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A RAPID RESPONSE ASSESSMENT

BLUE CARBON

THE ROLE OF HEALTHY OCEANS IN BINDING CARBON

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This report is produced as an inter-agency collaboration between UNEP, FAO and IOC/UNESCO, with special invited contribution of Dr. Carlos M. Duarte, Institut Mediterráni d'Estudis Avançats, Spain.

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BLUE CARBON

THE ROLE OF HEALTHY OCEANS IN BINDING CARBON

A RAPID RESPONSE ASSESSMENT

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PREFACE

The most crucial, climate-combating coastal ecosystems are disappearing faster than anything on land and much may be lost in a couple of decades.

If the world is to decisively deal with climate change, every source of emissions and every option for reducing these should be scientifically evaluated and brought to the international community's attention.

The burning of fossil fuels is generating levels of what one might term 'brown' and 'black' carbon in the atmosphere and unless checked may take global temperatures above a threshold of 2°C. Dramatic reductions are possible by accelerating energy efficiency measures and boosting the deployment of cleaner energy generation and renewables such as solar, wind and geothermal. Over the past few years science has been illuminating other sources of emissions and other opportunities for action. Deforestation for example now accounts for close to 20% of global greenhouse gas emissions.

In a matter of weeks, governments will meet in Copenhagen where there is an urgency to Seal the Deal on a new and forward-looking agreement. Part of that package of measures needs to include 'green' carbon – the carbon stored in the globe's forests and their soils and especially in the tropics. Financing a partnership for Reduced Emissions from Deforestation and forest Degradation (REDD) can play an important role in keeping that green carbon where it belongs while also assisting the development and employment objectives of developing economies by giving an economic value to these vital ecosystem services.

Science is now also telling us that we need to urgently address the question of 'blue' carbon. An estimated 50% of the carbon in the atmosphere that becomes bound or 'sequestered' in natural systems is cycled into the seas and oceans – another example of nature's ingenuity for 'carbon capture and storage'. However, as with forests we are rapidly turning that blue carbon into brown carbon by clearing and damaging the very marine ecosystems that are absorbing and storing greenhouse gases in the first place. This in turn will accelerate climate change, putting at risk communities including coastal ones along with other economically-important assets such as coral reefs; freshwater systems and marine biodiversity as well as 'hard' infrastructure from ports to power-stations. Targeted investments in the sustainable management of coastal and marine ecosystems – the natural infrastructure – alongside the rehabilitation and restoration of damaged and degraded ones, could prove a very wise transaction with inordinate returns.

This report, produced by some of the world's leading scientists and in collaboration with the FAO and IOC-UNESCO, finds that the most crucial, climate-combating coastal ecosystems cover less than 0.5% of the sea bed. But they are disappearing faster than anything on land and much may be lost in a couple of decades. These areas, covering features such as mangroves, salt marshes and seagrasses, are responsible for capturing and storing up to some 70% of the carbon permanenty stored in the marine realm.

If we are to tackle climate change and make a transition to a resource efficient, Green Economy, we need to recognize the role and the contribution of all the colours of carbon. Blue carbon, found and stored away in the seas and oceans, is emerging as yet another option on the palette of promising opportunities and actions, one that can assist in delivering a bright rather than a dark brown and ultimately black future.

Achim Steiner
UN Under-Secretary General and Executive Director, UNEP

EXECUTIVE SUMMARY

The objective of this report is to highlight the critical role of the oceans and ocean ecosystems in maintaining our climate and in assisting policy makers to mainstream an oceans agenda into national and international climate change initiatives. While emissions' reductions are currently at the centre of the climate change discussions, the critical role of the oceans and ocean ecosystems has been vastly overlooked.

Out of all the biological carbon (or green carbon) captured in the world, over half (55%) is captured by marine living organisms – not on land – hence it is called blue carbon. Continually increasing carbon dioxide (CO_2) and other greenhouse gas emissions are contributing to climate change. Many countries, including those going through periods of rapid growth, are increasing their emissions of brown and black carbon (such as CO_2 and soot) as a result of rapid economic development. Along with increased emissions, natural ecosystems are being degraded, reducing their ability to absorb CO_2. This loss of capacity is equivalent to one to two times that of the annual emissions from the entire global transport sector.

Rising greenhouse gases emissions are producing increasing impacts and changes worldwide on weather patterns, food production, human lives and livelihoods. Food security, social, economic and human development will all become increasingly jeopardized in the coming decades.

Maintaining or improving the ability of forests and oceans to absorb and bury CO_2 is a crucial aspect of climate change mitigation. The contribution of forests in sequestering carbon is well known and is supported by relevant financial mechanisms. In contrast, the critical role of the oceans has been overlooked. The aim of this report is to highlight the vital contribution of the oceans in reducing atmospheric CO_2 levels through sequestration and also through reducing the rate of marine and coastal ecosystem degradation. It also explores the options for developing a financial structure for managing the contribution oceans make to reducing CO_2 levels, including the effectiveness of an ocean based CO_2 reduction scheme.

Oceans play a significant role in the global carbon cycle. Not only do they represent the largest long-term sink for carbon but they also store and redistribute CO_2. Some 93% of the earth's CO_2 (40 Tt) is stored and cycled through the oceans.

The ocean's vegetated habitats, in particular mangroves, salt marshes and seagrasses, cover <0.5% of the sea bed. These form earth's blue carbon sinks and account for more than 50%, perhaps as much as 71%, of all carbon storage in ocean sediments. They comprise only 0.05% of the plant biomass on land, but store a comparable amount of carbon per year, and thus rank among the most intense carbon sinks on the planet. Blue carbon sinks and estuaries capture and store between 235–450 Tg C every year – or the equivalent of up to half of the emissions from the entire global transport sector, estimated at around 1,000 Tg C yr^{-1}. By preventing the further loss and degradation of these ecosystems and catalyzing their recovery, we can contribute to offsetting 3–7% of current fossil fuel emissions (totaling 7,200 Tg C yr^{-1}) in two decades – over half of that projected for reducing rainforest deforestation. The effect would be equivalent to at least 10% of the reductions needed to keep concentrations of CO_2 in the atmosphere below 450 ppm. If managed properly, blue carbon sinks, therefore, have the potential to play an important role in mitigating climate change.

The rate of loss of these marine ecosystems is much higher than any other ecosystem on the planet – in some instances up to four times that of rainforests. Currently, on average, between 2–7% of our blue carbon sinks are lost annually, a seven-fold increase compared to only half a century ago. If more action is not taken to sustain these vital ecosystems, most may be lost within two decades. Halting degradation and restoring both the lost marine carbon sinks in the oceans and slowing deforestation of the tropical forests on land could result in mitigating emissions by up to 25%.

Sustaining blue carbon sinks will be crucial for ecosystem-based adaptation strategies that reduce vulnerability of human coastal communities to climate change. Halting the decline of ocean and coastal ecosystems would also generate economic revenue, food security and improve livelihoods in the coastal zone. It would also provide major economic and development opportunities for coastal communities around the world, including extremely vulnerable Small Island Developing States (SIDS).

Coastal waters account for just 7% of the total area of the ocean. However the productivity of ecosystems such as coral reefs, and these blue carbon sinks mean that this small area forms the basis of the world's primary fishing grounds, supplying an estimated 50% of the world's fisheries. They provide vital nutrition for close to 3 billion people, as well as 50% of animal protein and minerals to 400 million people of the least developed countries in the world.

The coastal zones, of which these blue carbon sinks are central for productivity, deliver a wide range of benefits to human society: filtering water, reducing effects of coastal pollution, nutrient loading, sedimentation, protecting the coast from erosion and buffering the effects of extreme weather events. Coastal ecosystem services have been estimated to be worth over US$25,000 billion annually, ranking among the most economically valuable of all ecosystems. Much of the degradation of these ecosystems not only comes from unsustainable natural resource use practices, but also from poor watershed management, poor coastal development practices and poor waste management. The protection and restoration of coastal zones, through coordinated integrated management would also have significant and multiple benefits for health, labour productivity and food security of communities in these areas.

The loss of these carbon sinks, and their crucial role in managing climate, health, food security and economic development in the coastal zones, is therefore an imminent threat. It is one of the biggest current gaps to address under climate change mitigation efforts. Ecosystem based management and adaptation options that can both reduce and mitigate climate change, increase food security, benefit health and subsequent productivity and generate jobs and business are of major importance. This is contrary to the perception that mitigation and emission reduction is seen as a cost and not an investment. Improved integrated management of the coastal and marine environments, including protection and restoration of our ocean's blue carbon sinks, provides one of the strongest win-win mitigation efforts known today, as it may provide value-added benefits well in excess of its costs, but has not yet been recognized in the global protocols and carbon trading systems

KEY OPTIONS:

In order to implement a process and manage the necessary funds for the protection, management and restoration of these crucial ocean carbon sinks, the following options are proposed:

1 Establish a global blue carbon fund for protection and management of coastal and marine ecosystems and ocean carbon sequestration.

a. Within international climate change policy instruments, create mechanisms to allow the future use of carbon credits for marine and coastal ecosystem carbon capture and effective storage as acceptable metrics become available. Blue carbon could be traded and handled in a similar way to green carbon – such as rainforests – and entered into emission and climate mitigation protocols along with other carbon-binding ecosystems;

b. Establish baselines and metrics for future environmentally sound ocean carbon capture and sequestration;

c. Consider the establishment of enhanced coordination and funding mechanisms;

d. Upscale and prioritize sustainable, integrated and ecosystem-based coastal zone planning and management, especially in hotspots within the vicinity of blue carbon sinks to increase the resilience of these natural systems and maintain food and livelihood security from the oceans.

2 Immediately and urgently protect at least 80% of remaining seagrass meadows, salt marshes and mangrove forests, through effective management.

Future funds for carbon sequestration can contribute to maintaining management and enforcement.

3 Initiate management practices that reduce and remove threats, and which support the robust recovery potential inherent in blue carbon sink communities.

4 Maintain food and livelihood security from the oceans by implementing comprehensive and integrated ecosystem approaches aiming to increase the resilience of human and natural systems to change.

5 Implement win-win mitigation strategies in the ocean-based sectors, including to:

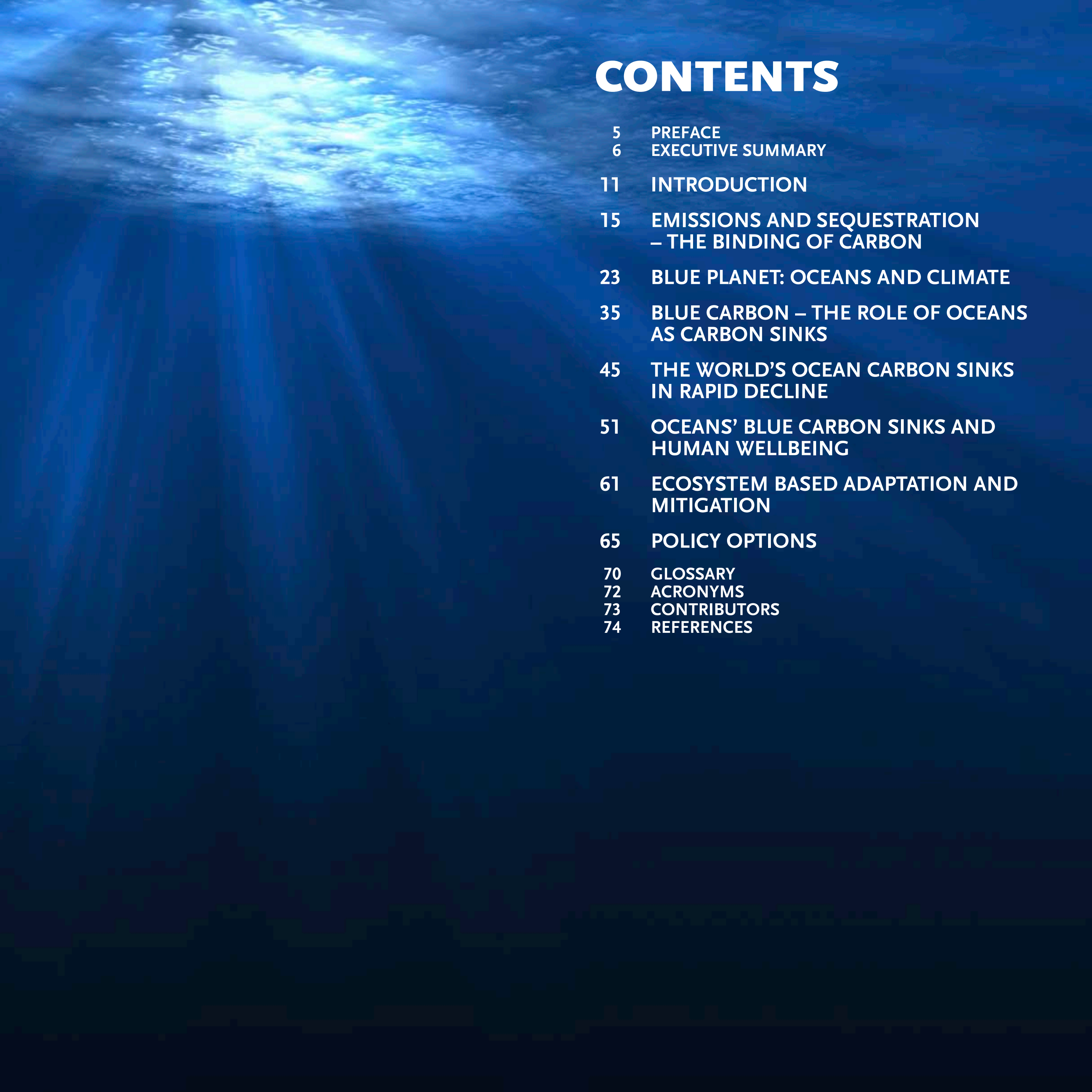
a. Improve energy efficiency in marine transport, fishing and aquaculture sectors as well as marine-based tourism;

b. Encourage sustainable, environmentally sound ocean based energy production, including algae and seaweed;

c. Curtail activities that negatively impact the ocean's ability to absorb carbon;

d. Ensure that investment for restoring and protecting the capacity of ocean's blue carbon sinks to bind carbon and provide food and incomes is prioritized in a manner that also promotes business, jobs and coastal development opportunities;

e. Catalyze the natural capacity of blue carbon sinks to regenerate by managing coastal ecosystems for conditions conducive to rapid growth and expansion of seagrass, mangroves, and salt marshes.



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INTRODUCTION

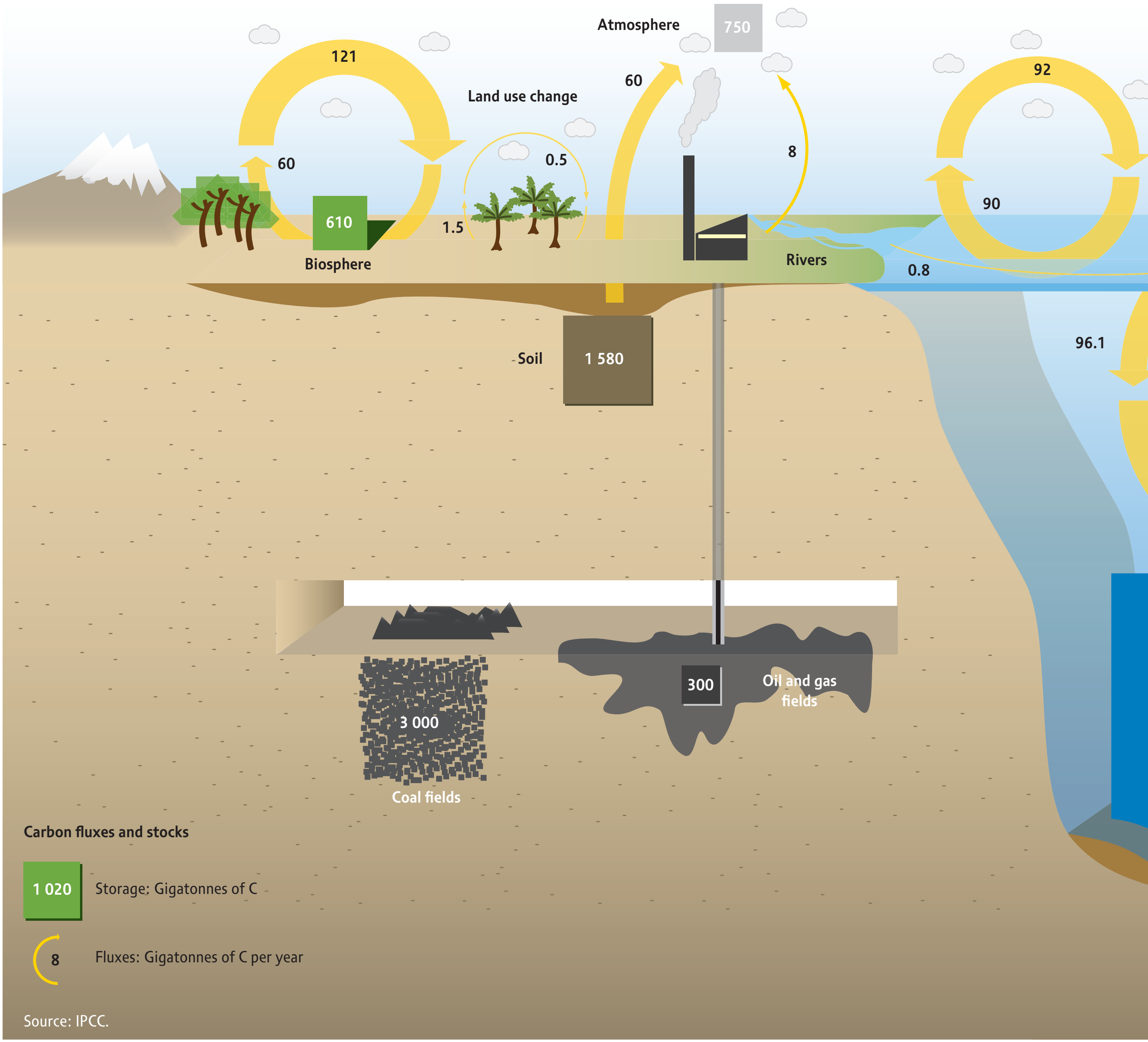
Of all the Green carbon captured annually in the world, that is the carbon captured by photosynthetic activity, over half (55%) is captured by marine living organisms (Falkowski *et al.*, 2004; Arrigo, 2005; González, *et al.*, 2008; Bowler, 2009; Simon *et al.*, 2009). This oceanic carbon cycle is dominated by micro-, nano-, and picoplankton, including bacteria and archaea (Burkill, 2002). Even though plant biomass in the oceans is only a fraction of that on land, just 0.05%, it cycles almost the same amount of carbon each year (Bouillon *et al.*, 2008; Houghton, 2007); therefore representing extremely efficient carbon sinks. However, while increasing efforts are being made to slow degradation on land, such as through protection of rainforests as a means to mitigate climate change, the role of marine ecosystems has to date been largely ignored.

Knowledge of the role of natural ecosystems in capturing CO_2 is an increasingly important component in developing strategies to mitigate climate change. Losses and degradation of natural ecosystems comprise at least 20–30% of our total emissions (UNEP, 2008a; 2009). While overall emissions from the burning of fossil fuels needs to be severely reduced, mitigating climate change can also be achieved by protecting and restoring natural ecosystems (Trumper *et al.*, 2009). Even from a narrow perspective of emission reductions alone, they can play a significant role. As steep reduction of fossil fuel emissions may compromise the development potential of some countries, it is critical that options are identified that can help mitigate climate change with neutral or even positive impacts on development. It is therefore absolutely critical to identify those natural ecosystems that contribute most to binding our increasing emissions of carbon or CO_2 and enhance this natural capacity (Trumper *et al.*, 2009). Some of these are in the oceans.

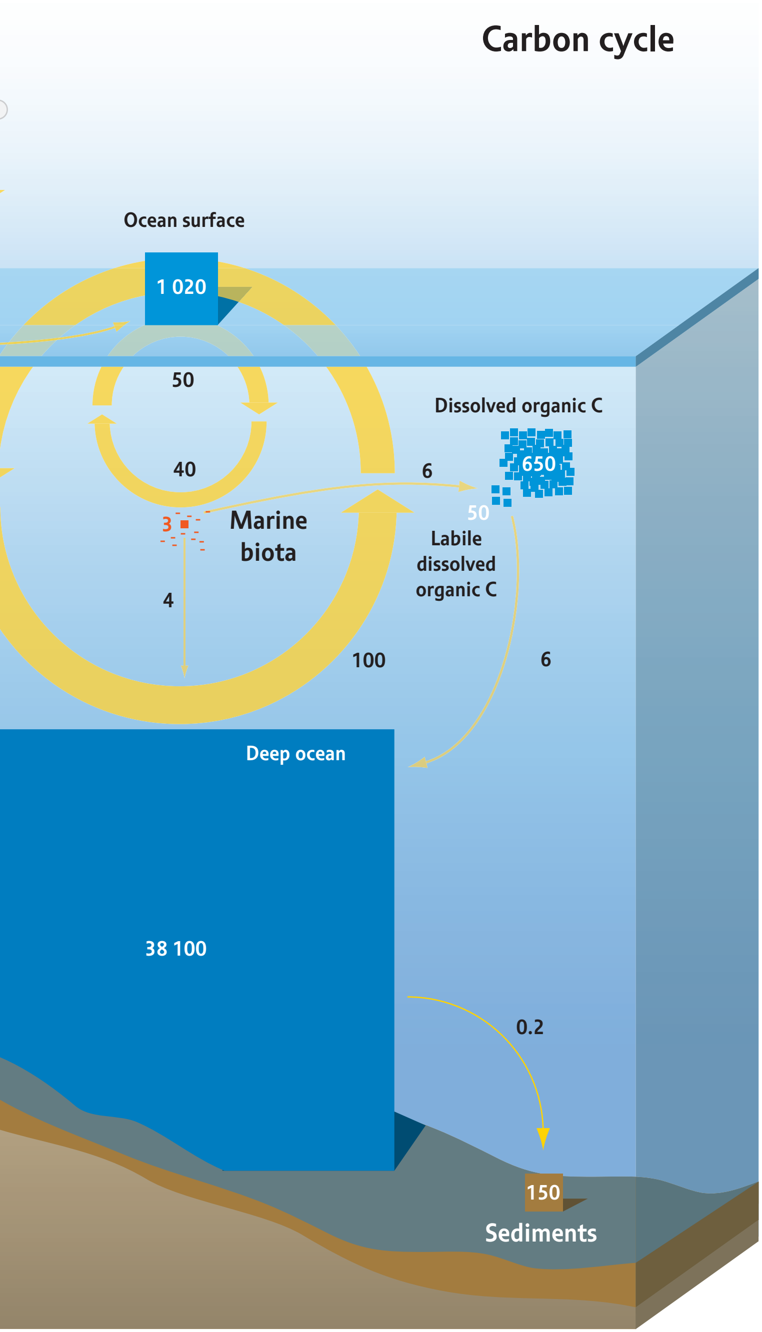
Some 93% of the earth's carbon dioxide – 40Tt CO_2 – is stored in the oceans. In addition, oceans cycle about 90 Gt of CO_2 yr^{-1} (González *et al.*, 2008), and remove over 30% of the carbon released to the atmosphere.

