Storage of carbon by marine ecosystems and their contribution to climate change mitigation

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1.0 Take-home messages

Carbon in the oceans: a tale of two entities

- **Seawater can be viewed as the "atmosphere" of our oceans.** It is essential to differentiate between inorganic carbon dissolved in seawater and the carbon bound up in marine organisms and sediments. One is part of the problem – the other could be part of the solution if properly protected and/or allowed to recover from damage and degradation.

- **Our oceans are by far the biggest reservoir of carbon in the biosphere.** The vast majority of that carbon is present as dissolved inorganic carbon in the form of bicarbonate, carbonate, dissolved carbon dioxide and carbonic acid, with a much smaller proportion present as organically-bound, biologically 'fixed' carbon. Both dissolved inorganic carbon and this biologically 'fixed' carbon are integral components of the global carbon cycle, but have a different influence on climate change and ocean acidification.

Inorganic carbon in the oceans

- **The pool of dissolved inorganic carbon in the oceans is being added to year on year** as a direct and unavoidable consequence of the continued rise in concentrations of CO_2 in the atmosphere. Each year, oceans absorb in the region of 20-35% anthropogenic CO_2 emissions, largely through simple physical and chemical processes of gas exchange and dissolution, largely independent of the biology; they would happen even in a dead ocean.

- **Some oceans contain greater stores of dissolved CO_2 than others.** The North Atlantic stores 23% of the global pool of dissolved inorganic carbon, yet the Southern Ocean stores just 9%, and the largest ocean, the Pacific, absorbs just 18%. 50% of anthropogenic CO_2 is found in water less than 400m deep. Also, CO_2 dissolves twice as readily in cold water at the poles than in warm waters near the equator.

- **Furthermore, just as the build-up of CO_2 in the atmosphere accelerates climate change**, so the build-up of CO_2 in seawater accelerates ocean acidification, with the potential for widespread and profound impacts on marine ecosystems. Surface ocean acidity has already increased by around 30% since pre-industrial times, with recent changes occurring faster than at any time in at least the last 400 thousand years.

- **The only mechanism open to us to reduce and ultimately reverse the accumulation of anthropogenic carbon dioxide in the oceans,** and mitigate climate change, is to stop the growth of carbon dioxide concentrations in the atmosphere by cutting emissions.

Biological carbon in marine ecosystems

- **The biological component of ocean carbon, i.e. carbon in living organisms, decaying matter and in organic compounds in water or sediments, is quite different.** The biologically fixed carbon pool is less than the inorganic pool, but is relevant in terms of uptake of atmospheric carbon dioxide and burial. This burial occurs as a proportion of the carbon in ecosystem compartments that are relatively isolated from the atmosphere (including sediments and deep water).

- **Different components of the biological carbon system in the marine environment operate over different scales and timeframes.** In coastal wetlands, carbon is stored short-term in living biomass and long-term in the soil and sediment. In the open ocean, long-term carbon sequestration takes place over millions of years, when microbial degradation of organic matter gives rise to gas hydrates, and carbon from decomposed plankton is mineralised to form oil. It is estimated that up to 1% of the total organic carbon production at the sea surface may be buried in the sediment.

- **Coastal and high seas ecosystems are inextricably linked**. Some carbon that originates in coastal vegetated ecosystems is exported to the deep sea, though how much from each ecosystem and region is unknown. Both the sources and deposition areas need to be protected for MPAs to be effective in climate change mitigation.

- **Scientists have modelled the contribution made by vegetated coastal habitats to the carbon cycle and have produced vastly different results.** Estimates of the contribution to carbon sequestration made by vegetated coastal habitats to coastal and deep-sea sediment vary from 73 to 866 Tg C yr^{-1}. The uncertainty highlights how difficult it is to arrive at unequivocal quantitative estimates for the part played by diverse marine ecosystems in the global carbon budget.

- **Some ocean regions can, at different times, act either as net carbon sinks or carbon sources.** Linking sources of carbon in coastal regions to long-term sinks in the open ocean is an emerging area of science. Monitoring is underway by research teams to further understand the processes involved, but it seems as though the movement and storage of carbon storage depends on factors including season, storm activity and ocean currents. All these factors may be affected by climate change.

- **Some areas may appear not biologically diverse** but may nonetheless be important for carbon cycling and storage.

- **The scientific community is divided on the notion of whether marine organisms are a short-term or long-term store of carbon**. In general, short-term storage refers to carbon that is locked away for up to decades; long term is carbon locked away for millennia. Most scientists refer to carbon held within the biomass of animals as being ‘temporary’ carbon storage.

- **Estimates of the carbon stored in marine vertebrates** are based on assumptions, such as estimating the global number of individuals and longevity. Therefore, caution must be used in citing these estimates.

- **Apex predators (i.e. those at the top of the food web) are important for maintaining carbon balance as well as ecosystem structure.** Removal of the top predator can affect lower trophic levels. An overabundance of herbivores can place coastal vegetated ecosystems under stress, which can mean that carbon sequestration in coastal areas is reduced.

Threats to marine biological carbon stores from other human activities

- **Coastal development can increase CO_2 emissions.** The outcome of some human activities could be to change a carbon sink into a carbon source. For example, draining a mangrove forest for development (such as into a fishery) can stimulate microbial activity in the soil that had previously been inhibited by naturally low oxygen concentrations, leading to rapid oxidation of the carbon stores and re-release into the atmosphere.

- **Once damaged and degraded, coastal habitats can be even more difficult and expensive to restore that terrestrial habitats** (between 10 to 400 times more expensive according to some estimates). In addition, restored habitats may take a long time to recover the same rates of carbon burial and rebuild those buried stores. For example, research indicated that coastal seagrass areas allowed to regenerate after a period of disturbance had 35% less carbon than undisturbed areas. Although restoration of all degraded habitats is important, priority needs to be given to preventing removal of virgin coastal blue carbon ecosystems.

- **Other human activities at sea, such as bottom trawling and deep-sea mining,** physically disturb the sediment, can disrupt carbon sequestration and re-suspend stored carbon into the water where it can more easily break-down. Areas in the north-western Mediterranean where bottom trawling had taken place had up to 52% less organic matter than un-trawled areas. Deep-sea mining has the potential to cause widespread disturbance to the carbon flux and to the organisms that inhabit the deep-sea ecosystem. Exploiting gas hydrates an energy source would release carbon that has been sequestered in the ocean for millennia.

The importance of protection of natural biological carbon stores and storage mechanisms

- **Although scientific uncertainties surrounding quantitative estimates of carbon storage within many marine ecosystems remain high**, it is without doubt that these ecosystems play an important and irreplaceable role in cycling and storing carbon over short, medium and long timescales.

- **Further disruption of marine ecosystems, of the carbon they already store and of their future capacity to sequester more carbon reserves, will inevitably work against the achievement of climate targets**, as well as allowing the ongoing depletion of biodiversity to continue.

- **It is imperative to protect the biological and ecological mechanisms by which carbon is taken up, cycled and stored within the marine environment,** in order to protect natural carbon sequestration potential for the future. This means protection of coastal ecosystems – such as mangrove, seagrasses and saltmarshes – as well as offshore and deep-sea ecosystems.

- **The inclusion of goals for protection of carbon sources and sinks, alongside species and habitats**, in the design of an effective network of marine reserves could provide key strategic opportunities for climate change mitigation.

- **For effective marine conservation, scientists have recently suggested that MPAs would need to cover 37% of the ocean in total,** very similar to the 40% coverage recommended by others for a representative network of **marine reserves** designed to protect biodiversity. Currently, there are in the region of 14,600 marine protected areas (MPAs) listed on the World Database on Protected Areas, which is just over 4% of the global ocean.

- **Involving coastal communities as stakeholders in marine protection is more likely to result in more effective blue carbon management.** Community involvement results in better adherence to the terms of the protection measures. Local communities have, over time, acquired tacit knowledge to manage blue carbon resources.

- **There are many gaps in the understanding of how carbon flows through food webs and becomes sequestered** in the long-term in ocean sediments. As technology advances, e.g. DNA sequencing, chemical tracers, it is anticipated that within the next decade the science on the processes that drive sequestration rates will also develop.

- **In the near future, scientific research** is expected to focus increasingly on understanding the turnover of carbon in the ocean, in particular to better quantify the long-term fate and effects of anthropogenic CO_2 sequestered in the oceans, and the contribution that may be made through the better protection of marine ecosystems in terms of mitigating the speed, extent and effects of climate change.

2.0 Executive summary

All life forms on Earth need and cycle carbon. The ocean carbon cycle is complex and quantifying the carbon that is stored in marine ecosystems is not straightforward. Because of this complexity, scientific publications that quantify the carbon stored in the ocean vary broadly and many figures are estimates only.

Just as is the case in the terrestrial/atmospheric environments, carbon is found in the ocean in different forms, in different locations and in different quantities:

Organic: Carbon that is stored in living plants and marine organisms, in organic-rich detritus or as dissolved organic carbon

Inorganic: Atmospheric carbon dioxide that dissolves into seawater to form carbonic acid, bicarbonate and carbonate
Carbonate excreted by and incorporated into marine invertebrates' skeletons and secreted by vertebrates

There are several reasons for the complexity of the carbon cycle in the ocean. One reason is that carbon is stored in the ocean for different durations: long term and short term. Terminology in the published scientific literature varies when discussing timescales, so for this reason definitions have been included here and in a glossary for clarity:

Short-term storage: Carbon (both organic and inorganic) in living biomass that is stored in a marine plant or organism for the duration of its lifetime.

Long-term sequestration: Carbon (again both organic and inorganic, see definitions) sequestered for millennia in marine soil and sediment, including as gas hydrates.

To further add to the complexity of the ocean carbon cycle, carbon 'fixed' in one marine location can be exported over great distances to another location and either recycled or deposited there. The processes driving this export are currently not fully understood by science.

One way in which carbon is transported in the ocean is by marine organisms. Marine organisms are important both in cycling carbon and for redistributing it vertically in the water column and laterally across ocean basins. The process is described as the 'biological pump': photosynthesising organisms such as phytoplankton that fix CO_2 are, in turn, consumed by other organisms and in this way carbon enters the food chain. The biological pump is integral to the global carbon cycle, but the efficiency of the pump depends on healthy marine ecosystems. The health of an ecosystem will be affected by the widespread removal of certain marine organisms, such as a large marine predator or key prey, which may have indirect implications for carbon cycling and sequestration that have not yet been fully characterised by science.

When describing carbon in the ocean it is important to point out that no one area of the ocean should be regarded as more important than another. For example, coastal and high seas ecosystems may seem very different but they are inextricably linked. The amount of carbon in the ocean, and the amount that is sequestered in sediments, varies spatially and temporally. Some areas of the seabed can be either a net sink or a net source of carbon and for this reason, more research by ocean scientists is needed to fully understand the processes that drive these changes.

Scientists have attempted to model and quantify the contribution made by coastal habitats to the carbon cycle, but different teams have produced vastly different results. Significant knowledge gaps confound the estimates of the spatial area of vegetated coastal habitats and their carbon sequestration rates. Preventing removal or damage to vegetated coastal ecosystems – in particular mangrove forest, seagrass meadows and saltmarsh – is far more effective than restoring such habitats that have been degraded. Reasons include the high financial cost and the release of stored carbon, but also because there is no guarantee that a habitat will re-establish successfully. Coastal development can result in an ecosystem changing from being a net sink of carbon to a significant source of carbon. Even many years after restoration, published research suggests that coastal blue carbon ecosystems do not sequester carbon as efficiently as before disturbance.

Human activities have the potential to impact ocean biological carbon sequestration. Coastal developments remove coastal habitats, and bottom-trawler fishing and seabed mining disturb the seabed, which can re-suspend into the water column carbon that has been stored in the sediment for millennia. Where long-term studies have measured the carbon stored in the seabed, bottom-trawler fishing has been shown to significantly reduce the rate of carbon sequestration. The ecological impacts of seabed mining are likely to be numerous. For example, the effects of removing benthic organisms and redistributing sediments in the formation of plumes are poorly understood by science. Seabed mining has the potential to cause widespread disturbance to the carbon flux and to the organisms that inhabit the deep sea.

A network of marine protected areas (MPAs) or marine reserves that maximises protection of biodiversity and promotes carbon sequestration at the same time would undoubtedly need to incorporate principles of adaptive management (see definitions) from the outset. The network would need to be ecologically coherent and developed with the carbon budget in mind, with the aim to protect both the sources *and* long-term sinks of carbon to promote effective sequestration. Recent modelling has suggested that such a network of MPAs may need to cover as much as 37% of the global ocean to achieve adequate biodiversity conservation, very similar to the 40% coverage recommended previously by others for designation of an effective and representative network of marine reserves. The design of such networks will need to incorporate comprehensive protection of the water column and the seabed, and take account of the life cycles, ranges and migratory habits of species.

The oceans are integral to the global carbon cycle, but there are significant knowledge gaps in the scientific understanding of certain processes involved. Research will help to understand the turnover of carbon in the ocean, in particular to accurately describe the location and quantity of anthropogenic CO_2 that could be sequestered. Because of the rapid shifts being brought by climate change, estimating the climate mitigation potential in coastal blue carbon habitats and in the open ocean is becoming increasingly important – but generating accurate figures to illustrate the importance of these ecosystems is challenging. Scientists still need to accurately measure the global area covered by coastal blue carbon habitats. Also, the links between the sources of carbon and the long-term sinks are not well understood, neither are the drivers of carbon sequestration. Research is ongoing to address these, and other, gaps in knowledge.

Notwithstanding the quantitative uncertainties, it is clear that further disruption of marine ecosystems, of the carbon they already store and of their future capacity to sequester further carbon reserves, will inevitably work against the achievement of climate targets, as well as allowing the ongoing depletion of biodiversity to continue. Furthermore, the inclusion of goals for protection of carbon sources and sinks, alongside species and habitats, in the design of an effective network of marine reserves could provide key strategic opportunities for climate change mitigation.

3.0 Definitions and glossary of terms

Adaptive management: A flexible approach to the management and restoration of a habitat that incorporates regular review of current practices and learns from any mistakes to improve the future of the project/s.

Anthropogenic carbon: Excess carbon emissions in addition to the natural carbon cycle, mainly from burning fossil fuels and cement production. Natural carbon production occurs between the atmosphere, the ocean and the terrestrial biosphere on timescales ranging from days to millennia. Carbon in geologic reservoirs is stored for long periods (Le Quere *et al.,* 2016).

Apex predator: The predator at the top of the food chain.

Biological pump: The process in which carbon is sequestered from the atmosphere into the deep ocean by biological systems.

Blue carbon: The preservation of carbon in aquatic systems, particularly in soils and sediment.

Carbon sink: An area or habitat that absorbs significant amounts of CO_2 from the Earth's atmosphere to reduce the effects of global warming.

Carbon sequestration: Carbon sequestration is the process by which atmospheric CO_2 is taken up by trees, grasses and plants through photosynthesis, or when CO_2 converts to bicarbonate and forms $CaCO_3$ and is incorporated into marine animal shells and then becomes fossil. In plants, CO_2 is stored as carbon in biomass (trunks, branches, foliage, and roots) and soils. In animals the carbon is stored in the body of the animal. In this report we refer to carbon sequestration as that which is stored in the long-term, i.e. hundreds to thousands of years.

Carbon drawdown: A carbon sink.

Carbon pool: A system with the capability of storing and releasing carbon, such as the ocean, soils, plants and atmosphere.

Carbon cycle: The carbon cycle is the movement of carbon, in its many forms, between all living plants and animals, the atmosphere, the oceans, and soil and rocks (UK Forestry Commission).

Carbon burial: Carbon sequestration.

Carbon flux: The movement of carbon from one part of the carbon cycle to another.

Dissolved inorganic carbon (DIC): Dissolved carbon in the form of CO_2, bicarbonate and carbonate.

Dissolved organic carbon (DOC): Non-living organic carbon molecules dissolved in water that can pass through filter paper with ~0.45 μm pore size. In general, DOC compounds result from the decay of organic matter such as algae and are important food for microorganisms.

Ecosystem approach: Recognises the complexity of living systems and takes into account the interconnections between its components, for example flora and fauna.

Functional complexity: The number of distinct actions carried out by an ecosystem.

Global ocean carbon unit: Initiates debate around how to measure ocean carbon emissions, and the impacts of human activities on the carbon cycle. How countries will take responsibility for the ocean carbon emissions or sinks in the form of 'units' that will be part of a national carbon inventory. See Laffoley *et al.,* 2014.

Gross primary production (GPP): The rate at which an ecosystem's producers capture and store chemical energy as biomass.

Heterotrophic: An organism that cannot manufacture its own food and instead obtains its food and energy by taking in organic substances, usually plant or animal matter. All animals, protozoans, fungi and most bacteria are heterotrophs.

High seas: The area of the open ocean beyond national jurisdiction.

Inorganic carbon: Generally of mineral origin and does not contain hydrogen, which includes CO_2 and calcium carbonate ($CaCO_3$).

Net primary production (NPP): The rate at which an ecosystem's producers store net chemical energy (GPP – R = NPP).

Mineralisation: A term used in geology to mean the conversion of an element from its organic form to an inorganic form as a result of microbial decomposition. The term has a slightly different meaning in oceanography.

Mobile carbon unit: Animals (such as krill, fish and other megafauna) that are important for carbon cycling.

Mole (mol): A scientific unit to record the mass of a chemical. For example, 1 mole of carbon weighs 12 grams.

Ocean acidification: The rapid uptake of CO_2 by the ocean as a result of anthropogenic activity such as burning fossil fuels. The changes in seawater carbonate chemistry, including reductions in pH and carbonate saturation state, as well as increases in dissolved CO_2 and bicarbonate ions.

Organic carbon: Produced by living organisms and contains carbon bound to hydrogen (C-H) and is often large and complex. A simple form is methane, a more complex example is glucose.

Particulate organic carbon (POC): Particles containing organic matter that are too large to be pass through a ~0.45 µm filter. POC can be living (for example picoplankton, bacteria and viruses) or non-living (for example faecal pellets).

Physical carbon pump: Physical processes that mix water in the ocean. Vertical deep mixing occurs when warm water in oceanic surface currents is carried from low latitudes to high latitudes on Earth and cooled, making the water heavy enough to sink below the surface layer and, in some places, all the way to the bottom of the body of water.

Respiration (R): The rate at which organisms release heat energy produced by work.

