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OUT OF THE BLUE

THE VALUE OF SEAGRASSES TO THE ENVIRONMENT AND TO PEOPLE

WORLD SEAGRASS ASSOCIATION

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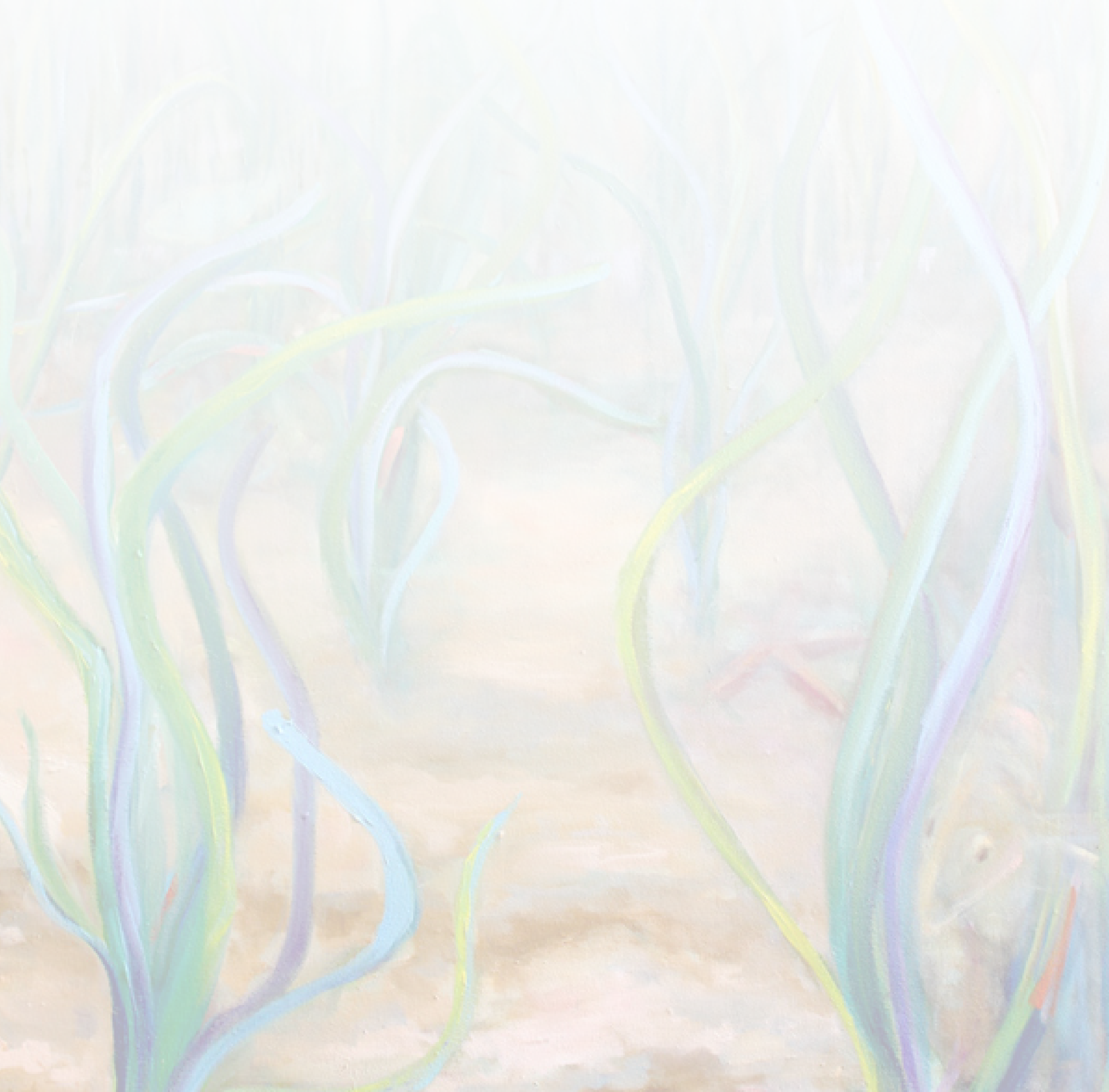

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OUT OF THE BLUE

THE VALUE OF SEAGRASSES TO THE ENVIRONMENT AND TO PEOPLE

Foreword

Seagrasses are one of the most valuable coastal and marine ecosystems on the planet, providing a range of critical environmental, economic and social benefits.

They provide food and livelihoods to hundreds of millions of people, and they support rich biodiversity, with their sediments constituting one of the planet's most efficient stores of carbon.

However coastal development and population growth, rising pollution and climate change, are threatening the survival of this vital ecosystem. This global synthesis report, which is the first of its kind, aims to improve our understanding of the value of seagrasses and provide recommendations to protect and manage them.

One billion people live within 100km of seagrass meadows and 20 per cent of the world largest fisheries depend on these ecosystems. Emissions from loss of seagrass are estimated to contribute up to 299 Tg carbon to the atmosphere per year.

At a time of climate emergency, the worrying decline of global seagrass area, estimated to be about 30 per cent since the late nineteenth century, requires a range of actions and policies that recognize the multiple benefits of seagrass ecosystems.

Maintaining the health of seagrass ecosystems is important for healthy marine life and for healthy people around the world. In doing so, they represent powerful nature-based solutions to the climate challenge and sustainable development.

Inger Andersen
Executive Director
United Nations Environment Programme

Preface: Seagrasses – their health, our wealth

Seagrasses are the forgotten ecosystem, despite being ubiquitous along coastlines worldwide and found in 159 countries on six continents, covering an area over 300,000 km^2. Swaying gently beneath the surface of the ocean, seagrasses are too often out of sight and out of mind, overshadowed by colourful coral reefs and mighty mangroves. When seagrasses are noticed, they are sometimes regarded as a nuisance, though in fact they offer huge value to humankind.

Seagrass meadows are of fundamental importance to nature and people. For some 100 million years, they have protected coastal waters, the creatures that live there, and more recently us, humans. Seagrasses are among the most productive natural habitats on land or sea: they purify water, they protect us from storms, they provide food to hundreds of millions of people, and they support rich biodiversity, with their sediments constituting one of the planet's most efficient stores of carbon.

In light of everything seagrasses do for people and nature, protecting and restoring them is vital. Seagrass ecosystems can help us fulfil many of the international environmental commitments that are necessary to save our planet, from the Sustainable Development Goals to the Paris Agreement to the Convention on Biological Diversity.

It is time to boost the profile of this underappreciated marine ecosystem and shine a spotlight on the many ways that seagrasses can help us solve our biggest environmental challenges.

Ronald Jumeau
Permanent Representative to the United Nations and Ambassador for Climate Change, Republic of Seychelles

A note from the World Seagrass Association

Seagrasses have long been overlooked as essential foundation species for coastal ecosystems. Our knowledge of their global contributions to the function, diversity, and beauty of near shore regions increases every year as researchers and citizen scientists continue to ask questions and make observations. Combined with the tireless efforts of coastal managers and policy makers, a comprehensive understanding of the ecological and socioeconomic importance of seagrasses across local, regional and global scales is becoming clearer. Unfortunately, as our understanding increases, so to do the stressors which have resulted in a pattern of seagrass decline on a global scale. It is therefore necessary to increase the awareness of this resource and to outline steps necessary to protect this essential habitat in the future.

This global synthesis report builds on the foundation laid by countless individuals around the world who put their time, energy, and resources into understanding these amazing habitats. The World Seagrass Association was established in 2000 by a group of 11 such individuals from 7 different countries to raise awareness of the importance of seagrasses, facilitate training and information exchange, collect and make management information readily available for the conservation of seagrass habitats, and to provide political support for the sustainability, biodiversity, and resilience of the marine environment. Since then the WSA has grown to include members from more than 20 countries, facilitated scientific exchange via the International Seagrass Biology Workshop series, contributed to the development of the first Global Atlas of Seagrass, and most recently, spearheaded an effort to develop an informal 'World Seagrass Day', in order to heighten global awareness on these important ecosystems. It is the hope of the World Seagrass Association that this report will further raise the profile of these underappreciated resources and provide a path forward for their conservation and science-based management.

As the President of the WSA, I am pleased to endorse this global synthesis report and eagerly anticipate the positive effects of an increased global focus on seagrasses.

Dr Jessie Jarvis
President of the World Seagrass Association


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Summary for Policymakers

Seagrasses are marine flowering plants that are found in shallow waters in many parts of the world, from the tropics to the Arctic circle. They exist in 159 countries on six continents, covering over 300,000 km^2, making them one of the most widespread coastal habitats on Earth. Seagrasses form extensive underwater meadows, creating complex, highly productive and biologically rich habitats. Seagrasses also play a significant role in providing a plethora of highly valuable ecosystem services that greatly contribute to the health of the world's ecosystems, human well-being and the security of coastal communities.

Seagrass meadows are of fundamental importance to world fisheries production, providing valuable nursery habitat to over one fifth of the world's largest 25 fisheries, as well as shelter and food for thousands of species, including fish, shellfish and threatened, endangered and charismatic species, such as dugongs, seahorses and sea turtles. Seagrasses can improve water quality by filtering, cycling and storing nutrients and pollutants and can reduce the incidence of pathogenic marine bacteria, which not only directly protects humans, but also reduces coral diseases and contamination in seafood. Seagrasses additionally provide cultural benefits worldwide by supporting tourism and recreational opportunities.

Seagrasses provide powerful nature-based solutions to tackle climate change impacts, as a key component of mitigation and adaptation efforts. Despite covering only 0.1 per cent of the ocean floor, these meadows are highly efficient carbon sinks, storing up to 18 per cent of the world's oceanic carbon. Seagrasses can also buffer ocean acidification, thus contributing to the resilience of the most vulnerable ecosystems and species, such as coral reefs, and act as the first line of defence along coasts by reducing wave energy, protecting people from the increasing risk of floods and storms.

However, seagrasses have been declining globally since the 1930s, with the most recent census estimating that 7 per cent of this key marine habitat is being lost worldwide per year, which is equivalent to a football field of seagrass lost every 30 minutes. Only 26 per cent of recorded seagrass meadows fall within marine protected areas (MPAs) compared with 40 per cent of coral reefs and 43 per cent of mangroves. Threats with the highest impact to seagrasses include agricultural and industrial run-off, coastal development and climate change. Unregulated fishing activities, anchoring, trampling and dredging also pose major threats. However, despite a general global trend of seagrass loss, there is reason for hope, as some areas have shown abating declines or substantial recovery of seagrasses. These recoveries can often be attributed to human interventions reducing the effect of human-caused stressors.

Increasing recognition of the importance of seagrass ecosystems to both biodiversity and human well-being can

drive efforts around the world to conserve, better manage and restore these ecosystems. Ensuring a sustainable future for seagrasses can help countries achieve multiple economic, societal and nutritional objectives, aligning with and supported by policies implemented at the national, regional or global levels. The benefits from conserving and restoring seagrass meadows can also help countries achieve 26 targets and indicators associated with 10 Sustainable Development Goals (SDGs). Seagrasses are critical for life underwater, but also provide wide-ranging benefits to people on land. Given the carbon storage and sequestration capacity of seagrass ecosystems, including them in nationally determined contributions (NDCs) can help nations achieve their targets under the Paris Agreement and the United Nations Framework Convention on Climate Change (UNFCCC). Inclusion of seagrass ecosystems in the post-2020 global biodiversity framework and the Convention on Biological Diversity (CBD) is also critical for protecting the integrity of marine ecosystems and biodiversity. Restoration of seagrasses also provides countries with opportunities to achieve commitments to be made to the upcoming United Nations Decade on Ecosystem Restoration.

This global synthesis report highlights the unique range of values provided by seagrasses to people around the world. It aims to provide a science-based synthesis of the numerous services linked to seagrasses and the associated risks in losing them in the age of climate change, as well as ongoing global habitat loss and degradation. This report provides management and policy options at the local, regional and global levels, with the aim to share best practices and prevent further losses. It also highlights the opportunities that effective conservation measures, sustainable management and successful restoration efforts for seagrass ecosystems can provide to governments in order to achieve their international environmental policy commitments, targets and objectives. It is hoped that this report will generate increased interest in seagrasses by policymakers, helping to ensure a sustainable future for these essential but undervalued ecosystems.

Key messages and findings

Seagrasses are one of the most widespread coastal habitats on the planet. Seagrasses are found in shallow waters worldwide, ranging from subarctic to tropical latitudes, and exist in 159 countries on six continents. Around 300,000 km^2 of seagrass has been mapped across the globe, but current estimates suggest that the actual coverage could be many times greater.

Seagrasses provide a range of environmental, economic and social benefits to humans, making them one of the most valuable coastal and marine ecosystems on the planet. Seagrasses have a significant global role in supporting food security, mitigating climate change, enriching biodiversity, purifying water, protecting coastlines and controlling diseases. The integrity and provision of services by seagrass meadows are enhanced by their proximity and connectivity to other coastal ecosystems, such as tidal marshes, coral reefs, mangrove and kelp forests, and oyster and mussel beds. The maintenance of these services is essential to support human well-being and promote future development.

Seagrass meadows are threatened globally by natural and anthropogenic stressors. Almost 30 per cent of global seagrass area has been lost since the late nineteenth century and at least 22 of the world's 72 seagrass species are in decline. Main threats include urban, industrial and agricultural run-off, coastal development, dredging, unregulated fishing and boating activities and climate change. Global losses of seagrass cover have major implications for humans due to the numerous ecosystem services they provide. Seagrass conservation, rehabilitation and restoration can reverse patterns of seagrass decline and rebuild lost ecosystem services.

There is an urgent need to develop and implement integrated policies and management options that recognize the multiple benefits of seagrass ecosystems. The conservation and restoration of seagrasses can help countries achieve multiple international commitments, contributing directly or indirectly to meeting 26 SDG targets as well as other international policy objectives, such as the Aichi Biodiversity Targets, the Paris Agreement, the United Nations Decade on Ecosystem Restoration, the United Nations Decade of Ocean Science for Sustainable Development, the Ramsar Convention on Wetlands and the Sendai Framework on Disaster Risk Reduction.

There are several regional, national and local practices that have led to proven benefits for seagrass ecosystems. Protection of seagrass ecosystems can be achieved by considering multiple pressures and cumulative impacts from marine and land-based activities. Management frameworks require cross-sectoral approaches and integration across jurisdictions, aligning with the global move towards holistic, inclusive and sustainable ocean-based economies.

Citizen science can be used to increase the influence on and effectiveness of policies, thereby strengthening seagrass conservation. Citizen scientists can help generate scientific information for conservation, implement restoration, provide input and engage in natural resource and environmental management and policymaking. Engaging local communities in co-managing seagrass ecosystems or associated protected areas can help build more effective and well-rounded initiatives.

Multiple private and public funds can be accessed for seagrass conservation and restoration, with a mixed approach likely to be the most effective. Payments for ecosystem services (PES) projects are rare for seagrass ecosystems at present, though multiple options exist for their development and they are a promising way forward. Inclusion of seagrass management, conservation and restoration should be a critical component of sustainable blue economy strategies in the future.

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Recommended actions

1 Support the development of a policy expert group for seagrasses in order to further analyse the current effectiveness of policies related to seagrasses and to make recommendations to the international community.

2 Develop a comprehensive global map of seagrass distribution and health. Build on and coordinate efforts to address the gaps that currently exist in global data sets for seagrass extent and distribution, strengthening existing in situ seagrass monitoring networks, exploring new opportunities for remote sensing and investing in data management for the long-term maintenance of a global database.

3 Invest in further understanding and quantifying the value of seagrass ecosystem goods and services. Invest in understanding and quantifying ecosystem services associated with different seagrass species, prioritizing underrepresented bioregions, such as the coasts of South America, South-East Asia and West Africa.

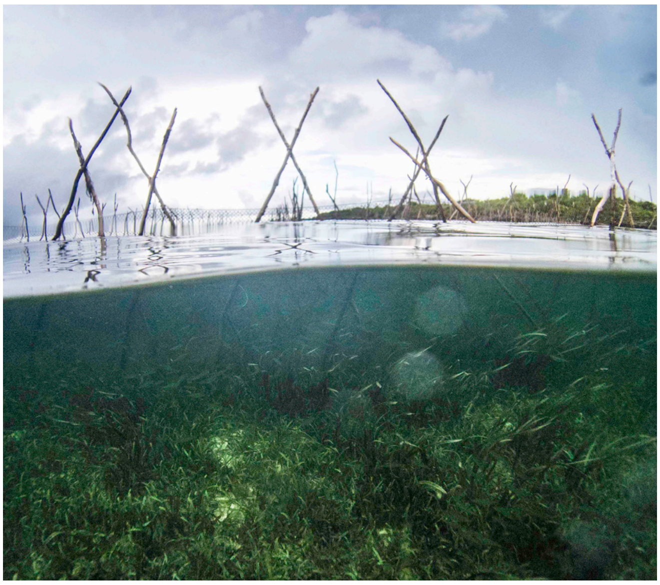
4 Raise awareness and communicate the economic and social importance of seagrasses, as well as the consequences of their loss. Address the 'charisma gap' for seagrass ecosystems by better communicating to the public the goods and services that seagrasses provide to humanity.

5 Develop national action plans for seagrass ecosystems. Actions plans should be connected to and help deliver on various international commitments. They should also be well integrated and recognize connectivity with neighbouring ecosystems, such as coral reefs, mangroves, kelp forests, saltmarshes or shellfish beds as appropriate.

6 Integrate seagrasses into planning and implementation of the post-2020 global biodiversity framework. Specific, measurable, attainable, relevant and time-bound targets for seagrass ecosystems globally would be a positive outcome for seagrasses and coastal regions generally from the 2020 CBD Conference of the Parties (COP).

7 Include actions on seagrass ecosystems in plans for the United Nations Decade on Ecosystem Restoration and the United Nations Decade of Ocean Science for Sustainable Development. Develop targets for restoring seagrass ecosystems and invest in seagrass science and monitoring with regards to food security, disaster risk reduction, climate change adaptation and climate change mitigation.

8 Recognize the value of seagrasses in NDCs as a key component of climate change adaptation and mitigation. Include seagrass ecosystems in national greenhouse gas inventories, appropriate Intergovernmental Panel on Climate Change (IPCC) tier reporting and NDC reporting.



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9 Recognize the value of protecting seagrasses for the SDGs, the 2030 Agenda for Sustainable Development and other international policy targets. Develop seagrass indicators within monitoring systems, based on both in situ and remote sensing methods, including these in the context of the SDGs, Paris Agreement, CBD and Sendai Framework.

10 Increase national, bilateral and multilateral funding for comprehensive actions required to conserve and sustainably manage seagrass ecosystems. Identify opportunities for specific funding windows under multilateral environmental funds. Explore the potential for developing a global fund for seagrass conservation, restoration and capacity development.

11 Engage stakeholders at all levels and stimulate partnerships to facilitate integration of seagrass conservation into planning and implementation phases. The role and knowledge of local and indigenous communities is fundamental to the long-term effectiveness and sustainability of interventions.

12 Designate more MPAs or locally managed marine areas (LMMAs) that include or focus on management measures for seagrass ecosystems. With only 26 per cent of known seagrasses occurring in protected areas, this is a critical step in preventing seagrass loss and maintaining the ecosystem services that they provide to humanity.

13 Stimulate seagrass conservation and restoration by providing financial mechanisms and incentives. Promote economic incentives or integrate seagrasses into existing PES as a source of local income from protection and restoration activities. Develop methodologies and guidance for seagrasses to enter the carbon market.

Introduction

Seagrasses are an often overlooked but vital part of the seascape. While they have been described as the 'lungs' and 'ecosystem engineers' of the sea, their contributions to planetary health and human well-being are not as well-known as those of other marine ecosystems, such as coral reefs and mangroves. To overcome this 'charisma gap' (Unsworth et al. 2019), this report synthesizes current knowledge of seagrass ecosystems, highlights the many values they provide to people and provides policy recommendations that fully recognize these values.

Seagrasses, coral reefs and mangroves are often interconnected and interdependent, supporting coastal communities around the world. There are more than 70 species of seagrass around the world (Short et al. 2011), found in 159 countries on six continents, potentially covering over 300,000 km^2 (see Figure 1), with more than 1 billion people living within 100 km of a seagrass meadow (Small and Nicholls 2003). The compiled global seagrass area composite to date has been estimated at 160,387 km^2 across 103 countries/territories with Moderate to High confidence, with an additional 106,175 km^2 across another 33 countries with Low confidence (McKenzie et al. 2020).

The multiple benefits that seagrasses provide contribute to community well-being, whether through food security from fish production, improved quality of water filtered by seagrasses, protection of coasts from erosion, storms and floods or carbon sequestration and storage. Seagrasses support an estimated 20 per cent of the world's biggest fisheries (Unsworth et al. 2018), which have a total value of at least €200 million per year in the Mediterranean alone (Jackson et al. 2015), with the loss of seagrass habitat linked to rapid declines in fish stocks (McArthur and Boland 2006). Seagrasses reduce the incidence of pathogenic marine bacteria in seawater by 50 per cent (Lamb et al. 2017) and reduce wave energy hitting the coast by about 40 per cent, lessening damage to coasts (Fonseca and Cahalan 1992). They can accrete 30 mm per year more than unvegetated areas, helping communities adapt to sea level rise (Potouroglou et al. 2017). Seagrass ecosystems are important for climate change mitigation, with emissions from global seagrass degradation potentially reaching 0.65 $GtCO_2$ per year (Hoegh-Guldberg et al. 2018), which is roughly equivalent to yearly emissions from the entire global shipping industry. Seagrasses are also used for a wide range of goods and services, from pharmaceuticals to materials and

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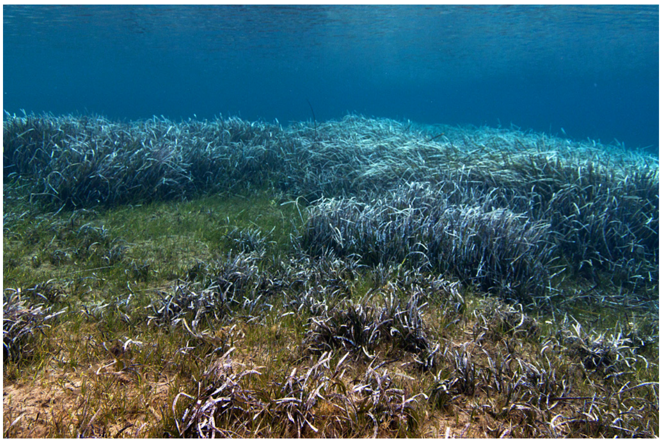

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food, such as Japanese sake. This versatility underpins local economies, while also yielding national, regional and global benefits and nature-based solutions. This report highlights the multiple benefits from protecting and restoring seagrass ecosystems for the international community.

Unfortunately, seagrasses are among the least protected coastal ecosystems (United Nations Environment Programme World Conservation Monitoring Centre [UNEP-WCMC] and Short 2018; United Nations Environment Programme [UNEP] and International Union for Conservation of Nature [IUCN] 2019) and often face cumulative pressures from coastal development, nutrient run-off and climate change. Only 26 per cent of recorded seagrass meadows fall within marine protected areas (MPAs) compared with 40 per cent of coral reefs and 43 per cent of mangroves. Most seagrass is not covered by management plans or protected against anthropogenic impacts. The most up-to-date figures state that nearly 50 per cent of coastal wetlands have been lost over the last 100 years, with a further 20–90 per cent of current coastal wetlands at risk of being lost by 2100 (Intergovernmental Panel on Climate Change [IPCC] 2019). Seagrass meadows alone have decreased by over 10 per cent per decade between 1970 and 2000 (Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services [ISPBES] 2019), with current projections suggesting that the distribution of seagrasses will shift towards the poles in the coming decades in response to climate change (IPCC 2019).

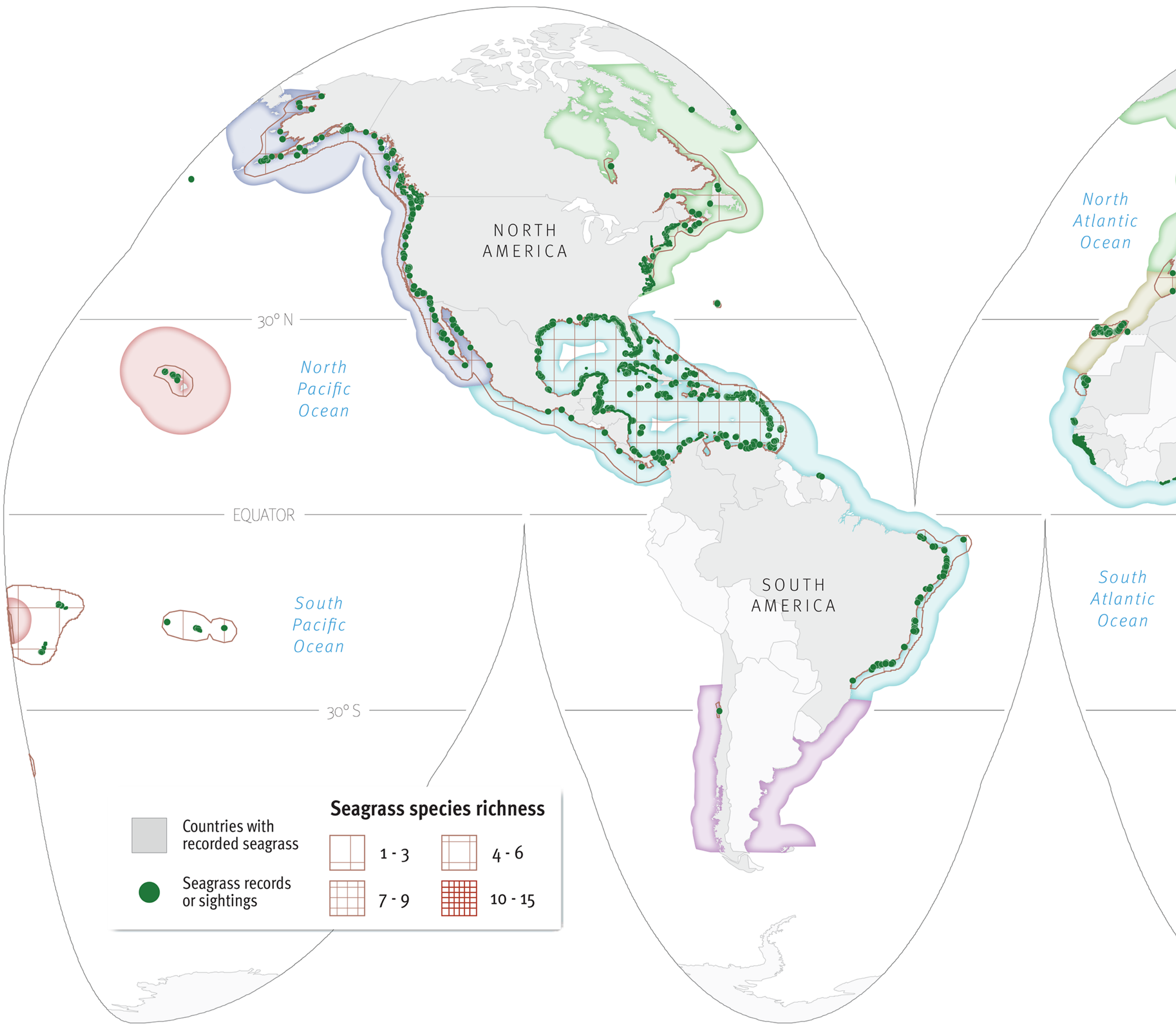
Given the importance of seagrasses to communities around the world, there is an urgent need to address these key cumulative drivers of seagrass degradation through integrated policies and cross-sectoral management measures, reflecting dependencies at the land–sea interface. As this report demonstrates, implementing effective management, conservation and restoration of seagrass ecosystems can help countries achieve multiple economic, societal and nutritional objectives, aligning with their national Sustainable Development Goals (SDGs). The benefits from conserving and restoring seagrass meadows can help countries achieve 26 targets and indicators associated with 10 SDGs, including SDGs 1, 2, 5, 6, 8, 11, 12, 13, 14 and 17. Seagrasses are critical for life underwater, but also provide huge benefits to people on land. Given the carbon storage and sequestration potential of seagrass ecosystems, including them in nationally determined contributions (NDCs) can help nations achieve their targets under the Paris Agreement and the United Nations Framework Convention on Climate Change (UNFCCC). Inclusion of seagrass ecosystems in the post-2020 global biodiversity framework and the Convention on Biological Diversity (CBD) is critical for protecting the integrity of marine ecosystems and biodiversity. Restoration of seagrasses also provides countries with opportunities to achieve commitments to be made to the upcoming United Nations Decade on Ecosystem Restoration. This report highlights the opportunities that management, conservation and restoration of seagrass ecosystems provide to national governments in achieving their international environmental policy targets and objectives.

Finally, financing of seagrass conservation and restoration is an important hurdle in sustainably managing seagrass ecosystems, implementing policies effectively and tracking progress towards management and policy objectives. This report explores the various options that exist for private, public and payments for ecosystem services (PES) funding, with a range of case studies from around the world. Furthermore, sustainable management of seagrass ecosystems is a critical component of sustainable 'blue economies', as the services provided by these ecosystems underpin diverse economic activities and sources of revenue. Inclusion of seagrass management, conservation and restoration should be a critical component of sustainable blue economy strategies moving forward.

This is the first global report by the United Nations on the importance of seagrass ecosystems to the environment and to people; it is hoped that this report will help raise awareness of the importance, but also the vulnerability, of this critical but often undervalued marine ecosystem.

FIGURE 1

Global map of seagrass distribution, species richness and bioregions



Sources: Short, F.T. et al. (2007); United Nations Environment Programme World Conservation Monitoring Centre (UNEP-WCMC) and Short, F.T. (2018).

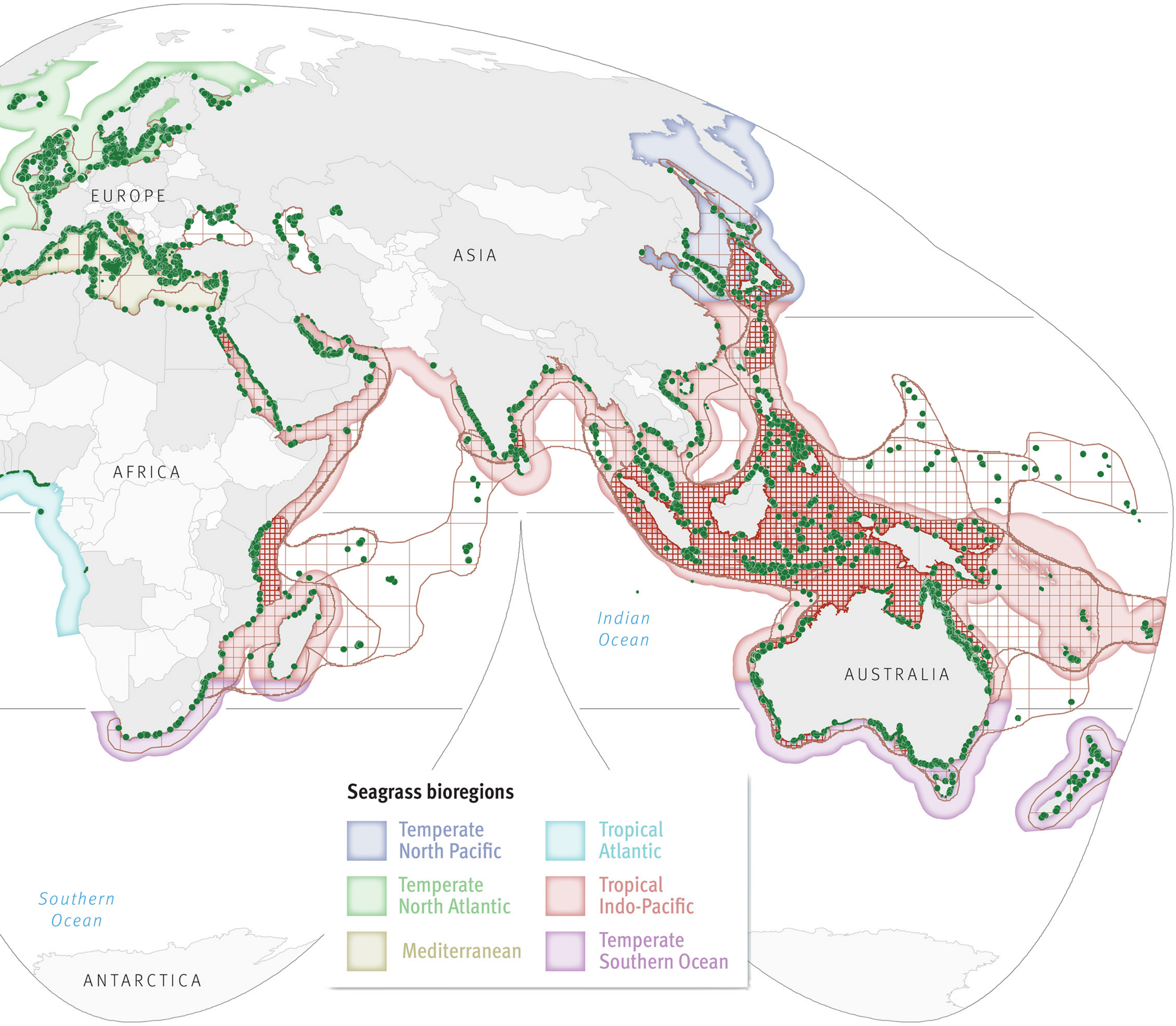
Countries and areas with recorded seagrass:

NORTH AMERICA: Canada, United States.

SOUTH AMERICA: Brazil, Chile, Colombia, Suriname, Venezuela.

CENTRAL AMERICA AND THE CARIBBEAN: Anguilla, Antigua and Barbuda, Aruba, Bahamas, Barbados, Belize, Bermuda, British Virgin Islands, Cayman Islands, Costa Rica, Cuba, Dominica, Dominican Republic, Grenada, Guadeloupe, Guatemala, Haiti, Honduras, Jamaica, Mexico, Montserrat, Nicaragua, Panama, Saint Barthelemy, Saint Kitts and Nevis, Saint Lucia, Saint Martin, Saint Vincent and the Grenadines, Trinidad and Tobago, Turks and Caicos Islands, United States Virgin Islands.

EUROPE: Albania, Croatia, Cyprus, Denmark, Estonia, Finland, France, Germany, Greece, Greenland, Guernsey, Iceland, Ireland, Isle of Man, Italy, Jersey, Lithuania, Malta, Monaco, Montenegro, Netherlands, Norway, Poland, Portugal, Romania, Slovenia, Spain, Sweden, Ukraine, United Kingdom.
AFRICA: Algeria, Angola, Benin, Comoros, Egypt, Eritrea, French Southern and Antarctic Lands, Ghana, Guinea, Guinea-Bissau,



Map produced by Levi Westerveld/GRID-Arendal (2019).
Projection: Goode Homolosine

Kenya, Libya, Madagascar, Mauritania, Mauritius, Mayotte, Morocco, Mozambique, Nigeria, Reunion, Sao Tome and Principe, Senegal, Seychelles, Sierra Leone, Somalia, South Africa, Sudan, Togo, Tunisia, Tanzania.