Resilient aquatic ecosystems not only play a crucial role in binding carbon, they are also important to economic development, food security, social wellbeing and provide important buffers against pollution, and extreme weather events. Coastal zones are of particular importance, with obvious relations and importance to fisheries, aquaculture, livelihoods and settlements (Kay and Alder, 2005) – over 60% of the world's population is settled in the coastal zone (UNEP, 2006, 2008b). For many coastal developing countries, the coastal zone is not only crucial for the wellbeing of their populations, it could also, as documented in this report, provide a highly valuable global resource for climate change mitigation if supported adequately.

This report explores the potential for mitigating the impacts of climate change by improved management and protection of marine ecosystems and especially the vegetated coastal habitat, or blue carbon sinks.


Atmosphere
750
121
60
Land use change
0.5
1.5
60
8
610
Biosphere
Rivers
0.8
92
90
96.1
Soil
1 580
300
Oil and gas fields
3 000
Coal fields
Carbon fluxes and stocks
1 020
Storage: Gigatonnes of C
8
Fluxes: Gigatonnes of C per year

Source: IPCC.



Definition: Measuring Carbon

Units of Carbon used. This report will use Tg C, but readers will also see values for C and CO_2, provided in a wide range of formats. The following information may assist in wider reading.

Name	Factor	Symbol
One thousand	10^3	k (Kilo)
One million	10^6	M (Mega)
One billion	10^9	G (Giga)
One trillion	10^{12}	T (Tera)
	10^{15}	P (Peta)

$1km^2$ = 100ha
1 ton = 2,240lbs
1 (metric) ton = 1,000kg or $1x10^6g$
Blue carbon sinks capture CO_2 through photosynthesis from the air and water and store it as carbon.

The rate of converting C to CO_2 is 44/12; i.e. 1 aton of C is equivalent to 3.67t CO_2

← **Figure 1: Carbon Cycle.** Oceans are crucial in the global carbon cycle. It was here where life first evolved; they are the source of our wealth and development. The living oceans capture over half of all the Green carbon – the carbon bound by living organisms through photosynthesis.

EMISSIONS AND SEQUESTRATION – THE BINDING OF CARBON

Anthropogenic climate change is caused by the rising content of greenhouse gases and particles in the atmosphere. Firstly by the burning of fossil fuels, releasing greenhouse gases such as CO_2, ("brown carbon") and dust particles (part of "black carbon"); secondly by emissions from clearing natural vegetation, forest fires and agricultural emissions, including those from livestock; and thirdly – by the reduced ability of natural ecosystems to bind carbon through photosynthesis and store it – so called green carbon (Trumper *et al.*, 2009). The uptake of CO_2 into a reservoir over long (several decades or centuries) time scales, whether natural or artificial is called carbon sequestration (Trumper *et al.*, 2009).

Fact box 1. The colours of carbon: Brown, Black, Blue and Green

Climate Change has driven widespread appreciation of atmospheric CO_2 as the main greenhouse gas and of the role of anthropogenic CO_2 emissions from energy use and industry in affecting temperatures and the climate – we refer to these emissions as "brown carbon" for greenhouse gases and "black carbon" for particles resulting from impure combustion, such as soot and dust. The Emissions Trading System of the European Union (EU-ETS) is a "black-brown carbon" system as it does not incorporate forestry credits. The Kyoto Protocol's Clean Development Mechanism (CDM) does in principle include forestry credits, but demand (in the absence of a linking directive and demand from the EU-ETS) and prices have always been too low to encourage success, so CDM has also become, for all practical purposes, another "black carbon" mechanism.

Terrestrial carbon stored in plant biomass and soils in forest land, plantations, agricultural land and pasture land is often called "green carbon". The importance of "green carbon" is being recognized through anticipated agreement at the United Nations Framework Convention on Climate Change Conference of the Parties (COP) in Copenhagen, December 2009, which includes forest carbon – through various mechanisms, be they REDD and afforestation, REDD-Plus, and/or others (e.g. 'Forest Carbon for Mitigation'). The world's oceans bind an estimated 55% of all carbon in living organisms. The ocean's blue carbon sinks – particularly mangroves, marshes and seagrasses capture and store most of the carbon buried in marine sediments. This is called "blue carbon". These ecosystems, however, are being degraded and disappear at rates 5–10 times faster than rainforests. Together, by halting degradation of "green" and "blue" carbon binding ecosystems, they represent an emission reduction equivalent to 1–2 times that of the entire global transport sector – or at least 25% of the total global carbon emission reductions needed, with additional benefits for biodiversity, food security and livelihoods. It is becoming increasingly clear that an effective regime to control emissions must control the entire "spectrum" of carbon, not just one "colour".

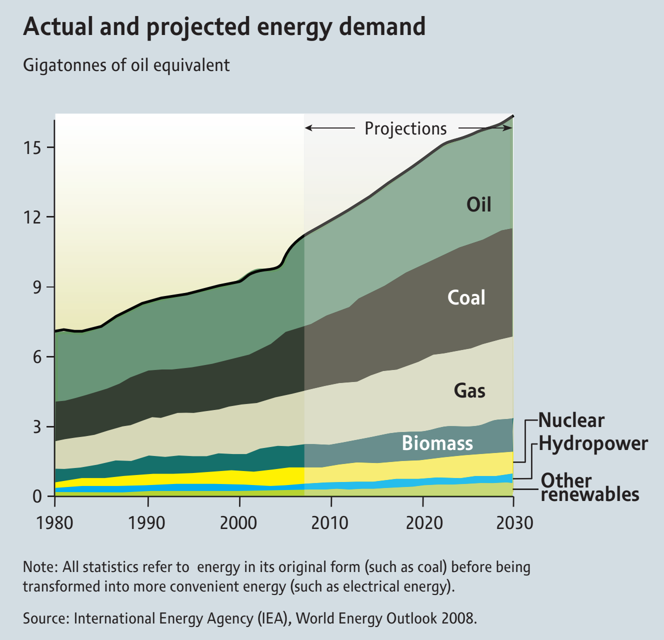
In the absence of "Green Carbon", biofuel cropping can become incentivized, and can lead to carbon emissions if it is not done correctly. The conversion of forests, peatlands, savannas and grasslands to produce food-crop based biofuels in Brazil, Southeast Asia and the United States creates a biofuel carbon debt by emitting 14 to 420 times more CO_2 than the annual reductions in greenhouse gases these biofuels provide by replacing fossil fuels. In contrast, biofuels produced from waste biomass and crops grown on degraded agricultural land do not accrue any such carbon debt.

BROWN, BLACK, GREEN AND BLUE CARBON

Brown and black carbon emissions from fossil fuels, biofuels and wood burning are major contributors to global warming. Black carbon emissions have a large effect on radiation transmission in the troposphere, both directly and indirectly via clouds, and also reduce the snow and ice albedo.

Black carbon is thought to be the second largest contributor to global warming, next to brown carbon (the gases). Thus, reducing black carbon emission represents one of the most efficient ways for mitigating global warming that we know today.

Black carbon enters the ocean through aerosol and river deposition. Black carbon can comprise up to 30% of the sedimentary organic carbon (SOC) in some areas of the deep sea (Masiello and Druffel, 1998) and may be responsible for 25% of observed global warming over the past century. Black carbon tends to remain in the atmosphere for days-weeks (Hansen and Nazarento, 2004) whereas CO_2 remains in the atmosphere for approx 100 years (IGSD, 2009).



Note: All statistics refer to energy in its original form (such as coal) before being transformed into more convenient energy (such as electrical energy).

Source: International Energy Agency (IEA), World Energy Outlook 2008.

Figure 2: Projected growth in energy demand in coming decades.

The total CO_2 emissions of are estimated to be between 7,200 Tg C yr^{-1}, and 10,000 Tg C yr^{-1} (Trumper *et al.*, 2009), and the amount of carbon in the atmosphere is increasing by approximately 2,000 Tg C yr^{-1} (Houghton, 2007).

GREEN CARBON

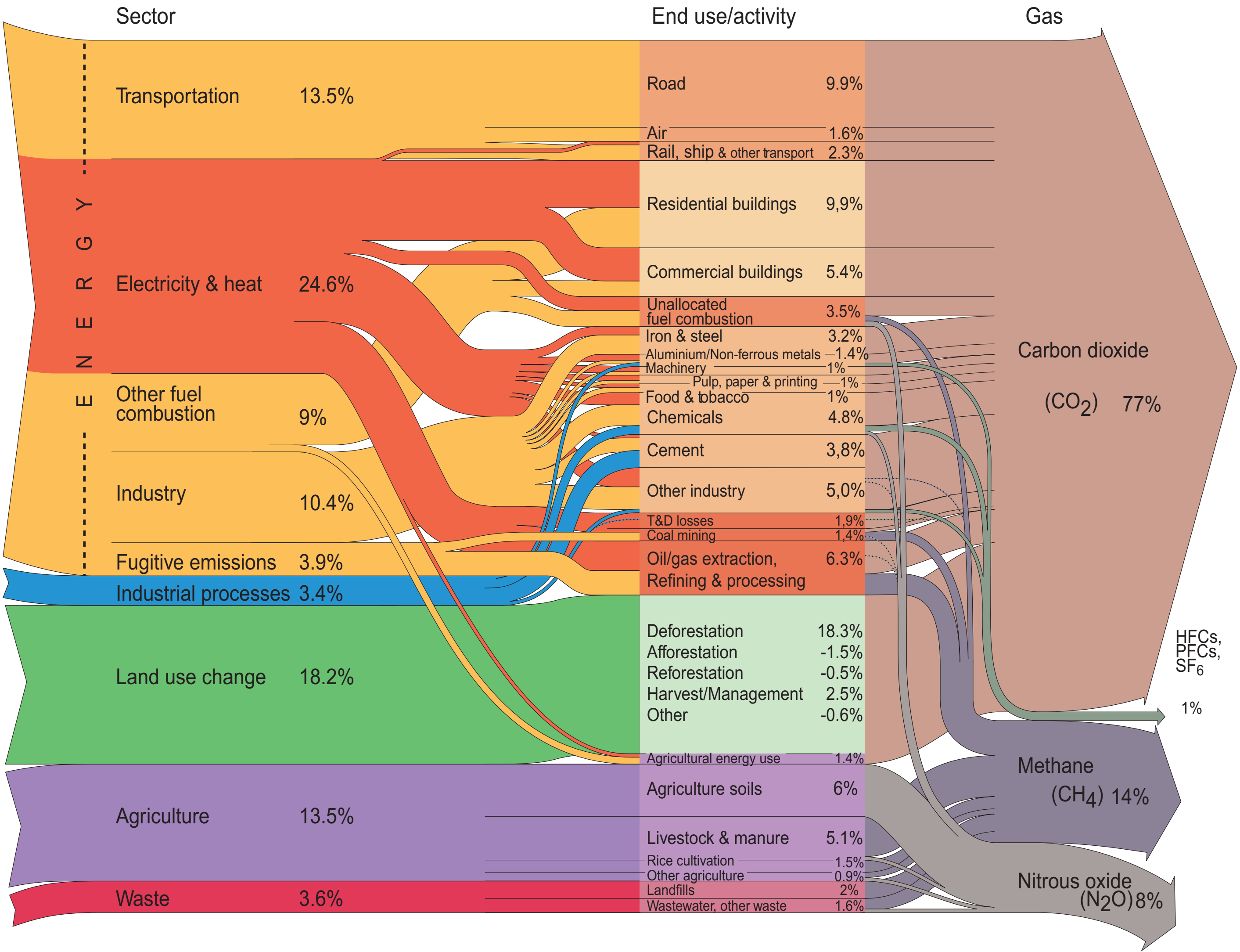
Green carbon is carbon removed by photosynthesis and stored in the plants and soil of natural ecosystems and is a vital part of the global carbon cycle. Sofar, however, it has mainly been considered in the climate debate in terrestrial ecosystems, though the issue of marine carbon sequestration has been known for at least 30 years.

A sink is any process, activity or mechanism that removes a greenhouse gas, an aerosol or a precursor of a greenhouse gas or aerosol from the atmosphere. Natural sinks for CO_2 are for example forests, soils and oceans.

Unlike many plants and most crops, which have short lives or release much of their carbon at the end of each season, forest biomass accumulates carbon over decades and centuries. Furthermore, forests can accumulate large amounts of CO_2 in relatively short periods, typically several decades. Afforestation and reforestation are measures that can be taken to enhance biological carbon sequestration. The IPCC calculated that a global programme involving reduced deforestation, enhanced natural regeneration of tropical forests and worldwide re-afforestation could seques-

➔ **Figure 3: World greenhouse emission by sector.** All transport accounts for approximately 13.5% of the total emissions, while deforestation accounts for approximately 18%. However, estimates of the loss of marine carbon-binding ecosystems have previously not been included.

World greenhouse gas emissions by sector



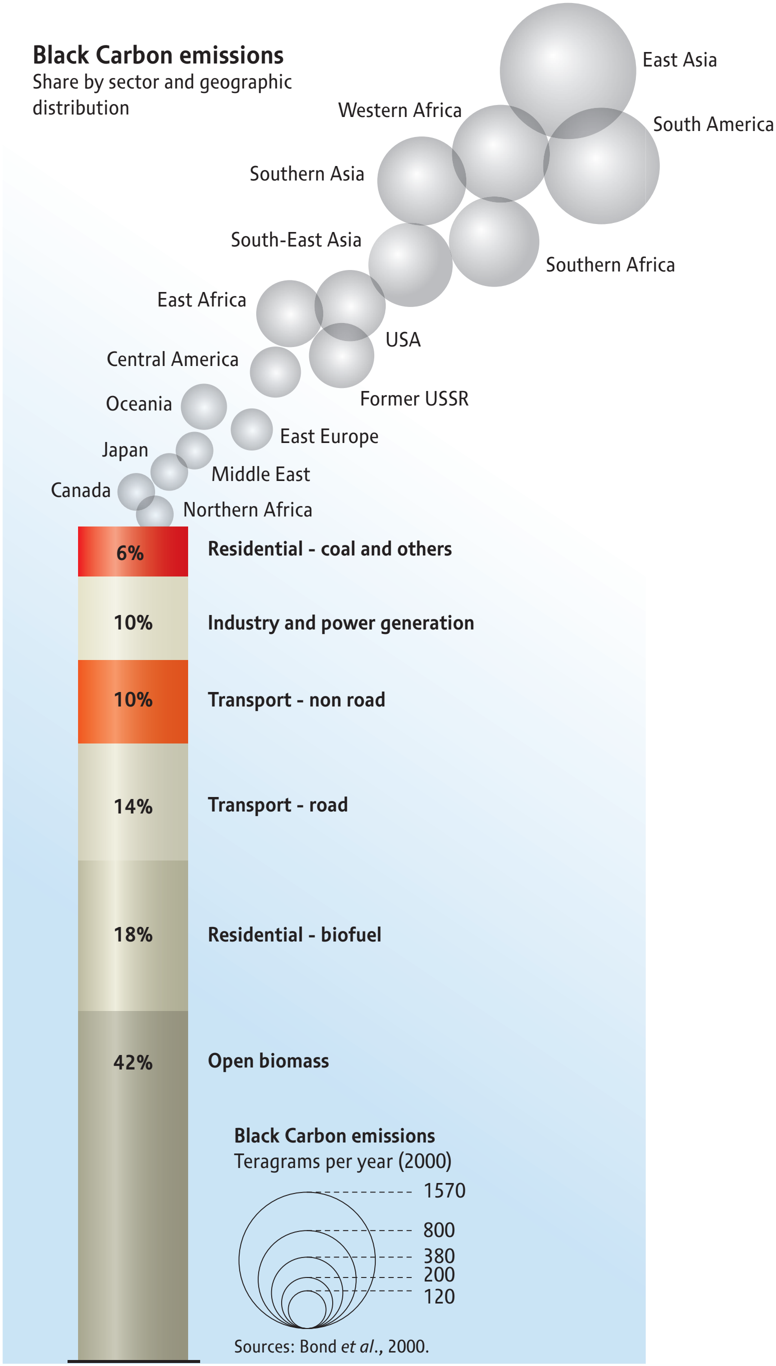
All data is for 2000. All calculations are based on CO_2 equivalents, using 100-year global warming potentials from the IPCC (1996), based on a total global estimate of 41 755 $MtCO_2$ equivalent. Land use change includes both emissions and absorptions. Dotted lines represent flows of less than 0.1% percent of total GHG emissions.

Source: World Resources Institute, Climate Analysis Indicator Tool (CAIT), Navigating the Numbers: Greenhouse Gas Data and International Climate Policy, December 2005; Intergovernmental Panel on Climate Change, 1996 (data for 2000).

ter 60–87 Gt of atmospheric carbon by 2050, equivalent to some 12–15% of projected CO_2 emissions from fossil fuel burning for that period (Trumper *et al.*, 2009).

It is becoming better understood that there are critical thresholds of anthropogenic climate change, beyond which dangerous thresholds will be passed (IPCC, 2007a). For example, to keep average temperature rises to less than 2°C, global emissions have to be reduced by up to 85% from 2000 levels by 2050 and to peak no later than 2015, according to the IPCC (Trumper *et al.*, 2009).

But while the loss of green carbon ecosystems have attracted much interest, for example by combating the



← **Figure 4: Combustion sources of black carbon.** (Source: Dennis Clare, State of the World 2009, www.worldwatch.org).

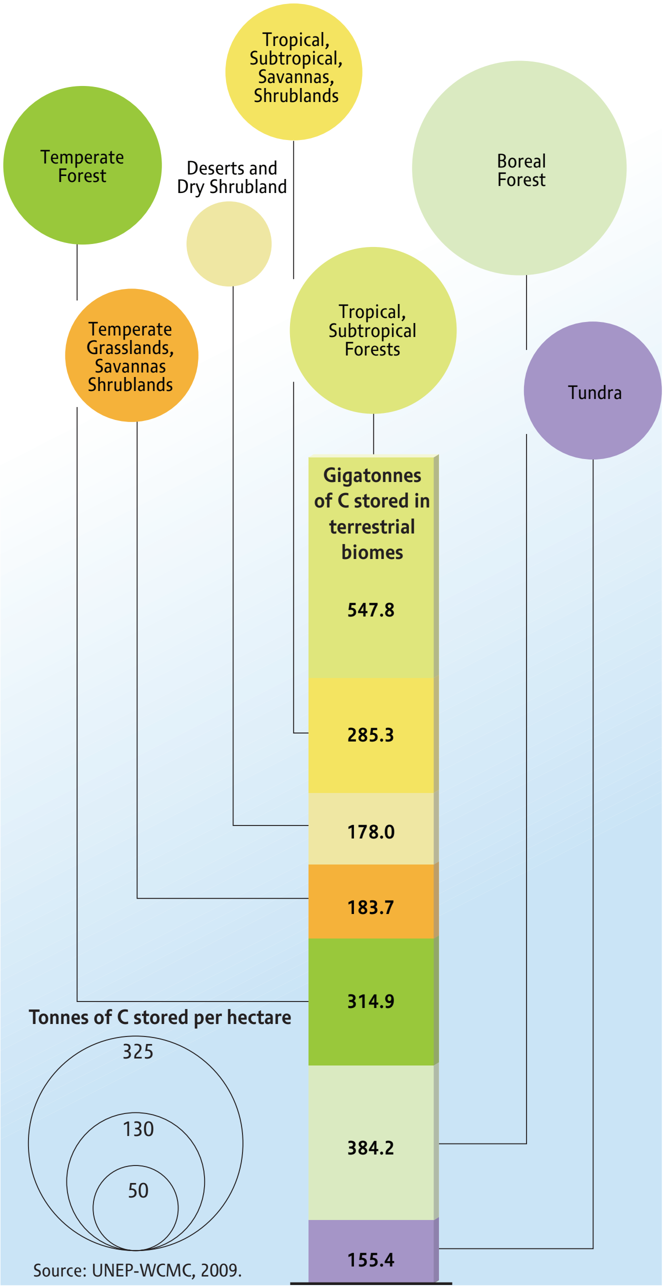
loss of tropical rainforests, the fact that near 55% of all green carbon is captured by living organisms not on land, but in oceans, has been widely ignored, possibly our greatest deficit in mitigating climate change. The carbon captured by marine organisms is herein called “blue carbon”.

BLUE CARBON

Blue carbon is the carbon captured by the world’s oceans and represents more than 55% of the green carbon. The carbon captured by living organisms in oceans is stored in the form of sediments from mangroves, salt marshes and seagrasses. It does not remain stored for decades or centuries (like for example rainforests), but rather for millennia. In this report, the prospects and opportunities of binding carbon in oceans is explored.

➔ Figure 5: 45% of green carbon stored in natural terrestrial ecosystems and the remaining 55% is captured by living organisms in oceans by plankton and ocean’s blue carbon sinks.

Green Carbon



Source: UNEP-WCMC, 2009.

Look again at that dot.

That's here. That's home. That's us.

On it everyone you love, everyone you know, everyone you ever heard of, every human being who ever was, lived out their lives. The aggregate of our joy and suffering, thousands of confident religions, ideologies, and economic doctrines, every hunter and forager, every hero and coward, every creator and destroyer of civilization, every king and peasant, every young couple in love, every mother and father, hopeful child, inventor and explorer, every teacher of morals, every corrupt politician, every 'superstar', every 'supreme leader,' every saint and sinner in the history of our species lived there – on a mote of dust suspended in a sunbeam.

