collection of reliable data on sea-level rise in PICTs through the South Pacific Sea Level and Climate Change Monitoring Project.
- Higher-resolution topographic maps to identify more accurately (1) the projected losses of mangroves and intertidal flats blocked from migrating landward by infrastructure; and (2) the areas likely to be inundated that have potential for colonisation by mangroves and seagrasses.
- Surveys of the biodiversity, relative abundance and size composition of fauna associated with coral reefs, mangroves, seagrasses and intertidal flats at representative locations to improve our understanding of the food webs for coastal fisheries supported by these habitats.
- Research on key fish and invertebrate species harvested by coastal fisheries to determine:
  - how their distributions and abundances are linked to the coral reef, mangrove, seagrass and intertidal flat habitats that support them, and how these relationships are likely to change as these habitats are degraded (Chapters 5 and 6);
  - the likely effects of increases in SST and ocean acidification, and changes in the strength of major ocean currents, on successful recruitment of fish to coastal habitats;
  - whether the incidence and virulence of ciguatera fish poisoning is likely to vary as SST increases, and as coral cover decreases and macroalgae increase; and
  - the possible effects of increased runoff from high islands on the abundance of small pelagic fish species.

13.9.2.4 Freshwater and estuarine fisheries

- Higher-resolution elevation maps and flood modelling to identify likely changes to floodplain and estuarine fish habitats. This information will allow national planners to provide for increased fisheries production when developing cross-sectoral strategies to adapt to projected increases in rainfall and sea-level rise.
- Development of fisheries production models for the Fly and Sepik-Ramu rivers in PNG, based on (1) inventories of freshwater habitats and elevation mapping; (2) better data for catch and fishing effort, especially for subsistence fisheries; and (3) improved projections of flow rates, nutrient loads, water temperature and dissolved oxygen from downscaled global climate models.

13.9.2.5 Aquaculture

- Impact risk assessments for the introduction or further translocation of Nile tilapia for pond aquaculture. These assessments should provide decision-makers with science-based advice about any possible effects on freshwater biodiversity, ensuring that any such potential effects are not confounded with habitat degradation, and are relative to any existing impacts on biodiversity that can be attributed unequivocally to Mozambique tilapia.

- Assessments of how long existing shrimp ponds are likely to function efficiently, followed by modifications to, or relocation of, ponds when required to ensure that they can be dried completely between crops as sea level rises (Chapter 11).
- Research to determine the likely effects of ocean acidification on growth and survival of juvenile and adult pearl oysters, and pearl quality. In the event of projected deleterious effects, investments should be made to identify micro-sites that may retain adequate aragonite saturation levels due to buffering by nearby reefs and seagrasses to support continued farming of pearls and other commodities likely to be affected by ocean acidification (e.g. corals and giant clams for the ornamental trade).

13.9.3 Investments to strengthen partnerships

Because many PICTs have limited national technical capacity, investments are needed to develop the technical and scientific teams required to assist PICTs to (1) implement and refine the key adaptations described in Section 13.4; (2) improve their understanding of the vulnerability of fish habitats, fish stocks, and the enterprises and communities depending on these resources; and (3) fill the remaining gaps in knowledge.

In the case of coastal fisheries, this will involve providing continued support to the scientific institutions, regional organisations and NGOs already assisting PICTs to implement CEAFM. For oceanic fisheries, partnerships are needed to provide research teams with better access to Pacific basin-wide fishing data sets, i.e. combined databases from WCPFC and IATTC, as the distributions of skipjack, yellowfin and bigeye tuna move progressively east.

Support for the continued development of the Global Partnership for Climate, Fisheries and Aquaculture (PaCFA)[xvi] should also be considered to ensure that lessons learned from other regions can be passed on to PICTs, and vice versa.

13.9.4 Investments to monitor changes in resources and the success of adaptations

Investments in a variety of monitoring programmes are required to assist PICTs to improve their understanding of the status of natural resources, assess whether the projected effects of climate change on these resources are occurring, and measure the success of adaptations. The specific investments needed are outlined below.

[xvi] www.climatefish.org

- Development of a digital image analysis system to record changes in species composition and size-frequency of tuna caught by purse-seine vessels, where data can preferably be processed by computers on board and transmitted to the Forum Fisheries Agency and Secretariat of the Pacific Community via the vessel monitoring system.
- Regular mapping of vegetation cover in catchments to monitor the success of revegetation programmes.
- Long-term monitoring programmes to (1) inform PICTs about changes in coastal fish habitats and stocks of demersal fish (including market sampling); (2) determine the variation in habitats and stocks due to climate change, as opposed to other drivers; and (3) assess whether the effects of climate change are occurring as projected.
- Modifications to HIES and censuses to measure the success of adaptations (against socio-economic baselines) in maintaining the contributions of fisheries and aquaculture to food security and livelihoods.

13.9.5 Investments to localise the vulnerability assessment

The results of this assessment need to be transferred to the local level by supporting NGOs and other agencies to assist communities to make semi-quantitative evaluations of their vulnerability[29,114] based on the information in Chapters 2–12. Such semi-quantitative evaluations involve applying regional and local knowledge at a community level to identify and understand the specific sources of vulnerability, and how these can be minimised. This approach allows integration across sectors and scales to produce effective adaptation plans. It also builds capacity within communities to implement adaptations.

Photo: Jack Fields

Women fishing in Fiji

13.10 Considerations for financing adaptations

PICTs will need to devote substantial resources to evaluate and implement the priority adaptations for the fisheries and aquaculture sector. Investments for many of the win-win adaptations outlined in Section 13.4 need to be made now, whereas others may not be required for several decades. As well as identifying when to make these investments, it is essential that PICTs understand (1) the relative costs and benefits of recommended adaptations, including their sustainability and social acceptability; and (2) the opportunity costs of investments relative to other development needs and priorities.

It is widely recognised that PICTs require substantial financial assistance to make the necessary investments. Bilateral and multilateral funding for adaptation of PICTs has already been provided by Australia, EU, France, Germany and USA, and the Asian Development Bank and the World Bank. The broader international community is also planning to provide significant funds during the coming decades to meet the costs of adaptation in developing countries through the United Nations Framework Convention on Climate Change (UNFCCC). Several funding opportunities are offered under the Convention, including the Adaptation Fund, the Global Environment Facility, and the Least Developed Countries Fund[xvii]. The Pacific Islands Forum Secretariat is presently evaluating options for PICTs to receive their share of this longer-term climate change financing, including the possible establishment of a dedicated Pacific climate change finance mechanism.

In collaboration with their technical partners, PICTs will need to develop a strong business case for adaptation financing at community, national and regional levels. The key activities involved in making this case are listed below.

- Build the capacity of fisheries departments and managers, and national planning officials, to explore the implications of climate change for the contributions of fisheries and aquaculture to economic development, government revenue, food security and livelihoods.
- Identify the magnitude and timing of the effects of climate change on the fisheries and aquaculture sector, and the appropriate adaptations to reduce the threats and capitalise on the opportunities.
- Develop action plans that clearly identify the costs, benefits and implementation timelines for priority adaptations, including fully-costed proposals for submission to bilateral, regional and multilateral financing programmes.
- Work with technical agencies and community groups to enable priority adaptations for the fisheries and aquaculture sector to be evaluated against other adaptation financing needs, taking into account the likely total financing opportunities available from international sources.

[xvii] www.unfccc.int/adaptation/implementing_adaptation/adaptation_funding_interface/items/4638.php

- Develop and implement appropriate monitoring and evaluation mechanisms, so that the success of adaptation responses can be estimated to identify their strengths and weaknesses, and refined to deliver optimal benefits.

The information presented in this book, and the companion 'Summary for Pacific Island countries and territories'[115] is intended to facilitate this task.

13.11 Concluding remarks

This book sets out the sequence of projected changes to surface climate and the tropical Pacific Ocean under the B1 and A2 emissions scenarios in 2035 and 2100 (and A2 in 2050[xviii]), to fish habitats and fish stocks and, ultimately, to the contributions of fisheries and aquaculture to the economic development and government revenue of PICTs, national food security, and livelihood opportunities (Chapters 2–11). Contrary to assessments for some other parts of the world[8,88,116,117], the implications of the projected changes are not all negative.

The deleterious effects for Pacific communities are expected to be greatest for demersal coastal fisheries, where production is projected to decrease by 20% in 2050 and by 20–50% in 2100 under the A2 emissions scenario. This decrease is due to the direct effects of climate change on demersal fish, and the indirect effects of declines in the coral reef, mangrove, seagrass and intertidal flat habitats that support these species due to global warming and ocean acidification (Chapters 5, 6 and 9). However, notwithstanding the need to manage catchments and coastal fish habitats and stocks to secure reliable levels of fish production, coastal communities also have the option of switching some fishing effort from demersal fish to the tuna that often frequent coastal waters. This can be done by developing the nearshore fishery for these large pelagic species, and by installing anchored FADs close to shore to attract and temporarily hold these species (Section 13.4).