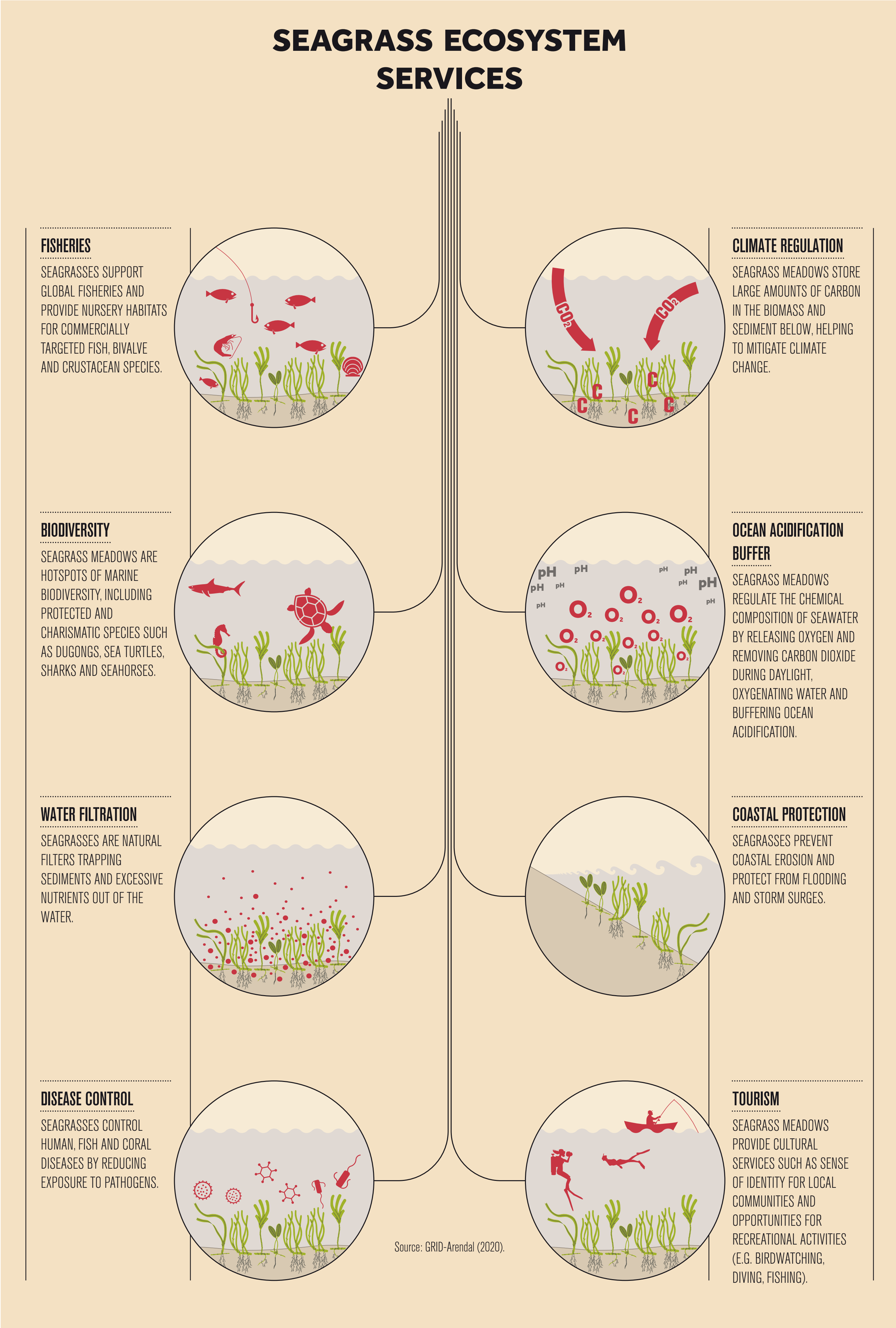
ASIA: Azerbaijan, Bahrain, Bangladesh, Burma, British Indian Ocean Territory, Cambodia, China, Christmas Island, Cocos Islands, Honk Kong, India, Indonesia, Iran, Iraq, Israel, Japan, Jordan, Kazakhstan, Kuwait, Lebanon, Malaysia, Maldives, North Korea, Oman, Palau, Papua New Guinea, Philippines, Qatar, Russia, Saudi Arabia, Singapore, South Korea, Sri Lanka, Syria, Taiwan, Thailand, Turkey, Turkmenistan, United Arab Emirates, Viet Nam, Yemen.

OCEANIA: American Samoa, Australia, Fiji, French Polynesia, Guam, Kiribati, Marshall Islands, Martinique, Micronesia, New Caledonia, New Zealand, Norfolk Island, Northern Mariana Islands, Samoa, Solomon Islands, Timor Leste, Tonga, Vanuatu.

PART 1

SCIENTIFIC EVIDENCE

FIGURE 2



Source: GRID-Arendal (2020).

SEAGRASS ECOSYSTEM SERVICES: ASSESSMENT AND SCALE OF BENEFITS

Carmen B. de los Santos, Abbi Scott, Ariane Arias-Ortiz, Benjamin Jones, Hilary Kennedy, Inés Mazarrasa, Len McKenzie, Lina Mtwana Nordlund, Maricela de la Torre-Castro, Richard K.F. Unsworth, Rohani Ambo-Rappe

All authors' affiliations are found on page 4

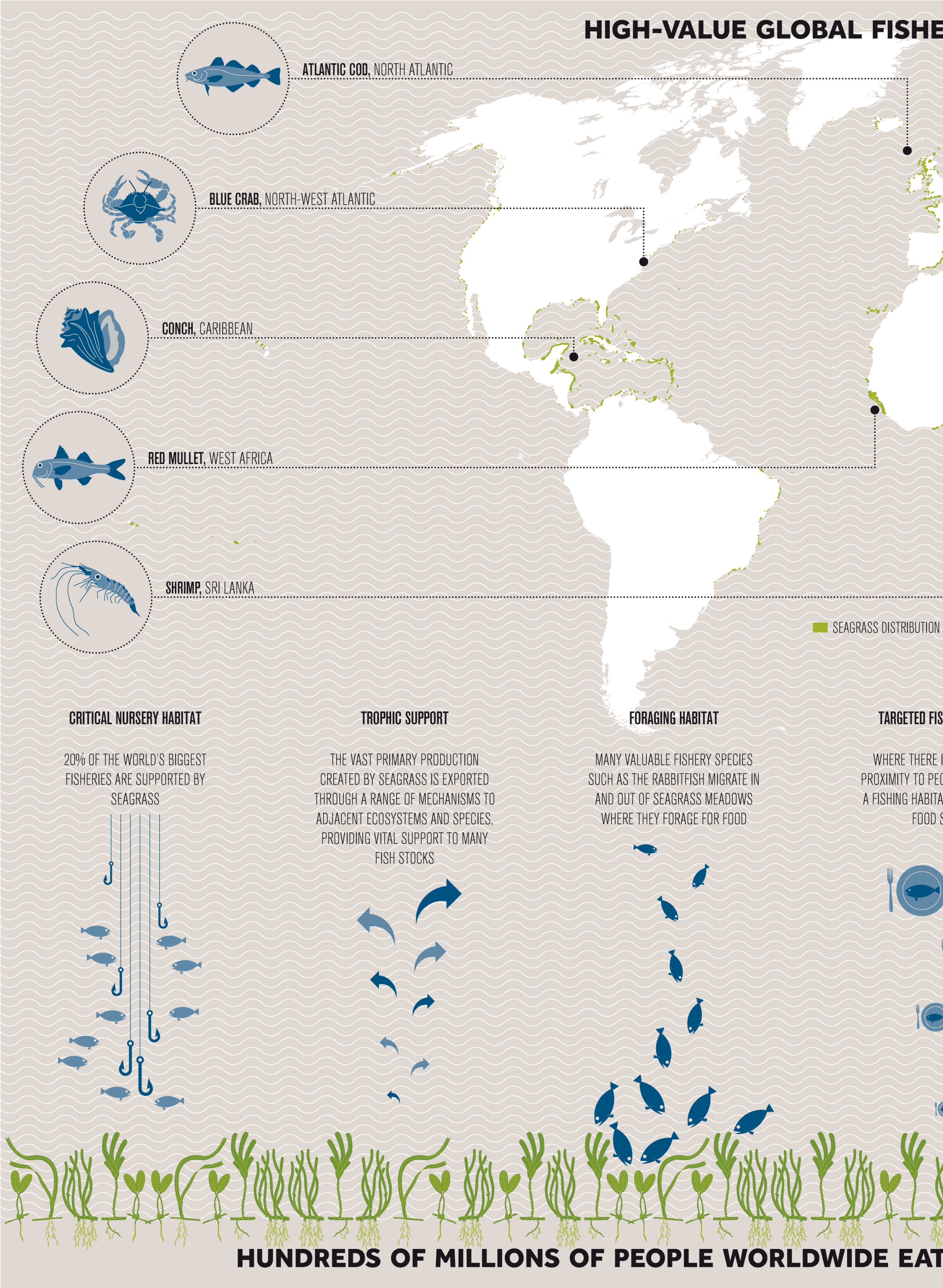
Seagrass ecosystems provide a wide variety of services that support human well-being around the world (Barbier et al. 2011). It is estimated that more than 1 billion people live within 100 km of a coast with seagrass meadows, thus potentially benefiting from their provisioning, regulating and cultural services. Seagrasses play a significant global role in supporting food security, mitigating climate change, enriching biodiversity, purifying water, protecting the coastline and controlling diseases (Figure 2). The integrity and provision of services by seagrass meadows are enhanced by their proximity and connectivity to other coastal ecosystems such as tidal marshes, coral reefs, mangrove and kelp forests, and oyster and mussel beds. The maintenance and regulation of these services is therefore essential to support human well-being and promote development in the future.

Seagrasses support world fisheries production

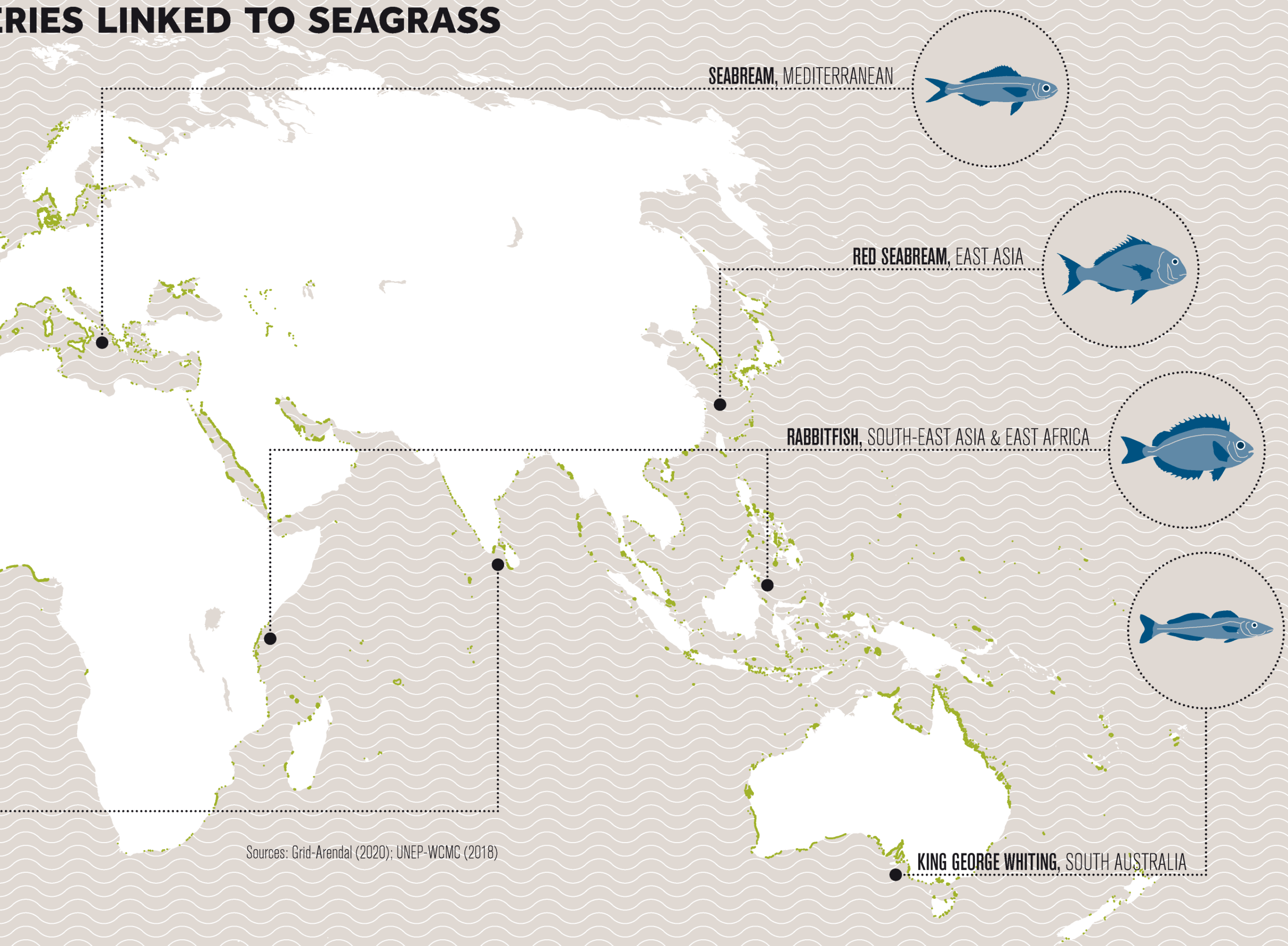
Seagrass meadows are of fundamental importance to world fisheries production of both vertebrates and invertebrates in various ways (Nordlund et al. 2018; Unsworth et al. 2019) (Figure 3). Seagrass meadows provide valuable nursery habitat to over one fifth of the world's largest 25 fisheries, including walleye pollock, the most landed species on the planet (Unsworth et al. 2019). Juveniles of high-value stocks, such the Atlantic cod, have improved growth rate and survival when living in seagrass and intentionally choose this habitat (Lilley and Unsworth 2014). Seagrass fisheries around the world have subsistence, commercial and recreational value, targeting anything that can be eaten, sold or used as bait worldwide. In cases where seagrass meadows are in close proximity to communities, they are often an important fishing habitat for local food supply (Nordlund et al. 2018). Invertebrate gleaning fisheries occurring within seagrass meadows are considered to be an accessible fishing activity mainly due to their shallow nearshore environment and the ease of collecting such fauna (Unsworth et al. 2019). In many parts of the Indo-Pacific region, these gleaning fisheries are vital for maintaining daily protein needs and alleviating poverty (Unsworth et al. 2014). In many cases, the beneficiaries of the fisheries supported by seagrass meadows are not co-located. Seagrasses provide 'extra-local' benefits to people that do not live next to the seagrass meadows or even in coastal areas, such as in the case of Atlantic cod (see case study 1). Seagrasses also have a range of indirect roles in enhancing fisheries, such as providing a trophic subsidy to offshore or deeper water fisheries or filtering terrestrial run-off.

In the context of a changing global environment where many marine habitats such as coral reefs are increasingly becoming degraded, the need for fishers to compensate for this loss of fishing habitat by exploiting different habitats and locations is only likely to increase. As a habitat potentially less vulnerable to climate change, many seagrass meadows are likely to become more highly targeted for their fish assemblages, placing their sustainability in doubt (Unsworth et al. 2019). Although there is widespread recognition that seagrasses support fisheries, there is limited documented examples of the consequences of seagrass loss on associated fisheries. In many areas (for example, the United Kingdom) extensive seagrass loss has occurred outside the realm of recent recorded history, with the loss overshadowed by the wholesale overexploitation of fisheries. This 'shifting baseline' has led to the role of habitat in supporting fisheries being poorly recognized, causing biodiversity and habitat conservation in the coastal seascape to be disconnected from fisheries management (Sundblad et al. 2013). New methods and global databases of habitat trends and use of habitats by fishery species are required to properly attribute causes of decline in fisheries (Brown et al. 2018). It is crucial to look beyond stock production models and consider the role of habitat in fisheries production in order to improve the sustainable exploitation of fish stocks.

FIGURE 3


HIGH-VALUE GLOBAL FISHE
ATLANTIC COD, NORTH ATLANTIC
BLUE CRAB, NORTH-WEST ATLANTIC
CONCH, CARIBBEAN
RED MULLET, WEST AFRICA
SHRIMP, SRI LANKA
SEAGRASS DISTRIBUTION
CRITICAL NURSERY HABITAT
20% OF THE WORLD'S BIGGEST FISHERIES ARE SUPPORTED BY SEAGRASS
TROPHIC SUPPORT
THE VAST PRIMARY PRODUCTION CREATED BY SEAGRASS IS EXPORTED THROUGH A RANGE OF MECHANISMS TO ADJACENT ECOSYSTEMS AND SPECIES, PROVIDING VITAL SUPPORT TO MANY FISH STOCKS
FORAGING HABITAT
MANY VALUABLE FISHERY SPECIES SUCH AS THE RABBITFISH MIGRATE IN AND OUT OF SEAGRASS MEADOWS WHERE THEY FORAGE FOR FOOD
TARGETED FIS
WHERE THERE I
PROXIMITY TO PEO
A FISHING HABITA
FOOD S
HUNDREDS OF MILLIONS OF PEOPLE WORLDWIDE EAT

ERIES LINKED TO SEAGRASS



Sources: Grid-Arendal (2020); UNEP-WCMC (2018)

HING HABITAT

S SEAGRASS IN
OPLE IT IS ALWAYS
T IMPORTANT FOR
SUPPLY

REDUCED PATHOGENS IN FISH STOCKS

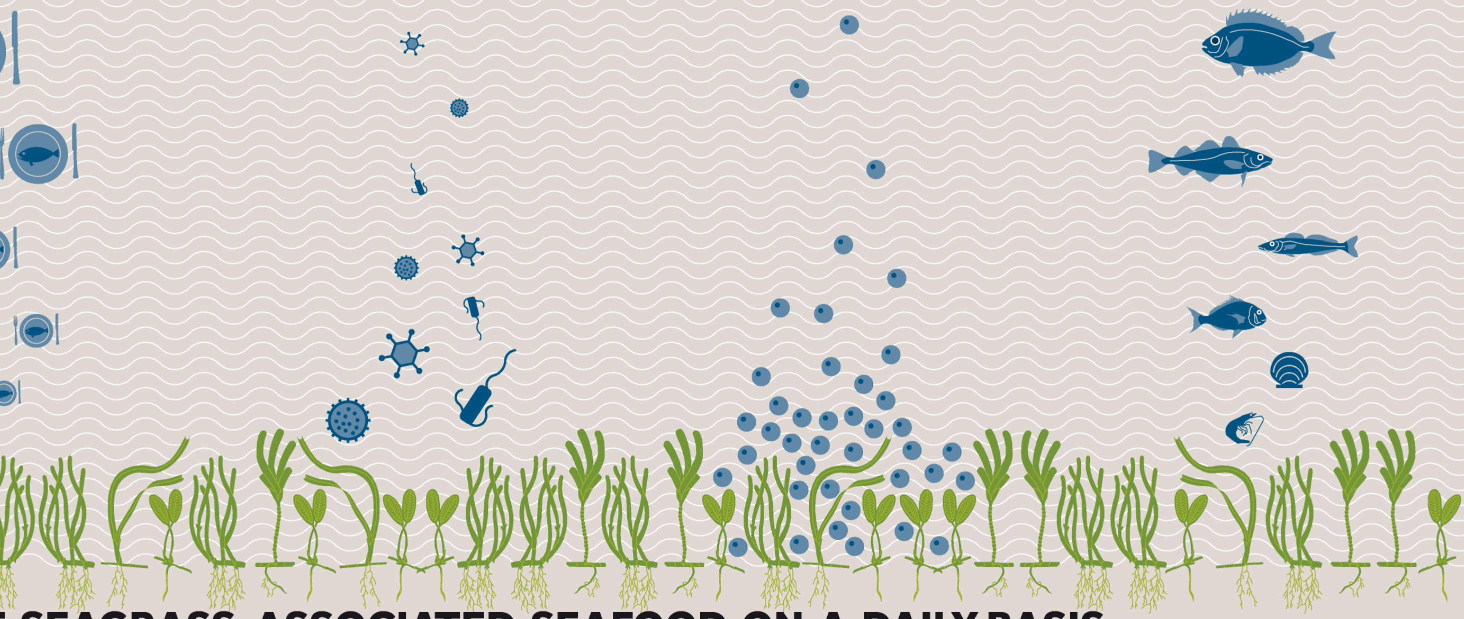
50% REDUCTION IN THE RELATIVE ABUNDANCE OF POTENTIAL BACTERIAL PATHOGENS CAPABLE OF CAUSING DISEASE IN HUMANS AND MARINE ORGANISMS

SPAWNING HABITAT

SEAGRASS MEADOWS PROVIDE AFFABLE ENVIRONMENTS WHERE FISH CAN SPAWN. THE PACIFIC HERRING COMMONLY LAYS EGGS ON SEAGRASS LEAVES

BIODIVERSITY SUPPORT

SEAGRASS MEADOWS SUPPORT AT LEAST 200 SPECIES OF FISH WORLDWIDE, MANY OF WHICH ARE IMPORTANT TO FOOD SUPPLY



T SEAGRASS-ASSOCIATED SEAFOOD ON A DAILY BASIS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CASE STUDY 1

Extra-local benefits of seagrass meadows in supporting fisheries: Atlantic cod fisheries

In the North Atlantic region, Zostera marina meadows are important contributors to stocks of Atlantic cod, one of the world's major commercial species (Lilley and Unsworth, 2014). Juvenile Atlantic cod are normally confined to shallow coastal areas, where seagrass meadows can occur. The juveniles are normally found in high density in locations with seagrasses, where their growth and survival can be enhanced, thereby increasing their chances of reaching the adult stage. Experimental evidence also indicates that these juvenile fish may actively choose seagrass as their habitat. In the North Atlantic, juvenile cod were recorded in shallow nearshore waters along eastern (England, Germany, Norway, Scotland, Sweden and Wales) and western (Canada, Greenland and the United States of America) coasts, as well as in deeper waters of the Grand Banks of Newfoundland. These waters comprise two major fishing areas (FAO 21 and 27), where fleets from local and foreign countries operate. Most of the catch (81 per cent) comes from Iceland, Norway and the Russian Federation, with some minor contributions from Canada, Denmark, the Faroe Islands, France, Germany, Greenland, Poland, Portugal, Spain and the United Kingdom. After the Atlantic cod is shipped and processed (for example, dried and salted), it is distributed to many countries throughout Europe, in particular the Netherlands, Portugal, Sweden and Spain, as well as China, Brazil and Nigeria, among others (Figure 4). This example illustrates how benefits of nature, specifically seagrass, can be distributed beyond the ecosystem location. The habitats that seagrasses provide for juvenile Atlantic cod generates nutritional (food for people) and economic (job creation) benefits. The beneficiaries are not only the people from the countries where seagrasses act as nursery habitat, but also from countries that import part of the Atlantic cod landings, such as the Netherlands, Portugal and Spain. Local management of Zostera marina in shallow coastal areas of the North Atlantic region should be considered not only for the maintenance of the Atlantic cod fisheries, but also for their impacts over the flow of ecosystem services and the extra-local benefits beyond local boundaries.

FIGURE 4

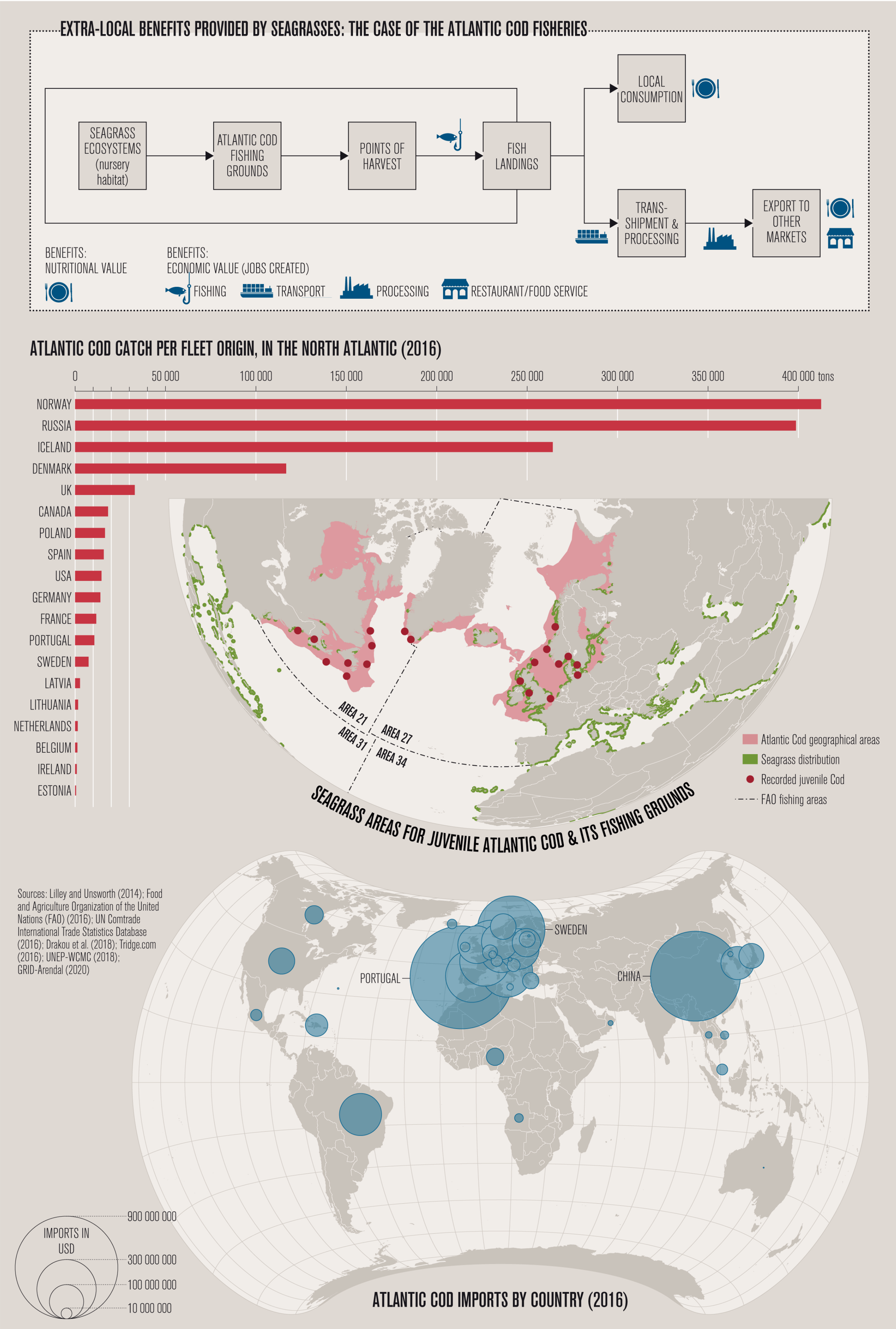
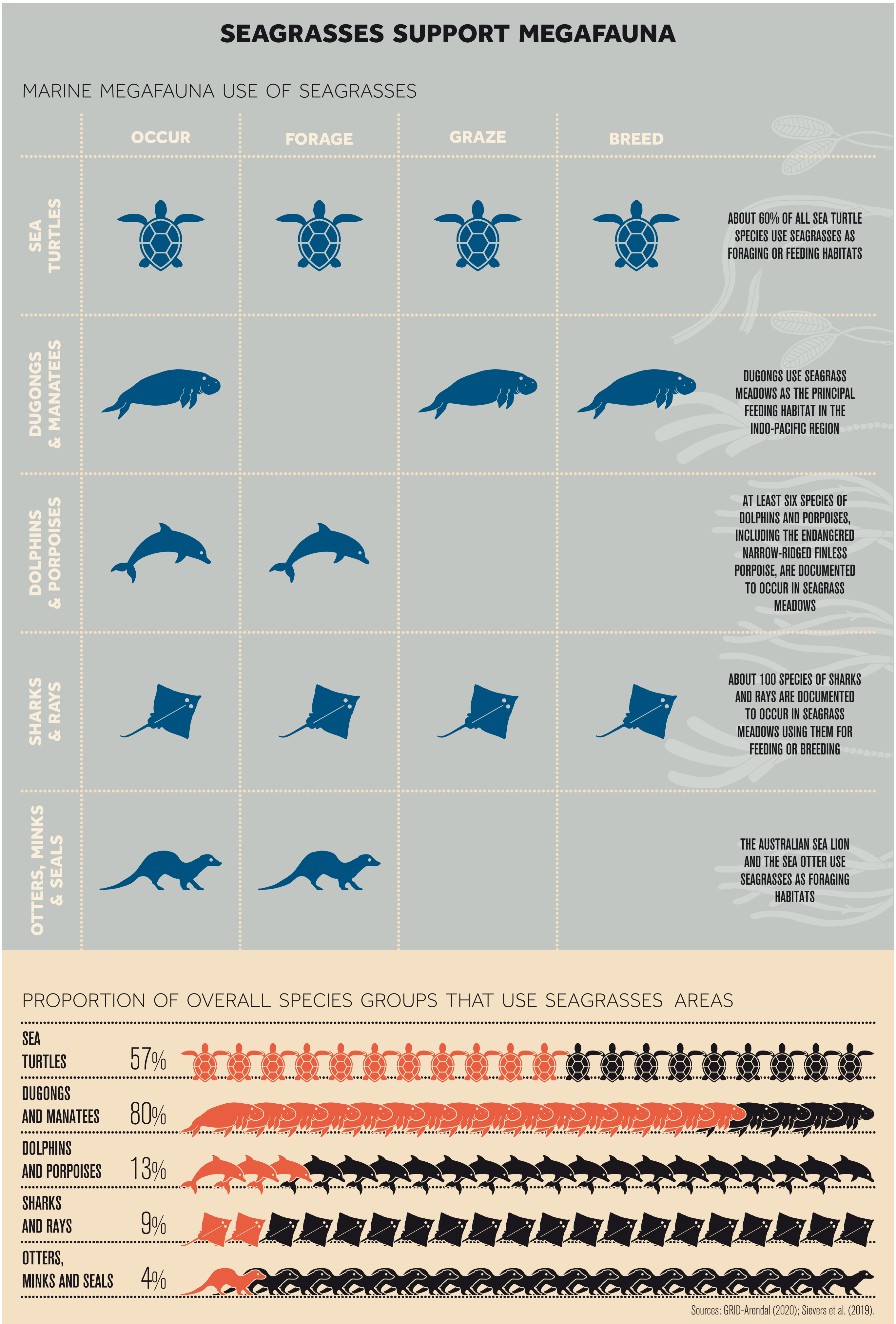

EXTRA-LOCAL BENEFITS PROVIDED BY SEAGRASSES: THE CASE OF THE ATLANTIC COD FISHERIES
SEAGRASS ECOSYSTEMS (nursery habitat)
ATLANTIC COD FISHING GROUNDS
POINTS OF HARVEST
FISH LANDINGS
LOCAL CONSUMPTION
TRANS-SHIPMENT & PROCESSING
EXPORT TO OTHER MARKETS
BENEFITS: NUTRITIONAL VALUE
BENEFITS: ECONOMIC VALUE (JOBS CREATED)
FISHING
TRANSPORT
PROCESSING
RESTAURANT/FOOD SERVICE
ATLANTIC COD CATCH PER FLEET ORIGIN, IN THE NORTH ATLANTIC (2016)
0
50 000
100 000
150 000
200 000
250 000
300 000
350 000
400 000 tons
NORWAY
RUSSIA
ICELAND
DENMARK
UK
CANADA
POLAND
SPAIN
USA
GERMANY
FRANCE
PORTUGAL
SWEDEN
LATVIA
LITHUANIA
NETHERLANDS
BELGIUM
IRELAND
ESTONIA
AREA 21
AREA 27
AREA 31
AREA 34
Atlantic Cod geographical areas
Seagrass distribution
Recorded juvenile Cod
FAO fishing areas
SEAGRASS AREAS FOR JUVENILE ATLANTIC COD & ITS FISHING GROUNDS
Sources: Lilley and Unsworth (2014); Food and Agriculture Organization of the United Nations (FAO) (2016); UN Comtrade International Trade Statistics Database (2016); Drakou et al. (2018); Tridge.com (2016); UNEP-WCMC (2018); GRID-Arendal (2020)
SWEDEN
PORTUGAL
CHINA
IMPORTS IN USD
900 000 000
300 000 000
100 000 000
10 000 000
ATLANTIC COD IMPORTS BY COUNTRY (2016)

FIGURE 5



SEAGRASSES SUPPORT MEGAFAUNA
MARINE MEGAFAUNA USE OF SEAGRASSES
OCCUR
FORAGE
GRAZE
BREED
SEA TURTLES
ABOUT 60% OF ALL SEA TURTLE SPECIES USE SEAGRASSES AS FORAGING OR FEEDING HABITATS
DUGONGS & MANATEES
DUGONGS USE SEAGRASS MEADOWS AS THE PRINCIPAL FEEDING HABITAT IN THE INDO-PACIFIC REGION
DOLPHINS & PORPOISES
AT LEAST SIX SPECIES OF DOLPHINS AND PORPOISES, INCLUDING THE ENDANGERED NARROW-RIDGED FINLESS PORPOISE, ARE DOCUMENTED TO OCCUR IN SEAGRASS MEADOWS
SHARKS & RAYS
ABOUT 100 SPECIES OF SHARKS AND RAYS ARE DOCUMENTED TO OCCUR IN SEAGRASS MEADOWS USING THEM FOR FEEDING OR BREEDING
OTTERS, MINKS & SEALS
THE AUSTRALIAN SEA LION AND THE SEA OTTER USE SEAGRASSES AS FORAGING HABITATS
PROPORTION OF OVERALL SPECIES GROUPS THAT USE SEAGRASSES AREAS
SEA TURTLES 57%
DUGONGS AND MANATEES 80%
DOLPHINS AND PORPOISES 13%
SHARKS AND RAYS 9%
OTTERS, MINKS AND SEALS 4%
Sources: GRID-Arendal (2020); Sievers et al. (2019).

Seagrasses support diverse, unique and threatened marine biodiversity

The provision of shelter, feeding and nursery grounds are critical ecosystem services delivered by seagrasses worldwide, as evidenced by the high diversity and abundance of fauna within seagrass meadows. Many of these animals are of special interest and include threatened, endangered or charismatic species, in particular marine megafauna such as dugongs, sea turtles and sharks (Sievers et al. 2019) (Figure 5). Several marine species that use seagrasses as a nursery habitat are classified as Threatened, Endangered or Critically Endangered by the International Union for Conservation of Nature (IUCN) (Lefcheck et al. 2019), such as the case of the European eel (*Anguilla anguilla*). Dugongs and adult green turtles use seagrass meadows as principal foraging habitat in the Indo-Pacific region, as they eat up to 40 kg and 2 kg of seagrass a day respectively. Feeding on seagrass by these megafauna species is an important process, resulting in significant export of nutrients to nearby ecosystems such as coral reefs, as well as promoting carbon storage in seagrass meadow substrates (Scott et al. 2018). Seahorses spend most of their time attached with their tails to seagrasses where they hunt for food. About 30 per cent of seahorse species, which use seagrass meadows as their main habitat, are included in the IUCN Red List (Hughes et al. 2009). Seahorses are considered a flagship species for the conservation of seagrasses and the associated fauna (Shokri et al. 2008).

Seagrasses purify water from nutrients, particles and contaminants

Seagrasses can improve water quality by filtering, cycling and storing nutrients and pollutants through uptake by their leaves and roots. For instance, seagrasses act as natural biofilters for the ammonium produced by intensive oyster farming (Sandoval-Gil et al. 2016). Seagrasses can also accumulate contaminants such as trace metals, which they can store in the sediment for millennia (for example, *Posidonia oceanica* in the Mediterranean Sea) (Serrano et al. 2011). However, when the concentration of pollutants is very high, this is not only harmful for the seagrass itself, but is also a threat to the seagrass-supported food web due to biomagnification processes. Thanks to their bioaccumulating capacity and sensitivity to environmental changes, seagrasses are used as bioindicators of water quality (Marbà et al. 2013). Their capacity for purifying water could potentially help in managing emerging contaminants, such as microplastics or chemicals that leach from plastics, though research on this topic is still in its infancy.