Solubility pump: The process by which carbon is transported from the atmosphere by gas transfer into the ocean.

Trophic level: The hierarchy of organisms in an ecosystem (Ripple *et al.*, 2016)

Trophic cascade: The trophic cascade is the simplest top-down interaction: (i) predators suppress herbivores and allow plants to thrive, and (ii) apex predators suppress smaller predators, releasing herbivores to suppress plants (Ripple *et al*., 2016)

Scale of units

Value	Symbol	Name	Symbol	Value
10^3 g	Kg	Kilo-		
10^6 g	Mg	Mega-	t	1 t
10^9 g	Gg	Giga-	Kt	10^3 t
10^{12} g	Tg	Tera-	Mt	10^6 t
10^{15} g	Pg	Peta-	Gt	10^9 t

One hectare = 10,000 m^2
Tg = teragram = 1 million tonnes.
Pg = petagram = 1 billion tonnes.

4.0 Introduction

The oceans are an integral part of the global carbon cycle (McKinley *et al*., 2017). A complex suite of processes transfer atmospheric carbon from the surface to the deep ocean where it can be stored, or sequestered, for millennia. The deep ocean zones constitute the largest reservoir of stored carbon on Earth (3,150 Pmol, 1 petamole = 10^{15} moles), which corresponds to more than 50 times the amount of carbon in the atmosphere (currently estimated as 62.5 Pmol) and more than one order of magnitude greater than all the carbon held in terrestrial vegetation, soils and microbes combined (Honjo *et al.*, 2014). Estimates suggest that roughly one quarter of all the anthropogenic CO_2 emitted over the past 20 years has been taken up by the global oceans (Le Quere *et al.*, 2014).

Carbon is predominantly available in the oceans in the form of dissolved inorganic Carbon (DIC) – dissolved carbon dioxide (CO_2), bicarbonate (HCO_3) and carbonate (CO_3) – which are tightly coupled in ocean chemistry (DIC, ~38,000 PgC) (Ciais *et al.*, 2013). In addition, the ocean also holds a pool of dissolved organic carbon (DOC, ~700 PgC) some of which has a turnover period of 1,000 years or longer. Phytoplankton and microorganisms represent a small organic carbon pool (~3 PgC), which is turned over in days to a few weeks. Carbon storage can be either short term (a temporary pool where storage is from days to years) or long term (where long term sequestration can be from hundreds to thousands of years). For the purposes of this report we refer to sequestration as the long-term storage of carbon for at least one hundred years to millennia. In terms of climate mitigation, there is a need to assist the long-term sequestration (or mineralisation, see glossary) of carbon. Processes within the global oceans influence how carbon moves in the carbon cycle and between atmospheric and marine reservoirs. The importance of conserving large areas of terrestrial ecosystems, such as native forests, as a climate mitigation strategy is well recognised, yet ocean conservation as a mitigation strategy is less well understood or discussed by the scientific community.

Blue carbon strategies to protect areas of the oceans for climate mitigation have only begun to emerge within the scientific literature and policy since the early 2000s. The linkages between coastal and open ocean carbon reservoirs and how broad oceanic processes influence the fluxes between these reservoirs have not been studied extensively. To expand or to prevent degradation of the marine areas in which carbon is stored for the long-term, will require both the sources and the areas where carbon is sequestered to be preserved. Scientists need to increase understanding of how the different processes link and modulate carbon fluxes between sources and long-term sequestration.

Currently, most blue carbon strategies focus on quantifying and preserving coastal carbon sinks, such as mangroves, seagrass beds and tidal mud flats (Thompson & Miller, 2016). Coastal areas are easier to access and to study than the deep ocean, and are under national jurisdiction in terms of management of human activities. Coastal and continental shelf areas constitute around 7% of the oceanic surface, yet are highly productive and dynamic in terms of biological activity. The coastal ocean is the interface between the land and the deep ocean and is dominated by highly productive communities (phytoplankton, macroalgae or seaweeds, and corals). Some of the carbon within these communities is buried in coastal sediments and the remainder is exported to the open ocean in the form of particulate organic carbon (POC, matter that is too large to pass through a ~0.45 μm filter; see glossary) and DOC (dissolved organic carbon; see glossary; Barrón & Duarte, 2015).

Quantifying the export of the different forms of carbon to the open ocean from coastal ecosystems is problematic even though it is an important part of the open ocean carbon budget. Large (tenfold) uncertainties exist in estimating the geographic area covered by these productive coastal communities and there is significant variability in estimates of carbon flux. Scientists have modelled the contribution made by vegetated coastal habitats to the carbon cycle and have produced vastly different results. Duarte (2017) reviewed estimates of the contribution to carbon sequestration made by vegetated coastal habitats to coastal and deep-sea sediment. Duarte found that the sequestration rate varied from 73 to 866 Tg C yr^{-1}. The uncertainty in the estimates highlights how difficult it is to make a clear scientific assessment of the part played by the ocean in the global carbon budget.

Coral reefs are important in marine ecosystems and are biodiversity hotspots. However, in this review coral reef systems have not been included because they are primarily net carbon sources, not sinks (for further information refer to Howard *et al.*, 2017).

Open ocean productivity and carbon sequestration rates are also difficult to quantify. The relationships between different compartments of the carbon cycle are complex. The open ocean, which is the zone beyond the continental shelf break, is the area beyond national jurisdiction (ABNJ) that is costly to access, study and actively manage. A new focus of science is to try to better understand how the sources and sinks of carbon interact and how human activities might influence long-term carbon sequestration, or burial. The scientific community is, as yet, divided as to whether the carbon ‘stock’ in living biomass of the oceans can be termed ‘sequestration’. Most scientists state that although carbon in living biomass is important in the global carbon cycle, it is a temporary reservoir and not long-term sequestration.

In this review, we present current peer-reviewed literature on how ocean ecosystems sequester carbon, including descriptions of the sources and sinks of carbon and what is known about the interactions between them. We also underline the many uncertainties surrounding the ocean carbon cycle and rates of carbon sequestration. Finally, we provide key messages relevant to how marine protection could help with climate mitigation.

5.0 Ocean ecosystems

Chapter summary

1. Areas of the seabed where carbon sequestration occurs can be net sources or sinks of carbon depending upon the season, sea-surface temperature, ocean currents and turbulence from storms.
2. Carbon is transferred from surface waters vertically and laterally to deep-sea areas by trophic interactions the movement organisms – this process is known as the biological pump. Carbon is also moved laterally through oceanographic processes.
3. Photosynthesis in surface waters produces around 100 Gt of organic carbon per year, of which between 5–15% is exported to the deep ocean.
4. The mesopelagic community is important in carbon sequestration because foraging moves carbon from surface waters to deeper waters and long-term storage in the sediment.
5. The bottom or benthic zone is nutrient limited and is fuelled by organic matter produced in the photosynthetic zone at the surface, some of which sinks to the seafloor.
6. Long-term storage of carbon is a process known as mineralisation, where the element is converted from its organic form (such as a dead sea snail or fish) to an inorganic form as a result of microbial decomposition.
7. There are other processes, greenhouse gases and nutrients that are likely to affect the global carbon cycle in the ocean: notably climate change, methane, iron, nitrogen, phosphorus and fertilisers.

The global oceans include coastal areas within the continental shelves and the open ocean zone that is beyond the continental shelf. The continental shelves occupy around 7–10% of the global ocean area but contribute around 10–30% of the global marine primary production (Laruelle *et al*., 2013) and are important for carbon burial (shelf sediments may contain 30–50% inorganic and 80% organic carbon). The continental shelves may also contribute up to 50% of the organic carbon supplied to the deep ocean.

Deep-sea regions (>200 m depth) cover around 65% of the Earth's surface and 95% of the global biosphere (Smith *et al.*, 2009; Danovaro *et al.,* 2014b). In terms of the seabed, most research has been directed either towards coastal regions or the chemosynthetic ecosystems associated with mid-ocean ridges that cover < 1% of the deep ocean floor. The remaining vast expanse of the deep ocean is covered by abyssal plains that are less well documented or understood by scientists.

Directly linking and quantifying sources of carbon in coastal regions to long term sinks in the open ocean is an emerging area of science. Carbon moves from coastal areas to the deep ocean, and in some cases back to shallower water. This can be as a result of physical mixing of water and ocean circulation patterns. The waters of the deep ocean form a reservoir that comes to the surface during upwelling with a rate of turnover from hundreds to thousands of years.

Carbon from coastal areas can come from primary production in coastal ecosystems and input from rivers (Bauer *et al*., 2013). Most of what is known about long-term carbon sequestration in coastal vegetated ecosystems refers to areas of mangrove, seagrass beds and saltmarsh. For further information on coastal vegetated areas, please see Thompson & Miller (2016) and also section 6.1 of this report, which gives examples from the current literature that quantify the contribution of carbon from coastal ecosystems to the open ocean.

The interplay between the lateral (coastal to deep ocean) and the vertical (surface to deep ocean) movement of carbon make carbon sequestration highly dynamic. Areas of the seabed where carbon sequestration occurs can be net sources or sinks of carbon depending on seasonal, oceanographic factors or turbulence from storms. Much of the monitoring of carbon sequestration rates is geographically and temporally patchy, making accurate estimates of carbon sequestration difficult. Scientific research is continuing to focus on long-term and more geographically comprehensive monitoring so that net carbon sinks in the ocean can be characterised (Bauer *et al.*, 2013; McKinley *et al.*, 2017).

5.1 Introduction to vertical zonation in the oceans

Understanding the vertical zonation of the open ocean is important for linking carbon cycling from the surface to the seabed. The global carbon cycle broadly interacts with ocean ecosystems through the action of three ‘pumps’: the solubility pump (transport of CO_2 through the air–sea interface), the biological pump (primary production from plants using CO_2 and then carbon moving through trophic layers to eventually be mineralised) and the physical pump (the transport of carbon to the deep sea through the mixing of layers of the ocean) (Fig. 1)

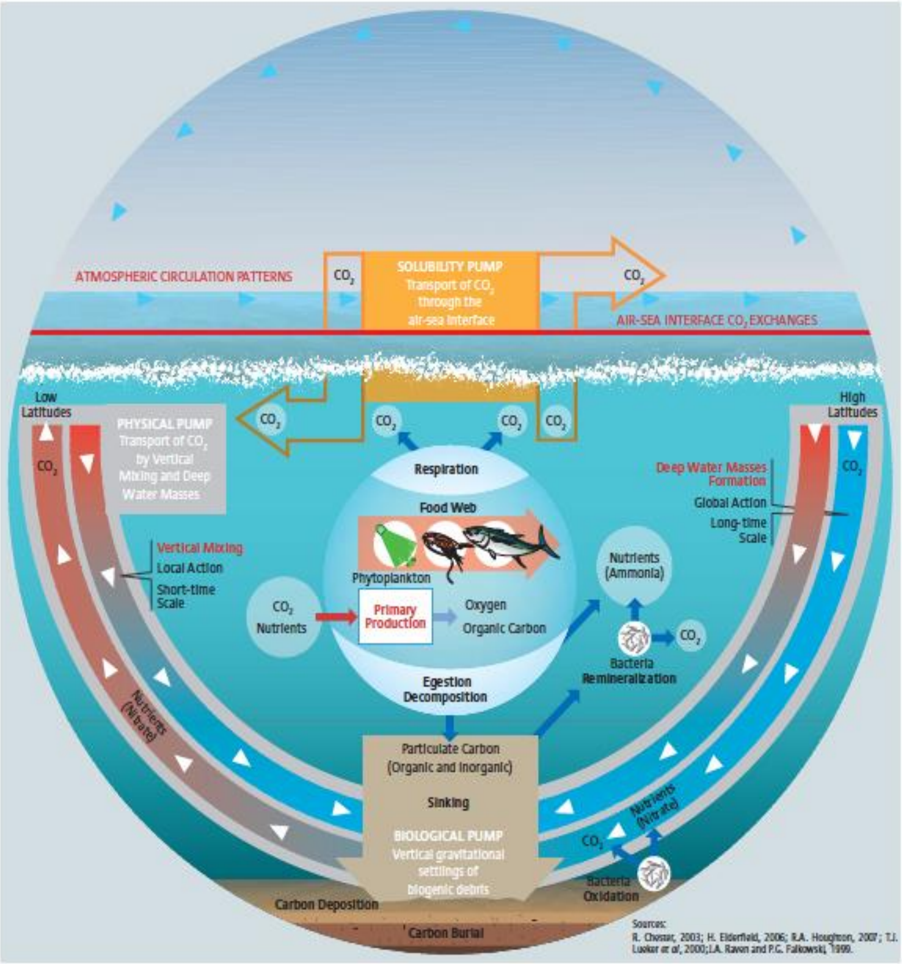

Figure 1. **A schematic showing the solubility, physical and biological pumps, with the flux of carbon from the atmosphere through to burial in the deep sea.** Source: Lutz & Martin (2014).

5.2 The atmosphere–sea surface interface

Gas exchange occurs at the interface between the atmosphere and the sea surface. With regard to carbon this means that a higher concentration of CO_2 is found in the sea surface water. The mixing of surface water with deep-sea water can take centuries (Sabine *et al.*, 2004).

The ocean is characterised by complex trophic links and multiple interactions between chemical, hydrological and geological processes. Beyond the continental shelf, the ocean encompasses several different zones throughout the water column from the surface to the seafloor (Fig. 2). Each zone is differentiated by depth and possesses a range of physical conditions that depend upon pressure and the extent of sunlight penetration. Physical conditions dictate which organisms can exist in each zone, although there is some vertical movement between zones.

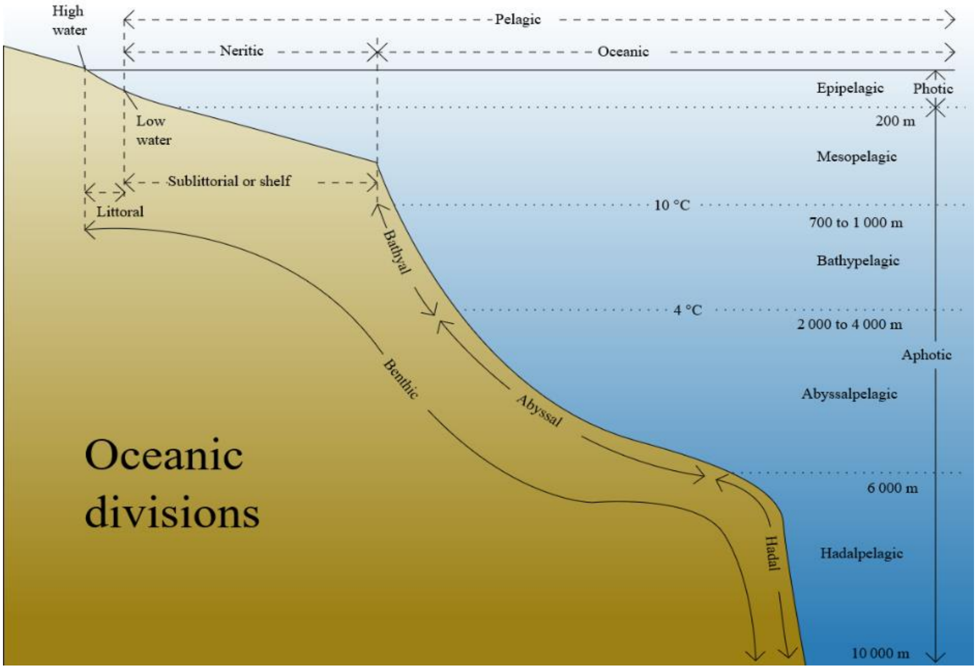

Figure 2. Stratification of the ocean from the epipelagic zone (< 200 m depth) to the Hadal zone (> 6000 m depth) within the deep ocean trenches. Source: Creative Commons Attribution.

The biological pump transfers carbon from surface waters, vertically and laterally, to deep-sea areas by trophic interactions and the movement of marine organisms (Fig. 3). Carbon fluxes are influenced by marine organisms and physical oceanography. Bathymetric features within sea-bed topography – deep abyssal plains, trenches and seamounts – drive vertical and horizontal mixing of the overlying water column that significantly influence biological processes. These processes are heterogeneous across open ocean areas, giving distinct hotspots of biological activity (De Leo *et al.*, 2010; Palacios *et al.*, 2006). Areas of high biological activity can be temporally persistent or dynamic over inter-annual (such as corresponding to global-scale atmospheric Rossby waves in the North Pacific), annual (such as seasonal intensification of wind in the California Current System) or intra-seasonal (such as equatorial waves in the Galapagos) timeframes.

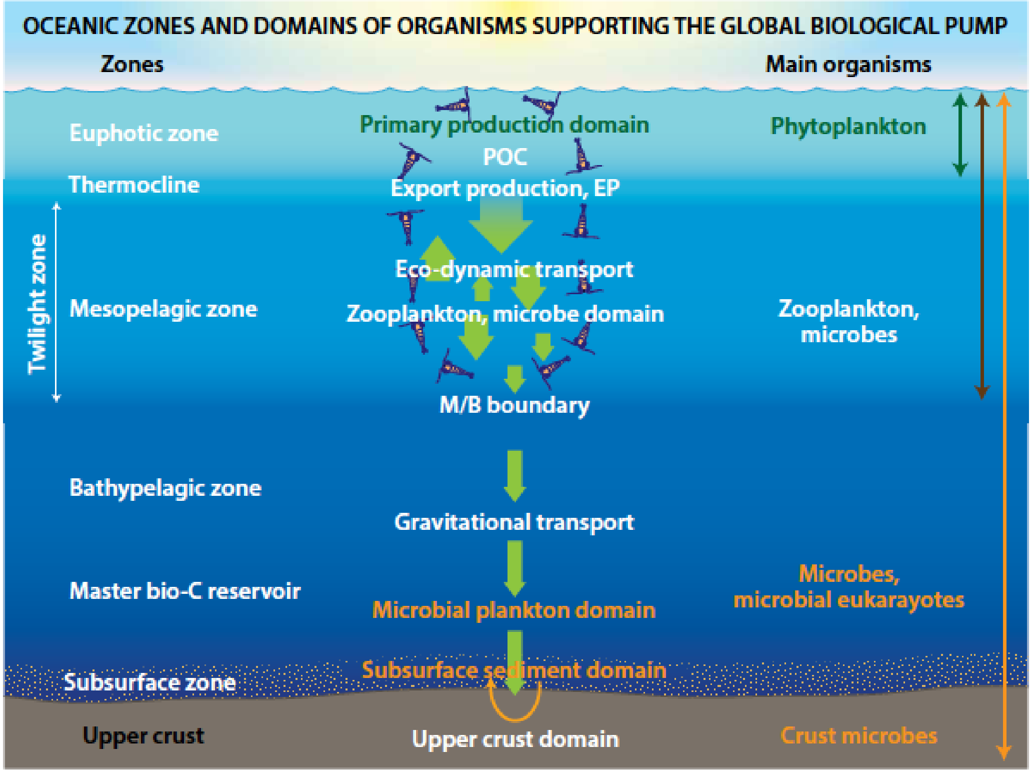

Figure 3. Schematic illustration of the major oceanic zones and the biological domains between surface waters and the deep ocean floor. Below the mesopelagic / bathypelagic boundary there is little zooplankton activity and the large population of microbes is supported by bio-mineralised particles from the waters above. Source: Honjo *et al.*, 2014 and reproduced with permission from The Oceanography Society.