Carl Sagan 1997.
Image from the solar system taken by the Voyager 1 spacecraft (NASA/JPL).

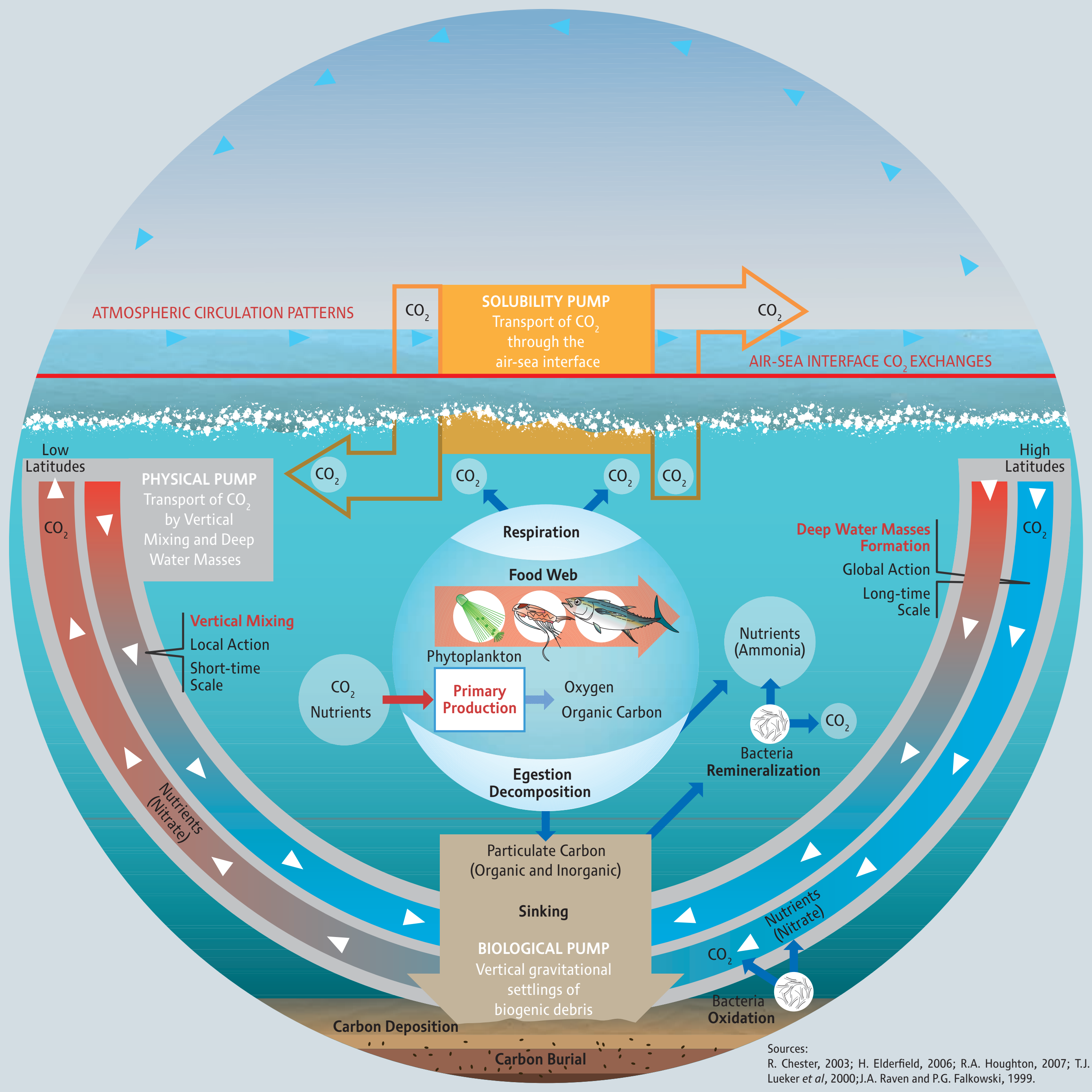
BLUE PLANET: OCEANS AND CLIMATE

The existence of the vast ocean is the main defining characteristic of our planet, making earth unique in the solar system and the only Blue Planet. Although water is not uncommon in the universe, oceans are probably extremely rare. Other planets in the solar system have evidence of ice, ancient water basins and valleys, or even subsurface liquid water, but planet earth is the only one which has liquid surface water; probably due to our privileged position in respect to the sun: not close enough to evaporate and escape, nor far enough to freeze. Water is also linked to the origin of life, in which early organic molecules rested protected from temperature swings and from the sun's destructive ultraviolet radiation, and where they could move freely to combine and evolve. This successful combination of water and life changed the composition of the atmosphere by releasing oxygen and extra water vapour, and shaped our landscape, through erosion, weathering and sedimentation, in a continuous interchange of water between the ocean, the land and the atmosphere.

> ***How inappropriate to call this planet earth when it is quite clearly Ocean.***
>
> **Arthur C. Clarke**

Water moves in a continuous cycle that begins and ends in the ocean. This hydrologic cycle is powered by solar radiation, which provides energy for evaporation. Then precipitation, transpiration from plants, runoff into streams and infiltration to ground water reservoirs complete the cycle, which will start over again when most of the initial evaporated water reaches the ocean. Although during the cycle, water can be present in different states as ice, liquid or vapor, the total water content of the ocean has remained fairly constant since its formation, with an average residence time of approximately 3,000 years. At the moment, 97.25% of the water in planet earth is in the form of liquid salty water in the oceans, with only 2.05% forming ice covers and glaciers, 0.68% groundwater, 0.01% rivers and lakes, and 0.001% in the atmosphere (Campy and MaCaire, 2003).

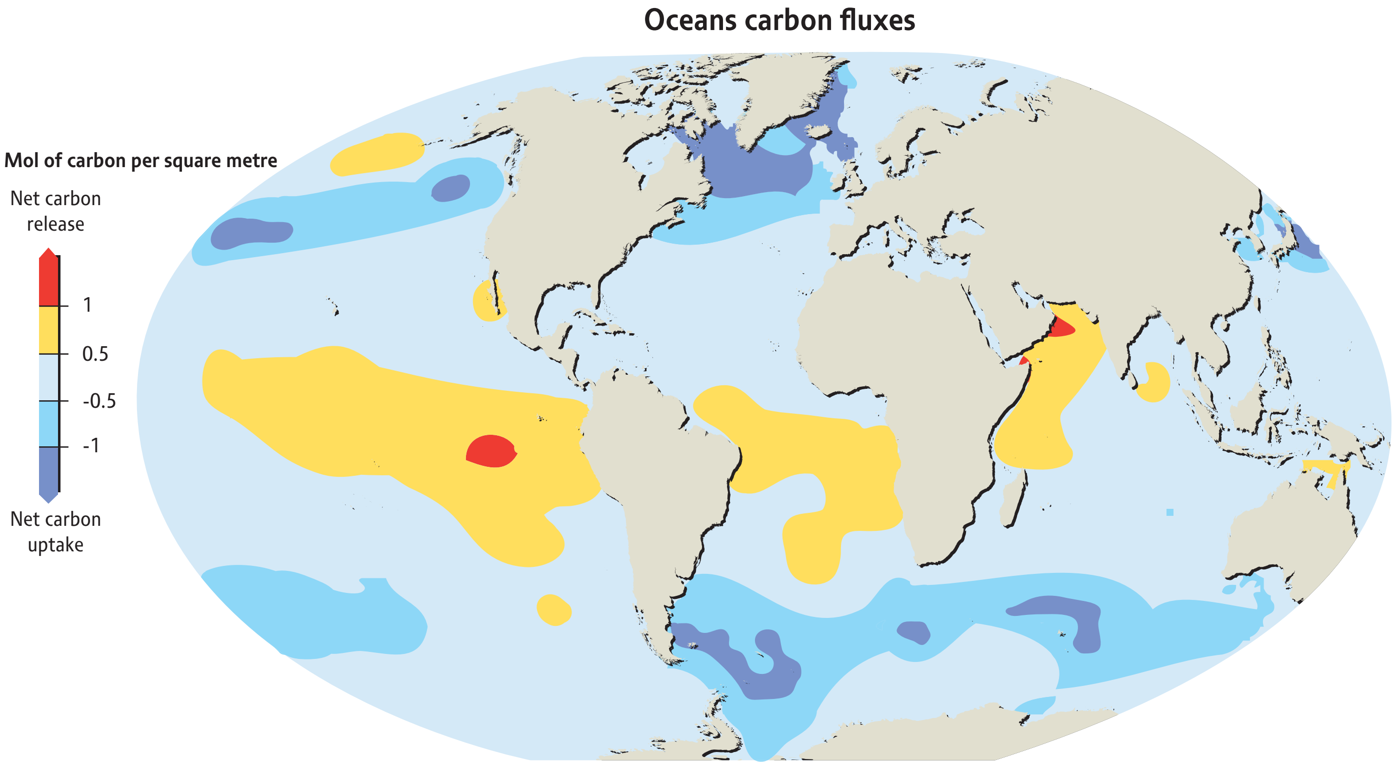
Oceans have been influencing the climate and the ecology of the planet since the very beginning of life on earth. Over time, both the physical oceans and living organisms have contributed to the cycling of carbon. Plankton in marine ecosystems produces more organic material than is needed to maintain the food chain. The excess carbon slowly accumulates on the sea bed during geological time (biological pump) (Longhurst, 1991; Siegenthaler and Sarmiento, 1993; Raven and Falkowski, 1999). With that process, sediment and fossilized carbonate plankton have changed the shape of our coasts.



Sources:
R. Chester, 2003; H. Elderfield, 2006; R.A. Houghton, 2007; T.J. Lueker *et al*, 2000;J.A. Raven and P.G. Falkowski, 1999.

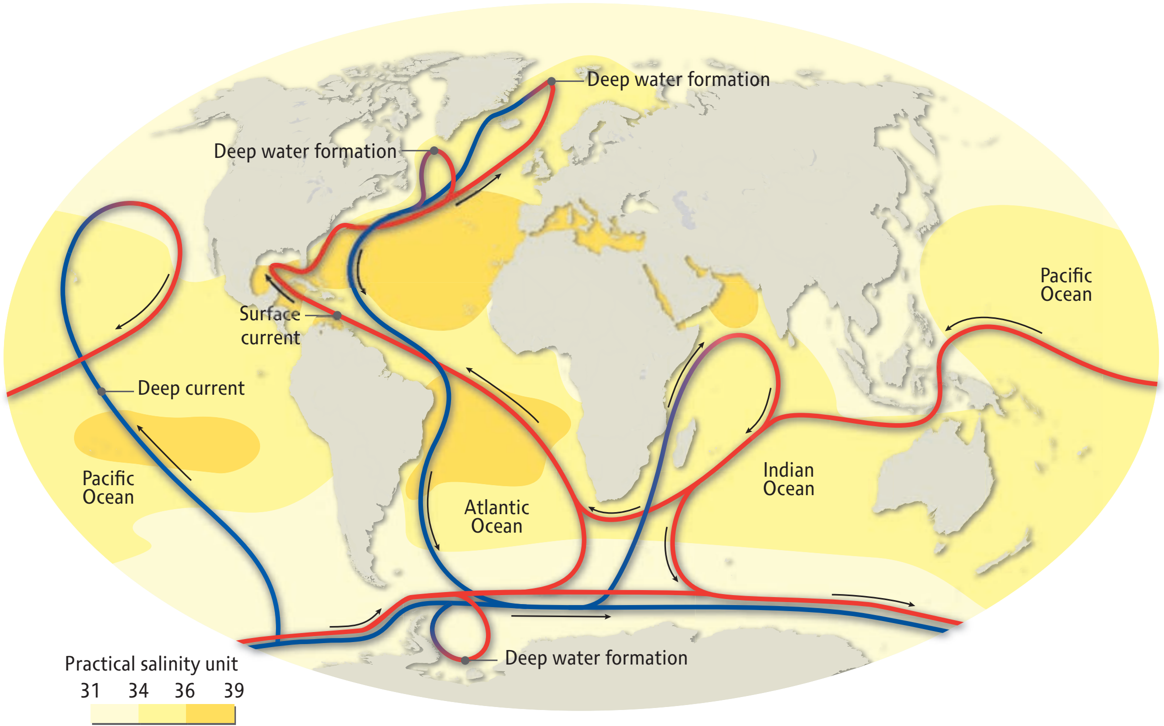
← **Figure 6: Carbon cycling in the world's oceans.** The flow of carbon dioxide across the air-sea interface is a function of CO_2 solubility in sea water (Solubility Pump). The amount of CO_2 dissolved in sea water is mainly influenced by physico-chemical conditions (sea water temperature, salinity, total alkalinity) and biological processes, e.g. primary production. The solubility pump and the biological pump enhance the uptake of CO_2 by the surface ocean influencing its values for dissolved CO_2 and transferring carbon to deep waters. All these mechanisms are strongly connected, subtly balanced and influential to the ocean's capacity to sink carbon. The net effect of the biological pump in itself is to keep the atmosphere concentration of CO_2 around 30% of what it would be in its absence (Siegenthaler and Sarmiento, 1993).

Oceans are absorbing both heat and carbon from the atmosphere, therefore alleviating the impacts of global warming in the environment. Covering more than two-thirds of the earth's surface, the oceans store the sun's energy that reaches earth's surface in the form of heat, redistribute it, from the coast to the mid-ocean, shallow to deep waters, polar to tropical, and then slowly release it back to the atmosphere. These storage and circulation processes prevent abrupt changes in temperature, making coastal weather mild and some high latitude areas of the globe habitable. However this huge heat storage capacity can have undesirable consequences with the advent of climate change. With global warming, the ocean is absorbing a large portion of the excess heat present in the atmosphere (almost 90%), resulting in a measurable increase of surface water temperatures (an average of approximately 0.64°C over the last 50 years) (Levitus *et al.*, 2000; IPCC, 2007b). As water warms, it ex-



Source: Marine Institute, Ireland, 2009.

Figure 7: Carbon fluxes in the oceans. (Source: adapted from Takahashi *et al.*, 2009).


Thermohaline circulation

(1 psu = 1 gram of salt per kilogram of water)

Source : NASA, 2009.

Figure 8: Thermohaline circulation is a 3-dimensional flow involving surface and deep ocean waters, which is driven by differences in water temperature and salinity. (Image source: NOAA/NCDC).

pands causing the ocean surface to rise (UNEP, 2008b). Over time, this heat will descend to greater ocean depths, increasing expansion and triggering further changes in sea level.

Melting of sea ice in the Arctic, inland glaciers and continental ice sheets of Greenland and Antarctica is changing the salinity of sea water and in some cases also contributing to sea level rise (UNEP, 2008b). So, melting and warming will have further consequences on ocean circulation, as ocean currents are driven by the interactions between water masses through a balance with temperature and salinity, which controls the density. Changes in oceanic currents could expose local climates to abrupt changes in temperature. Higher water temperatures also lead to increased evaporation, making more energy available for the atmosphere. This has direct consequences on extreme weather events, as warming sea temperatures boost the destructive energy of hurricanes, typhoons, etc. Tropical sea-surface temperatures have warmed by only half a degree Celsius, while a 40% increase in the energy of hurricanes has been observed (Saunders and Lea, 2008).

Warmer, low salinity surface waters together with the annual seasonal heating are extending and strengthening the seasonal layers in the water-column (stratification), limiting the vertical movement of water masses. This phenomenon together with changes in wind regimes has implications for some of the most productive parts of earth's oceans (Le Quéré *et al.*, 2007), where upwelling of deep waters and nutrients enhances primary production, supporting massively abundant surface ecosystems. If reduction of upwelling occurs to any degree, marine ecosystems, fisheries and communities will be negatively affected. It is important to highlight that enhanced stratification is already a fact in temperate seas at mid-latitudes, where stratification is diminishing the total annual primary production as a result of the reduction in the supply of nutrients to the surface layers (Cushing, 1989; Valdés and Moral, 1998; Valdés *et al.*, 2007). Warming temperatures are also changing the geographical ranges of marine species. Changes in depth range are occurring, as species shift down in the water column to escape from warming surface waters. There is also evidence that the distribution of zooplankton, fish and other marine fauna has shifted hundreds of kilometers towards higher latitudes, especially in the North Atlantic, the Arctic Ocean, and the Southwest Pacific Ocean (Cheung *et al.*, 2009)

Another important role played by the ocean is the storage and exchange of CO_2 with the atmosphere, and its diffusion toward deeper layers (solubility pump) (Fact box 2) (Siegenthaler and Sarmiento, 1993). The ocean has absorbed approximately one-third of the total anthropogenic CO_2 emissions since the beginning of the industrial era (Sabine and Feely, 2007). In so doing, the ocean acted as a buffer for earth's climate, as this absorption of CO_2 mitigates the effect of global warming by reducing its concentration in the atmosphere. However, this continual intake of CO_2 and heat is changing the ocean in ways that will have potentially dangerous consequences for marine ecology and biodiversity. Dissolved CO_2 in sea water lowers the oceans' pH level, causing acidification, and changing the biogeochemical carbonate balance (Gattuso and Buddemeier, 2000; Pörtner *et al.*, 2004). Levels of pH have declined at an unprecedented rate in surface sea water over the last 25 years and will undergo a further substantial reduction by the end of this century as anthropogenic sources of CO_2 continue to increase (Feely *et al.*, 2004).

Fact box 2. The ocean – a giant carbon pump

The solubility pump: CO_2 is soluble in water. Through a gas-exchange process CO_2 is transferred from the air to the ocean, where it forms of dissolved inorganic carbon (DIC). This is a continuous process, as sea water is under-saturated with CO_2 compared to the atmosphere. The CO_2 is subsequently distributed by mixing and ocean currents. The process is more efficient at higher latitudes as the uptake of CO_2 as DIC increases at lower temperatures since the solubility of CO_2 is higher in cold water. By this process, large quantities of CO_2 are removed from the atmosphere and stored where they cannot contribute immediately to the greenhouse effect.

The biological pump: CO_2 is used by phytoplankton to grow. The excess of primary production sinks from the ocean surface to the deep sea. In the very long term, part of this carbon is stored in sediments and rocks and trapped for periods of decades to centuries. In order to predict future CO_2 concentrations in the atmosphere, it is necessary to understand the way that the biological pump varies both geographically and temporally. Changes in temperature, acidification, nutrient availability, circulation, and mixing all have the potential to change plankton productivity and are expected to reduce the trade-off of CO_2 towards the sea bed.

As the ocean continues to absorb further heat and CO_2, its ability to buffer changes to the atmosphere decreases, so that atmosphere and terrestrial ecosystems will face the full consequences of climate change. At high latitudes, dense waters sink, transferring carbon to the deep ocean. Warming of the ocean surface inhibits this sinking process and therefore reduces the efficiency of CO_2 transport and storage. Furthermore, as water warms up, the solubility of CO_2 declines, therefore less gas can be stored in the sea water. With acidification, warming, reduced circulation and mixing, there has been a significant change in plankton productivity in the ocean, reducing the portion of the carbon budget that would be carried down to the deep seafloor and stored in sediments.

So, the ocean system is being threatened by the anthropogenic activities which are causing global warming and ocean acidification. As waters warm up and the chemical composition of the ocean changes, the fragile equilibrium that sustains marine biodiversity is being disturbed with serious consequences for the marine ecology and for earth's climate. There is already some clear evidence that the global warming trend and increasing emissions of CO_2 and other greenhouse gases are affecting environmental conditions and biota in the oceans on a global scale. However, we neither fully appreciate nor do we understand how significant these effects will be in the near and more distant future. Furthermore, we do not understand the mechanisms and processes that link the responses of individuals of a given species with shifts in the functioning of marine ecosystems (Valdés *et al.*, 2009). Marine scientists need urgently to address climate change issues, particularly to aid our understanding of climate change effects on ecosystem structure, function, biodiversity, and how human and natural systems adapt to these changes.

Fact box 3. The role of ocean viruses and bacteria in the carbon cycle

Free living marine microorganisms (plankton, bacteria and viruses) are hardly visible to the human eye, but account for up to 90% of living biomass in the sea (Sogin *et al.*, 2006; Suttle, 2007). These microscopic factories are responsible for >95% of primary production in oceans, producing and respiring a major part of the reduced carbon or organic matter (Pomeroy *et al.*, 2007).

Plankton

More than 36.5Gt of CO_2 is captured each year by planktonic algae through photosynthesis in the oceans (Gonzalez, *et al.* (2008). Zooplankton dynamics are a major controlling factor in the sedimentation of particulate carbon in open oceans (Bishop and Wood, 2009). Of the captured CO_2, and an estimated 0.5Gt C yr^{-1} is stored at the sea bed (Seiter *et al.*, 2005).

Marine viruses and bacteria – significant in the carbon budget

Marine viruses require other organic life to exist, but in themselves have a biomass equivalent to 75 million blue whales (11.25Gt). The estimated $1x10^{30}$ viruses in the ocean, if stretched end to end, would span farther than the nearest 60 galaxies (Suttle, 2007). Although the story of marine viruses is still emerging, it is becoming increasingly clear that we need to incorporate viruses and virus-mediated processes into our understanding of ocean biology and biogeochemistry (Suttle, 2007).

Interactions between viruses and their hosts impact several important biological processes in the world's oceans including biogeochemical cycling. They can control carbon cycling due to cell lysis and microbial diversity (by selecting for various hosts) (Wiggington, 2008). Every second, approximately $1x10^{23}$ viral infections occur in the ocean and cause infection of 20–40% surface water prokaryotes every day resulting in the release of 108–109 tonnes of carbon per day from the biological pool within the oceans (Suttle, 2007). It is thought that up to 25% of all living carbon in the oceans is made available through the action of viruses (Hoyle and Robinson, 2003).

There is still a critical question as to whether viruses hinder or stimulate biological production (Gobler *et al.*, 1997). There is an ongoing debate whether viruses (1) shortcircuit the biological pump by releasing elements back to the dissolved phase (Poorvin *et al.*, 2004), (2) prime the biological pump by accelerating host export from the euphotic zone (Lawrence and Suttle, 2004) or (3) drive particle aggregation and transfer of carbon into the deep sea through the release of sticky colloidal cellular components during viral lysis (Mari *et al.*, 2005).