Seagrasses can control diseases by removing pathogens from the water

Seagrasses can remove microbiological contamination from the water, thus reducing exposure to bacterial pathogens for fish, humans and invertebrates. Seagrasses produce bioactive secondary metabolites with antibacterial and antifungal

activity. Extracts from three tropical seagrass species – *Halophila stipulacea*, *Cymodocea serrulata* and *Halodule pinifolia* – were active against *Staphylococcus aureus*, a bacterium that causes a range of illnesses in humans (Kannan et al. 2010). In small islands in central Indonesia, the levels of potentially pathogenic marine bacteria that cause diseases in humans, fish and invertebrates, can be reduced by 50 per cent if seagrass meadows are present compared with sites without seagrasses (Lamb et al. 2017). Coral reefs also benefit from seagrasses, with coral disease levels halved when seagrasses are adjacent to reefs (Lamb et al. 2017). Seagrass meadows can also control harmful algal blooms through algicidal and growth-inhabiting activities against the microalgae causing the blooms (Inaba et al. 2017).

Seagrasses help mitigate climate change by sequestering and storing carbon

Seagrass meadows are significant carbon sinks at the global scale with high capacity for taking and storing carbon in the sediment, which is also known as 'blue' carbon (Nellemann et al. 2009). Globally, seagrasses are estimated to store as much as 19.9 Pg in organic carbon (Fourqurean et al. 2012). For this service, seagrass ecosystems have great potential in combating climate change, with benefits for the whole planet (case study 2). Carbon is sequestered and stored as seagrass biomass (autochthonous Corg), and through the trapping of organic particles derived from adjacent ecosystems (allochthonous Corg). The anoxic conditions of seagrass sediments enhance the preservation of the sedimentary Corg (below-ground tissue and allochthonous Corg) leading in some cases to the formation of large carbon deposits in the sediment that can remain for millennia, if left undisturbed. The carbon stored in the above-ground living biomass (for example, leaves) is more prone to grazing, export or decomposition, and is considered a short-term carbon sink. Most of the carbon sequestered by seagrass meadows is stored in the sediment. The capacity of seagrasses to sequester carbon varies among seagrass species, meadow characteristics and environmental conditions. In general, the largest organic carbon deposits occur in permanently undisturbed meadows formed by large and persistent species with complex canopies and when located in sheltered, shallow, low-energy environments with low to medium nutrient inputs. Smaller seagrass species located in sheltered bays or lagoons with high mud content can also develop large soil carbon stocks, mainly through the accumulation of organic matter produced in other ecosystems. The loss of seagrass meadows leads to reduced carbon sequestration and storage capacity and to

CASE STUDY 2

Application of the extra-local ecosystem service framework to the climate regulation service of seagrasses in Gazi Bay, Kenya

Although maps of carbon sequestration and storage capacity of seagrasses have increased considerably in recent years, the beneficiaries of this ecosystem service are often not specified or mapped. As a first approach, the beneficiaries of seagrass sequestration and storage of atmospheric carbon are the global population, given that regulating and mitigating climate change provide global benefits. To what extent people benefit from this service will likely vary among countries, with benefits depending on the population's vulnerability to climate change, countries' investment regimes and gross domestic product (GDP).

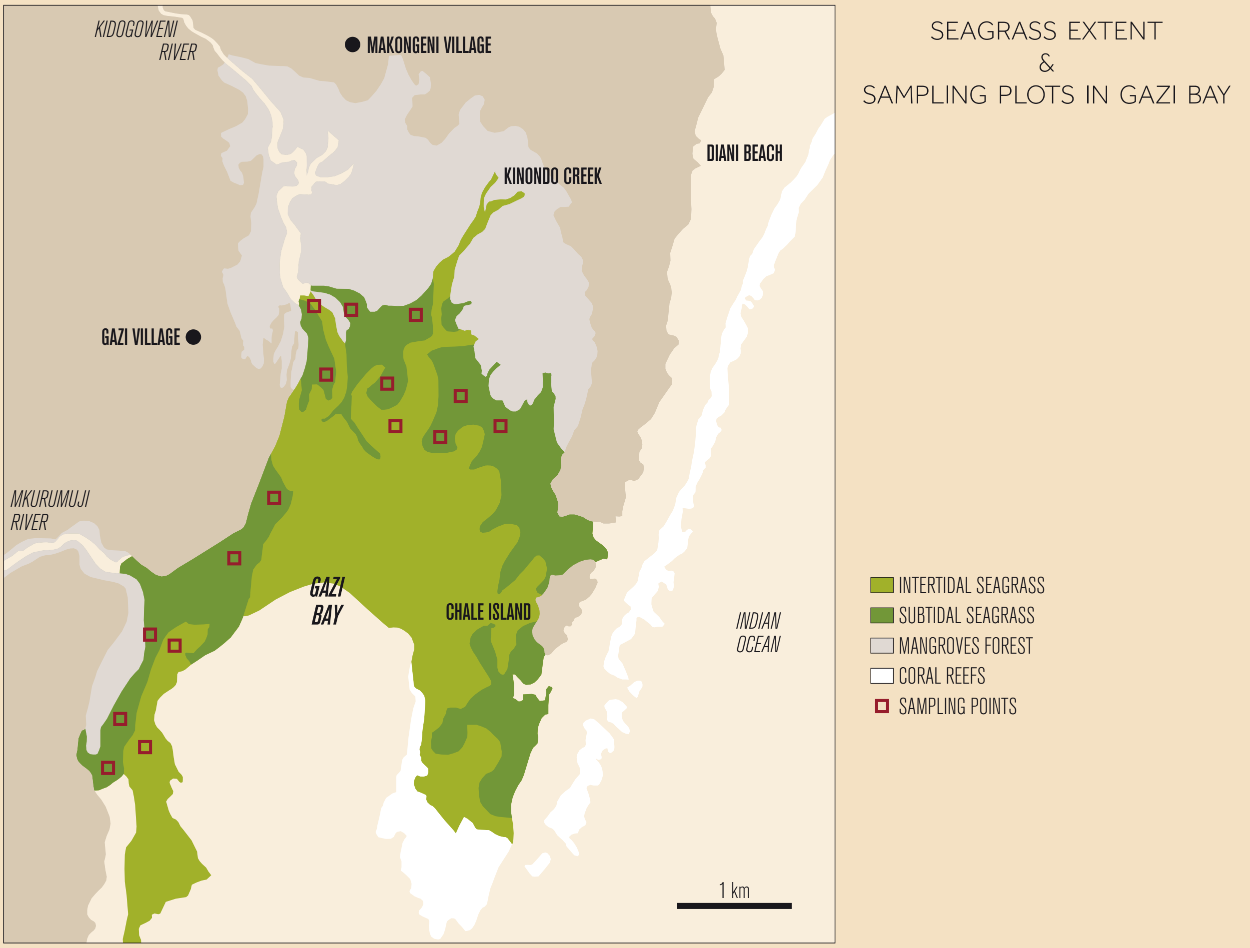
This example illustrates the global benefits of climate regulation provided by tropical seagrasses in Gazi Bay, Kenya. This bay is part of the Diani-Chale Marine National Reserve, located in the southern coast of Kenya. The bay has a mean depth of less than 5 m and a surface area of 17 km^2. Seagrasses are found at the centre of the bay, covering an area of 7 km^2, with *Thalassodendron ciliatum*, *Thalassia hemprichii*, *Enhalus acoroides* and *Syringodium isoetifolium* the dominant species. The total carbon stock of the seagrass meadows in Gazi Bay is around 620,000 Mg, including the living biomass (5.9 Mg C ha^{-1}) and the top 1-m sediment (235.6 Mg C ha^{-1}) (Githaiga et al. 2017).

The beneficiaries of this service provided by seagrasses can be assessed following the extra-local approach (Drakou et al. 2017; Ganguly et al. 2018), based on the social cost of carbon (SCC) for different regions across the world. SCC denotes the value of avoided damages as a result of a unit reduction of CO_2 or its equivalent emissions. Based on the revised DICE-2016R model (Dynamic Integrated model of Climate and the Economy), the monetary value of the total carbon stored in the Gazi Bay seagrass meadows is estimated to be $19 million at a global scale. This value is unevenly shared across the globe as illustrated in Figure 6, with China, Europe and the United States of America as the main beneficiaries. Although this analysis is heavily influenced by regional SCC estimates, the major goal of this approach was to show that while Kenyan seagrass ecosystems may be an important supplier of this service, Kenyan people are not the only beneficiaries. This is an excellent example of how the climate regulation benefits provided by seagrass meadows in a specific part of the world, have extra-local benefits for people in geographically disconnected regions.

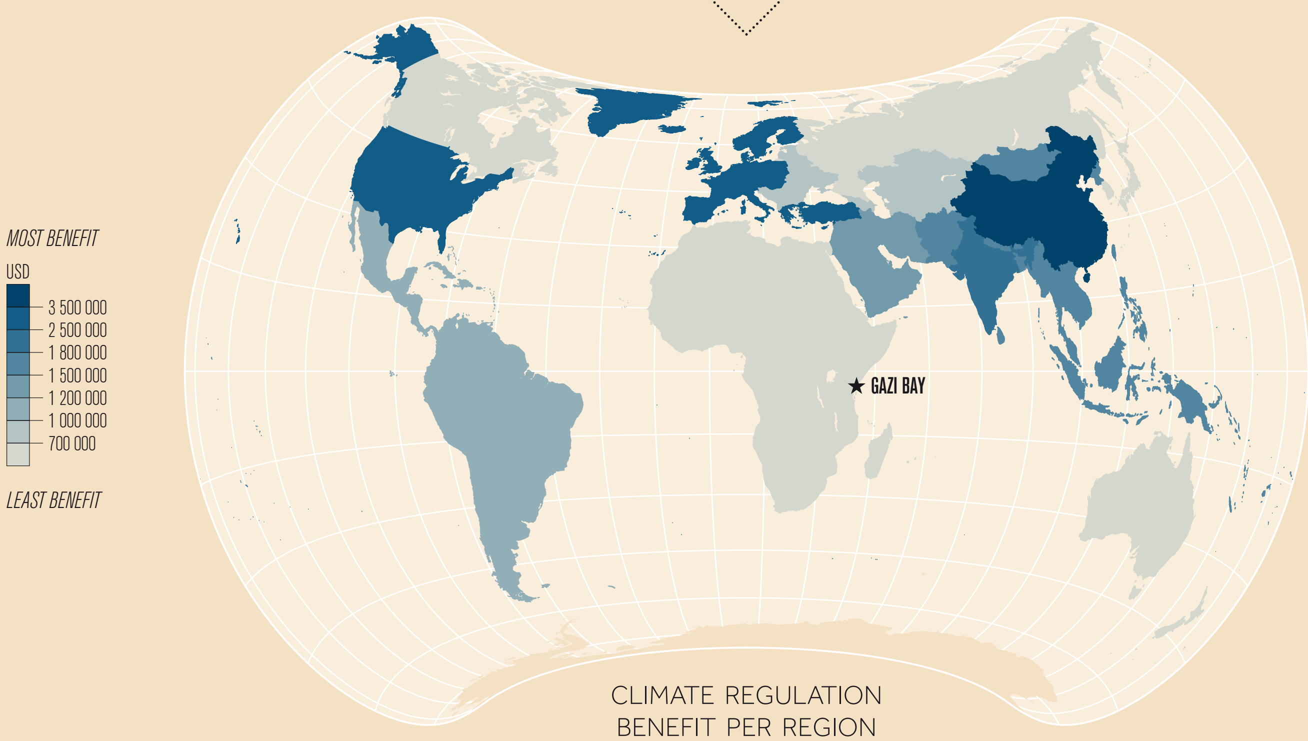
FIGURE 6

THE CLIMATE REGULATION VALUE PROVIDED BY SEAGRASSES IN GAZI BAY, KENYA TO DIFFERENT REGIONS ACROSS THE GLOBE

SEAGRASS EXTENT & SAMPLING PLOTS IN GAZI BAY



CARBON STORAGE × TOTAL SEAGRASS AREA × SOCIAL CARBON COST = CLIMATE REGULATION BENEFIT
(SOIL AND SEAGRASS BIOMASS)



CLIMATE REGULATION BENEFIT PER REGION

Sources: Githaiga et al (2017); GRID-Arendal (2020).

more CO_2 emissions derived from the remineralization of the soil Corg deposits. With present rates of loss, seagrasses are estimated to release up to 299 Tg carbon per year (Fourqurean et al. 2012). Similar to what happens with the degradation of terrestrial carbon sinks, the loss of seagrass ecosystems may significantly contribute to anthropogenic CO_2 emissions and to the acceleration of climate change.

Despite the significant role that seagrass meadows play as carbon sinks and the risk of CO_2 emissions following degradation, they have been traditionally overlooked in greenhouse gas emission accounting inventories, and subsequently in the development of climate change mitigation strategies, all of which tend to focus on terrestrial ecosystems (for example, the United Nations Programme on Reducing Emissions from Deforestation and Forest Degradation in Developing Countries (REDD+)). The publication of two seminal reports by Nellemann et al. (2009) and Laffoley and Grimsditch (2009), pointed to the potential that restoring and conserving seagrass meadows (along with mangroves and saltmarshes) has as a climate change mitigation approach within a novel framework termed blue carbon strategies. Since these reports, significant advances in science and policy have been made towards implementing blue carbon strategies. The development of guidelines by the Intergovernmental Panel on Climate Change (IPCC) supports the reporting of greenhouse gas emissions or sequestration derived from the conversion and restoration of seagrass meadows within countries' national inventories (IPCC 2013). Also, carbon standards have been developed so that restoration projects can benefit from carbon credits (for example, the Verified Carbon Standard) (Needelman et al. 2018). However, there are still some challenges that prevent the widespread implementation of these strategies, such as the lack of Corg sequestration rates and stocks for some regions, the lack of accurate seagrass maps, the spatial variability in greenhouse gas emissions derived from seagrass degradation and the uncertainties related to legal aspects such as land tenure, tidal boundaries or legal responsibilities (Herr et al. 2017; Needelman et al. 2018; Lovelock and Duarte 2019). Although no projects have used seagrass as a tool for emissions reduction to date, the markets and methods are currently being developed and it is likely that they will be tested and applied soon (see chapter on financial incentives).

Seagrasses can mitigate the effect of ocean acidification

The high productivity of seagrasses affects the carbonate chemistry of the surrounding seawater due to the large quantities of dissolved inorganic carbon taken up during photosynthesis. As a result, seagrasses tend to increase seawater pH during the daytime, potentially offsetting the deleterious effects of the increasing anthropogenic CO_2 in the seawater. Marine organisms, particularly calcifying organisms, such as corals (Manzello et al. 2012) and shellfish (Wahl et al. 2017) living within or adjacent to seagrasses, may benefit from this service, since they can find a local refugium from ocean acidification. Although their role in buffering ocean acidification depends on environmental conditions (Koweek et al. 2018), healthy seagrass meadows can contribute to enhancing the resilience of the most vulnerable species to ocean acidification in the short-term (Wahl et al. 2017).

Seagrasses provide coastal protection and contribute to climate change adaptation

Seagrass meadows play an important role in protecting coastal areas from erosion, flooding and storm surges (Duarte et al. 2013; Ondiviela et al. 2014). Their leaves reduce flow velocity and decrease wave energy favouring sedimentation and, along with roots and rhizomes, prevent erosion and stabilize the sediment. In addition, seagrass litter that accumulates on the beach contributes to stable dunes. In the particular case of large seagrass species, such as Posidonia, the thick piles of beach-cast seagrass material, called banquettes, can reach up to 3 m in height, protecting the shoreline from erosion. Seagrass meadows also enhance vertical accretion of sediments and seabed elevation (Potouroglou et al. 2017) through the accumulation of below-ground biomass and particles trapped from the water column. The coastal protection service that seagrass meadows provide is particularly important in the context of climate change, considering that the frequency and strength of waves and storm surges are expected to increase. Seagrass meadows may adapt to sea level rise through soil elevation or inland migration, if they are not hindered by any coastal infrastructure (Duarte et al. 2013). Traditional engineering solutions are based on building so-called 'grey' infrastructures (for examples, dykes, seawalls), though these solutions may involve direct loss of coastal habitats. Such infrastructures also need to be maintained and upgraded to assure their efficiency in future climate change scenarios, making them economically unsustainable (Morris et al. 2018). In contrast, natural barriers from ecosystems such as seagrasses have the capacity of self-repair and adapt to sea level rise while also providing other multiple ecosystem services. In tropical areas, seagrasses together with sediment-producing calcifying algae have been shown to be an effective natural solution for nourishing beaches, offering a self-sustainable alternative to traditional engineering solutions and increasing the resilience of coastal areas to climate change (James et al. 2019). This highlights seagrasses as one of the best ecosystems for eco-engineering, nature-based solutions.

Seagrass meadows provide various cultural services

Seagrass meadows have cultural benefits worldwide, from providing tourism and recreation opportunities to being of spiritual and religious importance. Such cultural services are rarely included in ecosystem accounts at the national, regional or global levels, as their quantification is not as straightforward

as for other services. Language is considered an indicator of cultural diversity and can be used to identify where seagrass is valued culturally. For example, if seagrasses have specific names in a local language, then there is some perceived value of the resources they provide (in other words, people know what they are and value them as specific plants for certain reasons). Numerous languages denote the distinct value of seagrass as a biological entity. This is shown by the specific names given to seagrass in local languages, such as Lamun in Indonesian and Nyasi bahari in Swahili. Some local names also relate to the ecology of such species in providing important services, as in the case of the Monken tribes from the Myeik Archipelago (Myanmar), who refer to seagrass as Leik-Sar-Phat-Myet or 'the food of marine turtles' (Jones et al. 2018), as well as to reproductive ecology, with, for example, Seri in Mexico referring to the month of April as xnoois ihaat iizax or 'the month when the seagrass flowers' (Felger and Moser 1973).

The value of seagrasses for tourism and recreation is often not acknowledged, despite the vast indirect income they provide to such industries. For example, the Quintana Roo region in Mexico is famous for its sport fish populations of tarpon, bonefish, snook and permit, yet much of the recreational fishing activity occurs in the seagrass lagoons of the peninsula. Similarly, many tourists flock to seagrass areas in Akumal in Mexico to swim with green turtles, and to Marsa Alam in Egypt to snorkel and dive with dugongs. In temperate areas, brant geese, as well as numerous other birds, attract birdwatchers to locations with seagrass meadows such as the Solent in the United Kingdom and Puget Sound in the United States of America (Plummer et al. 2013).

In many regions of the world, seagrass meadows also represent a traditional way of life and identity for fishers and communities, as they are directly associated with food and livelihoods, as well as spiritual fulfilment (de la Torre-Castro and Rönnbäck 2004). For instance, in Zanzibar, Tanzania, seagrasses are believed to be sent from God as a decoration of the sea (de la Torre-Castro and Rönnbäck 2004), while in Roviana Lagoon, Solomon Islands, fishers twist seagrass leaves together and shout "Kuli pa Kovi!" (seagrass of Kaovi!) as a call to seagrass spirits to increase their luck (Lauer and Aswani 2010). From a religious perspective, the opercula of molluscs collected in seagrass meadows have been used to produce ceremonial incense. Seagrass deposits play a key role in preserving valuable underwater archaeological and historical heritage across the world, such as Roman and Phoenician shipwrecks, prehistoric settlement sites and submerged ancient cities, and also constitute historical archives of human cultural development over time (Krause-Jensen et al. 2019). Therefore, better understanding and integration of cultural services in this framework will require the use of socioecological tools to link the seagrass structure and functions with the cultural values and benefits.

Seagrass and its direct uses

Seagrass in the fermentation industry

Research in bioethanol production has been on the rise since 2000, with researchers studying freshwater species such as water hyacinth, and marine macroalgae such as Saccharina japonica and Ulva spp. In 2014, scientists from Japan studied the possibility of using Zostera marina seeds to obtain fermented products that contained ethanol at high concentrations (Uchida et al. 2014). They processed eelgrass seeds following a similar method used in the manufacture of Japanese sake or rice wine. This allowed the production of 16.5 per cent ethanol, which is stronger than most wines. As Zostera marina is a widespread plant in the northern hemisphere, it has the potential to be utilized not only for biofuel, but also by food and beverage industries in the future. It could also potentially be harvested as a crop, which would allow for the development of a new marine fermentation industry.

Seagrass as biochar

Seagrass wrack (washed up seagrass on coastal areas) can be beneficial for both terrestrial and marine ecosystems, as well as for humans. Biocharrring is the process of converting biomass through thermochemical processes in an oxygen-limited environment to create a solid material with high carbon content. It has recently gained recognition as a tool to enhance the sequestration of atmospheric carbon, thereby helping to mitigate climate change. Seagrasses were found to have high conversion efficiency, which was comparable to high-quality terrestrial biochar products (Macreadie et al. 2017).

Seagrass in medicine

Despite promising achievements in pharmaceutical biotechnology and the development of new drugs, cancer and infectious diseases are still the main causes of mortality and morbidity in the world. Green synthesis has been introduced as a simple, economically viable and environmentally friendly alternative approach for the synthesis of nanoparticles. In a typical green synthesis, biological compounds (such as plant extracts) act as both a reducing agent and a stabilizing agent, leading to the production of desirable nanoparticles with predefined features. The seagrass Cymodocea serrulata is a valuable bioresource to generate rapid and eco-friendly bioactive nanoparticles for lung cancer therapy (Palaniappan et al. 2015).

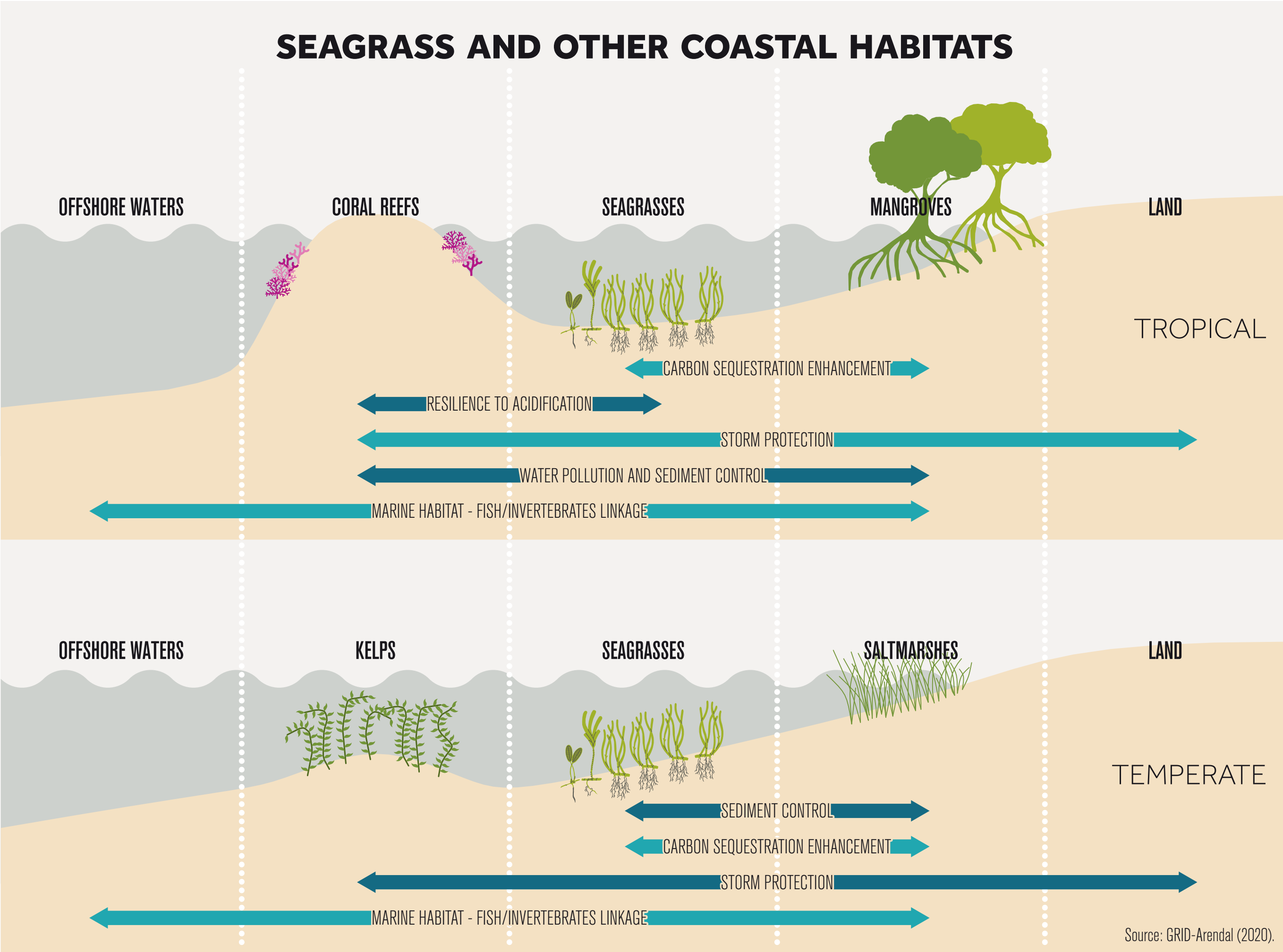
Seascape connectivity and ecosystem services provision

Seagrass ecosystems do not occur in isolation and are instead interconnected across a continuous land–sea interface, known as a seascape. In the tropics, seagrass meadows typically exist in close proximity to mangroves and coral reefs, whereas in temperate locations, seagrasses are often connected to saltmarshes, estuaries, kelp forests or bivalve reefs (Figure 7). The connectivity of ecosystems across the seascape suggests a direct transfer of carbon, nutrients and sediments (Gillis et al. 2013; Huxham et al. 2018), and is also important for the ontogenetic and foraging movements of marine fauna across habitats within seascapes (Campbell et al. 2011). There are several examples of how such interconnected ecosystems enhance the services they provide (Figure 7). In the tropics, seagrasses and coral reefs moderate the impact of waves and storms, enhancing the coastal protection service provided by mangroves (Huxham et al. 2018). In turn, mangroves can buffer seagrass ecosystems from excess nutrient and sediment run-off from land sources (Gillis et al. 2014). The seascape connectivity may be particularly important in the face of climate change, since the association of habitats can improve their resilience and thus maintain the flow of services they provide. For example, the existence of seagrass meadows in shallow tropical marine areas depends on the degree to which coral reefs reduce wave energy, an interdependency that could be altered by sea level rise. Under moderate scenarios of future sea level rise, rates of coral accretion at 3 mm yr^{-1} could buffer the negative effects of deepening water on seagrass habitat suitability until 2050, although this facilitation process will not be supported under severe sea level rise trajectories or for longer periods of time (Saunders et al. 2014). There is still a lack of understanding of how seascape connectivity affects the different services that seagrasses provide. Research is therefore needed to determine which services are most influenced by connectivity and how connectivity influences the way people access and benefit from ecosystem services.

Mapping seagrass ecosystem services

Mapping the services provided by seagrass ecosystems is key to tracking their changes over time and space. In addition, the presentation of the services and their beneficiaries in a spatially explicit way is an effective approach to inform policy- and decision-making processes. Mapping ecosystem services is also one of the steps in ecosystem accounts, which aim to track changes in ecosystem assets and to link this information to economic and other human activities (UNEP-WCMC 2017). Despite advances to assess seagrass ecosystem services and map their extent, there are still many data gaps that hinder the acquisition of comprehensive maps of the services. For instance, seagrass distribution maps are still poorly resolved in many areas, making habitat mapping a key priority for

FIGURE 7



seagrass ecosystem services assessments. In addition, better understanding of the relationships between seagrass extent, status and service provision, as well as defined indicators of the services and their benefits, are key to mapping ecosystem services at different temporal and spatial scales.

Degradation and loss of seagrass ecosystem services

Ecosystem services that support human well-being have been degraded as a consequence of human activities, especially during the past half century when changes have occurred more rapidly and extensively than in previous times. Seagrass ecosystems are being subjected to impacts from coastal development and water pollution, as well as other coastal uses that can cause their decline or degradation. As a consequence, the ecological functions that seagrasses provide can be impaired, thereby affecting their services and benefits, which will eventually lead to negative economic and social repercussions. Losses in seagrass ecosystem services are reported in many locations around the globe. These losses are resulting in declines of seagrass-associated animals, such as dugongs, seahorses and commercially-targeted species (Scott et al. 2018; Sievers et al. 2019). The loss of seagrass capacity to sequester and store carbon is also of high concern, since seagrass loss eventually leads to significant emissions of CO2 into the atmosphere (Arias-Ortiz et al. 2018). For instance, Shark Bay (Australia), one of the largest seagrass meadows in the world, was damaged following a marine heatwave in 2010/2011, causing an estimated 2–9 million tons of CO2 to be released into the atmosphere and leading to the decline of seagrass-associated species, many of them of conservation concern or commercially targeted (see case study 4 and chapter on threats and resilience). In Chesapeake Bay in the United States of America, a decline of 29 per cent in the eelgrass area between 1991 and 2006 resulted in severe ecological and economic consequences. The estimated loss of 693,000–1,859,000 tons of carbon after the seagrass decline implied an economic loss of $96.5–259 million. The seagrass loss also led to an estimated loss of 523–1,403 million juvenile blue crabs and 47,800–80,200 tons of silver perch, which represents, in economical values, 1–2 and 10–20 years of their fisheries respectively (Lefcheck et al. 2017).

Restoring seagrass ecosystem services

Restoration of degraded seagrass ecosystems, whether by planting or natural recolonization, can be effective in reversing biodiversity loss and recovering ecosystem services. For instance, seagrass-associated faunal communities can recover following natural meadow recolonization, as observed in a *Zostera muelleri* meadow in a New Zealand urban estuary (Lundquist et al. 2018). Over a 15-year period, the benthic macrofaunal diversity and abundance had increased, which also enhanced

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the nutrient and carbon cycling. Other long-term studies have also shown the effectiveness of seagrass restoration in the re-establishment of seagrass services; for example, the successful restoration projects in Oyster Harbour, Western Australia (case study 3), and in the Coastal Bays of Virginia, United States of America. In the latter, re-seeding of Zostera marina led to a distinct change in nitrogen removal and carbon storage (Reynolds et al. 2016). The restored meadow removed 4,100 tons of nitrogen through plant uptake and sediment storage, and had carbon stocks and carbon accumulation rates similar to those of natural meadows, with an estimated 15,000 tons of carbon being sequestered. The recovery of these services was estimated as having an economic value of $8 million per year. These high economic and environmental benefits of the restored services highlight the importance and necessity to invest in resources to restore seagrass. Even more valuable is the facilitation of natural restoration by controlling water quality through nutrient pollution, which has, for example, successfully

Assessing seagrass ecosystem services: quantification and mapping

Assessing ecosystem services requires the use of indicators in relation to the capacity, the flow or the benefits of the service in question (Liquete et al. 2013). For example, studies assessing the seagrass service of fisheries support normally use the fish biomass of commercially targeted species associated to seagrass meadows along with indicators of flow, such as annual fish catch, and indicators of benefits, such as the fish market price. This approach yields estimations of the annual revenues of the fish catch associated to seagrasses. In the case of the Cymodocea nodosa seagrass meadows in Gran Canaria (Tuya et al. 2014), the fisheries support service was estimated at 895 kg ha^{-1} of commercially-targeted fish based on fish visual census. This service was translated into economic benefits of 866 € ha^{-1}, or ca. 600,000 € yr^{-1} when accounting for the total seagrass area extent in the island. Another approach to assess the fisheries support service is the use of the seagrass residency index for economically important species to estimate the proportion of commercial fishery landing values and recreation fisheries total expenditure that can be attributed to seagrass. Using this approach, it has been estimated that the Mediterranean seagrass Posidonia oceanica has a direct annual contribution of 4 per cent to the total value of landings of commercial fisheries and 6 per cent to the total expenditure of recreational fisheries, despite covering < 2 per cent of the marine area (Jackson et al. 2015). Seagrass fisheries support assessments normally lack the spatial or temporal component, which are essential to improve understanding of the dynamics of the ecosystem services provision and demand, as well as to inform managers and policymakers. Assessments of other ecosystem services provided by seagrasses, such as water purification or coastal protection, rarely include indicators of the benefits. Quantification of the water purification service provided by seagrasses normally includes indicators of the flow, such as the nitrogen removal rate or uptake rate (Asmala et al. 2019), but rarely indicators of the benefits or the associated value. Mapping ecosystem services requires data with a degree of detail that vary with the selection of the spatial scale, from local to global, and the purpose of the maps (Burkhard and Maes 2017). Basic data requirements include the ecosystem extent and condition, and more advanced maps in order to visualize the associated service flow in biophysical units, and the benefits and values in socio-economic units. Local assessments normally require high-resolution extent maps and a deep understanding of the ecological processes underlying the service provision, which may involve costly in situ measurements of the service indicators. On the other hand, global assessments may use lower resolution maps and scaling-up estimations from local or regional quantification of the service. The lack of the required data fitting the desired scale is one of the identified constraints to map seagrass ecosystem services. Some countries and regions are more data-rich, which allows a robust assessment of seagrass ecosystem services. Such is the case of the recent assessment of Australia's blue carbon resources (Serrano et al. 2019), which includes scientific data from 637 seagrass meadows on soil and biomass carbon stocks and sequestration rates, compiled by over 40 researchers. This is an example on how data sharing can open the way towards more comprehensive maps of seagrass services at national or regional levels. In data-poor areas, mapping seagrass habitats should be the priority, so services could be roughly mapped and estimated using ranges of ecologically meaningful indicators from available data for services assessed in similar locations.

Loss and recovery of seagrass carbon sinks following meadow degradation and restoration – Oyster Harbour, Western Australia

An example of a loss and subsequent successful seagrass restoration was documented in Oyster Harbour, a marine inlet on the south coast of Western Australia. The inlet was colonized by lush seagrass meadows until the early 1960s. Eutrophication and siltation events, due to extensive land clearing for agriculture and fertiliser use, caused around 80 per cent of seagrass cover to be lost in the early 1980s. A successful restoration project was initiated in November 1994 and finished in January 2006, which encompassed five planting events of the seagrass *Posidonia australis*, making it the longest seagrass restoration project ever monitored. Twenty-five years after the first tentative pilot restoration trial in 1994, widescale recovery is apparent (see image), thanks to the initial planting efforts and continuous management of the catchment area and water quality monitoring, as well as the low precipitation rates. The long-term monitoring of seagrass recovery has enabled organic carbon (C_{org}) sequestration and storage capacity developments to be studied since restoration. The loss of seagrass canopy had diminished the meadow's capacity to sequester carbon and triggered the erosion of historic carbon deposits accumulated prior to the seagrass loss. Restored meadows showed almost fourfold higher soil C_{org} stocks than bare sediments and reached similar C_{org} burial rates as intact meadows by 18 years after planting. This example shows that seagrass restoration can provide opportunities to enhance CO_2 sequestration and avoid CO_2 emissions, while recovering several additional ecosystem services.

Oyster Harbour: Seagrass Restoration Network project

Aerial images of *Posidonia* seagrass transplant plots in Oyster Harbour, Albany, Australia.

Sources: Aerial photographs showing details of the *Posidonia* seagrass transplant plots in Oyster Harbour, Albany, after 3.6 years growth (October 2001) showing progress over a decade (January 2010) where separated plants in each plot had grown together to form a continuous dense meadow. (Photos: Geoff Bastyan).

restored extensive areas of previously degraded seagrass in Chesapeake Bay (Lefcheck et al. 2017) and Tampa Bay, United States of America (Greening et al. 2011).