The rich tuna resources of the Western and Central Pacific Ocean can also be used to provide increased access to fish for the rapidly growing urban populations of the region, supplemented by the development of peri-urban pond aquaculture. More emphasis on the management of freshwater fisheries and development of pond aquaculture where conditions are suitable also promises to provide improved access to fish in inland areas.

The assessments in this book indicate that adaptations based on increased access to tuna are likely to be favoured by climate change until 2035 for all PICTs, and for the eastern part of the region until at least 2100. Production from freshwater fisheries and pond aquaculture is also expected to increase throughout much of Melanesia because the projected increases in rainfall and temperature are likely to enhance yields of the key species.

[xviii] Based on the simulations for B1 in 2100.

The key challenges for the region are to:

1. reduce the effects of local stressors on fish habitats by legislating to restore and protect catchment vegetation and prevent direct damage to coral reefs, mangroves, seagrasses and intertidal flats, caused by excess sediments, nutrients, pollution and poor management of waste;
2. launch win-win adaptations to address the imminent reductions in the fish available per person for good nutrition, due to predicted population growth in many PICTs (Chapter 12), in ways that should be favoured by climate change;
3. create flexible policy arrangements to ensure continued supplies of fish to the established and proposed processing facilities in the region as the distribution of tuna shifts to the east; and
4. manage coastal aquaculture enterprises producing commodities for export and local markets to optimise employment opportunities in the face of increasingly adverse conditions due to climate change and ocean acidification.

Meeting these challenges by implementing the adaptations presented here, and the suggested policies and investments needed to support them, will also address other pressures that face the sector. Some longstanding problems caused by these pressures need immediate attention, for example, integrated coastal zone management to protect fish habitats (Chapters 5–7), restoration of sea cucumber fisheries (Chapter 9) and providing better access to tuna for food security (Chapter 12). Investments in both the win-win and lose-win adaptations described in Section 13.4 designed to address these problems have the added benefit of making natural resources, communities and economies more resilient to the effects of the changing climate. Such investments are priorities for the fisheries and aquaculture sector of PICTs across the region.

Nevertheless, the recommended adaptations resulting from this vulnerability assessment are not definitive. Uncertainty remains about the magnitude of the projected effects of climate change on the sector due to the coarse resolution of the CMIP3 global climate models used to determine changes to surface climate, the tropical Pacific Ocean, and tuna stocks (Chapters 2–4 and 8). Some of this uncertainty will be reduced through the development of downscaled models by Australia's Pacific Climate Change Science Programme, and related initiatives. The investments in modelling and monitoring proposed in Sections 13.5 and 13.7 should also allow PICTs and their technical partner agencies to (1) examine interactions and synergies among potential adaptation options; (2) track changes in the habitats and stocks that underpin oceanic, coastal and freshwater fisheries, and aquaculture, and (3) measure the success of selected adaptations.

We recommend that the technical agencies supporting PICTs adopt a process similar to that used by the IPCC for its assessment reports to regularly evaluate (1) the effects of climate change on the region's vital fisheries and aquaculture resources, and

(2) the plans to use these resources sustainably for economic development, government revenue, food security and livelihoods. In particular, the ‘Summary for Pacific Island countries and territories’ accompanying this book should be updated every 5–7 years with the latest projected changes to surface climate, the tropical Pacific Ocean, fish habitats and fish stocks. Updating this vulnerability assessment on a regular basis will allow the main economic and social implications to be understood more clearly, and the key adaptations required to maintain benefits from the sector to be adjusted accordingly.

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Appendix 13.1 Overview of qualitative modelling

Qualitative modelling[107,124–129] describes the relationships linking variables within a system, and the implications of these links to the feedback properties and dynamics of the whole system. Qualitative models use the sign (i.e. positive, negative, zero) for direct effects between variables, which are depicted as links in a signed-directed graph (**Figure 1**). A link ending in an arrow represents a positive direct effect of one variable on another, and one ending in a filled circle indicates a negative direct effect. All possible pairwise ecological relationships can thus be represented as: predator-prey (+,-), competition (-,-), mutualism (+,+), commensalism (+,0), and amensalism (-,0). Signed digraphs can also be used to describe various kinds of relationships, for example, the two variable systems in **Figure 1a** can be used to represent an ecological predator-prey relationship, or an economic supply-demand relationship. Links leading from a variable to itself denote self-effects. Processes that lead to self regulation, such as a density-dependent rate of reproduction in a population, confer a negative self effect, whereas self-enhancing processes create positive self effects. If the growth of a variable is determined solely from the other variables included in the model, then it will possess no self effect.

Qualitative models can also depict interactions that are enhanced or suppressed by another variable. For example, **Figure 1c** shows how variable Z acts to increase the intensity of the predator-prey interaction of X and Y, which is indicated by a dash-lined positive link. This modified interaction results in direct effects leading from Z to variables X and Y, the sign and direction of which is determined by the product of the dashed-lined link and the individual pairwise links. In this example, the product of the positive dashed-lined link from Z and the negative link leading to X creates a negative link leading from Z to X.

Tracing the cyclical pathway of links in a system defines its feedback cycles, and analysis of these cycles is used to determine the stability of the system. The model system in **Figure 1a** has two negative feedback cycles. One cycle of length one is from the self effect of variable X, while a feedback cycle of length two is defined from the product of the positive and negative links connecting X and Y. This system has only negative feedback, and thus an increase in X leads to an increase in Y, which then acts to limit X. This negative feedback guarantees that the system has the ability to recover from a disturbance through self correction. **Figure 1b** presents an example of a model system with a positive feedback cycle involving three variables. Here an increase in population diminishes available resources. This lack of resources creates an incentive for development of additional resources, which thereby supports further increase in population, i.e. when available resources are plentiful there is little incentive to develop new resources, but when availability is limited there is increased effort to secure new resources; this dynamic creates a negative link from variable Z to Y in the model of **Figure 1b**. Such a positive feedback, if not counterbalanced by the three negative self effects, can continually drive the system and prevent it from reaching equilibrium.

Where a variable is the point of input to the system, the response of the other variables can be determined from the product of the links along direct and indirect pathways emanating from that variable. For example, an input that acts to increase Z in **Figure 1c** will cause X to decrease by two negatively signed pathways, i.e. a direct negative effect from Z and an indirect negative effect via Y. The response of variable Y to this input, however, is qualitatively ambiguous, as there is both a positively and negatively signed pathway leading to Y from Z. This ambiguity can be resolved through knowledge of the relative strengths of the links involved. In larger and more complicated systems, however, there can be a vast number of oppositely signed pathways and interpreting the ambiguity through the relative strength of links is impossible. In such cases, a probabilistic interpretation of the number of positively and negatively signed pathways is used to predict the likely sign of a variable's response.

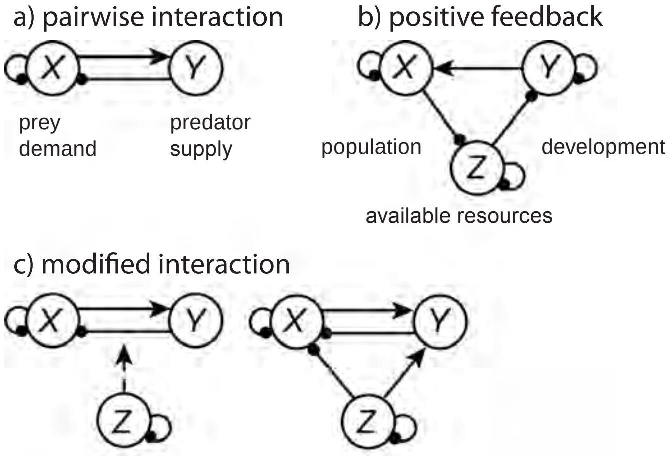


Figure 1 Examples of signed digraphs showing model systems with (a) two variables with negative feedback between them; (b) three variables with positive feedback; and (c) a system where one variable modifies the intensity of the interaction of two other variables; see text for further explanation.

Glossary

Acclimation: adjustment by an individual organism to a gradual change in its environment, such as increasing temperature.

Accretion: build-up of sediment typically on floodplains, which results in progressive increases in the elevation of floodplain habitats.

Acidosis: increased acidity (i.e. increased hydrogen ion concentration) in the blood, usually in the plasma.

Adaptation: (autonomous) evolutionary process whereby a population becomes better suited to its changing habitat; **(planned)** a strategic change in anticipation of a variation in climate.

Aerobic: needing air, particularly oxygen.

Alluvial: loose or unconsolidated sediment deposited by flowing water, typically used to describe floodplain sediments or terraces formed from material deposited by floods.