Bacteria

Ocean bacteria are capable of taking up CO_2 with the help of sunlight and a unique light-capturing pigment, proteorhodopsin, which was first discovered in 2000 (Beja *et al.*, 2001). Proteorhodopsin can be found in nearly half of the sea bacteria. Knowledge of marine bacteria may come to be of major importance to our understanding of what the climate impact of rising CO_2 emissions means for the oceans.

Life deep below the sea bed

Life has been shown to exist in the deep biosphere, even 800m below the sea floor. It is estimated that 90 Gt of microbial organisms (in terms of carbon mass) are living in the sediments and rocks of the sea bed, with bacteria dominating the top 10 cm, but more than 87% made up by a group of single cell microorganisms known as Archaea. It is still not clear what their ecological functions are, or even how they survive in such a low flux environment, living on previously digested fossil remains (Lipp *et al.*, 2008).

SEVEN DETRIMENTAL WAYS IN WHICH THE OCEANS THEMSELVES WILL BE AFFECTED BY CLIMATE CHANGE

The ecology of the planet is closely linked to different ocean processes, most of which are directly affected by climate change.

1 MELTING OF ARCTIC SEA ICE

Arctic sea-ice reductions have significant impacts on climate, wildlife and communities. The opening of open water across the Arctic ocean will have unknown consequences in terms of changes in water circulation and redistribution of species from the Atlantic and Pacific oceans. As sea ice coverage declines, albedo diminishes and more radiation is absorbed by the sea water, in a feed-back process that enhances warming and melting sea ice.

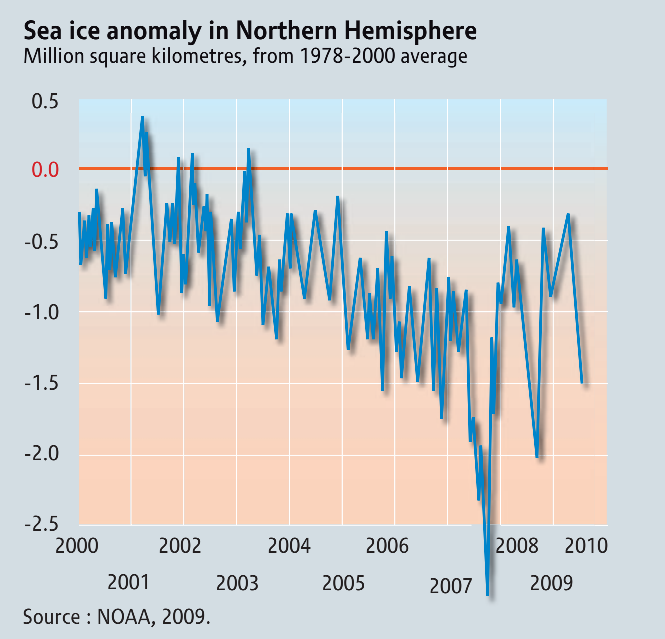
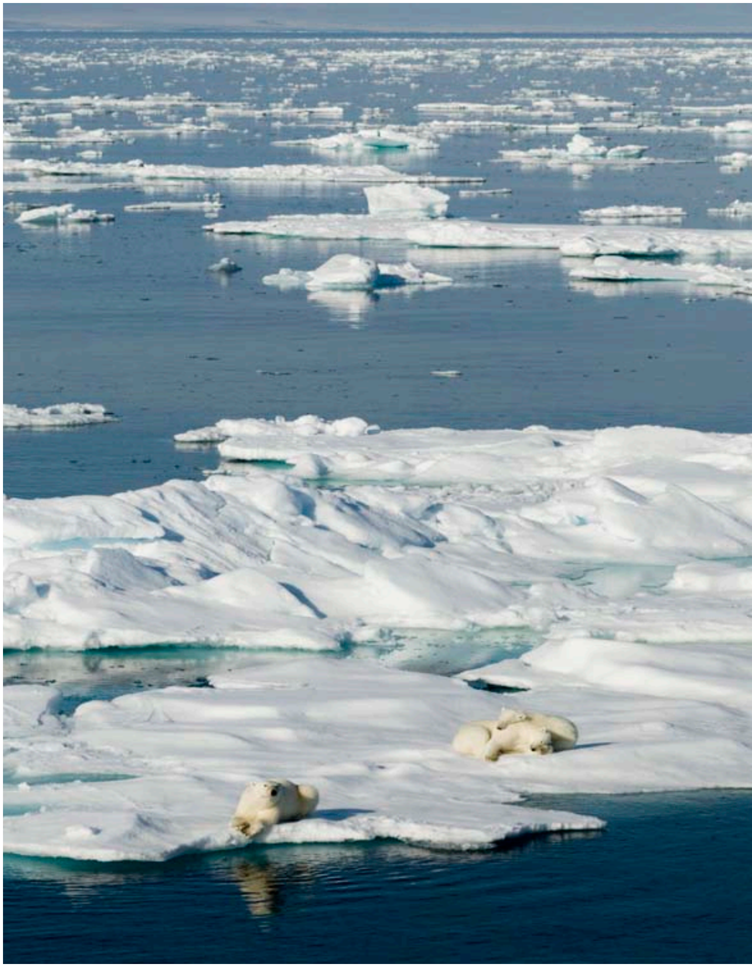
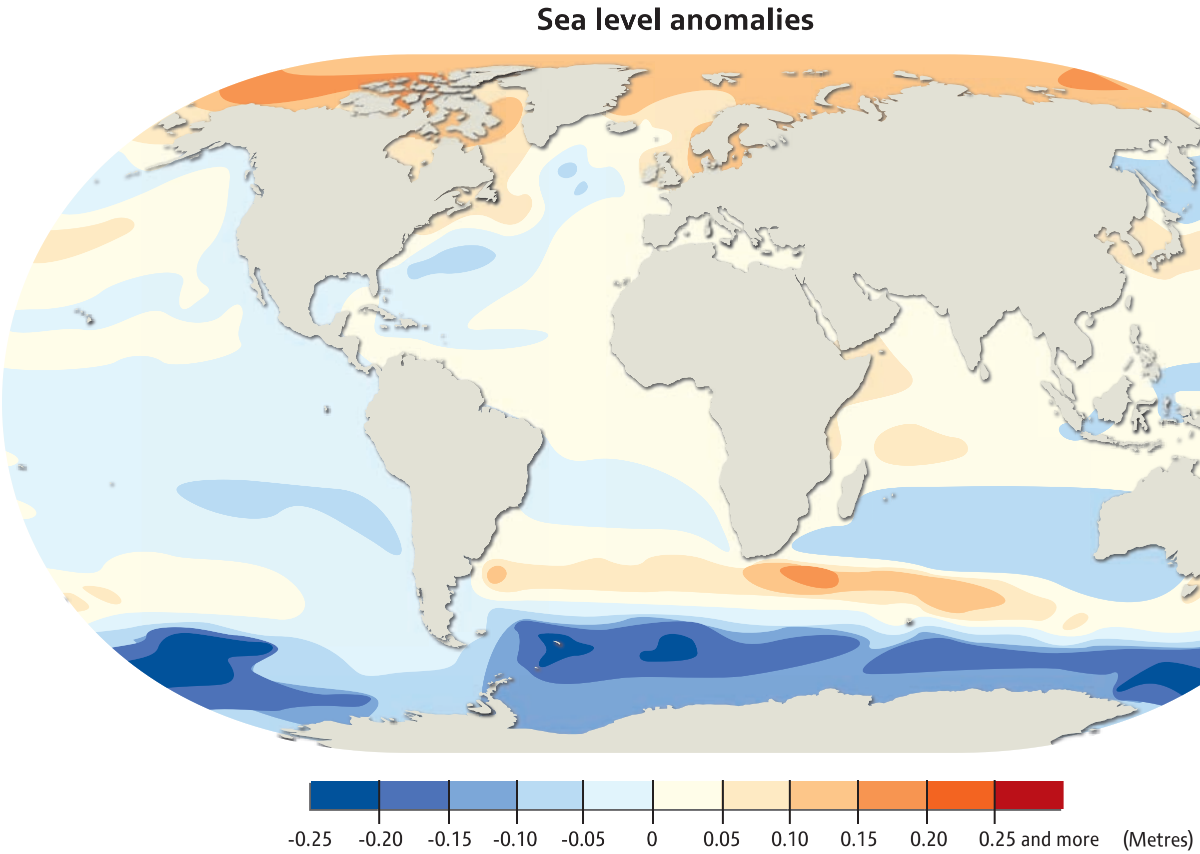


Figure 9: Loss of the ice sheet.





Source: IPCC, 2007.

Figure 10. Sea level anomalies (see text).

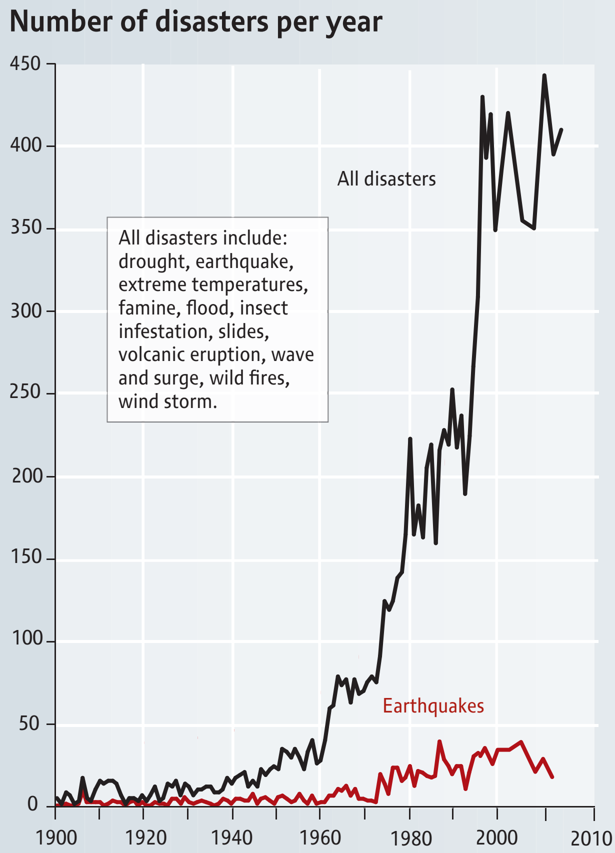
2 OCEAN CIRCULATION AND THERMAL EXPANSION

Melting and warming will have consequences on ocean circulation, as ocean currents are driven by the interactions between water masses though balance in temperature and salinity, in other words, their density. Additionally melting of inland glaciers and continental ice sheets on Greenland and Antarctica, and the thermal expansion of ocean waters are causing sea level rise.

3 INCREASED FREQUENCY AND SEVERITY OF STORM EVENTS

Higher water temperatures lead to increased evaporation, making more energy available for the atmosphere, which boosts the destructive force of extreme weather events like hurricanes, typhoons etc.

Figure 11. Trends in number of reported disasters (see text).


Number of disasters per year

Source: CRED Annual Disaster Statistical Review 2006, 2007.

Trends in number of reported disasters

Much of the increase in the number of hazardous events reported is probably due to significant improvements in information access and also to population growth, but the number of floods and cyclones reported is still rising compared to earthquakes. Is global warming affecting the frequency of natural hazards?

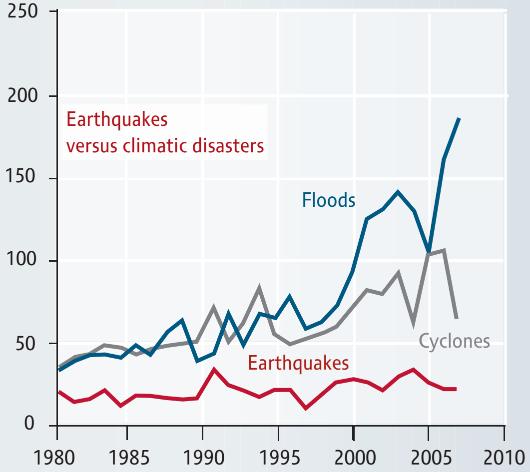
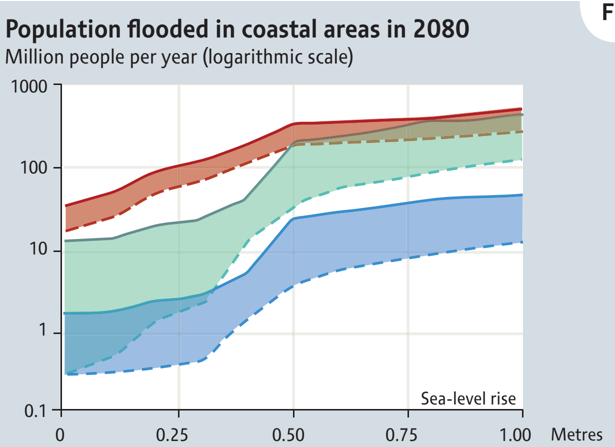


Figure 12. Projected population flooded in coastal areas by 2080 (see text).


Population flooded in coastal areas in 2080

Million people per year (logarithmic scale)

- 🟥 no additional efforts undertaken
- 🟩 more protection efforts than today
- 🟦 strong efforts to protect coastal populations against floods

Note: The upper margin of each band shows the amount of people affected in the A2 scenario according to which global population will reach 14 thousand million by 2080 with the lowest GDP of all IPCC scenarios. Therefore little capacity exists to adapt, and more people will be affected by floods. The lower end of each curve shows the impact for the A1/B1 scenario assuming the highest per captia income and world population at 8 thousand million, allowing for higher investments in the protection of the population.

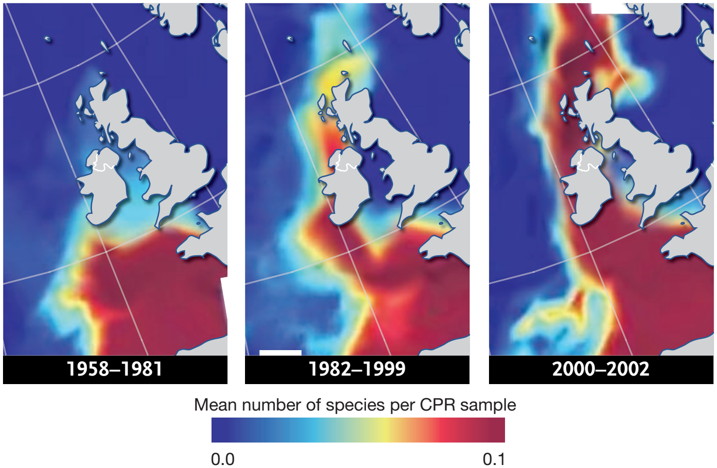
Source: H. Ahlenius, GEO Ice and Snow, 2007, based on Nicholls, R.J. and Lowe, J.A., 2006.

4 WATER-COLUMN STRATIFICATION AND LOSS OF COASTAL PUMPS

Warming and melting is enhancing seasonal water-column stratification in the ocean on a global scale, mainly in temperate seas. Some coastal ”flushing” mechanisms – so-called dense-shelf water cascading – may also be weakened with climate change, resulting in slower “cleaning” of polluted coastal waters, more algae blooms and dead zones, and lack of transport of food particles to organisms living in the deep sea and on the sea floor. The resulting reduction in nutrient flux will cause a decline in primary production and possibly in ocean productivity.

5 SHIFTS IN DISTRIBUTION OF SPECIES AND MIGRATORY ROUTES

The distribution of plankton, fish and other marine fauna has shifted hundreds of kilometers toward higher latitudes, especially in the North Atlantic, the Arctic Ocean, and the Southwest Pacific Ocean. Additionally ocean warming has noticeable effects on the migratory routes of many species.



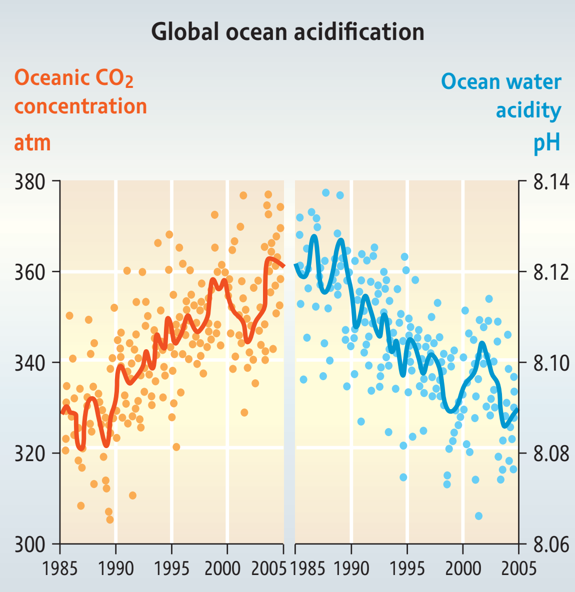
Source: based on Ahlenius, H., 2008; Personal communication with Chris Reid, SAHFOS, November 2007.

Figure 13. Plankton migration shift.

➔ Figure 14. As carbon concentrations in the atmosphere increase, so do concentrations in the ocean, with resultant acidification as a natural chemical process.

6 OCEAN ACIDIFICATION

The ocean is absorbing excess CO_2 from the atmosphere which is causing changes in the biogeochemical carbonate balance of the ocean, and thus significant acidification of ocean waters. The ocean is thus somehow alleviating the impacts of global warming in the biosphere. With climate change and ocean acidification a large reduction in the ability of the ocean to take up atmospheric CO_2 is expected. The reduction of pH and calcium carbonate saturation levels in the oceans will affect thousands of species from the wide range of marine organisms which need carbonate in their development and for forming shells and skeletons. The structure of marine ecosystems are expected to be severely impacted by acidification with potential extinctions and large-scale reduction in biodiversity and ecosystem services, primarily because of the speed at which these water chemistry changes are occuring.



Source: IPCC, 2007.

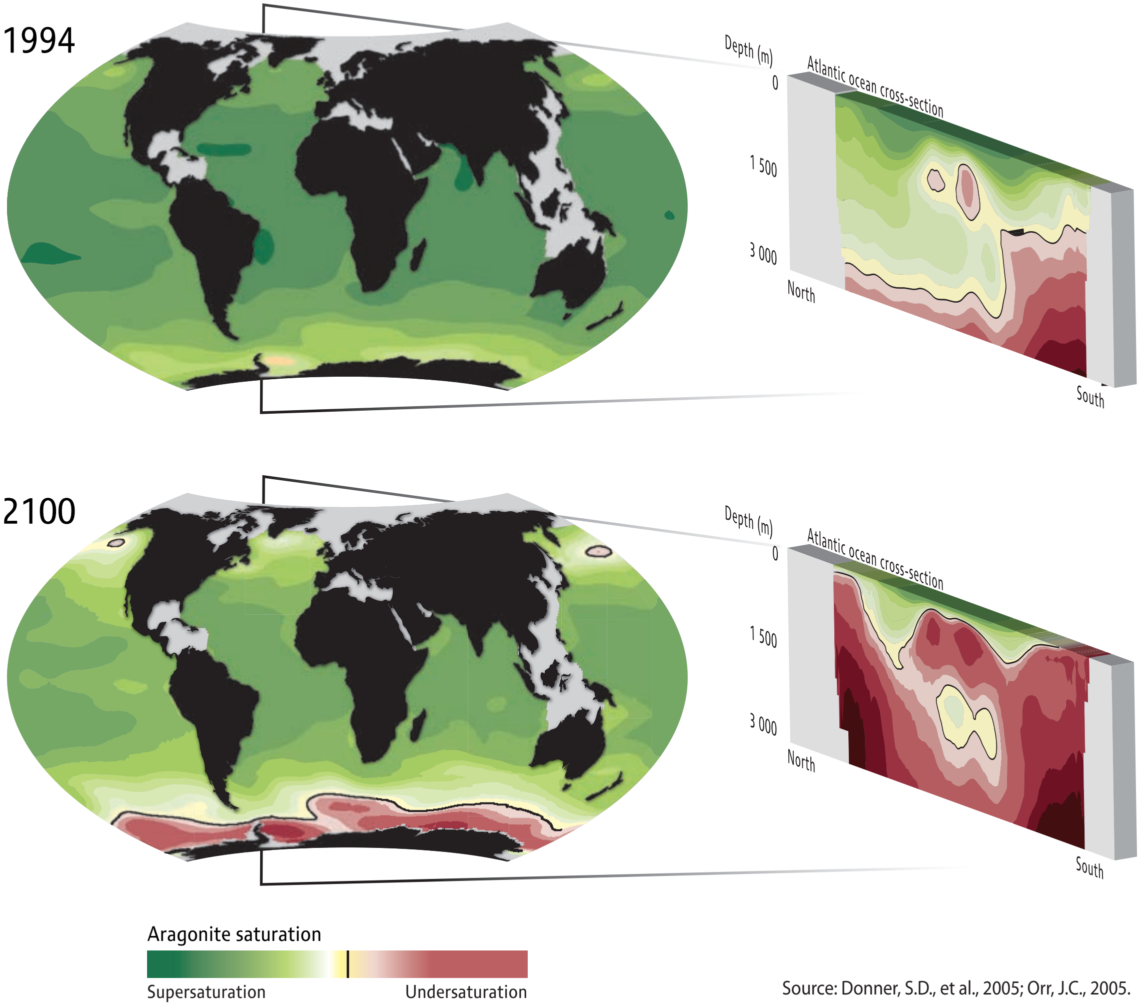


Figure 15. Ocean acidification – as carbon concentrations increase in the atmosphere, so do concentrations in the oceans, with resultant acidification.

Source: Donner, S.D., et al., 2005; Orr, J.C., 2005.

7 LOSS OF CORAL REEFS AND ASSOCIATED MARINE BIODIVERSITY

Coral bleaching is a phenomenon caused primarily by above-average water temperatures and high radiation from the sun, that stress the micro-algae ("zooxanthellae") living symbiotically in corals and giving them their spectacular colours. When these micro-algae become stressed, the coral expels them, so that the coral's white calcareous skeleton is visible through the transparent tissue – hence the term 'bleaching'. Bleached corals are very weak and prone to disease, algal overgrowth and mortality if the stress is high or continues over longer time periods. In 1998, a mass global bleaching event caused the mortality of an estimated 16% of the world's coral reefs, and unfortunately because of rising sea temperatures mass bleaching events are predicted to increase in frequency and intensity. Loss of coral reefs also means loss of revenue and food for coastal communities who depend on them.