Research needs in seagrass ecosystem services

To advance the current knowledge on seagrass ecosystem services, three broad themes have been identified: 1) investigate variability of ecosystem services taking into account the distribution of different seagrass species, meadow characteristics and environmental conditions; 2) investigate seagrass ecosystem services within the seascape by comparing service provision among the different coastal and marine habitats and investigate the effects of connectivity, juxtaposition of habitats, configuration of habitat patches and seascape dynamics; and 3) improve communication of seagrass ecosystem services to the public by analysing which messages are most effective to communicate, how to reach broader levels of society, and the mechanisms by which to communicate (Nordlund et al. 2017). Seagrass ecosystem services are most important to local people in lower economic areas of the developing world, which are also often the areas that are poorly mapped and studied. Research on the characteristics of seagrass ecosystems and the services they provide should be expanded into currently underrepresented geographical areas, such as the coasts of South America, South-East Asia and West Africa. Cultural services should receive more attention so that they are understood to the same extent as provisioning and regulating services. Finally, seagrass ecosystem services need to be investigated as part of social-ecological systems, highlighting how services translate into benefits for people by using not only biophysical units, but also social and economic indicators relevant for policy and management actors.

THREATS TO SEAGRASSES AND ECOSYSTEM RESILIENCE

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Rohani Ambo-Rappe, Salomão Bandeira, Wawan Kiswara

All authors' affiliations are found on page 4

Seagrasses are a key marine habitat that has been globally declining since the 1930s (Orth et al. 2006), with the most recent census estimating that 7 per cent of seagrass is being lost worldwide per year, which is equivalent to a football field of seagrass every 30 minutes (Waycott et al. 2009). Seagrass meadows are threatened by natural and anthropogenic stressors attributed to a variety of physical factors (for example, increased temperatures, salinity changes, hypoxia, extreme weather events, sedimentation and altered wave and current dynamics) and biological factors (for example, invasive species, algal blooms, eutrophication, altered grazing patterns, competition and disease) (Short and Wyllie-Echeverria 1996). These impacts are magnified throughout the ecosystem because seagrasses engineer their environment and provide a foundation for entire communities. Global losses of seagrass cover have major implications for humans due to the numerous ecosystem services they provide.

Seagrasses are flowering plants that produce seeds, which also grow through substrate by extension of their underground rhizomes and production of new leaves as bundles called shoots. Several biophysical parameters determine whether seagrass can grow and reproduce, including temperature, salinity, hydrodynamics, depth, substrate and light availability (Unsworth et al. 2011). The specific levels of each need vary among the 72 different seagrass species occurring globally (Erftemeijer and Robin Lewis III 2006). These needs can be grouped into three classes:

1. habitat suitability – depth, sediment substrate, temperature and water movement
2. water quality – adequate light for photosynthesis, salinity, absence of toxicants
3. grazing and recruitment processes – suitable assemblages of grazing animals, water movement to transport seeds and vegetation fragments.

Evaluating the threats to and resilience of seagrass is critical in order to identify management strategies. The highest impact threats to seagrass are urban/industrial run-off, urban/port infrastructure development, agricultural run-off and dredging (Grech et al. 2012). The greatest climate-related threat is perceived to be from increased frequency and intensity of tropical storms, with more uncertainty about the impact of increasing temperatures and sea level rise. For example, turbulent seas during cyclones can directly uproot seagrass plants, while extreme rainfall events associated with cyclones can increase contaminant loads, resulting in poor water clarity and light availability. Fishing activities, anchoring, trampling and dredging (Erftemeijer and Robin Lewis III 2006) also pose major threats to seagrass.

Though not always considered, it is essential to understand and acknowledge the different spatial and temporal scales and intensities of threats. The impacts of multiple activities occurring together can interact, increasing or decreasing the effects of individual activities (Grech et al. 2011). At this stage, there is little quantitative understanding of these interactions and management plans do not account for them (Griffiths et al. 2019). The sensitivity of seagrasses to some threats can vary seasonally, meaning the timing of threatening activities can be critical. For example, many species are most at risk during their growing and reproductive phases. During these phases, threats that affect the production of a seedbank within a single year can be catastrophic for future generations (van Katwijk et al. 2010). Slow-growing perennial seagrasses are able to resist threats for longer periods, but this slower growth strategy also means that loss can take decades to repair, even for relatively small-scale impacts, such as seismic surveys, which can cause patches in an otherwise continuous *Posidonia australis* meadows (Meehan and West 2017). Beyond seasonal effects, the frequency of threats can also be problematic, especially if threatening processes recur faster than seagrass is able to recover (O'Brien et al. 2017; Wu et al. 2017). Threats can be land-based, sea-based or climate-related (Figure 8), all of which can affect seagrasses either directly or indirectly.

Land-based threats

Seagrasses are predominantly found in shallow coastal waters (although there are some exceptions) (Coles et al. 2009) and are therefore in proximity to areas most heavily used by humans. Several widespread threats originate from land-based sources, such as run-off from agricultural, urban and industrial regions that carries contaminants, including excessive sediments, nutrients, pulses of reduced salinity and toxicants (for example, herbicides) into seagrass habitats (Grech et al. 2012). Land-based run-off can also indirectly impact seagrass meadows by affecting multiple core habitat needs through a process known as eutrophication, which is a state of excessive plant and algal growth caused by nutrients (predominantly nitrogen and phosphorus) in the water (Burkholder et al. 2007). The threat from pollutants is particularly high in regions with high levels of agricultural activity or urban development (Bainbridge et al. 2018). With rivers capable of transporting contaminants for hundreds, even thousands, of kilometres, and sediments capable of storing contaminants for long periods, the effects can be far-reaching and long-standing (Thangaradjou et al. 2014). These threats can be recurring due to resuspension of sediments through wave energy, driven by wind or boats, which can reduce light penetration and release stored contaminants or nutrients (Bainbridge et al. 2018). Seasonal remineralization of organic matter can also release nutrients from sediment storage and prolong the impacts of nutrient loads (van Katwijk et al. 2010). Quantitatively establishing the relative influence of land-based threats requires local data or modelling that can account for locally-specific loads, hydrodynamics and biological processes (Serrano et al. 2016). For example, in one estuary in California, hydrodynamic changes related to sedimentation appear to be responsible for estuary-wide eelgrass loss (90 per cent loss) due to warmer, more saline, less oxygenated and more turbid waters (Walter et al. 2018).

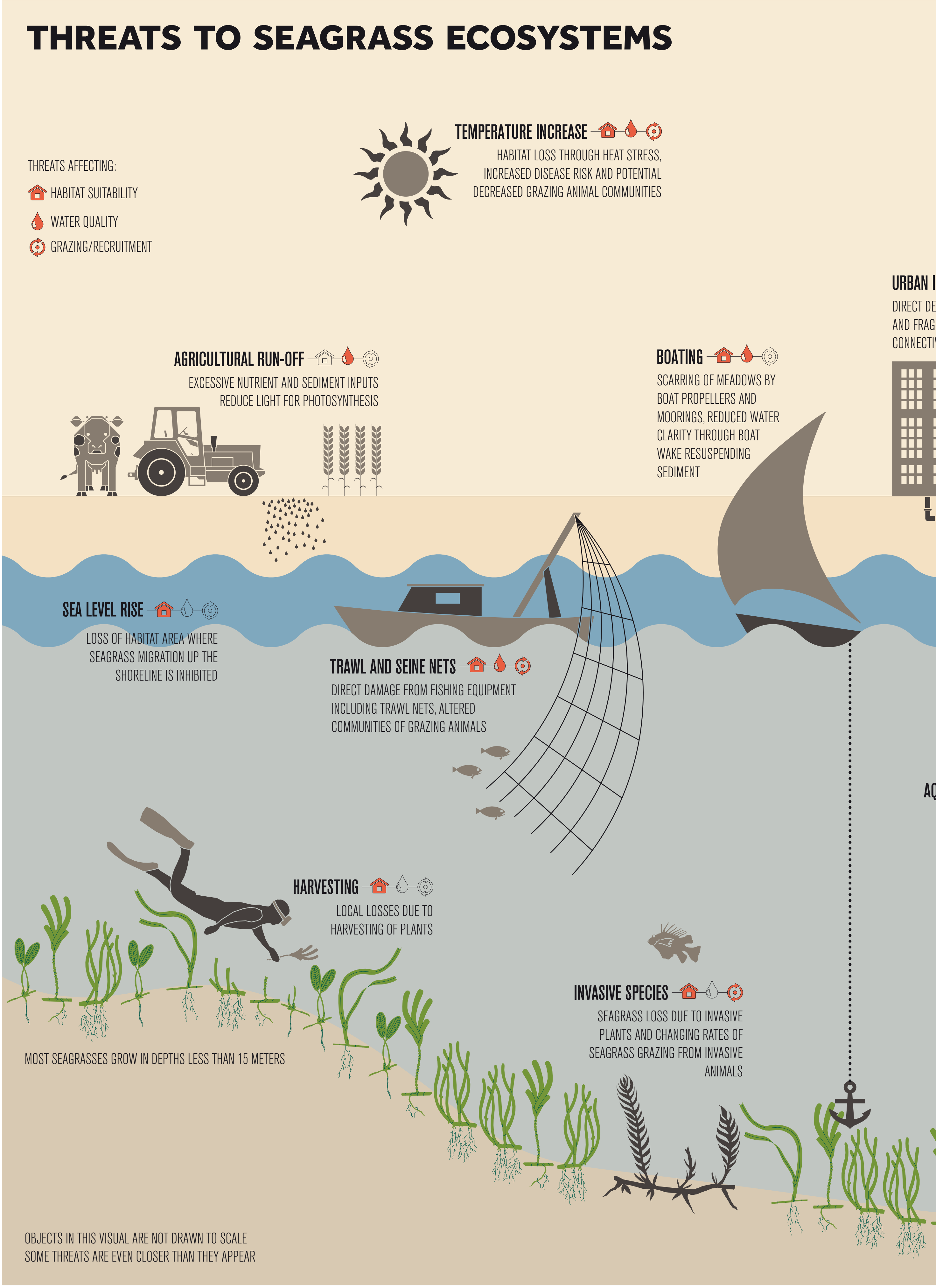
Coastal development is another land-based threat that can directly or indirectly minimize suitable habitat area for seagrasses (Yaakub et al. 2014). Land reclamation allows urban structures to be built on top of (former) seagrass habitat, permanently and irreversibly removing seagrasses or shading them from light (Yaakub et al. 2014). Nearshore developments can also shade seagrass habitat or create a phenomenon called 'coastal squeeze' which interacts with sea level rise to reduce the habitat available to seagrasses and other coastal wetlands (saltmarshes and mangroves). Coastal developments reduce or convert (for example, into rock walls) the space available for these habitat types to move into, resulting in overall losses of all three habitats as sea levels increase (Holon et al. 2015). Sea level rise is addressed in more detail in the section on climate-related threats.

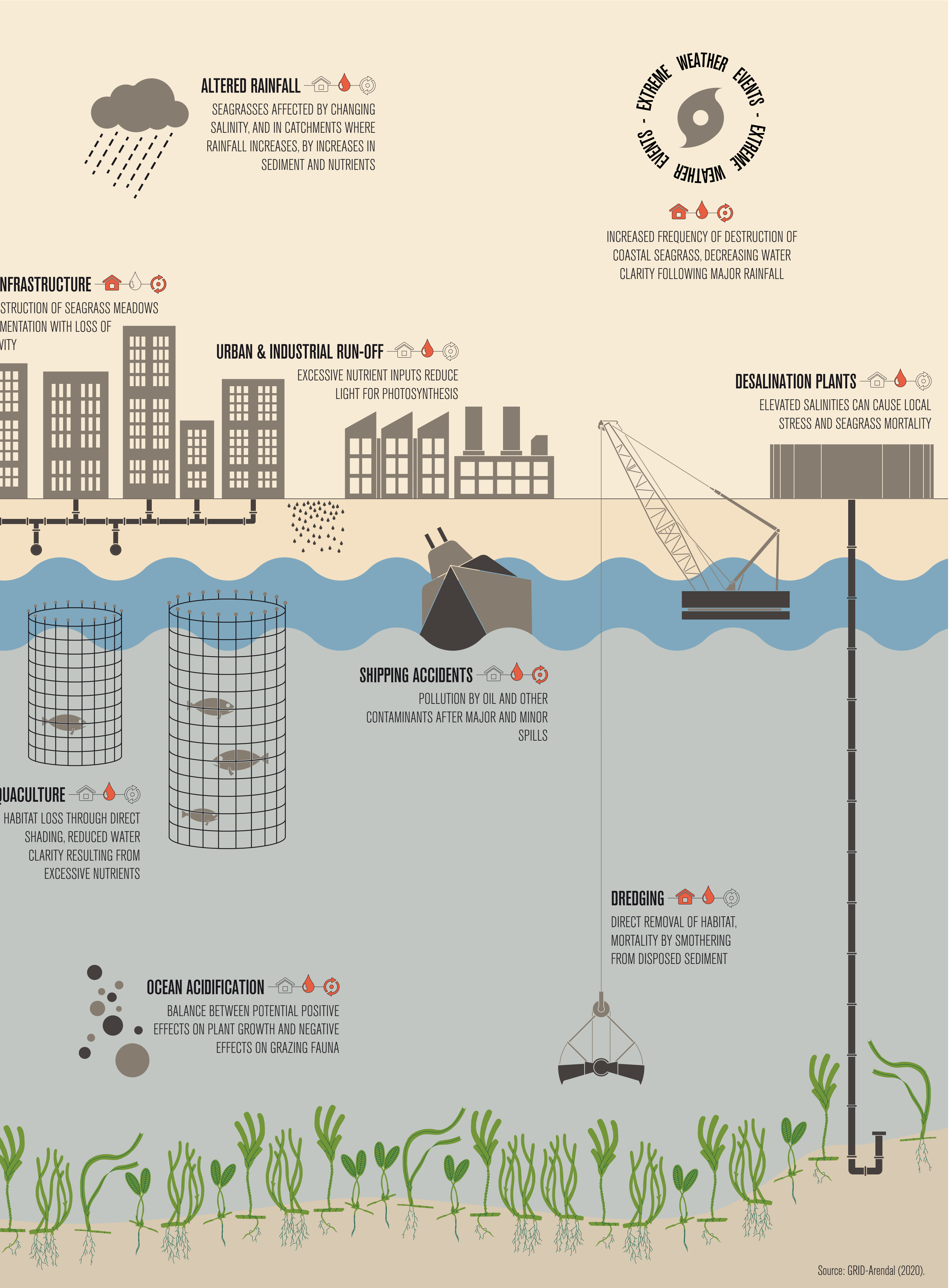
Sea-based threats

There are also many threats from activities occurring in estuaries and seas where seagrass grows. The shallow coastal areas that seagrasses typically occupy can attract a high density of industrial and recreational activity, bringing several potential threats that range from direct physical damage or removal to long-term degradation. Direct physical damage to seagrasses can occur from dredging, boating (from propellers and moorings) and shipping accidents, fishing (especially trawling), harvesting, aquaculture and invasive species (especially grazing animals) (Grech et al. 2012). As an example, along the coast of Kenya, seagrass has been impacted by the extensive use of beach seine nets in artisanal fisheries. In one example, seagrass density in fished areas was half that in a nearby protected section of a marine park. Once seine netting ceased, the seagrass recovered to densities similar to that in the park within 18 months (see www.smartseas.org).

Beyond direct physical removal, dumping of dredge spoil can also smother seagrass, while resuspension of fine sediments can affect seagrasses tens of kilometres from the dredge site (Lavery et al. 2009). Resuspension of sediments can cause persistent or recurrent stress in much the same way as land-based threats by releasing sediments and contaminants (Erftemeijer et al. 2006). However, in some areas, management protocols (including mitigation measures and enforcement) and new dredging techniques help minimize the impacts of dredging on seagrass habitat (Erftemeijer et al. 2006). Aquaculture structures can physically displace and shade seagrasses directly but can also cause widespread indirect shading and stress due to increased turbidity, nutrients and contaminants or the introduction of exotic species and pathogens. Boating, fishing and trawling often have acute, localized effects related to direct removal of seagrasses if not effectively regulated (Orth et al. 2002). Boating and fishing also have indirect effects, such as long-term damage caused by oil spills originating from refuelling mishaps and accidents. Boating activity also creates wave energy, which can re-suspend sediments and reduce light penetration. Fishing can alter the composition of animal species associated with seagrasses and also has the potential to alter grazing regimes (for example, if predators are removed then prey species can thrive). This can directly result in reduced seagrass biomass through consumption by grazers, changes in the facilitation of seagrass reproductive processes (such as seed dispersal), or trophic cascades that cause algal overgrowth. In general, although sea-based activities are conspicuous and often noticed by the community, when scale and frequency are taken into account, they typically rank a lower threat to seagrass than the more diffuse land-based threats (Grech et al. 2012).

FIGURE 8


THREATS TO SEAGRASS ECOSYSTEMS
THREATS AFFECTING:
HABITAT SUITABILITY
WATER QUALITY
GRAZING/RECRUITMENT
TEMPERATURE INCREASE
HABITAT LOSS THROUGH HEAT STRESS, INCREASED DISEASE RISK AND POTENTIAL DECREASED GRAZING ANIMAL COMMUNITIES
AGRICULTURAL RUN-OFF
EXCESSIVE NUTRIENT AND SEDIMENT INPUTS REDUCE LIGHT FOR PHOTOSYNTHESIS
BOATING
SCARRING OF MEADOWS BY BOAT PROPELLERS AND MOORINGS, REDUCED WATER CLARITY THROUGH BOAT WAKE RESUSPENDING SEDIMENT
SEA LEVEL RISE
LOSS OF HABITAT AREA WHERE SEAGRASS MIGRATION UP THE SHORELINE IS INHIBITED
TRAWL AND SEINE NETS
DIRECT DAMAGE FROM FISHING EQUIPMENT INCLUDING TRAWL NETS, ALTERED COMMUNITIES OF GRAZING ANIMALS
HARVESTING
LOCAL LOSSES DUE TO HARVESTING OF PLANTS
INVASIVE SPECIES
SEAGRASS LOSS DUE TO INVASIVE PLANTS AND CHANGING RATES OF SEAGRASS GRAZING FROM INVASIVE ANIMALS
MOST SEAGRASSES GROW IN DEPTHS LESS THAN 15 METERS
OBJECTS IN THIS VISUAL ARE NOT DRAWN TO SCALE
SOME THREATS ARE EVEN CLOSER THAN THEY APPEAR



Source: GRID-Arendal (2020).

Climate-related threats

The threats associated with climate change cover a very broad spatial area (global) and impact via both terrestrial and marine avenues. Such threats include rising sea and air temperatures, sea level rise, ocean acidification, altered rainfall patterns and increased frequency and intensity of extreme weather events. Each of these has the potential to dramatically reduce seagrass extent over short and long timescales.

At present, the accuracy of predictions about the likely effects of climate change on seagrass is limited due to challenges in downsizing global climate models to a scale that is appropriate for seagrass biology (Hobday and Lough 2011) and also because there is a lack of studies testing the interactive effects of climate change and addressing long-term responses, variation among and within species, local acclimation and potential for adaptation (Duarte et al. 2018). Predictions of future change are still based on expert opinion and semi-quantitative assessments, such as relative risk, for example (Aumen et al. 2015).

Future increases in water temperature will lead to changes in community composition and ecosystem services because of differences in the optimum temperature for growth of each species relative to local conditions. Some species have broad tolerance to fluctuations in water temperature, while others appear to have limited capacity for acclimation to changing temperature (Collier et al. 2017), leading to mortality during prolonged warming events (Marbà and Duarte 2010). Seagrasses near the edge of their distributional range are most at risk of rising temperatures. This includes species at their latitudinal limit (Hyndes et al. 2016) and in shallow water which can warm well above surrounding ocean water temperature, particularly at low tide (Seddon et al. 2000). The effects of heatwaves can be confounded by other cumulative impacts, such as high salinity (Thomson et al. 2015).

Table 1. Seagrass losses and gains in area – examples from seagrass bioregions

↑ gain ↓ loss

Bioregion*	Location	Threat	Pressures and recovery action	Study area (km²)	Change in cover (%)	Period of study
Temperate North Atlantic	Chesapeake Bay, Maryland, Virginia, USA	Land-based	Nutrient and sediment loading	11,600	29 ↓	1984–2015
Tropical Atlantic	Tampa Bay, Florida, USA	Land-based	Nutrient reduction[a]	959	25 ↑	1982–2004
Temperate North Pacific	Bahía de San Quintín, Baja California, Mexico	Land-based	Sediment	48	13 ↓	1987–2000
Tropical Indo-Pacific	Great Sandy Strait, Queensland, Australia	Land-based	Natural recovery[b]	500	86 ↑	1998–2002
Mediterranean	Mediterranean Sea	Land and sea-based	Mixed (fishing, boating, nutrients and sediment)	2.5×106	20 ↓	1869–2016
Tropical Indo-Pacific	Kenya, East Africa	Land and sea-based	Fishing and sediment	NA	26 ↓	1986–2016
Temperate Southern Oceans	Rottnest Island, Western Australia, Australia	Sea-based	Boating (moorings)	1	5 ↓	1930–2009
Tropical Indo-Pacific	Shark Bay, Western Australia, Australia	Climate-related	2011 heatwave (water temperature 2–4°C above average)	8,900	22 ↓	2002–2014

Notes: For gains, the 'pressure' column shows action leading to recovery. Rows ordered by type of threat.
* Bioregions from Short et al. (2007).
a Improved water quality management practices to reduce nitrogen loading from wastewater treatment.
b Natural recovery from elevated nutrient and sediment loading following a large storm event in February 1999.

Indian Ocean – small threats can have big consequences

Large-scale impacts to seagrass from widely acknowledged threats, such as extreme weather events or run-off from degraded lands, often receive most attention. For example, cyclones contributed to the loss of more than half the seagrass area of Inhambane Bay in Mozambique (Amone-Mabuto et al. 2017), and led to major losses in southwest Madagascar (Côté-Laurin et al. 2017). Local threats and activities that result in smaller scale, local impacts (generally less than 100 km^2 in area) are often overlooked, even though they can occur at higher frequencies and cause great concern to coastal communities. Impacts to seagrass from local threats may be rare, such as an oil spill, but the majority are regular or persistent. While some localized threats are small in impact, such as boat anchoring or moorings, they can also occur at larger scales and with such high frequency that they make seagrass highly vulnerable (Grech et al. 2012). The nature of local threats also differs geographically, particularly with respect to socioeconomic circumstances (Grech et al. 2012). For example, Kenya and Tanzania have suffered substantial seagrass losses as a result of seaweed farming (Eklöf et al. 2008), and the overharvesting of natural sea urchin (Tripneustes gratilla) predators, which has led to overgrazing by sea urchins. In Indonesia, sand and coral mining for construction material has severely impacted local seagrass meadows. Aside from the nature of the threat, the consequences of local impacts can be more severe when coastal communities depend on seagrass ecosystem services for food and livelihoods. For example, in Zanzibar, Tanzania, a decline in seagrasses from invertebrate overharvesting, boat scarring and digging had a negative impact on the well-being and livelihoods of people, especially women (Cullen-Unsworth et al. 2014). Most local impacts are incidental, including physical damage from vessel groundings, propeller scars and trawling. However, some impacts are deliberate, such as reclamation of areas for coastal development or active removal of seagrasses to create clear soft, sandy lagoons and beaches to appeal to tourists (Daby 2003). Fortunately, current efforts in the Maldives have been successful in mitigating such impacts by convincing more than 25 per cent of resorts to protect their seagrass meadows (Malsa 2019). Local threats rarely occur in isolation and it is the cumulative effect of multiple threats that is having the greatest impact at the local level. For example, in west Maputo Bay, Mozambique, there have been recent seagrass losses of more than 7 per cent per annum due to sedimentation, flooding and clam collection (Bandeira et al. 2014). Small localized impacts not only cause direct seagrass losses, but most importantly make them more vulnerable to large scale impacts and climate change. Identifying and managing local threats is therefore an important consideration in forming management or conservation goals (Unsworth et al. 2018).

CASE STUDY 4

Extreme climate event: marine heatwave drives massive losses of one of the world's largest and continuous seagrass ecosystem – Shark Bay

The Shark Bay Marine Park is part of a UNESCO World Heritage site located in Western Australia that supports the local economy through tourism and fisheries. It has several exceptional natural features, including the world's most extensive populations of stromatolites and one of the largest (over 4,000 km^2) continuous and most diverse seagrass meadows in the world.

In the austral summer of 2011, a marine heatwave impacted the west coast of Australia (Wernberg et al. 2012) resulting in extensive declines of seagrass meadows in Shark Bay. Mapping inside the marine park in 2014 revealed a net reduction of approximately 22 per cent in seagrass habitat from the 2002 baseline. The seagrass landscape also changed dramatically across large areas of the bay, with dense and continuous seagrass meadows becoming sparse, declining from 72 per cent in 2002 to 46 per cent in 2014 (Arias-Ortiz et al. 2018). The temperate species *Amphibolis antarctica*, which occupied 85 per cent of the total cover and whose dense and tall thickets provide ample food and shelter for numerous species, was the most widely affected seagrass. Given its massive extension and ecological importance, its loss and degradation had catastrophic implications (Kendrick et al. 2019).

Seagrass habitat structure was lost over an estimated area of 1,000 km^2, resulting in the malfunction of important ecosystem services (see image). Loss of the seagrass canopy caused a progressive decrease in water clarity and quality. Defoliated and dead beds converted to bare sand lost their capacity to trap and stabilize sediments and decaying seagrass biomass and erosion of sediment C_{org} stocks produced increased nutrient loads to the water column, nourishing widespread phytoplankton and bacterial blooms (Nowicki et al. 2017). This caused favourable conditions for CO_2 emissions, which were estimated at 2–9 million tons of CO_2 in the three years following the event, and resulted in a loss of annual carbon sequestration capacity of 52 ± 14 GgC yr^{-1}, which will remain permanent as long as the seagrass meadows do not recover (Arias-Ortiz et al. 2018).

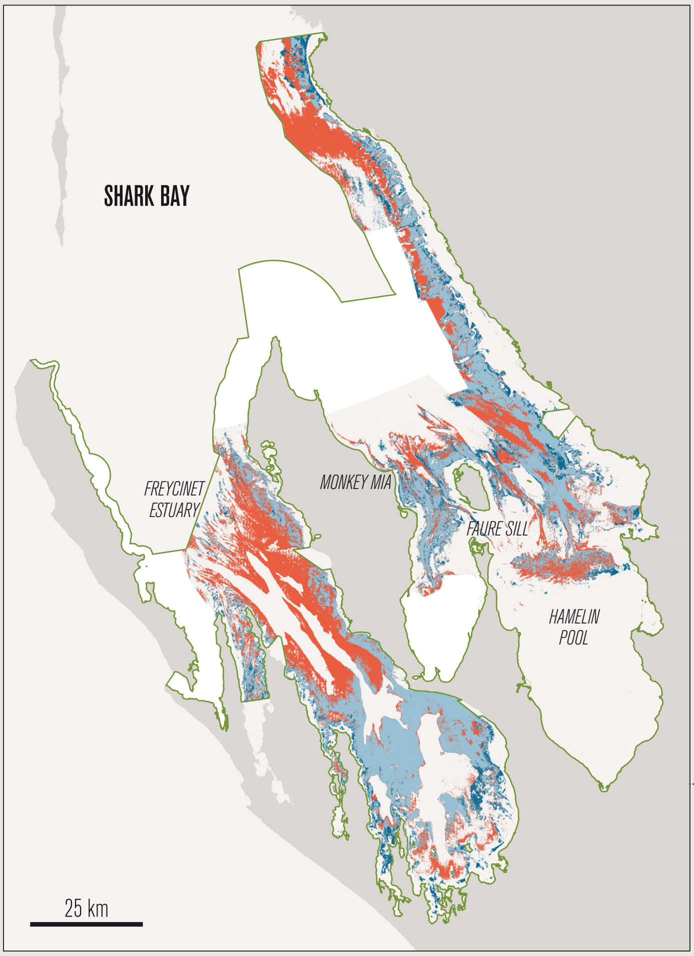
The loss of seagrass habitat structure and composition also had indirect impacts on consumers at different trophic levels. The loss of forage habitat led to declines in species of conservation concern, such as green turtles, dugongs and sea snakes (multiple species), and also affected the survival and reproduction of bottlenose dolphins (Kendrick et al. 2019) which forage on seagrass-associated fishes. The commercial crab and scallop fisheries also suffered heavy declines due to direct effects, such as temperature-related mortality and indirect legacy effects of seagrass loss. Temporary closures for these fisheries had to be implemented, which were catastrophic for industry. The spatial scale of seagrass loss due to climate and oceanographic events is generally much greater than loss associated with direct anthropogenic impacts at the local scale, and may therefore also cause the biggest impact at the ecosystem scale. There is a need to learn how seagrass ecosystems will respond to global change threats and to build seagrass resilience in order to ensure the functioning of the entire ecosystem.

Beyond the direct effects of temperature rise on seagrasses themselves, there are also potential problems arising from the effect of temperature increases on seagrass-associated organisms, including animals that feed on seagrasses or competing algae, and pathogens (Sullivan et al. 2018). For example, temperature rise has already triggered changes in species distribution, causing grazing animals that are known ecosystem engineers (for example, sea urchins and siganid fish, known as rabbitfish) to move from tropical to temperate areas, and has altered grazing pressure on submerged vegetation (Vergés et al. 2014). Temperature rise may also alter the performance of grazing animals (how much each individual is capable of eating) (Pearson et al. 2018). These changes in grazing pressure have the capacity to alter the abundance of habitat-forming taxa, including seagrasses. Unusually warm temperatures are also associated with the wasting disease that decimated eelgrass across the northern hemisphere in the 1930s.

Under rising sea levels, seagrass habitats would naturally migrate to more elevated areas to maintain their optimal zonation relative to water depth. However, colonization could be impeded by conditions unfavourable to seagrasses, such as hardened shorelines causing a reduction in habitable area. In these cases, improvements in water clarity will enable the deeper edges of meadows to persist, resulting in smaller losses from sea level rise (Saunders et al. 2013).

Responses to increasing partial pressure of carbon dioxide (pCO_2) or ocean acidification are difficult to predict (Koch et al. 2013) and there is insufficient evidence to determine whether seagrasses will be 'winners' of ocean acidification (Fabricius et al. 2011) or merely less affected by it than more sensitive habitats, such as coral reefs. Their capacity to respond to increasing pCO_2 depends on other limiting conditions, such as light availability (Kroeker et al. 2017). There can also be downregulation in the response to pCO_2, so that short-term gains in net productivity observed during acute experiments

SEAGRASS EXTENT CHANGE WITHIN SHARK BAY'S MARINE PARK
CHANGE BETWEEN 2002 & 2014



SEAGRASS CHANGE

MARINE PARK BOUNDARY
LAND
UNPROCESSED AREA
SEGRASS LOSS
SEAGRASS STABLE
SEAGRASS GAIN

Sources: Arias-Otiz et al. (2018);
Government of Western Australia, Department of Biodiversity, Conservation & Attractions; GRID-Arendal (2020).

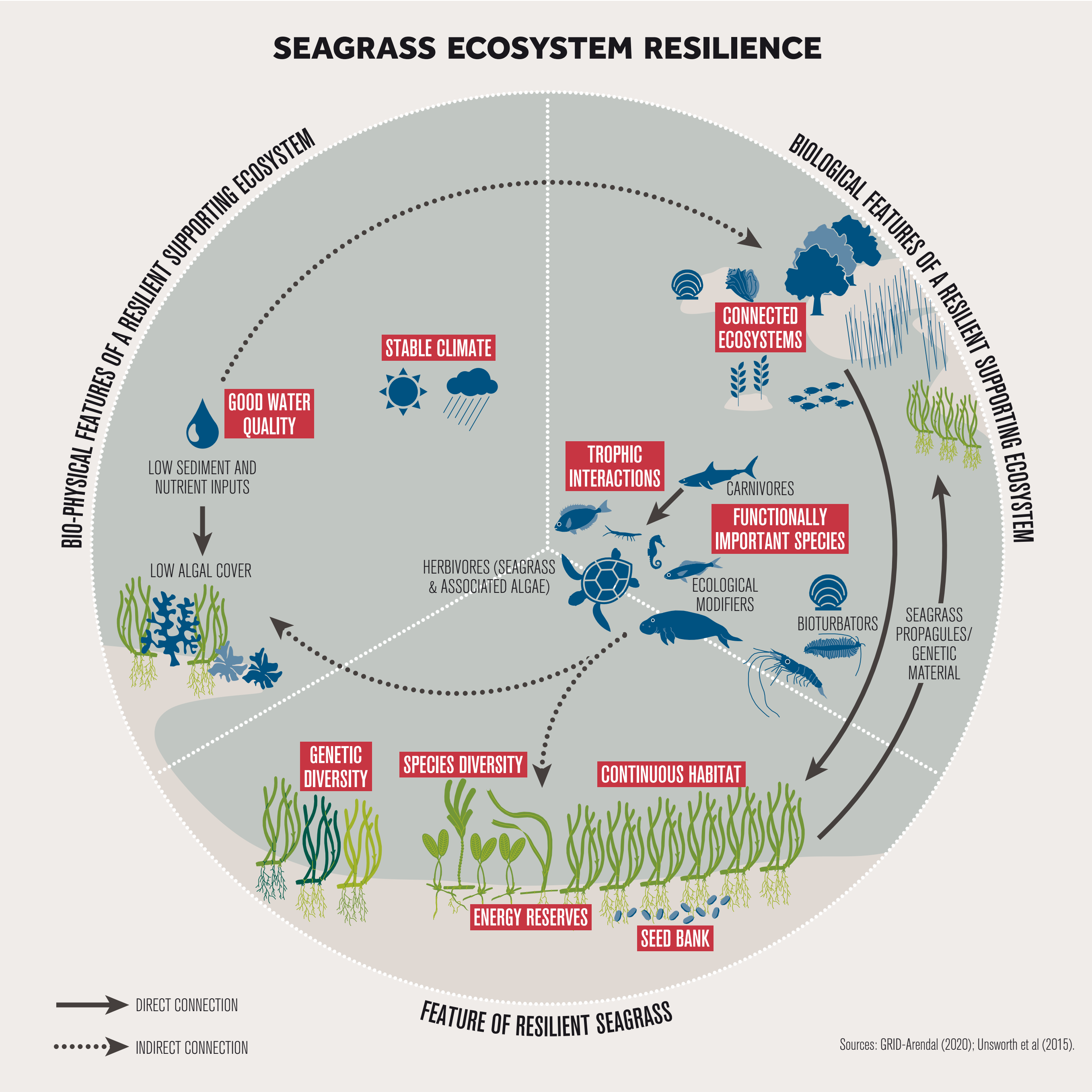
are not necessarily realized in the long term (Smith and Dukes 2013). Furthermore, inshore fluctuations in pCO_2 are highly variable and the rates of change differ compared with more offshore areas (Uthicke et al. 2014), adding further complication to predicting future responses to ocean acidification.

Climatic events, including hurricanes, cyclones and rainfall, are likely to become more extreme in the future, though this will vary from region to region. High water energy associated with cyclones can directly uproot seagrass and mobilize seedbanks, leaving modified seascapes which are vulnerable to recalcitrant degradation (O'Brien et al. 2017; McKenzie et al. 2019). Although impacts of land-based run-off and pollutant loads from extreme events can be far-reaching and long-lasting (as previously described), management goals to promote diverse seagrass communities and lower chronic threats may make meadows less vulnerable to extreme events (Steward et al. 2006; Cole et al. 2018).