Altimetric measurement: height measurement in relation to the centre of the Earth. Height is defined using an ellipsoid approximating the Earth's shape. It can be measured from space by radar or laser at accuracies of 1–3 cm.

Amphidromy: migration to the sea as larvae of fish or invertebrates that live in fresh water as adults, and then return to fresh water as juveniles to develop (e.g. some species of gobies).

Anoxic: total loss of oxygen, an extreme form of hypoxia or low oxygen (see also **hypoxic**[i]).

Aphotic zone: area of the water column in the ocean beneath the **photic zone** where light intensity is not sufficient for **photosynthesis**.

Aquaculture: the farming of aquatic organisms, including fish, molluscs, crustaceans and aquatic plants using some form of intervention in the rearing process to enhance production.

Aquaculture commodity: raw material or primary product from **aquaculture**, which can be bought and sold.

Aquatic animal health: measures required to diagnose risks to animal health and responses needed to minimise the spread of any detected disease.

[i] Words in bold represent terms defined in the glossary.

Aragonite: one of the two commonly occurring crystal forms of **calcium carbonate** ($CaCO_3$), which make up the skeletons of organisms such as reef-building corals.

Aragonite saturation: levels of dissolved **calcium carbonate** in the ocean, which are available for calcifying organisms (e.g. corals) to build their skeletons as they grow.

Artisanal fishing: small-scale harvesting of fish and invertebrates for consumption or local trade.

Atmospheric (surface) pressure: pressure exerted by the weight of the air above a point on the Earth's surface. Horizontal variations of atmospheric pressures can drive winds, storms and other processes.

Autotroph: an organism capable of synthesising its own energy/food from **inorganic** substances using light (e.g. **photosynthesis**) or chemical energy. Examples include **phytoplankton** (microalgae), **macroalgae**, seagrass and certain bacteria.

Barrier layer: area in the vertical structure of the ocean where variation in salinity occurs within a zone of uniform temperatures and where density changes only as a result of changes in salinity.

Bathymetry: measurement of the depths of oceans and seas.

Bêche-de-mer: processed (boiled and dried) sea cucumbers.

Benthic organisms: plants or animals living on the bottom or in the sediment (infauna).

Biodiversity: variability among living organisms from all sources including, *inter alia*, terrestrial, marine and other aquatic **ecosystems** and the ecological complexes of which they are a part; includes diversity within species, between species, and of **ecosystems** (also known as biological diversity).

Bioerosion: erosion of hard ocean substrates, particularly **calcium carbonate** (e.g. coral skeletons), by living organisms such as worms, bivalves, fish and barnacles.

Biofloc technologies: techniques that facilitate intensive aquaculture while reducing investment and maintenance costs and incorporating the potential to recycle feeds. Techniques are based on zero or minimal water exchange to maximise **biosecurity**, while minimising the environmental effects of **aquaculture**.

Biofuel: fuel derived from living organic matter.

Biogeochemical processes: chemical interactions between the atmosphere, water and land, and the organisms inhabiting these components of the Earth's biosphere.

Biomass: mass of living biological organisms (including microorganisms, plants and animals) in a given area or **ecosystem** at a given time; includes the mass of one or more species, or the mass of all species in the community.

Biosecurity: set of preventive measures designed to reduce the risk of transmission of infectious diseases, quarantined pests, invasive alien species and living modified organisms.

Blood-oxygen affinity: amount of oxygen that can be carried in the blood, usually determined by the quantity of oxygen-carrying pigments within red blood cells.

Bycatch: fish and other species caught unintentionally while intending to catch other fish. Bycatch also includes undersized individuals of the target species.

Calcification: process by which **calcium carbonate** is precipitated to form hard crystalline materials that make up the skeletons of many marine organisms (e.g. corals, molluscs).

Calcium carbonate: a chemical compound with the formula $CaCO_3$; this common substance is found in rocks in all parts of the world, and is the main component of shells of marine organisms, e.g. corals and molluscs.

Carbon footprint: a measurement of the amount of carbon dioxide or other carbon compounds (**greenhouse gases**) emitted to the atmosphere by the activities of an individual, enterprise, nation, etc.

Carbon labelling: marking of products to specify the total carbon (**greenhouse gases**) emissions involved in all aspects of production and the **supply chain** from manufacturer to purchaser, to the treatment of waste.

Carbon sequestration: a process by which carbon dioxide is removed from the atmosphere and typically stored in the tissues of plants.

Carbonate buffering: partial offsetting of pH increase (due to ocean acidification) by free carbonate ions (HCO_3^-, CO_3^{2-}), which may originate from eroding coral skeletons, sand or other sources.

Carbonate saturation: carbonate ion concentration threshold below which the ambient water becomes corrosive to **calcium carbonate** shells and skeletons.

Carnivore: a species that feeds on fish or invertebrates.

Catadromy: migration to the sea to breed of fish species that live in fresh water as adults, and then return to fresh water as juveniles (e.g. barramundi).

Catch per unit effort: quantity of fish or shellfish taken by a given amount of fishing effort. Often used as an indirect measure of the abundance of a target species. An unchanging catch per unit effort indicates sustainable harvesting.

Catchment: land bounded by natural features such as hills or mountains, from which all runoff water flows to the same low collection point.

Chlorophyll: photosynthetic pigment common to all plants including **phytoplankton** cells; also used extensively as a proxy for measuring the biomass of **phytoplankton**.

Climate-proofing: measures taken to reduce the risk of damage to infrastructure that could occur as a result of projected changes to surface climate and the ocean.

Climax species (equilibrium species): slower growing, structurally large species, which are good competitors but poor colonisers and appear late in the succession of an **ecosystem**, and eventually come to define older, more stable communities.

Climate change: a change of climate attributed directly or indirectly to human activity, which alters the composition of the global atmosphere and which is in addition to the natural climate variability observed over comparable time periods (see **climate variability**).

Climate model: mathematical model based on the laws of physics constructed to understand and predict the dynamics of the Earth's climate, through the simulation of key variables, such as air and **sea surface temperature**, precipitation, and wind.

Climate variability: variations in the mean state and other statistics of the climate (such as the occurrence of extremes) on all temporal and spatial scales beyond that of individual weather events. Variability may be due to natural internal processes in the climate system, or to variations in natural or anthropogenic external forcing (see also **climate change**).

Coastal fisheries: harvesting of fish and invertebrates from inshore marine habitats to a depth of 50 m, as well as pelagic fish caught in near shore waters within 10 km of the coast.

Cold tongue: large zonal band along the equator characterised by high productivity due to the equatorial divergence bringing nutrient-rich waters to the surface layer, also called equatorial upwelling or Pacific Equatorial Divergence (PEQD).

Commercial fisheries: harvesting of fish and invertebrates for the purpose of making or intending to make a profit. Commercial fisheries often involve large-scale industrial fishing fleets but may also include small-scale fisheries that target species exclusively for local sales or export.

Community-based management: arrangements under which a community takes responsibility, usually with government or NGO assistance, for managing its coastal environment and fisheries.

Confidence: an evaluation of the level of scientific understanding in support of a conclusion.

Connectivity: combination of processes, which provide physical and biological connections between habitats and maintain suitable conditions for fish and invertebrates to move between habitats (including through **larval dispersal**). High levels of connectivity confer increased **resilience** to local populations as a result of larval replenishment from remote populations following severe exploitation or **habitat degradation**.

Continental effect: the effect of continental lands on local climate, which results in a greater daily and annual range in surface air temperature, and in runoff of rainwater to marine habitats.

Coral bleaching: the paling of corals and other animals with symbiotic **zooxanthellae**, caused by disintegration of symbiosis and loss of the symbionts. Bleaching occurs in response to physiological stress due primarily to periods of increased water temperature and high light levels (see **mass coral bleaching**). Bleaching can also be caused by changes in salinity or turbidity.

Corallivore: any animal that eats coral polyps (e.g. butterflyfish, crown-of-thorns starfish).

Coral reefs: underwater structures made from the **calcium carbonate** secreted mainly by scleractinian corals. These structures are usually dominated by reef-building corals and are typified by high levels of accompanying **biodiversity**.

Cost–benefit analysis: economic decision-making approach to assess the merit of a proposed project or investment, or to choose between alternatives. Such analysis involves comparing total expected costs with total expected benefits to determine whether benefits outweigh costs or vice versa, and by how much.

Cross-sectoral management: managing coastal fisheries with the aid of all sectors (e.g. forestry, agriculture, public works, water supply and sanitation, waste disposal) with responsibility for use of land and water resources that directly affect fish habitats and fish stocks.

Crustose coralline algae: red algae from the order Corallinales, characterised by a thallus (body) that is dominated by calcareous deposits. Red algae can play an important ecological role in forming coral reefs by binding the calcareous parts of other organisms, such as corals, into the broader reef framework.