5.3 The epipelagic zone

The epipelagic zone is also the euphotic or sunlight zone where photosynthesis occurs and is dominated by a mixture of phytoplankton species (for example diatoms and picoplankton) that are grazed upon by zooplankton. Plankton community composition and the relative contributions to carbon cycling have been documented (Richardson & Jackson, 2007; Packard & Gómez, 2013). Photosynthesis in these surface waters produces around 100 Gt of organic carbon per year, of which between 5–15 % is exported to deeper ocean zones (Laws *et al.*, 2000; Henson *et al.*, 2011). In addition to organisms such as fish, crustacea, molluscs and mammals, the epipelagic zone contains bacteria that are associated with oceanic production and nutrient cycling (Ducklow, 1999).

5.4 Mesopelagic zone

The mesopelagic zone (approximately 200–1,000 m depth) is also known as the twilight zone because it does not receive sufficient sunlight to fuel photosynthesis. Therefore, heterotrophic organisms that inhabit this zone must rely on ingesting organic matter that sinks down from the surface layer of the ocean to survive. The rate at which sinking carbon is converted into CO_2 by the organisms in the mesopelagic zone is important in carbon sequestration and research is now focused on accurately assessing these processes (Giering *et al.*, 2014; Honjo *et al.*, 2014).

A diverse collection of approximately 245 species of lanternfish (myctophiids), various crustaceans (shrimps), cephalopods (squid) and marine snails live in the mesopelagic zone (St John *et al.*, 2016). This community forms a distinct layer at around 500 m depth during the day and performs a vertical migration ascending to the upper 150 m during the night to disperse and feed. The process is known as diel migration and is considered to be the largest migration on Earth; the community itself is known to be integral to nutrient cycling in the oceans (Hays, 2003). Mesopelagic fish biomass alone is estimated to reach 10 billion tonnes globally, though figures differ (St John *et al.*, 2016). Many lower trophic species are a key food source for higher trophic levels and, therefore, their migration greatly influences the distribution of larger marine vertebrates such as fish, turtles and mammals. Modelling suggests that cephalopods, pelagic sharks and toothed cetaceans are important ecological components of these deep-sea ecosystems; overfishing these organisms can result in trophic downgrading that influences ecological complexity (Roman *et al.*, 2014; Morato *et al.*, 2016; St John *et al.*, 2016).

The mesopelagic community is important in carbon sequestration because foraging moves carbon from surface waters to deeper waters and long-term storage in the sediment. Mesopelagic organisms repackage organic carbon into fecal pellets that sink more quickly than the original material (Wilson *et al*., 2008) and fragment large, aggregated particles into small, slow-sinking particles (De La Rocha & Passow, 2007; Anderson & Tang, 2010).

5.5 Bathypelagic and abyssopelagic zones

The benthic communities that inhabit the deep oceans are also known to play an integral role in the global carbon cycle. The deep-ocean zones are nutrient-limited and fuelled by organic matter produced in the photosynthetic zone at the surface. Studies have shown the link between the surface–ocean and processes that take place in the deep sea is variable across seasons and between years. In particular, changes in the upper ocean temperature can influence stratification and reduce vertical mixing, which in turn reduces the availability of nutrients to deep ocean communities and induces large-scale changes that can impact the global carbon cycle (Smith *et al*., 2009).

Estimates of the rate of transfer of carbon through the water column are necessary to calculate sequestration to the deep ocean (Robinson *et al.*, 2010; Packard & Gómez, 2013). A continuous, passive rain of particulate organic carbon (POC) falls gravitationally through the water column to the depths below. In addition, carbon is actively 'pumped' between the different ocean zones during the diel vertical migration of zooplankton – zooplankton eat phytoplankton and other microorganisms in the epipelagic zone during the night, then swim down to the mesopelagic layer during the day to rest and excrete organic matter. Dissolved organic carbon (DOC) is transported through mixing of water between the surface and subsurface ocean. Finally, there is lateral movement of carbon as it is transported horizontally along isopycnal gradients (connecting layers of water that share the same density) between oceanographic provinces.

5.6 The seabed

Research on oceanic species lags far behind that of terrestrial ecosystems and emerging technological innovations have only recently (from 2000 onwards) facilitated access to the deeper parts of the oceans. Research has focused on trying to understand the importance of microbes and viruses in deep-sea ecosystems (Schippers *et al*., 2005; Danovaro *et al.*, 2008).

The long-term storage of carbon is a process known as mineralisation, in which the element is converted from its organic form to an inorganic form by microbial decomposition. An example of this could be when a sea snail dies and sinks to the seabed and by microbial decomposition the components of its body are broken down. Particulate organic matter that contains carbon undergoes microbial decomposition as it falls through the water column to reach the seabed (Fig. 3). Microbes are found throughout the water column, even in the deepest parts of the ocean. Complex relationships exist between microbes (and various plankton species) that are necessary to complete the carbon remineralisation process (Danovaro *et al.*, 2014a; Karl *et al.*, 2012). Accounting for each of these different fluxes is important in quantifying carbon sequestration rates, as is understanding the efficiency of bacterial decomposition (Karl *et al.*, 2012; Packard & Gómez, 2013). The dynamics of these biological interactions are influenced by seasonal factors and nutrients such as nitrogen and iron that affect the rate of carbon sequestration (Karl *et al.*, 2012; Jónasdóttir *et al.*, 2015). Oceanic fronts greatly influence the spatial distribution of biological activity and, therefore, carbon sequestration (Woodson & Litvin, 2015).

5.7 Other considerations: natural variability, climate change, limiting nutrients and methane

A focus on climate change, and potential mitigation methods, has meant that assessing the global ocean carbon sink and its natural variability versus variability because of climate change has become increasingly urgent in the past two decades (Siegal *et al*., 2016; McKinley *et al.*, 2017). The carbon cycle is well studied but it is more difficult to make global estimates of sequestration rates and how these will be affected in the future by climate change. Sequestration rates may be affected by changes in the ocean as a result of climate change. For example, ocean warming may change stratification (layering) of water and upwelling patterns that will affect the biological pump and the physical carbon pump (Boyd *et al*., 2014; de Lavergne *et al*., 2014; Barton *et al*., 2016). Ocean warming can impact the occurrence, frequency and regional variability of extreme events, such as El Niño and the monsoon system. In simplified terms, the warming atmosphere and sea are leading to melting glaciers and ice sheets, which will mean a rise in sea level (please see more information in Summary for Policymakers IPCC 2013 report; Stocker, 2015). Changing ocean circulation and the frequency of storms can impact on carbon sequestration rates at the sea bed.

Nitrogen, phosphorus and iron. Phytoplankton activity is limited by the availability of certain elements. When those elements become available, populations of phytoplankton increase, which will result in elevated levels of CO_2 being drawn into the biological pump in the ocean. Research suggests that, in general, nitrogen availability limits phytoplankton at the surfaces of low-latitude oceans and iron limits productivity in the main upwelling regions of the Southern Ocean and the eastern equatorial Pacific. Phosphorus, vitamins and other micronutrients may also be important in limiting phytoplankton productivity. Proposed geoengineering strategies, such as ocean fertilisation with iron, rely on artificially adding these elements into the oceans as a means of increasing phytoplankton populations and overall CO_2 drawdown from the atmosphere. These are highly controversial with a number of unpredictable and irrevocable potential environmental effects (Shepherd, 2009; Santillo & Johnston, 2016).

Fertiliser release from the terrestrial environment. It is beyond the remit of this report to discuss in detail non-carbon impacts on the ocean, but the release into the ocean of anthropogenic compounds such as nitrogen and phosphorous in agricultural fertilisers are having a profound effect on the ocean by stimulating algal blooms. More algal blooms are observed now than before the onset of industrial agriculture (Glibert *et al.*, 2014). When such blooms persist, the oxygen content in the water is depleted and in the worst case scenario the area could become a ‘dead zone’ devoid of biodiversity. The situation can be exacerbated when the microbes respire and produce CO_2, adding to the anthropogenic CO_2 burden on the ocean (Arellano-Aguilar *et al.,* 2016).

6.0 Quantifying carbon in the oceans

Chapter summary

1. The ocean carbon cycle is complex and quantifying the carbon that is stored in marine ecosystems is not straightforward. Because of the complexity, reports published in the scientific literature that quantify the carbon store in the ocean vary and many figures are estimates only.
2. Carbon is found in different forms, in different locations and in different quantities throughout oceans – forms include particulate organic carbon (POC), dissolved organic carbon (DOC) and dissolved inorganic carbon (DIC).
3. The carbon sequestered long-term is known to come from sources within the open ocean and from coastal ecosystems such as saltmarshes, mangroves, kelp forests (and other macroalgae). However, the links between these sources and the rates of sequestration in the seabed are currently poorly characterised in the scientific literature.
4. The movement of carbon in the deep sea, including its mineralisation during long-term sequestration, is dominated by the action of microbes.
5. Marine organisms (vertebrates, invertebrates and microbes) provide essential goods and services to the ocean ecosystem.
6. Approximately 1% of the total organic carbon production at the sea surface will be buried in the sediment.

The ocean carbon cycle is complex and quantifying the carbon that is stored in marine ecosystems is not straightforward. Because of this complexity, reports published in the scientific literature that quantify the carbon stored in the ocean vary broadly and many figures are estimates only.

Carbon is found in the ocean in different forms, in different locations and in different quantities:

Organic: Carbon that is stored in living plants and marine organisms, in organic-rich detritus or as dissolved organic carbon.
Inorganic: Atmospheric carbon dioxide that dissolves into seawater to form carbonic acid, bicarbonate and carbonate.
Carbonate: Excreted by and incorporated into marine invertebrates' skeletons and secreted by vertebrates.

The oceanic carbon cycle is not a straightforward process. One reason is that carbon is stored in the ocean for different durations: long term and short term. Terminology in the published scientific literature varies when discussing timescales, so for this reason definitions have been included here and in the glossary.

Short-term storage: Carbon (both organic and inorganic) in living biomass that is stored in a marine plant or organism for the duration of its lifetime.
Long-term sequestration: Carbon (again both organic and inorganic) sequestered for millennia in marine soil and sediment and deep below the seabed as hydrocarbons.

To further add to the complexity of the ocean carbon cycle, carbon 'fixed' in one marine location can be exported over great distances to another location and either recycled or deposited there. The processes driving this export are currently not fully understood by science.

The scientific community is divided as to whether the carbon 'stock' in the living biomass of the oceans can be considered as long-term sequestration. Many scientists state that although this type of 'living' carbon is important in the global carbon cycle it is a temporary reservoir and not long-term sequestration.

6.1 Organic carbon: Vegetated coastal ecosystems

One of the issues being discussed in the scientific literature concerns the rate and quantity of carbon sequestration that occurs in and is exported from coastal vegetated ecosystems. Some of the organic carbon forms that originate in vegetated coastal ecosystems is exported to the deep sea, and some remains in the coastal regions.

6.1.1 Saltmarsh

Tidal saltmarshes are intertidal systems that are physically dominated by vascular plants, but also include other primary producers (macroalgae, phytoplankton and cyanobacteria). The marsh's plants take in CO_2 from the atmosphere (rather than sea). Rates of above- and belowground carbon sequestration vary across plant families and regions. Unlike terrestrial soils, the sediments in which healthy saltmarsh plants, mangrove and seagrasses grow do not become saturated with carbon as the sediments accrete vertically with a rising sea level. This means that the rate and quantity of carbon sequestration can increase over time (Chmura *et al.*, 2003).

6.1.2 Mangrove

Mangrove is a highly carbon-dense tropical forest and for this reason is an important carbon reserve (Donato *et al.*, 2011). Mangrove trees store carbon equally between the roots, leaves and wood but in mangrove habitats, the majority of carbon is actually stored not in the living biomass but in the soil and in the dead, belowground roots (Alongi, 2014).

The rate of carbon storage in mangrove ecosystems is approximately 10 times greater than in temperate forests and 50 times greater than in tropical forests per unit area (Bouillion *et al.*, 2009). Mangroves store more carbon per unit area (956 Mg C ha^{-1}) than do saltmarshes (593 Mg C ha^{-1}), seagrasses (142 Mg C ha^{-1}), peat swamps (408 Mg C ha^{-1}) and terrestrial rain forests (241 Mg C ha^{-1}). Although mangroves occupy only 1.9% of the tropical and subtropical coast, this ecosystem accounts for 5% of net primary production of carbon and 30% of all coastal ecosystems' carbon burial (Alongi & Mukhopadhyay, 2015).

6.1.3 Seagrass

Seagrasses export 24.3% of their net primary production to destinations that include fauna (which feed on the grasses); remineralisation (when dead plants or leaves fall to the seabed); and the deep sea. Storm activity can enhance the export of seagrass carbon stocks, which suggests that the carbon-export system is intermittent rather than regular (Duarte & Krause-Jensen, 2017).

6.1.4 Macroalgae

Macroalgae are large photosynthetic marine plants colloquially called 'seaweed'. These plants export 43% of production as particulate organic carbon or dissolved organic carbon when detached fronds from coastal zones or free-floating genera such as Sargassum contribute to carbon stock reaching the seafloor. This process is usually intermittent and increases after a major storm. The drivers of macroalgae sequestration have not been researched in detail, as they have been for mangrove, seagrass and saltmarsh. Changes in the sequestration of carbon by macroalgae by factors such as climate change and harvesting macroalgae as a foodstuff need to be monitored and incorporated into blue carbon accounting (Krause-Jensen & Duarte, 2016).

Three vegetated coastal ecosystems – mangrove forests, saltwater marshes and seagrass meadows – are widely regarded in the literature as being key to removing anthropogenic CO_2. A proportion of atmospheric CO_2 that has dissolved in seawater will be sequestered for the long-term in soil and sediment (see section 6.5 of this report). For more details on the qualitative and quantitative aspects of vegetated coastal ecosystem carbon storage and sequestration please see the Greenpeace internal briefing on blue carbon (Thompson & Miller, 2016). The knowledge that coastal ecosystems export organic carbon stocks has implications for policy relating to marine protected areas because protection may need to be extended beyond a coastal ecosystem (Duarte & Krause-Jensen, 2017).

6.2 Organic carbon: Microbial activity

The movement of carbon in the deep sea is dominated by microbial activity. Most of the easily available dissolved organic matter (DOM) in the ocean is produced by phytoplankton, which use photosynthesis to convert atmospheric CO_2 and nutrients to sugar using light energy from the Sun.

The photosynthesis equation:

$$6CO_2 + 6H_2O \rightarrow C_6H_2O_6 + 6O_2$$

Carbon dioxide + water → Glucose + oxygen

Technological advances in the past decade have enabled scientists from different disciplines to collaborate on research projects to understand the key part played by microbes in the marine ecosystem. DOM comprises hundreds of thousands of different organic compounds, some of which contain elements and micronutrients. DOM is important to both terrestrial and marine cycles, and the store of carbon, which is similar in quantity to atmospheric CO_2, is used in many marine ecosystems as well as storing atmospheric CO_2.

Some of the organic matter produced by phytoplankton is transported to the deep ocean, where it is mineralised and sequestered. The processes involved are complex and the fate of dissolved organic carbon is not fully understood by the scientific community. Some aims of future scientific research will be to understand the turnover of carbon in the ocean, in particular to accurately quantify the anthropogenic CO_2 that could be sequestered in the ocean, methods to decrease emissions and ways to mitigate the effects of climate change. Scientists do not yet know the extent to which drivers such as increasing sea temperature or ocean acidification could affect the production of DOM by microbes (Moran *et al*., 2016).

Particulate organic carbon (POC) is an essential part of the global carbon cycle, particularly long-term carbon sequestration. Different fates await POC that reaches the sediment on the ocean floor. POC can be in the form of deceased plankton, fragments of marine flora or fecal pellets, to give a few examples. Some POC will be ingested by marine organisms, but much of it will be degraded by microbes. POC degradation is part of the process that forms the vast gas hydrate reservoir; gas hydrates are a long-term carbon store that lock carbon up for millennia (for background information on gas hydrates see section 8.3.3 of this report). POC degradation produces inorganic carbon that is released into the surrounding seawater, but this carbon release is balanced out by the amount of carbon that is sequestered for millennia in gas hydrates (Malinverno & Martinez, 2015).

Carbon sedimentation is related to surface productivity. In other words, the quantity of carbon production in the surface waters will influence the quantity of carbon sinking to the sediment on the ocean floor, which in turn will influence the quantity of carbon that is sequestered or buried for geological timescales. Only some of the carbon that falls to the ocean floor as POC will be sequestered in a long-term carbon store. Approximately 1% of the total organic carbon production at the sea surface is buried in the sediment (Nath, 2012; Suess, 1980).

6.3 Organic carbon: Marine invertebrates

Marine organisms (vertebrates, invertebrates and microbes) provide essential goods and services to the ocean ecosystem. All living marine organisms are essential to biogeochemical processes such as the regulation of oxygen and CO_2 and cycling elements that include phosphorous, nitrogen and sulphur (Beaumont *et al.,* 2007). Marine invertebrates inhabit all vertical zones.

Barnes *et al*. (2016) report that the Ross Sea in the Southern Ocean is a globally significant site for carbon sequestration, which is increasing in the region. The reason for the increase in carbon sequestration is because the rising sea temperature and resulting ice-sheet melt has meant more sea surface is available to phytoplankton. Phytoplankton (microscopic plants) and algae are primary producers – they absorb atmospheric CO_2 during photosynthesis in the euphotic, sunlit zone in the uppermost 50m of the ocean causing a 'bloom'. Phytoplankton are consumed by zooplankton, zooplankton perform diel vertical migration to the deeper pelagic zones and are in turn consumed by benthos (invertebrates that inhabit the marine sediments). Here is one key to the carbon cycle because when benthos die, they fall to the ocean floor and lock the carbon away for long periods of time. For more information on ocean zonation, see section 5.5 of this report.