BLUE CARBON – THE ROLE OF OCEANS AS CARBON SINKS

Vegetated coastal habitats – mangrove forests, salt-marshes and seagrass meadows – have much in common with rain forests: they are hot spots for biodiversity, they provide important and valuable ecosystem functions, including a large carbon sink capacity, and they are experiencing a steep global decline (Duarte *et al.*, 2008, Duarte, 2009). Indeed, the world is losing its coastal habitats four times faster than its rain forests (Duarte *et al.*, 2008, Duarte, 2009) and the rate of loss is accelerating (Waycott *et al.*, 2009). However, whereas society is well informed of the benefits and threats associated with rainforests, there is a comparative lack of awareness on the status and benefits of vegetated coastal habitats. This is perhaps because of a "charisma" gap, where these often submerged, out of sight coastal habitats, are not as appealing to the public as their terrestrial counterparts (Duarte *et al.*, 2008). Yet, because of their similar functions and threats, coastal habitats can be considered as blue carbon sinks.

BLUE CARBON SINKS

One key function of vegetated coastal habitats is their role as carbon sinks. Benefiting from the excellent conditions available to support plant growth, vegetated coastal habitats rank amongst the most productive habitats in the world, comparable in production to the most productive agricultural crops (Table 1, Duarte and Chiscano, 1999). Much of their production is used to support ecosystem functions (Duarte and Cebrián, 1996). However, blue carbon sinks are strongly autotrophic, which means that these ecosystems fix CO_2 as organic matter photosyntheticaly in excess of the CO_2 respired back by biota (Duarte and Cebrián, 1996; Gattuso *et al.*, 1998; Duarte *et al.*, 2005a), thus removing CO_2 from the atmosphere. Some of this excess carbon is exported and subsidises adjacent ecosystems, including open ocean and beach ecosystems (Duarte and Cebrián, 1996; Heck *et al.*, 2008; Bouillon *et al.*, 2008). The remaining excess production of mangrove forests, salt-marshes and seagrass meadows is buried in the sediments, where it can remain stored over millenary time scales (Mateo *et al.*, 1997), thereby representing a strong natural carbon sink. This is most evident in the case of seagrass meadows, which accumulate enough materials as to significantly raise the seafloor, forming mats that can exceed 3 metres in depth.

In addition to burying a fraction of their own production, blue carbon sinks reduce flow, alter turbulence and attenuate wave action (Koch *et al.*, 2006), thereby promoting sedimentation and reducing sediment resuspension (e.g. Gacia and Duarte, 2001). Recent research has shown that the canopies of seagrass meadows trap particles entrained in the flow, which lose momentum upon impacting on the leaves, thereby promoting the sedimentation of suspended material to the seafloor (Hendriks

Source: UNEP-WCMC, 2009; Valiela *et al.*, 2001

Source: UNEP-WCMC, 2009; Duarte *et al.*, 2008.

Source: UNEP-WCMC, 2009; Waycott *et al.*, 2009.

Figure 16a–c: Distribution of the world's blue carbon sinks – seagrasses, mangroves, and salt marsh communities (Source: UNEP-WCMC).

et al., 2007). Isotopic analyses of the organic carbon accumulated in sediments of vegetated coastal habitats have shown that a significant fraction derives from plankton (Gacia *et al.*, 2002). On the continental shelf and in estuaries, terrestrial sources of carbon are also significant (Bouillon *et al.*, 2008), adding to the carbon sink capacity of these blue carbon sinks.

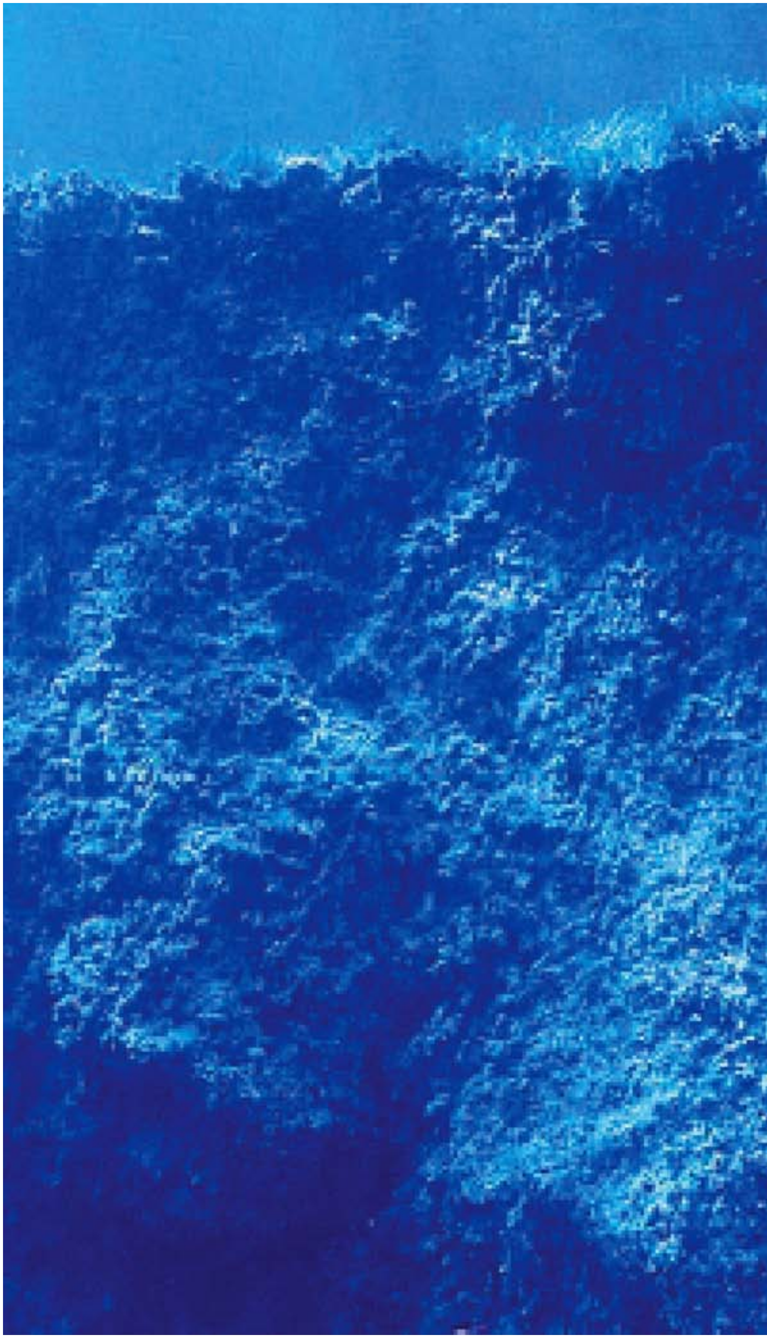
A consequence of the capacity of vegetated coastal habitats to accumulate materials in the seafloor is that they act as efficient carbon sinks, globally responsible for the burial of 120–329 Tg C yr^{-1}, which accounts for at least half of the lower estimate for global carbon burial in marine sediments (Table 1). Blue carbon sinks therefore play a major role in the oceanic carbon cycle (Duarte *et al.*, 2005a). The carbon burial capacity of marine vegetated habitats is phenomenal, 180 times greater than the average burial rate in the open ocean.

Carbon burial in the ocean represents slightly over 10% of the oceanic carbon sink capacity (up to 25% using maximum estimates, Table 1, see below), estimated, from observations and inverse models, to be about 2,000 Tg C year^{-1} (Sarmiento and Gruber, 2002). However, this 2,000 Tg C year^{-1} is the carbon annually transferred from the atmosphere to the oceans, where it is largely stored as dissolved inorganic carbon. The long-term residence of anthropogenic CO_2 in the oceans is uncertain, as this carbon does not penetrate deep enough to remain in the ocean over extended time scales. Indeed, half of the anthropogenic carbon stored in ocean waters is contained within the top 400 metres, where it may equilibrate back to the atmosphere within a few decades, and the amount present in the deep ocean – where it may remain over much longer time scales – is below the detection limit (Sabine *et al.*, 2004). Only a minute amount of the carbon taken up by the oceans is preserved in the deep-sea sediments, where it is effectively buried over long periods of time, representing 6 Tg C yr^{-1}, with a carbon burial per unit area of seafloor 180 times lower than the rate for blue carbon sink sediments (Table 1). In addition, there are concerns that the capacity of the water column of the oceans to act as a sink for atmospheric carbon will weaken in the future, and there is evidence that it may have started to do so (Doney *et al.*, 2009). Hence, only carbon sequestered in marine sediments, as in the case of blue carbon sinks, can be safely considered to represent a long-term marine carbon storage. Blue carbon sinks, which cover less than 0.2% of the seafloor, contribute about 50% (71% using maximum estimates, see Table 1) of the total burial of organic carbon in ocean sediments and therefore rank amongst the most intense carbon sinks in the biosphere (Duarte *et al.*, 2005a). Yet coastal vegetated habitats have been neglected from accounts of the global carbon cycle and global inventories of natural carbon sinks.

Blue carbon sinks are built by plants and trees (otherwise known as angiosperms such as mangroves, salt-marsh plants and seagrasses) but the coastal ocean also contains vast areas covered by algal beds. Most macroalgal beds (including kelp forests) do not bury carbon, as they grow on rocky substrates where burial is impossible.

UNCERTAINTY AND UPPER ESTIMATES OF CARBON SINK BY BLUE CARBON SINKS

There is uncertainty about these global rates, due to uncertainties in their areal extent as well as variability in carbon burial rates among individual ecosystems, although independent estimates for some ecosystems, such as mangrove forests, agree remarkably well (Bouillon *et al.*, 2008). For instance, estimates of the area covered by mangroves, probably the best constrained amongst vegetated coastal habitats, ranges from 0.11 to 0.24 million sq km (Bouillon *et al.*, 2008). Estimates of the area covered by seagrass meadows, the least constraint estimate, range from a documented area of 0.12 million sq km (Green and Short, 2003), to an upper estimate of 0.6 million sq km (Duarte and Chiscano, 1999) as the South East Asian archipelagos, such as Indonesia, are likely to hold vast, uncharted seagrass meadows (Duarte *et al.*, 2009). Indeed, the coastal area with sufficient submarine irradiance as to support seagrass meadows has been estimated at 5.2 million sq km (Gattuso *et al.*, 2006). Hence, a thorough inventory of blue carbon sinks may well yield a cover twice as large as the mean area considered in current, conservative global assessments (Table 1). Individual blue carbon sink ecosystems also vary greatly in their capacity to bury carbon, with the maximum reported rate corresponding to 17.2t C ha^{-1} yr^{-1} in a salt marsh (Table 1). The maximum carbon burial rates for any one habitat type are 3 to 10 times higher than the global mean value for these ecosystems (Table 1), providing evidence of the very



large carbon sink capacity of some specific vegetated coastal habitats. Indeed, the maximum reported carbon sink capacity of salt-marsh, mangrove and seagrass ecosystems (Table 1) exceeds by over 10, 6 and 2 fold that of undisturbed Amazonian forest, estimated at 1.02 t C ha^{-1} (Grace *et al.*, 1993). For instance, carbon burial by salt marshes, which cover a small area of the conterminous USA, has been estimated to account for 21% of the total carbon sink of all USA ecosystems (Bridgham *et al.*, 2006). Hence, an upper estimate of the carbon capture capacity of blue carbon sinks can be derived by combining maximum estimates of the area covered globally with upper estimates of the carbon buried per unit area (Table 1). These calculations yield an upper estimate for the carbon capture capacity of blue carbon sinks at 329 Tg C year^{-1}, accounting for 71% of the burial of organic carbon in the ocean (Table 1).

Table 1. Mean and maximum (in brackets) estimates of the area covered by blue carbon sinks and the annual organic carbon burial rates. Carbon burial rates are presented per hectare (mean,range and , the upper confidence limit of the mean of individual ecosystem estimates, in brackets) and globally (as reported ranges of mean rates of global carbon burial derived using different methods and, in brackets, an upper estimate derived using the maximum area and the upper confidence limit of the mean burial rate). The data is for vegetated coastal areas and their percentage contribution to carbon burial in the coastal and global ocean (in brackets the burial rate and percentage contribution of vegetated habitats calculated from the upper estimates). Total burial rates of organic carbon in estuarine and shelf sediments and deep-sea sediments are provided for comparison. Data derived from reviews by Cebrián and Duarte (1996), Duarte *et al.* (2005a), and Bouillon *et al.* (2008).

Component	Area	Organic Carbon burial	
	Million km^2	Ton C ha^{-1} y^{-1}	Tg C y^{-1}
Vegetated habitats			
Mangroves	0.17 (0.3)	1.39, 0.20 – 6.54 (1.89)	17 – 23.6 (57)
Salt Marsh	0.4 (0.8)	1.51, 0.18 – 17.3 (2.37)	60.4 – 70 (190)
Seagrass	0.33 (0.6)	0.83, 0.56 – 1.82 (1.37)	27.4 – 44 (82)
Total vegetated habitats	0.9 (1.7)	1.23, 0.18 – 17.3 (1.93)	114 – 131 (329)
Depositional areas			
Estuaries	1.8	0.5	81.0
Shelf	26.6	0.2	45.2
Total depositional areas			126.2
Total coastal burial			237.6 (454)
% vegetated habitats			46.89 (0.72)
Deep sea burial	330.0	0.00018	6.0
Total oceanic burial			243.62 (460)
% vegetated habitats			45.73 (0.71)

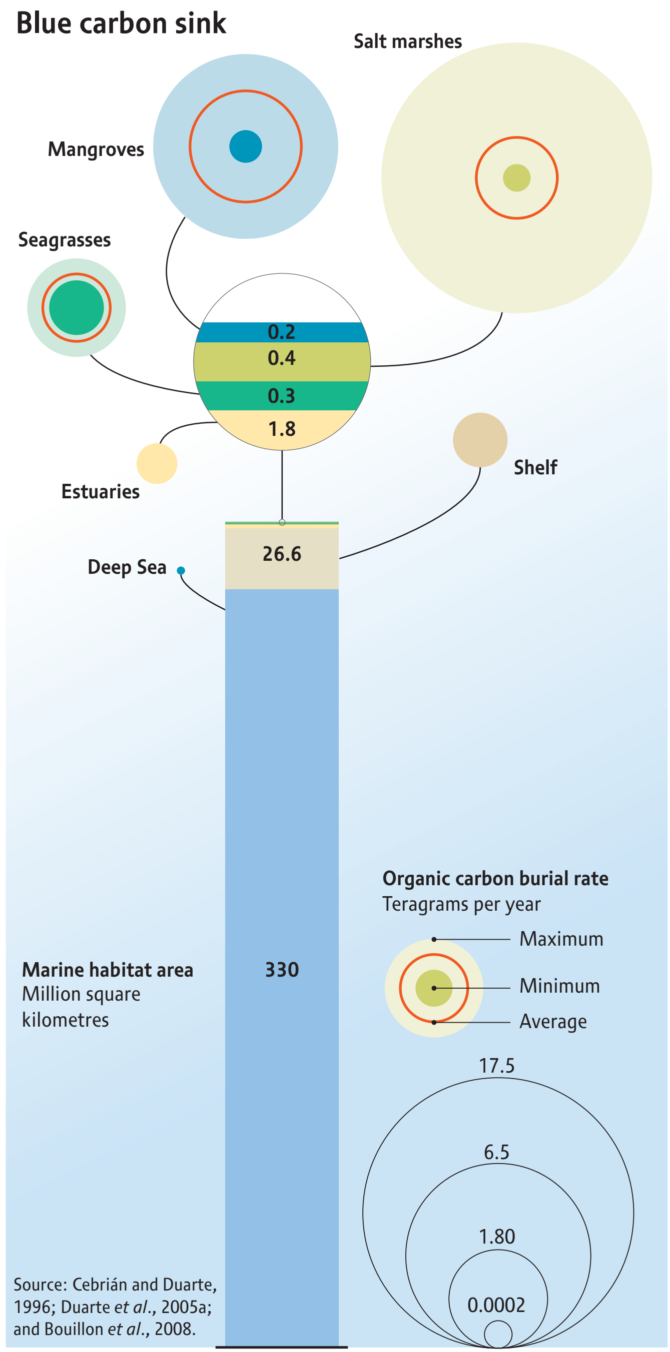
Fact box 4. Ocean carbon in the global cycle?

Several studies suggest that the oceans have taken up around 2,000–2,200 Tg C yr^{-1} over the past two decades (Gurney *et al.* 2002, Plattner *et al.* 2002, Sabine *et al.* 2004, Bender *et al.* 2005, Miller *et al.* 2005, Manning and Keeling 2006). The uptake increased slightly from around an estimated 1800 in the 1980s, to 2,200 Tg C yr^{-1} in the 1990s and the first half decade of the twenty-first century (McNeil *et al.* 2003, Canadell *et al.* 2007). However, only a portion of this carbon is actually stored permanently in the oceans, as much is recycled and released back within a few decades. Coastal ecosystems are currently storing an amount of carbon equivalent to around 25% of the estimated annual increase of approximately 2,000 Tg C yr^{-1} in the atmosphere.

Currently, fossil fuel emissions are estimated at 7,200 Tg C yr^{-1}, which results inapproximately 2,000 Tg C yr^{-1} increase in the atmosphere per year. Losses of seagrass communities, mangroves, and salt marshes have accelerated from around 0.9% per year in the first three quarters of a century to up to 7% per year in the more recent decades. Under current scenarios, most blue carbon sinks will be lost in the next two decades leading to a loss of annual carbon binding capacity equivalent to 4–8% of the total anthropogenic input. Hence, total emissions would therefore have to be reduced by an additional 4–8% by 2030 to retain the status quo, or 10% by 2050. In comparison, the total gain estimated from the UN REDD programme if fully implemented (including slowing deforestation and wide afforestation programmes), would by 2050 according to the IPCC amount to approximately 12–15% of the required emission reductions. Preventing the loss of the oceans blue carbon sinks would mean a significant contribution to reducing climate change, even compared to slowing deforestation of tropical rainforests. Afforestation programmes of mangroves could enhance this even further. The upper estimate of storage in oceans is approximately 450 Tg C yr^{-1} – equivalent near 10% of the required emission reductions. Hence, “Blue” and “Green” carbon combined could bind at least 25% of the projected required emission reductions.

	1980s (Tg C yr^{-1})	1990s (Tg C yr^{-1})	2000–2005 (Tg C yr^{-1})
Fossil fuel emissions	5200 ± 300	6400 ± 300	7200 ± 300
Atmospheric increase	–2900 ± 100	–3200 ± 200	–4200 ± 100
Oceanic uptake	–1900 ± 600	–2200 ± 700	–2200 ± 400
Net terrestrial flux	–400 ± 700	–100 ± 800	–800 ± 800
Land-use change	1500 ± 800	1600 ± 800	1500 ± 800
Residual terrestrial flux	–1900 ± 1100	–2600 ± 1100	–2300 ± 1100

Table 2. The Global carbon budget Tg C yr^{-1} – around 2,200 Tg C are captured per year in oceans, but only a portion of it is stored, mainly in sediments in oceans blue carbon sinks, such as mangroves, marshes and seagrass communities (Canadell *et al.*, 2007; Houghton, 2007).



Source: Cebrián and Duarte, 1996; Duarte *et al*., 2005a; and Bouillon *et al*., 2008.

Figure 17: Blue carbon sinks.

Fact box 5. Geo-engineering proposals for mitigating CO_2

Interest has been growing in the use of geo-engineering to provide a technically and potentially commercially viable mitigating solution to combat increasing atmospheric CO_2 concentrations (see IPCC, 2005 for an overview). Several of these proposals intend to enhance the function of the ocean as a carbon sink, or to store CO_2 in subsea geological formations. Some of these suggestions might sound dramatic and farfetched, but if the concepts are scientifically sound and technically feasible, they should not be disregarded. However, evaluating these new innovations is in most cases not a simple story, as they pose significant ecological, economic, political and ethical challenges (Nature News, 2009) giving cause for concern. With too many unknown variables and current modeling limitations, assessment of the risks and consequences of these proposals will be a challenge.

There are two main approaches. The first is to reduce energy entering the earth's system by blocking radiation so it cannot be absorbed in the first instance (e.g. spraying aerosols to increase cloud cover, use of solar shades, increasing reflective capacity of urban areas); the second is to reduce the concentration of CO_2 in the atmosphere by transferring it into long term storage reservoirs, thereby facilitating the escape of energy from the earth (Lenton and Vaughn, 2009; IEA, 2004). These approaches are at varying degrees of development; while some have been through in-situ experimentation, others are still just theoretical. Current research shows that most ocean geo-engineering concepts are high risk for undesirable side-effects (e.g. increase in ocean acidification), have limited application, uncertain outcome and potentially non-reversible impacts on the marine environment. This highlights the need to apply a precautionary approach when investigating ocean geo-engineering interventions.

Table 3. An overview of the main ocean carbon cycle geo-engineering proposals, the concept behind these ideas and current status of investigation.