Seagrass ecosystem resilience

The concept of ecosystem resilience is now commonly considered in the management of coastal habitats. Resilience is the ecosystem's capacity to maintain its ecological structure and function in the face of disturbance from natural events or human activities. It arises through one, or a combination of, two pathways: resistance to change and rapid recovery after a temporary loss (Folke et al. 2004). For seagrasses in particular, resilience has become a prominent aspect of management and research due to their extensive provision of ecosystem services and their vulnerability to multiple threats (York et al. 2017). One of the most common changes observed in seagrass meadows is the shift to an unvegetated or algal-dominated habitat, both of which provide fewer ecosystem services, thus making resilience important for seagrass ecosystems, which is why it is now applied so frequently (see chapter on ecosystem services).

FIGURE 9



The scientific understanding of the drivers underpinning seagrass resilience has advanced rapidly in recent years. In a global review and expert opinion survey on factors leading to resilience in seagrass (and other biogenic habitats) facing climatic disturbance, 40 per cent of papers showing climatic disturbance and 70 per cent of interviewed global seagrass experts (n=17) had observed resilience (O'Leary et al. 2017). Factors shown to be important can be categorized in terms of whether they are characteristics of the meadow itself or the surrounding environment, either biological or biophysical (Figure 9). In another study, seagrasses further from river mouths had higher resilience because river outflow altered salinity, turbidity and phytoplankton blooms following hurricanes, the impacts of which were more severe than the initial physical loss (Carlson Jr. et al. 2010). Generally, factors determining seagrass resilience relate to location, diversity, water quality, connectivity and food web interactions (called trophic interactions; see Table 2). Both genetic diversity and species diversity of seagrasses can also provide resilience against stressors. Higher genetic diversity of transplants is related to higher production of flowering shoots, increased seed germination and increased leaf shoots (Williams 2001), all of which enhance recruitment and clonal reproduction. In addition, transplanting multiple seagrass species increased survival and coverage compared with transplanting single species.

Different seagrass species vary in their adaptations for resistance to, and recovery from, disturbance. Some species tolerate short-term reductions in the amount of light they receive by storing carbohydrate reserves (Fraser et al. 2014), while others show adaptations in photosynthesis (Campbell et al. 2007). Resilience also depends heavily on asexual and sexual reproduction, such as rapid growth rates, dispersed,

Table 2. Seagrass resilience traits, management actions and practical methods used to increase resilience of seagrass ecosystems

Trait	Action	Method
Diversity – species and genetic	Increase genetic diversity	Deploy seeds from a wider region Enhance genetic connectivity, e.g. by minimizing artificial barriers
Good water quality	Reduce physical impacts	Local management to avoid direct impacts such as anchoring and bait digging
	Reduce algal overgrowth	Improve water quality and manage fisheries to increase herbivory in the food web
	Increase photosynthetic productivity	Improve water quality, e.g. through improved land management
	Reduce chemical toxicity	Control entry of chemical toxicants into waterways
	Increase compliance with environmental regulations relating to seagrass	Improve local knowledge of the locations of seagrass meadows and their value and sensitivities
Connected ecosystems and continuous habitat	Reconnect isolated and fragmented meadows	Targeted restoration
	Maintain connectivity	Ensure continued presence and health of associated habitats (e.g. reefs, mangroves)
Balanced trophic interactions	Encourage balanced herbivory and bioturbation	Manage fisheries species, including predators, through fisheries and habitat management (e.g. marine reserves)
	Provide early warning of issues of concern	Monitoring of structure and functions linked to feedbacks

Sources: Unsworth et al. (2015); Connolly et al. (2018)

long-lasting seed banks and the potential for fragments of plants to break off and be transported by currents to new areas (McMahon et al. 2014). Seascape-scale increases in seagrass cover have occurred over several decades, for which seedling recruitment played a key role in colonization and recovery (Kendrick et al. 2000).

Feedback loops play an important role in maintaining the ecological functions of seagrass ecosystems. These feedback loops are properties of the meadow, that, for example, efficiently remove excess nutrients, suppress sediment resuspension and support populations of small grazing animals. In recent years, research has revealed that the shift from seagrass to a less productive unvegetated or algal-dominated seabed occurs when environmental stressors weaken feedback loops. Impacts such as reduced water quality potentially overcome key feedbacks to the extent that the ecosystem reaches a tipping point, causing a major change in the state of the ecosystem (Maxwell et al. 2016). Importantly, different feedback loops operate in this altered state with very serious implications for coastal managers. Because the feedback loops in the altered state (for example, unvegetated seabed) work to maintain the new system, simply reducing or removing the original stressor often will not recover the seagrass (Maxwell et al. 2015). The stressor (for example, excessive nutrient concentrations in coastal waters) may have to be reduced to a much lower level than the point at which the original loss of seagrass occurred (Duarte et al. 2009). Other active restoration measures might also be needed, such as sand capping to reduce resuspension of fine sediment (Flindt et al. 2016) and planting of seeds or shoots to encourage seagrass regrowth (van Katwijk et al. 2016). For coastal managers, an increased understanding of seagrass resilience may potentially shift the focus towards managing to protect key feedback loops (Connolly et al. 2018).

Threats to connectivity across ecosystems

The links between seagrass and other habitats in the broader seascape is important for the delivery of ecosystem services or extra-local benefits (see chapter on ecosystem services). Seagrass meadows have connectivity with other habitats, such as mangrove forests, coral reefs, saltmarshes and kelp forests, which is most evident in terms of animal movement, the dispersal of plant propagules and animal larvae, and the transfer of nutrients and organic matter (Lavery et al. 2013; Kendrick et al. 2017). Connectivity plays a vital role in structuring biological populations and maintaining biodiversity (Sheaves 2009). Connectivity of seagrass with other habitats drives numerous ecological processes that are critical to the health of seagrass ecosystems. For example, seagrass meadows in close proximity to mangrove forests support a greater abundance and diversity of fish and crustaceans, including important fisheries species (Jelbart

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et al. 2007). Furthermore, reef fish are more abundant when coral reefs are connected to nearby seagrass beds (Berkström et al. 2013), suggesting that connectivity benefits both seagrass and the connected habitats. The health of individual animals is often greater in more connected habitats too. Rockfish within seagrass beds adjacent to kelp forests, for instance, consume higher quality prey and have higher body condition than those within seagrass beds adjacent to bare sand (Olson et al. 2019). Finally, connectivity between seagrass and other coastal habitats can reduce the impacts of waves and storms, enhance conditions for habitat-forming species, such as corals, by altering the chemical composition of water (Unsworth et al. 2012), and increase overall carbon storage (Huxham et al. 2018). Overall, substantial ecosystem services rely on connectivity between seagrass and other habitats.

Global habitat destruction and change, however, is compromising habitat connectivity and consequently threatening the important benefits that both the environment and humans gain from it (Gerber et al. 2014; Bishop et al. 2017). Habitat loss is the most conspicuous disruptor of connectivity; it can interfere by removing an entire habitat type or by modifying the configuration of remaining habitat patches. For example, coastal squeeze is causing saltmarshes to be lost in many parts of the world, as sea level rise is forcing saltmarshes landward in areas where the urban fringe inhibits such migration (Saintilan et al. 2014). The loss of saltmarsh will have considerable impacts, since the combination of seagrass, mangroves and saltmarshes, and thus the connectivity between them, is important for supporting productive fisheries (Nagelkerken et al. 2013). Where seagrass diversity is low or distribution is limited, loss is expected to have especially strong impacts on marine biodiversity and ecosystem health (Short et al. 2011). For example, along the Pacific coast of the United States of America, seagrass (Zostera marina) is relatively sparse (occurs in 17–36 per cent of estuaries in Washington, Oregon, and California) (Sherman and DeBruyckere 2018), and thus separated by large distances. Loss of seagrass in any one estuary (as in the recent case in Morro Bay, California) (Walter et al. 2018) will result in major connectivity gaps of seagrass-dependent species. Similarly, the construction of physical barriers such as seawalls can restrict or modify the connectivity between seagrasses and adjacent wetlands, such as saltmarshes and mangroves (Bishop et al. 2017). This decreases the transfer of individuals and resources among habitats, which could impact ecosystem productivity.

Fisheries harvesting can also affect the degree of connectivity between seagrass and other habitats. For example, the overharvesting of fish and crustaceans directly and indirectly affects connectivity (for example, through a reduction in larval supply) by reducing the transfer of resources among habitats (Hyndes et al. 2014). Overharvesting of top-order marine predators, for instance, is likely to interrupt food web connections across seagrasses, mangroves and coral reefs (Hyndes et al. 2014). Additional human threats to coastal systems, such as eutrophication and environmental contamination, affect animals that utilize multiple habitat types, and are likely to have similar impacts on connectivity by disrupting distribution patterns and energy fluxes. Overall, many of the threats of rapid increases in coastal human populations to coastal habitat connectivity remain speculative, but there is a growing interest in establishing these more rigorously (Bishop et al. 2017).

Seagrass optimism – some good news

Despite a general global trend of seagrass loss, there are some areas where past declines have abated and shown substantial recovery. These recoveries can often be attributed to human interventions reducing the effect of human-caused stressors. For example, focused management plans aimed at improving water quality for seagrass restoration, especially those that address nutrient sources and reduce input, have had considerable success in some areas. This section discusses two case studies in areas where seagrasses have recovered from substantial past declines, with both demonstrating the benefit of improving water quality for seagrass health.

In Tampa Bay, Florida, United States of America, the size of seagrass areas declined by 46 per cent during 1950 and 1980, while the coastal human population grew. In these tropical waters, the meadows consisted predominantly of Thalassia testudinum, Syringodium filiforme and Halodule wrightii (Greening and Janicki 2006; Sherwood et al. 2017). This loss was largely attributed to an increase in nutrient loads (particularly nitrogen) within nearby estuaries, triggered by rapid population growth and land-use conversion. Recognition of this problem in the 1980s and 1990s triggered the implementation of management measures to improve water quality in order to promote seagrass health and return coverage to 1950s levels (Sherwood et al. 2017). Since this time, there has been roughly a 90 per cent reduction in nitrogen loads within Tampa Bay, largely due to management of nutrient sources (Tomasko et al. 2018). Alongside this improvement in water quality, Tampa Bay seagrass area increased markedly to double that recorded in 1982 (8,761 ha) and returned to approximately 1950s levels (>16,300 ha) by 2014 (Tomasko et al. 2018).

Intertidal seagrasses have also shown substantial recovery from past losses in the cool temperate waters of the Wadden Sea, which forms part of the North Sea. This seagrass habitat is part of the world's largest coherent tidal flats system (de los Santos et al. 2019). Despite occurring on the opposite side of the Atlantic Ocean with a different seagrass species composition (*Zostera marina* and *Zostera noltii*), this case study closely parallels the events in Tampa Bay. Throughout the twentieth century, the Wadden Sea experienced a dramatic increase in nutrient loads until approximately 1980, when levels began declining (van Beusekom 2010). Seagrasses in the affected area declined dramatically to levels well below those in both the 1930s and 1950s. Signs of recovery were first noted in the late 1980s, several years after water quality began improving, and continued through to around 2012 alongside improving water quality and some physical restoration efforts (Dolch et al. 2017). By 2005, the total seagrass area was estimated to be approximately 16 per cent of possible intertidal habitat, which was roughly equivalent to coverage observed from aerial photography in the 1930s and much higher than the < 5 per cent coverage recorded throughout the 1990s. Seagrass extent continued to increase in the Wadden Sea until approximately 2012, when it appears to have reached a maximum level, which has remained stable ever since (Dolch et al. 2017).

Given the demonstrated impacts of beach seine nets in coastal East Africa on seagrass (www.smartseas.org), recent enforcement (September 2019) of the national ban on use of these nets is likely to result in widespread seagrass recovery along the nation's coast.

These case studies demonstrate that there are clear benefits of reducing nutrient input into waterways to improve habitat suitability for seagrasses. However, as highlighted in this chapter, there are many other stressors and potential management options that should be considered alongside water quality when attempting to minimize loss and/or restore seagrass ecosystems. For example, Dolch et al. (2017) suggest that while the threat of eutrophication has been addressed in the Wadden Sea, it is possible that changing sediment dynamics and/or sea level rise may trigger future losses.

The increasing use of automation in environmental monitoring also provides an opportunity for improved management of activities that threaten seagrass. To date, the monitoring of changes in seagrass extent, cover and associated ecological functions has been too expensive or difficult to do frequently. A lack of up-to-date monitoring data has also hampered management. This limitation could be overcome through advanced digital platforms integrating automated data streams with big data analysis. Automated analysis of remotely sensed satellite imagery (see chapter on mapping and monitoring), in situ water quality and meteorological data can all now be achieved in close to real-time. The challenge is coupling remote sensing with in situ validation to improve the algorithms for seagrass recognition and mapping. Automation, in combination with citizen science, can support more efficient and effective adaptive management.

SEAGRASS MAPPING AND MONITORING

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Mapping and monitoring seagrass extent, cover and species composition is vital to understanding these complex and dynamic ecosystems, highlighting areas of resilience and sensitivity, and predicting their response to climate change-induced pressures. However, seagrass mapping and monitoring extends beyond these direct measurements to include their benefits, processes and pressures relating to food regulation, fishery production, the global carbon cycle, biodiversity and climate change, among other aspects.

There are many challenges when mapping seagrasses globally. According to the best available knowledge, seagrasses occupy over 300,000 km^2 of seabed – an area equivalent to the size of Germany – distributed in all continents except Antarctica (Figure 1). However, this information is based on an amalgamation of diverse data sets, including field data measurements (points), remotely sensed measurements (often polygons) and expert knowledge collected over varying spatial scales between 1934 and 2015. The nature of the information and its large temporal variation could result in a possible underestimation of the global area covered by seagrasses. The compiled global seagrass area composite to date has been estimated at 160,387 km^2 across 103 countries/territories with Moderate to High confidence, with an additional 106,175 km^2 across another 33 countries with Low confidence (McKenzie et al. 2020).

The diversity of seagrass ecosystems makes it challenging to monitor their locations and health over time. Seagrasses are found across a broad depth range, from the intertidal zone to 80 metres deep, and grow anywhere from very clear to very turbid waters. Seagrass beds also vary in density, from single patches to square kilometres of homogeneous meadows, and species composition, ranging from single species to mixed grounds of more than 10 species (Green and Short 2003).

In order to achieve innovative and timely seagrass mapping and monitoring, a globally coordinated matrix approach is necessary. This matrix should consist of top-down and bottom-up approaches – from remote sensing instruments to in situ measurements – at all spatio-temporal scales, from the local to global and seasonal to decadal levels. Remote sensing alone (satellites, airplanes, drones, sonars) could miss information on seagrasses, such as variables that can signal ecosystem condition (such as shoot density, species composition), while global in situ sampling alone is very resource intensive and can vary in timing, consistency and methodologies. When combined, spatio-temporal information from remotely sensed and in situ methods can yield critical information on the health and trends of seagrass ecosystems for researchers and policy- and decision makers, including governments, businesses and local communities. The three main components of the matrix to perform mapping and monitoring of seagrasses at the global scale in the near future are: the techniques, the technology and the data.

The techniques

There are three main techniques to map and monitor seagrasses: 1) optical-based techniques using remote sensing instruments such as satellites and drones; 2) acoustic-based techniques using remote sensing instruments such as side-scan sonars; and 3) field-based techniques conducted through diving, snorkelling and ecological monitoring.

1) Optical: satellites and drones

Over the last 20 years, there has been an evolution in Earth observation – the gathering of information about the biophysiochemical properties of Earth via remote sensing techniques. Currently, satellite-based remote sensing can identify and map seagrass between spatial resolutions of 0.30 and 30 m, temporal resolutions between 1 and 17 days, and spectral bands between 400 and 700 nm – the visible spectrum. Within these ranges, satellites can see seagrasses with satisfactory detail and frequency to maximum water depths of 40 m in many, but not all, cases, depending on water clarity. The final decision on selecting the appropriate satellite sensor highly depends on the scope of the project (scale and extent), spatial and temporal capabilities of the sensors and the available funds (Figure 10).

The recent development of lightweight drones, also known as Unoccupied Aerial Systems (UAS), is the latest addition to Earth observation and remote sensing toolkit. Drones have been used in a series of intertidal seagrass monitoring studies (Duffy et al. 2018; Konar et al. 2018; Nahirnick et al. 2019), demonstrating their capacity for very high, often subdecimetre, spatial resolution at a relatively low cost and with high flexibility in deployment capabilities and customization. Moreover, the ability to fly the same route repeatedly and collect data as necessary has made drones a very useful tool in the routine monitoring of seagrass ecosystems. However, drones acquire images at a lower altitude (maximum height dependent on permissions but usually no higher than 300 m) which provides coverage of a smaller ground area compared to satellites, and require special permissions and licence.

Drones and satellites can work synergistically: drones can collect high-quality, high-resolution reference data to validate the lower-resolution, satellite-derived seagrass mapping products. This approach can reduce costs associated with collecting field validation data in situ (by means of snorkelling and/or diving), increasing the feasibility of a given seagrass mapping project.

2) Acoustic: side-scan sonars, multibeam and single beam echosounders

Acoustic sensors are commonly used to map sea floor physical and biological properties. Using ultrasound techniques, it is possible to map seagrass meadows using an acoustic apparatus, usually towed from or installed on a boat. The size of the surveyed area generally falls between that of in situ methods and satellite imagery. Side-scan sonars have been used to map seagrass beds since the 1970s in the Mediterranean Sea (Newton and Stefanon 1975; Meinesz et al. 1981; Pasqualini et al. 1998; Fakiris et al. 2019), though it is difficult to measure densities and canopy heights. Multibeam echosounders, on the other hand, are one of the most effective acoustic tools, as they can create a three-dimensional image of the seagrass meadow (Komatsu et al. 2003). Single beam echosounders have been developed to detect distributions of fish schools and to measure underwater bottom topography, which has been very useful for mapping the lower depth limit of seagrass distribution. However, unlike side-scan sonars and multibeam echosounders, single beam echosounders do not provide full coverage of the sea floor.

3) Field-based (in situ) sampling and monitoring

Field-based monitoring can provide information on the health status (ecological status) of seagrass meadows as a number of variables are collected at a fine scale, including percentage cover, shoot density, canopy height, biomass and species composition, among others. The best established and the most commonly used variable for seagrass monitoring is percentage cover. Seagrass cover, referred to as 'the horizontally projected foliage cover of the canopy', has wide application and can reduce overall sampling error because it is simple and promotes replication. While estimating cover can be subjective, using of common reference cards and quality assurance/quality control (QA/QC) procedures can greatly improve the method's accuracy.

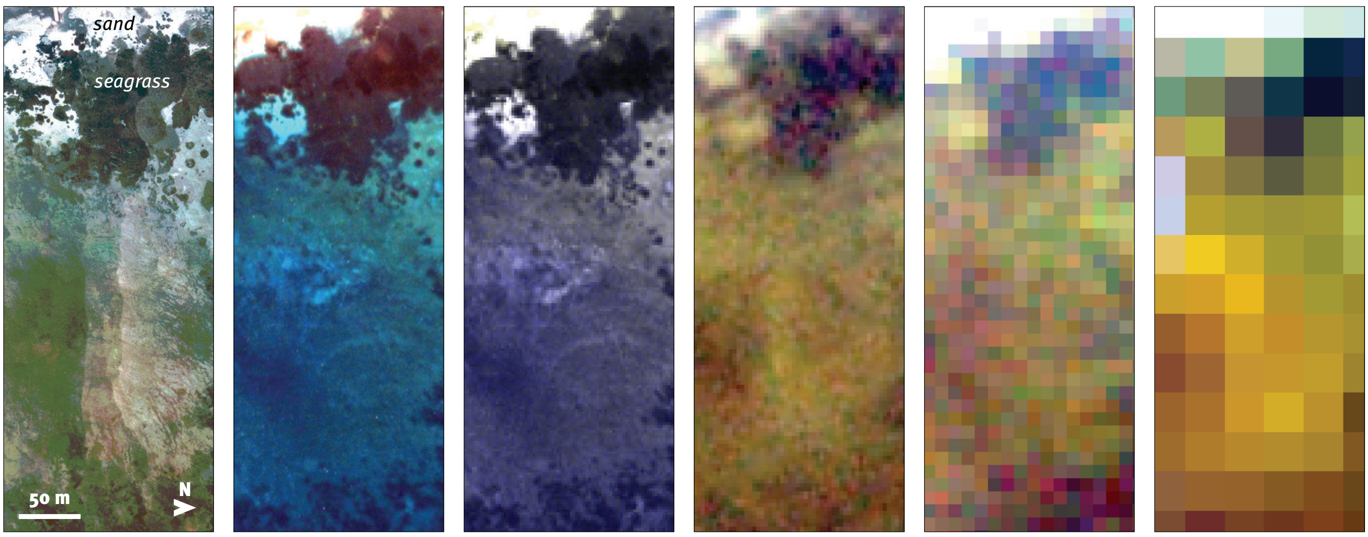
Coordinated monitoring networks increase the power and value of local monitoring by connecting data sets and standardizing protocols, thus facilitating comparisons across time and space. Networks provide an excellent and cost-

FIGURE 10

Seagrasses from above - drones and satellites

Example images from Lesbos, Greece. 39°09'30.6"N 26°32'01.8"E

Drone | **WVII PAN** | **WVII MUL** | **PlanetScope** | **Sentinel-2** | **Landsat-8**



Drone — *resolution: 4 cm*
- (+) Very high spatial resolution, Low cost of acquisition, High flexibility of deployment
- (−) Small ground area coverage, Limited optical bands, Required laborious image pre-processing

WVII PAN — *resolution: 50 cm*
- (+) Very high spatial resolution, High spectral information, Direct and flexible sensor tasking
- (−) Commercial imagery, Very high cost of imagery

WVII MUL — *resolution: 2 m*
- (+) Very high spatial resolution, High spectral information, Direct and flexible sensor tasking
- (−) Commercial imagery, Very high cost of imagery

PlanetScope — *resolution: 3 m*
- (+) High spatial resolution, High temporal resolution, Free under a scientific license
- (−) Radiometric differences betweem, Low spectral information

Sentinel-2 — *resolution: 10 m*
- (+) High spatio-temporal resolution, Open, free and public datasets, Archive between 2015-2029
- (−) Multiple spatial bands, Spectral technological-related artifacts over seagrass areas

Landsat-8 — *resolution: 30 m*
- (+) Large area coverage, Free datasets, Historical archive back to 1972
- (−) Low spatial resolution, Low temporal resolution

Sources: Topouzelis, K. University of Aegean (2018); Digital Globe (2018); PlanetScope (2018); Copernicus Sentinel data (2018); Lansdat-8 (2018) U.S. Geological Survey.

Global seagrass monitoring networks

The **Seagrass-Watch** programme, established in 1998, is a global participatory scientific monitoring and science-based education programme which accurately monitors the status and trends in seagrass condition from 408 sites across 21 countries using globally standardized protocols. To ensure quality control and data accuracy, assessments are predominately conducted by experienced scientists and environmental practitioners, in partnership with the wider community. Seagrass condition is assessed from 33 quadrats (50 cm × 50 cm) within permanent and replicated monitoring sites (0.25–5.5 ha), established in representative meadows (McKenzie et al. 2003). The measures include seagrass percentage cover and species composition, seagrass canopy height, epiphyte cover, macroalgae cover and sediment grain size (McKenzie et al. 2003). Depending on local capacity, additional measures include seagrass flowers/fruits, seed densities, meadow seascape (for example, fragmentation), herbivory, leaf tissue nutrient concentrations, temperature and light. The frequency of assessments depends on local capacity and can be quarterly (every three months), biannual, annual or ad hoc. Status reports on seagrass condition are provided on the programme website (www.seagrasswatch.org), with results used at the local and regional levels to support conservation objectives and management of threats.

The **Global Seagrass Monitoring Network (SeagrassNet)**, established in 2001, investigates and documents the status of seagrass meadows by monitoring 126 sites in 33 countries. It uses a global monitoring protocol derived from standard sampling techniques and a web-based data reporting system (www.seagrassnet.org). Each monitored area has three permanent 50-metre transects with 12 replicate sampled positions, with sampling predominately conducted by local government and environmental practitioners up to four times per year (Duffy et al. 2019). Biological parameters include species, cover, canopy height, biomass and flowers/fruits, and meadow expansion/retraction, which are measured along with temperature, light, salinity and sediment characteristics. SeagrassNet results reveal seagrass change over timescales relevant to management, while also informing scientifically supported statements about the status of seagrass habitat and the magnitude of the need for management action. The SeagrassNet protocol (adapted) has been taken as the national standard in Brazil (Copertino et al. 2015).

The **Global Ocean Observing System (GOOS)** and **Marine Biodiversity Observation Network (MBON)** have been working to coordinate these global seagrass monitoring efforts (for example, SeagrassNet and Seagrass-Watch) within the context of the essential variable frameworks, namely the essential ocean variables (EOVs) of the GOOS and essential biodiversity variables (EBVs) of the Group on Earth Observations Biodiversity Observation Network (GEO BON). The goal of the biological essential ocean variables (EOV) approach, including the seagrass EOV, is to develop communities of practitioners around the globe to measure key biological variables, such as seagrass, in a globally coordinated and inter-comparable way. In addition to developing partnerships and a community of practitioners, this community is working to develop best practices for monitoring, metadata, and data management. For example, the Ocean Best Practices repository (www.oceanbestpractices.net) has been developed to collate and archive the best practices in ocean research, observation, and data and information management.

effective method of obtaining standardized and comparable data on seagrass change and related drivers over several different locations worldwide through time. There are numerous seagrass monitoring programmes around the world collecting a variety of data on seagrass ecosystems. A recent global assessment identified 19 active long-term seagrass monitoring programmes (Duffy et al. 2019), the largest of which were the global programmes Seagrass-Watch (www.seagrasswatch.org) and SeagrassNet (www.seagrassnet.org) (see box on global seagrass monitoring networks). Both networks aim to provide up-to-date online data submission systems, as well as resources to support monitoring, such as manuals or protocols, field guides and data sheets (McKenzie et al. 2003; Short et al. 2006), news, details of seagrass sites and participants. By following standardized methods, data from different areas are directly comparable and can be used to assess their ecological status.

The technology

In the last decade, technological advances in computation have enabled two cornerstones of today's mapping and monitoring via satellite and drone imagery: cloud computing platforms and artificial intelligence (AI), which includes machine learning and deep learning. This technology sets the stage for highly scalable, repeatable and accurate techniques that can facilitate seagrass mapping and monitoring.

Cloud computing platforms

The last five years have seen the establishment and growth of cloud computing platforms, which represent an unprecedented 'big data' approach to science and management, emphasizing data-intensive analyses, time- and cost-efficient data access, huge computational

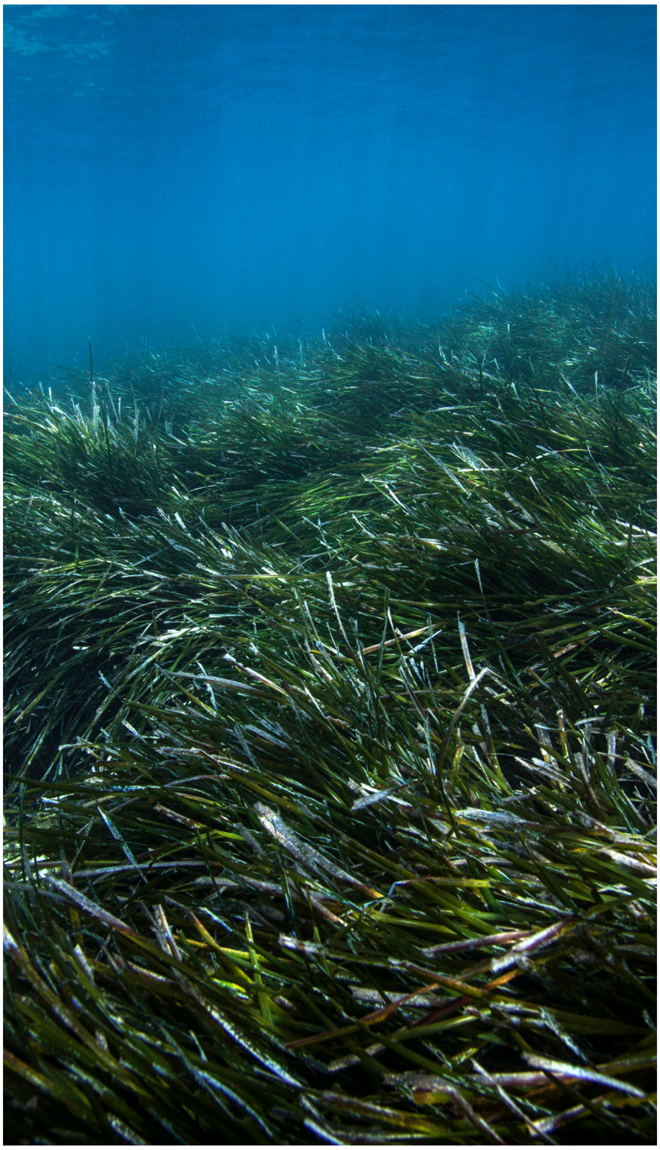
Open seagrass distribution data: now and the future

To date, efforts to collate seagrass distribution data have led to the development of the Global Distribution of Seagrasses data set (Green and Short 2003; UNEP-WCMC and Short 2003), as well as regional or national inventories of data held by intergovernmental, governmental and non-governmental organizations (for example, the European Marine Observation and Data Network's (EMODnet) broad-scale map of seabed habitats, including recently launched seagrass, macroalgae and live coral essential ocean variable (EOV) data sets). Individual point records are also available through the Global Biodiversity Information Facility (GBIF) and the Intergovernmental Oceanographic Commission (IOC) of the United Nations Educational, Scientific and Cultural Organization's (UNESCO) Ocean Biogeographic Information System (OBIS), which can be used to complement those found in the global data set. While these efforts are continuing to strengthen understanding of seagrass locations, there are still gaps in knowledge. Aside from coordinated observation programmes such as SeagrassNet and Seagrass-Watch, which provide important time series capturing the status of seagrasses in specific locations around the world, comprehensive, large-scale time series on the state of seagrasses remain scarce. Emerging technologies face challenges in capturing the variety of seagrasses that exist globally and can be expensive to use on a regular basis. Short-term projects establish critical baseline data, but often do not provide the long-term, consistent information required for decision-making. To address these challenges, the IOC-UNESCO Global Ocean Observing System (GOOS) is developing a set of EOVs, including one on seagrass cover and composition. The resultant specification sheets and monitoring protocols will help standardize seagrass data collection worldwide, contributing to data standards and best practices to ensure that national, regional and global data inventories can be meaningfully compared.

resources and high-end visualization (Goodchild et al. 2012). Global-scale seagrass estimates, information and insights can be facilitated by this 'big data' paradigm. As of the first quarter of 2019, four main cloud-based platforms had been developed and were offering their cloud environment for storage, processing, analysis and visualization of data in the Earth observation domain: Google Earth Engine (Gorelick et al. 2017), Amazon Web Services (2019), Microsoft Azure (2019), and the European Commission's Copernicus Data and Information Access Services (2019). In 2018, a new cloud-based workflow was designed and utilized on the Google Earth Engine cloud platform to leverage more than 1,000 high-resolution, open satellite images, mapping the extent of the seagrass Posidonia oceanica across more than 16,000 km of the Greek coastline, with 72 per cent overall accuracy (see case study 2).

Artificial intelligence

It would be more difficult for scientists to achieve and scale up seagrass estimations in space and time without the use of AI. This technology refers to non-human programmes or models that can tackle sophisticated mathematical problems. AI now includes: machine learning – a programme that uses input data to build and employ a predictive model; and deep learning – a broader member of the family of machine learning based on the structure and function of the brain, which uses so-called artificial neural networks. These algorithms and frameworks could lead to breakthrough innovations in data-driven seagrass monitoring, especially within cloud environments through: a) improved classification accuracy; b) increased automation of data processing and analysis; and c) development of automated change detection of seagrasses.



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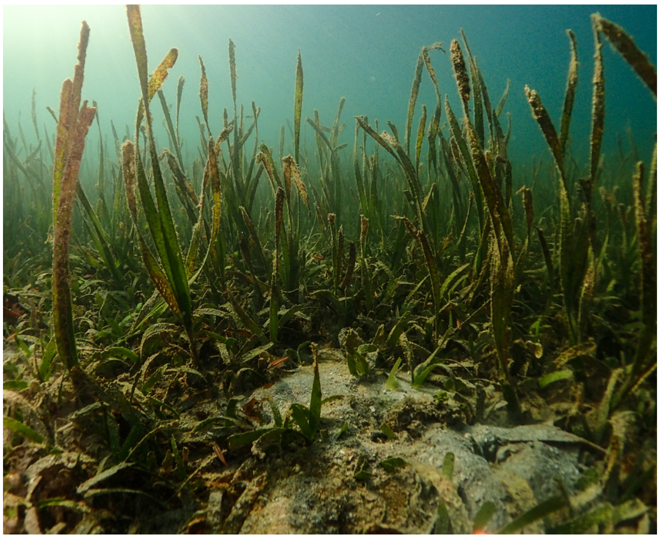

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The data

Reference data: training and validation data

Analysis of Earth observation data using machine learning methods requires high-quality training data for the calibration of algorithms. Such data can be collected by field campaigns collecting in situ observations coupled with GPS or via customized mobile applications. Alternatively, satellite and drone-based, georeferenced and high-resolution images, when available, can be used as basemaps by experienced users who design training data sets in the form of spatial points or polygons. Data validation or ground-truthing is the process of evaluating the accuracy and quality of the classified image. The validation data should be representative of the population, with all the classes sampled (same number of classes as used for classification and training data). The validation data sets can be obtained from various sources such as existing maps and inventories, images from high-resolution satellites or drones, and in situ (diving, snorkelling or on foot in intertidal seagrass areas).

Metadata

Rigorous metadata are an essential but often overlooked requirement for the future use of the collected data, following the 'collect once, use many times' principle. Metadata provide details on the source, location, time frame, version and methodologies used for each data record, and enable comparison between records to determine whether they can be meaningfully combined and compared to inform decisions and develop indicators. Global and regional standards exist, such as ISO 19115 and the INSPIRE Directive, along with platforms that can document available in situ data sets, such as the Dynamic Ecological Information Management System – Site and Data Set Registry (DEIMS-SDR), and help improve the accessibility and reusability of ecological data. Metadata standards commonly used for biological and ecological data include the Ecological Metadata Language (EML) and Darwin Core standards (Madin et al. 2007). The essential variable frameworks – EOVs and EBVs – are working to foster the widespread use of these metadata standards in the observing communities.

From local mapping...

Temporal changes of tropical, intertidal seagrass meadows at Koh Libong, Thailand

The intertidal seagrass meadows at Koh Libong are among the largest meadows in Thailand. They support various ecosystem services, with the most important fisheries for the l ocal population and feeding sites for dugongs, an endangered marine mammal.

To investigate the seagrass distribution changes here, a series of remote sensing images was acquired from Landsat 5 TM and Landsat 8 OLI every five years, starting from 1999. The seagrass area was classified using a machine learning-based supervised classification, while the accuracy was assessed using field data for 2014 and 2019, and image overlap for 1999, 2004 and 2009.

In the years before the 2004 tsunami, seagrass area was increasing at a rate of 0.94 km^2 per year. Large areas (8.85 km^2) were constantly covered with seagrass and only a small portion of the seagrass bed (2.62 km^2) was lost. After the tsunami (2004–2009), large areas of seagrass remained (9.3 km^2), but a large proportion of the meadows was lost (6.88 km^2). Similar trends of seagrass loss (with the loss rate at almost 0.6 km^2 per year) were detected until 2014 when the seagrass meadows started to recover at a rate of 0.38 km^2 per year. By 2019, the total area of seagrass meadows (11.98 km^2) slightly exceeded the original meadow areas in 1999. The onset of the seagrass meadows loss coincides with the Indo-Pacific tsunami in 2004. However, the meadows were not directly impacted by the tsunami wave; rather, it appears that the rise in water level could have triggered the loss.