Deep Chlorophyll Maximum (DCM): depth at which the greatest amount of **chlorophyll** occurs; is rarely seen just below the surface and is affected by nutrient availability, adaptation of **phytoplankton** cells to low light intensity, and specific differences in the populations of **phytoplankton**.

Demersal fish: species of fish that live close to the ocean floor (substratum). In the tropical Pacific these species are strongly associated with coral reefs (e.g. coral trout, groupers), seagrasses (e.g. emperors) or mangroves (e.g. mullet).

Destructive fishing: fishing activities (usually involving dynamite, derris root and cyanide) that deplete both target and non-target species, and also contribute to **habitat degradation**.

Diazotrophy (or nitrogen-fixation): biological process allowing some plants to use molecular nitrogen (N_2 or diazote); it is achieved by cyanobacteria in ocean regions.

Dinoflagellates: large group of unicellular organisms, about half of which are **photosynthetic**. Dionoflagellates are an important component of the **phytoplankton**. Some species, called **zooxanthellae**, are endosymbionts of marine animals and play an important part in the biology of **coral reefs**.

Diurnal (variations): fluctuations that occur during a 24-hour period.

DNA: deoxyribonucleic acid, which contains the genetic instructions used in the development and functioning of all known living organisms (with the exception of RNA viruses). The sequence of nucleotides determines individual hereditary characteristics.

Domestication of fisheries: increasing the proportion of the industrial fish catch taken by local fleets and processed in national facilities.

Downscaling: techniques that take outputs from numerical models and add information at scales smaller than the grid spacing. Global climate models (GCMs) are run at coarse spatial resolution and are unable to resolve important sub-grid scale features such as clouds and topgraphy. Downscaling methods have been developed to obtain local-scale surface weather from regional-scale atmospheric variables provided by GCMs.

Downwelling: physical process where surface waters sink deeper, as opposed to **upwelling**.

Economic development: sustained increase in the production levels of goods and services and standard of living of a nation's Population resulting in a greater real **gross domestic product** (GDP), but measured in more ways than increases in GDP.

Ecosystem: a dynamic entity comprising a biological community, made up of all the organisms living in a particular area, which interacts with the non-living, physical components of its environment such as air, soil and water.

Eddies: formations of swirling water caused when a bend in a surface ocean current lengthens and eventually makes a loop which separates from the main current.

Ekman transport: near surface ocean current that moves perpendicular to the prevailing wind direction as a result of Earth's rotation.

El Niño: the 'warm' phase of ENSO (see below) characterised by unusually warm **sea surface temperatures** in the eastern equatorial Pacific associated with a weakening of the **Walker Circulation** and trade winds. Eastward shift towards the dateline of the centre of maximum tropical convection results in the western Pacific experiencing unusually dry conditions, whereas the central and eastern Pacific have unusually wet conditions. Changes also occur in the main location of tropical cyclone activity and the South Pacific Convergence Zone (**SPCZ**).

El Niño-Southern Oscillation (ENSO): the major source of interannual tropical climate variability characterised by periodic variations evolving over 12–18 months in the coupled ocean-atmosphere system of the tropical Pacific. These variations result in distinct and different surface climate (temperature, rainfall, tropical cyclone activity) anomalies during ENSO's two phases, **El Niño** and **La Niña**.

Emissions scenario: plausible description of future emissions of greenhouse gases, based on a coherent and internally consistent set of assumptions ('scenario logic') about the key relationships and driving forces (e.g. rate of technology change or prices).

Energy audit: an evaluation of energy consumption, as in a home or business, to determine ways in which energy can be conserved.

Energy budget: equation describing how energy consumed by an individual is balanced through the different vital functions of the organism.

Epibiota: organisms living, usually parasitically, on the surface of plants or animals, for example, fungi.

Epifauna: benthic animals that live on a surface, such as sediment, other organisms or objects.

Epiphytes: plants living on other plants. In marine ecosystems, epiphytic plants are typically algae.

Euryhaline: species able to tolerate a wide range of salinities (e.g. most estuarine species).

Eutrophic: habitats with high nutrient loads, which typically result in increased development of aquatic plants, especially **phytoplankton**.

Eutrophication: natural or artificial addition of nutrients to bodies of water resulting in negative effects, such as excessive growth of algae and oxygen depletion (see **anoxic**).

Exclusive economic zone (EEZ): UN-granted rights and responsibilities of coastal states to control, exploit, manage, and conserve the living and non-living resources of the sea up to 200 nautical miles off their coasts, while allowing freedom of navigation to other states beyond 12 nautical miles of their coasts.

Extensive aquaculture: farming of fish or invertebrates at low densities and without the addition of formulated feeds. Organic and inorganic fertilisers are often used to promote the growth of **phytoplankton**, zooplankton, and other living food for fish and invertebrates leading to production.

Fingerling: a young fish about a ‘finger’ long, usually less than ~ 50 mm long.

Fish aggregating device: also commonly known as FAD, and consisting of buoys or floats near the surface which are either anchored or drifting. FADs attract and temporarily retain pelagic fish, increasing the probability of catching them. Anchored FADs are used by small-scale coastal fishers and drifting FADs are used by industrial tuna fleets.

Fish stock: exploited portion of a fish population.

Fishing effort: a measure of the amount of fishing done with a particular type of gear, calculated by multiplying fishing capacity by the time that this capacity is in use.

Fishing mortality at MSY (FMSY): the level of fishing mortality, or intensity of exploitation, that results in the **maximum sustainable yield** (MSY).

Floodplain habitat: flat land bordering a river and made up of alluvium (sand, silt and clay) deposited during floods. When a river overflows, the floodplain is covered with water.

Food security: sufficient availability of food to ensure that all people have physical and economic access to safe and nutritious food to meet their dietary needs and food preferences for an active and healthy lifestyle.

Food web: the sum of pathways between consumers and their prey in an **ecosystem**; usually a complex network.

Fry: very young and recently-hatched fish which have absorbed their yolk sacs and can hunt and consume live food.

Functional process zone: the part of a river within the hierarchical arrangement of habitats where discharge, channel gradient and sediment regimes are similar.

Geographic range: spatial extent where a species lives. For marine organisms, a distinction must be made between geographical locations that constitute the normal or permanent range of the species, versus locations where the species is a 'vagrant' and infrequently found or fails to establish a permanent population.

Geomorphology: scientific study of landscapes and the processes that form them, particularly the role of flowing water in forming rivers, lakes and estuaries.

Geostrophic flow: motion in the ocean due to pressure forces on a rotating planet.

Global climate model: a numerical representation of the global climate system based on the physical, chemical, and biological properties of its components, their interactions and feedback processes, and accounting for all or some of its known properties.

Global warming: an increase in the average temperature of the Earth over the past 100 years, attributed to the accumulation of **greenhouse gases**, including carbon dioxide, as a result of human activities such as the burning of fossil fuels and agricultural activities (also embodied in the term **climate change**).

Government revenue: income available to a government, obtained mostly from taxation and licence fees.

Greenhouse gases: atmospheric gases that contribute to the 'greenhouse effect' (trapping energy in the climate system). Naturally occurring greenhouse gases include water vapour, carbon dioxide, methane, nitrous oxide and ozone. Certain human activities, such as burning fossil fuels, have increased the concentrations of these gases in the atmosphere, particularly carbon dioxide, causing **global warming**.

Gross domestic product (GDP): total value of goods produced and services provided in a country during one year.

Habitat degradation: decline in the quality or quantity of habitats used by fish and invertebrates for reproduction and/or survival.

Habitat patches: units within the hierarchical arrangement of river habitats that describes discrete habitats, such as macrophytes, mangroves and sandbars.

Hadley Circulation: main meridional (north–south) atmospheric circulation of the tropics, characterised by rising moist air near the equator, and high poleward air flow that sinks and dries in the subtropical high pressure cells and returns to the equator as the surface trade winds.

Herbivore: a species that feeds predominantly on plant material, including phytoplankton, benthic algae and macrophytes.

Heterotrophs: organisms that cannot make their own food from **inorganic** molecules and depend on **organic** compounds either soluble (bacteria) or particulate (e.g. zooplankton, fish) for growth and energy.

Hierarchical habitat patches: arrangement of habitat units at increasing spatial and temporal scales, e.g. macrophyte beds, mangroves or sandbars within the hierarchical arrangement of river habitats. At larger scales, habitat units include pools and riffles, river reaches, functional process zones, salinity realms and marine catchment basins.

High nutrient–low chlorophyll regions: areas where **phytoplankton** production is not limited by macronutrients (e.g. nitrate), but by a micronutrient, presumably iron, such as the Pacific Equatorial Divergence.

Homeostasis: the ability or tendency of an organism or cell to maintain internal equilibrium by adjusting its physiological processes.