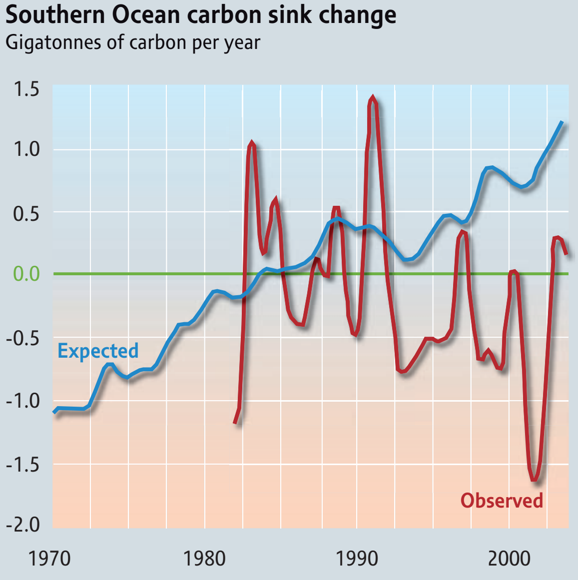
Proposal	Concept	Status of research
Ocean fertilization	Primary production in some areas of the ocean is limited by macro or micro nutrients (such as iron, silica, phosphorus or nitrogen). By increasing the availability of these nutrients, primary productivity could be increased resulting in an acceleration of the natural rate of CO_2 uptake by the oceans from 2 Gt C yr^{-1} (Huesemann, 2008) and increase CO_2 storage in the deep sea. Any CO_2 stored in this way would be removed from the global carbon cycle for up to 1,000 years. Promoted by commercial groups and enterprises (e.g. Climos) and with potential for trading credits on the voluntary carbon market.	• Approximately 13 small scale in situ experiments have been conducted since 1993, but have proven inconclusive about the CO_2 sequestration effectiveness of ocean fertilization; • To make a viable contribution to reducing atmospheric CO_2 concentrations, ocean fertilization would have to be carried out over large areas, and potentially would need to be sustained on a millennial timescale (Lenton and Vaughan, 2009); • International concern has been expressed, inter alia, about the high ecological risks. International bodies and experts have called for restrictions and caution (e.g. IMO, 2007; CBD 2008; Gilbert *et al.*, 2008; Seibel and Walsh 2001); • Parties to the London Convention agreed that, given the present state of knowledge, ocean fertilization activities other than legitimate scientific research should not be allowed. An assessment framework for future scientific research and in-situ experiments is under development (IMO, 2008).
Altering ocean mixing	Use of 200m long ocean pipes to enhance the mixing and upwelling of nutrient rich waters (e.g. Lovelock and Rapley, 2007); Enhance downwelling by using floating pumps to cool waters and form and thicken sea ice (Zhou and Flynn, 2005)	• Never reached field trial stage; • Calculations indicate sequestration flux that would be achieved is trivial on any meaningful timescale; and costly (Lenton and Vaughan, 2009).
Increasing ocean alkalinity	Increasing the alkalinity of the oceans by: • Adding carbonate, thereby increasing the capacity of the water to absorb CO_2 (Kheshgi, 1995). Harvey (2008) suggested the use of finely ground limestone, other proposals foresee the use of thermally decomposed limestone (Cquestrate, 2009); • Enhancing the solubility of CO_2 in the oceans by a process equivalent to the natural silicate weathering reaction. HCl is electrochemically removed from the ocean and neutralized through reaction with silicate rocks.	• This is as yet highly theoretical, but under active research, e.g. by Cquestrate, which is an opensource project to explore the idea, encouraging evidence based debate and investigation (Cquestrate, 2009); • It is possible that the CO_2 emissions generated from preparing the carbonate material would match the CO_2 sequestered (Lenton and Vaughan, 2009).

Proposal	Concept	Status of research
	The increase in ocean alkalinity resulting from the removal of HCl causes atmospheric CO_2 to dissolve into the ocean where it will be stored primarily as HCO^{3-}. (House *et al.*, 2007); • These are the only marine geo-engineering proposals that would remove CO_2 from the atmosphere without causing an increase of ocean acidification.	
Geological carbon storage	Injection of CO_2 into deep geological formations such as saline aquifers or depleted oil and gas reservoirs below the sea floor	• In operation since 1996. Measures and guidance (e.g. to reduce the risk from leakages) were adopted by international bodies (IMO/London Convention, OSPAR). Studies have being conducted to research and model long term consequences and how secure such storage would be (e.g. Gilfillan *et al.*, 2009, Statoil Sleipner Project)
Dissolution injection of CO_2 into the water column CO_2 injection onto the sea floor	CO_2 is transported by ship or pipeline offshore and then injected into the water column at great depth (>1000m or deeper) where the CO_2 dissolves and remains isolated from the atmosphere for centuries. (UNESCO-IOC/SCOR, 2007); CO_2 is placed directly onto the sea floor at depths greater than 3000m, where the CO_2 would form long-lasting 'lakes' with low dissolution rates.	• Both concepts been subject to years of theoretical research/modeling and some small scale field experiments, but have yet been deployed or fully tested (UNESCO-IOC/SCOR, 2007). Research indicates that there would be a gradual release of injected CO_2 back to the atmosphere over a timescale of hundreds of years to millennia (depending on depth and local site conditions); • There is no known mechanism for preventing catastrophic acute release of injected CO_2 (UNESCO-IOC/SCOR, 2007), there are significant environmental risks and impacts associated with these proposed methods of storage (IPCC, 2005; Sedlacek *et al.*, 2009). Injection of CO_2 into the water column or on the sea bed affects marine organisms nearby and ocean chemistry (e.g. by increasing acidity). In the light of the potential for severe environmental impact, the placement of carbon dioxide streams in the water column or on the sea bed has been prohibited in 2007 via the amendment of the London Convention Protocol and in a legally binding decision agreed under OSPAR (OSPAR, 2007).

THE WORLD'S OCEAN CARBON SINKS IN RAPID DECLINE

Vegetated marine coastal habitats, blue carbon sinks, rank amongst the most threatened marine ecosystems (Duarte *et al.*, 2008; Duarte 2009). Coastal eutrophication, reclamation, engineering and urbanisation have lead to the loss of a substantial fraction of the earth's blue carbon sinks since the 1940s (Duarte *et al.*, 2008; Duarte 2009)

A recent assessment indicates that about one-third of the global seagrass area has been already lost, and that these losses are accelerating, from less than 0.9% year^{-1} in the 1970's to more than 7% year^{-1} since 2000 (Waycott *et al.*, 2009). About 25% of the area originally covered by salt-marshes has been globally lost (Bridgham *et al.*, 2006), with current loss rates at about 1 to 2% year^{-1} (Duarte *et al.*, 2008). Valiela *et al.* (2001) estimated that a total of about 35% of the area once covered by mangroves had been lost globally since the 1940s, with current loss rates at about 1 to 3% year^{-1}. Hence, about one-third of the area covered by blue carbon sinks has been lost already and the rest is severely threatened. Marine vegetated habitats, blue carbon sinks, rank amongst the most threatened habitats in the Biosphere, with global loss rates 2 to 15 times faster than that of tropical forests (0.5% year^{-1}, Achard *et al.*, 2002). The loss of blue carbon sinks represents, in addition to the impacts on biodiversity and coastal protection involved, the loss of a natural carbon sink, eroding the capacity of the biosphere to remove anthropogenic CO_2 emissions.



Southern Ocean carbon sink change

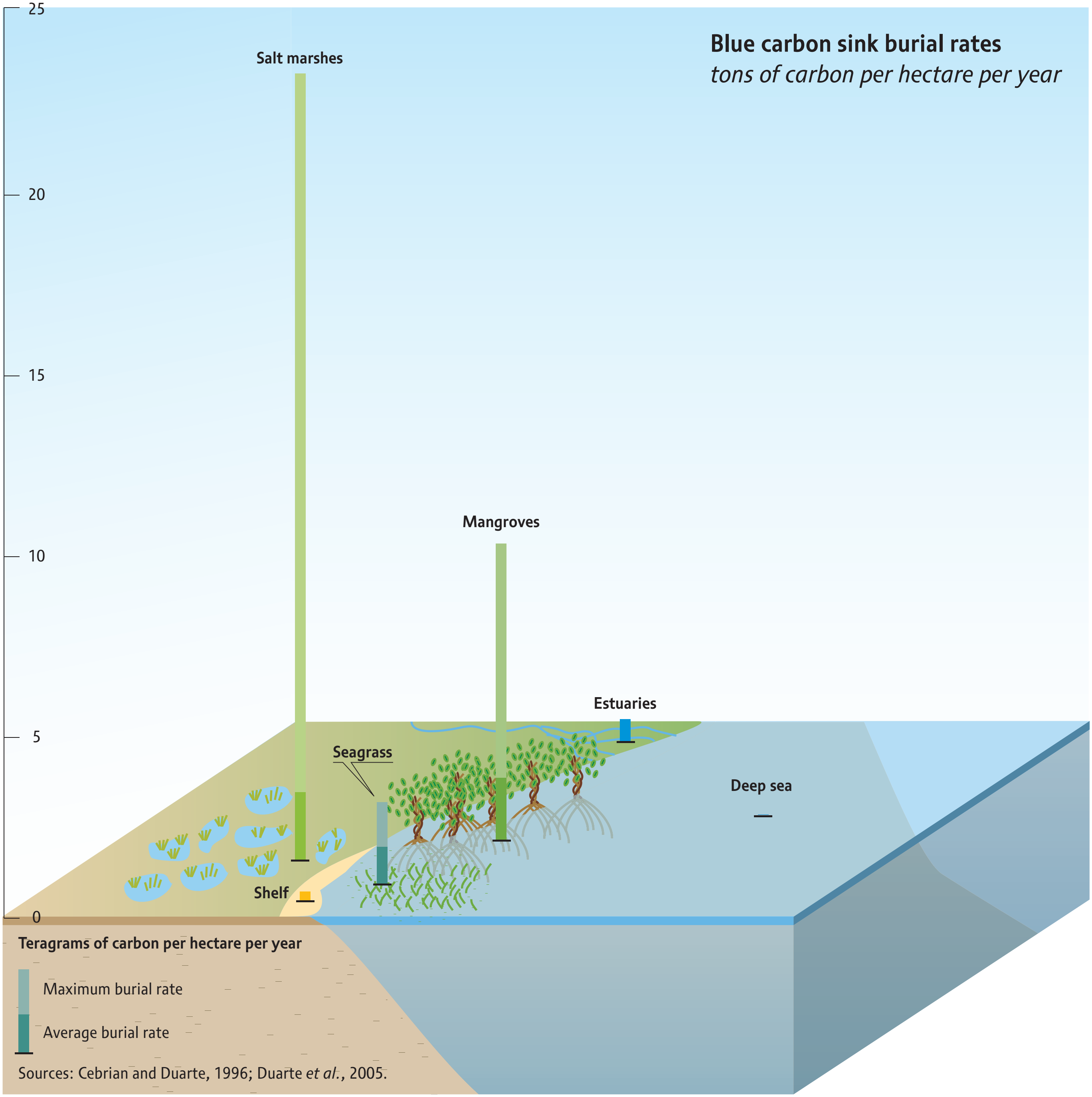
Gigatonnes of carbon per year

Source : NASA, 2008.

Fact box 6. Is the ability of the Southern Oceans to bind carbon also weakening?

The Southern Oceans are recognised as an important carbon sink currently taking up approximately 15% of anthropogenic CO_2 (CSIRO, 2007). Models predict that as the atmospheric concentration of CO_2 increases, so should the ocean's absorbtive capacity. This seems to be happening in most areas, but not so in the Southern Ocean (CSIRO, 2007; Le Quéré *et al.*, 2007; Lenton and Metzl, 2009). Whilst scientists agree on the data, there is some debate as to why this may be – possibly decreased ozone with increased GHG leading to stronger winds and therefore greater mixing, but despite the cause, this trend has potentially serious implications for amtmospheric CO_2 concentrations in coming years.

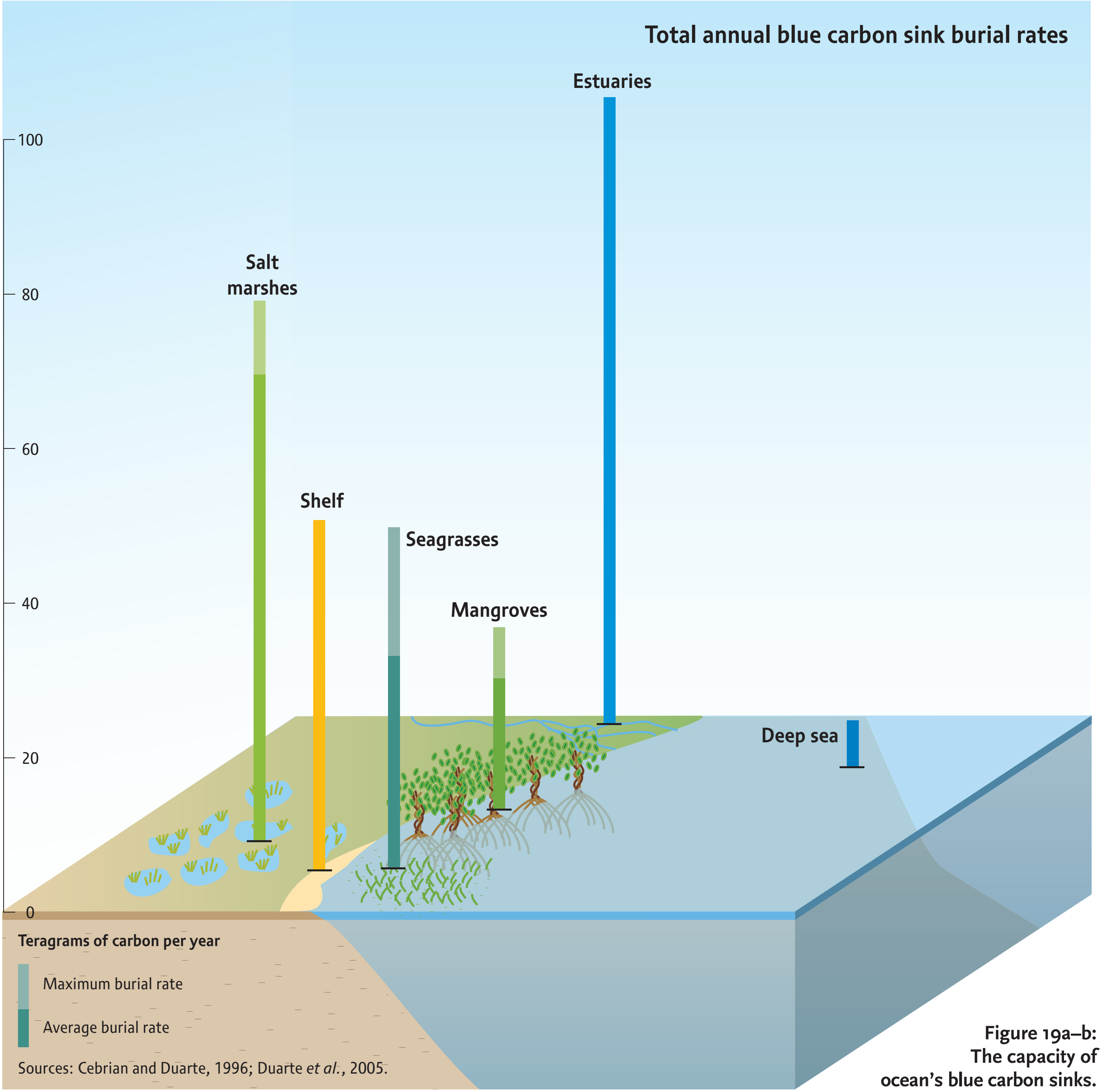
← Figure 18: Declining ability of the Southern ocean's ability to absorb CO_2.



Blue carbon sink burial rates

tons of carbon per hectare per year

Sources: Cebrian and Duarte, 1996; Duarte *et al.*, 2005.



Sources: Cebrian and Duarte, 1996; Duarte *et al.*, 2005.

Figure 19a–b: The capacity of ocean's blue carbon sinks.


HUTAN BAKAU (Mangrove) BERFUNGSI
SEBAGAI TEMPAT BERLINDUNG IKAN DAN
PERLINDUNGAN PANTAI. SEHINGGA PERLU
DI PELIHARA DAN DI LESTARIKAN
PSL-P3K.NAD-2004

OCEANS' BLUE CARBON SINKS AND HUMAN WELLBEING

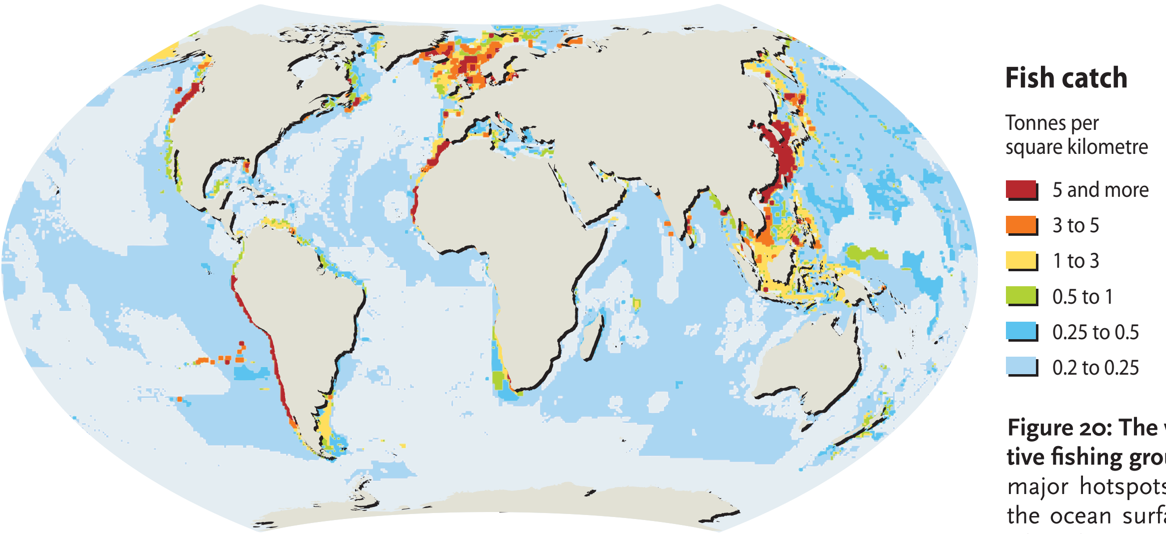
Aquatic ecosystems provide services that contribute to human welfare, both directly and indirectly. These may be recognized by their direct benefits, such as sources of employment, income and food security, tourism, scientific research and mineral extraction; by their indirect benefits, such as climate regulation and transportation; and by their intrinsic value, such as the conservation of biodiversity and social identities and their continuation to support future generations (Kay and Alder, 2005).

It is estimated, that the average annual value of services from the world's coastal ecosystems exceeds US$25,000 billion per year (Martínez *et al.*, 2007). Hence, the coastal zone is of major economic importance today much as it has been throughout human history.

Climate change is projected to impact across ecosystems, societies and economies, increasing pressures on all livelihoods and food supplies, including those in the fisheries and aquaculture sector. Maintenance of food quality will have a more pivotal role as resources come under greater pressure, and availability and access to, for example, fish supplies will become an increasingly critical development issue (Cochrane *et al.*, 2009; FAO, 2008).

IMPACTS TO FOOD SECURITY THROUGH THE OCEANS AND COASTS

The climate change induced alterations which the oceans will experience, including increasing temperatures, acidification and changes in currents will ultimately affect fisheries and aquaculture. Fish distributions are predicted to change, and already we



Source: based on Alhenius, H., 2008; Sea Around Us project, personal communication October 2007 (University of British Columbia).

Figure 20: The worlds most productive fishing grounds are confined to major hotspots in around 7.5% of the ocean surface, where over half of the fish are caught.

Current ranges of total valuation estimates of blue carbon sinks per hectare

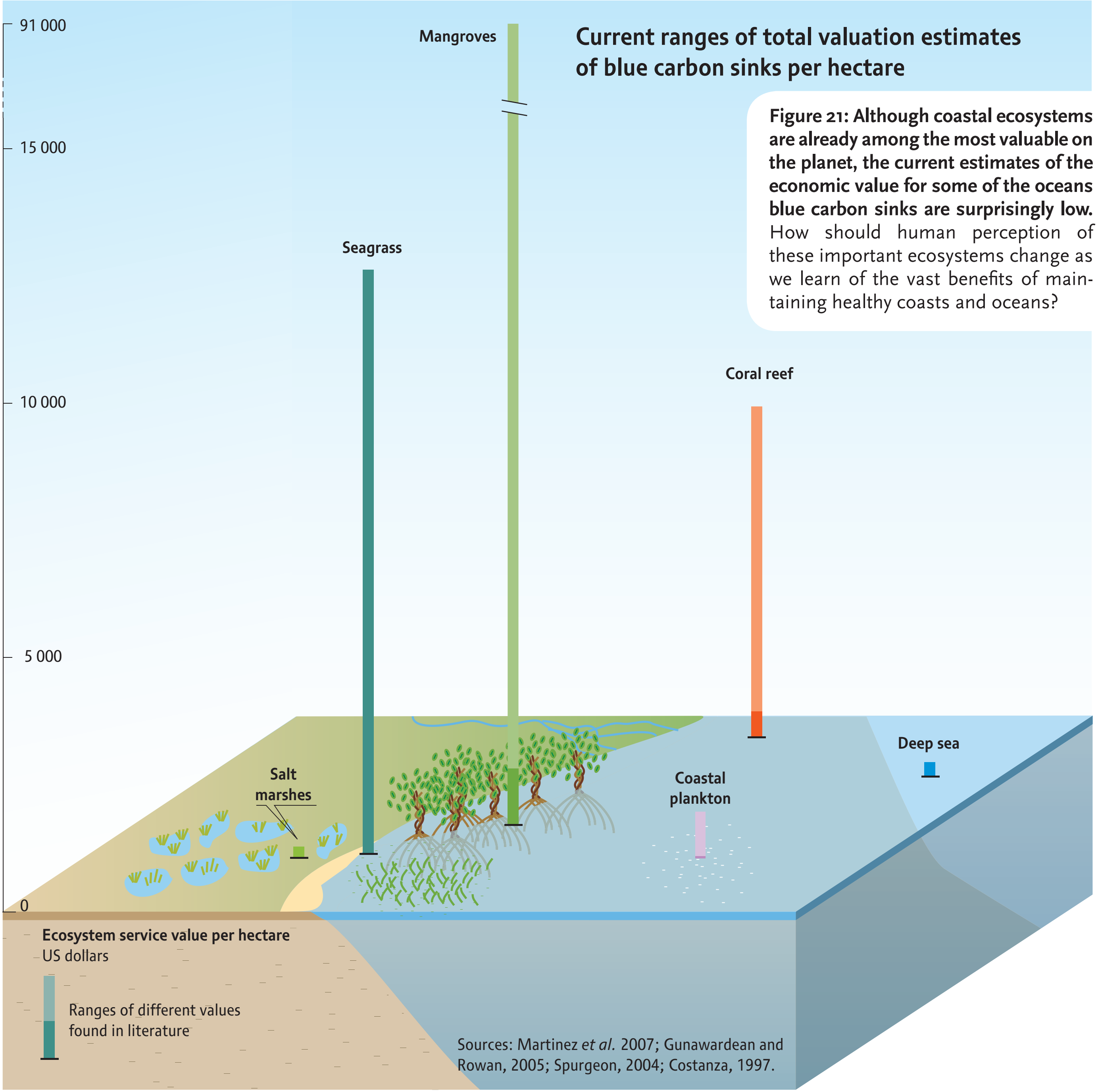


Figure 21: Although coastal ecosystems are already among the most valuable on the planet, the current estimates of the economic value for some of the oceans blue carbon sinks are surprisingly low. How should human perception of these important ecosystems change as we learn of the vast benefits of maintaining healthy coasts and oceans?

