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Blue Carbon in Marine Protected Areas – Progress Review

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Summary

This report provides a global review of progress in the development of the evidence base relating to the occurrence and recognition of blue carbon habitats and species in Marine Protected Areas (MPAs). The report introduces what blue carbon is and the importance of the sequestration and long-term storage processes of both organic and inorganic carbon for climate change mitigation. The report advocates the broadest possible interpretation of blue carbon and includes not only the most widely recognised blue carbon habitats – mangroves, salt marsh and seagrass meadows – but also other important marine and coastal carbon standing crops, pools and sinks, such as kelp forests, maerl beds, coral reefs, biogenic reefs and seabed sediments. Details of how blue carbon habitats can also become carbon sources if damaged by human activities is discussed and the importance of implementing the correct management measures to halt the decline in their condition and restore them by using high and full levels of protection under MPAs. The first half of the report introduces blue carbon ecosystems and provides essential background information on the importance of blue carbon in the consideration for inclusion in MPAs, prior to detailing existing policy frameworks and detailing suggested improvements to management.

Currently, the main focus of international MPA policy has been the protection, recovery and restoration of biodiversity, and in order to consider the specific inclusion of blue carbon habitats in the identification of existing and future MPA designations, changes to and a strengthening of current policies will be required. There are key international and regional policy frameworks in place which are vital for effective global MPA implementation, however, the linkages between blue carbon and biodiversity must be explored further and the results used to inform global political action to safeguard these important ecosystems from the impacts of climate change and damaging human activities. There are further actions which this report details for countries to complete, to integrate blue carbon services into MPAs. These include identifying the full range of blue carbon habitats within MPAs and incorporating them into existing or new MPAs by undertaking further research to identify blue carbon sources, assess the impacts of anthropogenic activities and detail the transfer of carbon to and from these ecosystems. Other measures include the restoration of degraded blue carbon habitats and implementation of effective protective management measures to aid this recovery. This report reviews the current process and policy frameworks to determine the way forward and provides compelling reasons to protect the resilience of blue carbon habitats by highlighting the need for their integration into MPA networks.

Contents

1 Introduction

"You cannot solve the climate crisis without addressing the problems of the ocean and you cannot solve the problems of the ocean without solving the crisis of climate."

H.E. Mr John Kerry, Special Presidential envoy for climate, USA. Monaco, March 2022.

The International Partnership on MPAs, Biodiversity and Climate Change is an alliance of government agencies and organisations from across the world, working together to document and share the evidence base for the role of Marine Protected Areas (MPAs) and biodiversity in addressing climate change. Their vision is to support global decision makers in the implementation of MPA networks as nature-based solutions for biodiversity conservation and climate change mitigation, adaptation, and resilience. On behalf of the International Partnership, the Joint Nature Conservation Committee (JNCC) commissioned this report to undertake an independent high level strategic global review of progress to date on advancing the evidence base of blue carbon ecosystems and their protection in MPAs.

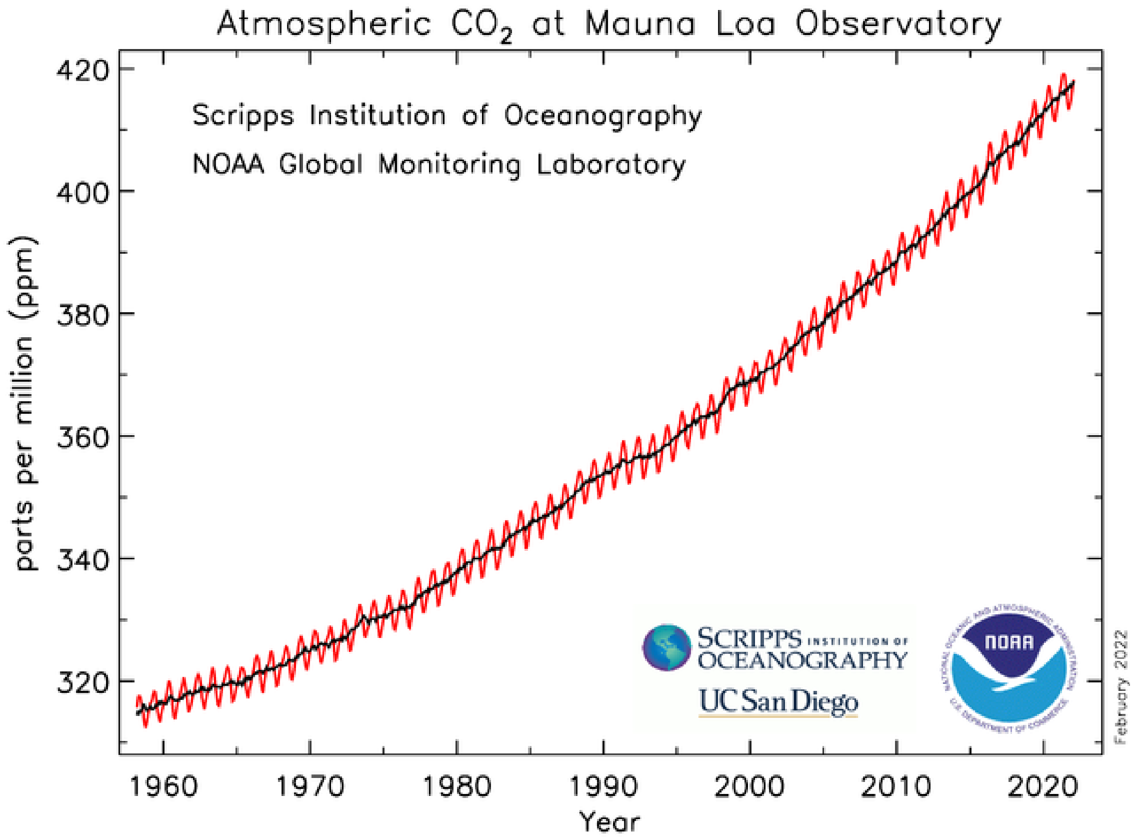

Figure 1. Sustained rises recorded in atmospheric concentrations of carbon dioxide at Mauna Loa Observatory in Hawaii. Note no discernible pause is visible due to the impacts of the COVID pandemic on trade and industry (Image provided by NOAA Global Monitoring Laboratory, Boulder, Colorado, USA, NOAA research on rise of carbon dioxide)).

The purpose of this report is to recognise and highlight the full value (not simply in monetary terms or Nationally Determined Contributions (NDCs)) of blue carbon ecosystems, but to also investigate the issues, opportunities and challenges associated with expanding the application of blue carbon, using experience and information drawn from around the world. This report accordingly focuses on the links between the ocean, MPAs, climate change and ecosystem restoration. Understanding these connections is vital if effective interconnected MPA networks are to be put in place in ways that help mitigate climate change, conserve, and actively restore biodiversity, and thereby over time increase ecosystem resilience. There is a pressing need for such action because despite renewed efforts by governments globally there is still a lack of sufficient ambition and urgency to put climatic and natural processes back in balance, countering the, at present, overwhelming anthropogenic pressures human population growth and consumption are placing on the Earth system.

The recent Intergovernmental Panel on Climate Change report (IPCC 2022) highlights that climate change has caused substantial damages, and increasingly irreversible losses, in terrestrial, freshwater and coastal and open ocean marine ecosystems, with the extent and magnitude of impacts now larger than estimated in previous assessments, causing widespread deterioration of ecosystem structure and function, resilience and natural adaptive capacity, with adverse socio-economic consequences. Despite all efforts, and even with the 2021 global economic shutdown caused by the COVID pandemic, greenhouse gas concentrations in the atmosphere have continued to rise unabated, accompanied by continual decline in global biodiversity on land, freshwater and in the ocean.

What is now alarming some atmospheric scientists is not just the continual rise in carbon dioxide (Figure 1) but the apparent upturn in methane emissions (Figure 2), a greenhouse gas which is 25 times more potent than carbon dioxide. The upturn in methane emissions started in 2007 and may be due to positive feedback loops now taking hold in the warming of the Earth. As the climate warms, more methane is released, which in turn causes more climatic warming. The recent unprecedented record warm temperatures recorded at both poles of at least 30°C above normal in March 2022 do nothing to allay such fears.

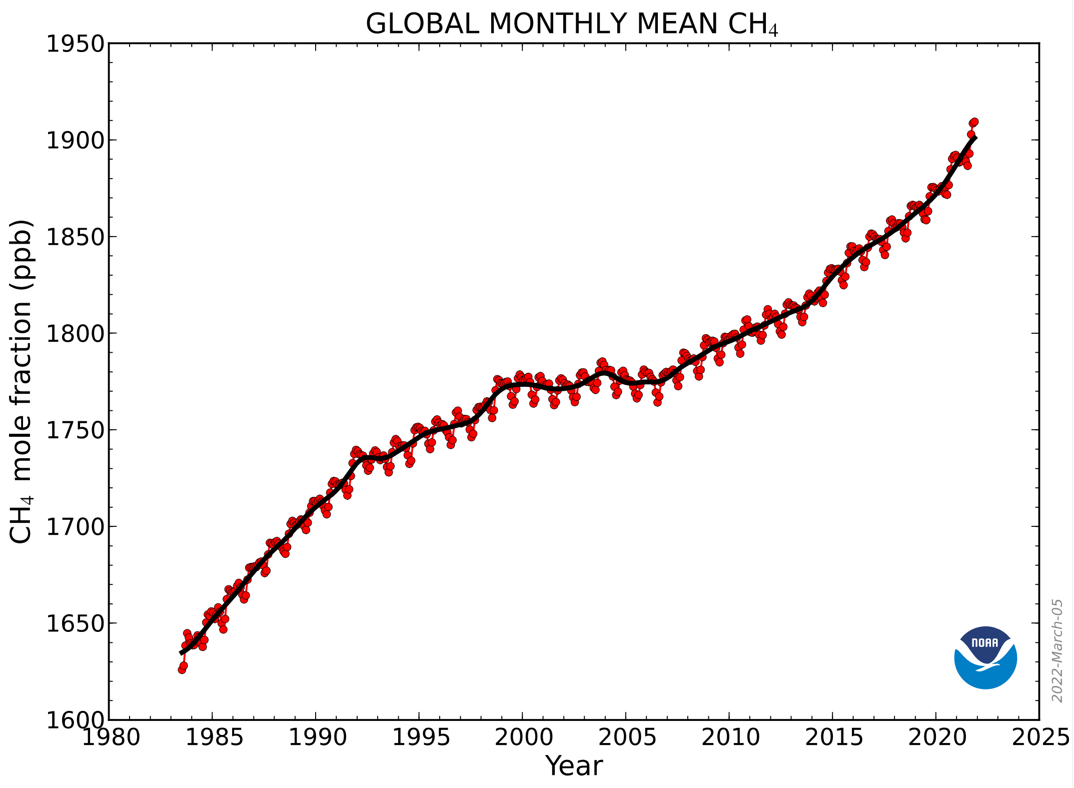

Figure 2. Rising levels of the powerful greenhouse gas methane appear to have accelerated since 2007, perhaps due to positive feedback loops now kicking in due to the degree of warming already being experienced. (Image provided by Ed Dlugokencky, NOAA Global Monitoring Laboratory, Boulder, Colorado, USA (https://www.esrl.noaa.gov/gmd/ccgg/trends_ch4/).