The pelagic zone is the water between the uppermost photosynthetic zone and the benthic zone, or seabed. Invertebrates inhabiting the pelagic zones include pteropods, crustaceans and molluscs. Organisms inhabiting this zone (including vertebrates) perform diel vertical migrations from around 500 m depth during the day, to 150 m depth at night and are known to play an important part in carbon sequestration (St John *et al.*, 2016).

The connections between and contributions to the carbon cycle by marine organisms inhabiting the different ocean zones are not fully understood by scientists, and research is ongoing. For example, the part played by salps in marine ecosystems has been understudied, according to Henschke *et al.* (2016). Salps are zooplankton with gelatinous bodies that are found in the pelagic zone in every ocean except the Arctic. There are 48 species of salp, which range in size from 0.5-190 mm and they play an important part in the trophic food web and in biogeochemical cycles. Filter-feeding salps are in the lower trophic levels and are consumed by at least 149 species of fish, as well as molluscs, crustaceans and turtles. Salps are eaten by pelagic and benthic predators. Salps excrete heavy carbon-rich fecal pellets, which scientists refer to as particulate organic carbon (POC), that sink rapidly and contribute to the carbon transfer to the sea floor. One broad estimate is that, depending on the size of the species, a salp swarm can export between 128–4,970 mg C m^{-2} $month^{-1}$ from the euphotic or sea surface zone to a depth of 1,000m, but scientists have not yet fully quantified salps' carbon sequestration.

The marine invertebrates that inhabit marine sediment are known as 'benthic' and include small organisms (macrofauna) such as polychaetes, molluscs and crustaceans. Marine macrofauna, of which there are an estimated 500,000 to 10,000,000 species, perform essential functions in the ocean carbon cycle as well as other ecosystem processes, such as nutrient cycling and metabolising pollutants (Snelgrove, 1998).

6.4 Organic carbon: Marine vertebrates

Marine vertebrates play an important part in the carbon cycle because they both store and export marine carbon, and secrete carbonate (Pershing *et al.*, 2010). Fish carbonate is covered in section 6.8 of this report. Vertebrates contribute by effectively mixing nutrient-rich water throughout the water column, which in turn can help primary production (photosynthesis) by phytoplankton and therefore increase uptake of excess atmospheric CO_2 (Lutz & Martin, 2014). Cetaceans and other large marine vertebrates, such as tuna fish, can facilitate bio-mixing of significant quantities of water. Large vertebrates help with vertical and horizontal transport of nutrients in the water, leading to increased primary production and fixing atmospheric carbon.

Whales and other marine vertebrates are important components in the oceanic global biogeochemical cycle. A study published by Lavery *et al.* (2010) estimates that in the Southern Ocean the population of 12,000 sperm whales can act as a carbon sink, removing 2.4×10^5 tonnes of carbon each year. Scientists had thought that Southern Ocean sperm whales were a source of CO_2 because they add CO_2 to their environment through respiration but this view changed because it had overlooked the fact that whales defecate iron-rich faeces that stimulate primary production and carbon export to the deep ocean.

Marine vertebrates store organic carbon for the entirety of their lives, removing that carbon from the atmosphere for the duration of the life of the animal. Large animals are more efficient at storing carbon than small ones because they require less food per unit of mass (Pershing, 2010). However, scientists are still investigating the role that large vertebrates have in the sequestration and cycling of carbon in the marine environment. The process, including moving carbon from one area to another and through food webs, is poorly understood by scientists and represents a knowledge gap (St John *et al.,* 2016).

Marine vertebrates occupy the upper part of the food web. Evidence suggests that removal of organisms – particularly top predators – on one trophic level can have an effect on other organisms and flora on other levels. For example, the loss of predatory crabs meant an increase in the abundance of grazing snails that fed on saltmarsh that led to the loss of the saltmarsh habitat (Atwood *et al.,* 2015). Saltmarsh ecosystems are important in long-term carbon sequestration (see section 6.1.1 of this report). Disrupting the food web by the removal of one or more species can affect the balance of organisms in the food web and can have an unpredictable effect on the carbon cycle. For more details on the impact of removing a species from the food web please see section 7.0 of this report.

6.5 Inorganic carbon: Atmospheric carbon dioxide

The oceans absorb anthropogenic CO_2 but it is not evenly distributed and some oceans have a higher concentration of dissolved CO_2 than others. The North Atlantic stores 23% yet the Southern Ocean stores just 9% (Sabine *et al.*, 2004) and the largest ocean, the Pacific, absorbs just 18% (Feely *et al.,* 2001). A higher proportion of CO_2 is found in the surface water and although the flux of CO_2 between the atmosphere and the sea is affected by air temperature, ocean currents and photosynthesis, 50% of anthropogenic CO_2 is found in water less than 400m deep. Also, CO_2 dissolves twice as readily in cold water at the poles than in warm waters near the equator (Feely *et al.,* 2001).

As the concentration of atmospheric CO_2 continues to increase as a result of anthropogenic activities (particularly burning fossil fuels and cement production), the oceans will continue to absorb CO_2. Absorption of CO_2 by the sea will continue to contribute to ocean acidification. However, the extent to which the oceans will continue to absorb atmospheric CO_2 is not fully understood – research has suggested that in future the ocean may become less efficient as a CO_2 sink because seawater will become saturated. Sabine *et al.* (2004) estimate that without the global ocean CO_2 sink, the amount of CO_2 in the atmosphere would have been in the region 55 ppm higher than the estimated 380 ppm in 1994. The global atmospheric concentration of CO_2 reached 399.4 ± 0.1 ppm when averaged over 2015 (Le Quéré *et al.,* 2016). Atmospheric CO_2 is 40% greater in the 21st century than pre-industrial era (circa 1750), which is mostly because of fossil-fuel burning and land-use change (Ciais *et al*., 2013).

Continuing to burn fossil fuels will cause the Earth's climate to continue warming (Ciais *et al*., 2013). Because of the warming atmosphere, permafrost may begin to melt over the next 100 years or so. Climate scientists are as yet uncertain how much carbon will be released into the atmosphere when this does happen. Part of the reason for their uncertainty can be illustrated in the following example:

Comparing data that estimate the cumulative impact of total anthropogenic CO_2 emissions from 1750 to 2011 (which include fossil fuel-burning, cement production and land-use change such as deforestation), shows that the carbon released is 555 ± 85 PgC. But when the total increase in atmospheric CO_2 over the same time period is less than expected at 240 ± 10 PgC. This discrepancy is because ocean and terrestrial ecosystems have acted as carbon sinks, absorbing an estimated 155 ± 30 PgC and 160 ± 90 respectively (Ciais *et al*., 2013).

6.5.1 The fate of excess atmospheric CO_2

Sabine *et al.* (2004) suggest that one-third of anthropogenic CO_2 produced in the period 1800–1994 has been dissolved into the world's oceans and the remainder is in Earth's atmosphere. The anthropogenic CO_2 that is in the ocean is absorbed in the form of dissolved inorganic carbon (DIC). The CO_2 that does not become dissolved in the ocean will remain in Earth's atmosphere, where it can persist for more than 1,000 years. To remove anthropogenic CO_2 from ocean and land sinks will take more than 100,000 years (Ciais *et al*., 2013).

Feely *et al.* (2001) suggest that a significant portion of atmospheric CO_2 that has dissolved into the oceans is used by phytoplankton during photosynthesis. Approximately 30% of the carbon from the dissolved CO_2 that the phytoplankton use will sink (as faeces or deceased plankton) to deeper waters, where marine bacteria convert it back into CO_2. The team estimates that only 0.1% of all the atmospheric CO_2 that has dissolved in the surface water and that reaches the seafloor will be buried in sediments. Only a very small percentage of atmospheric CO_2 is sequestered in ocean sediments, which highlights the importance of ensuring that the *entire* vertical ecosystem – flora *and* fauna from ocean surface to seabed – is protected as much as possible to maximise carbon sequestration in the future. For a detailed description of ocean zonation and associated processes, please refer to section 5.1 of this report.

Ocean carbon is estimated using field data and modelling. As modelling improves and becomes increasingly sophisticated to include more elements of and connections within the carbon cycle, research outcomes will be better able to predict environmental changes, which will help to inform policy change.

6.6 Inorganic carbon: Ocean acidification

This section summarises current understanding. Changes to ocean chemistry caused by an increase in atmospheric CO_2 from burning fossil fuels, particularly since the industrial revolution circa 1750, have been widely reported. Ocean acidification is covered in detail in a report from the Plymouth Marine Laboratory (Turley *et al.,* 2013).

The process of ocean acidification can be summarised as: excess atmospheric CO_2 dissolves into the surface layers of the ocean, reducing the pH of seawater by increasing the concentration of hydrogen ions (H^+). Since the pre-industrial era, there has been a 26% increase in H^+, and the pH of seawater has decreased by 0.1 (Ciais *et al*., 2013). The process is represented in the following equation:

$$CO_2\,(aq) + H_2O \leftrightarrow H_2CO_3 \leftrightarrow H^+ + HCO_3^- \leftrightarrow 2H^+ + CO_3^{2-}$$

The above equation shows that carbon dioxide (CO_2) dissolves in water (H_2O) to form carbonic acid (H_2CO_3), which dissociates to form bicarbonate (HCO_3), carbonate (CO_3) and hydrogen ions. The increased hydrogen ions cause the seawater to become more acidic over time, despite countering from factors such as the mixing of centuries-old seawater, weathering from the land, and seafloor carbonate buffer the reactions (Hönisch *et al.*, 2012).

6.7 Inorganic carbon: Plankton carbonate

The change in concentration of carbonate ions in seawater that has been caused by excess anthropogenic CO_2 dissolving in the ocean is widely reported to negatively affect the formation of shells and skeletons by marine organisms (Cyronak *et al.,* 2016). However, research published by Toyofuku *et al*. (2017) has implications for ocean carbon. The accepted view, which is based on chemical equations, is that if less carbonate is available in acidic seawater then marine organisms will find it harder to form lime to grow their shells and skeletons.

But Toyofuku *et al*. (2017) report that some single-celled marine organisms called foraminiferans exhibit biochemical regulation of their immediate marine environment and are able to continue forming calcareous structures even in an acidic environment. The organisms do this by pumping out excess hydrogen ions so that they can maintain homeostasis and continue functioning as normal. The researchers report that if other marine organisms are able to regulate their environment in this way and continue to form shells and skeletons in an acidifying ocean then there could be implications on the ocean carbon cycle. The reason can be explained: excess atmospheric CO_2 will dissolve into the ocean until saturation point. After this point, the excess CO_2 will remain in the atmosphere, which will contribute to global warming. More research is needed to find out how other marine organisms respond to an acidified ocean in relation to shell and skeleton formation.

6.8 Inorganic carbon: Fish carbonate

Calcification is an important part of the inorganic carbon cycle in the marine ecosystem. Carbonate is a short-term carbon store and is formed in the following process in which calcium reacts with bicarbonate in the seawater and produces calcium carbonate, which is insoluble, carbon dioxide and water:

$$Ca^{2+} + HCO_3^- \leftrightarrow CaCO_3 + CO_2 + H_2O$$

Most of the calcification that takes place in the oceans is by plankton (coccolithophores and foraminifera), but 3-15% of carbonate in the ocean is produced by fish. Fish produce carbonate as a by-product to maintain homeostasis. Increasing concentrations of oceanic CO_2 as a result of anthropogenic activity could increase carbonate production by fish, which means that fish will become more important in the inorganic carbon cycle (Wilson *et al.,* 2009).

6.9 Ocean carbon cycle: Schematic representation

In the schematic below (Fig. 4), the numbers represent reservoir mass, also called 'carbon stocks' in PgC (1 PgC = 1015 gC) and annual carbon exchange fluxes (in PgC yr−1). Black numbers and arrows indicate reservoir mass and exchange fluxes estimated for the time prior to the Industrial Era, about 1750 (see Section 6.1.1.1 of Ciais *et al.* (2013) for references). Fossil fuel reserves are from GEA (2006) and are consistent with numbers used by IPCC WGIII for future scenarios. The sediment storage is a sum of 150 PgC of the organic carbon in the mixed layer (Emerson & Hedges, 1988) and 1600 PgC of the deep-sea CaCO3 sediments available to neutralize fossil fuel CO2 (Archer *et al.*, 1998).

Red arrows and numbers indicate annual 'anthropogenic' fluxes averaged over the 2000–2009 time period. These fluxes are a perturbation of the carbon cycle during Industrial Era post 1750. These fluxes (red arrows) are: Fossil fuel and cement emissions of CO_2 (Section 6.3.1 of Ciais *et al.* (2013)), Net land use change (Section 6.3.2 of Ciais *et al.* (2013)), and the Average atmospheric increase of CO_2 in the atmosphere, also called 'CO_2 growth rate' (Section 6.3 of Ciais *et al.* (2013)). The uptake of anthropogenic CO_2 by the ocean and by terrestrial ecosystems, often called 'carbon sinks' are the red arrows part of Net land flux and Net ocean flux.

Red numbers in the reservoirs denote cumulative changes of anthropogenic carbon over the Industrial Period 1750–2011 (column 2 in Table 6.1 of Ciais *et al.* (2013)). By convention, a positive cumulative change means that a reservoir has gained carbon since 1750. The cumulative change of anthropogenic carbon in the terrestrial reservoir is the sum of carbon cumulatively lost through land use change and carbon accumulated since 1750 in other ecosystems (Table 6.1 of Ciais *et al.* (2013)). Note that the mass balance of the two ocean carbon stocks Surface ocean and Intermediate and deep ocean includes a yearly accumulation of anthropogenic carbon (not shown). Uncertainties are reported as 90% confidence intervals. Emission estimates and land and ocean sinks (in red) are from Table 6.1 in Section 6.3 of Ciais *et al.* (2013). The change of gross terrestrial fluxes (red arrows of Gross photosynthesis and Total respiration and fires) has been estimated from CMIP5 model results (Section 6.4 of Ciais *et al.* (2013)). The change in air–sea exchange fluxes (red arrows of ocean atmosphere gas exchange) have been estimated from the difference in atmospheric partial pressure of CO2 since 1750 (Sarmiento & Gruber, 2006).

Individual gross fluxes and their changes since the beginning of the Industrial Era have typical uncertainties of more than 20%, while their differences (Net land flux and Net ocean flux in the figure) are determined from independent measurements with a much higher accuracy (see Section 6.3 of Ciais *et al.*, (2013)). Therefore, to achieve an overall balance, the values of the more uncertain gross fluxes have been adjusted so that their difference matches the Net land flux and Net ocean flux estimates. Fluxes from volcanic eruptions, rock weathering (silicates and carbonates weathering reactions resulting into a small uptake of atmospheric CO2), export of carbon from soils to rivers, burial of carbon in freshwater lakes and reservoirs and transport of carbon by rivers to the ocean are all assumed to be pre-industrial fluxes, that is, unchanged during 1750–2011. Some recent studies (Section 6.3) indicate that this assumption is likely not verified, but global estimates of the Industrial Era perturbation of all these fluxes was not available from peer-reviewed literature. The atmospheric inventories have been calculated using a conversion factor of 2.12 PgC per ppm (Prather *et al.*, 2012).

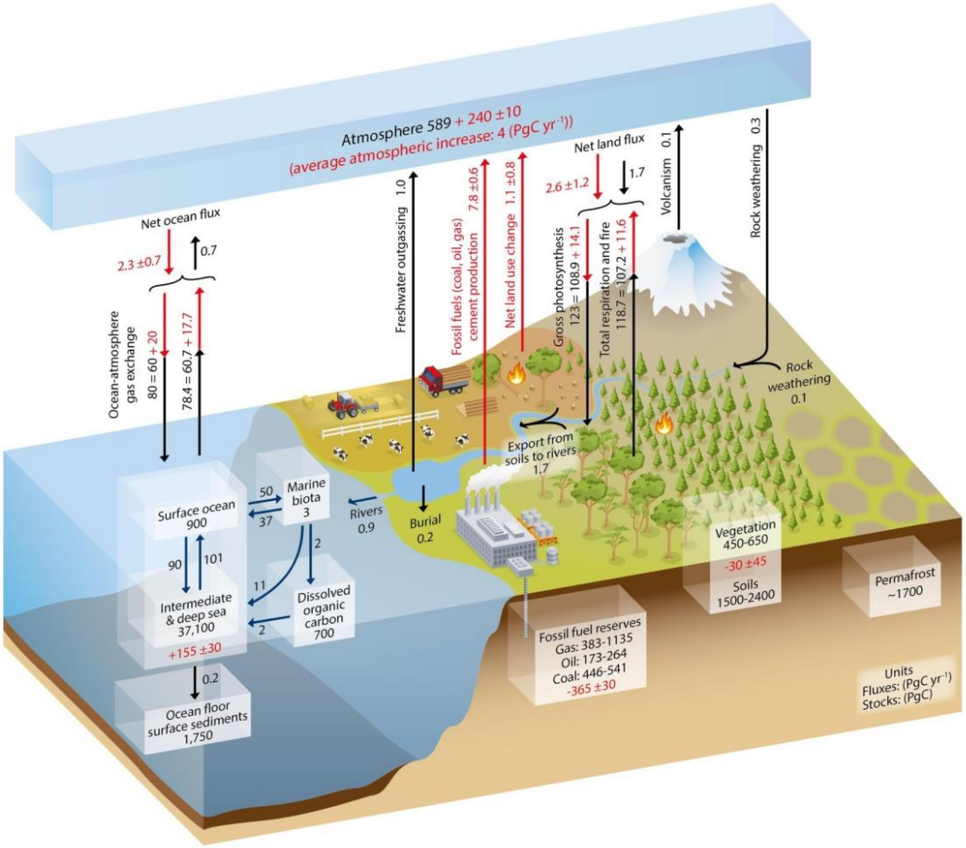

Figure 4. Simplified schematic of the global carbon cycle. Source: Figure 6.1 Ciais *et al.* (2014).