To national mapping...

Greek territorial waters


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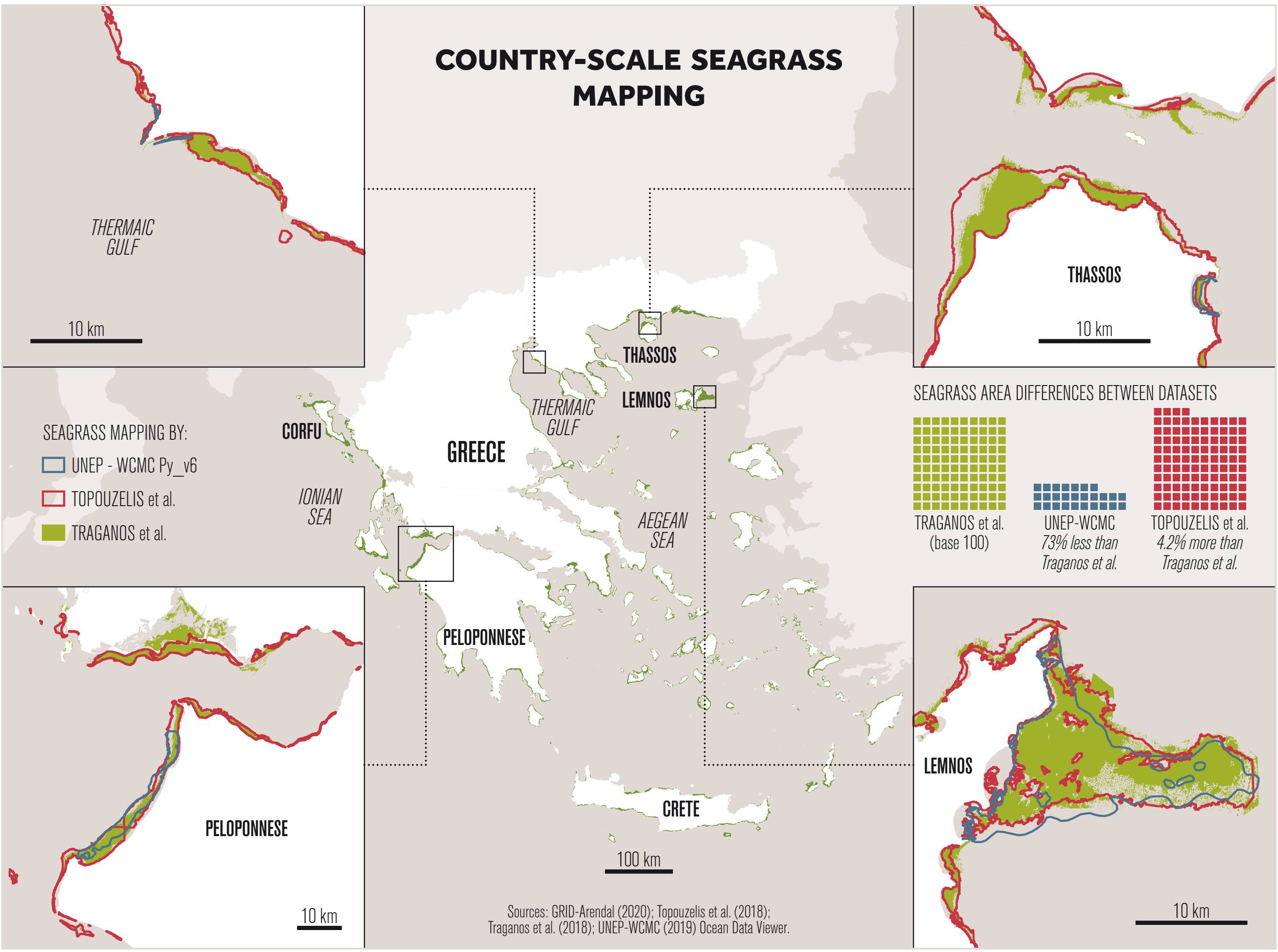
Situated in the Mediterranean bioregion, the Greek coastline covers approximately 16,000 km in length, featuring more than 1,400 islands or islets, a large diversity of sandy beaches, rocky shores, cliffs, coastal lagoons and deltaic systems, along with a variety of coastal habitat types, including subtidal seagrasses.

Utilizing 1,045 satellite images from Sentinel-2, around 1,457 training data polygons and a machine learning-based classification framework in a recently developed end-to-end, cloud-based mapping workflow, Traganos et al. (2018) estimated that there was around 2,510 km^2 of temperate seagrasses between 0 and 40 m deep across the full 40,951 km^2 of the Greek territorial waters (Figure 11). The overall accuracy of seagrass detection was 72 per cent, as revealed by an independent field-based validation data set. These results suggest that there is 4.2 per cent less seagrass than the respective Greek-wide calculation of seagrasses using the satellite imagery of Landsat 8 (Topouzelis et al. 2018). This discrepancy is due mainly to methodological differences in spatial resolution (10 m versus 30 m), field data and image analysis and classification approaches. Conversely, and more importantly, the Traganos et al. (2018) inventory shows about four times more seagrass than estimated by the UNEP-WCMC and Short (2018) seagrass inventory of Greece (639.5 km^2). This could indicate that the latter inventory is an underestimate, which may be attributed to the data source, points and interpolated expert's knowledge. This could have implications for possible underestimation of seagrass distribution estimates at the global scale.

FIGURE 11



To regional mapping solutions

Regional efforts for mapping seagrass in Asia

As part of the Ocean Remote Sensing Project (ORSP) for Coastal Habitat Mapping of the IOC Sub-Commission for the Western Pacific (WESTPAC), seagrasses have been mapped by analysing satellite imagery from the Western Pacific region since 2010. To date, the members of ORSP have mapped seagrass beds in Cambodia (Phauk et al. 2012), Indonesia (Nurdin et al. 2019), Japan (Tsujimoto et al. 2016), Malaysia (Hashim et al. 2014), Thailand (Komatsu et al. 2012) and Viet Nam (Van Luong et al. 2012), after standardizing satellite image analysis methods. The Northwest Pacific Action Plan (NOWPAP), one of UN Environment's Regional Seas programmes, has also started seagrass mapping using remote sensing in China, Japan, Korea and the Russian Federation since 2016. ORSP and NOWPAP decided to use the same methods to map seagrass meadows using satellite images. Recently, both organizations have started to develop an automated web-based system for satellite image analysis in the Asia and Western Pacific region using cloud computing technologies. The cloud-based mapping workflow used at the national and regional levels is highly flexible in terms of space, time and data input. With sufficient validation data, the tool can be used for large-scale, accurate and effective seagrass mapping and monitoring efforts and projects in other areas and seagrass bioregions, although it will be most useful in clear-water regions and for certain species.

Towards a global picture of seagrass location and health

By combining information generated from remote sensing and field monitoring techniques, emerging technologies and existing or new reference data, there is an opportunity to design and apply standardized methodologies to measure the location and condition of seagrass ecosystems globally in a way that is accurate, effective, repeatable and comparable (Duffy et al. 2019; Traganos et al. 2018). The resulting inventories would strengthen understanding of ecosystem tipping points or regime shifts in the broader seascape environment, potentially facilitating forecasts of ecosystem change, and would also strengthen management, conservation and sustainable resource use in these regions. To achieve this goal, similar planetary-scale mapping and monitoring efforts targeting other habitats in the coastal seascape, such as the Allen Coral Atlas, Global Mangrove Watch and Global Forest Watch, should be used for inspiration and capacity-building. These online platforms have emerged from developments linked to cloud computing, open and free satellite image archives, AI and suitable reference data in order to provide relevant baseline and monitoring data.

Global-scale seagrass mapping is increasingly feasible by leveraging the aforementioned technological and data advances. Using open-access satellite image data sets of Sentinel-2 at a 10-m spatial resolution and approximately 15,960 tiles (100 x 100-km area per tile) or 159,600,000 km^2 of three-month satellite mosaics, seagrasses could be mapped worldwide in just one year. To scale up such baseline measurements and quantify the spatio-temporal patterns of seagrasses in the past and future, the following actions are needed:

1. develop and standardize an algorithmic framework
2. design and collect new global-scale reference data to train and validate the AI tools
3. develop and adapt interoperability and complementarity between the different cloud platforms, their utilized codes and data formats
4. find suitable methods for detecting short-living, dynamic, less dense and deep seagrass species.

When combined with national and local in situ monitoring efforts to provide further information on species and ecosystem health, remote sensing approaches can provide a more complete picture of the state and location of seagrass ecosystems globally.

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TRANSFORMING CONSERVATION AND UNDERSTANDING OF SEAGRASS ECOSYSTEMS THROUGH THE USE OF CITIZEN SCIENCE

Richard K.F. Unsworth, Benjamin Jones, Miguel Fortes, Abbi Scott, Peter Macreadie, Fanny Kerninon, Len McKenzie

All authors' affiliations are found on page 4

Members of the public have recorded their observations of the natural world for centuries (Miller-Rushing et al. 2012). In an era of professional ecological science, the use of members of the public acting as volunteers creates a low cost means of data collection. The use of volunteers from the general public creates a much-needed workforce, while helping to link science, policy and practice as a core part of coastal natural resources management (Jones et al. 2018). Volunteers trained to undertake citizen science projects also learn about the topic, enabling them to communicate its importance beyond the scientific field. Finding a way to engage the general public about seagrass ecosystems is vital given the consistent evidence showing the poor level of societal appreciation for them (Duarte et al. 2008).

Current seagrass citizen science projects

Citizen science can help address major conservation challenges by: (1) enabling science that might not otherwise be feasible because of scale or other practical reasons; and (2) better engaging the public in decision-making (McKinley et al. 2017). Within a seagrass context, there is increasing inclusion of citizen science in a range of monitoring and assessment programmes (Jones et al. 2018) (Table 3). Nearly one third of the current long-term seagrass observing networks include some level of citizen science, including Seagrass-Watch and SeagrassSpotter (Duffy et al. 2019). In addition, a growing number of seagrass research and conservation projects are including a volunteer component (for example,

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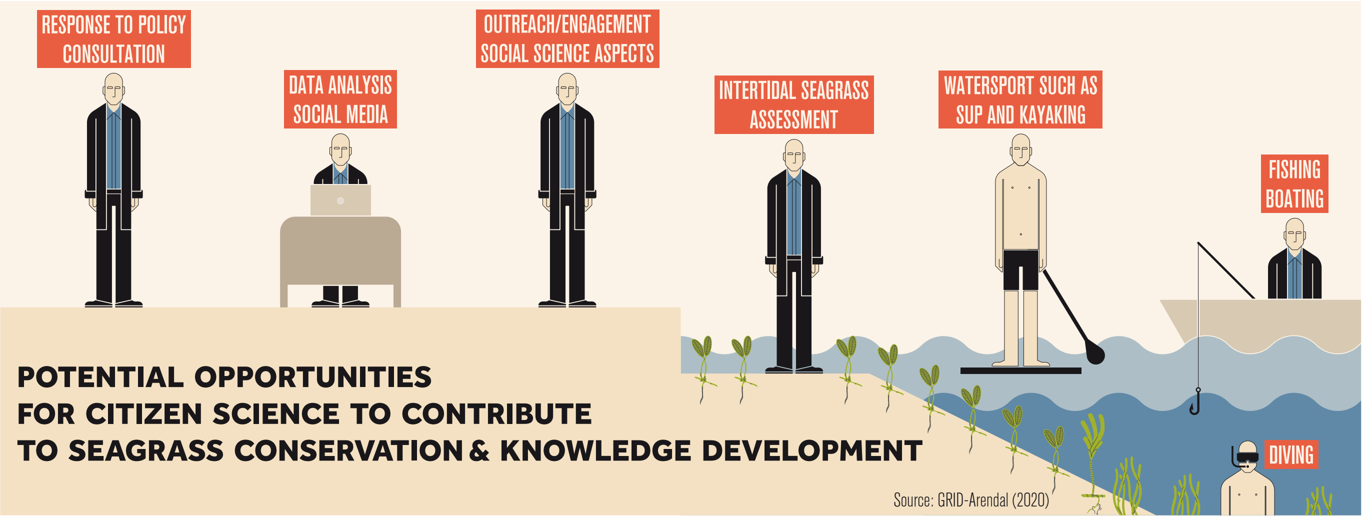
Table 3. Seagrass projects that are either based on or use citizen science and have contributed to environmental policy

Project	Project type	Responsible organization	Reach	Description of citizen science element	Example influence upon policy and management
Seagrass-Watch *seagrasswatch.org*	Scientific lead programme incorporating contributory and collaborative citizen science and citizen engagement	Seagrass-Watch, Australia	Global	Utilizes groups of trained volunteers to collect monitoring data.	Data collected by Seagrass-Watch volunteers assisted with the Great Sandy Marine Park (southern Queensland) zoning plan. In Bantay, the Philippines, Seagrass-Watch helped with lobbying for Executive Order 02-01 Municipal Ordinance 04-01 (an ordinance conserving seagrasses in the Municipality of Puerto Galera).
SeagrassSpotter *seagrassspotter.org*	Contributory citizen science and citizen engagement	Project Seagrass	Global	Uses a phone app and website where users upload georeferenced seagrass pictures and answer basic questions pertaining to health and threats.	Provision of data to the Government conservation body on seagrass locations in Scotland to assist with conservation planning.
Community eelgrass mapping initiative *www.seagrassconservation.org/conservation*	Citizen science	Seagrass Conservation Working Group, British Columbia, Canada	Regional	Utilizes groups of trained volunteers to collect monitoring data.	Mapping data used by the Canadian Government department to analyse seagrass ecosystem value.
Sarasota County Seagrass Survey	Contributory citizen science and citizen engagement	Sarasota County, United States of America	Regional	Utilizes a large group of volunteers for assistance with an annual monitoring survey.	Creation of annual seagrass maps to assist the Southwest Florida Water Management District's SWIM programme.
Skomer Marine Conservation Zone (MCZ) volunteer diving	Citizen science	United Kingdom	Local	Training and utilizing volunteers to assist with detailed seagrass surveys and mapping.	Data assists Special Area of Conservation (SAC) reporting and directly links to MCZ management. In addition, data are sent to the Welsh Government to assist with Section 7 of the Environment (Wales) Act 2016, reporting on key species and habitats.
Seasearch (United Kingdom)	Citizen science	United Kingdom	Regional	Utilizes groups of trained volunteers to collect monitoring data.	Assists with seagrass mapping within SACs and understanding of impacts within SACs to support management.
Seagrass Ocean Rescue *www.projectseagrass.org/seagrass-ocean-rescue*	Citizen science	United Kingdom	Regional	Utilizes groups of trained volunteers to collect material for seagrass restoration projects.	Information is used to create a national policy brief on seagrass restoration best practices.

Source: Adapted from Jones et al. (2018)

TeaComposition H2O, Seagrass Ocean Rescue). At several locations around the world, government entities have created their own bespoke seagrass monitoring programmes driven by volunteers. One of the biggest programmes is in Sarasota Bay, Florida (United States of America), where hundreds of citizen scientists collect data on the spatial extent of seagrass in order to contribute to the creation of annual seagrass maps to assist with the Southwest Florida Water Management District's Surface Water Improvement and Management (SWIM) programme. Citizen scientists conduct water and intertidal assessments at pre-determined locations, often using their own boats. Data are collected using a phone app or paper-based methodologies. Available information indicates that citizen science is most successful when it requires minimal

FIGURE 12



specialized equipment and resources (Duffy et al. 2019). In this way, the incorporation of information and communication technology (ICT) into citizen science has expanded its reach, as in the case of SeagrassSpotter for example, which to date has collected data in 75 countries, including observations of 36 species, using a web and phone app approach. Other programmes, such as the Indo-Pacific Seagrass Network, that include some volunteer aspects have pioneered the use of the Open Data Kit as an ICT platform, facilitating rapid collection and QA/QC of data.

The potential for citizen science to support policy change

Citizen science can help members of the public play an active role in creating an evidence base for policymaking, while understanding and monitoring the changes taking place around them. There are two ways that citizen science can improve conservation policies and outcomes (McKinley et al. 2017). One pathway involves acquiring scientific knowledge, just like conventional research. Volunteers help generate scientific information for conservation scientists, natural resource and environmental managers and other decision makers (McKinley et al. 2017). The other pathway stimulates public input and engagement in natural resource and environmental management and policymaking. Volunteers can directly provide input into decisions, for example, by using what they learned in a citizen science project to comment on proposed government action (Figure 12). Given the generally poor understanding of seagrass meadows and their importance to society by the general public, citizen science can be used as a mechanism to increase influence on policy by volunteers, thereby strengthening seagrass conservation. In a seagrass context, there are a range of examples where policy could benefit from data collected by citizen science (see Table 4).

Table 4. Example of research and conservation questions and challenges that can be answered using citizen science

Viewpoint	Focus level	Activity
Understanding phenology in the context of a changing climate	Biological	Identification of flower occurrence Sediment seed counts
Understanding disease extent and causes	Biological	Occurrence of wasting disease
Seagrass distribution and abundance	Ecological	Presence of seagrass locally, regionally, nationally or globally Site-specific species abundance
Biodiversity within seagrass	Ecological	Presence of fish within seagrass Presence of invertebrates within seagrass Identification of large marine fauna within seagrass
Threats to and management of seagrass	Socioecological	Identification of current threats, e.g. mooring surveys
Historic seagrass loss	Socioecological	Use of local ecological knowledge
Fisheries use	Socioecological	Identification of fisheries use of seagrass meadows
Responses to land-use changes	Socioecological	Monitoring change over time
Restoration	Biological	Collection of materials

Source: Adapted from Jones et al. (2018)

Building partnerships for seagrass citizen science

While many citizen science projects rely upon the goodwill of genuinely interested members of the public, finding ways of increasing this pool of participants is necessary to increase the impact of citizen science. One approach is for conservationists and scientists to build partnerships with public and private organizations, businesses, clubs and societies. This could include working with Scout groups and youth clubs to undertake field sampling activities, for example. This has the advantage of high levels of group organization and guaranteed numbers associated with such activities, as well as the ability to more readily direct their participation. Private companies are increasingly looking at environmental volunteering opportunities for their staff through their corporate social responsibility (CSR) programmes in order to increase staff well-being (Ondiviela et al. 2014). One such example is the HSBC/Earthwatch programme run in collaboration with Deakin University, which involves corporate staff members assisting the university by collecting data on the carbon storage content of a range of coastal environments. In addition, Project Seagrass has recently developed a partnership with an international research-tourism company to roll out the use of the SeagrassSpotter platform to volunteers.

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PART 2

POLICY AND MANAGEMENT OPTIONS

POLICY AND MANAGEMENT OPTIONS

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All authors' affiliations are found on page 4

Protecting and restoring seagrass ecosystems provides an opportunity for countries to achieve several national targets in relation to the Sustainable Development Goals (SDGs), strengthening local economies while meeting numerous global commitments. As demonstrated in the chapter on seagrass ecosystem services, seagrass goods and services underpin the well-being of many coastal communities around the world, with direct links to food security, local economies and climate change resilience. Despite this importance, seagrasses have often been a secondary consideration within policy and management measures. Of the known distribution of seagrasses, only one quarter (26 per cent) occurs within MPAs (UNEP-WCMC and Short 2018), with only a few examples existing of integrated management approaches that explicitly reference seagrasses and account for cumulative pressures. This level of protection does not distribute evenly among the different seagrass bioregions, with only 17 per cent of seagrasses in the Tropical Indo-Pacific bioregion occurring within MPAs. In contrast, 40 per cent of warm-water coral reefs, 43 per cent of mangroves, 42 per cent of saltmarshes and 32 per cent of cold-water corals are placed within gazetted MPAs, making seagrasses the least protected marine ecosystem (Tables 5 and 6). Of course, it must be acknowledged that being gazetted within a MPA does not necessarily confer protection to marine ecosystems, and that many MPAs exist without effective compliance or management plans. Nevertheless, this figure does indicate that seagrasses are not the focus of policy and management strategies. To achieve the biodiversity and sustainable development goals and targets set out by the global community in the coming decade, there is an urgent need to develop and implement integrated policies and management options that recognise the multiple benefits of seagrass ecosystems.

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Table 5. Recorded area of ecosystems and percentage within MPAs

Type of ecosystems	Globally recorded area (km²)	% within MPA
Seagrasses	324,248	26
Mangroves	152,233	43
Saltmarshes	54,661	42
Cold-water corals	18,993	32
Warm-water corals	150,045	40

Table 6. Recorded seagrass area per bioregion and percentage within MPAs

Seagrass bioregion	Recorded seagrass area (km²)	% within MPA
Mediterranean	25,777	35
Temperate North Atlantic	3,031	77
Temperate North Pacific	1,134	70
Temperate Southern Oceans	19,609	48
Tropical Atlantic	108,887	32
Tropical Indo-Pacific	165,663	17

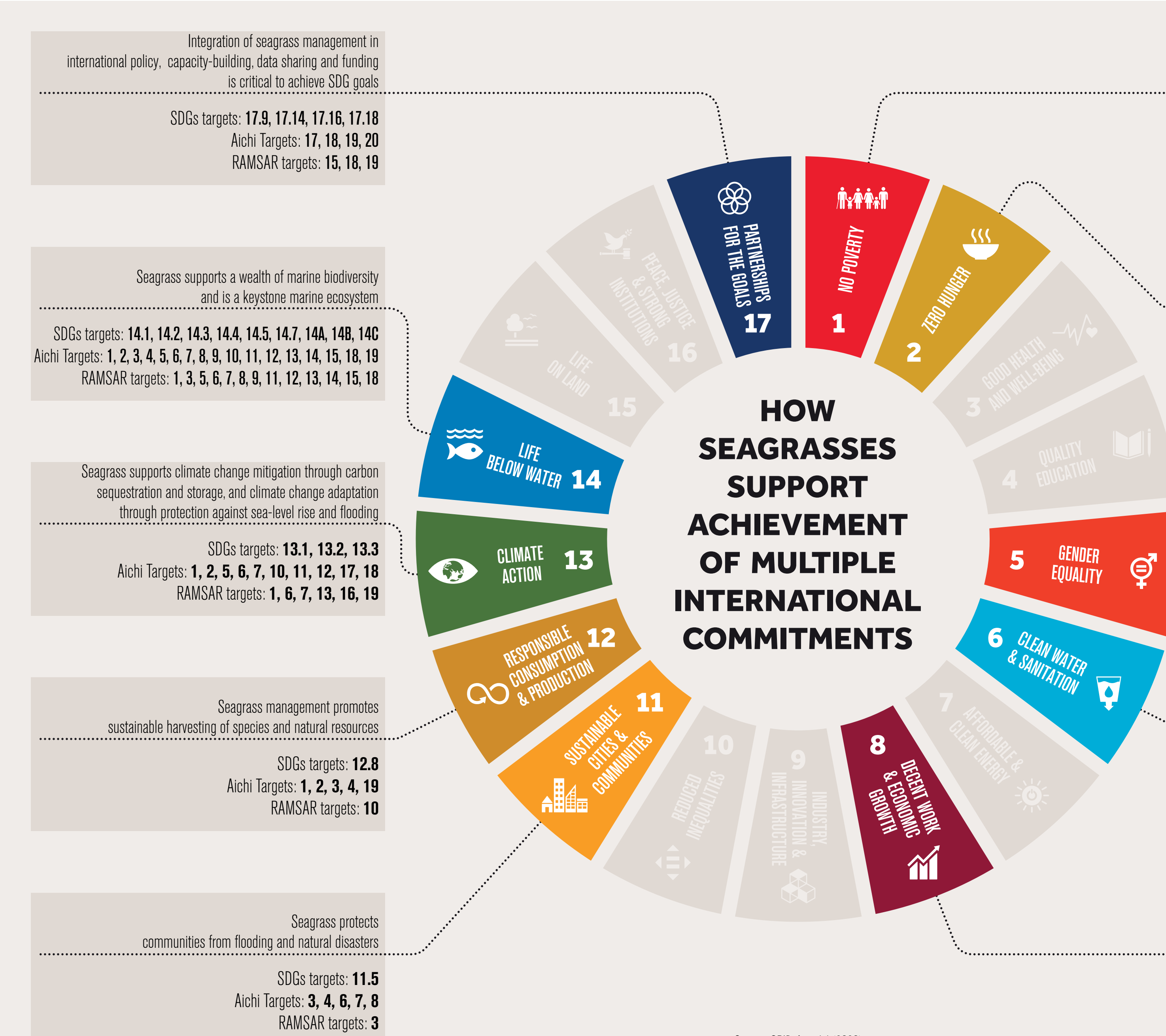
These tables are based on best available data and may be subject to error or improvement as better data become available.

Policy frameworks

2030 Sustainable Development Agenda and Sustainable Development Goals

Seagrass ecosystems can directly or indirectly support progress towards most of the United Nations SDGs and are essential to the delivery of targets relating to climate change and food security. The benefits from conserving and restoring seagrass meadows can help countries achieve 26 targets and indicators associated with 10 SDGs, including SDGs 1, 2, 5, 6, 8, 11, 12, 13, 14 and 17 (Figure 13). For instance, seagrasses contribute to climate change mitigation through carbon sequestration and storage, while helping to buffer the impacts of extreme weather events, thereby enhancing the climate resilience of local communities. Seagrasses also contribute to economic and food security through fish nursery grounds that improve fisheries yields, or through tourism-generating income for communities (see chapter on ecosystem services).

FIGURE 13



Source: GRID-Arendal (2020)

When combined with financial mechanisms, such as Payment for Ecosystem Services (PES) schemes, these approaches can generate income for local communities through a portfolio of nature-based solutions (see chapter on financial incentives). Seagrass management practices need to be gender sensitive recognizing the differentiated knowledge, roles and needs of men and women, thus facilitating gender equality in governance and decision making. Conservation and restoration of seagrasses can thereby provide countries with multiple benefits and help them achieve commitments that align with their national targets.

Aichi Biodiversity Targets and the post-2020 biodiversity framework

Of the CBD's Strategic Plan for Biodiversity 2011–2020 and its 20 Aichi Biodiversity Targets that are directed at five strategic goals, many are directly or indirectly relevant to seagrasses (see Figure 13). Several goals, in particular those addressing habitat loss (Target 5), fish and invertebrate stocks (Target 6), pollution (Target 8), MPAs (Target 11), ecosystem service provision for livelihoods and well-being (Target 14) and climate security (Target 15), directly map to benefits received from seagrasses or activities that will help protect and restore them. The 2015-2020 Gender Plan of Action, adopted in 2014 at the CBD COP 12, constitutes a significant mandate for Parties on the integration of gender considerations as well as a strengthened framework of actions for the Secretariat, to mainstream gender across policy, organizational, delivery and constituency spheres. Coastal wetlands, such as seagrasses and mangroves, are also documented in, and can support the delivery of, countries' national biodiversity strategies and action plans (NBSAPs) and national reports, which are intended to define the current status of biodiversity, as

At least 1 billion people live within 100km of a seagrass meadow, potentially depending on seagrass ecosystems for their livelihoods (fishing, tourism, etc.)

SDGs targets: **1.5**
Aichi Targets: **1, 2, 14**
RAMSAR targets: **11**

Hundreds of millions of people are dependent upon seagrass for their daily protein needs

SDGs targets: **2.1, 2.3**
Aichi Targets: **3, 4, 7, 8, 18**
RAMSAR targets: **3, 10**

Women play a central role in the management and safeguarding of seagrass ecosystems

SDGs targets: **5.5**
Aichi Targets: **14, 18**
RAMSAR targets: **10**

Seagrasses are filters for nutrients, pollutants, disease and provide clean water

SDGs targets: **6.1, 6.3, 6.6**
Aichi Targets: **2, 3, 4, 5, 6, 7, 8, 11, 12**
RAMSAR targets: **1, 2, 3, 5, 6, 7, 8, 12**

Seagrass supports livelihoods from fisheries and tourism

SDGs targets: **8.9**
Aichi Targets: **2, 6, 7**
RAMSAR targets: **1, 13**

How nationally determined contributions recognize seagrasses and other coastal and marine ecosystems

197 countries signed the Paris Agreement

185 counties submitted NDCs (by 2019)

64 coastal and marine ecosystems in terms of adaptation and mitigation

64 coastal and marine ecosystems in terms of adaptation

34 coastal and marine ecosystems in terms of mitigation

21 measurable targets for coastal and marine ecosystems

45 mangroves in terms of adaptation and mitigation

10 seagrass in terms of adaptation and mitigation *(see appendix for these NDCs)*

8 seagrass in terms of adaptation

5 seagrass in terms of mitigation

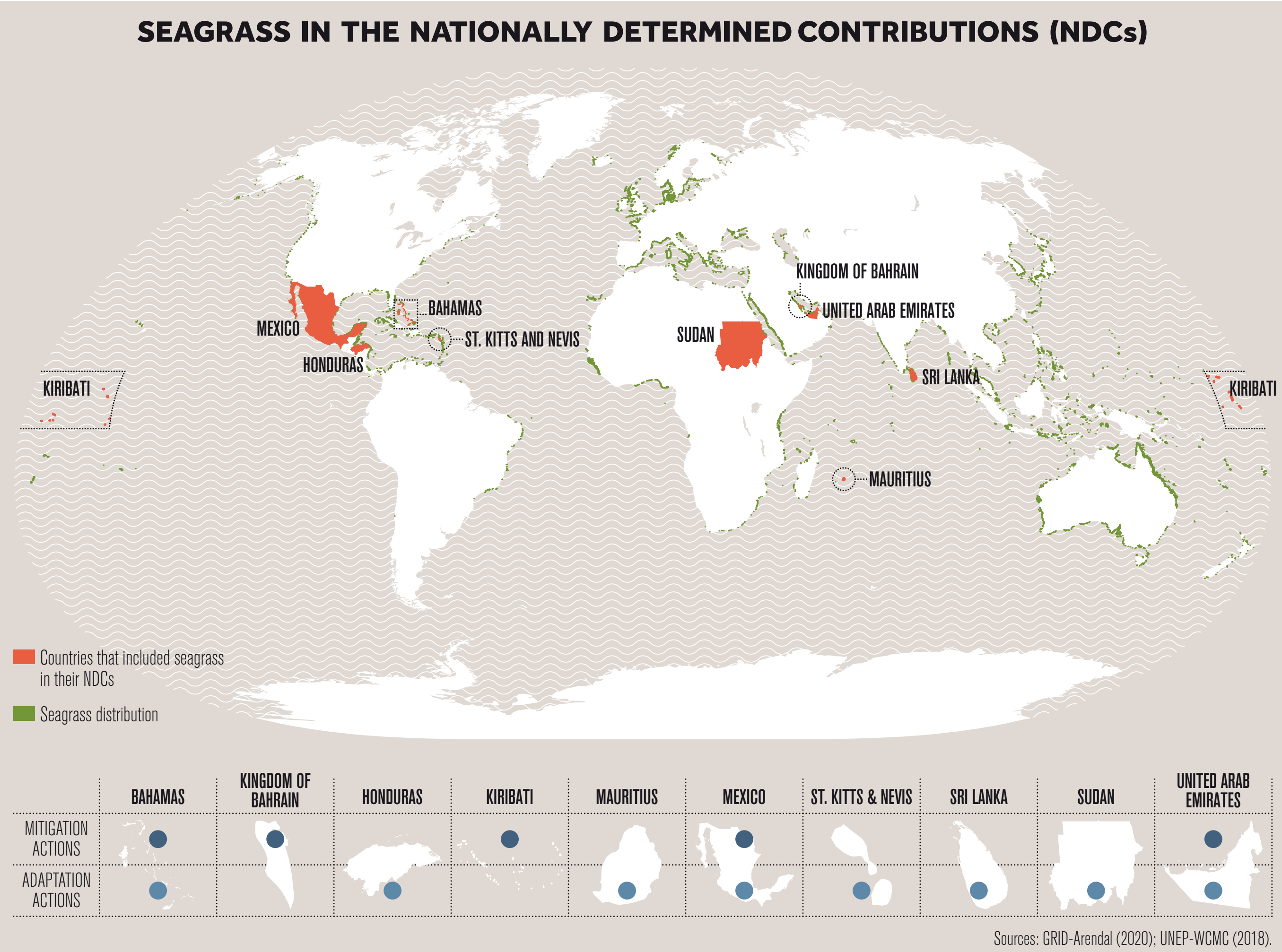
1 measurable target that includes seagrass

well as the strategies and actions necessary for conserving and sustainably using biodiversity in accordance with the successful implementation of the CBD and the 2050 Vision for Biodiversity – 'Living in harmony with nature'. Consultations for the development of the post-2020 biodiversity framework are currently ongoing, offering an opportunity to develop SMART targets (specific, measurable, achievable, relevant and time-bound) for the effective management of seagrasses and associated ecosystems.

Paris Agreement and nationally determined contributions

Seagrasses support both nature-based solutions to climate change mitigation (Fourqurean et al. 2012) and adaptation (Potouroglou et al. 2017). Through the UNFCCC, several international agreements have established frameworks of relevance to seagrasses. For instance, the Kyoto Protocol, an international treaty which entered into force in 2005, established several mechanisms. Particularly noteworthy was the establishment of international trading in carbon offsets, especially through the Clean Development Mechanism, which allows for investment of projects that reduce greenhouse gas emissions. The Paris Agreement, adopted in 2015 and signed in 2016, further promotes actions on climate change mitigation and aims to keep the increase in global average temperature to well below 2°C above pre-industrial levels, and to pursue efforts to limit the increase to 1.5°C. One of the key instruments under the Paris Agreement is the establishment of NDCs, which provide a forum for each nation to outline self-determined steps they will take to achieve emissions reductions. An important contributor to NDCs is the establishment of national greenhouse gas inventories, and the IPCC has provided a set of guidelines on how to

FIGURE 14



account for greenhouse gases in wetlands, which include seagrasses. Like other coastal blue carbon ecosystems (for example, mangroves and saltmarshes), these values are being recognized by countries in their NDCs. In 2016, Martin et al. reported that 28 countries had acknowledged the importance of coastal blue carbon habitats in terms of mitigation, with 59 countries having referenced coastal ecosystems in relation to adaptation strategies. As of September 2019, an estimated 64 countries have included a reference to coastal and marine ecosystems in terms of adaptation and mitigation in their NDCs. Of these, only 10 countries include an explicit reference to seagrasses, with 8 referring to adaptation and 5 referring to mitigation, though these do not necessarily include a measurable target. Only 1 country so far includes a measurable target that references seagrass ecosystems in its NDC. The NDC for the Bahamas includes a target for the protection of 20 per cent of the country's nearshore marine environment by 2020. These protected areas will conserve and protect habitats for grouper and bonefish spawning aggregations, coral reefs, seagrass meadows, mangrove nurseries and important migratory bird areas. Accounting for seagrass climate change mitigation and adaptation benefits are important for the development of policies that protect and restore such ecosystems. Combining these values with other seagrass economic benefits and financial mechanisms (see chapter on financial incentives) could support sustainable long-term NDC actions.

Sendai Framework for Disaster Risk Reduction

In addition to carbon benefits, seagrasses mitigate risks to coastal communities and infrastructure associated with extreme weather events such as storm surges and flooding (Duarte et al. 2013; Ondiviela et al. 2014). By minimizing risk, seagrasses can also reduce risks related to economic loss, aligning with the targets of the Sendai Framework for Disaster Risk Reduction. Although nature-based solutions do not feature prominently, there is mention of a need to "strengthen the sustainable use and management of ecosystems and implement integrated environmental and natural resource management approaches that incorporate disaster risk reduction" (United Nations 2015).