The ocean lies at the heart of any solution to these problems. It is the major global regulatory system, keeping conditions just right for life, and is key to future climate actions, absorbing significant amounts of the excess atmospheric carbon dioxide and heat generated by human activities (IPCC 2019). The rate, for example, at which dead plankton draw carbon to the deep ocean and permanently store it in seabed sediments, is equivalent to a significant proportion of human carbon dioxide emissions and it is likely to increase in the future (Sutherland *et al.* 2022). Through this and other processes, the ocean is shielding us from

more severe climatic change. However, as the ocean takes the brunt of climate change it is now rapidly warming – breaking overall heat records year on year, tending towards more acidic conditions, and experiencing regionally widespread reductions in oxygen levels. Significant changes across the global ocean are now being observed, exacerbated by regional variance and local conditions. Similar changes to the ocean are thought to have accompanied each of the last five major extinction events in Earth's history (Barnosky *et al*. 2011).

Alongside this continuing bleak outlook, countries are beginning to recognise the importance of protecting the ocean and the ecosystem services it provides. In recent decades, the Convention on Biological Diversity (CBD) has recognised the need to protect ocean ecosystems through Marine Protected Areas (MPAs), and more recently also through Other Effective Area-based Conservation Measures (OECMs). Significant global actions, such as the creation of UNESCO's (United Nations Educational, Scientific and Cultural Organization) marine World Heritage Programme has driven improved management of many large key sites, and the United Nations Climate Change Convention (UNFCCC) and the Paris Agreement have given visibility to ocean issues. At COP26, the Glasgow Climate Pact 2021 built on the outcomes of the first ocean and climate change dialogue held in 2020 and governments permanently anchored the inclusion of strengthened ocean-based action under the UNFCCC multilateral process, including through a recurring annual ocean-climate dialogue.

Through this increased awareness, decision makers now have an opportunity to use all available agreed policy routes and through ongoing international negotiations on climate and biodiversity to keep carbon in natural systems in the way nature intended, and in so doing and with sufficient ambition, significantly restore lost ecosystem resilience and functionality. An important part of achieving these goals is to ensure widespread understanding of the evidence base, state of action, and implementation of management measures to prevent damaging activities taking place in MPAs and OECMs to best secure the combined biodiversity protection, restoration and recovery, and climate change mitigation opportunities provided by these areas.

2 What is blue carbon? The scope and definition of marine and coastal carbon sinks

Just as on land, many coastal and marine ecosystems trap and store appreciable amounts of carbon, locking it away for anything from decades to many thousands of years. Blue carbon is the name coined by experts to the UNFCCC to describe some of this trapped carbon held in marine and coastal ecosystems.

The origin of studies combining biodiversity protection and carbon stocks and sink management in MPAs can be traced back the early 2000s (Laffoley & Grimsditch 2009; Nellemann *et al*. 2009), when seagrass meadows, salt marshes and mangrove forests were identified as being particularly effective at storing carbon on a per area basis (Figure 3). These studies were particularly important because they drew attention to the critical role of coastal and marine ecosystems in the carbon cycle, comparable to studies for long-recognised land systems such as forests and peatlands.

Evidence showed that despite these coastal and marine ecosystems occupying smaller areas relative to tropical forests on land, the density and quality of carbon stored meant that they warranted attention from policy makers and better protection and management at national scales. Although the combined global area of the three widely recognised blue carbon ecosystems – mangroves, salt marshes and seagrass meadows – equates to only 2 –6% by area when compared to the area of tropical forest (Herr *et al*., 2017), their degradation accounts for up to 19% of carbon emissions from global deforestation (Pendleton *et al*., 2012), so they are disproportionately important. This highlights the critical importance of actions to protect and restore these ecosystems for carbon storage.

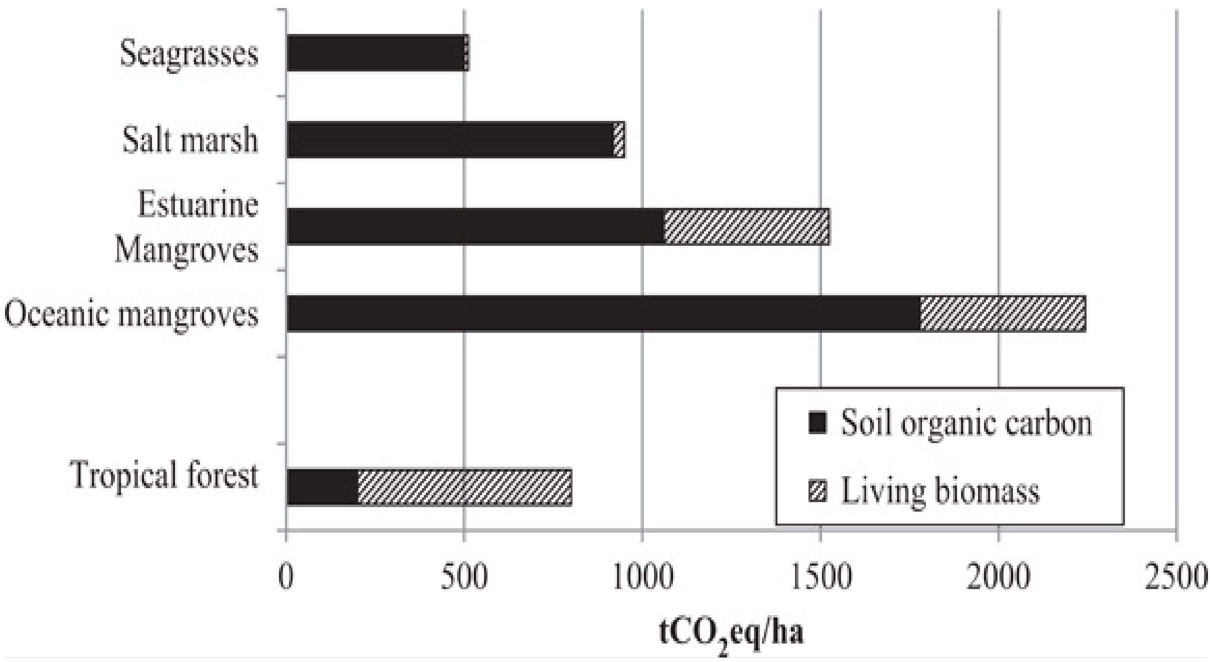

Figure 3. The global average values (top metre only) for soil organic carbon and living biomass carbon pools of mangroves, salt marshes, and seagrass meadows, compared to tropical forests (measured by carbon dioxide equivalents on a per hectare basis). (Image from Pendleton *et al*., 2014).

A growing array of international efforts since this evidence emerged have been directed at recognising this stored carbon in these three ecosystem types and taking measures to integrate it into carbon action through the policy routes offered under the UNFCCC (see for example IPCC 2014).

While the carbon benefits of salt marshes, seagrasses and mangroves are best understood and documented, there is a much wider array of actions needed to secure the carbon stored in marine systems. The primary one is recognition and acceptance of the much greater range of coastal and marine ecosystems that contain significant stores of carbon. Such ecosystems equally warrant recognition and protection, though their contributions may not yet be sufficiently quantified at this time to allow for inclusion in national greenhouse gas inventories (Table 1), so other routes such as that offered by the CBD need to be urgently utilised. Alongside such ecosystems, consideration must also embrace the biological (e.g. marine vertebrate carbon, zooplankton/phytoplankton carbon export, etc.) and other routes by which carbon is moved into such sinks.

Table 1. Examples of marine and coastal ecosystems and habitats that are or can be rich in organic and inorganic carbon – some depending on location and conditions (derived from Burrows *et al*., 2017).

Biological ecosystems	**Geological habitats**
Mangroves	Rock
Kelp (Temperate)	Gravel
Kelp (Deep water tropical)	Gravel/mud
Intertidal macroalgae	Gravel/sand
Subcanopy algae	Sand
Maerl beds	Sand/mud
Seagrass	Sand/mud/gravel
Saltmarshes	Mud
Horse mussel beds (*Modiolus modiolus*)	Enclosed inlet mud (e.g. Fjords)
Flame shell beds (*Limaria hians*)	Submerged marine peat
Cold water coral reefs (*Lophelia pertusa*)	
Tubeworm reefs (*Serpula vermicularis*)	
Brittlestar beds	
Blue mussel beds (*Mytilus edulis*)	
Sandworm reefs (*Sabellaria* spp.)	

Many other coastal and marine ecosystems contain similarly vast stores of carbon compared to mangroves, seagrass, and saltmarsh, in terms of both organic and inorganic stocks. In this report 'blue carbon' is used in the widest possible sense and it includes all those marine habitats and those species that form biogenic reefs that sequester and/or store carbon. Sediments in deep water for example if undisturbed can store carbon for thousands of years or more. Some sediment types in some regions of the world also overlie vast stores of submerged peatlands - relics from previous geological time periods when sea levels were lower (e.g. see Historic England's Intertidal and Coast Peat Database).

It is therefore important that the broadest array of coastal and marine ecosystems rich in stored carbon are considered by policy advisers, decision makers, and the wider community of experts and practitioners responsible for designating and managing MPAs and other OECMs so that responsible climate-related biodiversity management actions can be taken through all available policy routes.

3 The relationship between and importance of organic and inorganic marine carbon stocks and stores

In designing management actions to support marine biodiversity and carbon services, it is important to understand the main forms of carbon found in marine ecosystems that are relevant to carbon services. Carbon occurs in benthic, coastal, and marine ecosystems in two basic forms – organic carbon (OC) which is the main building block of all living tissue, and inorganic carbon (IC), which largely takes the form of calcium carbonate found in the shells and skeletons of animals and plants.

There is an important distinction to be made between carbon stocks and carbon stores. Organic carbon stocks comprise the living fauna and flora which are in continual flux through various processes such as growth, grazing, predation, death, and decay. Such stocks can fluctuate considerably over varying timescales for example the seasonal growth and subsequent die-back in species such as seagrass and saltmarsh flora. In other cases, long-term trends in abundance, such as the almost 90% decline in the bull kelp forests along the coastline of north-central California that prior to the decline, are estimated to have contributed around 600 Mt/yr of organic carbon to long-term storage, result in lasting changes to carbon storage potential (see the Blue Carbon in Marine Protected Areas case study: Greater Fallarones National Marine Sanctuary Kelp Recovery Program).