6.10 Carbon sequestration in different oceans

The oceans sequester carbon, but research suggests that oceans sequester carbon in different amounts. The International Panel on Climate Change report that an estimated 28% of anthropogenic carbon produced from 1750–1994 is stored in Earth's oceans (IPCC, 2013). Continued uptake of CO_2 by the world's oceans is leading to ocean acidification. Changes to ocean chemistry will affect marine organisms, but the impact of large-scale ocean acidification is not fully understood. However, should marine flora and fauna be negatively affected by a change in ocean pH, their ability to sequester carbon could be affected (Stocker, 2015).

An inventory of CO_2 by Sabine *et al*. (2004) looked at different oceans and found an uneven distribution of CO_2 within and between oceans (Fig. 5). Vertical integration of water from the surface with water from deeper regions can take centuries. The concentration of CO_2 in different depths of an ocean or sea can vary substantially (Sabine *et al.*, 2004). Because atmospheric CO_2 is absorbed into the sea at the surface, higher concentrations of CO_2 are found in surface waters. Most of the anthropogenic CO_2 in the world's oceans is found in the thermocline, which is a region in the mesopleagic zone of the oceans in which warm surface sea water mixes with cold water from the deep zone: 50% of anthropogenic CO_2 is found in water up to 500m deep. Only 7% of anthropogenic CO_2 is found at depths greater than 1,500m (Sabine *et al.*, 2004).

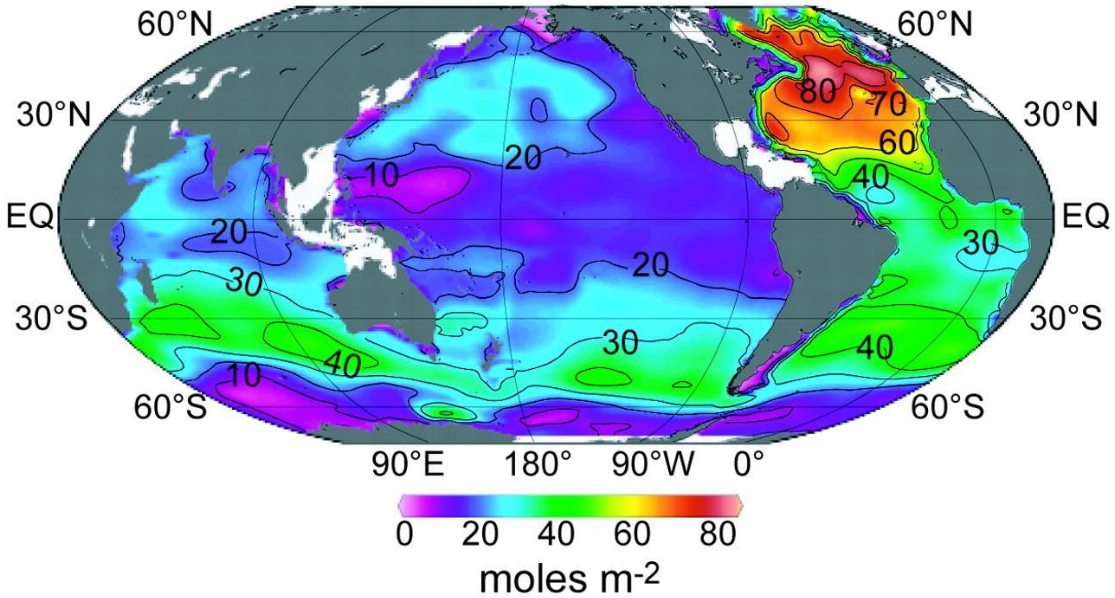

Figure 5. World map showing the amount of anthropogenic CO_2 in different oceans. Broadly speaking, the highest levels of CO_2 are associated with deep-water currents in the North Atlantic. Source: Sabine *et al.* (2004).

The solubility pump is more efficient in polar regions because CO_2 is twice as soluble in cold water than in warm tropical waters. The ocean currents (Fig. 6) transport warm water from tropical regions towards colder areas at the poles, during which time the sea water cools and absorbs atmospheric CO_2. Then the cool water sinks, taking with it the dissolved CO_2 (Feely *et al.,* 2001).

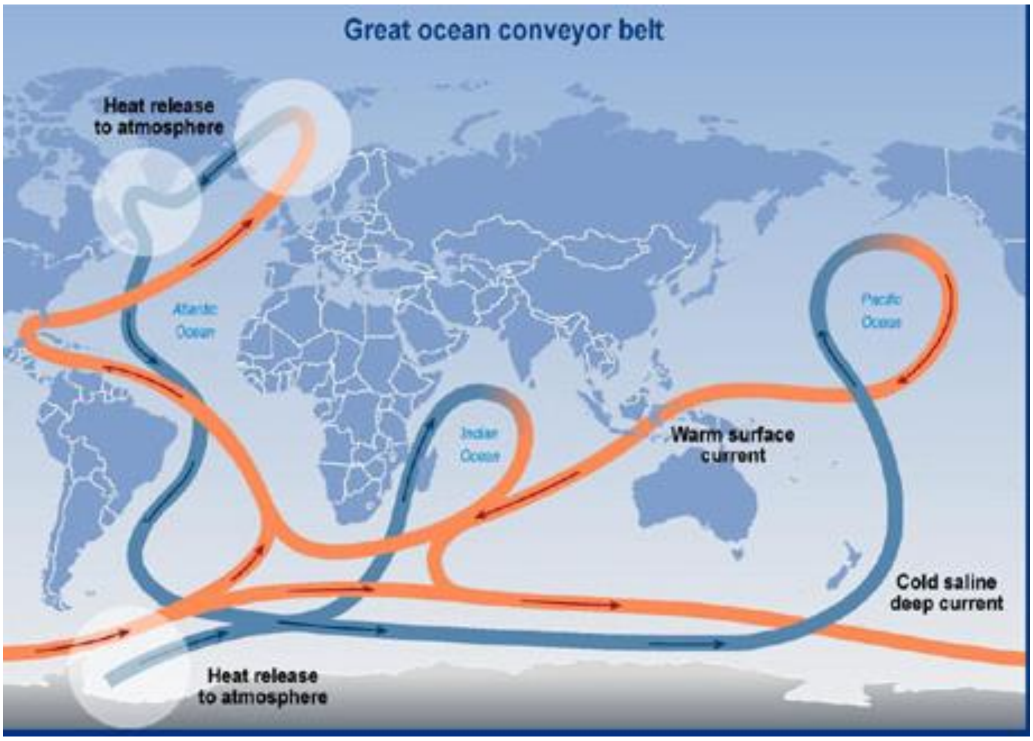

Figure 6. **The global conveyer belt showing the circulation of the oceans.** Cold water is shaded in blue and warm water is shaded in orange. Copyright Intergovernmental Panel on Climate Change (2001).

North Atlantic

The North Atlantic Ocean has high vertical integration, which refers to water from the surface meeting with water from deeper zone. The North Atlantic stores 23 % of anthropogenic CO_2, yet it covers 15 % of the global ocean area. This is the only area in which large concentrations of anthropogenic CO_2 are found in the deep ocean – this is because of ocean currents in the region (Sabine *et al*., 2004).

Southern Ocean

The Southern Ocean is important in dissolving atmospheric CO_2. Hoppema (2004) suggests that the Weddell Sea, and maybe other sub-polar gyres or seas, are important in carbon sequestration into the deep sea. The amount of CO_2 remineralised in the subsurface Weddell Sea that is sequestered into the deep sea is approximately 6% of global CO_2 sequestration in the deep oceans – this is a significant amount considering that the Weddell Sea is 0.4 % of the world's ocean (Hoppema, 2004). The Southern Ocean contains in total 9% of the global anthropogenic CO_2 concentration (Sabine *et al*., 2004).

Caldeira & Duffy (2000) suggest that most of the anthropogenic CO_2 entering the Southern Ocean is not sequestered in that region because it is transported north to the subtropical convergence by ocean currents. Caldeira & Duffy (2000) conclude their modelling study by suggesting that uptake of CO_2 in the Southern Ocean is large but that sequestration of carbon is low. They suggest factors that would affect oceanic CO_2 uptake in the future as changes to the ocean circulation, changes in the coverage of sea ice, and changes in biological activity.

The relevance of deep-sea carbon sequestration is that the carbon stored in the deep sea – the area known as the abyss – is released in upwelling zones. The carbon stored in such zones might have been stored for decades (Canu *et al.,* 2015).

Arctic Ocean

The Arctic Ocean is an atmospheric CO_2 sink, although its role in the carbon cycle may alter as a result of climate change. However, the Arctic Ocean's part in the carbon cycle is poorly quantified (MacGilchrist *et al.,* 2014).

Red Sea and Persian Gulf

These waters are high in anthropogenic CO_2. The high air temperature causes seawater to evaporate, which increases the salinity of the water and makes it more dense than less salinated water. The dense water sinks and carries dissolved CO_2 towards the equator and across the Indian Ocean (Sabine *et al*., 2004).

Pacific Ocean

The Pacific Ocean is the world's largest ocean, covering approximately half of the world's marine area. Yet it is a store for just 18% of anthropogenic CO_2 (Feely *et al*., 2001).

Chu *et al.* (2016) found that storage of anthropogenic CO_2 is increasing in the Northwest Pacific. The team compared data collected on a cruise in 2001 with data collected along the same route in 2012 and found elevated levels of anthropogenic CO_2 in the surface water of the section studied. The increased CO_2 has contributed to acidifying the ocean water in that region.

6.11 Carbon accounting: Tabulated data

Table 1 Quantification of carbon in the Earth's atmosphere, ecosystems and oceans.

Component	**Carbon accounting**	**Reference**
Atmospheric greenhouse gases		
CO_2 in the year 1750*	278 ppm	Ciais *et al.,* 2013
CO_2 in the year 1800	281 ± 2 ppm	Sabine *et al*., 2004
CO_2 in the year 1994	359 ± 0.4 ppm	Sabine *et al*., 2004
CO_2 in the year 2011	390.5 ppm	Ciais *et al.,* 2013
CO_2 in the year 2015	399.4 ± 0.1 ppm	Le Quéré *et al.,* 2016
Inorganic ocean carbon		
Atmospheric CO_2 to ocean flux 1750-2011, in the entire ocean	–155 ± 30 PgC (the negative figure indicates a gain of C in the ocean)	Ciais *et al.,* 2013 (table 6.1)
Estimated global cumulative anthropogenic CO_2 sink in the oceans 1800 to 1994 (almost 200 years). Note that the concentration of anthropogenic CO_2 is not evenly distributed in the world's oceans.	118 ± 19 PgC	Sabine *et al*., 2004
Global fish carbonate production	0.04 to 0.11 Pg of $CaCO_3$ C year^{-1}	Wilson *et al,* 2009
Organic ocean carbon		
Flora		
Estimated carbon storage by macroalgae (including Sargassum and kelp) in coastal regions and deep ocean across the globe	173 (range 61–268) TgC yr^{-1} 88% or 152 TgC yr^{-1} is sequestered to the deep sea.	Krause-Jensen & Duarte, 2016
Global carbon burial in mangrove systems (assuming an area 160,000 km^2)	18.4 Tg C yr^{-1}	Bouillion *et al*., 2008

*1750 = taken to be the beginning of the industrial era.

Component	**Carbon accounting**	**Reference**
Organic ocean carbon, Flora continued		
Global carbon burial in mangrove systems	23.6 Tg C yr^{-1} (the figure is the geometric mean of 27 published estimates).	Duarte *et al.,* 2005
Global carbon burial in saltmarsh	60.4 Tg C yr^{-1} (the figure is the geometric mean of 96 published estimates).	Duarte *et al.,* 2005
Global carbon burial in seagrass	27.4 Tg C yr^{-1} (the figure is the geometric mean of 5 published estimates).	Duarte *et al.,* 2005
Contribution to carbon sequestration to the deep sea sediment and sea water made by vegetated coastal habitats	73–866 Tg C yr^{-1}	Duarte, 2017
Total oceanic carbon burial (upscaled estimate from individual measurements)	244 Tg C yr^{-1}	Duarte *et al.,* 2005
Fauna		
Estimated total global carbon sequestration by the carcasses that fell to the seafloor of 8 species of large baleen whales in 2001.**	28,862 tons C yr^{-1}	Pershing *et al*., 2010
Estimated total global carbon sequestration by carcasses of 8 species of large baleen whales pre-whaling (pre-1900) using estimated figures of whale populations at that time.**	192,702 tons C yr^{-1}	Pershing *et al*., 2010
Estimated total global carbon storage by pelagic fish	40-110 Tg C yr^{-1}	Schmitz *et al.,* 2014

** Figures have been calculated using estimations of whale populations both pre-1900 and in 2001. The pre-1900 figures are based on the number of whales caught and may be an underestimation because of underreporting. Therefore these figures should be regarded as conservative estimates.

7.0 Biodiversity in marine ecosystems

Chapter summary

1. Marine organisms inhabiting a balanced ecosystem are central to the carbon cycle. Biodiversity within a balanced ecosystems is also linked to overall resilience and severe depletion of one species can have disruptive effects.
2. Each species will have a differing relative importance to overall carbon burial but this is very difficult to characterise, particularly in marine ecosystems.
3. In terrestrial ecosystems, however, a loss in plant diversity has been shown to result in reduced carbon sequestration.
4. The standing stock of carbon in the biomass of living marine organisms is regarded by many scientists as a temporary carbon store and not long-term sequestration.
5. Marine megafauna (mammals, large fish and birds) consume large amounts of food and can balance trophic dynamics. Through excreta, nutrients that have passed through megafauna will be spatially redistributed because these large marine animals access the depths of the ocean and bring nutrients to the surface and/or swim over great distances and so connect different ocean ecosystems.
6. Widespread removal of a top predator will result in lower trophic levels, i.e. lower level predators or herbivores, become increasingly abundant. An overabundance of herbivores can place coastal vegetated ecosystems under stress, which can mean that carbon sequestration in these areas is reduced. Many species that are fished commercially in the open ocean, for example tuna and sharks, are apex predators. Removing these top predators from the food chain in the open ocean will result in imbalances that marine ecologists have not yet characterised.
7. Protecting specific species on lower trophic levels that are important prey may be prudent in protecting carbon cycling. One example is krill.
8. An ecosystem-based approach to ocean, and carbon, management may be a useful tool to apply to ocean protection and climate mitigation.

Biodiversity. Marine organisms inhabiting a balanced ecosystem are central to the carbon cycle (Schmitz *et al.*, 2014). Biodiversity within this balanced ecosystems is also linked to overall resilience (Loreau *et al.*, 2001). If a species within an ecosystem is depleted, another species will take its place, which can have a disruptive effects. In terrestrial systems, a loss in plant diversity can result in reduced carbon sequestration (Cardinale *et al.*, 2012), but this effect is less well characterised in the marine environment. Functional complexity in marine ecosystems, that is, the number of distinct functions carried out by the ecosystem, is important to overall carbon burial. Each biological component has a differing relative importance (Fig. 7; Danovaro *et al.*, 2014a). This means that removing a particular species from an ecosystem or food web can have unpredictable consequences because interactions between species and the environment are complex.

The standing stock of carbon in the biomass of living marine organisms is regarded by many scientists as a temporary carbon store and not long-term carbon sequestration. The rate of biological carbon fixation will affect the annual carbon flux but not necessarily long-term sequestration. However, if biological food webs and trophic interactions are disrupted, for example by removing an apex predator such as a fish or marine mammal, this will affect the carbon cycle. Characterising the effect on carbon sequestration is difficult because only a few long-term studies on coastal ecosystems have been published.

Megafauna. Estes *et al.* (2016) consider the impact of megafauna (organisms that are > 45 kg) in marine ecosystems and how changing populations may affect how an ecosystem functions. These animals can be marine mammals, fish, reptiles and molluscs – many of which, though charismatic, are still classed as 'data deficient' by the International Union for Conservation of Nature (IUCN). Birds are apex predators and are classified by many scientists as marine megafauna. Megafauna consume large amounts of food, including plankton and small fish, which potentially affects trophic dynamics (the effects of an imbalance in the food web is explained in the following section). Through excreta, nutrients that have passed through megafauna will be spatially redistributed because these large marine animals swim over great distances and so connect different ocean ecosystems.

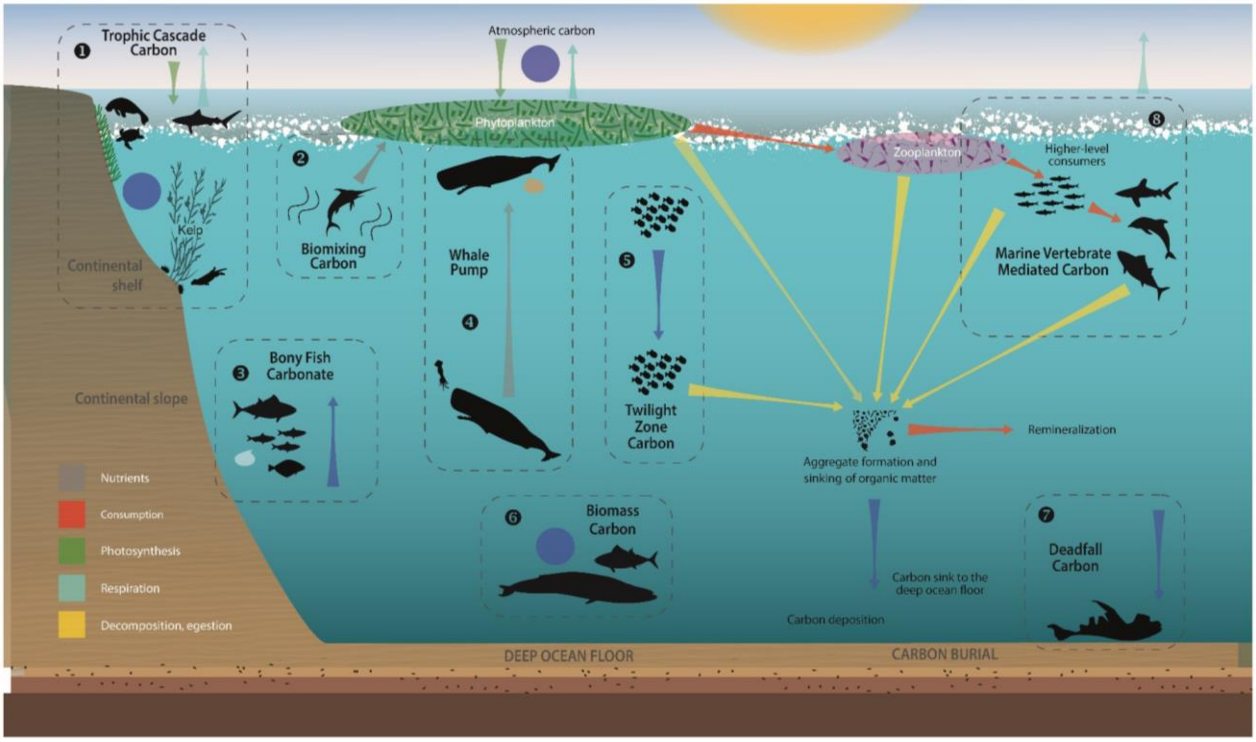

Figure 7. Marine vertebrate carbon services. Source: Lutz & Martin (2012).