Sources: Martinez *et al.* 2007; Gunawardean and Rowan, 2005; Spurgeon, 2004; Costanza, 1997.

Fact box 7. Healthy aquatic ecosystems contribute to food security and livelihoods

- Fisheries and aquaculture contribute significantly to food security and livelihoods, but depend on healthy aquatic ecosystems. These contributions are often unrecognized and undervalued.
- Over 500 million people in developing countries depend, directly or indirectly, on fisheries and aquaculture for their livelihoods. Fish (including shellfish) provides essential nutrition for 3 billion people and at least 50% of animal protein and essential minerals to 400 million people in the poorest countries.
- Aquaculture is the world's fastest growing food production system, growing at 7% annually – but the production of externally fed aquaculture (48% of total aquaculture production) is largely dependent upon marine fisheries for feed.
- Fish products are among the most widely traded foods, with more than 37% by volume of world production traded internationally.
- Natural barriers such as sand dunes, mangrove forests and coral reefs dampen the impacts of a range of coastal hazards, including storm/cyclone surges and tsunami waves, helping to protect coastlines from their full impact.

Source: PaCFA, 2009

are seeing shifts in species distributions in the North Sea with nearly two thirds of the commercially important species shifting northward in mean latitude or deeper in depth or both since 1970 (Perry *et al.*, 2005; Dulvey *et al.*, 2008). Recent projections of changes in the distribution ranges of more than 1,000 commercially important fish species, based on climate change scenarios to 2050 predict numerous species extinctions in sub-polar regions, the tropics and semi-enclosed seas (Cheung *et al.*, 2009). Climate change will also impact the levels of invasive marine organisms, which often damage commercial fish stocks. Studies predict species invasion will be profound in the Arctic and Southern Oceans (Cheung *et al.*, 2009). Indeed, together these changes could result in a significant turnover of species of more than 60% of present biodiversity. This has the potential to disrupt a range of marine ecosystem services including food provisioning.

Climate change will impact across all the four dimensions (availability, stability, access and utilization) of food security.

Availability of aquatic products will vary through changes in ecosystems, production, species distribution and habitats. Changes will occur at regional and local levels in freshwater and marine systems due to ecosystem shifts and changing aquaculture options, which depend on availability of key inputs. Production

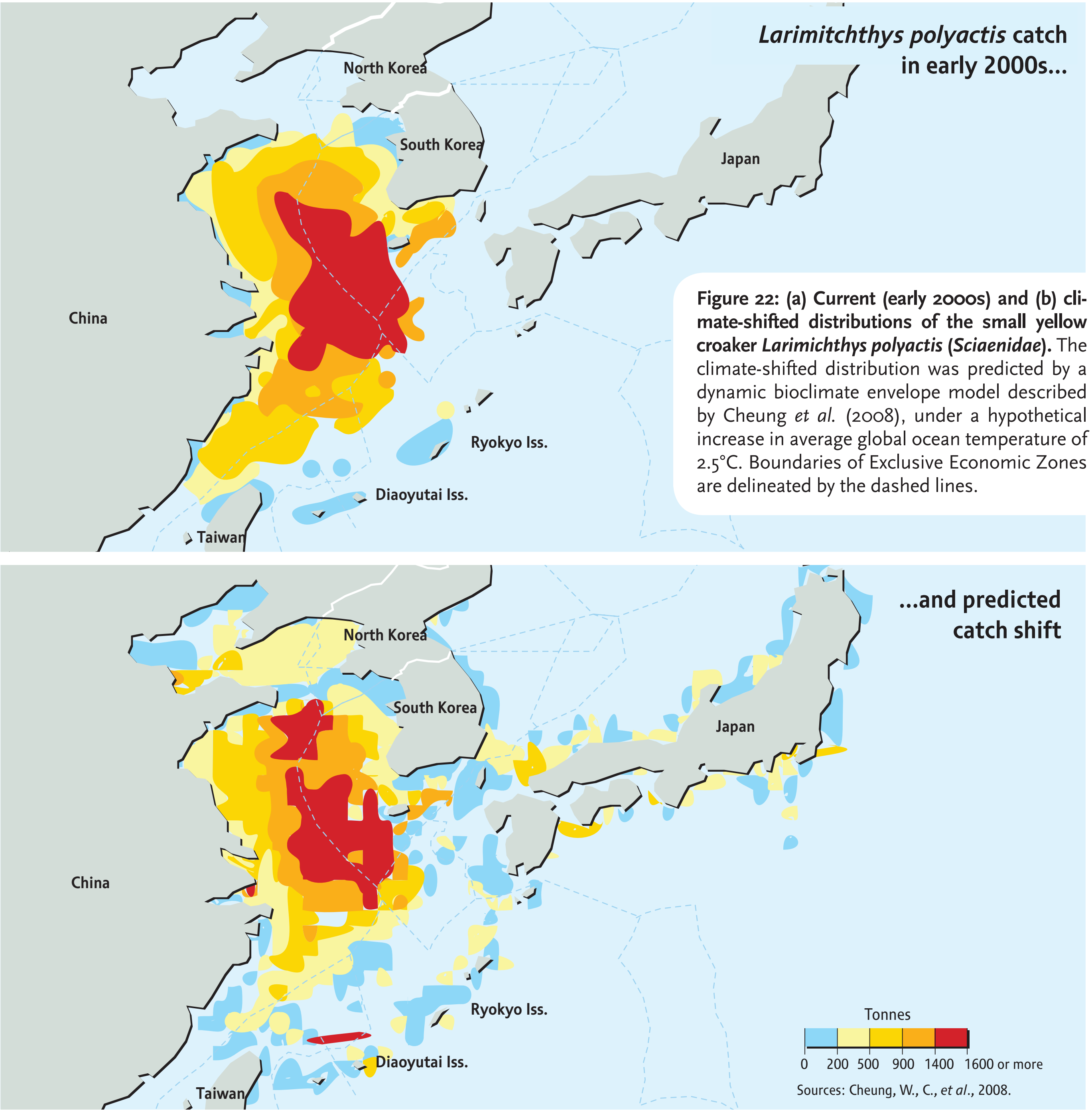


Figure 22: (a) Current (early 2000s) and (b) climate-shifted distributions of the small yellow croaker *Larimichthys polyactis* (*Sciaenidae*). The climate-shifted distribution was predicted by a dynamic bioclimate envelope model described by Cheung *et al.* (2008), under a hypothetical increase in average global ocean temperature of 2.5°C. Boundaries of Exclusive Economic Zones are delineated by the dashed lines.

Sources: Cheung, W., C., *et al.*, 2008.

from aquatic resources, whether through fisheries or aquaculture, may be impacted by the adaptive capacity of management measures controlling temporal and spatial access.

Stability of supply will be impacted by changes in seasonality, increased variance of ecosystem productivity, increased supply risks and reduced supply predictability – issues that may also have large impacts on supply chain costs and their flexibility to respond to variation.

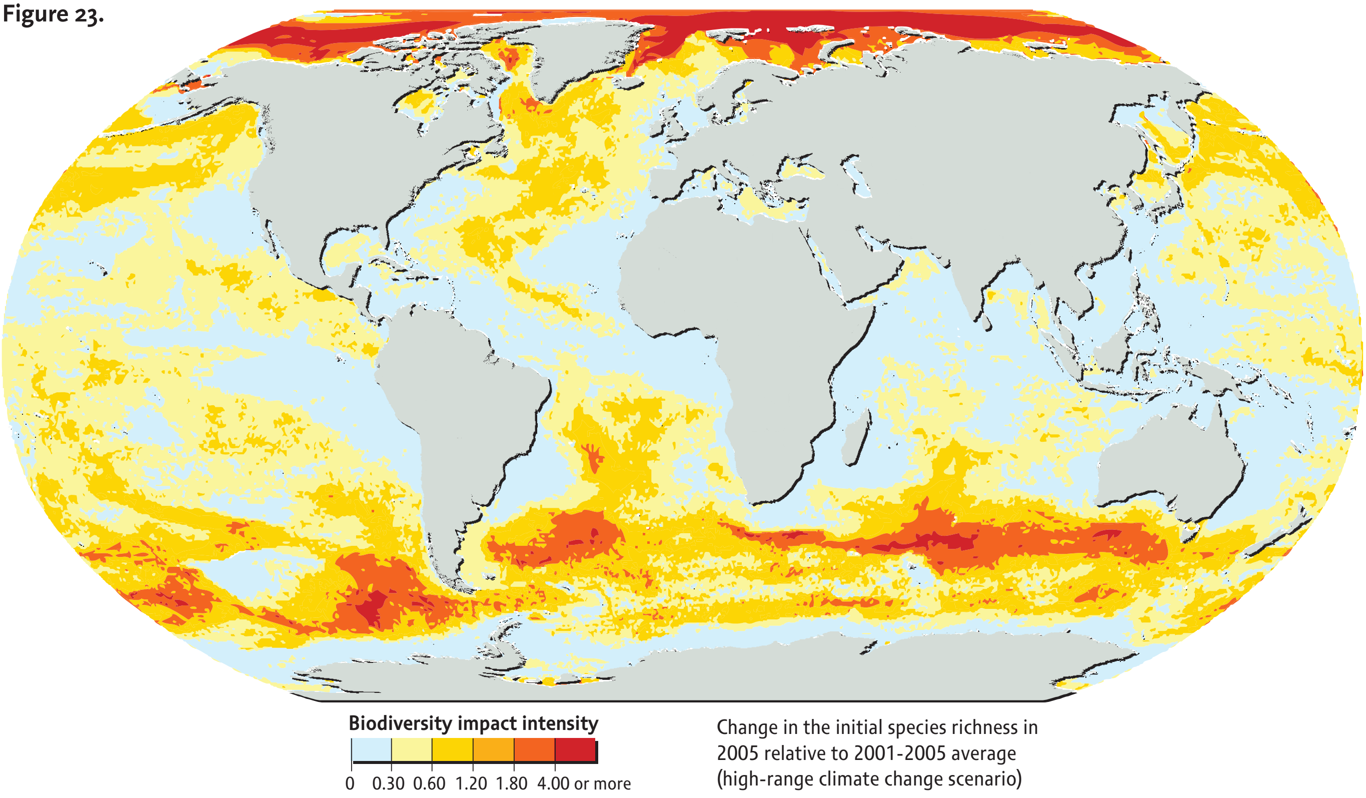
Access to fish for food will be affected by changes in the distribution of fish species and in livelihoods combined with transferred impacts from other sectors (increases in prices of substitute food products), competition for supply, and information asymmetries. Policies and measures tackling climate change impacts may indirectly hamper people's access to food by constraining individuals' expression of their entitlements and rights to food.

Utilization of nutrients (i.e. their nutritional value) from fishery products will be affected through changing supply quality and market chain disruptions. In some cases, a period of adjustment will be required to move to species that are not traditionally consumed. These issues are most critical for countries with a high per capita consumption of aquatic proteins.

Harmful algal blooms (HABs), which affect fisheries, and in some cases result in making shellfish and finfish toxic to humans are expected to vary in frequency, distribution and timing with climate change. HABs are primarily composed of dinoflagellates (algae/phytoplankton) that can swim up and down the water col-

Figure 23.

Species turnover



Change in the initial species richness in 2005 relative to 2001-2005 average (high-range climate change scenario)

Source: redrawn from Cheung W.W.L. *et al.,* 2009.

umn. It is predicted that when oceanic waters become more stratified, these algae are expected to survive better than other phytoplankton, and therefore the frequency of harmful algal bloom events could increase (Moore *et al.*, 2008). Their range is expected to extend to higher latitudes as sea temperatures rise due to climate change. HABs have already been observed more frequently in northern Europe (Tester, 1994). The timing and duration of HAB events is also predicted to change as sea temperatures will reach their maximum earlier and for longer periods of time, with optimal growing conditions lasting longer (Moore *et al.*, 2008). These combined changes will expose more people for longer time periods and over wider geographic ranges to the toxins associated with harmful algal blooms either as aerosols or as accumulations in shellfish and finfish (Moore *et al.*, 2008).

WHO ARE THE MOST VULNERABLE TO CLIMATE CHANGE IMPACTS ON OCEANS?

As mentioned in the previous chapters, impacts on the oceans from growing climate change are likely to include rising sea levels, increasing acidity, increasing frequency and intensity of extreme weather events, and decline in fisheries. The impacts of these physical and biological changes on fisheries and aquaculture communities will be as varied as the changes themselves (FAO, 2008; Cochrane *et al.*, 2009). Both negative and positive impacts could be foreseen, their strength depending on the vulnerability of each community; combining potential impacts (sensitivity and exposure) and adaptive capacity. Impacts would be felt through changes in capture, production and marketing costs, changes in sales prices and possible increases in risks of damage or loss of infrastructure, fishing and aquaculture tools and housing. Fishery-dependent communities may also face increased vulnerability in terms of less stable livelihoods, decreases in availability and/or quality of fish for food, and safety risks, for example, fishing in harsher weather conditions and further from their landing sites.

Impacts on aquaculture could also be positive or negative, arising from direct and indirect impacts on the natural resources they require, primarily water, land, seed, feed and energy. As fisheries provide significant feed and seed inputs, the impacts of climate change on them will also, in turn, affect the productivity and profitability of aquaculture systems, thus jeopardizing food security (Cochrane *et al.*, 2009). Vulnerability of aquaculture-based communities will stem from their resource dependency and also on their exposure to extreme weather events. Climatic changes could increase physiological stress on cultured stock, which would not only affect productivity but also increase vulnerability to diseases, in turn imposing higher risks and reducing returns to farmers. Interactions between fisheries and aquaculture sub-sectors could create other impacts, for example extreme weather events resulting in escapes of farmed stock and contributing to potential reductions in genetic diversity of the wild stock and affecting marine biodiversity and ecosystems more widely.

These impacts will be combined with other aspects affecting adaptive capabilities, such as the increased pressure that ever larger coastal populations place on resources, any political, institutional and management rigidity that negatively impacts on communities' adaptive strategies, deficiencies in monitoring and early-warning systems or in emergency and risk planning, as well as other non-climate factors such as poverty, inequality, food insecurity, conflict, and disease.

The degradation of these marine ecosystems by climate change, poor coastal waste management, as well as from unsustainable natural resource extraction practices including bottom trawling (UNEP, 2008b), will impact a broad range of aspects of food and livelihoods security. Adaptation and mitigation to ensure improved integrated coastal and aquatic resource management is therefore essential both for restoring carbon sink capacity, as well as for health, livelihoods, incomes and food security.

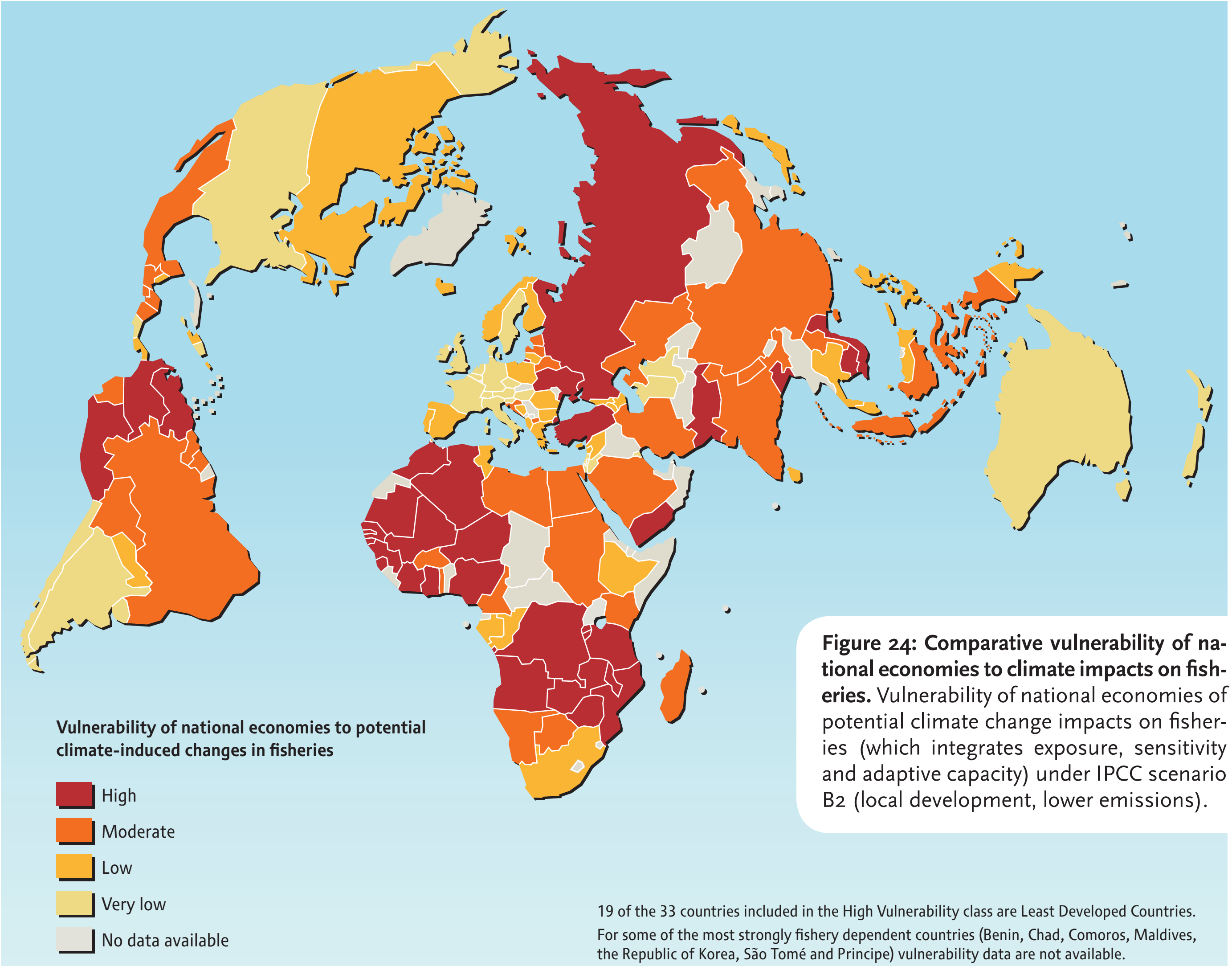


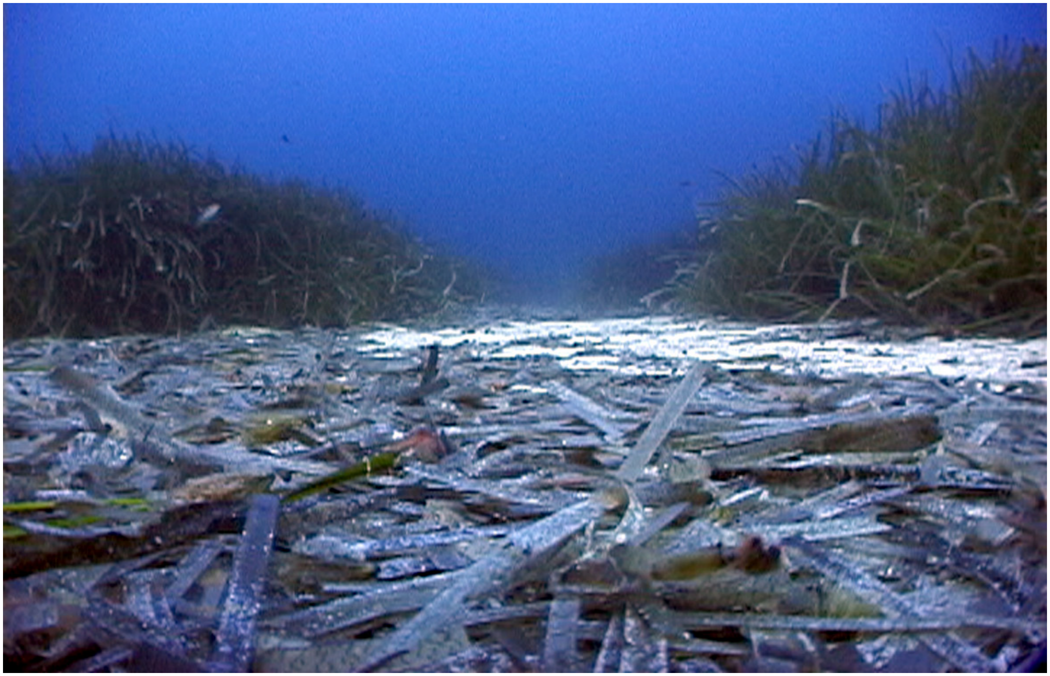
Figure 24: Comparative vulnerability of national economies to climate impacts on fisheries. Vulnerability of national economies of potential climate change impacts on fisheries (which integrates exposure, sensitivity and adaptive capacity) under IPCC scenario B2 (local development, lower emissions).

19 of the 33 countries included in the High Vulnerability class are Least Developed Countries.

For some of the most strongly fishery dependent countries (Benin, Chad, Comoros, Maldives, the Republic of Korea, São Tomé and Principe) vulnerability data are not available.

Source: E. H. Allison *et al*, Vulnerability of national economies to the impacts of climate changes on fisheries, Fish and Fisheries, 2009, 10, pp. 173-196.

The vulnerability of national economies to potential climate change impacts on fisheries was calculated combining composite indicators that evaluate the adaptive capacity of countries, their exposure to climate change and their fisheries dependence.
The adaptive capacity indicator is calculated from indexes of health, education, governance and size of economy.
The country-specific mean surface temperature increase by 2050 for IPCC scenario B2 (local development, lower emissions) was considered as indicator of exposure to climate change.
The indicator of fisheries dependence was deduced from the national number of fishers (absolute and relative to the labour force) and landings, the income dependency on fisheries-derived exports and per capita fish proteins as a proportion of total animal proteins consumed.