In contrast to organic carbon, inorganic carbon stocks in the form of calcium carbonate comprise the skeletal material of a range of organisms. The shells and skeletons of phytoplankton and encrusting and free-living calcareous algae, such as maerl, the spicules and spines on organisms such as bryozoans and echinoderms, and the shells of molluscs and bones of marine mammals are all examples of inorganic marine carbon. The creation of inorganic carbon by living organisms in the form of spicules, spines and shells has a carbon cost associated with it, as living organisms produce carbon dioxide as a part of their metabolism. However, where large deposits of inorganic carbon are laid down in deposits over thousands of years from past biological activity the carbon dioxide 'cost' has already been paid in past climatic conditions. The issue then becomes whether and how the carbon in such deposits could be released back into the climate system due to anthropogenic disruption of natural sinks coupled with climate impacts driving remineralisation (Chen *et al*. 2022).

Our understanding of the rate of flux in recycling the carbon trapped through photosynthesis and its subsequent remineralisation or long-term storage is still in its infancy but as organic matter becomes buried ever deeper in sediments it is increasingly unavailable for remineralisation. The inorganic carbon stored as calcium carbonate is more inert but in places is becoming increasingly susceptible to remineralisation due to ocean acidification whilst ocean warming may result in increased growth rates. It remains unclear whether the combination of ocean acidification and ocean warming will ultimately increase or decrease calcification rates (Pinsonneault *et al*. 2012).

The quantities of OC and IC stored in the marine environment are significant. Within the UK Economic Exclusion Zone (EEZ), for example, Smeaton *et al*. (2021) estimated that the top 10 cm of seabed sediments contain 524 ± 68 Mt of OC and 2,582 ± 168 Mt of IC. Globally, seabed sediments are estimated to contain 3,117,000 Mt OC within the top 1 m, but no equivalent estimate for IC exists (Atwood *et al*. 2020). Much of this stored carbon has been accumulating over millennia and represents a considerable store which needs to be protected.

Many of the habitats that contain these carbon stores are also features within MPAs. For example, maerl beds are not only important for their biodiversity value, but also contain large amounts of carbon (both OC and IC). One such bed in an MPA in Orkney, Scotland was found to contain dead maerl around 4,000 years old (MacPherson *et al*. 2017).

Given the uncertainties over the consequences of climate change and ocean acidification on the marine environment it is important to act now to protect and enhance the organic and inorganic stocks and stores contained within the various marine habitats. The various biogenic reef habitats not only help in the capture of carbon but also act as a living cap protecting the underlying sediments where carbon-rich detritus can accumulate undisturbed.

4 Interrelationship between blue carbon ecosystems and other ecosystem types

Carbon stored in mangroves or in ecosystems such as kelp forests or muds does not exist in isolation – all these systems are interconnected with flows of carbon between them. It is important to understand the interrelationship between carbon-rich coastal and marine ecosystems and other ecosystem types (both 'upstream' on land and in catchments, and also 'downstream' in the sea that trap carbon produced and released in ecosystem located elsewhere) if effective protection and management measures are to be devised for marine biodiversity. This is critical to ensure that the carbon they store is retained long-term in these natural systems as nature intended, and that the natural processes that sequestrate it are not disrupted, changed or destroyed by anthropogenic impacts. Understanding the linkages of such carbon flows and stores is critical and much more complex than simply 'drawing lines' around the extent of particularly important ecosystems.

For example, the three 'traditional' blue carbon habitats (mangroves, seagrass meadows and saltmarsh), which are all important in their own rights for their carbon sequestration and storage potential, are also recipients of considerable amounts of allochthonous (i.e. derived from elsewhere) carbon. This carbon is derived from a range of other habitats located elsewhere, including both terrigenous and marine sources, which becomes entrained and buried in the underlying sediments of the recipient habitats.

Certain biogenic habitats, such as, horse mussel beds, maerl beds and oyster reefs, contain a surface living veneer overlying relic habitat that can be several metres thick. Within these biogenic habitats there are considerable deposits of both OC and IC. The IC is largely autochthonous (i.e. derived from where it was formed), mainly comprising the dead shell and skeletal material of the various reef forming organisms. In contrast, a large proportion of the OC is allochthonous, comprising terrigenous material transported by freshwater run-off or leaf fall, or from other marine sources such as cast macroalgal fragments. While the OC in this organic material was not directly drawn out of the atmosphere by these habitats, except in the case of maerl beds, it becomes entrained within the surface layers of the biogenic reef where it remains undisturbed and is eventually buried. For example, under experimental conditions it was shown that there was enhanced sedimentation and OC deposition rates in the presence of live oysters compared to dead oyster shells or bare sediment (Lee *et al*. 2020), making them important reservoirs of blue carbon. This highlights the importance of the need for the protection of the living crust that makes up these various biogenic habitats to not only enhance carbon deposition and storage rates but also ensure their long-term persistence.

There remain considerable gaps in knowledge as to the sources and scale of various allochthonous OC sources to the marine sedimentary areas. These sources are not only marine in origin but also include significant terrigenous sources, especially in the coastal areas. As yet, there is very little information to allow accurate measurement of the scale of such contributions but with the development of eDNA and isotopic analyses it is becoming possible to obtain a better understanding of the breadth of the interconnectedness of the marine and terrestrial environments.

Extensive kelp forests in the shallow subtidal and intertidal seaweed beds sequester substantial amounts of carbon. For example, the area of Scottish coastal waters that are estimated to have greater than 20% coverage with kelp (i.e. kelp forest) is 2,155 km^2 which is equivalent to an annual production of 1.73 Mt C/yr (Burrows *et al*. 2014). The proportion of this annual production that is ultimately incorporated into long-term stores is unknown. However, using eDNA techniques, O'Dell (2022) has shown that macroalgal detritus can make an important contribution to the carbon stores in sediments of Scottish sea lochs and the wider north-east Atlantic, some considerable distance from the source of the material.

At a global level, Krause-Jensen and Duarte (2016) estimate about 170 Mt C/yr of macroalgal detritus is stored in seabed sediments (10% in coastal sediments and 90% in deep-sea sediments). This exceeds quantities of carbon sequestered in mangroves and saltmarsh. This macroalgal carbon is not stored in the macroalgal-dominated habitats, which are predominantly rocky, but in adjacent and distant sediment habitats. This reinforces the importance of taking the broadest possible view when seeking to protect the processes involved in carbon sequestration and long-term storage due to the connectivity and synergy of key carbon storing habitats.

5 Marine and coastal carbon sinks as just one aspect of multiple ecosystem services

Whilst carbon values are critical to engaging the wider community and fostering action under the UNFCCC, as is explained in previous sections such carbon services only constitute a part of the wider array of important ecosystem services provided by carbon-rich coastal and marine ecosystems. There is a need for focused science to ensure uptake of carbon mitigation opportunities under the UNFCCC. However, whilst the UNFCCC is an important lever to progress mitigation efforts using blue carbon habitats, it is important to consider other opportunities to deliver these benefits. This is especially critical for many other widespread ecosystems that are not included under IPCC definitions, but which also warrant protection due to the appreciable amounts of carbon they contain.

It is important to maintain a balanced view and act through all available policy routes. A 2013 scientific assessment for example states that mangroves, saltmarshes and seagrass meadows remain the key actionable coastal and marine ecosystems under the UNFCCC process (Table 2). This particular mitigation-focused analysis groups other coastal and marine ecosystems into ‘emerging blue carbon ecosystems’ and ‘other ocean ecosystems not actionable’ (Lovelock & Duarte 2019).

Given recent knowledge about carbon and the sequestration importance offered by many other coastal and marine ecosystems, such analysis is in urgent need of updating, to show routes to action from, not just UNFCCC opportunities, but also those offered by the CBD and other policy imperatives and initiatives. There are clear dangers of over promoting the UNFCCC mitigation angle in the absence of acting on other important policy routes. Such analyses can be misleading to policy advisers and decision makers as it does not embrace the carbon importance of other ecosystems, or the supporting role ‘not actionable’ ecosystems provide for key mitigation processes. For example, coral reefs are defined by the authors as ‘not actionable’ for mitigation, but mitigation for mangroves and seagrasses in many areas will only be successful if coral reefs are also the focus of action to protect and restore them. If coral reefs are lost, then the wave barrier such reefs form protecting the ‘actionable blue carbon ecosystems will fail, and those blue carbon ecosystems will be lost. Similarly, if the extensive offshore kelp beds are lost, then saltmarsh areas become much more vulnerable to erosion caused by increased wave action (Laffoley 2020).

A much broader action agenda is essential to support mitigation measures under the UNFCCC, which is constrained by strict reporting requirements, accompanied by a far greater appreciation of ecosystem services. Such an integrated perspective is the key to acting through all relevant policy routes to secure protection and restoration of coastal and marine biodiversity and its carbon services.

Table 2. An example of the analysis underlying the focus of mitigation action under the UNFCCC on mangroves, seagrass meadows and salt marshes (after Lovelock & Duarte 2019)

		Scale of GHG removals or emissions are significant	**Long term storage of fixed CO_2**	**Anthropogenic impacts of the ecosystem are leading to C emissions**	**Management is practical/possible to maintain/ enhance C stocks and reduce GHG emissions**	**Included in IPCC GHG accounting guidelines**	**Climate Adaptation Value**
Actionable Blue Carbon Ecosystems for Mitigation	Mangrove	YES	YES	YES	YES	YES	YES
	Tidal marsh	YES	YES	YES	YES	YES	YES
	Seagrass	YES	YES	YES	YES	YES	YES
Emerging Blue Carbon Ecosystems	Macroalgae	YES	YES	YES	YES	NO	YES
	Benthic sediments	?	YES	YES	?	NO	?
	Mud flats	?	?	YES	?	NO	YES
Other Ocean Ecosystems (Not Actionable)	Coral reef	NO	NO	NO	NO	NO	YES
	Oyster reefs	NO	NO	NO	NO	NO	YES
	Phytoplankton	YES	?	?	NO	NO	NO
	Marine fauna (fish)	NO	NO	YES	NO	NO	YES

Taking mangroves, and seagrass meadows as examples, the evidence shows that regulation of greenhouse gases through carbon sequestration is only one of many important services provided by them, and not the most important in all the analyses examined (Figures 4 & 5).