Whales can help primary production in ocean ecosystems because of their large size and extensive movements both vertically in the water column when foraging and laterally during migrations (Roman *et al.*, 2014; Pershing *et al.*, 2010). For example, Roman & McCarthy (2010) suggest that humpback whales in the Gulf of Maine may increase phytoplankton production because the whales feed in the mesopelagic layer and excrete nutrient-rich faeces at the surface. In the Southern Ocean, low levels of iron limit the growth of plankton. Baleen whales in the Southern Ocean can help primary production by plankton by making iron available in the water. They do this through their consumption of krill in a process that concentrates iron and deposits it in surface zones in faeces (Nicol *et al.*, 2010).

Removal of higher trophic levels. Apex predators are key in marine (and terrestrial) ecosystems and their absence can result in trophic imbalances. Removal of the top predator can present a situation in which species in a lower trophic level, such as lower level predators or herbivores, become increasingly abundant. An overabundance of herbivores can place coastal vegetated ecosystems under stress, which can mean that carbon sequestration in vegetated areas is reduced. The consequences of removing top predators is complex because the interplay between the behaviour and ecology of species in lower trophic levels can make predicting the effects on the food chain challenging.

Atwood *et al.* (2015) discuss the removal of predators in the context of carbon sequestration in three example coastal blue carbon habitats – salt marshes in New England, and mangroves and seagrass ecosystems in Australia. In all cases the functional loss of predators resulted in decreased carbon sequestration rates due to increased populations of herbivores (Fig. 8).

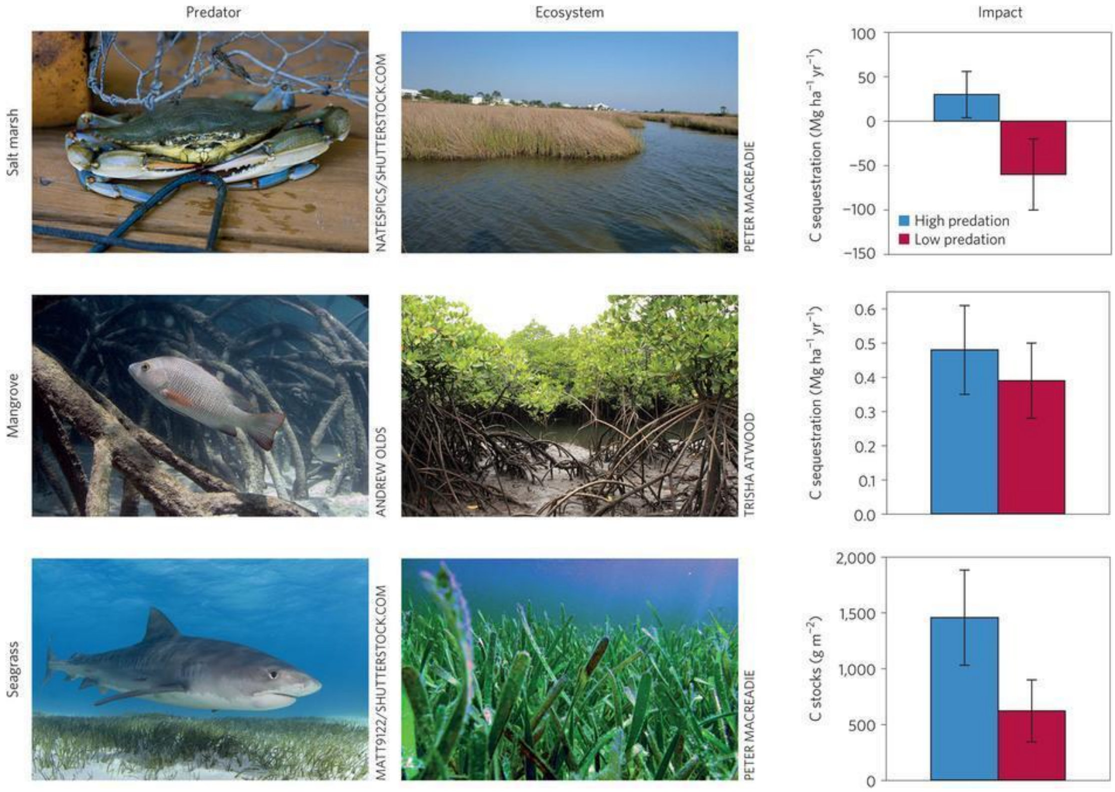

Figure 8. Reductions in predatory blue crabs in New England salt marshes (top panel) and in predatory fish (mangrove jack) in Australian mangroves (middle panel) resulted in increased abundance of bioturbators (for example sesarmid crabs) and a reduction in the C sequestration capacity of these ecosystems. Non-consumptive effects of tiger sharks (bottom panel) in Shark Bay, Western Australia, create a landscape of fear in which sea turtles and dugongs preferentially forage in seagrass microhabitats that are low in predation risk. Seagrass microhabitats associated with low predation risk have lower C stocks than do microhabitats associated with high predation risk. Plots show mean ± 1 standard deviation. Source: Atwood *et al.* (2015).

Wilmers *et al.* (2012) have combined data on sea otters and carbon production and storage within the kelp ecosystem on Vancouver Island, Alaska. The study found that otters suppress sea urchin populations and, in the absence of otters, increased grazing by urchins resulted in reduced kelp growth with consequences on carbon sequestration. Over an ecosystem area of approximately 510,000 km^2, the effect of sea otter predation on kelp living biomass was estimated to represent an increase of 4.4 to 8.7 Tg in carbon storage.

Fisheries management. Many species that are fished commercially in the open ocean, for example tuna and sharks, are apex predators (Fig. 9). Removing a top predator from the food chain in the open ocean will result in imbalances that ecologists have not yet characterised. Predicting the effect of food chain imbalances on carbon sequestration is particularly difficult given how little is known about what drives carbon flux in these areas.

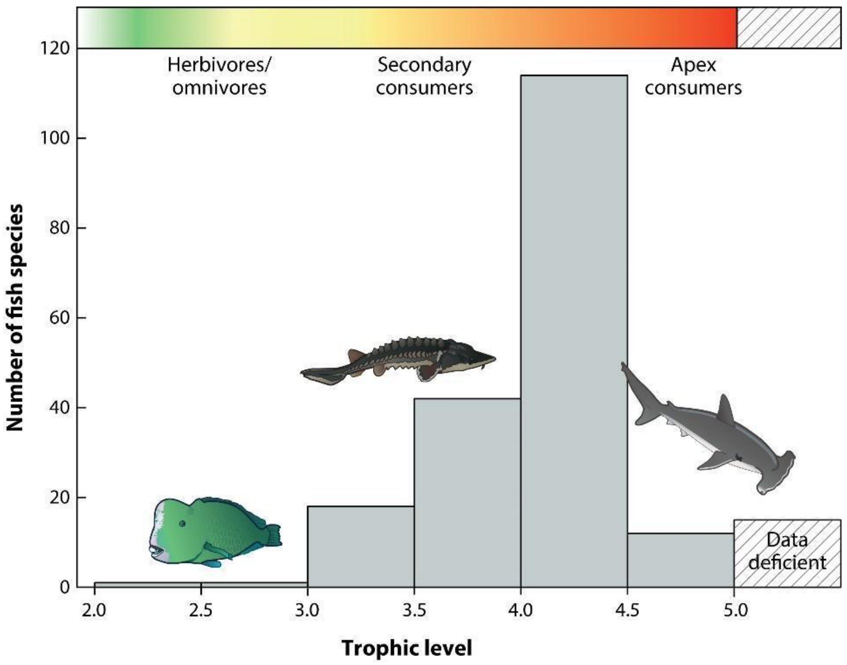

Figure 9. A histogram of trophic level and large (megafaunal, < 45 kg) marine fish. A diverse array of feeding modes are present but most of these large fish are high-level predators. Source: Estes *et al.* (2016).

Protecting specific species on lower trophic levels that are important prey may be prudent in protecting carbon cycling. One example is krill. The estimated biomass of krill in the Southern Ocean is between 60-500 million tonnes depending on various methods of estimation (Nicol *et al.*, 2000; Siegel, 2005). The large population estimates of both these organisms – krill and salps – mean that they are key in moving carbon throughout the Southern Ocean ecosystem and a large temporary stock of carbon. See section 9.4 of this report.

Ecosystem-based approach to quantify ocean carbon. Martin *et al.* (2016) attempted to evaluate ecosystem services for the Eastern Tropical Pacific using an ecosystem-based approach that includes carbon storage in this area. The study tried to estimate the economic value of carbon storage in terms of temporary carbon in fish biomass, the regulatory services provided by cetaceans and changes in export to the deep sea as a result of removing fish from the ecosystem. Such comparisons are rarely built into fisheries or marine protected area management policy. Martin *et al.* (2016) found that characterising the economic benefit of carbon storage was not straightforward, and their estimates were relatively crude in that the analyses did not take into account the spatial and temporal trends. However, it was estimated that the market value for carbon export to the deep ocean (a flow worth billions of US dollars) was higher than the estimated value to commercial fisheries (also worth billions of dollars). Both Martin *et al.* (2016) and Lau (2013) explore the concept of payment schemes for preventing ocean degradation that mirror terrestrial REDD programmes. With regard to commercial fisheries, it would be necessary to estimate how much (in millions of tonnes (mt)) a particular level of fishing (in mt) would reduce the standing stock biomass from its equilibrium, and then apply an estimate of carbon price associated with the loss of storage.

8.0 The impact of human activities on ocean carbon sequestration rates

Chapter summary

1. Aquaculture, urban development and other construction work is destroying coastal vegetated ecosystems, which have high rates of *in situ* carbon sequestration and are important for exporting carbon to the open ocean. Mangroves are being lost at an estimated 1-2% per year; around 50% of saltmarsh has been lost or irreparably damaged by human activity; the level of carbon in an area of seagrass that had been regenerated after a period of disturbance was 35% lower than the level of carbon in an undisturbed area.
2. Overfishing restructures biological communities at all trophic levels.
3. Geoengineering is highly controversial and has unpredictable and irrevocable potential environmental effects. There has been relatively little research on the potential impacts of geoengineering on marine (and terrestrial) ecosystems and biodiversity.
4. Exploiting gas hydrate reserves would release carbon that has been sequestered for millennia.
5. Areas in the Mediterranean in which bottom-trawler fishing had taken place had up to 52% less organic matter and around 37% slower organic carbon turnover than untrawled areas.
6. Deep-sea mining has the potential to cause widespread disturbance to the carbon flux and to the organisms that inhabit the deep-sea. The process of mining involves machinery that causes extensive and indiscriminate disturbance to the sediment, flora and fauna. Scientists are not yet certain how movement of carbon in the deep sea and carbon sequestration would be affected by such disturbances.

Myriad human activities impact the ocean and although some actions cause more disturbance than others, the net effect is degradation of ecosystems in all regions, from the coastal areas to the deep sea. The following sections highlight the anthropogenic activities that most affect the rate of carbon sequestration.

8.1 Coastal development

Aquaculture and urbanisation. Coastal ecosystems have high rates of *in situ* carbon sequestration and are important for exporting carbon to the open ocean (see Thompson & Miller, 2016; and section 6.1 of this report). But these ecosystems are being removed and degraded by human intervention. Mangroves, for example, are being lost at an estimated 1-2% per year, and around 50% of natural saltmarsh ecosystems are thought to have been lost or irreparably damaged through pressure of human activities. Activities such as installing aquaculture facilities and urbanisation are reducing the global area of these coastal blue carbon ecosystems. Ahmed & Glaser (2016) report that aquaculture is accountable for the loss of a significant amount of mangrove habitat globally, specifically 1.4 million ha to shrimp farming and 0.49 million ha to other forms of coastal aquaculture. Destroying habitats such as tidal saltmarsh and mangrove by building roads and pavements prevents these habitats from natural expansion and regeneration.

Disturbance of sediments. Disturbance of coastal blue carbon sediments rapidly reduces accumulated carbon that has taken hundreds to thousands of years to accumulate. Macreadie *et al*. (2015) reported that a seagrass ecosystem that was disturbed 50 years ago showed a 72% decline in carbon stocks. Seagrass areas that had regenerated after a period of disturbance had a level of carbon that was 35% lower than undisturbed areas. Widespread disturbance of carbon sequestered in sediment can reduce sequestration rates and unlock carbon that has been stored for millennia.

Fisheries management. Overfishing is the oldest and greatest source of disturbance to coastal areas, depleting target species and restructuring biological communities at all trophic levels (Jackson *et al.* 2001).

Geoengineering. The aim of geoengineering is to counteract anthropogenic climate change, but it could have unintended side-effects. Various geoengineering strategies have been proposed to artificially alter the global carbon cycle. One such strategy is ocean fertilisation with iron, which relies on artificially adding the element into the oceans as a means of increasing phytoplankton populations and overall CO_2 drawdown from the atmosphere. Other strategies include (i) enhanced weathering and (ii) artificial modification of upwelling or downwelling processes (Shepherd, 2009; Williamson & Bodle, 2016). Geoengineering is highly controversial and has unpredictable and irrevocable potential environmental effects (Shepherd, 2009; Santillo & Johnston, 2016). There has been relatively little research on the potential impacts of geoengineering on ecosystems and biodiversity (Shepherd, 2009).

Lack of research. Research on how to sustainably manage coastal areas is limited in certain areas of the world, particularly in areas of Africa, Asia and sub-regions of the Pacific. Partlow *et al.* (2017) carried out a systematic review examining 753 peer-reviewed articles focusing on tropical marine and coastal research across both the social and natural sciences. The study found that research into mangroves accounted for only 9% of articles; ecosystems including seagrasses, open seas, rocky reefs, soft-bottoms, intertidal zones (excluding coral reefs and estuaries) accounted for only 6% of articles. In comparison, research focusing on coral reef, estuaries and lagoons accounted for 48.7% of articles.

8.2 Disturbing the seabed: Bottom trawling

Fishing by bottom trawling causes extensive damage to the seafloor and seamount habitats. Studies of trawled seamounts off Tasmania (Althaus *et al.,* 2009) and New Zealand (Williams *et al.,* 2010) found that there was no clear signal of recovery of the benthic organisms where trawling had ceased almost ten years earlier. These two studies indicate that a decade may be too short a period to detect any recovery of coral communities. Research suggests that recovery of seamount benthos will take decades or longer (Althaus *et al.,* 2009). In an attempt to limit potential damaging impacts to the sea bed, the European Union passed Regulation (EU) 2016/2336 to only permit bottom trawl fishing at or above 800m (EU, 2016; DSCC, 2016).

Damage to the seabed can affect carbon sequestration because trawling resuspends sediments. Pusceddu *et al.* (2014) show that, compared to untrawled areas of the north-western

Mediterranean, trawled areas were characterised by up to 52% less organic matter and around 37% slower organic carbon turnover. This study also reported that intensive trawling reduced meiofauna by 80%, biodiversity by 50% and nematode richness by 25%. Pusceddu *et al.* (2014) estimated that in their study area, the continuous sediment resuspension induced by deep sea trawling could remove 60-100% of the daily organic carbon flux from the area.

8.3 Disturbing the seabed: Seabed mining

A search of the scientific literature using the terms 'seabed mining' and 'impact' calls up 77 papers that discuss different ecological issues, including the physical effects to the seabed, the impact of sand extraction, environmental management strategy and conservation considerations. Far fewer papers discuss the potential impact of seabed mining specifically on carbon sequestration. A search using the terms 'seabed mining' and 'carbon' calls up just seven papers.

Because of the lack of commercial operations so far, the potential impact on the seabed and carbon sequestration by mining operations is often determined using natural extinction events such as volcanic eruptions or disturbance experiments with follow-up monitoring. For obvious reasons, recovery studies have not been conducted on a spatial or temporal scale similar to those planned for commercial seabed mining, following which the potential for colonisation from adjacent areas may be considerably reduced. Disturbance experiments are small-scale and low impact and therefore provide valuable data but are limited in predicting how commercial mining will affect the ocean ecosystem.

All seabed-mining operations follow a similar system using a seabed resource collector, lifting system and support vessels. Most proposed deep-seabed collection systems envisage the use of remotely operated vehicle (ROV) techniques, which extract deposits from the seabed using mechanical or pressurised water drills.

The International Seabed Authority (ISA) is currently in the process of developing its environmental management strategy and has produced a lengthy working document that addresses topics such as provision of an environmental impact assessment and baseline studies of an ecosystem (ISA, 2017).

For a detailed analysis of the impacts of seabed mining, please refer to the Greenpeace Research Laboratories technical report (Allsopp *et al.,* 2013).

Seabed disturbance: Experimental studies. In 1989, the first long-term disturbance and recolonisation experiment (abbreviated to DISCOL) was established in the Peru Basin in the southeast Pacific Ocean at a depth of 4,140-4,160 m. The experiment replicated the disturbance that would be caused by commercially mining manganese nodules by plough harrowing a circular area of the seabed measuring 10.8 km^2. The aim of the project was to monitor the recolonisation of benthic flora and fauna. The experiment area was sampled five times: before, immediately after the disturbance, after six months, three years and seven years. Even after seven years, the tracks made by the plough were still visible. Mobile animals began to repopulate the disturbed area soon after the damage was caused, but even after seven years the total number of taxa was still low when compared to pre-disturbance data (Bluhm, 2001).

JPI Oceans is running a project called Ecological Aspects of Deep-Sea Mining that revisited the DISCOL experiment area in 2015 after a 20-year hiatus. Preliminary results and observations note that the original plough marks are still visible and there has been only a low level of recolonisation, suggesting that disturbing nodules for commercial mining will cause long-term damage to the benthic ecosystem (JPI, 2016).