Hypersaline habitats: conditions where salinity exceeds normal marine salinities of around 36 practical salinity units (PSU). Hypersaline conditions typically arise in tropical coastal wetlands and estuaries where freshwater inflows or tidal mixing are insufficient to diminish the salt-concentrating effects of water loss through evaporation.

Hypoxic: deficient or starved of oxygen. Hypoxic habitats have low availability of dissolved oxygen that most animals find stressful (see also **anoxic**).

Industrial fleet: purse-seine fishing vessels targeting tuna for sale to canneries, and longline vessels catching tuna for the sashimi market or for canneries.

Infauna: aquatic benthic animals that live in the substrate, especially in soft sediment. Marine infauna usually construct tubes or burrows and are commonly found in deeper and subtidal waters. Examples include clams, tubeworms, burrowing crabs and mantis shrimp.

Inorganic: chemical compounds of a mineral, not of biological origin (see also **organic**).

Integrated coastal zone management: process for the management of the coast using a **cross-sectoral** approach to minimise the effects of development in any one sector on all other sectors.

Intensive aquaculture: farming operations for fish and invertebrates that are almost totally dependent on the use of commercial feeds. Stocking densities are usually limited not by the availability of food but rather by the tolerance of species to crowding, and by the ability of the farmer to maintain environmental parameters in optimal ranges for fish growth and survival.

Intergovernmental Panel on Climate Change (IPCC): an intergovernmental body which has been tasked by the United Nations and World Meteorological Organization to review and assess the most recent scientific, technical and socio-economic information on anthropogenic **climate change** and its impacts on **ecosystems** and society.

Internal wave: a gravity wave, generally linked to the tide, which oscillates within, rather than on, the surface of the ocean. Internal waves move water particles up and down several dozens of metres.

Intertidal zone: region between the high tide mark and the low tide mark.

Intertidal gleaning: opportunistic gathering of seafood from intertidal and shallow subtidal habitats mostly undertaken as a **subsistence** activity, although some gastropods are sold for their shells, while sea cucumbers are dried and sold as **bêche-de-mer**.

Intertropical Convergence Zone (ITCZ): region near the equator where trade winds from the two hemispheres converge and the air rises, resulting in a distinctive cloud band and enhanced rainfall (the ascending branch of the **Hadley Circulation**).

Introduced species: a species that lives outside its native **geographic range** as a result of human activity, either deliberate or accidental. Some introduced species cause damage to the ecosystem into which they are introduced, but others have no negative effect and can be beneficial to aquaculture and fisheries.

Invasive species: introduced species that spread within the habitats they colonise, and which can create adverse environmental, social or economic effects by disrupting habitats or through negative interactions with other species.

Isotherm: a line drawn on a weather map or chart linking all points of equal or constant temperature.

Key functional groups: ecologically equivalent species that perform a critical role in maintaining the normal state and function of a given **ecosystem**.

La Niña: the 'cool' phase of **ENSO** characterised by unusually cool **sea surface temperatures** in the eastern equatorial Pacific associated with a strengthening of the **Walker Circulation** and trade winds. Westward shift of the centre of maximum tropical convection results in unusually dry conditions in the eastern Pacific and unusually wet conditions in the western Pacific. Changes also occur in the main locations of tropical cyclone activity and the **SPCZ**.

Larval dispersal: development and growth of the larvae of marine organisms in the water column before transition to a more site-attached life stage (see **larval settlement**). Most marine larvae are capable of dispersing long distances from their release site, usually aided by ocean currents. Many larvae also have the ability to return to the general area where they were spawned (see also **pelagic dispersive phase**).

Larval replenishment: addition of new individuals to local populations of marine organisms through the arrival of larvae, which may have been released by the local population or by a distant population.

Larval settlement: process by which larvae of marine **benthic** or **demersal** species end their **pelagic dispersive phase** and adopt site-attached behaviour. Successful settlement relies on detecting and locating suitable habitats. Many marine larvae face very high levels of mortality (predation) during this transitional phase.

Latent heat flux: movement of heat from the Earth's surface to the atmosphere associated with evaporation or condensation of water vapour at the surface.

Latitudinal range: latitudinal extent of the **geographic range** of a species.

Life cycle: period involving all different development steps from egg to adult of a given species; a period from one generation of organisms to the next generation.

Life-span: average or maximum length of time an organism can be expected to live, or a material or object can be expected to last.

Likelihood: the probability that a future projection or prediction will occur.

Live rock: decorative, small coral boulders covered in encrusting organisms and coralline algae which act as biological filters in marine ornamental aquaria.

Livelihood: the capacity, assets (including both material and social resources) and activities required to earn an income or acquire resources that can be used or exchanged to satisfy the needs of an individual, family or social group.

Macroalgae: a collective term used to describe multi-cellular algae that are also known as seaweeds.

Macrophytes: aquatic plants that grow as fully submerged or emergent forms extending above the water surface. Includes both attached and floating plant species.

Mangrove associates: other plants such as shrubs, vines, herbs and epiphytes generally found at the back of mangrove communities, defined by their ability to survive in mangrove environments.

Marine ornamentals: marine fish, such as damselfish (Pomacentridae), butterflyfish (Chaetodontidae), triggerfish (Balistidae) and cardinalfish (Apogonidae), and invertebrates such as giant clams, cleaner shrimp and hard and soft corals, collected or cultured for export as aquarium specimens.

Marine protected area: an intertidal or subtidal area dedicated to protect part or all of its physical and biological components.

Mass coral bleaching: coral bleaching extending over large spatial scales as a result of usually high **sea surface temperatures** (see also **coral bleaching**).

Maximum Sustainable Yield (MSY): maximum average long-term catch that can be taken from a fishery assuming that the productivity characteristics of the stock do not change over time.

Melanesia: one of the three subregions of the Pacific Islands region, including Fiji, New Caledonia, Papua New Guinea, Solomon Islands and Vanuatu.

Metabolic demand: the energy and oxygen needed by an organism for normal life functions.

Microbial loop: tight coupling in **oligotrophic** waters between small **phytoplankton** cells, detritus, bacteria and small flagellates, making them largely independent of the rest of the food chain.

Micronesia: one of the three subregions of the Pacific Islands region, including Federated States of Micronesia, Guam, Kiribati, Marshall Islands, Nauru, Commonwealth of the Northern Mariana Islands and Palau.

Mineralisation: transformation of **organic** matter into **inorganic** compounds, such as nitrate or phosphate, via bacterial activity or other biological and chemical processes.

Mixed layer: upper layer of the ocean where the density and temperature of the water are both uniform. The top of the **pycnocline** and the **thermocline** start at the base of the mixed layer.

Nacre: iridescent internal layer of a mollusc shell formed by deposits of **calcium carbonate**. In pearl oyster shells, this layer is known as ‘mother-of-pearl’, and forms the outer layers of cultured pearls.

Near shore pelagic fish: fish that typically live in the upper layers of the open sea, but are attracted to near shore environments for food or shelter.

Net primary production (NPP): growth of **phytoplankton** per day; equivalent to primary production as long as the latter does not include **phytoplankton** catabolic compounds, such as carbon dioxide or exudates.

New production: the part of **primary production** based on nutrients brought to the **photic zone** by **upwelling** and other physical processes, or on atmospheric di-nitrogen (N2).

Non-extractive use: activities used to derive economic and social benefits from a resource without removing or altering that resource, e.g. scuba diving tourism.

Nursery habitats: shelter and feeding areas used by newly-settled or juvenile life-stages of marine organisms before they move (recruit) to habitats occupied by adults. Many species of fish use mangroves and seagrass meadows as nursery habitats before recruiting to coral reefs as adults.

Nutricline: nutrient gradient, generally located within the **pycnocline** at the base of the **mixed layer**.

Ocean acidification: reduction in the pH of the ocean, caused by greater concentrations of atmospheric carbon dioxide dissolved in sea water, resulting in the formation of carbonic acid (H_2CO_3). The carbonic acid then dissociates to form hydrogen ions (H^+) and bicarbonate ions (HCO_3^-). The potential for acidification is reduced because some of the hydrogen ions combine with carbonate ions (CO_3^{2-}). This combination, however, reduces the availability of carbonate ions to form **calcium carbonate** ($CaCO_3$), required by calcifying organisms (e.g. the scleractinian corals that build **coral reefs**) to construct their shells and skeletons.

Oligotrophic: water bodies with low concentrations of nutrients, resulting in low biological productivity.

Organic: chemical compounds of biological origin, i.e. made of carbon, hydrogen and other elements; as opposed to **inorganic** compounds.

Ornamental trade: sale of wild or cultured marine or freshwater fish and invertebrates to hobbyists or enterprises for display in aquariums.

Orographic effects: influence of mountains, especially on high oceanic islands, to capture water vapour and form clouds around their peaks which then create rainfall on the windward side, with a drier rain shadow on the leeward side.