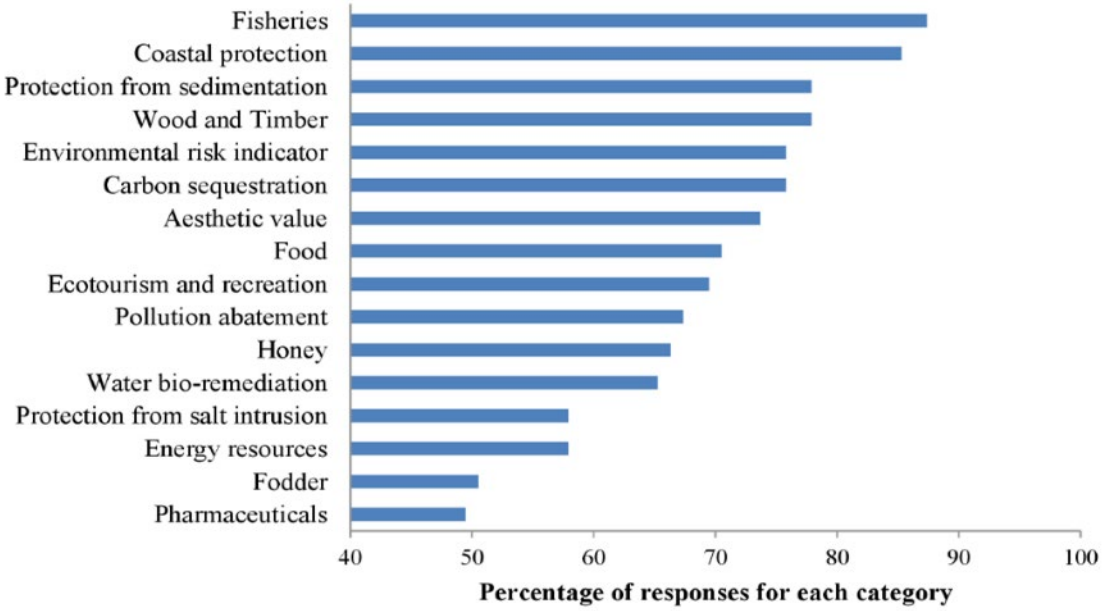

Figure 4. Ranked ecosystem services categories of mangroves based on a score given by 106 experts (scientists, reserve managers and field-based conservationists) in the Delphi technique (Image from Mukherjee *et al*. 2014; © 2014 The PLoS ONE Staff).

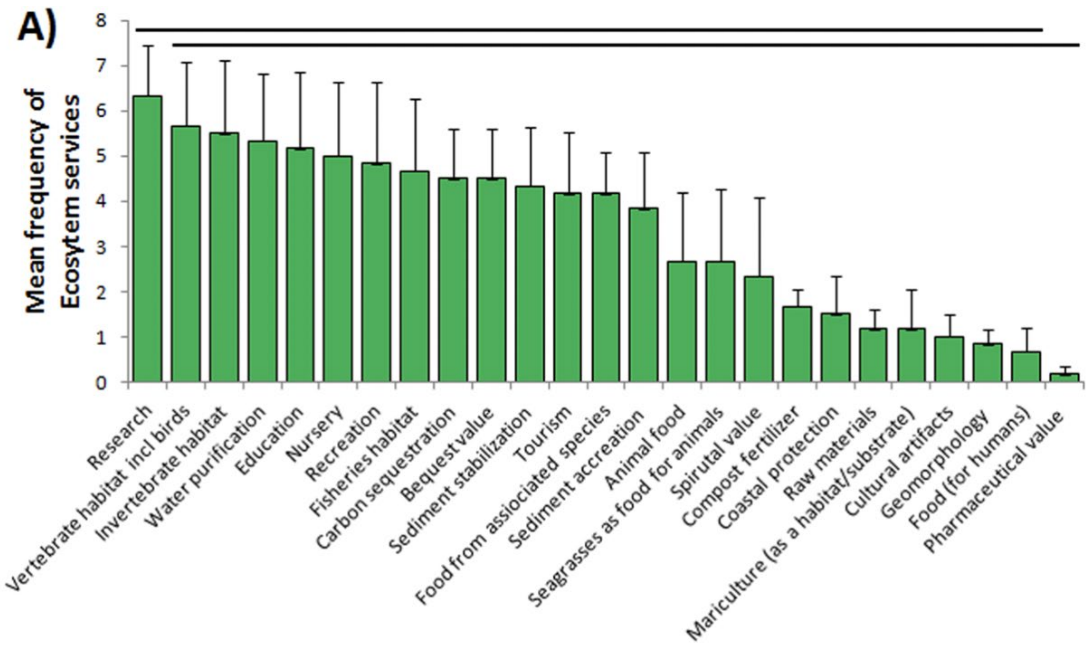

Figure 5. Perceived provision of seagrass ecosystem services. Global mean frequency of perceived provision of different ecosystem services of seagrasses. The higher mean the more frequently that service is provided. Data are across bioregion and genera means ± SE. Horizontal bars represent homogenous subsets (Tukey test) (Nordlund *et al*. 2016).

What the relative positioning of the carbon sequestration service means in terms of perceived economic values at the global scale is difficult to determine in a credible way due to paucity of comprehensive global studies, compounded by regional and local variances due to differing settings of study locations and methodologies used, but some figures can nevertheless be proposed (Table 3).

Table 3. Examples of ecosystem service values for mangroves, tidal marshes, and seagrass meadows (from Barbier *et al*. 2011).

Ecosystem Service	Ecosystem Process or Function	Ecosystem Service Value Example		
		Mangrove	**Seagrass Meadow**	**Coastal Marsh**
Raw materials and food provisioning	Generates biological productivity and diversity	\$484-595 ha^{-1} $year^{-1}$ (2007 USD)	N/A	GBP 15.27 ha^{-1} $year^{-1}$ (1995 GBP))
Natural hazard regulation	Attenuates and/or dissipates waves	\$8,966-10,821 ha^{-1} (2007 USD)	N/A	\$8,236 ha^{-1} $year^{-1}$ (2008 USD)
Regulation of erosion	Provides stabilization and soil retention in vegetation root structure	£3,679 ha^{-1} $year^{-1}$ (2001 USD)	N/A	N/A
Regulation of pollution and detoxification	Provides nutrient and pollution uptake, as well as retention particle deposition	N/A	N/A	\$785-15,000/acre (1995 USD)
Maintenance of fisheries	Provides sustainable reproductive habitat and nursery grounds, sheltered living space	£708-987 ha^{-1} (2007 USD)	\$18.50/ha (2006 AUD)	\$981-6,471/acre (1997 USD)
Organic matter accumulation	Generates biogeochemical activity, sedimentation, biological productivity	\$30.5 ha^{-1} $year^{-1}$ (2011 USD)	N/A	\$30.5 ha^{-1} $year^{-1}$ (2011 USD)
Recreation and Aesthetics	Provides unique and aesthetic submerged vegetated landscape, suitable habitat for diverse flora and fauna	N/A	N/A	GBP 32.80/person (2007 GBP)

It is often difficult to monetize the service values, which is perhaps why mangrove carbon valuations, which are easier to define and most like ‘forests’, have come to the fore. Despite any shortcomings in how they can be calculated, these global values emphasise the wide range of services and associated values that each of these three blue carbon ecosystems provide socially, economically, and environmentally, alongside the often referred to carbon values.

In all these representations and valuations of ecosystem services there is a note of caution in that such assessments are still incomplete to one degree or another. They therefore underestimate the range but especially the value of services, as methodologies are still to be developed to provide such a comprehensive perspective.

6 Threats to and impacts on blue carbon services in MPAs.

Unlocking how management regimes in MPAs can be established or altered to maximise the protection and restoration of coastal and marine biodiversity and associated carbon services, is key to addressing the combined biodiversity and climate crisis.

Central to this is an understanding of how human activities interact with biogeochemical processes in marine and coastal ecosystems (i.e. the process of, and around, carbon sequestration). For some coastal ecosystems, such as mangroves and salt marshes, the causes and threats to carbon sequestration and storage range from cutting and burning of mangroves, to the draining, overgrazing, and destruction of saltmarshes, all of which release vast amounts of stored carbon back into the atmosphere and destabilise sediments, reducing their future carbon sequestration and storage potential.

Subtidal carbon-rich marine ecosystems are also vulnerable to human activities that abrade, remove, or smother them. Such activities include those that disturb the seafloor, such as bottom trawling, dredging, aquaculture, and renewable energy developments (see Figure 6). The impacts of anthropogenic disturbance on subtidal carbon stores are an area of active research. However, bottom disturbance such as interaction with bottom fishing gear (trawls and dredges for example), could result in damage or even destruction of these subtidal carbon rich ecosystems and a reduction or changes to sequestration processes and associated carbon stores. Thus, given the irreversibility of any potential impacts, a cautious approach to management that minimises bottom disturbance to subtidal carbon stores is prudent until the science can be resolved (Laffoley 2020).

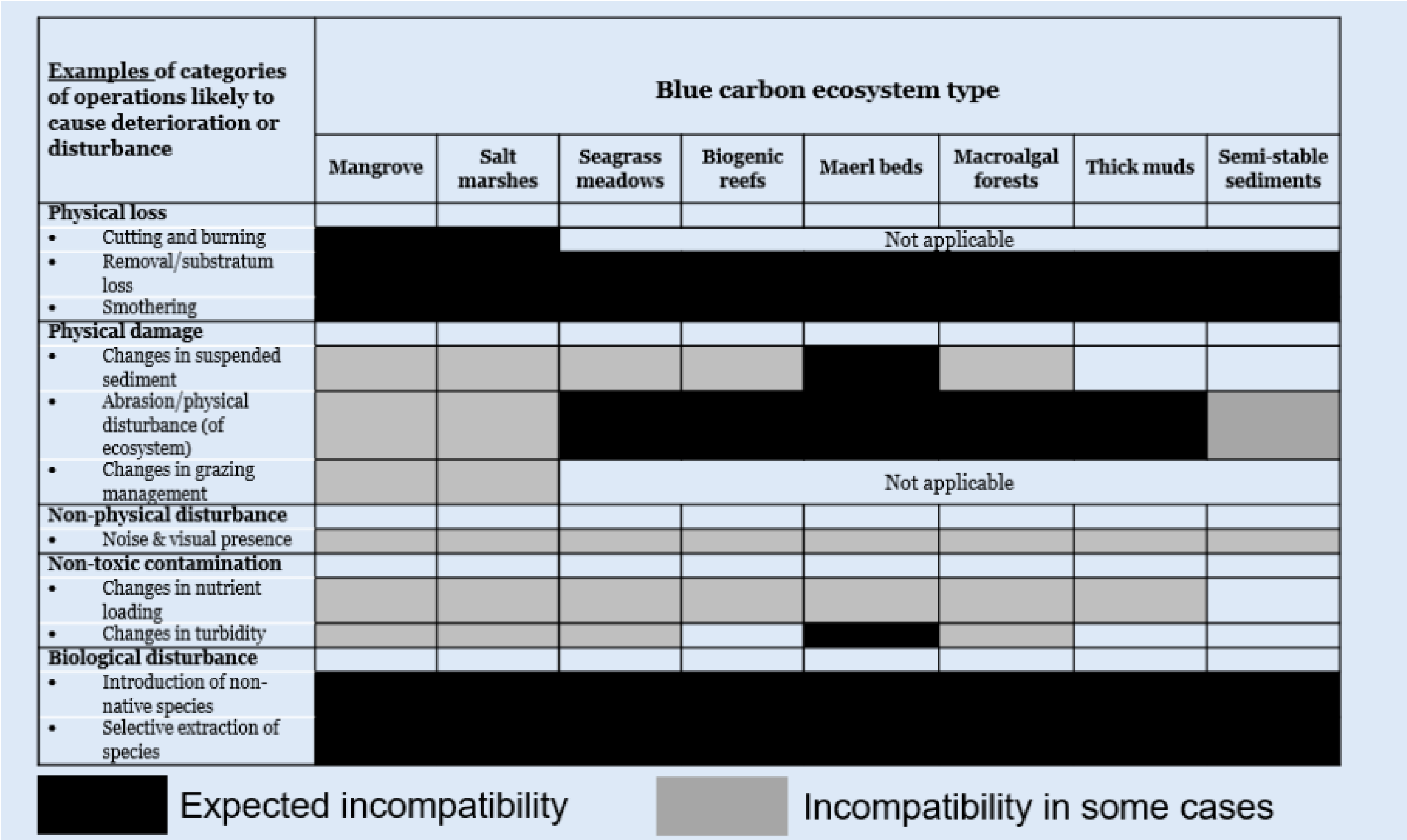

Figure 6. The relationship between impacts of human activities and the well-being of carbon rich coastal and marine ecosystems (Laffoley 2020). Note: Activities likely to cause deterioration or disturbance through abrasion, removal, or smothering predominantly involve bottom trawling and other seabed contact fisheries, and other operations such as existing (and new plans for) fish farms, capital dredging, dumping of dredge spoil, seabed mining, and some renewable energy developments.