Nath *et al.* (2012) describe a disturbance experiment on a manganese nodule field in the Central Indian Basin. The team's aim was to quantify the impact of disturbing the seabed on the biogeochemical processes that regulate carbon. The team wanted to learn how large-scale commercial mining could affect an ocean ecosystem. After a 9-day benthic trawl to mimic manganese nodule mining, the team noted a 52% reduction in abundance of marine fauna, and the abundance of bacteria decreased by two to three orders of magnitude. The team also noted that the rate of organic carbon burial was reduced in some areas but had increased in others – the difference was because the sediment resettled in the direction of the prevailing ocean current. There was a reduction in organic carbon in deep sediment following the disturbance to the seabed. Organic carbon in sediment is an important food source for benthic organisms and the team noted a decrease in the quantity of nutritional organic carbon that benthic organisms consume. There was also a reduction in oxygenation of the bottom water. In summary, deep-sea mining has the potential to cause widespread disturbance to the carbon flux and to the organisms that inhabit the deep-sea ecosystem.

8.3.1 Shallow mining: Currently, diamond mining off the coast of Namibia uses either a hose attached to an ROV to collect shallow diamond-bearing gravels or a drill to reach deeper gravel deposits (De Beers, 2016). Another mining technique is dredging. Dredging is proposed for mining phosphates off the coast of Namibia and New Zealand (Chatham Rock Phosphate Ltd, 2016).

8.3.2 Deep-sea mining: Metals. Around 50% of the deep seabed is abyssal plain, superimposed on to the plains are features – all high in biodiversity – including submarine canyons, oceanic trenches, hydrothermal vents and underwater mountains called seamounts. Scientists have only researched a small proportion of the world's oceans and much remains to be discovered about the biodiversity associated with the deep seabed (Vanreusel *et al*., 2016), which highlights a vast knowledge gap.

Advances in technology are enabling scientific expeditions to explore more of the ocean floor. For example, the United States Oceans Observatories Initiative is undertaking a number of studies to help understand the geological and biological systems of the deep sea. The 10-year international research project Census of Marine Life, which operated from 2000 to 2010, identified 1,200 newly discovered and described species as well as aggregating existing records. The census confirmed that 250,000 marine species have been confirmed in the literature and estimated that there are some 750,000 more species yet to be described. It also remarked that, together with fisheries and hydrocarbons, minerals extraction has the greatest impact on marine life (Williams *et al*., 2011).

Mining the deep-sea for minerals (such as nickel, cobalt, copper, manganese and rare earths) would be extremely physically destructive to marine ecosystems. The process of mining involves machinery that causes extensive and indiscriminate disturbance to the sediment, flora and fauna. Sediment plumes, noise and light pollution could also affect the marine habitat (Glover & Smith, 2003; Van Dover, 2010; Van Dover, 2014; Nautilus Minerals, 2017). Scientists are not yet certain how movement of carbon in the deep sea and carbon sequestration would be affected by disturbances. In 2015, Hawkes *et al*. reported that hydrothermal vents are important for converting ancient sources of carbon into simpler forms that can be recycled and reused to form new organisms. Hydrothermal vents are found on oceanic ridges and are the site of seafloor massive sulphides, which are rich in copper, gold, zinc, lead, barium and silver (Hein, 2012).

The organic carbon 'rain' reaching the deep sea is estimated at 1-10g G m^{-2} yr^{-1} which comes from, for example, the remains of phytoplankton and whale carcasses (Glover & Smith, 2003). Many deep-sea habitats are characterised by slow sediment accumulation, absence of sunlight and low productivity. Higher productivity occurs in seabed features such as hydrothermal vents, seamounts and canyons. The inaccessibility and costs associated with research projects investigating the deep sea has limited scientific study in the region. At the moment scientists are still uncertain of the impact of climate change, ocean acidification and anthropogenic disturbance will have on the deep sea.

MIDAS (Managing Impacts of Deep-sea resource exploitation) is a multidisciplinary programme across 11 countries partly funded by the European Commission. Its three-year investigation was completed in October 2016. Its report noted that if the upper 10–20 cm of seabed is removed, total biological activity will also be removed, limiting any future recovery. Many species have extremely long life cycles and therefore there is no knowledge recovery period (MIDAS, 2016; Gjerde *et al.*, 2016b).

Levin *et al.* (2016) advocate adopting the precautionary principle with regard to seabed mining and other commercial activities that could have an adverse impact on the marine environment. The team state that further scientific research is needed because there are major knowledge gaps in understanding how mining activities will impact marine ecosystems.

The lack of scientific studies focused on the deep sea limits the ability to predict the environmental impacts of mining operations and to determine if habitats can recover from disturbance. Given the nature, scale and locations of proposed seabed mining activities serious and, in some cases, widespread negative impacts on habitats and marine life – and therefore carbon sequestration – can reasonably be expected.

8.3.3 Deep-sea mining: Gas hydrates

Gas hydrates have attracted attention because of their potential as a future energy resource (Lee & Holder, 2001). But exploiting this resource would release carbon that has been sequestered in the ocean for millennia.

Gas hydrates are ice-like solid crystalline structures that form when water molecules create a cage structure around a guest molecule such as a gas. Methane hydrate is the most common that occurs naturally.

Gas hydrates have been found at more than 40 locations around the globe. Formation of gas hydrates depends on a number of factors including: accumulation of particulate organic carbon at the seafloor; the microbial degradation of organic matter and its related generation of methane; and the thickness of the gas hydrate stability zone (Piñero *et al*., 2013; Malinverno & Martinez, 2015). Estimates of the global mass of marine methane hydrates varies: Piñero (2013) says in the region of 550 Gt C, but Kretschmer *et al.* (2015) is higher at 1,146 Gt C. See also section 9.5.5 of this report.

Methane hydrates are most commonly found at depths of 1,000-3,000 m; they do not usually form in water less than 600m deep because the water is too warm, but in the Arctic it is possible for them to form in shallow waters of around 250m, where water at the seabed is cooler (Buffett & Archer, 2004). Abyssal sediments are not thought to contain large quantities of hydrates because of the low amount of organic matter produced and the slow rate of sedimentation.

Chemosythetic life and higher order organisms have been found on seafloor hydrate mounds. Fisher *et al*. (2000) noted a previously undescribed species of polycheate worm or 'ice worm' (*Hesiocaeca methanicola*) that was able to burrow into sediment to reach the hydrate deposits. Chemosynthetic life is also found at hydrate deposits (Boetius & Suess, 2004). Such observations raise questions because mining at these sites could impact surrounding biota and the movement of carbon.

Potential problems associated with extracting methane hydrates include a rise in the temperature of the sea at the seabed level that could destabilise the hydrates, which could melt. Dissociation of the methane hydrates to form free methane could then result in the release of gas to the sea or to the atmosphere, which could affect ocean acidification and, therefore, the carbon cycle. Should methane reach the atmosphere, this could have consequences for global warming; methane has a global warming potential 25 times greater than carbon dioxide (Kretschmer *et al.*, 2015).

Research indicates that over the past two decades the increase in atmospheric methane, CH_4, has been greater than the increase in atmospheric CO_2. The increased amount of methane has been attributed to a number of factors including agriculture. The relevance of this is strong because CH_4 has a greater global warming potential than CO_2 (Saunois *et al.,* 2016a and 2016b).

9.0 Marine protected areas that include climate mitigation benefits

Chapter summary

1. Since 2000, marine spatial planning has included ecosystem services as a focus. The particular purpose of many recent MPAs is to increase resilience in the context of climate change.
2. Marine habitats that are declining at the greatest rate are those that deliver some of the most valuable ecosystem services, for example mangroves.
3. Whether MPAs include protection of both the water column and the seabed will depend on the national or regional framework by which they have been designated.
4. There are more than 14,600 MPAs representing 4.12% of the global ocean and 14.9 million km^2. The coverage of MPAs is increasing, though the focus is in the EEZs of Australia, New Zealand, United States, United Kingdom and Spain. Only 0.25% of MPAs are in areas beyond national jurisdiction. Estimates to quantify the area that would need protecting to achieve goals for biodiversity are varied. A review of 144 studies suggests that, on average, for effective marine conservation, MPAs would need to cover 37% of the ocean in total.
5. Protecting marine biodiversity requires network design, rather than a specific focus on the area of coverage. Establishing a network of MPAs to maximise conservation benefits in tandem with carbon sequestration has been recognised in the literature. These networks need to be ecologically coherent and based on the principles of adaptive management from the outset.
6. A coherent network of MPAs that has climate mitigation as a focus will need to protect both the sources of carbon and the areas where long-term sequestration occurs. Research is still needed into how to police MPAs effectively.
7. It is important to prioritise protection of blue carbon habitats over restoration. When coastal blue carbon ecosystems are removed, drained or degraded, this results in these systems both not acting as future sinks and in the release of carbon, some of which has been stored for millennia.
8. To maximise the climate mitigation benefits of the ocean, targets for protection will include preventing degradation of ecosystems throughout the water column and down to the seabed. Sustainable fisheries management and restoration of overexploited stocks could be important. It is also important to protect ecosystems and areas of the seabed that are known to be involved in carbon sequestration for millennia.
9. There are many knowledge gaps relating to our understanding of how to protect the climate mitigation potential of the ocean. To implement effective ocean-based climate mitigation strategies, the following are needed: carbon sequestration rates; current carbon stocks, including the stability and permanence of those stocks; geographic area; anthropogenic drivers of system loss leading to carbon emissions or removals; and emission rates from both degraded and intact states.

The use of protected areas as a core conservation strategy for marine species and habitats is more recent than for the terrestrial equivalent (Watson *et al.*, 2014). Most marine protected areas (MPAs) were historically designated with either a target species or habitat focus. Since 2000, there has been an increasingly diverse focus that includes ecosystem services, such as protecting fisheries for local communities (Fig. 10). There are also numerous examples in which marine spatial planning, and the use of marine protected areas, has been designed for the purpose of increasing ecosystem resilience in the context of climate change (for example McLeod *et al.*, 2009; Green *et al.* 2014; Mellin *et al.*, 2016).

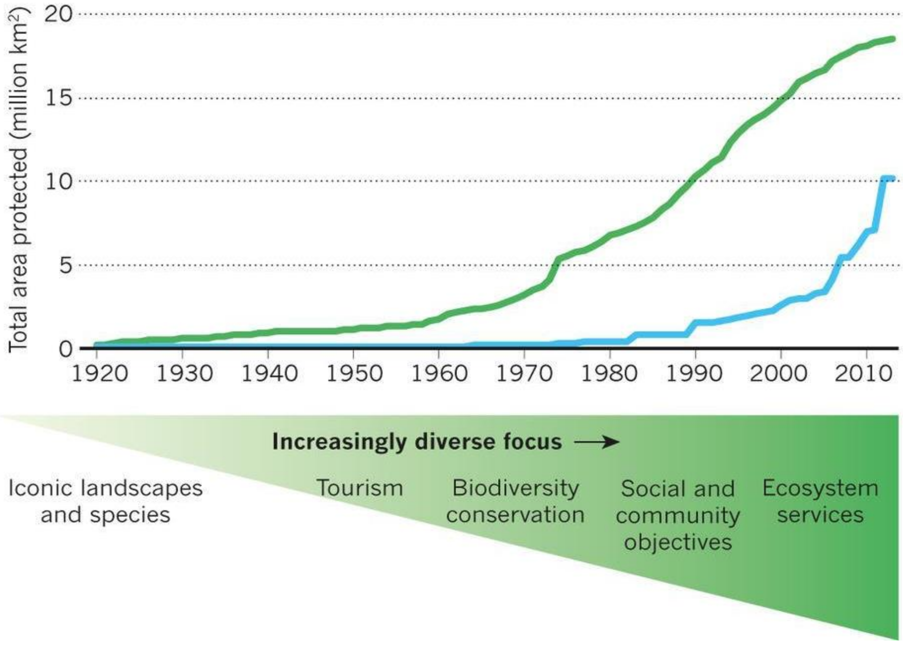

Figure 10. Marine protection lags behind terrestrial protection and, since 2000, has been driven by an increasingly diverse focus that includes ecosystem services. The green line denotes terrestrial protection and the blue line denotes marine protection. Source: adapted from Watson *et al.* (2014).

Only since the early 2000s has it become increasingly apparent that the marine habitats that are declining at the greatest rate are those that deliver some of the most valuable ecosystem services. This has stimulated protection of coastal blue carbon ecosystems (see the Greenpeace internal briefing on coastal blue carbon, Thompson & Miller, 2016) but protection is lacking in continental shelf and open ocean areas. However, there are examples in which regional seas conventions are assessing the climate mitigation value of MPAs that have already been designated within contracting party waters, for example, see Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR) Biodiversity Committee Agenda March 2017.

Whether MPAs include protection of both the water column and the seabed will depend on the national or regional framework by which they have been designated. For instance, OSPAR has designated a network of MPAs throughout high seas areas and within the extended continental shelf, that is, areas that are also under national jurisdiction. Some of the MPAs within this network include protection of the seabed and some do not. For example, the Charlie-Gibbs South High Seas MPA includes water column, seabed and subsoil protection whereas the seabed and subsoil within the Charlie-Gibbs North High Seas MPA remains unprotected (OSPAR, 2014).

9.1 The extent of ocean protection: current and future

There are more than 14,600 MPAs representing 4.12% of the global ocean and 14.9 million km^2 (UNEP-WCMC & IUCN, 2016). The coverage of MPAs is increasing, though the focus is in the EEZs of Australia, New Zealand, the United States, the United Kingdom and Spain. The establishment of MPAs by developed countries could be financial; Zarate-Barrera & Maldonado (2015) discuss the problems of securing funding in Colombia to help establish protected areas. The majority of MPAs are in the EEZs, with only 0.25% of MPAs in areas beyond national jurisdiction. Marine areas are classified into coastal and shelf areas (Spalding *et al.,* 2007) and surface pelagic water (Spalding *et al.,* 2012). These biogeographic regions are used to assist conservation with 12 realms, 62 provinces, and 232 ecoregions for coastal and shelf, and 4 broad oceanic realms with 37 pelagic provinces in the off-shelf waters, most of which is in ABNJ.

In 2015, the United Nations passed a resolution to develop a legally binding instrument on the conservation of marine biological diversity in the high seas in an attempt to increase the global area of protection. The Convention on Biological Diversity (CBD), Aichi Target 11, aims to protect 10% of the global oceans. However, studies suggest that such coverage will not be sufficient to protect biodiversity (O'Leary *et al*., 2016). Even with the announcement in November 2016 of the new marine protected area in Antarctica's Ross Sea, the total area of ocean subject to some degree of protection – which includes coastal and high seas regions – is still approximately 4% (O'Leary *et al.,* 2016; Schiermeier, 2016; UNEP-WCMC & IUCN, 2016; MPAtlas, 2017).

Estimates to quantify the area that would need protecting to achieve goals for biodiversity are varied. A review of 144 studies suggests that, on average, for effective marine conservation, MPAs would need to cover 37% of the ocean in total (O'Leary *et al*., 2016). This is not dissimilar from the 40% coverage recommended by Roberts *et al.* (2006) for the extent of a representative network of marine reserves capable of conferring the necessary level of protection for marine biodiversity. As our knowledge of deep-sea ecosystems advances we will be better informed to quantify the climate mitigation benefits of deep-sea ecosystems and identify regions to protect (Danovaro *et al.,* 2014a; Snelgrove *et al.,* 2014; Gjerde *et al*., 2016a).

Protecting appropriate areas of the marine environment will be the key to conserving biodiversity, because careful selection of regions that are high in biodiversity or are known carbon sinks can facilitate carbon sequestration. The IUCN operates a database of Key Biodiversity Areas (KBA), which it recognises as global areas (KBAs cover terrestrial and inland waters as well as marine areas) that "contribute significantly to the global persistence of biodiversity" (IUCN, 2016). Data can be requested by application on the website: www.keybiodiversityareas.org. The KBA process extends the work that other organisations have used to identify, for example, Important Bird Areas (IBAs, Birdlife International), Important Marine Mammal Areas (IMMAs, IUCN Taskforce) and the Ecologically and Biologically Significant Areas in the high seas (EBSAs, CBD).

The ISA, which issues permits for seabed mining in the high seas and elsewhere, is working on an environmental management strategy related to mining (ISA, 2017). However, there is concern that this strategy may not be comprehensive and one group of scientists suggests broadening the bodies involved with the UN setting up a deep-sea ecosystem monitoring network that would involve governments, as well as the ISA, that and could be operated under the UN umbrella with international funding (Danovaro *et al.,* 2017).

9.2 The design of MPA networks

The importance of establishing a network of MPAs to maximise conservation benefits in tandem with carbon sequestration has been recognised in the literature (Zarate-Barrera & Maldonado, 2015). With regard to policy, ecologically coherent networks of MPAs would need to be multi-focused and prioritise climate change mitigation as well as biodiversity conservation.

The design of MPAs should facilitate regular monitoring pertinent to carbon sequestration. Regional seas conventions that designate MPAs based on adaptive management principles, such as OSPAR, need to factor climate mitigation potential when reviewing and adjusting management plans (Fig. 11).

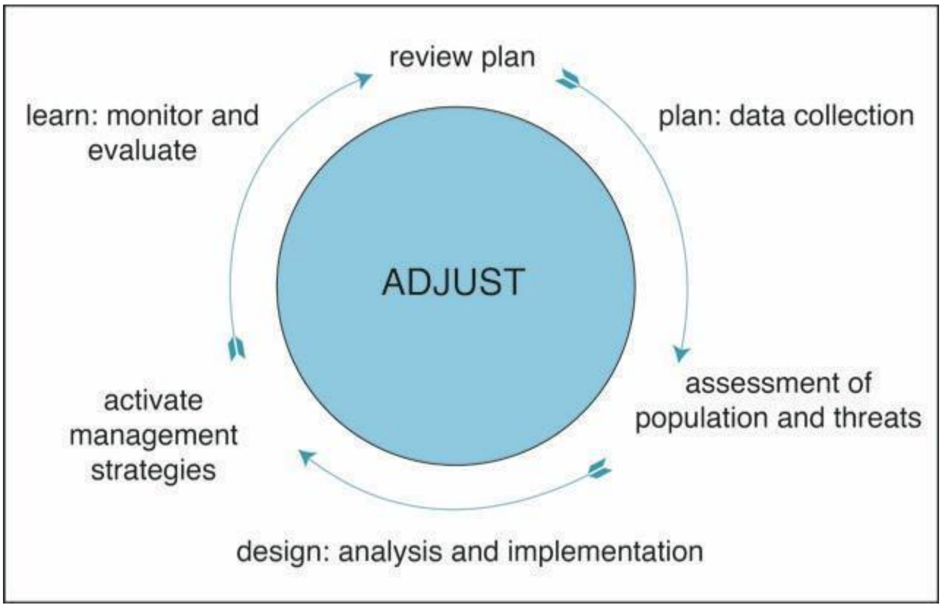

Figure 11. **A schematic for adaptive management process for marine protected areas.** Redrawn by authors, adapted from Fuentes *et al.* (2014).