The United Nations Decade on Ecosystem Restoration (2021–2030) and the United Nations Decade of Ocean Science for Sustainable Development (2021–2030)

Both of the United Nations Decades, proclaimed by the United Nations General Assembly through resolution 73/284 on 1 March 2019, provide excellent opportunities to draw focus to and attract funding for the protection and restoration of seagrass ecosystems. The United Nations Decade on Ecosystem Restoration (2021–2030) aims to support and scale up efforts to prevent, halt and reverse the degradation of ecosystems worldwide, and to raise awareness of the importance of successful ecosystem restoration, which includes marine and coastal ecosystems. To achieve decade-related goals, stakeholders can include seagrasses in their commitments and action. The United Nations Decade of Ocean Science for Sustainable Development (2021–2030) supports efforts to reverse the cycle of decline in ocean health and to gather ocean stakeholders worldwide behind a common framework that will ensure ocean science can fully support countries in creating improved conditions for sustainable ocean development. As a critical marine habitat, seagrasses should be well recognized in this process.

Ramsar Convention on Wetlands

The Ramsar Convention is an international agreement promoting the conservation and wise use of wetlands, which include seagrass meadows. Resolution XIII.20, created at the 2018 Ramsar Conference of Contracting Parties, specifically promotes the conservation and wise use of intertidal wetlands and ecologically associated habitats, with explicit mention of seagrass ecosystems.

United Nations Environment Assembly resolutions

Although there is no United Nations Environment Assembly (UNEA) resolution specifically adopted for the sustainable management of seagrass ecosystems, several resolutions are related to seagrass ecosystems, including resolutions 4/11 on protection of the marine environment from land-based activities, 4/12 on sustainable management for global health of mangroves, and 2/12 and 4/13 on sustainable coral reefs management. Many of the drivers of seagrass degradation are covered in these resolutions without specifically mentioning seagrass ecosystems, with Member States calling for actions to address multiple and synergistic stressors. A positive development for international seagrass policy would be the proposition and adoption of a UNEA resolution specifically on the sustainable management of seagrass ecosystems.

Regional, national and local approaches

While seagrasses have not typically been the main focus of policies and management measures, there are examples of regional, national and local policy approaches that have led to proven benefits for seagrass ecosystems. A recent global review identified 20 case studies covering five of the six seagrass bioregions represented the range of potential pressures and governance structures (Griffiths et al. 2019). This review found that management frameworks require more cross-sectoral management approaches and integration across jurisdictions, aligning with the global move towards holistic, inclusive and sustainable ocean-based economies.

Regional

- In the **European Union**, seagrasses are explicitly referenced under Annex I of the European Union Habitats Directive, which can lead to designation as 'special areas of conservation', and as 'biological quality elements' or indicators of overall ecosystem health in the European Union Water Framework Directive. A recent study by de los Santos et al. (2019) showed that the rate of seagrass loss in European waters has slowed down for most species, and that here has been a reversal of the trend for fast-growing species, with gains in seagrass cover occurring in the 2000s.
- In the **Wider Caribbean region**, the Cartagena Convention is the only legally binding regional environmental treaty and includes the Protocol Concerning Specially Protected Areas and Wildlife (SPAW) signed in 1990. This protocol includes, among other actions, objectives to "mobilize the political will and action of governments and other partners for the conservation and sustainable use of coral reefs and associated ecosystems such as mangroves and seagrass beds" and "effectively communicate the value and importance of coral reefs, mangroves and seagrass beds, including their ecosystem services, the threats to their sustainability, and the actions needed to protect them" (UNEP, The Caribbean Environment Programme).
- In the **East Asian Seas**, national action plans were developed for seagrasses in the South China Sea and Gulf of Thailand, including the legislation needed to maintain nationally important habitat areas (UNEP and Global Environment Facility [UNEP-GEF] 1999).
- The **Memorandum of Understanding on the Conservation and Management of Dugongs and their Habitats throughout their Range** (effective as of 31 October 2007), aims to promote internationally coordinated actions to ensure the long-term survival of these animals and their seagrass habitats throughout their extensive range. It covers 46 range states across Africa, Asia and Oceania (Dugong and Seagrass Conservation Project).

National

- In **India**, seagrass meadows are listed as ecologically sensitive areas as per the Coastal Regulation Zone (CRZ) Notification of 2011 (Ramesh et al. 2018).
- In **New Zealand**, seagrass management is inextricably linked with the management of estuaries and coastal ecosystems. A holistic, ecosystem-based approach to managing these systems and their catchments is therefore being practised (Turner and Schwarz 2006).
- In **Australia**, management of the Great Barrier Reef is supported by various policies and programmes, including the Reef 2050 Cumulative Impact Management Policy and Net Benefit Policy passed in July 2018. The Reef 2050 Policy includes seagrass in its Integrated Monitoring and Reporting Program.
- In **Indonesia**, a national plan of action has been developed for the conservation for dugongs and seagrasses.

Subnational

- In **Chesapeake Bay, Maryland, United States of America**, the Clean Water Act, Watershed Implementations Plans and cooperation between federal, state, local and scientific agencies (the Chesapeake Bay Program) led to nutrient reductions that have helped seagrasses recover, showing a 5 per cent increase from 2016 to 2017 and an overall improvement of 32 per cent from 1986.

- In **Tampa Bay, Florida, United States of America**, local and regional partners working together through the Tampa Bay Estuary Program (TBEP) adopted numerical seagrass protection and restoration goals, water transparency targets and annual nitrogen loading rates. The development of the goals and targets followed a multistep process involving joint collaboration between public and private sectors, which led to an ad hoc public-private partnership known as the Tampa Bay Nitrogen Management Consortium (TBNMC). Seagrass extent has increased by more than 65 per cent since the 1980s, and in 2014, it exceeded the recovery goal adopted in 1996 (Greening et al. 2016).

Management options

In order to effectively attain policy objectives, there are management measures and tools available for use at the national, regional and global levels to ensure a sustainable future for seagrass ecosystems. Policy- and decision makers can consider the following key options:

- **Develop national action plans for seagrass ecosystems.** Currently very few countries have prepared plans specifically for the protection and management of seagrass ecosystems, compared with the many countries that have developed national plans for coral reefs and mangrove ecosystems. An important step to protect and manage seagrass ecosystems sustainably would be to develop national plans for seagrass management, including targets for protection and health. National action plans for seagrass should be connected to, and help to deliver on, NDCs to the Paris Agreement, CBD targets and the SDGs. National action plans for seagrass should also be well integrated and recognize connectivity with adjacent ecosystems, for example coral reefs, mangroves, kelp forests or saltmarshes, as appropriate.

- **Develop integrated coastal zone management or marine spatial plans, with management measures for seagrasses.** Spatial planning that integrates stakeholder and cross-ministerial consultation can help with developing more holistic management measures that are effective across the land–sea interface, and that reduce cumulative pressures facing seagrasses and associated ecosystems.

- **Implement ecosystem-based fisheries management measures.** Adoption of the ecosystem approach to fisheries of the Food and Agriculture Organization of the United Nations (FAO) takes into account protection of the habitats supporting sustainable fisheries, with a focus on reducing pressures on seagrasses and associated species, while also reducing or eradicating the use of destructive fishing gear (Garcia et al. 2003).

- **Implement temporally or spatially defined closures or no-take zones that boost larval production and reduce pressures on degraded areas.** These should be designed through community engagement and co-management structures, to help enhance support for, and the effectiveness of, these zones.

- **Enhance explicit protection of seagrass meadows within protected and conserved areas.** MPAs, locally managed marine areas (LMMAs) or other effective area-based conservation measures (OECMs) that are designed with specific measures for conserving seagrasses and associated ecosystems are likely to have more effective conservation outcomes for these ecosystems.

- **Address direct and indirect drivers of seagrass degradation.** To halt degradation and promote recovery, management must take into account the factors necessary to strengthen seagrass ecosystem resilience and avoid 'ecosystem regime shifts' that fundamentally alter the potential for these ecosystems to recover. Focusing on measures that enhance genetic diversity, species diversity, species biological traits, ecosystem connectivity and continuous, non-fragmented habitat can contribute to the resilience of seagrass ecosystems. For instance, pressures such as water quality issues arising from nutrient loads can be addressed by treating wastewater, reducing deforestation upstream or reducing use of fertilizers in agriculture, among other practices. Likewise, ballast water management can reduce the risk of invasive species transferring to seagrass habitats. If these drivers of ecosystem degradation or fragmentation affecting seagrass ecosystem resilience are not addressed, restoration activities are unlikely to be successful (Unsworth et al. 2015).

- **Invest in seagrass ecosystem restoration.** Although the number of seagrass restoration trials have been relatively small, a review of 1,786 trials found that restoration success depends on several factors, including the removal of threats and proximity to, and recovery of, donor seagrass beds (van Katwijk et al. 2015). Planting techniques also play a role in success: large-scale planting can increase survival rates, while site selection is important. Seagrass ecosystem restoration contributes not only to local benefits through associated services, such as food provision and coastal protection, but also to global targets such as those associated with the United Nations Decade on Ecosystem Restoration.

- **Implement consistent remote sensing and in situ monitoring of seagrass habitats.** This approach can help to track the effectiveness of management measures, detecting inter-annual trends and supporting adaptive management and future planning. Monitoring can also play a role in informing sustainable development ambitions, tracking derived benefits associated with ecosystem services and reporting on national commitments in accordance with global targets.

- **Increase public awareness campaigns and education programmes.** Enhancing local communities' or tourists' awareness of the value of seagrass ecosystems can help to strengthen compliance with management measures and generate appreciation for these ecosystems to overcome the 'charisma gap'.

- **Encourage the use of traditional and local ecological knowledge in developing management strategies.** Engaging local communities in co-managing seagrass ecosystems or associated protected areas can help build more effective and well-rounded initiatives.

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To be effective, these options should be considered at appropriate scales and levels of governance and understood in terms of their implementation approaches (for example, step-zero analysis, adaptive management, stakeholder participation). Inclusiveness and equitable distribution of impacts, privileges, and opportunities (for example, gender roles and access to resources) are also important considerations. Bioregional, political, cultural and species-specific factors determine the best methods for influencing policy- and decision makers to implement management actions that reduce impacts on seagrass ecosystems. Every situation therefore requires careful consideration of a range of socioecological factors (Coles and Fortes 2001).

Moving towards just seagrass conservation practices

The concept of justice in the marine realm is an emergent field critical to policymakers, researchers and practitioners (Bennett 2018; Jentoft 2019; Martin et al. 2019). 'Blue growth' agendas are being designed, based on the large economic opportunities the ocean offers, though there are emerging concerns about marginalization of coastal people, small-scale fisheries and women. The concept of 'blue justice' is evolving in parallel as a response to those economic developments. Justice is intuitively related to what people in society perceive as fair and correct. It has a formal legislative component as well as an informal component related to moral, ethics and ideology. As a complex, debated concept, justice needs to be operationalized for the marine realm in general and for seagrasses in particular. Considering justice for seagrass socioecological systems (SES) is a promising path to enhance governance, management, conservation and the overall sustainability of seagrass SES. Integrating justice in governance and management processes will not only increase the likelihood of compliance and success, but is ethically and morally desirable.

Justice in seagrasses can have at least three entry points:

1. Individual justice (for example, ensuring use rights for women collecting invertebrates in seagrass meadows)
2. Social justice (for example, management and legislation for a coastal community using seagrass meadows for daily protein provision)
3. Justice for nature (referring to the application of justice to non-humans (Nussbaum 2006) and considering the intrinsic value of the seagrass meadows).

The main goal is to have a long-term productive seagrass SES. Achieving this will require considering justice for both the ecosystem and people. Seagrasses' intrinsic values must be preserved, and people's activities and needs should be considered and underpinned by a deep consideration of nature. Where human activities are abundant and populations rely on seagrass goods and services, 'inclusive management' (de la Torre-Castro 2019) and/or other approaches could be implemented to effectively promote justice. The diversity of resource users (men and women fishers, elders, children, managers, entrepreneurs, hoteliers, tourists, etc.) should be considered and included in all processes.

Practical considerations for integrating justice in seagrass SES include:

- investing adequate resources to develop in-depth knowledge of the specific seagrass SES, and defining clear objectives and the scale at which justice considerations should be addressed
- reaching all key actors in the seagrass SES, particularly when resource dependence is high, and explicitly considering gender differences, roles, activities and power issues
- increasing process legitimacy by giving the right weight to the different actors
- creating institutions that provide fair access to the seagrasses and associated goods and services
- considering both the intrinsic value of the meadows and their value for human needs
- directly tailoring specific management plans and/or legislation for those in need.

PART 3

FINANCIAL INCENTIVES

FINANCIAL INCENTIVES

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What sources of investment exist for seagrass conservation?

The protection and restoration of seagrass may be supported through the broad investment domains of a) conservation; and b) climate mitigation and adaptation. These are sometimes merged but are more typically considered separately. These domains are broad and complex, leading to widespread misunderstanding of the opportunities and constraints they each bring. Each has arisen largely in response to separate drivers, which are themselves multi-layered and complex. For example, while intergovernmental agreements outline a broad agenda, and government and financial institutions determine how much money is available, restoration actions are often implemented by small groups of individuals. This therefore leads to the issue of how to make sense of such a complex and tangled network of actors and money in order to generate the best outcomes for seagrass protection and restoration.

Understanding the complexity can be helped by recognizing that there is a coarse dichotomy between public and private investment, although the two can be combined. This report uses the word 'investment' loosely to include funds (defined as money given without the explicit expectation of financial return, such as through grants) and finance (defined as money given with an explicit expectation of repayment or other financial return). Internationally, there are significant public funds available to support nations – especially developing nations – to achieve obligations they have under international agreements and treaties, such as the SDGs, Aichi Biodiversity Targets, Kyoto Protocol and Paris Agreement. Examples include the Global Environment Facility (see box) and the Green Climate Fund (https://www.greenclimate.fund/who-we-are/about-the-fund), which was founded to provide funds to help nations, especially least developed countries and small island developing States, achieve the commitments they have made under the Paris Agreement.

Global Environment Facility

The Coral Reef Funding Landscape website (www.coralfunders.com) provides a very useful resource for identifying investments in coral, seagrass and mangrove conservation. It hosts a data set of 314 projects, with the Global Environment Facility (GEF) Trust Fund – the leading source of finance. The GEF serves as a financial mechanism for many environmental conventions, helping developing countries to meet their obligations under the Convention on Biological Diversity (CBD) and the United Nations Framework Convention on Climate Change (UNFCCC), among others. Since 1994, this source has provided over $1.05 billion to more than 40 projects concerned with seagrass conservation and restoration.

Some other intergovernmental organizations also provide supplemental public funds to support initiatives for member states in specific regions. For example, the Commonwealth Climate Finance Access Hub (http://thecommonwealth.org/climate-finance-access-hub) provides funds for Commonwealth member states (currently numbering 53 nations) to address climate change, including to leverage funds from sources such as the Green Climate Fund.

Many nations also have public funds for achieving specific conservation or climate objectives, either for activities within their own borders or as part of overseas development assistance to support activities in other countries. Some of these are classic donor-style funds, such as bilateral aid, in which money is provided for activities with no expectations of direct financial return. However, increasingly there are efforts to create more innovative financial interactions with the potential to leverage more investment, such as debt-for-nature swaps, which confer a greater set of expectations.

These public funds collectively comprise tens of billions of dollars in finance. However, the amount of finance needed to achieve global conservation and climate goals is estimated to be hundreds of billions or even trillions of dollars (Huwyler et al. 2014). As a result, significant efforts have been made in developing mechanisms that allow private and corporate investment. Perhaps the simplest of these is philanthropy. Like public funds, there is usually no explicit expectation of financial returns for such donations, although motivations often arise from a need to fulfil CSR strategies. Although important in some specific contexts, the amount of money available through philanthropy is typically a small proportion of the total (Huwyler et al. 2014).

Biodiversity offsetting (or compensatory mitigation) may provide another source of funds. In this case, entities (individuals, governments or businesses) provide money as a compensation payment for an action that has a detrimental impact on nature in order to restore or enhance similar ecosystems elsewhere. In some jurisdictions, including the United Kingdom, the United States of America and some Australian states, offsetting is a mandatory or optional part of the planning process (Bull et al. 2013). Note that these 'biodiversity offsets' are not to be confused with carbon offsets, which are described later.

A growing, and potentially very substantial, source of investment is through finance, in which money (or assets) is provided with an explicit set of expectations about direct or indirect financial returns. These exist in many forms, from simple loans that require repayment to purchases of specific goods and services (Vanderklift et al. 2019). Several reports from financial institutions suggest that this is a domain with large potential to expand (Suttor-Sorel 2019). For example, the International Finance Corporation, a member of the World Bank Group, estimates that achieving the Paris Agreement obligations of just 21 countries will open $23 trillion in investment opportunities by 2030 (International Finance Corporation 2016).

Some financial mechanisms already exist, but their application to seagrass protection and restoration is currently limited. Other mechanisms need to be developed and structural reforms are required to facilitate this. For example, 'natural capital', meaning all the living and non-living components of ecosystems that generate ecosystem services used by people, is not usually explicitly accounted for in market-based transactions (such as when wood is harvested from mangrove forests), leading to a gradual decline in the quality of this capital and therefore of the value it generates. This phenomenon, resulting from an incorrect perception and incorporation of the value of the natural ecosystems that create the goods and services, has been called a "market failure" (Guerry et al. 2015). There are numerous consequences to this, including the generation of problems that cost far more to fix than the revenue created by the original transactions (such as the cost of repairing storm damage from infrastructure that would otherwise have been protected by mangroves).

What are payments for ecosystem services schemes?

One promising class of financial investment is a PES scheme. This type of scheme embodies the principle that the beneficiary pays for the delivery of ecosystem goods or services in a way that also recognizes the value of the natural capital that underpins it. Those who benefit from an ecosystem service pay those who are responsible for producing or maintaining it. Although conceptually simple and with a relatively recent coinage, the idea has a long pedigree (Gómez-Baggethun et al. 2010). Implementation of effective PES schemes can be challenging, and the concept has generated considerable theoretical debate (Hejnowicz et al. 2015). A useful and influential clarification was provided by Wunder (2005), who applied five principles, stating that PES schemes should:

1. Involve a voluntary transaction, in which providers negotiate with buyers or intermediaries. This implies that providers have the freedom (politically, culturally and economically) to make choices.
2. Involve a well-defined ecosystem service (rather than, for example, simply 'conservation' of a habitat).
3. Involve payments by at least one ecosystem service purchaser; these payments will usually be monetary but could take other forms.
4. Involve at least one provider responsible for securing the provision of the ecosystem service.
5. Involve conditionality; payments are made only if services are provided. PES will therefore usually involve the monitored compliance with negotiated targets.

The most frequently commodified ecosystem services are carbon storage and sequestration, biodiversity (usually for tourism), landscape protection and hydrological services such as clean water and flood regulation. Of these, the largest and most well-developed market is for carbon. Since seagrass meadows provide all of these services, there is clearly more scope to apply PES to seagrass conservation and restoration.

In theory, PES may have economic and ethical advantages over more traditional approaches to conservation funding, such as donor-based top-down projects. Economic advantages can occur because the conditionality requirement should bring greater efficiency in resource allocation than simple transfers of cash. Ethical advantages can occur when the inequities in transactions are made explicit (such as when providers who are often comparatively poor, maintain a flow of services to beneficiaries who are comparatively rich without compensation) and choices can be made based on this information. Despite these attractions and the growing academic and policy literature outlining opportunities for PES in coastal ecosystems (Locatelli et al. 2014; Hejnowicz et al. 2015), examples of successful schemes for these ecosystems remain rare.

Pathways towards payments for ecosystem services funding

The strong focus in international policy on climate change mitigation, along with the widespread commodification of carbon, has meant that the most common application of PES is through the trading of carbon credits (also called offsets) in carbon markets. Broadly, these operate through either compliance or voluntary markets.

Compliance markets (also called mandatory or regulatory) markets are those that exist in order to meet certain laws or regulations, such as caps on the amount of greenhouse gases that a company can emit. These markets exist in various forms, such as cap-and-trade, in which carbon offsets can be bought and sold to achieve a net result that meets regulations. In general, they involve major emitters and favour low-cost options. Nature-based solutions (which include seagrass restoration) are not typically among the lowest cost options and so do not form a major proportion of these markets. Compliance markets regulate activities within particular jurisdictions (such as the European Union Emission Trading Scheme), but carbon markets are international, and activities to mitigate emissions can occur outside the jurisdiction.

The Clean Development Mechanism (CDM), implemented through the Kyoto Protocol, provides a way for carbon offsets to be traded internationally. The broad intent was to facilitate the use of finance available in developed countries to support climate mitigation efforts in developing countries. Land-based reforestation projects have been prominent, with some mangrove reforestation projects emerging, but large transaction costs and uncertainty about carbon benefits has meant that seagrass projects are absent.

In 2007, the Conference of the Parties (COP) meeting of the UNFCCC produced the Bali Action Plan, which launched the REDD+ programme. The term is now generally used to refer to "the aggregate of initiatives and policies aiming to achieve reduced emissions from forests in developing countries" (Angelsen et al. 2018). REDD+ therefore emphasizes the maintenance and enhancement of current ecosystem carbon, rather than encouraging the planting of new trees or forests, and was initially envisaged as a form of PES. REDD+ approaches are more likely to stimulate blue carbon management in the future than the original CDM afforestation and reforestation protocols. This is because there can be relatively fast potential carbon gains from avoided destruction in blue carbon habitats (if rates of destruction are high, along with subsequent carbon losses from soil), whereas restoration or creation of habitat is usually slow and shows small carbon increments in the early years. At present, most REDD+ approaches remain focused on forests, although the IPCC Wetlands Supplement incorporates standard methodologies for seagrass and other blue carbon wetlands. REDD+, combined with the nationally appropriate mitigation actions (NAMAs) of the UNFCC Durban platform, both suggest potential pathways for international, regulated investment in seagrass conservation. However, these are yet to be developed and there are still various policy, financial and technical barriers that need to be overcome. If this does occur, using these mechanisms to fund seagrass conservation may involve some forms of PES or may be more traditional donor or government funded programmes. Current REDD+ projects give some indication of the scope and challenges for blue carbon development. Around 350 REDD+ projects are under way in 53 countries. Of these, around one third has already sold carbon credits, while another third has chosen not to generate credits at all, but rather to rely on other sources of funding such as bilateral aid (Angelsen et al. 2018). This reflects in part the slack demand on carbon markets.

Voluntary markets exist because certain emitters (who may be individuals, organizations or businesses) seek to achieve emission reductions for their own reasons. Such reasons vary wildly, ranging from achieving a competitive advantage to improving brand perception to adhering to a set of sustainability values. The voluntary market is much smaller than the compliance carbon market, with less than 1 per cent of the transactions (Hejnowicz 2015), though it provides a flexible alternative that allows innovation and a better fit to local contexts. In addition, carbon offsets in voluntary markets typically command higher carbon prices than those in compliance markets, partly due to the inclusion of co-benefits (meaning benefits other than carbon mitigation), such as improved livelihoods and biodiversity conservation, which fit the motives of buyers in these markets. Nature-based solutions are popular in voluntary markets and numerous reforestation and afforestation projects exist (including for mangroves). Third-party organizations provide independent accreditation for projects and develop methods to enable this to be carried out in a robust and transparent manner. Several methods are being developed for seagrass restoration, including through the Verified Carbon Standard (part of Verra, an umbrella accrediting organization).

Examples of community-based payments for ecosystem services projects involving seagrass

Examples of projects that are focused on or involve seagrass conservation, and that also include local communities and/or incorporate elements of PES are provided in Table 7. These are drawn from an appraisal of literature and websites, as well as from consultations with experts, but do not represent an exhaustive review. The examples include projects in developing and developed nations, and cases where PES has been suggested but is not yet initiated. Although there are examples of projects meeting some or most of the criteria established by Wunder (2005), no community-based PES projects were identified that focused primarily on seagrass or met all criteria.

For example, in Fiji, PES based on reef tourism include seagrass meadows as part of the seascape, but seagrass is not the focal point of the PES schemes (Sykes et al. 2018). Under these schemes, tourists pay towards the conservation of the marine habitats that they enjoy experiencing when diving or snorkelling. Fiji has a traditional land–sea tenure system, and its people have a strong cultural connection to the environment, which facilitates marine conservation activities at the community level. A significant economy based on reef tourism also facilitates PES. Long-term involvement of conservation NGOs has also provided the technical expertise and potential to source funding to develop PES and PES-like projects, although at present none focus on seagrass. Some communities undertake reef- and fishery-related restoration, which are funded through PES, suggesting there is also potential to involve seagrass restoration activities.

Another example is Mikoko Pamoja, an established community-based mangrove PES project in Kenya (Huff and Tonui 2017). The project aims to incorporate seagrass carbon into activities in 2019 and provides a case study for the opportunities and challenges around seagrass PES projects. It also provides an opportunity to showcase the possibilities

Table 7. Examples of seagrass conservation and/or restoration projects with community-based, Payment for Ecosystem Services-funded and seagrass-focused relevance

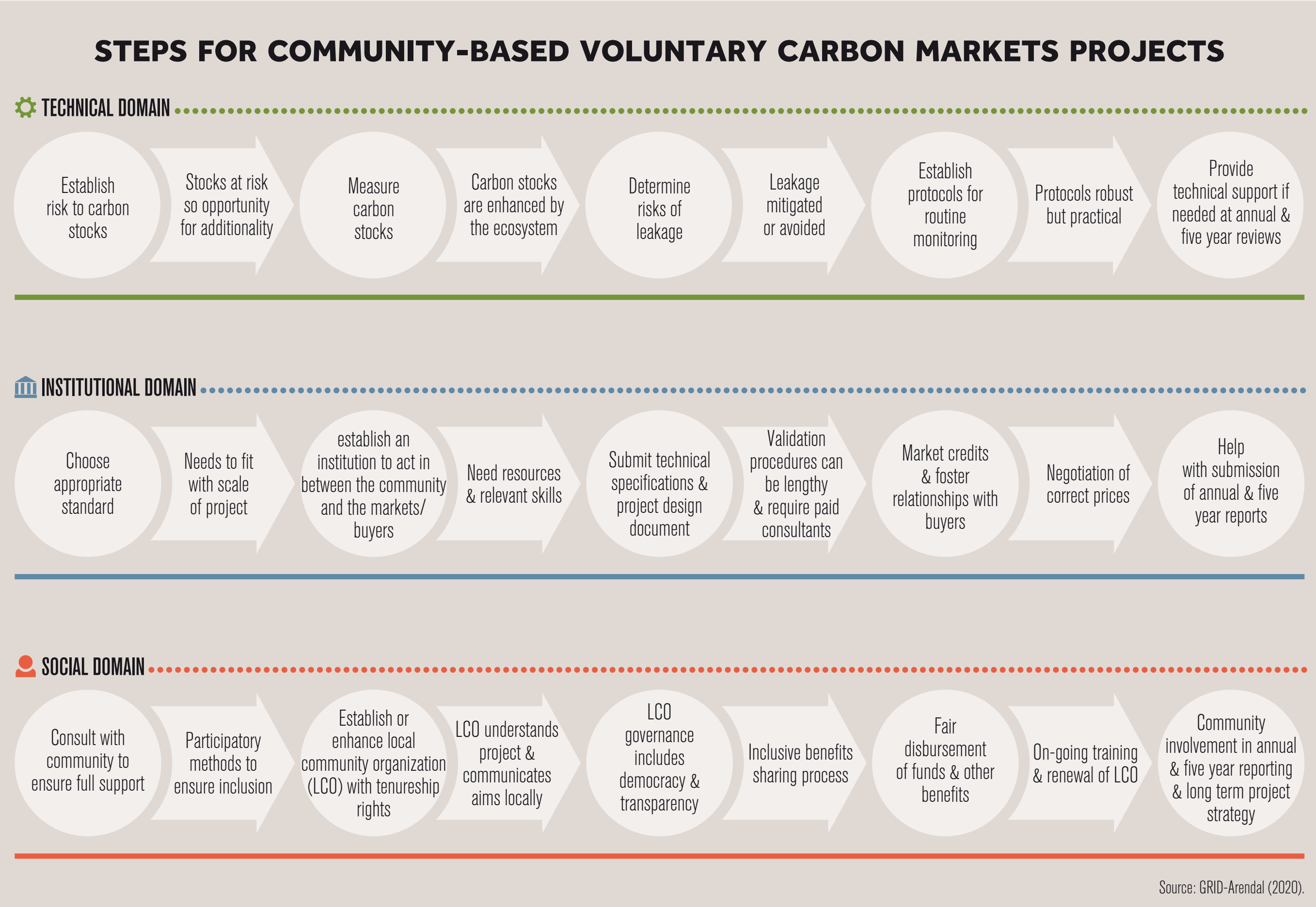
Project	Objectives	Description	Community	Payment for Ecosystem Services	Seagrass	Source
Mikoko Pamoja, Kenya	Mangrove and seagrass conservation with local benefits.	A payments for ecosystem services (PES) scheme that sells carbon credits based on mangrove conservation, aiming to incorporate stacked credits from seagrass meadows.	High.	High (but not yet launched).	Medium (bundled with mangroves).	www.aces-org.co.uk
Marine Conservation Agreements (MCAs), Fiji	Primarily to support tourism activities, including diving, snorkelling and megafauna viewing. Secondary aims include safety and security (e.g. tourist resorts controlling access to beaches, or limiting access of diving areas to spear fishers). One project involved mangrove restoration for carbon offsets.	A report by the Wildlife Conservation Society identified 56 tourism operators in Fiji that are participating in MCAs. These generally meet Wunder's definition of PES (2005). Most are focused on reef or megafauna tourism, so seagrass protection is incidental.	High. All MCAs involve community members.	High. Many MCAs included payments or other economic incentives for local communities. Many were informal agreements between operators and communities, while some were formally recognized by the Government.	Low to medium. Seagrass ecosystem protection occurs when it is part of the reef seascape. No reports of seagrass-specific tourism.	Sykes et al. 2018
Taveuni Waitabu Marine Park, Fiji	Ecotourism business to provide employment and funds to local communities.	Ecotourism business run by a local community cooperative. Employs local community members and surplus funds are used in the community.	High.	The local community run the business as a co-op. Tourists or education groups pay to visit. Ecosystem services related to tourism/culture. The community provides the service and monitors the marine protected area (MPA).	Low to medium. Seagrass meadows are explicitly recognized as part of the seascape that this protected area covers.	Sykes et al. 2018
Ataúro, Timor-Leste ecotourism project	Encourage community-based natural resource management through locally managed marine areas (LMMA).	Ecotourists are housed as homestays in the village and pay access fees, bringing income to help seagrass mapping and LMMA management.	High.	Low.	High.	Piludu 2010
Banc d'Arguin National Park, Mauritania	Conserve marine habitat, specifically as nursery grounds, for commercial fish.	Payments from the European Union for access to Mauritanian fishing grounds.	Low. Government agreement.	High (but no conditionality).	Medium (seagrass one key habitat).	Binet et al. 2013

Table 7 *(continued)*

Project	Objectives	Description	Community	Payment for Ecosystem Services	Seagrass	Source
Beach nourishment, Tarquinia Lido, Italy	Cost benefit analysis of a beach nourishment scheme that involves damage to seagrass.	A net present value analysis of a programme using dredged sand to 'nourish' a tourist beach, which concludes that PES should be used to mitigate damage to seagrass.	Low.	Medium (but only hypothetical).	High.	Martino et al. 2015
Pari Island coastal tourism, Indonesia	Provide funding to maintain coastal ecosystems, particularly turtle nesting.	Pari Island, Seribu, Indonesia, attracts foreign beach tourism which is increasing pressure on resources. It is suggested that tourists contribute payments towards habitat conservation.	Low.	Medium (but only hypothetical).	Low.	Hidayati et al. 2018
Jobos Bay National Estuarine Research Reserve, Puerto Rico	Restore seagrass meadows and mangroves damaged by hurricanes and promote natural resilience.	A restoration project run by the Ocean Foundation and funded partly by 'charitable offset contributions' (non-certified credits) for carbon sold through the SeagrassGrow website.	Low.	Medium (charitable offsets are one source of funding).	High (seagrass and mangroves).	www.oceanfdn.org/calculator
Diving and research-based ecotourism in Wakatobi National Park, Sulawesi, Indonesia	Encourage healthy reefs and associated ecosystems by establishing no-take zones.	A diving operator and research ecotourism organization pay local communities compensation as a form of 'reef leasing'. Local fishers agree not to use protected areas.	Medium.	High (but limited conditionality).	Low (focus on coral reefs).	Clifton 2013
Koh Libong, Thailand	Conserve over 1,000 ha of seagrass using carbon offsetting funds from a private company.	The Thailand Greenhouse Gas Management Organization (TGO) will supervise a project using carbon offset funds from a private company in Thailand to conserve seagrass and later consider restoration. The project is proposed to start late 2019.	Low. Livelihood benefits for locals will be considered.	Medium. Details of conditionality and accreditation are unclear.	High. Focus on seagrass.	Stankovic (pers. commun.)

Note: The relevance of each project being 'community-based', 'PES-funded' and 'seagrass-focused' is assessed as high (green), medium (beige) or low (grey).

FIGURE 15



Sequence of objectives and processes needed across the technical, institutional and social domains during the development and running of community-based voluntary carbon markets projects. Objectives are shown in circles and processes in arrows. These sequences are based on the Mikoko Pamoja case study.

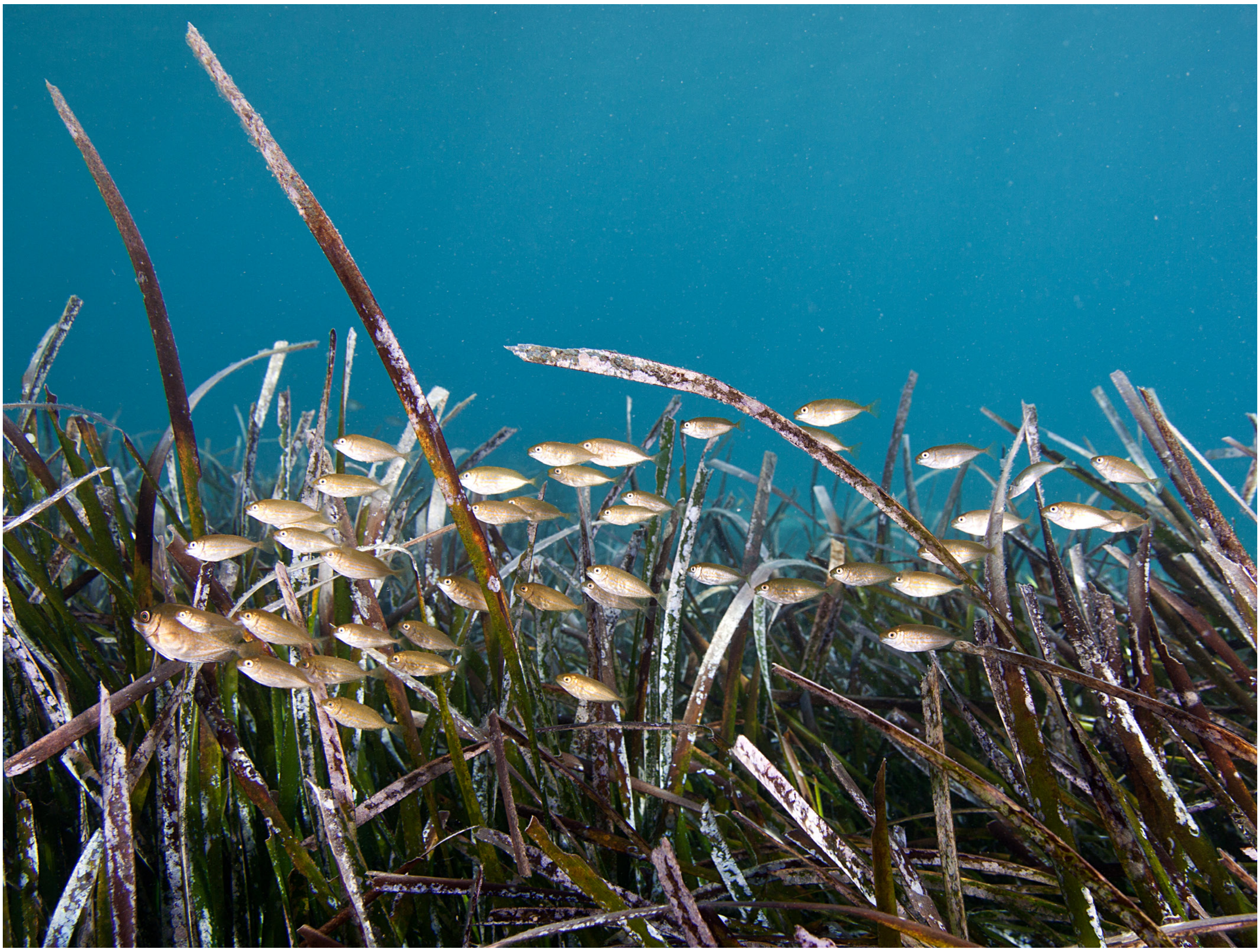
for bundling seagrass carbon and ecosystem services with mangrove ecosystems to promote an integrated seascape approach to management. There are considerable technical and financial barriers to the development of PES schemes for seagrass, and it is therefore recommended that consideration be given to bundling ecosystem services with adjacent ecosystems (for example, mangroves, saltmarsh or coral reefs) in order to improve the financial viability and the potential for project scalability.