Once the living surface veneer of a feature such as a maerl bed or a horse mussel bed is damaged or destroyed, the storage ability linked to the overall physical biogenic structure and the underlying organic and inorganic stores can be reduced or lost. For other ecosystems with the potential to store carbon such as seabed sediments (sands and muds), which are far more widespread than biogenic reefs, similar connections need to be made between human activities, geochemical cycling, and corresponding appropriate area-based management regimes. The degree to which these habitats can trap organic carbon is highly dependent on grain size, long-term stability, and degree of shelter from waves and currents (Laffoley 2020).

It is well documented that fishing gear such as trawls and dredges alter the distribution and abundance of marine species, impoverish seafood stocks, and result in extensive mortality of the benthos and sediment resuspension (Epstein *et al*. 2022). It is now also recognised that fishing operations interact with the biogeochemical processes associated with carbon sequestration and storage. In highly dynamic shallow water sandy seabed ecosystems, where natural disturbance from waves and currents is a significant source of disturbance that may continually change seabed contours and mix sediments, the link may be less evident. In sandy sediments that physical disturbance from bottom trawling has a significant impact on the mediation of macronutrient and carbon cycling. This is because bottom trawling impacts the organisms that assist in sequestration and as a result, the natural sediment sequestration processes are impaired (Hale *et al*. 2017). The reason for this is that animals that live at the sand–water interface, or deeper in the sediment, and that are impacted by bottom fishing, are the most important for sustaining the biogeochemical functioning of such ecosystems.

The case is even clearer for muddier seabed ecosystems. Such blue carbon reservoirs are more vulnerable to disruption of the carbon storage processes due to their inherent greater stability. Indeed, from a biodiversity perspective, vulnerabilities to seabed trawls and dredges are already understood and documented (e.g. see [MarLIN website: marine biodiversity and conservation]). In muds located in undisturbed conditions, macrofauna-mediated processes are considered to play a greater role compared to sands where hydrodynamics have a larger role in mediating the redox system (Sciberras *et al*. 2016). In muddier environments, it is the impact of the trawls and dredges on the sediment, rather than the loss of biodiversity alone that affects the carbon storage potential. Otter trawling, for example, may be affecting organic-matter remineralization and nutrient cycling through sediment resuspension and preventing the burial of organic matter to depth, rather than simply through the loss of the bioturbation potential of the benthic community (Sciberras *et al*. 2016).

For deeper water sediment ecosystems on the coastal continental slope that are removed from the effects of surface waves and currents, the situation is even clearer. Trawling such blue carbon reservoirs significantly decreases the organic matter content in the surface layers (up to 52%), slows organic carbon turnover (by about 37%), and reduces meiofaunal abundance (80%), biodiversity (50%) and nematode species richness (25%) (Pusceddu *et al*. 2014). Pusceddu *et al*. (2014) estimated that the OC removed daily by trawling in the region they studied (north-western Mediterranean) represented as much as 60–100% of the input flux. Exposing deeply buried sediments to oxygen triggers the aerobic microbial breakdown of ancient, stored carbon.

Historical losses of biogenic reefs (e.g. mussel beds, horse mussel beds, oyster reefs, maerl beds, etc.) are well documented. Stemming further losses and implementing recovery and restoration is now urgent. If the aim is a comprehensive approach to carbon management at the country level, then there are actions that need to be taken in the sea, and not just on land. Indeed, as was demonstrated in Burrows *et al*. (2014), some marine carbon sinks are capturing appreciable amounts of carbon lost from deteriorating carbon sinks on land (e.g. peat bogs), so there is a need to complement carbon management measures on land by protecting adjacent sinks in the sea. This brings into sharp focus the need to regulate human activities in the marine environment that are incompatible with the maintenance of natural carbon stores and their associated sequestration processes.

7 Progress in developing the evidence base for blue carbon in MPAs

From the carbon mitigation angle, significant work is underway to understand carbon fluxes of mangroves, saltmarshes and seagrass meadows. Action under the UNFCCC is predicated on the fact that carbon rich ecosystems sequester carbon from the atmosphere and if damaged or destroyed, release that stored carbon back into the air. Exploration of the emission pathways (i.e. how emissions change after a defined event) for the best-known ecosystems (mangroves, saltmarshes and seagrass meadows) show there are marked differences in emissions after such ecosystems are lost. In broad terms the widely differing emission pathways are related as much to their degree of submergence or not in the ocean, as to the conditions causing the ecosystem loss (e.g. burning mangroves).

The link between ecosystem condition and atmospheric emissions is far more immediate and direct for mangroves than for salt marshes and seagrass meadows (Figure 7 – note the markedly different scales of vertical axes). It is also evident that much of these emission pathways are based on modelled data rather than direct observations (Kennedy, pers. comm.), especially for ecosystems such as seagrass meadows. Furthermore, for saltmarshes and seagrass meadows the global distributions are still incompletely mapped, and in seagrass meadows the amount of carbon released is highly dependent on the species of seagrass involved (Nordlund *et al*. 2016).

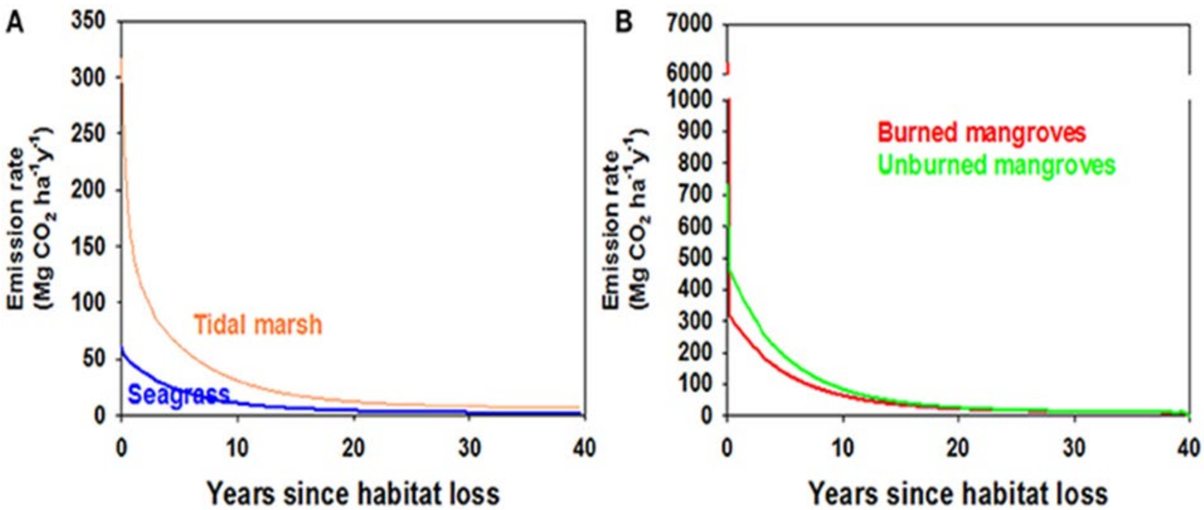

Figure 7. (A) Modelled CO2 emission rates from disturbed seagrass beds (blue) and saltmarshes (orange), with the assumption that half of the organic carbon was deposited in oxic environments (i.e. α = 0.5). (B) Modelled CO2 emission rates from disturbed mangroves where all above-ground biomass was burned (red) or the aboveground biomass was left to decompose in situ (green). The model was run with half of the sediment organic carbon deposited in an oxic environment (i.e. α = 0.5). Note the change of scale of the Y axis to accommodate high initial CO_2 emissions associated with burning of above-ground mangrove biomass (Image from Lovelock *et* al. (2017); © Fourqurean & Morris 2017, Creative Commons Licence).

There are still significant gaps in understanding the emission pathways and the exact relationships between the atmosphere and the carbon being sequestered for subtidal carbon rich ecosystems such as seagrass meadows. This is because the water column separates the atmosphere from the carbon stocks in such benthic systems. Direct atmospheric feedback loops when ecosystems are damaged or destroyed are stronger for mangroves and saltmarsh than they are for seagrass meadows. All carbon-rich ecosystems are, however, similarly worthy of protection due to the additional services they provide and significant associated social, economic, and environmental values. There are risks associated with focusing on mitigating carbon emissions (e.g. via the UNFCCC), that such wider values will be deprioritised and discussions on methodologies will take up valuable time that could otherwise be used through other routes such as via adaptation or the CBD to secure much better protection on the ground right (Laffoley 2020).

This risk is highlighted by the fact that for seagrass meadows, few if any direct measurements of the air-sea flux associated with a known disturbance have been made. It is inferred by modelling or simple calculations. There is, however, good evidence for such carbon rich ecosystems that human activities cause the sediment to be destabilised and eroded, ultimately resulting in the loss of the carbon sink. Whether the soil subsequently becomes oxidised, resulting in an emission back to the atmosphere, is not yet certain, but clearly this must not delay the need for action now to protect such important ecosystems. Significant attention is being given to identifying and addressing such research challenges (Macreadie *et al*. 2019).

For the other carbon rich coastal and marine ecosystems that are not the focus for UNFCCC action, global progress on developing a corresponding evidence base is far patchier. For this wider array of submerged coastal blue carbon ecosystems and reservoirs, the priority must be to protect the resilience and functioning of natural carbon stores. Few countries have yet to make significant progress on such matters, with the notable exception of Scotland (Burrows *et al*. 2017) and now other parts of the UK (Burrows *et al*. 2021; Flavell *et al*. 2020). In Scotland, such carbon rich coastal and marine ecosystems have been mapped and the relationship between them and MPAs has been established (Burrows *et al*. 2017), leaving the way clear, should it be decided appropriate, to embrace such carbon rich areas of the seabed in future MPAs and Marine Spatial Planning (e.g. Orkney Islands Council 2020; Porter *et al*. 2020).