Osmoregulation: physiological process by which fish regulate the internal salt content of their bodies at a different concentration from their surrounding water. Freshwater fish need to pump salt into their bodies to maintain required tissue concentrations, whereas saltwater fish need to prevent accumulation of excessive salt concentrations in their tissues.

Otoliths: small calcareous formation found in the inner ear of fish used in sensorial detection of movement.

Overfishing: depletion of a fish stock at a rate that is greater than the potential of the population to replenish itself.

Pacific Decadal Oscillation (PDO) or Inter-decadal Pacific Oscillation (IPO): a Pacific basin-wide pattern of **sea surface temperature** anomalies (with associated patterns of atmospheric variability), which operates on decadal and longer time scales. It persists in either a warm or cool phase for several decades and these phases appear to modulate the inter-annual variability associated with ENSO events. During PDO/IPO 'warm' phases (e.g. 1920s–1940s) **ENSO** events tend to have a weaker effect on tropical inter-annual climate variability compared with 'cold' phases (e.g. 1940s–1970s).

Paleo-environmental: reconstructing past natural environments including vegetation, climate and human impacts using microfossil (or other botanic) information.

Partial pressure of carbon dioxide (pCO_2): pressure exerted by carbon dioxide on the other gases in the (mixed gas) atmosphere and ocean.

Pathogen: a biological agent that causes disease or illness to its host.

Pelagic species: organisms that live near the surface of the water or in the water column itself.

Pelagic dispersive phase: important phase in the **life-cycle** of most marine organisms, which facilitates the movement of individuals among habitats and between different geographical regions. Marine organisms release eggs or larvae into the water column, which develop and grow in the **pelagic** environment and are capable of dispersing long distances from the release site (see also **larval dispersal**).

pH: a logarithmic scale used to measure the acidity or basicity of an aqueous solution. Pure water is said to be neutral, with a pH close to 7.0. Solutions with a pH less than 7 are said to be acidic and solutions with a pH greater than 7 are basic or alkaline.

Phase-shift: fundamental and persistent changes in the state of an **ecosystem**, which indicates a lack of resilience. A well known phase-shift on coral reefs represents declines in the abundance of habitat-forming corals and marked increases in the abundance of **macroalgae**.

Photic (or euphotic) zone: sunlit part of the upper ocean that is exposed to sufficient sunlight for **photosynthesis** to occur. The depth of the **photic zone** can be greatly affected by seasonal turbidity, and the lower boundary is generally considered to receive 1.0% (or 0.1% in tropical waters) of the surface light.

Photo-acclimation: adaptation of reef-building corals to changes in solar radiation (light levels), which can happen in a matter of days.

Photosynthesis: biological process by which plants produce carbohydrates and oxygen from carbon dioxide and water using solar radiation as an energy source.

Phytoplankton: the **autotrophic** component of the plankton community (drifting organisms that inhabit the pelagic zone of oceans).

Planktivore: animals that feed on plankton, e.g. most fish larvae and many pelagic fish.

Poïkilotherm: an organism whose body temperature varies with that of the surrounding environment.

Polynesia: one of the three subregions of the Pacific Islands region, including American Samoa, Cook Islands, French Polynesia, Niue, Pitcairn Islands, Samoa, Tokelau, Tonga, Tuvalu, and Wallis and Futuna.

Pond aquaculture: farming of aquatic organisms in freshwater earthen ponds.

Pool habitats: deep lengths of river channels characterised by slow flow, with an unbroken water surface. Such habitats are typically interspersed by riffles to form pool-riffle sequences.

Post-harvest processing: procedures used to increase the shelf life of fish and shellfish, often involving drying and smoking for small-scale fisheries in rural areas, and canning and loining for industrial tuna catches.

Postlarval fish: fish that have undergone transformation from pelagic larvae into the first juvenile stage of their adult form. In coral reef fish species, this transformation usually occurs just before or just after settlement to reefs or other coastal habitats.

Potamodromy: migration of fish or invertebrates solely within freshwater habitats (e.g. river herring in Papua New Guinea).

Prediction: a statement that something will happen in the future, based on known conditions at the time the prediction is made, and assumptions about the processes that will lead to change.

Primary productivity (or production): rate at which light energy is used by **autotroph**s to form **organic** substances that become food for consumers.

Projection: a set of future conditions, or consequences, derived from explicit assumptions, such as scenarios.

Pycnocline: depth of maximum density (salinity) changes in the ocean; often co-located with the **thermocline**.

Recruitment: process by which juvenile marine organisms effectively join the adult population. Recruitment in species that use distinct **nursery habitats** is the stage at which individuals leave the **nursery habitat** and start living in habitats or locations occupied by adult individuals of the same species.

Regenerated production: part of primary production based on nutrients regenerated by **heterotrophs** (bacteria and animals).

Remineralisation: transformation of **organic** molecules to **inorganic** forms, akin to **mineralisation**.

Resilience: the capacity of a system to absorb disturbence and reorganise while undergoing change so as to still retain essentially the same function, structure, identity and feedbacks.

Rete mirabile (latin for 'wonderful net'): network or mesh of arteries and veins lying very close to each other; the countercurrent blood fluxes within this net allow for an increase in muscle temperature and provides fish with some capacity for **thermoregulation**.

Riffle habitats: shallow lengths of river channels characterised by increased velocities and broken water surface as water flows over rock, cobble or gravel beds.

Runoff: water from rain or irrigation that flows over the land surface and is not absorbed into the ground, instead flowing into streams or other surface waters or land depressions.

Saturation horizon: ocean depth layer below which carbonate is saturated (see **carbonate saturation**).

Scenario: a plausible outline or model of an expected or supposed sequence of events.

Sea-level rise: changes in the height of the ocean as a result of changes in its volume. Human activities that have driven increased global temperatures have resulted in an accelerating rate of sea-level rise due to thermal expansion and the addition of water from melting glaciers and other land-locked ice bodies, such as the Greenland ice sheet.

Sea surface temperature (SST): water temperature close to the surface of the ocean; 'surface' generally refers to depths of less than 5–10 metres.

Seed set (mangroves): the production of seeds after flowering.

Semi-intensive aquaculture: farming operations characterised by addition of supplementary feed to ponds, which increases fish production above the levels achievable in **extensive aquaculture**. This production also depends on the natural food in the pond, however.

Shoaling: behaviour of waves as they approach a shelving shore: the sinusoidal, deepwater waves become asymmetrical and steeper. Also refers to the bottom of the **mixed laye**r or **thermocline** moving closer to the surface.

Small pelagic fish: species of small fish (< 500 g weight) caught near the surface, which are seasonally abundant and opportunistically exploited by coastal fisheries for food or bait.

Small-scale fishery: fisheries usually aimed at obtaining fish for household consumption or sale at local markets based on simple technology, often involving traditional and artisanal methods. Exceptions in the tropical Pacific are the fisheries for sea cucumbers and trochus as export commodities. Small-scale fisheries are typically poorly understood and governed.

Soluble reactive phosphorus (SRP): phosphorus fraction that consists of **inorganic** orthophosphate (PO4), a form of phosphorus that is directly taken up by algae for growth.

Southern Annular Mode (SAM): major source of variability in the atmospheric circulation of the mid-high latitudes of the Southern Hemisphere operating on time scales longer than ~ 50 days. SAM is a zonal pattern with sea-level pressure anomalies of opposite sign between about 45°S and 65°S. Fluctuations between the two phases affect the strength of the westerly winds over the Southern Ocean. Anomalies in surface atmosphere and ocean climate, primarily in mid-high latitudes of the Southern Hemisphere, are also associated with SAM.

Southern Oscillation Index (SOI): an atmospheric index of the strength of **ENSO** activity based on the difference in sea-level pressure between Darwin, Australia (representing the ascending branch of the **Walker Circulatio**n) and Tahiti, French Polynesia (representing the sinking branch of the **Walker Circulation**). Sustained high positive values characterise **La Niña** events and sustained negative values characterise **El Niño** events.

South Pacific Convergence Zone (SPCZ): an extension of the **Intertropical Convergence Zone** located between the **Western Pacific Warm Pool** and French Polynesia associated with low-level wind convergence and ascent. SPCZ creates a distinctive cloud band and enhanced rainfall.

Spat: young of oysters or other bivalve molluscs, both before and after they first adhere to a surface.

Spawning biomass at MSY, SB_{MSY}: level to which the spawning biomass of a **fish stock** will fall if the **maximum sustainable yield** is harvested on a continuous basis.

Sporulation: process of asexual reproduction in which any cell of an organism (e.g. **macroalgae** or seaweed) produces one or more reproductive cells inside its cell walls. The original cell is termed a sporangium and the new cells are termed spores. Spores are often produced in large numbers, resulting in a rapid increase in population size.

Stenohaline: species able to tolerate only a narrow range of salinities. Most freshwater species that do not migrate to sea are stenohaline.