> *Recognizing that healthy and productive coastal ecosystems, already increasingly stressed by land-based sources of pollution, coastal development, and habitat destruction, have a growing role in mitigating the effects of climate change on coastal communities and economies in the near term...*
>
> *We stress the need for sustainable management of coastal and marine ecosystems, including mangrove, wetland, seagrass, and coral reefs, as protective and productive buffer zones that deliver valuable ecosystem goods and services that have significant potential for addressing the adverse effects of climate change.*

The Manado Declaration (WOC, 2009).

ECOSYSTEM-BASED ADAPTATION AND MITIGATION

There is increasing awareness and evidence of the potential of restoring natural ecosystems as a way to mitigate climate change, but also ensuring the continued flow of ecosystem services (MA, 2005; Trumper *et al.*, 2009). These services, including, but not limited to, extreme weather and tsunami buffering effects, enhanced food supply, pollution mitigation and health issues, are mainly concentrated in the coastal zone of oceans (UNEP, 2006; 2008b). Indeed, oceans blue carbon sinks, along with coral reefs and kelp communities, all fulfil very important functions in the coastal zone while providing opportunities for jobs and coastal prosperity.

Unfortunately, blue carbon sinks are disappearing at an alarming rate. Human activities such as deforestation, pollution by nutrients and chemicals from agricultural and industrial runoff, unsustainable coastal development, overfishing, invasive species infestations, oil spills, dredging, filling or drainage that cause sediment-loading, mining, and loss of biodiversity are impacting coastal ecosystems worldwide, far exceeding the natural buffering capacity of these ecosystems (UNEP, 2006; 2008b).

MANAGEMENT OF BLUE CARBON SINKS AND THEIR RESTORATION

Blue carbon sinks are hot spots for carbon burial in the ocean where they play a globally significant role that needs be incorporated into current inventories of natural carbon sinks. About half of their sink capacity may have been lost already, mainly through the loss of these vegetated coastal habitats since the 1940s. Efforts to recover the capacity of blue carbon sinks needs be incorporated in current strategies to mitigate climate change, thus providing an impetus for restoration efforts. The recovery of blue carbon sinks will help countries mitigate their carbon emissions while restoring valuable ecosystem services and key natural resources. Integrated coastal management will become central in this process to ensure both the carbon binding capacity and the goods and services rendered for food security, coastal livelihoods and sustainable coastal development.

There is sufficient evidence that reversing the global decline of vegetated coastal habitats and recovering the lost area of blue carbon sinks would provide a very large improvement in the ecological status of the global coastal environment. This could result in the recovery of important services, such as their capacity to oxygenate coastal waters, serve as nurseries, helping restore world fish stocks, or shelter the shoreline from storms and extreme weather events (Hemminga and Duarte 2000; Danielsen *et al.*, 2005). At the same time by stopping the loss and degradation, we would rebuild an important natural carbon sink, thereby contributing to mitigating CO_2 emissions and, hence, climate change.

Because blue carbon sinks occur along the shorelines of all continents, except the Antarctic, states in regions with extensive shallow coastal areas across the world (e.g. India, south east Asia, Black Sea, West Africa, Caribbean, Mediterranean, eastern USA, Russia) could explore the potential to mitigate CO_2 emissions and improve their coastal resources by protecting and restoring their blue carbon sinks. Expanding blue carbon sinks is, therefore, a win-win strategy, (comparable to strategies in place to protect and rebuild the carbon sink capacity of rainforests) which, helps to address the commitments of states under both the Biological Diversity and Climate Change Conventions of the UN. For instance, the ongoing national wetland conservation action plan in China has been estimated to involve a potential for increased carbon sequestration by 6.57

Gg C $year^{-1}$ (Xiaonana *et al.*, 2008). Andrews *et al.* (2008) calculated that the net effect of returning of returning some 26 sq km of reclaimed land in the UK to intertidal environments could result in the burial of about 800 t C $year^{-1}$.

A first step is the protection of these important blue carbon sink habitats, already in place in many countries (e.g. EU members, USA, among others). This involves the regulation of activities responsible for their global loss, including coastal reclamation, deforestation of mangrove forests, excess fertilizer application on land crops and inputs of urban organic waste, siltation derived from deforestation on land, unsustainable fishing and fixing of coastlines through coastal development (Duarte, 2002; 2009). Best practices for the management of blue carbon sinks are available to help maintain these ecosystems healthy while preserving their functions (e.g. Borum *et al.*, 2004; Hamilton and Snedaker 1984; Melana *et al.*, 2000).

A second step should involve efforts for the large-scale restoration of the lost area, which is probably of the same order (if not larger) than the area currently still covered by these aquatic habitats (Duarte 2009; Waycott *et al.*, 2009). For instance, some countries in SE Asia have lost almost 90% of their mangroves since the 1940s (Valiela *et al.*, 2001). Large-scale restoration projects have been successfully conducted for mangroves. The single largest effort probably being the afforestation of the Mekong Delta forest in Vietnam, completely destroyed by the use of Agent Orange in the 1970's and replanted by the Vietnamese people (Arnaud-Haond *et al.*, in press). Salt-marsh restoration is also possible and has been applied largely in Europe and the USA (e.g. Boorman and Hazelden 1995). Restoring lost seagrass meadows is more complex, as the labour required to insert transplants under the water increases cost. Seagrass restoration projects have consequently remained comparatively limited in size (a few hectares) and number. However it is a viable option provided the benefits of seagrass restoration can be used strategically, for example to catalyze the great potential for natural recovery. This is a slow process when unassisted (Duarte *et al.*, 2005b), so has to be supported in parallel with actions to remove the pressures that caused the loss in the first place. Such efforts would provide initial sources of growth and subsequently benefit from the exponential capacity of seagrass meadows to expand, through the growth of their rhizomes, over the seafloor. While green forest can only grow upwards, seagrasses can spread horizontally at exponential rates.

The sequestration capacity of individual marine ecosystems varies substantially (Table 1). Not all blue carbon sinks are equally effective, with salt marshes having the highest carbon burial rate per unit area, followed by mangroves and seagrass. Our current understanding of what drives a high capacity for blue carbon sink ecosystems includes high biomass and production, where the plants produce large surplus of organic carbon (Duarte and Cebrián, 1996), and their location in an area where land-based materials can be intercepted, adding to the self-derived surplus to result in large carbon burial rates (Bouillon *et al.*, 2008). Restoration efforts must focus on the recovery of blue carbon sinks with high sequestration capacity, considering these drivers and catalyzing the capacity of these ecosystems to act as efficient carbon sinks. Additional research on the conditions that result in high carbon sink capacity of vegetated coastal habitats can help guide successful restoration projects.

Most efforts to restore blue carbon sinks have been driven by the need to restore coastal protection by vegetated habitats and their value as habitats for key species (Boorman and Hazelden, 1995; Fonseca *et al.*, 2000; Danielsen *et al.*, 2005). It is time that their beneficial role as carbon sinks is also taken into account and to include this in economic assessments of the benefits of restoring blue carbon sinks.

INTEGRATED ECOSYSTEM APPROACHES

Improving the resilience of the coastal and oceans communities, both human and aquatic, to the impacts of climate change will be key to sustaining the role of the oceans as providers of food and livelihood security. Comprehensive and integrated ecosystem approaches to managing coasts, oceans, and uses of aquatic resources should form the basis for climate change adaptation and mitigation strategies as they address the social, economic, ecological and governance aspects underlying vulnerability to climate change. Such integrated approaches would help to link the multiple sectors depending on coastal and ocean resources to those organizations with climate change and disaster risk management responsibilities; thereby assisting in climate proofing sector-specific development strategies as well as 'mainstreaming' the aquatic-based sectors into climate change strategies.

The management of coastal carbon sinks – a forthcoming IUCN/Natural England/UNEP report

The issue of marine carbon sequestration is attracting growing attention globally, and a new collaborative report titled 'The management of coastal carbon sinks' by the International Union for the Conservation of Nature and Natural England, further examines the issue in closer detail. This report documents the latest information from world-leading scientists on the carbon management potential of a number of coastal ecosystems: tidal salt marshes, mangroves, seagrass meadows, kelp forests and coral reefs. It explores the latest science for each ecosystem, explores their role in the carbon cycle, and outlines management options that would maintain and enhance the carbon sinking capability of each ecosystem. This report is planned released later this year (2009).

As is the case in land-based sectors, many mutually reinforcing synergies and benefits exist among mitigation actions and overall development goals for coastal and ocean resources. These benefits include, for example, improved fisheries and aquaculture production systems, biodiversity conservation through increasing mangrove populations, and increased energy efficiency in the shipping sectors. Efforts should include areas of mutual benefit to food and livelihood security and the responsibilities of these sectors to reduce and avoid emissions as well as to enhance natural removals of greenhouse gases.

In order to avoid negative trade-offs between adaptation and mitigation within and among sectors, an ecosystem approach and system-wide evaluation and planning of mitigation and adaptation strategies will need to include downstream impacts on other sectors. It is very clear from this report, that the carbon sink capacity of these valuable coastal ecosystems should provide massive additional impetus for improved integrated coastal zone management, protection and restoration.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POLICY OPTIONS

In the discussions on climate change, marine ecosystems have not received sufficient attention considering their importance for both mitigation and adaptation. A major contributing factor has been the complexity of marine ecosystems, their status as an international and common property resource, and the absence of robust mitigation metrics.

While numerous technical issues await full scientific and political consensus, international climate change instruments need to remain open to the development of agreed mechanisms and measures which support marine ecosystem coherence and resilience and build on the strong synergies between mitigation and adaptation.

Marine ecosystems have, until very recently, been vastly overlooked in climate change mitigation and adaptation debates. Today's economies are mainly based on burning of fossil fuels. For many countries, there will be major challenges in developing industry and expanding transport while reducing emissions. It is absolutely critical that while emission reductions of brown and black carbon are made, we must also maintain, and expand, the ability of the biosphere, and in particular the oceans, to continue to capture and bind the carbon that we emit. There is an urgent need for new ways to reduce the impact of continuing emissions, not just by adapting, but also by ensuring that as much carbon as possible is taken up by the natural system – and stored. Oceans have acted as one of the largest natural carbon sinks throughout history and their ability to continue this role should be enhanced. A word of caution is, however, warranted: there is no 'golden key' to solve all problems. New innovate short-term solutions, including geo-engineering options such as fertilizing the oceans or pumping CO_2 into the deep seas raise serious ecological, economic, political and ethical challenges, with many unknown variables and high risk of potential side effects (see Factbox 5). These proposals should not be dismissed, but before being operationalized on a large or commercial scale, more research and careful, thorough evaluation is required.

Options that can both reduce and mitigate climate change, increase food security, benefit health and subsequent productivity and generate jobs and business are therefore of major importance. This is contrary to the perception that mitigation or emission reduction is seen as a cost and not an investment. Improved integrated management of the coastal and marine environments, including protection and restoration of our ocean's blue carbon sinks, provides one of the strongest win-win mitigation efforts known today. It may provide value-added benefits well in excess of its cost, but has not yet been recognized in the global protocols and carbon trading systems.

Blue carbon sinks cover only a fraction of the world's oceans – and yet are critical and among the most effective carbon sinks known today. They provide valuable ecosystem services for fisheries, tourism and coastal economies. But they are disappearing at a rate higher than any other ecosystem on earth. Less than two decades remain to secure them and restore them, with immediate carbon-binding effect and immediate returns in terms of fisheries and added benefits from improved shoreline protection and ecosystem services.

Fact box 8. A 25% emission reduction could be gained from green and blue carbon

The most recent estimates indicate that human activities are currently responsible for annual global carbon emissions of around 7–10,000 Tg C yr^{-1}, of which around 1,500 Tg C or around 15–20% is the result of land use change. The remaining emissions are from fossil fuel use and cement production (Canadell *et al.*, 2007). This has led to an average annual rate of increase of CO_2 concentrations in the atmosphere of 1–2 ppm or up to 2,000 Tg C yr^{-1} for the years 1995–2005 compared with around 1.25 ppm for the years 1960–1995 (IPCC, 2007b; Houghton, 2007).

Green carbon: Reducing deforestation rates by 50% by 2050 and then maintaining them at this level until 2100 would avoid the direct release of up to 50 Gt C this century or approximately 555 Tg C yr^{-1}, which is equivalent to 12–15% of the emissions reductions needed to keep atmospheric concentrations of carbon dioxide below 450 ppm (Trumper *et al.*, 2009).

Blue carbon: According to this report, protection, improved management and restoration of the ocean's blue carbon sinks would result in preventing the annual loss of up to 450 Tg C yr^{-1}, or equivalent to a corresponding 10% of the reductions needed.

Combined with the green carbon – REDD – the effect would be at least 20–25% of the emission reductions needed – with huge benefits to food security, water resources, biodiversity – and the creation of jobs and incomes. But this would require a similar "REDD" programme for oceans as has been established for rainforests – a blue carbon fund.

KEY OPTIONS:

In order to implement a process and manage the necessary funds for the protection, management and restoration of these crucial ocean carbon sinks, the following options are proposed:

1 Establish a global blue carbon fund for protection and management of coastal and marine ecosystems and ocean carbon sequestration.

a. Within international climate change policy instruments, create mechanisms to allow the future use of carbon credits for marine and coastal ecosystem carbon capture and effective storage as acceptable metrics become available. Blue carbon could be traded and handled in a similar way to green carbon – such as rainforests – and entered into emission and climate mitigation protocols along with other carbon-binding ecosystems;
b. Establish baselines and metrics for future environmentally sound ocean carbon capture and sequestration;
c. Consider the establishment of enhanced coordination and funding mechanisms;
d. Upscale and prioritize sustainable, integrated and ecosystem-based coastal zone planning and management, especially in hotspots within the vicinity of blue carbon sinks to increase the resilience of these natural systems and maintain food and livelihood security from the oceans.

2 Immediately and urgently protect at least 80% of remaining seagrass meadows, salt marshes and mangrove forests, through effective management.

Future funds for carbon sequestration can contribute to maintaining management and enforcement.

3 Initiate management practices that reduce and remove threats, and which support the robust recovery potential inherent in blue carbon sink communities.

4 Maintain food and livelihood security from the oceans by implementing comprehensive and integrated ecosystem approaches aiming to increase the resilience of human and natural systems to change.

5 Implement win-win mitigation strategies in the ocean-based sectors, including to:

a. Improve energy efficiency in marine transport, fishing and aquaculture sectors as well as marine-based tourism;
b. Encourage sustainable, environmentally sound ocean based energy production, including algae and seaweed;
c. Curtail activities that negatively impact the ocean's ability to absorb carbon;
d. Ensure that investment for restoring and protecting the capacity of ocean's blue carbon sinks to bind carbon and provide food and incomes is prioritized in a manner that also promotes business, jobs and coastal development opportunities;
e. Catalyze the natural capacity of blue carbon sinks to regenerate by managing coastal ecosystems for conditions conducive to rapid growth and expansion of seagrass, mangroves, and salt marshes.

GLOSSARY

Acidification

See Ocean acidification.

Afforestation

Afforestation is defined under the Kyoto Protocol as the direct human-induced conversion of non-forest land to permanent forested land (for a period of at least 50 years) (Angelsen 2008).

Archaea

Unique, single celled organisms which are genetically and metabolically distinct from bacteria.

Autotrophic

Of or relating to an autotroph, an organism capable of making nutritive organic molecules from inorganic sources via photosynthesis (involving light energy) or chemosynthesis (involving chemical energy).

Biofuel

Any liquid, gaseous, or solid fuel produced from plant or animal organic matter. e.g. soybean oil, alcohol from fermented sugar, black liquor from the paper manufacturing process, wood as fuel, etc. Second-generation biofuels are products such as ethanol and biodiesel derived from ligno-cellulosic biomass by chemical or biological processes (IPCC 2007a).

Coastal ocean

The region extending from the beaches out across the continental shelf, slope, and rise (Brink, 1993).

Carbon Capture and Storage (CCS)

A process consisting of separation of CO_2 from industrial and energy-related sources, transport to a storage location, and longterm isolation from the atmosphere (IPCC, 2007a).

Carbon cycle

The term used to describe the flow of carbon (in various forms, e.g., as carbon dioxide) through the atmosphere, ocean, terrestrial biosphere and lithosphere (IPCC 2007c).

Carbon sequestration

The process of increasing the carbon content of a reservoir other than the atmosphere (Chopra *et al.* 2005).

Carbon sink

See Sink.

Carbon source

See Source.

Clean Development Mechanism (CDM)

A mechanism under the Kyoto Protocol designed to assist developed (Annex I) countries in meeting their emissions reduction targets. The mechanism reduces emissions through implementing projects in developing (Annex II) countries which are credited to the Annex I countries who finance and implement the project. The CDM aims to not only reduce emissions or increase sinks but also contribute to the sustainable development of the host country (Peskett *et al.* 2008).

Greenhouse gases

Greenhouse gases are those gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of infrared radiation emitted by the earth's surface, the atmosphere and clouds. This property causes the greenhouse effect. Water vapour (H_2O), carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4) and ozone (O_3) are the primary greenhouse gases in the earth's atmosphere (IPCC 2007a).

Kyoto Protocol

An agreement made under the United Nations Framework Convention on Climate Change (UNFCCC). Countries that ratify this protocol commit to reducing their emissions of carbon dioxide and five other greenhouse gases (GHG), or engaging in emissions trading if they maintain or increase emissions of these gases. The Kyoto Protocol now covers more than 170 countries globally but only 60% of countries in terms of global greenhouse gas emissions. As of December 2007, the US and Kazakhstan are the only signatory nations not to have ratified the act. The first commitment period of the Kyoto Protocol ends in 2012, and international talks began in May 2007 on a subsequent commitment period (Peskett *et al.* 2008).

Land Use, Land Use Change and Forestry (LULUCF)

A greenhouse gas inventory sector that covers emissions and removals of greenhouse gases resulting from direct human-induced land use, land-use change and forestry activities (UNFCCC 2009).

Leakage

In the context of climate change, carbon leakage is the result of interventions to reduce emissions in one geographical area (subnational or national) that lead to an increase in emissions in another area. For example, if curbing the encroachment of agriculture into forests in one region results in conversion of forests to agriculture in another region this is considered to be "leakage". In the context of REDD, leakage is also referred to as 'emissions displacement' (Angelsen 2008).

Mitigation

A human intervention to reduce the sources of or enhance the sinks for greenhouse gases (Department of Climate Change 2008).

Ocean acidification

A decrease in the pH of sea water due to the uptake of anthropogenic carbon dioxide (IPCC 2007c).

Open ocean

Where the water depth exceeds 200m around the boundaries of the major continental land masses. This definition excludes the marginal enclosed and semi-enclosed seas, but includes all ocean regions bordering lesser island systems regardless of water depth (UNEP and IOC-UNESCO, 2009).

Permanence

The duration and non-reversibility of a reduction in GHG emissions (Angelsen 2008). This is an issue in the land use sector as carbon stored and sequestered in ecosystems is theoretically always vulnerable to release at some undetermined point in the future.

Reforestation

Reforestation is "the direct human-induced conversion of non-forested land to forested land through planting, seeding and/or the human-induced promotion of natural seed sources, on land that was forested, but that has been converted to non-forested land". In the first commitment period of the Kyoto Protocol, reforestation activities have been defined as reforestation of lands that were not forested on 31 December 1989, but have had forest cover at some point during the past 50 years (Angelsen 2008).

Respiration

The process whereby living organisms convert organic matter to carbon dioxide, releasing energy and consuming molecular oxygen (IPCC 2007c).

Sequestration

The removal of atmospheric carbon dioxide, either through biological processes (for example, photosynthesis in plants and trees, see Biosequestration), or geological processes (for example, storage of carbon dioxide in underground reservoirs) (Department of Climate Change 2008).

Sink

Any process, activity or mechanism that removes a greenhouse gas, an aerosol or a precursor of a greenhouse gas or aerosol from the atmosphere (IPCC 2007c).

Source

Any process, activity or mechanism that releases a greenhouse gas, an aerosol or a precursor of a greenhouse gas or aerosol into the atmosphere (IPCC 2007c).

Sustainability

A characteristic or state whereby the needs of the present and local population can be met without compromising the ability of future generations or populations in other locations to meet their needs (Chopra *et al*. 2005).

United Nations Framework Convention on Climate Change (UNFCCC)

The United Nations Framework Convention on Climate Change (UNFCCC) is the first international climate treaty. It came into force in 1994 and has since been ratified by 189 countries including the United States. More recently, a number of nations have approved an addition to the treaty: the Kyoto Protocol, which has more powerful (and legally binding) measures (Kirby 2008).

UNFCCC

See United Nations Framework Convention on Climate Change.

ACRONYMS

C	Carbon
CDM	Clean Development Mechanism
CO_2	Carbon dioxide
EU-ETS	The Emissions Trading System of the European Union
FAO	Food and Agriculture Organization of the UN
GEF	Global Environment Facility
GHG	Green house gas
GRID	Global Resource Information Database
HAB	Harmful Algal Bloom
HCO^{3-}	Bicarbonate ion
HCl	Hydrochloric acid
MEDEA	Mediterranean Institute of Advanced Studies
IPCC	Intergovernmental Panel on Climate Change
°C	Degrees centigrade
ppm	Parts per million
REDD	United Nations Collaborative Programme on Reducing Emissions from Deforestation and Forest Degradation in Developing Countries
REDD-Plus	Reducing emissions from deforestation and degradation, conservation of existing carbon stocks and enhancement of carbon stocks
SIDS	Small Island Developing States
SOC	Sedimentary organic carbon
$T\ C\ yr^{-1}$	Tonnes of carbon per year
$Tg\ C\ yr^{-1}$	Tera grams of carbon per year
UNEP	United Nations Environment Programme
UNEP-WCMC	UNEP-World Conservation Monitoring Centre
UNESCO	United Nations Educational, Scientific and Cultural Organisation
IOC-UNESCO	Intergovernmental Oceanographic Commission of UNESCO
USA	United States of America
USD	US Dollars
yr^{-1}	per year

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