8 The strengthening international policy framework

It is now widely acknowledged that the ocean has been a missing central component from the climate change and biodiversity debates for far too long. A welcome development has been the progressive strengthening of the international policy framework that has driven greater attention and action to protect, restore, and increase the resilience of coastal and marine biodiversity and its associated carbon services.

Whilst the development of mechanisms within the UNFCCC to protect coastal and marine ecosystems have only developed in recent years, a far longer-term driver has been targets established under the CBD. Whilst the COVID pandemic continues to delay the setting of the latest targets, the 2020 targets already set ambitious protection measures for countries to meet. In relation to protecting marine biodiversity and carbon stocks two Aichi targets particularly stand out:

- Target 11: By 2020, at least 17 per cent of terrestrial and inland water, and 10 per cent of coastal and marine areas, especially areas of particular importance for biodiversity and ecosystem services, are conserved through effectively and equitably managed, ecologically representative and well-connected systems of protected areas and other effective area-based conservation measures and integrated into the wider landscapes and seascapes.
- Target 15: By 2020, ecosystem resilience and the contribution of biodiversity to carbon stocks has been enhanced, through conservation and restoration, including restoration of at least 15 per cent of degraded ecosystems, thereby contributing to climate change mitigation and adaptation and to combating desertification.

The Sustainable Development Goals (SDGs) adopted in 2015, also provide a further driver to help guide renewed actions through international conventions, as well as national policy making and implementation. These goals are part of the 2030 United Nations agenda to end poverty, fight inequality and injustices, and tackle climate change by 2030. Sustainable development goals 13 and 14 are the most relevant to blue carbon, focusing as they do on climate action and life below water, but other SDGs have some relevance also.

- 13.1 'Strengthen resilience and adaptive capacity to climate related hazards and natural disasters in all countries'
- 13.2 'Integrate climate change measures into national policies, strategies and planning'
- 14.2 'By 2020, sustainably manage and protect marine and coastal ecosystems to avoid significant adverse impacts, including by strengthening their resilience, and take action for their restoration in order to achieve healthy and productive oceans'
- 14.5 'By 2020, conserve at least 10 per cent of coastal and marine areas, consistent with national and international law and based on the best available scientific information'
- 14.c 'Ensure the full implementation of international law, as reflected in the United Nations Convention on the Law of the Sea for States parties thereto, including, where applicable existing regional and international regimes for the conservation and sustainable use of oceans and their resources by parties'

The outcome of the UN Ocean Conference in 2017 provided further impetus by calling on all stakeholders to 'develop and implement effective adaptive and mitigation measures that contribute to increasing and supporting resilience to ocean and coastal acidification, sea-level rise, and increase in ocean temperature, and to addressing the other harmful impacts of climate change on the ocean as well as on coastal and blue carbon ecosystems such as mangroves, tidal marshes, seagrass...'.

In the UN Climate Change Convention (UNFCCC) Parties have agreed to protect the climate system (Article 2), defined as the totality of the atmosphere, hydrosphere, biosphere and geosphere and their interactions (Article 1.3). In the Paris Agreement, Parties noted the importance of ensuring the integrity of all ecosystems, including oceans, and the protection of biodiversity, recognised by some cultures as Mother Earth.

However, it was not until the UN Conference of the Parties (COP) 25, the Chile Madrid Time for Action 2019, that governments recognised the need to strengthen the understanding of, and action on, ocean and climate change under the UNFCCC. COP25, held in December 2020, mandated the first ocean and climate change dialogue, drawing upon the knowledge and scientific findings from the IPCC Special Report on the Ocean and Cryosphere in a changing climate.

At COP26, in the Glasgow Climate Pact 2021, building on the outcomes of the first ocean and climate change dialogue, governments permanently anchored the inclusion of strengthened ocean-based action under the UNFCCC multilateral process. Parties:

- Noted the importance of ensuring the integrity of all ecosystems, including forests, the ocean and the cryosphere, and the protection of biodiversity (preamble).
- Emphasized the importance of protecting, conserving, and restoring nature and ecosystems, including forests and other terrestrial and marine ecosystems, to achieve the long-term global goal of the Convention by acting as sinks and reservoirs of greenhouse gases and protecting biodiversity, while ensuring social and environmental safeguards (para 2).
- Recognised the importance of protecting, conserving and restoring ecosystems to deliver crucial services, including acting as sinks and reservoirs of greenhouse gases, reducing vulnerability to climate change impacts and supporting sustainable livelihoods, including for indigenous peoples and local communities (para 50).
- Invited the relevant work programmes and constituted bodies under the UNFCCC to consider how to integrate and strengthen ocean-based action in their existing mandates and work plans and to report on these activities within the existing reporting processes, as appropriate (para 60).
- Invited the subsidiary body for scientific and technological advice (SBSTA) Chair to hold an annual ocean and climate change dialogue and prepare an informal summary report that is made available to the COP at each subsequent session (para 61).

Thus, the policy framework to encourage greater action across international and regional policy instruments is already in place. Using the hook of blue carbon can open the door to much greater political engagement and action.

If the global policy aim, as defined through the CBD and SDGs, is to retain resilience in marine ecosystems and restore them where degraded, then it is key to understand that there are such linkages between biodiversity and carbon services and act on them more comprehensively than at present via global and regional conventions and initiatives.

A strategy for policy action that is overly focused just on securing uptake through existing UNFCCC mechanisms will not, by itself, best serve to deliver the protection and management of carbon in such systems, or at the accelerated speed now required in the face of ever-increasing biodiversity threats and climate change impacts. Whilst engagement with mangrove carbon is likely to be achieved more quickly through the UNFCCC because the science and understanding is more advanced, and similar to ‘forest’ carbon with its established methodologies, it will take far longer to see equivalent actions for saltmarshes and seagrass meadows. The time that it takes to work such additional blue carbon measures through the UN policy framework will be longer than the time we have left within which to take effective actions to protect these rapidly declining ecosystems.

9 Management and protection strategies – from MPAs to wider measures under multiple UN Conventions – and the urgent need for action

There are a small number of routes through which countries are acting to better protect and manage coastal and marine carbon sinks. These routes are via the UNFCCC, the CBD and other regional and national strategies and approaches, but measures being taken are still falling far short of the opportunities such policy routes provide.

Under the Paris Agreement, which was adopted by all 196 Parties to the UNFCCC at COP21 in December 2015, countries can independently determine how to lower their emissions, which they outline in pledges called National Determined Contributions (NDCs). Every five years, Parties are asked to communicate a revised NDC (Art 4.9 of the Paris Agreement), with each successive NDC signifying a progression from the previous one. Parties can develop their NDC actions and priorities based on a portfolio of measures including the conservation and restoration of nature as a climate change solution. Some countries have started to do this by focusing on blue carbon ecosystems, namely mangroves, saltmarshes, and seagrass meadows, and included them in their NDCs. This involves 28 countries' NDCs including a reference to coastal wetlands in terms of mitigation, and 59 countries including coastal ecosystems and the coastal zone in their adaptation strategies.

The lead up to COP26 saw countries further recognising the ability of coastal and marine ecosystems to advance climate mitigation and adaptation objectives in line with the Paris Agreement. Overall, there has been an increase in countries' level of ambition with regards to the inclusion of coastal and marine nature-based solutions as part climate mitigation and adaptation measures (Figure 8). Half of the countries that submitted updated NDCs have increased their ambition relative to first NDCs. Further, 58 out of 113 countries added new coastal and marine nature-based solutions for either mitigation or adaptation purposes between the two submissions.

Such pledges by countries are reliant on area-based measures ranging from MPAs through Marine Spatial Planning. Once pledges are made via NDCs, the logic should prevail that corresponding management action is taken at the site level to deliver the outcomes required. One of the other main drivers to deliver such area-based measures is via the CBD through the designation and implementation of MPAs. This implementation route provides opportunities to protect a wide array of coastal and marine ecosystems rich in stored carbon. Many countries are already making considerable progress in establishing their MPA networks (although with little attention given to their interconnectivity). However, there is little evidence that they are yet making the direct link to the management measures that would be needed to keep carbon in natural systems in the way nature intended (as the primary drivers for MPAs has been biodiversity protection up to now) and to not just afford protection but also drive restoration and, in time, increase resilience.

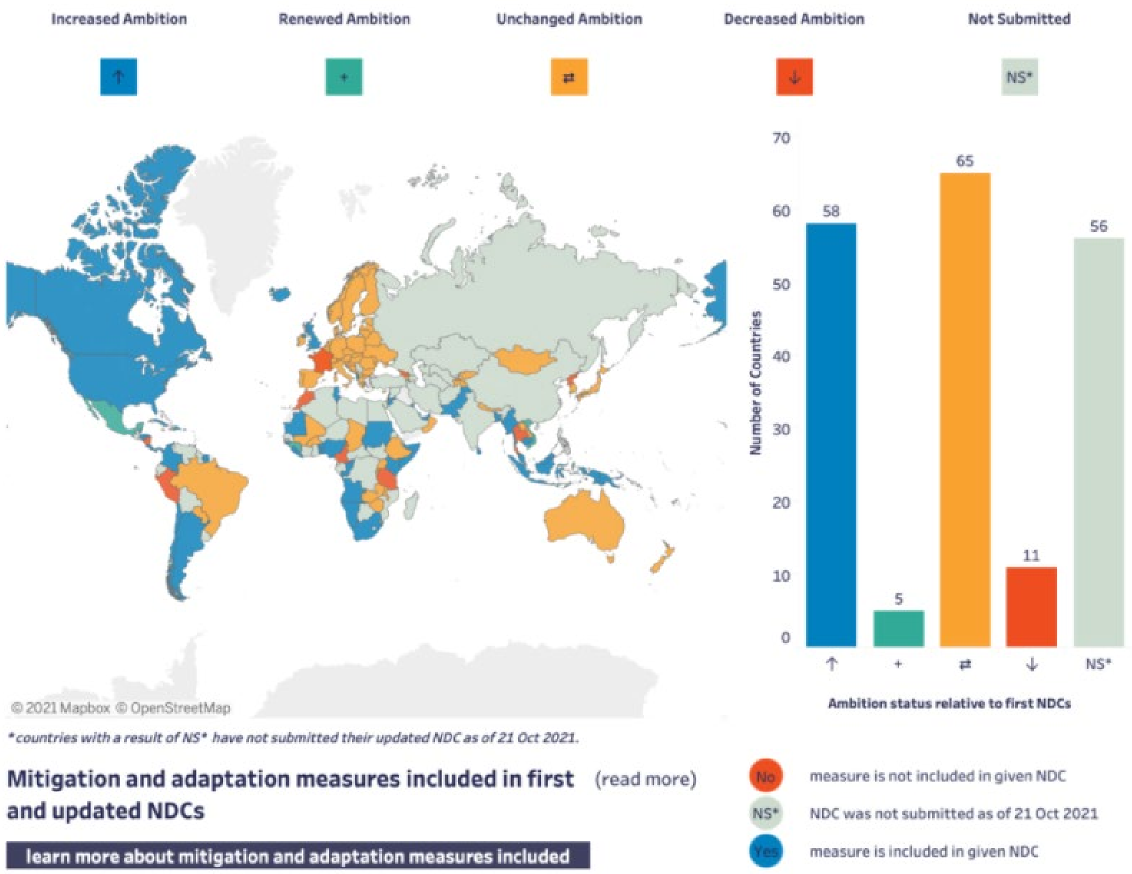

Figure 8. Global ambition for including coastal and marine ecosystems in NDCs has increased in the lead up to COP26. This is as part of countries' mitigation and/or adaptation measures in updated NDCs (Visualisation by Julia Biedry Gonzalez (https://public.tableau.com/app/profile/julia.biedry/viz/CoastalandMarineEcosystemsinNationallyDeterminedContributions/LandingPage) derived from Lecerf *et al*. (2021)).