Stocking density: number of individual organisms that are stocked per m^2 or m^3 in aquaculture operations.

Stratification: formation of distinct water layers based on differences in density (due to water temperature and/or salinity) with reduced mixing between warm surface waters and cool, nutrient-rich, deeper waters. Increasing ocean stratification, due to global **climate change**, is expected to reduce the productivity of the oceans.

Subduction: ocean process in which surface waters enter the ocean interior from the **mixed layer**.

Suboxic: a state (in the ocean) between oxygenated and anoxic conditions, where the oceanic concentration of oxygen is very low.

Subsistence fishing: harvesting of fish and invertebrates to meet basic food requirements of households, usually with no surplus fish available for sale at local markets.

Subtidal habitats: areas beneath the water surface at low tide.

Supply chain: all parties and processes involved in obtaining or manufacturing a product and delivering it to a customer.

Supratidal habitats: estuarine habitats that are above the high spring tide level and are only inundated by sea water during storms at high tide.

Surface mixed layer: see **mixed layer**.

Surplus production yield curves: method used to estimate **sustainable** fishing limits based on the relationship between fishing effort and long-term changes in the size of the **fish stock**.

Sustainable: long-term maintenance of the diversity, structure and productivity of an **ecosystem**; can also be applied to economic and social dimensions.

***Symbiodinium*:** genus of **dinoflagellates** that form symbiotic associations with reef-building corals and a large range of other marine invertebrates (see also **zooxanthella**e).

Symbiont shuffling: process by which the coral host selectively changes its **zooxanthellae** (***Symbiodinium***) community to increase the proportion of thermally tolerant **dinoflagellates**.

Temperature performance: typical relationship between individual performance and temperature, whereby performance (e.g. growth, reproduction, or movement) increases with increasing temperature until a certain point (the **thermal optima**) and then declines.

Teragram: one million metric tonnes, often used as a measure of CO2 emissions.

Thermal optima: range of temperatures in which individual performance (e.g. growth, reproduction, movement) is maximised.

Thermal stratification: formation of water layers of different temperatures in a pond, lake or ocean, which can inhibit mixing between layers, and thereby lead to depletion of oxygen in the bottom layer.

Thermocline: abrupt change in temperature occurring at the base of the mixed layer, typically found in oceans and lakes, which marks the separation between warmer surface water layers and the colder layers below.

Thermoregulation: ability of an animal to control its body temperature.

Topographic complexity: variation in the elevations of a landscape due to physical (abiotic) features and gradients.

Trade winds: easterly surface winds of the tropical Northern (north east trades) and Southern (south east trades) Hemispheres; originating in the sinking air of the subtropical high pressure belt of each hemisphere as a result of the **Hadley Circulation**. Trade winds are characterised by the constancy of their speed and direction.

Transboundary stock: **fish stocks** with distributions that span the **EEZs** of at least two countries or territories.

Transfer efficiency: ratio between consumer and prey production in the **food web**, which indicates the percentage of food transformed into the **biomass** of the consumer.

Translocated species: species that have been transported within their natural distribution to establish populations in new habitats.

Transshipment: moving fish landed in one port or at sea to another vessel for delivery to another port.

Tropical cyclone: non-frontal low pressure systems developed over warm waters with organised convection and maximum wind speeds of greater than 115 km/hr (63 knots). Tropical cyclones are the most destructive weather systems affecting tropical regions (also known as typhoons and hurricanes). They are particularly destructive when making landfall, bringing strong winds, high rainfall, storm waves and destructive storm surges. They rarely form within 5–10° of the equator.

Underwater visual census: survey methods used to record the size, abundance and biomass of fish and invertebrates without depleting local stocks. The general method involves swimming over a pre-defined area of habitat to record the local density of a given species.

Unsustainable: activities pertaining to fishing and harvesting or **habitat degradation**, which lead to long-term declines in the abundance of a species or population.

Upwelling: physical process (vertical advection) created by a divergence of surface waters, bringing deep, nutrient-rich waters to the ocean surface. Upwelling regions are often associated with high primary productivity and associated fisheries production (see also **downwelling**).

'Vehicle': fisheries and aquaculture operations used to catch or produce fish allocated for economic development, government revenue, food security or livelihoods.

Vortex: a spinning, often turbulent, flow of fluid. Includes ocean **eddies**.

Vulnerability (to climate variability and change): extent to which a natural or human system is susceptible to sustaining damage resulting from climate variability and change, despite human actions to moderate or offset such damage. Vulnerability is a function of the character, magnitude and rate of climate variation to which a system is exposed, the sensitivity of the system and its adaptive capacity.

Walker Circulation: zonal (east-west) atmospheric circulation of the tropical Pacific operating within about 20° of the equator. Characterised by rising moist air over Indonesia, which travels eastwards aloft and then sinks and dries in the region of French Polynesia. Closely linked with **ENSO**.

Wave setup: increase in water level over reef flats due to the persistent arrival and breaking of waves on the shore.

Western Pacific Warm Pool: near-equatorial region of the western Pacific with low sea surface salinity and temperatures greater than 28°C throughout the year. It is the warmest part of the tropical oceans.

Wind curl: rotational motion caused by wind, primarily related to north-south variations in the east-west wind stress. Regions of high wind curl correspond to regions of surface water convergence or divergence (due to changing **Ekman transport**), resulting in downward or upward vertical motion, respectively. Wind curl is dynamically related to the large-scale horizontal circulation of the ocean.

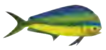
Zooxanthellae: microscopic algae that live as symbionts in the intracellular tissue of various marine hosts, including scleractinian (hard) corals, tropical sea anemones and giant clams. As plants, zooxanthellae photosynthesise and provide energy to the host organism which, in return, provides protection and access to sunlight (see also genus ***Symbiodinium***).

Glossary of symbols

Oceanic fish


Skipjack tuna


Sharks


Dolphinfish (mahi-mahi)


Yellowfin tuna


Broadbill swordfish


Rainbow runner


Bigeye tuna


Marlin


Albacore tuna

Other components of the oceanic ecosystem


Sea birds


Whale


Whale shark


Turtle


Dolphin

Coastal fish and invertebrates

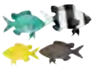

Snapper/juvenile


Unicorn fish


Butterflyfish


Emperor


Spanish mackerel


Damselfish


Coral trout


Mullet


Clownfish


Parrotfish


Trevally


Small pelagics


Rabbitfish


Bonefish


Spiny lobster


Sea cucumber

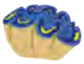

Mangrove crab


Mantis shrimp


Trochus


Penaeid shrimp


Octopus


Giant clam


Arc and venus shells


Oyster


Pina

Freshwater and estuarine fish and invertebrates


Barramundi


Freshwater mullet


Tilapia


Saratoga

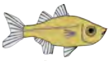

Mangrove jack


Archerfish

Freshwater and estuarine fish and invertebrates *(cont.)*


Catfish


Grunter


Mouth almighty


Eel


Jungle perch


Gobies


River herring


Milkfish


Freshwater clams


Gudgeon

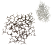

Long tom


Macrobrachium

Species used for aquaculture


Pearl oyster

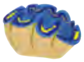

Penaeid shrimp


Seaweed


Tilapia


Milkfish


Branching corals


Giant clam

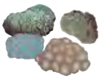

Rabbitfish


Macrobrachium


Sea cucumber


Trochus

Corals and associated species


Massive corals


Coral reef

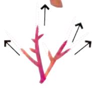

Broken coral fragments


Plate corals


Soft coral


Sponge


Branching corals

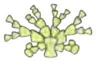

Coral growth


Anemone

Macroalgae associated with coral reefs


Macroalgae – general


Caulerpa


Halimeda


Hormosira

Seagrasses


Seagrass – general


Halophila ovalis


Cymodocea serrulata


Halodule uninervis


Halophila spinulosa


Cymodocea rotundata


Thalassia hemprichii


Halophila decipiens


Enhalus acoroides

Seagrasses *(cont.)*


Syringodium isoetifolium


Halophila capricorni


Thalassodendron ciliatum

Mangroves


Mangrove forest – general


Bruguiera


Xylocarpus


Excoecaria


Lumnitzera


Rhizophora

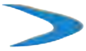

Ceriops


Avicennia


Channels in mangrove forest

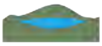

Saltmarsh

Freshwater and terrestrial habitats


Wetland


Macrophyte growth


Forest tree


Lake


Emergent freshwater macrophytes


Riparian tree


Snag


Water lilies


Riparian shrubs


Rocky habitat


Nypa palm


Coconut tree


Wetland vegetation


Vegetated catchment


Unvegetated catchment


Gravel


Sandbar/Mudbar


Freshwater stream

Marine food web


Plankton – copepods


Phytoplankton


Squid


Micronekton


Zooplankton


Predatory fish


Plankton – amphipods


Plankton – ciliates


Lanternfish


Plankton – mysid


Lobster larvae

Freshwater food web


Snails


Insects


Fruit


Aquatic invertebrates


Benthic worms


Detritus

Freshwater food web *(cont.)*

- Epiphytic algae
- Hardyhead
- Rainbowfish

Fishing methods

- Purse-seining
- Longlining
- Pole-and-line fishing
- Trolling
- Gill netting
- Cast netting
- Sea cucumber restocking
- Line fishing
- Line fishing
- Spearfishing
- Bouke-ami fishing
- Recreational fishing
- Fly fishing
- Digging
- Diving
- Diving for aquarium fish
- Push netting
- Hand collecting
- Gleaning
- Crushing derris root to extract poison
- Trapping