What are the prospects for expanding payments to ecosystem services to seagrass habitats?

Despite being used for decades in other habitats and its obvious policy and ecological relevance (Hejnowicz et al. 2015) there are no examples of community-based PES (CB-PES) projects in seagrass that meet all of Wunder's (2005) conditions (Table 7). This raises the question as to what the potential constraints and barriers may be that have so far prevented expansion, and whether there are any opportunities in the near future for expansion. With this in mind, this section draws on experiences of the Mikoko Pamoja project in Kenya. Although local conditions will always determine how easy or difficult any PES project may be, this section aims to highlight general features that are likely to be relevant to any similar projects.

Developing the Mikoko Pamoja project required work and innovation in three overlapping spheres – technical, institutional and social – each of which are relevant for any seagrass-focused CB-PES project. Although much of the focus in the scientific literature has been on the technical aspects (such as how to measure carbon stocks, flows and vulnerability), the experience of Mikoko Pamoja suggests that institutional and social issues are at least as important. One challenge is to ensure that these three spheres of concern are complementary and that they are developed together during the project's lifetime, so that effort, energy and goodwill is not squandered by, for example, establishing local representation and raising expectations of community benefit only to experience lengthy delays before accreditation and successful sales of credits can occur. Figure 15 shows some of the stages and processes required across these three spheres, and how they need to complement others.

Figure 15 also captures some of the complexity of supporting CB-PES projects and helps explain why they remain rare (and absent from seagrass ecosystems). The resources needed to establish and run a CB-PES project that is accredited for the voluntary carbon market are substantial. In the case of Mikoko Pamoja, project establishment cost around $400,000, of which around $360,000 came from research and charitable grants, with the rest being provided as mostly in-kind support. Running costs include around $4,000 per annum in fees (to retire credits, etc.), expenses for charity governance, trustee



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meetings, a website and marketing. This sum does not include salaries as the charity is run by volunteers, nor the direct costs of forest protection and tree planting. Income from the sale of carbon credits (typically sold for \$10–15 per ton) ranges from \$12,000–15,000 yr^{-1}. These costs partly reflect the rigours of achieving and maintaining accreditation in the voluntary market. There are schemes that trade carbon without accreditation (such as Climate Stewards), as well as opportunities for PES involving other ecosystem services which may prove cheaper to monitor.

These figures illustrate the limited money available on the voluntary market and the fact that initial and transaction costs are high. The Mikoko Pamoja project is successful largely because no profits are made and volunteers in Kenya and the United Kingdom commit their time for free. The financial constraints faced by seagrass-based CB-PES work that commodifies carbon are likely to be similar or worse. This is because the carbon intensity in seagrass is generally less than in mangroves (meaning there is less carbon per hectare to protect or restore) and the monitoring and policing costs may be more (particularly if the work involves subtidal seagrass, which requires diving). In Gazi Bay (the field site of Mikoko Pamoja) for example, mean carbon density in seagrass beds is 236 tC ha^{-1} (Githaiga et al. 2017), which is substantially less than the > 1500 t ha^{-1} stored below-ground in the adjacent mangrove forest (Gress et al. 2017). Recent trends in seagrass coverage in the bay show losses of 1.68 per cent per yr^{-1} (Harcourt et al. 2018), with seagrass removal leading to losses of 3.14 tC ha^{-1} yr^{-1} (Githaiga et al. 2019). A project in this area that therefore aimed to conserve 300 ha of seagrass and sell avoided emissions might commodify 300 × 3.14 × 0.0168 = 15.8 tC yr^{-1}, which is equivalent to around \$158–237 yr^{-1} sales on the voluntary carbon market. These calculations illustrate how small-scale CB-PES projects will not be viable if they rely only on selling carbon credits. Projects may be feasible if they involve much larger scales, other sources of income (perhaps including credits for other ecosystem services) and/or bundling seagrass carbon with other ecosystems. Mikoko Pamoja intends to adopt the latter option, combing seagrass with mangrove conservation.

Immediate and longer-term prospects for paying for seagrass conservation

High costs relative to returns hamper the use of carbon markets as a way of supporting seagrass protection and restoration. Blended finance is one way to address this, for which there are several models. In some cases, the initial investment is funded through grants or donations (such as the previously outlined Mikoko Pamoja project), paving the way for projects to be financially feasible. In others, the investment is underwritten through a guarantee or a flexible loan, in a way that requires finance to be paid back at low rates or over a flexible period. These models will likely become important for the development of seagrass-based projects, as they have been (and continue to be) for other nature-based climate mitigation solutions. Government bonds may also be a potential solution. So what are the main options available for financing seagrass protections and restoration? Herr et al. (2015) outlined multiple potential sources of funds and finance in the context of mangrove protection and restoration, though few have been investigated for seagrass. Below is a brief list of the main potential sources of private finance:

- Voluntary carbon finance: The availability of an accredited method for seagrass protection (avoiding emissions) or restoration (sequestering carbon) – for example, through the Verified Carbon Standard method, VM0033 – provides a new opportunity for investment into seagrass carbon offsets, although it is unlikely to generate sufficient funding on its own, unless protection and restoration can happen over large scales or seagrass carbon can be bundled with other desirable outcomes.

- Risk transfer mechanisms, such as insurance, or risk mitigation: Although these are at an early stage of development, insuring natural capital 'assets' seems to be promising. The essential concept is that buyers purchase premiums, with funds channelled into nature-based activities that reduce risks associated with extreme events. If they occur, holders of the premiums receive a payment. These remain unexplored for seagrass ecosystems.

- Bonds: There are various types of bonds (a type of loan) adapted for conservation or climate purposes, such as green bonds (issued by institutions, including the World Bank). The bonds are designed to facilitate investment in specific activities and typically have a range of benefits (such as tax incentives). The value of seagrasses to fisheries might make them attractive as options in 'blue' bonds that seek to improve sustainability of fisheries.

- One simple solution is to treat seagrasses as assets that can be bought or leased. Typically, most nations do not allow for portions of their ocean to be purchased outright in the same way as property on land, but lease arrangements are common (for example, for oil and gas extraction or for aquaculture operations). Leasing seagrass beds in some areas might allow exclusive use for ecotourism or long-term usage rights that allow for the provision of specific ecosystem services, such as fisheries. For example, in areas where formal or informal governance systems are sophisticated enough, catch-share fisheries can be effective. These allocate fishing rights (in particular areas or for particular species) to individuals which can become tradable investments in the long-term health of the fisheries. Empirical evidence shows that such approaches can incentivize conservation (Costello et al. 2008). Naturally, rights should include specific caveats that avoid uses that would degrade or damage the seagrass.

Seagrass in the blue economy

Sustainable blue economy policies aim to support inclusive and integrated sustainable development in the ocean. Seagrass meadows provide many ecosystem services and can therefore play an important role in sustainable blue economies. However, to date national and international blue economy strategies have not explicitly mentioned seagrasses, and when they are reflected it is often for its blue carbon value. For instance, a World Bank report on supporting the blue economy in small island developing states (World Bank and United Nations Department of Economic and Social Affairs [UN DESA] 2017) and the European Union Blue Economy Report (European Commission 2019), recognize the protection and restoration of blue carbon ecosystems, including seagrass, as important activities to indirectly support economic development through their contribution to climate mitigation.

Seagrass may also fall within aspects of sustainable blue economy strategies that recognize marine habitats for their supporting services, including as a habitat that supports fisheries and coastal stabilization. The poor representation of seagrass in blue economy strategies poses a challenge to the conservation of seagrass ecosystems, as other economic activities associated with the blue economy may contribute to the destruction of seagrass ecosystems.

There is, however, an important opportunity to effectively plan for seagrass conservation and restoration within blue economy strategies. Many strategies mention, for example, the need for marine spatial planning and ecosystem based management (World Bank and UN DESA 2017; National Marine Science Committee 2015), directly recognizing that coastal zones are often crowded with economic activities which may lead to seagrass degradation. Integrated spatial plans can manage seagrass conservation alongside multiple economic activities in a cost-effective manner (Giakoumi et al. 2015). A major hindrance to the inclusion of seagrass in blue economy strategies is understanding the full economic valuation of the supporting services that seagrasses provide. Future priorities for seagrass in the blue economy may therefore involve overcoming technical hurdles with ecosystem valuation and creating greater policy awareness of the value of seagrass-related ecosystem services (Nordlund et al. 2018). Excluding seagrasses from blue economy strategies is a missed opportunity.

RECOMMENDED ACTIONS

Recommended actions

1 Support the development of a policy expert group for seagrasses in order to further analyse the current effectiveness of policies related to seagrasses and to make recommendations to the international community.

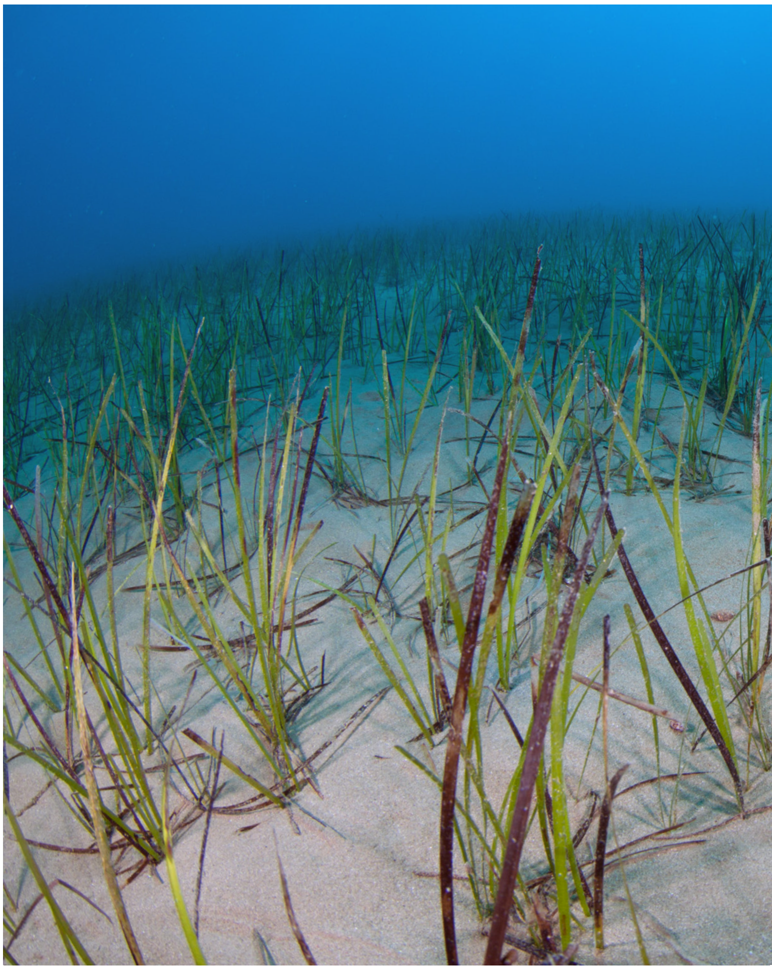
The International Seagrass Experts Network has provided an important platform for synthesizing seagrass science. However, at present there is no comprehensive study or understanding of the effectiveness of current seagrass policies around the world. A policy expert group on seagrasses, under the auspices of UN Environment Programme, could analyse the current status and effectiveness of seagrass-related policies globally, and provide recommendations to Member States. Furthermore, Member States may consider submitting a resolution on the sustainable management of seagrass ecosystems to the United Nations Environment Assembly.

2 Develop a comprehensive global map of seagrass distribution and health.

Address the gaps that currently exist in global data sets for seagrass extent and distribution by strengthening existing in situ seagrass monitoring networks, exploring new opportunities for remote sensing and investing in data management for the long-term maintenance of a global data set. Invest in additional mapping resources and design and apply standardized methodologies to address gaps in seagrass distribution and assess the condition of seagrass ecosystems globally in a way that is accurate, cost-effective and repeatable. It is also highly recommended that all projects collecting data on seagrass distribution: a) share these data openly (for example, under Creative Commons); b) contribute these data to regional or global networks and/or to global data sets, such as the Global Distribution of Seagrasses data set. A partnership of technical partners (United Nations organizations, government agencies and non-governmental organizations (NGOs)) could be developed that is dedicated to preparing an updated and comprehensive global map of seagrass distribution and health. Such a map could complement existing initiatives for mapping coastal ecosystems, such as the Allen Coral Atlas or Global Mangrove Watch. Technical recommendations can be found in the chapter on seagrass mapping and monitoring of this report. The global map should focus on addressing current mapping gaps, especially in regions such as Africa and South America.

3 Invest in further understanding and quantifying the value of ecosystem goods and services that seagrass ecosystems provide.

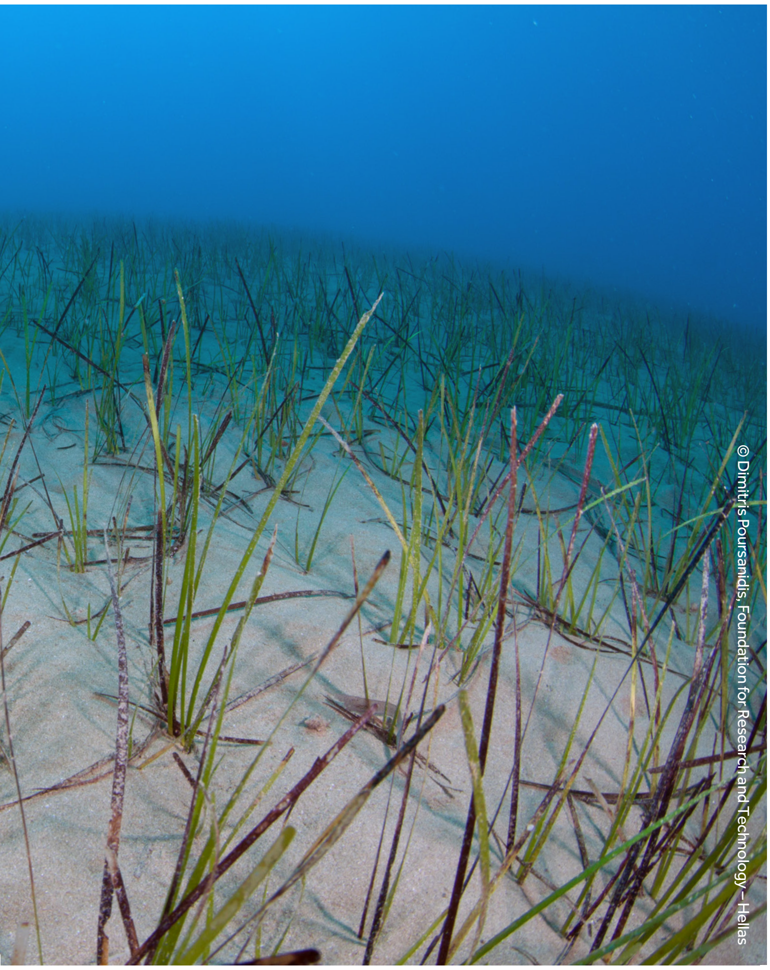
Invest in research gaps regarding our understanding and ability to quantify services and goods that seagrass ecosystems provide, including those associated with



different species and bioregions. Bioregions that are currently underrepresented in seagrass research include the coasts of South America, South-East Asia and West Africa. Further research is also needed on carbon flows in seagrass ecosystems and the fate of carbon stocks when seagrasses are degraded in order to understand the role that they can play in climate change mitigation. Furthermore, studies on ecosystem services including carbon storage and sequestration should support the potential development of payment for ecosystem services activities, as well as national natural capital accounting.

4 Raise awareness and communicate the economic and social importance of seagrasses, as well as the consequences of their loss.

Improve public outreach by creating messages and choosing media that users in each country or region are likely to access. Address the 'charisma gap' for seagrass ecosystems by better communicating to the public the goods and services that seagrasses provide to humanity. It is important that people and governments around the world recognize the value of seagrasses, the achievement of which requires targeted communications strategies. Such strategies can include dedicated media pieces or popular documentaries,



policy briefs and social media campaigns on the importance and vulnerability of seagrass. Over the years, March has become Seagrass Awareness Month in many parts of the world. Countries should consider declaring 1 March as World Seagrass Day, an international day to raise awareness of the need to conserve seagrass meadows.

5 Develop national action plans for seagrass ecosystems.

Currently, very few countries have prepared plans specifically to protect and manage seagrass ecosystems, in contrast to the many countries that have developed national plans for coral reefs and mangrove ecosystems. An important step in protecting and managing seagrass ecosystems sustainably would be to develop national plans for seagrass management, including targets for protection and health. National action plans for seagrass ecosystems should be connected to and help deliver on nationally determined contributions (NDCs) to the Paris Agreement, Convention on Biological Diversity (CBD) targets and the Sustainable Development Goals (SDGs). National action plans for seagrasses should also be well integrated and recognize connectivity with neighbouring ecosystems, such as coral reefs, mangroves, kelp forests or saltmarshes, as appropriate.

6 Integrate seagrasses into planning and implementation of the post-2020 global biodiversity framework.

The post-2020 global biodiversity framework provides an opportunity to redefine our relationship with nature and to develop new targets for protecting and restoring ecosystems. Specific, measurable, attainable, relevant and time-bound targets for seagrass ecosystems globally would be a positive outcome for seagrasses from the 2020 CBD Conference of the Parties (COP). Furthermore, countries should recognize and include seagrass ecosystems in their reporting to the CBD.

7 Include actions on seagrass ecosystems in plans for the United Nations Decade on Ecosystem Restoration and the United Nations Decade of Ocean Science for Sustainable Development.

Invest in seagrass restoration and develop targets for restoring seagrass ecosystems to help achieve goals under the United Nations Decade on Ecosystem Restoration (2021–2030). Investments in seagrass science can also support the goals of the United Nations Decade of Ocean Science for Sustainable Development, especially with regards to science on food security, disaster risk reduction, climate change adaptation and climate change mitigation.

8 Recognize the value of seagrasses in Nationally Determined Contributions (NDCs) as a key component of climate change adaptation and mitigation.

Recognize the importance of seagrass ecosystems as carbon stores and include seagrass ecosystems in national greenhouse gas inventories, appropriate Intergovernmental Panel on Climate Change (IPCC) tier reporting and NDC reporting. Develop targets for seagrass conservation and restoration that are specifically tailored for climate change mitigation and adaptation. These targets would include a range of activities, from simple recognition of the value of seagrasses for climate adaptation and mitigation to tangible and measurable actions.

9 Recognize the value of protecting seagrasses for the SDGs, the 2030 Agenda for Sustainable Development and other international policy targets.

Foster collaboration between national focal points for different conventions and focal points for SDG planning and implementation to advance broader seascape approaches to conservation and sustainable development. Include achievements related to the conservation and restoration of seagrass ecosystems in national SDG reporting. Understand and quantify how conservation and restoration of seagrass ecosystems helps national governments achieve and report on various international policy commitments and SDGs. Develop seagrass indicators within monitoring systems for global processes and include these, for example, in the context of the SDGs, Paris Agreement, CBD and Sendai Framework. Seagrasses should thus be included in national sustainable development strategies.

10 Increase national, bilateral and multilateral funding for comprehensive actions required to conserve and sustainably manage seagrass ecosystems.

Identify opportunities for specific funding windows for seagrass ecosystems under multilateral environmental funds. Identify priorities for bilateral funding for seagrass ecosystems, for example, under multilateral environmental agreements or international policy targets. Explore the potential for developing a global fund for seagrass conservation, restoration and capacity development.

11 Engage stakeholders at all levels and stimulate partnerships to facilitate integration of seagrass conservation into planning and implementation phases.

Include targets for seagrass ecosystems in marine spatial planning at the regional, national and subnational levels. Explore the development and gazetting of marine protected areas (MPAs), locally managed marine areas (LMMAs) or other effective area-based conservation measures (OECMs) with management plans that specifically address seagrass ecosystems, while also developing conservation areas specifically designated for seagrasses and associated ecosystems. The role and knowledge of local and indigenous communities is fundamental to the long-term sustainability of interventions.

12 Designate more MPAs or LMMAs that include or focus on seagrass ecosystems.

At present, seagrasses are underrepresented in MPAs and LMMAs around the world, with only 26 per cent of known seagrasses occurring in protected areas compared with 40 per cent of corals and 43 per cent of mangroves. Most seagrass is not covered by management plans or protected against anthropogenic impacts. Designating more MPAs or LMMAs that include seagrass or are specifically aimed at seagrass ecosystems is a critical step in reducing seagrass loss and conserving the ecosystem services that they provide to humanity.

13 Stimulate seagrass conservation and restoration by providing financial mechanisms and incentives.

Promote economic incentives or integrate seagrasses into existing payments for ecosystem services (PES) as a source of local income from protection and restoration activities. Develop methodologies and guidance for seagrasses to enter the carbon market, either as stand-alone projects or by combining with mangrove carbon projects. However, as there are still significant financial and technical barriers to developing PES schemes for seagrass, it is thus recommended that seagrass activities are combined with adjacent ecosystems, such as mangroves, to make schemes more financially viable and scalable.

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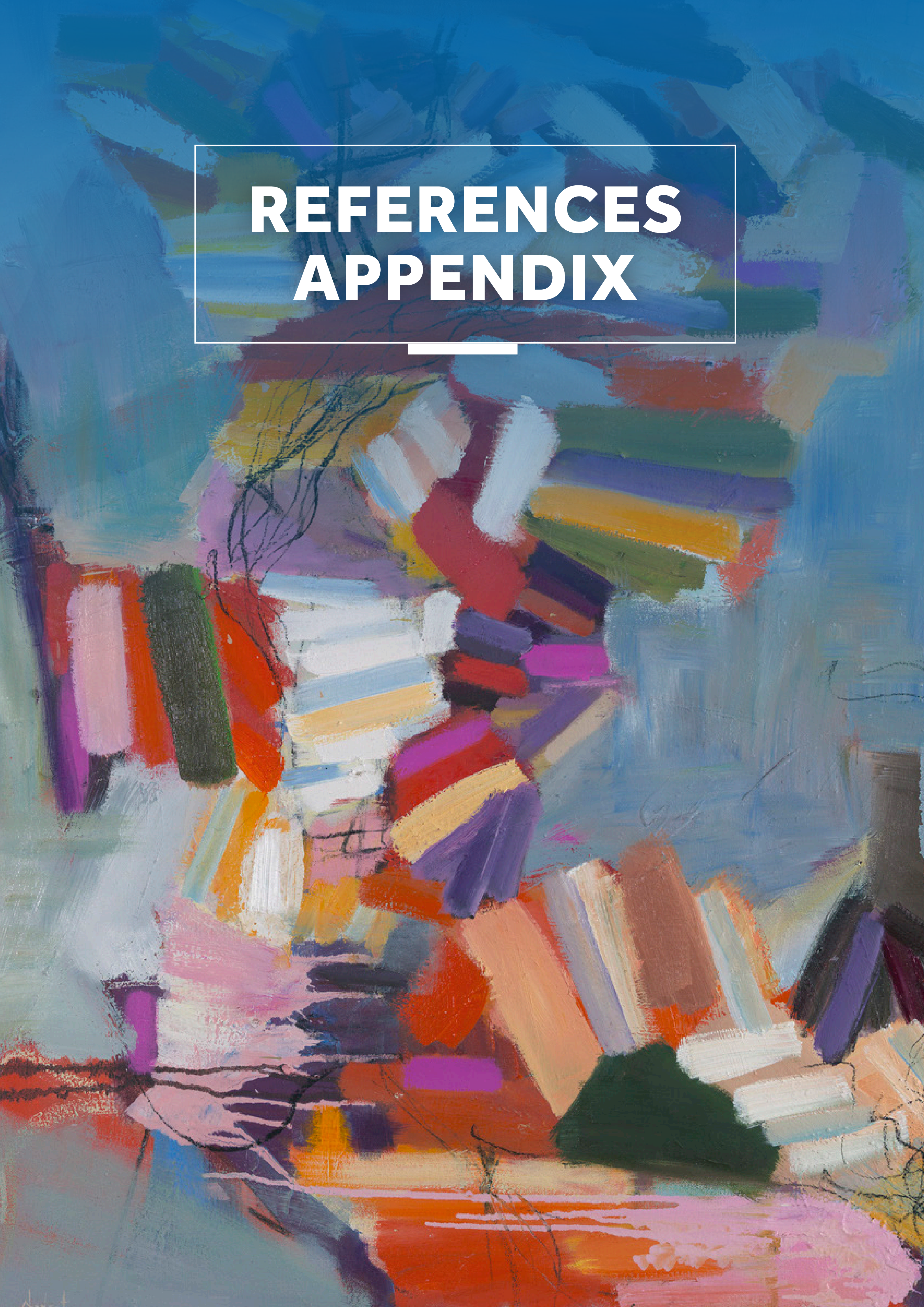
APPENDIX



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Nedret Andre

Nedret Andre is a contemporary artist in Boston's SOWA district. Her process art focuses on ocean life and seagrass habitats. The inspiration for her gestural paintings come from being out in the field with scientists and helping with seagrass restoration efforts in Massachusetts. She received her BFA in Painting at Massachusetts College of Art and her MFA from Maine College of Art.

Through her artistic vision, Nedret exhibits the resiliency of our natural world and the scientific community's effort to ameliorate the effects of climate change. Her art brings light to the important role seagrass plays in our oceans health.

Nedret uses washes of paint to mimic water and layers her paints with more opaque paint as she works through her abstract compositions.

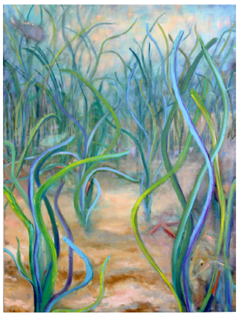
Nedret's solo shows have included: Beacon Gallery, Chashama Spaces NY, Copley Square Hotel's Art Square Gallery, Enso Gallery, Hess Gallery, Artlery, Boston University, Stetson Gallery, and Touch Gallery.

Her group shows have included: Monmouth Museum, Danforth Museum, Walsingham Gallery, Carole Calo Gallery, Soprafina Gallery, Kingston Gallery, and Piano Craft Gallery.

Her works are in collections in the US, Switzerland, Egypt, France, Germany, Turkey, and England.

In addition, her paintings have been acquired by Mount Auburn Hospital, Cape Cod Hospital, and Danvers Bank, and are included in the deCordova Museum Corporate Art Loan Program. Two of her paintings are in a Public Arts Collection at Lasell Village.

Nedret's paintings have also been reviewed in Art New England and ArtScope Magazine.

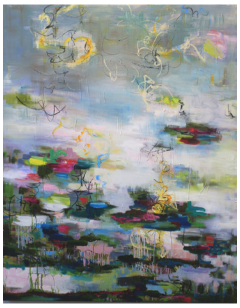


Seagrass *(cover)*
Oil on Canvas, 46" x 36", 2016

02 Bubbles *(pp.16-17)*
Oil on Canvas, 36" x 60", 2019

Intertidal *(pp.56-57)*
Oil on Canvas, 68" x 50", 2016

Harvest Moon *(pp.66-67)*
Oil on Canvas, 36" x 60", 2019



Carbon Capture *(p.77)*
Oil on Canvas, 60" x 48", 2017

Bubblegum Somersault *(p.81)*
Oil on Canvas, 36" x 36", 2016

Appendix.

Seagrass and nationally determined contributions inventory

Country	Year	NDC actions
Bahamas	2020–2030	**The role of seagrass is recognized in mitigation and adaptation with the protection of nearshore marine environments as an adaptation measure.** "Mitigation: [...] Enhanced management will improve our forest ecosystems, the ridge to reef linkages to protect corals, sea grasses important to sustainable livelihood and the functionality of our mangrove ecosystems increasing their carbon sink ability." "Adaptation: [...] Near shore marine environments play an integral role in the protection of critical infrastructure across the archipelago. On this basis, The Bahamas acts not only under the UNFCCC but also the United Nations Conventions on Biological Diversity (CBD), and Convention to Combat Desertification (UNCCD) and other relevant multilateral and regional environmental agreements (MBAs) and initiatives. As an example, in 2008, as a part of the CBD Programme of Work on Protected Areas (POWPA) and a new initiative across the Caribbean, The Bahamas, committed itself to Caribbean Challenge Initiative (CCI). This initiative builds on the work undertaken under the CBD to provide for the protection of 20% of our near shore marine environment by 2020. This year we have achieved half of our goal. These protected areas will conserve and protect habitats for Grouper and Bonefish spawning aggregations, coral reefs, sea grass meadows, mangrove nurseries and important migratory bird areas. Additionally, the Forestry Act [...] for the first time in The Bahamas protects designated Mangrove[s] and mangrove ecosystem[s] and important Biological and ecosystem services impacted by sea level rise."
Kingdom of Bahrain	2030	**The role of seagrass in mitigation is recognized and explicitly referenced as blue carbon.** "Seagrass beds, which constitute an important carbon sink, are distributed along the southeast coast, and along the west coast of Bahrain. At present the Kingdom of Bahrain does not have a full understanding of its seagrass areas as a carbon sink and is planning to further engage with the International Union for Conservation of Nature to do so."
Honduras		**The role of seagrass is recognized in adaptation with the protection, conservation and restoration of coastal and marine ecosystems identified as an adaptation measure.** "Adaptation: [...] plans and actions to protect, conserve and restore coastal and marine ecosystems and their biodiversity. [...] Adaptation measures: The group of Bay Islands comprised of Roatán, Utila, Guanaja and the Cayos Cochinos has one of the best reefs and is fundamental for the development of the country's tourism. These islands are surrounded by coral reefs that support important fisheries. The north coast of Roatán enjoys an almost continuous barrier reef. In addition to coral reefs, there are other characteristics of the marine-coastal ecosystem that are equally essential for their health and productivity. These include mangroves, wetlands, seagrass beds and sandy beaches."
Kiribati	2025	**The role of seagrass in mitigation is recognized with sustainable management identified as a mitigation measure.** "Mitigation: [...] In addition to these quantified outcomes, Kiribati will proactively protect and sustainably manage its mangrove resources, as well as protect and enhance coastal vegetation and seagrass beds. Together these actions represent effective stewardship of more than 6 million tonnes of Carbon Dioxide stored, more than 100 times the current annual national emissions inventory. [...] Land sector accounting approach: Appropriate methodologies drawn from international best practice to quantify sequestration from mangrove plantations."
Mauritius	2030	**The role of seagrass in adaptation is recognized with protection and rehabilitation of wetlands, seagrass and mangroves included in adaptation measures.** "Adaptation Measures: [...] Coastal Zone Management: Improve awareness, enhance rehabilitation and strengthen regulatory framework for protection of beach, dunes and vegetation. [...] Improve Marine and Terrestrial Biodiversity Resilience: Improvement of the management of marine and terrestrial protected areas and expansion of protected area network including rehabilitation of wetlands, sea-grass, mangrove plantation, increase in tree coverage areas and coral reef rehabilitation/farming."
Mexico	2020–2030	**The role of seagrass in mitigation is recognized with protection of mangroves, seagrass and other coastal and marine ecosystems identified as adaptation and mitigation measures.** "Ecosystem-Based Adaptation: Actions to be implemented for the period 2020–2030 on this topic include the following: [...] Increase carbon capture and strengthen coastal protection with the implementation of a scheme of conservation and recovery of coastal and marine ecosystems such as coral reefs, mangroves, sea grass and dunes."

Country	Year	NDC actions
Saint Kitts and Nevis		**The role of seagrass in adaptation is recognized and coastal ecosystems are identified as one of the most vulnerable sectors.** "Adaptation contribution: [...] For St. Kitts and Nevis the most vulnerable sectors and areas include: [...] Coastal Ecosystems [...] St. Kitts and Nevis, a twin island state, is abundant in nearshore and marine resources which provide the basis for a range of economic and social activity relevant to the tourism and fishing industries. Some of these marine resources include coral reefs, beaches, mangroves, freshwater lagoons and sea-grass beds."
Sri Lanka		**The role of seagrass beds in adaptation is recognized with restoration and conservation of these ecosystems identified as adaptation measures.** "NDCs of Adaptation to adverse effects of Climate Change: [...] Coastal and Marine Sector: [...] Being an island, sea level rise will pose many challenges to coastal communities, their livelihoods, and coastal ecosystems. With this rise, coastal systems and low-lying areas will experience adverse impacts such as submergence, coastal flooding, saltwater intrusion and coastal erosion. [...] The NDCs of Coastal and Marine sector: [...] 3. Restoration, conservation and managing coral, sea grass, mangroves and sand dunes in sensitive areas. 3.1 Survey and map coastal habitats (coral, sea grass, mangroves and sand dunes) in the entire coastal region, based on a method that is compatible with the survey department methods. 3.2 Scientifically identify suitable sites for conservation, rehabilitation and restoration. 3.3 Conduct pilot projects at high prioritized sites [...] 5. Establish 1000 ha of coastal forests and green belt along the coastal line of the island."
Sudan		**The role of seagrass in adaptation is recognized with protection for these ecosystems and coastal zone management identified as adaptation measures.** "Adaptation: [...] Coastal Zone: [...] Implement integrated coastal zone management: an integrated approach to land use planning, creation of ecological buffer zones, establishing protected inland zones to accommodate salt marsh, mangrove and sea grass."
United Arab Emirates		**The role of seagrass in mitigation is recognized and explicitly referenced as blue carbon. Minimizing impacts on coastal carbon systems is identified as a mitigation measure with adaptation co-benefits.** "Adaptation Actions with Mitigation Co-benefits: [...] Wetlands, Coastal and Marine Environment Conservation (Blue Carbon): The coastal and marine environments of the UAE are diverse and include mangrove forests, saltmarshes, sabkha, intertidal mudflats with cyanobacterial mats and extensive sub-tidal sea grass meadows. The UAE has developed and implemented a number of strategies and plans, which aim to improve understanding of wetlands, including coastal carbon systems, and will also assist in minimizing anthropogenic impacts. The UAE is also undergoing significant restoration and plantation efforts of both mangroves and sea-grass, supporting ecosystem-based adaptation as well. In 2013, the UAE initiated the Blue Carbon Demonstration Project, which provided decision-makers with a stronger understanding of the carbon sequestration potential in the Emirate of Abu Dhabi. In 2014, the project's scope was expanded to cover the entire country, and is known as the UAE's National Blue Carbon Project."

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