In addition, there is considerable policy opportunity now to act for blue carbon through the CBD. The general prognosis from examining the underlying science over the last decade or two is that digging up, farming or foresting carbon-rich environments on land, such as peatlands and cutting down tropical forests, is bad for the climate. It is now just as evident that in the ocean the trawling of carbon-rich environments is similarly harmful. Avoiding doing such 'irresponsible things' to the ocean's carbon-rich ecosystems is a logical thing to do to retain resilience or restore such functions. Alongside the UNFCCC the CBD offers significant opportunities to deliver effective management of MPAs in this respect.

The policy framework is also already in place under the SDGs, which provide a primary policy objective wherever the carbon lies to retain resilience of such carbon stores and restore them where damaged – in essence the protection and best management of carbon in such ecosystems. Recognising the stacked-service value of blue carbon in such ecosystems (Figure 9), making carbon management an objective of MPAs, and then securing such carbon stocks through effective and appropriate MPA management regimes is a logical step that could be taken with minimal delay by many nations right now.

Going further and using carbon as a primary reason to designate MPAs is also a logical step that countries should pursue. This has yet to happen in any meaningful way, but it is just starting to be considered in some locations such as Scotland, where the Climate Change (Emissions Reduction Targets) (Scotland) Act 2019 states under section 35(15) "The [Climate Change] plan must also set out the Scottish Ministers' proposals and policies regarding the consideration of the potential for the capture and long-term storage of carbon when designating marine protected areas under section 67 of the Marine (Scotland) Act 2010.". If all countries started to follow Scotland's initiative, acting on this via multiple UN Forums would be a much better-informed next step.

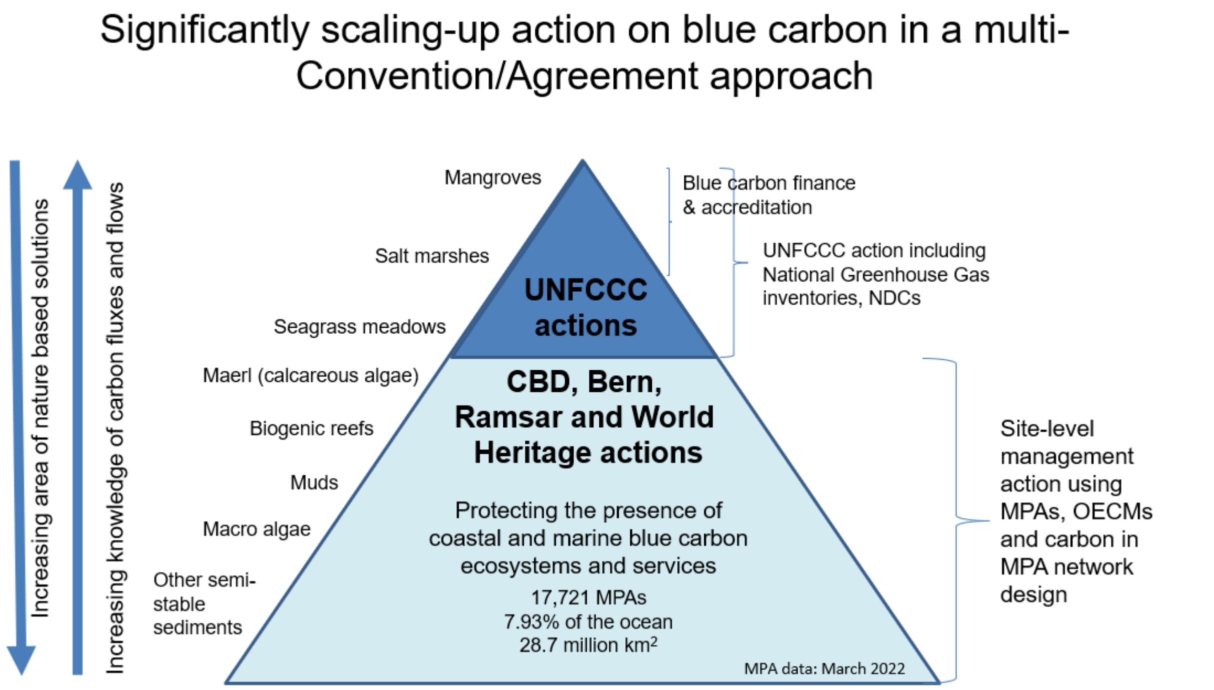

Figure 9. Scaling up unified action to better protect and manage marine biodiversity and associated carbon services using a simultaneous twin-track UN Convention approach (Image from Laffoley 2021, unpublished).

This twin-track UN Convention approach, working fully in alignment with the expectations set out in the SDGs, expands the range of useful measures that can be rapidly deployed by nations right now to help protect and better manage marine and coastal carbon sinks. This includes measures beyond those that can be achieved just by taking measures under the UNFCCC.

Using a twin-track UN Convention approach also avoids any need to overclaim and overreach the policy implications of the science around blue carbon under the UNFCCC, in favour of a more balanced action agenda delivered simultaneously through both Conventions. Carbon management-related measures should be incorporated now into global and national-level MPA policy. This also speaks directly to the benefits of higher levels of protection to MPAs to better drive restoration and recovery. At the national level, a simple five-point plan can be used to integrate and protect carbon services alongside biodiversity values using MPAs and wider measures (Laffoley 2021, unpublished):

1. Recognise the full extent of blue carbon ecosystems present in MPAs.
2. Act on operations likely to cause deterioration or disturbance and take the additional management measures needed now to secure the carbon values of well-documented blue carbon ecosystems.
3. Map extent and quality of the carbon values of less well-documented carbon ecosystems within current MPAs and implement relevant management measures.
4. Designate new MPAs based primarily on the carbon values for blue carbon ecosystems that lie outside existing MPAs, rather than just focus on traditional biodiversity values alone.

5. Take measures to complement the MPAs using tools such as marine spatial planning and fisheries management measures to recognise, protect and best manage blue carbon across seascapes.

What remains is to focus on the ideal management regimes in MPAs to not just protect carbon ecosystem services but also to drive ecosystem restoration and recovery. Significant work has now been done in this area over many years. First through initiatives such as 'The Science of Marine Reserves' and now more recently through a global consortium of key players via 'The MPA Guide' (Grorud-Colvert *et al*. 2021). The MPA Guide is a science-based tool and framework to identify distinct types of MPAs and connect these types of MPAs with the outcomes they are expected to achieve.

The Guide (Grorud-Colvert *et al*. 2021) shows that if the aim is biodiversity benefits, then restoration and recovery are best achieved in MPAs that are highly or fully protected and implemented or actively managed (Figure 10). Thus, if NDCs are to be effective there is a clear link that needs to be made to the type and nature of the MPA or area-based measure used to keep maintain healthy coastal and marine ecosystems and carbon storage. in natural systems in an effective manner.

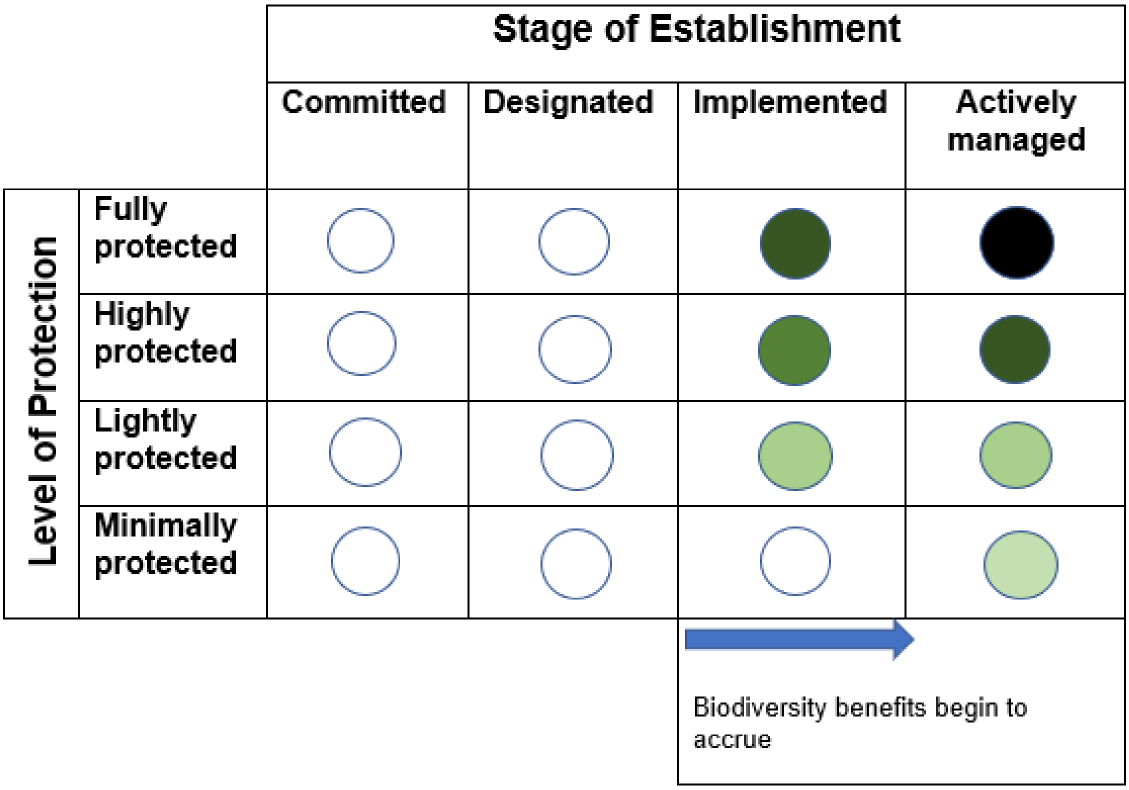

Figure 10. The level of protection and stage of establishment of MPAs that can be reliably expected to result in restoration of marine life and, over time, the development of enhanced resilience (depending on scale of the MPA). Increasing intensity of shading reflects the increasing scale of expected restoration. Figure derived and developed from the MPA Guide (Grorud-Colvert *et al*. 2021).