Fishing equipment

- Fish aggregating device
- Drifting fish aggregating device
- Capture of postlarvae

Aquaculture infrastructure

- Multi-species hatchery
- Seaweed farm
- Shrimp ponds
- Sea cage
- Pearl farm
- Marine ornamental farm

Features of the environment

- Rain
- Cyclone/Storm
- Wind strong/weak
- Cloud
- Sun
- Light attenuation
- Temperature high/low
- Salinity high/low
- Oxygen high/low

Environmental processes


Freshwater input


Nutrient flux


Sediment and nutrient input


Sediment and nutrient transfer


Scouring of streambank


Sediment deposition and burial of habitat


Evaporation


Diffusion small/ large barrier


Turbulent mixing


Mixing/circulation


Upwelling

Land use


Gardening/agriculture


Mining


Logging

Index

Abbreviations

ADB	Asian Development Bank
AR	Assessment Report
ARCH	Archipelagic Deep Basins
BMA	benthic microalgae
BMP	best management practice
Ca^{2+}	calcium ion
$CaCO_3$	calcium carbonate
CAMS-OPI	Climate Anomaly Monitoring System and OLR Precipitation Index
CCSM	community climate system model
CE	cold eddy
CEAFM	community-based ecosystem approach to fisheries management
Chl	chlorophyll
CMIP	Coupled Model Intercomparison Project
CMM	conservation and management measure
CNMI	Commonwealth of the Northern Mariana Islands
COFI	Committee on Fisheries
CORDEX	Coordinated Regional Climate Downscaling Experiment
CO_2	carbon dioxide
CO_3^{2-}	carbonate ion
CPUE	catch per unit effort
CSCC	Coral Sea Counter Current
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DCM	deep chlorophyll maximum
DNA	deoxyribonucleic acid
D-UVC	distance-based underwater visual census
DWFNs	distant water fishing nations
EAC	East Australian Current
EAF	ecosystem approach to fisheries
EEZ	exclusive economic zone
ENSO	El Niño-Southern Oscillation
EOF	Empirical Orthogonal Function
EPA	Economic Partnership Agreement
EPO	Eastern Pacific Ocean
EU	European Union
EUC	Equatorial Undercurrent
FADs	fish aggregating devices
FAME	Fisheries, Aquaculture and Marine Environment Division of SPC
FAO	Food and Agriculture Organization of the United Nations
Fe	iron
FFA	Forum Fisheries Agency
FSM	Federated States of Micronesia

GDP	gross domestic product
GIFT	genetically improved farmed tilapia
GIS	geographic information system
GR	government revenue
H^+	hydrogen ion
HCO_3^-	bicarbonate ion
H_2CO_3	carbonic acid
ha	hectare
HadISST	Hadley Centre Global Sea Ice and Sea Surface Temperature
HE	Halmahera Eddy
HIES	household income and expenditure surveys
HNLC	High Nutrient-Low Chlorophyll
HOT	Hawaii Ocean Time-Series
hPa	hectopascal
IATTC	Inter-American Tropical Tuna Commission
ICESCR	International Covenant on Economic, Social and Cultural Rights
IEPA	Interim Economic Partnership Agreements
ITF	Indonesian Throughflow
IPCC	Intergovernmental Panel on Climate Change
IPO	Interdecadal Pacific Oscillation
IPSL	Institut Pierre Simon Laplace
ITCZ	Intertropical Convergence Zone
IUU	illegal, unreported and unregulated
KURO	Kuroshio Current
MC	Mindanao Current
MCS	Monitoring, Control, Surveillance
ME	Mindanao Eddy
MLD	mixed layer depth
MSY	maximum sustainable yield
N_2	di-nitrogen
NAPAs	national adaptation programmes of action
NCEP	National Centers for Environmental Prediction
NCJ	North Caledonian Jet
NEC	North Equatorial Current
NECC	North Equatorial Counter Current
NFCC	North Fiji Counter Current
NGCUC	New Guinea Coastal Undercurrent
NGO	non-governmental organisation
NH_4 (NH_4^+)	ammonium (ion)
NOAA	National Oceanic and Atmospheric Administration
NO_3 (NO_3^-)	nitrate (ion)
NP	new production
NPP	net primary production

NPTG	North Pacific Tropical Gyre
NPZ	Nutrient-Phytoplankton-Zooplankton
NQC	North Queensland Current
NSTCC	North Subtropical Counter Current
NVJ	North Vanuatu Jet
O_2	oxygen
OA	ocean acidification
OFP	Oceanic Fisheries Programme
OMZ	Oxygen Minimum Zone
PaCFA	Global Partnership for Climate, Fisheries and Aquaculture
PAR	photosynthetically active radiation
pCO_2	partial pressure of carbon dioxide
PDO	Pacific Decadal Oscillation
PEQD	Pacific Equatorial Divergence
PICTs	Pacific Island countries and territories
PISCES	Pelagic Interaction Scheme for Carbon and Ecosystem Studies
PNA	Parties to the Nauru Agreement
PNG	Papua New Guinea
PO_4^{3-}	phosphate
ppm	parts per million
PROCFish	Pacific Regional Oceanic and Coastal Fisheries
PSU	practical salinity unit
RCPs	Representative Concentration Pathways
REDD	Reduced Emissions from Deforestation and Forest Degradation
RMS	root mean square
ROC	Republic of China
RP	regenerated production
SAM	Southern Annular Mode
SAT	surface air temperature
SB	spawning biomass
SCJ	South Caledonian Jet
SCUBA	self-contained underwater breathing apparatus
SD	standard deviation
SE	standard error
SEAPODYM	Spatial Ecosystem and Population Dynamics Model
SEC	South Equatorial Current
SECC	South Equatorial Counter Current
SiO_2	silicate
SODA	Simple Ocean Data Assimilation
SOI	Southern Oscillation Index
SOPAC	Applied Geoscience and Technology Division of SPC
SPC	Secretariat of the Pacific Community
SPCZ	South Pacific Convergence Zone

SPREP	Secretariat of the Pacific Regional Environment Programme
SPSG	South Pacific Subtropical Gyre
SRES	Special Report on Emissions Scenarios
SRP	soluble reactive phosphorus
SSH	sea surface height
SSS	sea surface salinity
SST	sea surface temperature
SSTCC	South Subtropical Counter Current
Sv	Sverdrup
SWH	significant wave height
TAO	Tropical Atmosphere Ocean
Tg	teragram
TIWs	tropical instability waves
TVMA	Te Vaka Moana Arrangement
UNCLOS	United Nation Convention on the Law of the Sea
UNFCCC	United Nations Framework Convention on Climate Change
UP	upwelling
USD	United States dollar
UVR	ultraviolet radiation
VDS	vessel day scheme
Warm Pool	Western Pacific Warm Pool
WCPFC	Western and Central Pacific Fisheries Commission
WCPO	Western and Central Pacific Ocean
WE	warm eddy
WPRFMC	Western Pacific Regional Fishery Management Council
WTPIA	Western Tropical Pacific Insular Area

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Fisheries and aquaculture are of great importance to the people of the tropical Pacific. Nowhere else do so many countries and territories depend as heavily on fish and shellfish for economic development, government revenue, food security and livelihoods.

This book examines how climate change could affect the region's plans to maximise sustainable economic and social benefits from fisheries and aquaculture – already a challenge in the face of predicted population growth. Scientists and managers from 36 institutions have collaborated to carry out this vulnerability assessment. Their analyses span the projected effects of global warming on surface climate, the ocean, fish habitats, fish stocks and aquaculture production across the vast domain of the 22 Pacific Island countries and territories. The likely effects of ocean acidification have also been evaluated.

The implications are mixed – there are likely to be winners and losers. Tuna catches are eventually expected to be higher around islands in the eastern tropical Pacific Ocean but lower in the west. Harvests from coastal fisheries and aquaculture are projected to decrease across the region but greater yields are likely from freshwater fisheries and pond aquaculture.

This book recommends adaptations, policies and investments that should enable governments and communities to reduce the threats of climate change to fisheries and aquaculture and capitalise on opportunities. These recommendations are relevant to the concerns of all stakeholders in the region and their development partners.