The design of coastal marine protected areas needs to include input from local stakeholders, particularly those in which communities have sustainably managed ecosystems throughout history. Veirros *et al.* (2017) say that involving communities is more likely to result in adherence to the terms of the protection measures. Local communities have, over time, acquired tacit knowledge to manage blue carbon resources.

MPA network design. A successful MPA network will need to protect both carbon sources and carbon sinks. In the open ocean, carbon sources and sinks might be in separate locations. In addition, the sources and/or sinks might be dynamic, which means that they might move depending on the time of year or even as a result of climate change. So even if we know where such areas are now, we have no guarantee that they will be in the same location in the future. Therefore we will need to create dynamic conservation areas, although doing so will present huge challenges on logistical and legislative levels. Protecting marine biodiversity also requires specific design, rather than a specific focus on the area of coverage (Gjerde *et al.,* 2016a). Literature suggests that a network of interconnected MPAs that includes oceanographic features such as seamounts and important habitats for maintaining biodiversity such as spawning grounds are most effective in protecting biodiversity. The EBSA process has identified many of these areas in most of the ocean. There may also be advantages in conserving these areas specifically for carbon budgeting.

Research is still needed into how to police MPAs effectively. In designating an extensive and connected network of carefully researched MPAs, we can achieve the complementary goals of carbon sequestration and biodiversity protection.

9.3 Prioritise protection over restoration

First and foremost it is imperative to protect the sources of carbon if we are to be successful in maximising carbon sequestration in the future. This means protection of coastal ecosystems – such as mangrove, seagrasses and saltmarsh – and deep-sea ecosystems to prevent or at the very least mitigate damage. Coastal ecosystems are a key store of carbon both for the short term, in the living biomass, and long-term in the sediment. Another reason to protect is because not only is the restoration of marine coastal habitats 10 to 400 times more expensive than restoring terrestrial habitats, research suggests that restoration of coastal habitats has only limited success (Bayraktarov *et al*., 2016). An analysis of 52 published studies on seagrass restoration and found that only 38% of the projects were successful (Bayraktarov *et al*., 2016). For more detail and case studies to illustrate attempts of habitat restoration in coastal habitats, please see section 3.0 in Thompson & Miller, 2016.

When coastal blue carbon ecosystems are removed, drained or degraded, these systems stop acting as CO_2 sinks and instead *release* carbon, some of which has been stored for millennia. In other words, these vegetated coastal areas become net *producers* of CO_2 (Fig. 12). Even after restoration, the ecosystems do not recover their ability to store carbon as efficiently as before they were damaged (see chapter 3.0 in Thompson & Miller, 2016).

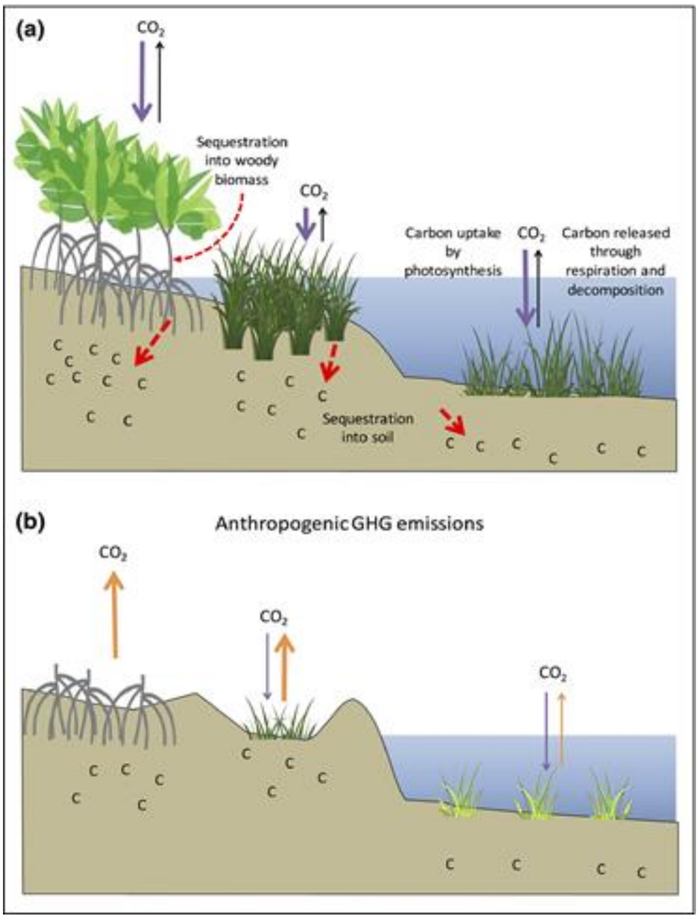

Figure 12. The consequences of damage to coastal ecosystems. CO_2 fluxes in intact and degraded, drained coastal blue carbon ecosystems (from left to right: mangroves, tidal marshes and seagrasses). Schematic (a) shows an intact wetland where carbon is taken up by photosynthesis (purple arrows) and sequestered long-term as biomass, into soil (red dashed arrows) or respired (black arrows). In schematic (b), soil is drained from degraded wetlands, the carbon stored in the soils is consumed by microorganisms, which respire and release CO_2 into the atmosphere as a metabolic waste product. This happens at an increased rate when the soils are drained because more oxygen is available, leading to higher CO_2 emissions. The degradation, drainage and conversion of coastal blue carbon ecosystems results in a reduction of the uptake of CO_2 and the release of globally important greenhouse gasses (orange arrows). Source: Howard *et al.* (2017).

Protection of marine ecosystems will need backing from national and international authorities in the form of policy. Scientists have recognised the value of marine ecosystems and need for effective conservation and management. To effectively inform policy, scientific data and findings must include evaluations of the ecosystem. In the light of widespread and global changes to ecosystems (terrestrial and marine) brought about by climate change and ocean acidification, the use of computer modelling data can help to predict those areas that may become important in the future for biodiversity conservation (Davies *et al.,* 2007; Queirós *et al.*, 2016).

9.4 Comprehensive protection of the ocean: from water to sediment

Marine protected area networks need to include protection and management that encompasses the whole ecosystem – vertically from the surface to the sediments. For protection within the water column, a variety of protection tools can be used including sustainable fisheries management and the prevention of pollution.

Fisheries management must include protection (and restoration) of existing fish stocks, for example, tuna and sharks, as well as those that may become future targets of exploitation. According to St. John *et al.* (2016), the organisms within the mesopelagic layer – fish, squid, snails and plankton – have already been identified as an unexploited resource by the European Union long-term blue growth strategy that focuses on "a long term strategy to support sustainable growth in the marine and maritime sectors as a whole. Seas and oceans are drivers for the European economy and have great potential for innovation and growth" (European Commission, 2017).

The organisms within the mesopelagic zone are key resources for marine mammals and predatory fish and are relatively understudied with high rates of new species discoveries. Robison (2009) suggests there may be in the region of one million undiscovered species within the deep pelagic layer. There may be significant benefits to harvesting such a large resource (recent but probably crude estimates suggest that there may be 10 billion tonnes of biomass) in terms of human food production, feedstock for terrestrial farming and aquaculture in addition to potential nutraceuticals, such as omega-3-fatty acids. However, the fact that this marine animal community is so vitally important in terms of vertical carbon cycling (moving carbon from the sea surface to deeper layers of the ocean) and as a prey resource for other species means that any exploitation could result in negative consequences for the wider marine ecosystem and the climate mitigation potential that it represents (St. John *et al.*, 2016).

Protecting specific species from commercial overexploitation may be prudent in protecting food webs, and therefore, carbon cycling. Antarctic krill (seven species dominated by *Euphausia superba*) and salps (mainly *Salpa thompsonii*) are highly important in the cycling of nutrients in the Southern Ocean. Both krill and salps are zooplankton and are major grazers of phytoplankton throughout their distribution. The estimated biomass of krill in the Southern Ocean is between 60-500 million tonnes depending on various methods of estimation (Nicol *et al.*, 2000; Siegel, 2005). The large population estimates of both these organisms – krill and salps – mean that they are key in moving carbon throughout the Southern Ocean ecosystem and a large temporary stock of carbon. The krill stock alone is estimated to contain approximately 3.5×10^{13} g C and this species is thought to sequestering 2.3×10^{13} g C annually (Kawaguchi and Nicol, 2014). In addition to being an important prey resource for many marine predators – marine mammals, birds and fish – they are also the target of commercial fisheries (Nicol *et al.*, 2012).

Krill are sensitive to changes in the environment, which results in large fluctuations in their populations. Fluctuations in various oceanographic conditions and the collapse of large whale populations that are known to cycle iron (a limiting nutrient for krill) are among some of the environmental conditions that have changed Southern Ocean krill abundance. Since 1926, long-term declines in krill abundance have corresponded in an increase in salps (their grazing competitor) (Atkinson *et al.*, 2004). A change in the balance of zooplankton may have implications for nutrient cycling throughout the Southern Ocean in addition to reducing the food available for higher trophic levels (salps are not a food source) (Alcaraz *et al.*, 2014).

Sustainable management of krill fisheries has been a focus of the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) and the working group on Ecosystem Monitoring and Management have used an ecosystem-based management framework to assess the implications of overfishing krill (Hill *et al*., 2006). Krill are also known to be sensitive to climate change and a lack of sustainable fisheries management may result in a diverse range of unexpected outcomes such as food web restructuring throughout the Southern Ocean and changes in nutrient cycling (Hill *et al.*, 2006; Kawaguchi *et al.*, 2013).

Protecting the organisms that are involved in the long-term sequestration of carbon at the seabed and the underlying substrate that is the location of carbon that has been stored for millennia is vital. Management of human activities should include the prevention of disturbance of sediment (see sections 8.2 and 8.3 of this report which discuss bottom trawling and seabed mining, respectively) as well as the prevention of extraction of methane hydrates (see section 8.3.3 specifically and the following section 9.5 of this report).

9.5 Protect areas in which carbon has been sequestrated for millennia

The ocean is the largest active carbon sink in the world, and absorbs in the region of 20-35% anthropogenic CO_2 (Howard *et al*., 2017). The value of terrestrial forests as a carbon store is well publicised in the scientific literature. Now the scientific community is acknowledging the value of coastal wetland ecosystems – in particular mangrove, seagrass and saltmarsh – as valuable long-term carbon sinks. An estimated 50-90% of all coastal wetlands carbon is stored in the soil (Howard *et al*., 2017). The organic carbon store in coastal systems is particularly stable because there are no fires underwater; most C stores in terrestrial forests are released during forest fires. By long-term, the literature means carbon that is locked away for millennia.

Coastal wetlands capture atmospheric carbon using photosynthesis and store it for the short term in the living biomass. The long-term carbon store is in the soil and sediment of the ecosystem. Evidence from the literature suggests that more carbon is stored in the soil and sediment of vegetated coastal systems than terrestrial systems. Per unit area, mangroves store, on average, more carbon (956 Mg C ha^{-1}) than salt marshes (593 Mg C ha^{-1}), seagrasses (142 Mg C ha^{-1}), peat swamps (408 Mg C ha^{-1}) and rainforests (241 Mg C ha^{-1}) (Alongi & Mukhopadhyay, 2015). Protection of these ecosystems needs to be such that it prevents the carbon stored within them from being released into the atmosphere or the ocean. Threats to vegetated coastal ecosystems include removal of indigenous species for replacement with oil palm plantations or aquaculture, timber harvesting, damming of rivers and sea-level rise.

Carbon sequestration in the ocean begins in seabed sediment. Over millions of years, microbial degradation of organic matter gives rise to gas hydrates, and carbon from decomposed plankton is mineralised to form oil.

9.5.1 Mangroves

On average globally, mangroves are being lost at a rate of 1–2% per year and much of the mangroves that remain are in a degraded condition. Over the past 50 years, 30–50% of mangrove forests have been lost; if destruction continues at the current rate then there could be no mangroves left by the turn of the next century. Destruction rates are highest in developing countries, which is where more than 90% of the mangrove forests grow. As the destruction of mangroves continues, so does the important capability of mangrove forests to act as both a carbon source and carbon sink (International Blue Carbon Initiative, 2016; Duke *et al*., 2007; Giri *et al*., 2010). This is significant because research suggests that mangrove habitats may play an essential part in mitigating the effects of anthropogenic CO_2 emissions.

9.5.2 Seagrass

Meadows of the Mediterranean seagrass *Posidonia oceanica* have been shown to store carbon for thousands of years in their soils, which have been found to be as much as 11 metres deep (Fourqurean *et al.,* 2012; Macreadie *et al*., 2014). Mangrove trees store carbon equally between the roots, leaves and wood but, in mangrove habitats, the majority of carbon is actually stored not in the living biomass but in the soil and in the dead, belowground roots (Alongi, 2014).

9.5.3 Saltmarsh

Tidal saltmarsh plants are found from sub-Arctic to tropical, with most extensive coverage in temperate regions. Saltmarsh plants take in CO_2 from the atmosphere (rather than sea). Unlike terrestrial soils, the sediments in which healthy salt marsh plants (in common with mangrove trees and seagrasses) grow do not become saturated with carbon over time as the sediments accrete vertically with a rising sea level. This means that the rate of carbon sequestration and the size of the sediment carbon sink can continue to increase with time (Chmura *et al*., 2003). Each molecule of CO_2 sequestered in tidal salt marsh soil (and also in mangrove, which replaces salt marsh in the subtropics) has a greater 'value' than any other ecosystem due to the lack of production of other greenhouse gases; this is because sulphates present in salt marshes reduce the activity of microbes that produce methane Weston *et al*. (2014).

9.5.4 Phytoplankton–oil reserves

Phytoplankton are primary producers that use photosynthesis to convert atmospheric CO_2 and nutrients in to sugar using light energy from the Sun – the process is outlined in section 6.2 of this report. Phytoplankton are a vital part of the trophic chain. The majority of phytoplankton are consumed by other marine organisms, but a very small fraction sink to the seafloor sediment where, over millions of years, they mineralise to form oil reserves. An estimated 0.1% of the organic carbon in phytoplankton sinks to the seafloor and is sequestered in the sediment. Scientists are uncertain how ocean acidification and the change in sea temperature could affect phytoplankton. The contribution made by phytoplankton to carbon sequestration is small and because of this these organisms are not included in policies to mitigate climate change (Falkowski, 2012; Howard *et al*., 2017). However, it is essential that phytoplankton continue to flourish in the oceans because they form a key part of the food web. Some scientists are advocating a whole-ecosystem approach to conservation rather than focusing on one or two species in an effort to mitigate the impact of climate change; ensuring that the organisms at the lower end of the food chain, such as plankton, are protected will secure food reserves for organisms further up the trophic levels and could help organisms cope with adaptations to changing environmental conditions (Queiros *et al.,* 2016).

9.5.5 Gas hydrates

Gas hydrates are ice-like solid crystalline structures that form when water molecules create a cage structure around a guest molecule such as a gas. The addition of a light natural gas molecule – such as methane, ethane, propane or butane – stabilises the hydrate and in turn produces a gas hydrate, of which methane is the most common that occurs naturally.

Gas hydrates have been found at more than 40 locations around the globe. Gas hydrates are found in polar permafrost and in marine shelf sediments in areas that have a particular range of high pressure and low temperature; continental shelf margins contain 95% of all methane hydrate deposits in the world (Demirbas, 2010). Estimates of the global mass of marine methane hydrates varies: Piñero (2013) says in the region of 550 Gt C, but Kretschmer *et al.* (2015) is higher at 1,146 Gt C. See also section 8.3.3 of this report.

9.6 Knowledge gaps and areas for future research

- **Carbon sources and sinks.** Scientists know there are carbon deposition areas in the ocean, such as coastal macrophyte ecosystems, but they also need to understand the links between the carbon sources and their associated sinks. Scientists have modelled the contribution made by vegetated coastal habitats to the carbon cycle but different research groups have produced vastly different results. Scientists have not been able to accurately quantify the global area covered by vegetated coastal habitats (that is, the area collectively covered by mangrove, saltmarsh and seagrasses). Duarte (2017) reviewed estimates of the contribution to carbon sequestration made by vegetated coastal habitats to coastal and deep-sea sediment. Duarte found that the sequestration rate varied from 73 to 866 Tg C yr^{-1}. The uncertainty in the estimates highlights how difficult it is to make a clear scientific assessment of the part played by the ocean in the global carbon budget.

- **Spatial and temporal differences in net carbon sequestration rates.** Research suggests that there can be temporal differences in whether an area is a net sink or a net source of carbon. A particular area of the seabed can be a carbon sink or a carbon source depending upon the time of the year. Long-term and more frequent sampling is necessary to help scientists understand the processes.

- **More information is needed on the regional carbon-cycling processes in the ocean.** For example, what are the links between areas such as the continental shelf, the deep ocean and regional seas.

- **Scientists are currently investigating the role that large vertebrates have in the sequestration and cycling of carbon in the marine environment.** The process, including moving carbon from one area to another and through food webs, is poorly understood.

- **Climate change.** Scientists don't yet fully understand the impact of climate change on carbon sequestration in the ocean. Literature is emerging on how climate change is impacting on biological and physical systems in the ocean, but how this will affect carbon sequestration rates is unknown.

- **To implement effective ocean-based climate mitigation strategies, the following are needed:** carbon sequestration rate; current carbon stocks, including the stability and permanence of those stocks; geographic area; anthropogenic drivers of system loss leading to carbon emissions or removals; and emission rates from both degraded and intact states (Howard *et al.,* 2017).

- Research on how to sustainably manage coastal areas is limited in certain areas of the world, particularly in areas of Africa, Asia and sub-regions of the Pacific.

- There are major knowledge gaps in understanding how deep-sea mining activities will impact marine ecosystems and carbon sequestration.

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