From a biological and geochemical perspective, MPAs that are highly or fully protected will over time result in the restoration of the 'living cap' of biodiversity over the seabed, resulting in greater habitat diversity, biomass, species diversity, and size of individuals (Figure 11).

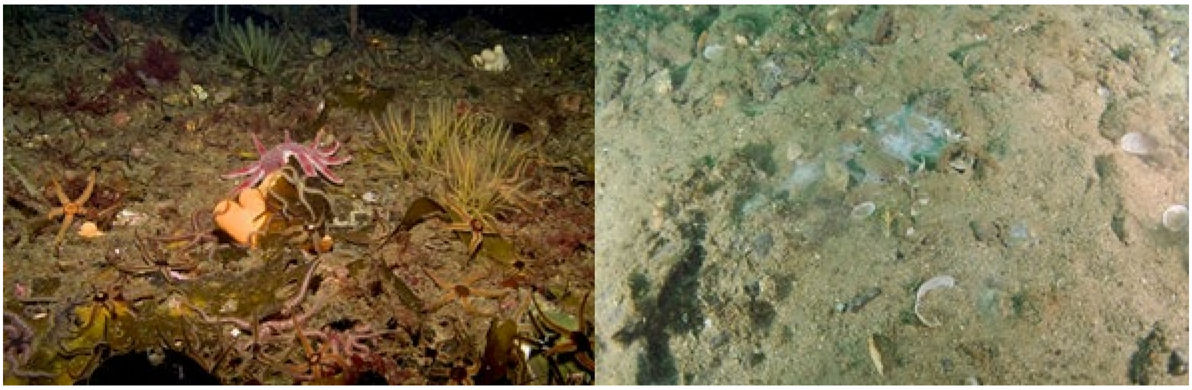

Figure 11. Highly and fully protected MPAs restore and maintain over time the 'living cap' of biodiversity, increasing resilience in capturing and securing more carbon – the example here shows a healthy, intact flame shell bed (left photo) in Loch Carron. Where damage from bottom trawling occurs (right photo) the living cap that develops over many years is destroyed (photo credit: NatureScot).

This has the effect of restoring ecosystem linkages, driving greater resistance and resilience. This greater seabed stability enables more carbon to be sequestered and ensures that existing carbon stores remain in place and are better protected against episodic change. Whilst climate change impacts in the ocean will disrupt and damage such areas along with surrounding exploited seabed, studies show that some such areas are able to recover more quickly and act to seed recovery in other areas (Sala & Giakoumi 2018).

Where the impacts of human activities are causing loss and damage to carbon rich coastal and marine ecosystems providing high or full levels of protection via MPAs and other area-based sectoral measures is needed to prevent such losses from continuing and to promote restoration and recovery (Laffoley 2020).

Taking such a position will also help secure other processes in the ocean that move and sequester carbon in natural systems. Considering the worrying climate and biodiversity trends, a strategy that protects such processes can only be regarded as the correct approach, given the limited time left to act. These processes are often less well understood or recognised but are important elements of carbon systems and include marine vertebrate carbon, trophic cascade carbon, biomass carbon, deadfall carbon, whale pump carbon, the great whale conveyor belt, bio-mixing carbon and twilight zone carbon. The degree of relevance that these processes have will vary between MPAs and MPA networks depending on geographical location and scale.

In conjunction with taking effective management measures within MPAs to protect and restore carbon services, there is also a need for far greater speed to implement such measures. This is because any measures taken now must be applied to a climate-driven and rapidly changing ocean environment that is changing in ways that progressively undermine the effectiveness of any measures taken. The longer we wait to act, the less likely measures are to be successful (Figure 12). Mechanisms we have at our disposal to deliver adaptation, protection, and recovery become less likely or will take much longer to succeed in the future due to the cumulative impact of human activities and climate change on such ecosystems. The consensus of most scientists is that we have perhaps a decade or less now to take substantive measures to change future climate and biodiversity trajectories to more positive ones, vital not only for our wellbeing but the wellbeing of all life on earth. There is also growing evidence that the rate of anthropogenic-driven climate change impacts is accelerating, and that we may be seeing the start of positive feedback mechanisms that will make measures to adapt, protect, and recover even harder to achieve in the coming years (Laffoley 2020).

An integrated approach and action now that works across all available policy instruments and removes the pigeon-holing of blue carbon as a 'climate issue' in favour of broader policy action, clearly has the highest potential for success.

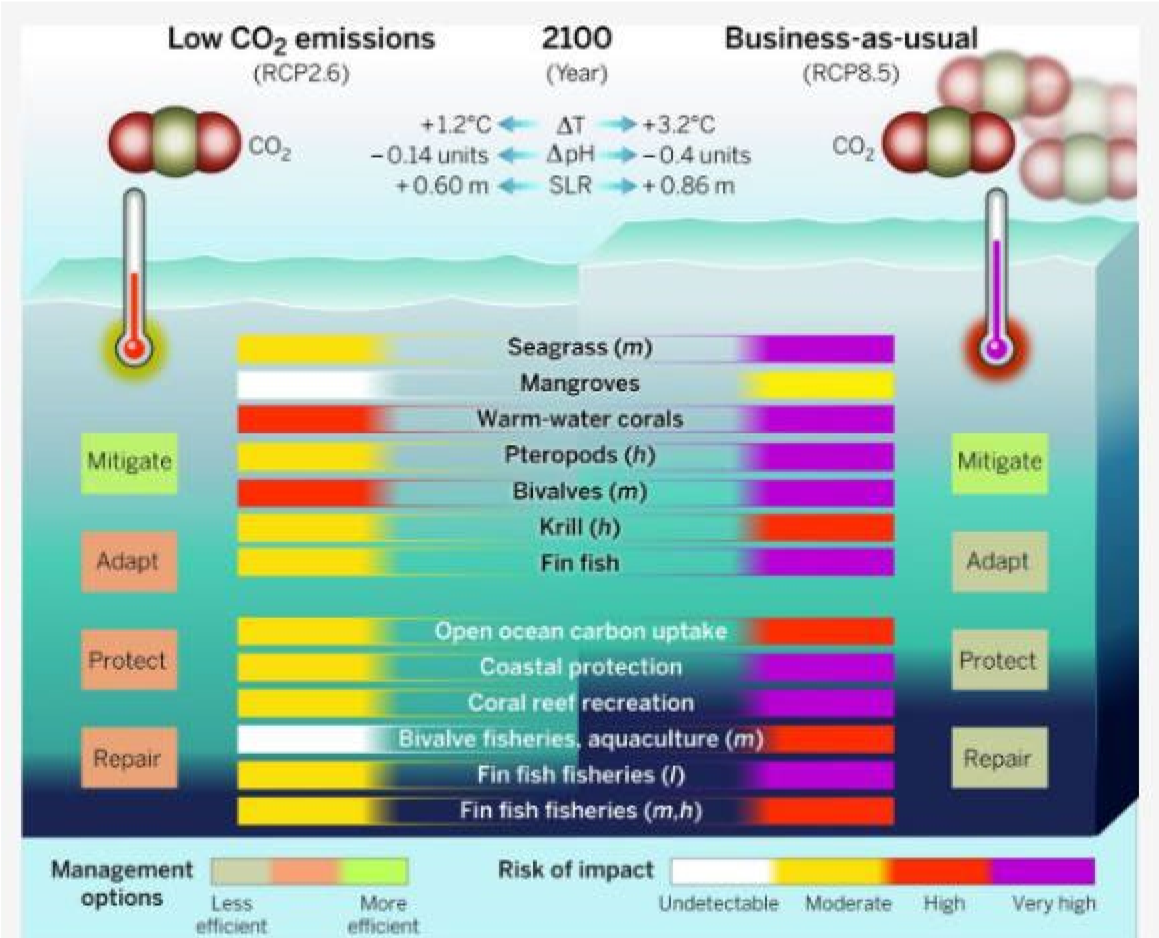

Figure 12. Contrasting futures for marine ecosystems under low emission scenario (on the left) and business as usual on the right. In business as usual and high emissions as is currently happening, the risks of impacts become much higher and the ability to adapt, protect and repair as management options become less efficient. Changes in ocean physics and chemistry and impacts on organisms and ecosystem services according to stringent (RCP2.6) and high business-as-usual (RCP8.5) CO_2 emissions scenarios. Changes in temperature (ΔT) and pH (ΔpH) in 2090 to 2099 are relative to pre-industrial (1870 to 1899). Sea-level rise (SLR) in 2100 is relative to 1901. RCP2.6 is much more favourable to the ocean, although important ecosystems, goods, and services remain vulnerable, and allows more-efficient management options. Key: l, m, h: low, mid-, and high latitudes, respectively (Image from Gattuso *et al*. 2015).

10 Recommendations to further develop the evidence base for blue carbon and MPAs

What countries can do:

- Undertake national-level assessments of the blue carbon resources (including habitats that both sequester and store carbon, (i.e. saltmarsh, seagrass meadows and mangroves) and habitats that either capture carbon (i.e. kelp beds) or act as carbon stores (e.g. biogenic reefs, seabed sediments, etc.) within existing MPAs and the effectiveness of management and the level of protection these resources receive.
- Identify areas of high carbon sequestration and storage potential within coastal and marine areas including working towards a greater understanding of the relationships between habitat forming species and their ability to function as a carbon sink, then designating additional MPAs, as necessary, to protect them.
- Understand and assess the connectivity within marine ecosystems supporting blue carbon habitats and carbon rich habitats in national MPA networks, to identify any important disconnects.
- Review the implications and sensitivity and vulnerability of key blue carbon habitats and carbon rich habitats to the impacts of climate change including sea-level rise, temperature increase, and acidification, and identify appropriate adaptation options.
- Restore blue carbon habitats and carbon rich habitats, especially those with important additional ecosystem services such as supporting high biodiversity, through effective protection and where possible active restoration and management actions.
- Undertake research on the release of carbon from these habitats/species as a result of damaging anthropogenic activities. (i.e. fisheries, renewables, cabling, aggregate extraction, oil and gas developments).
- Undertake research into the various routes of carbon transfer from source to sink, to determine the scale of the contribution of different sources, both terrigenous and marine, through eDNA and isotope tracers.

11 Conclusions

The problem with current measures is that integrated action to protect carbon in coastal and marine ecosystems has not happened at the speed and scale needed to address the joint threats of climate change and biodiversity loss. However, delivering such speed and scale is now increasingly seen as essential to respond to the immediate gravity and scale of climate change impacts and associated declines in ocean health now being observed.

What can be concluded from history, values, policy frameworks, emission pathways, and how sequestrated carbon may be disrupted or lost from natural coastal and marine systems are the following:

- We can make significantly greater progress than is being achieved at present by using an integrated approach to implementing existing policy tools, primarily the UNFCCC, CBD and SGDs. We must act quickly to consolidate current approaches more effectively and implement them now to the full degree envisaged in the SDGs.
- We must recognise and act to better protect the full range of coastal and ocean ecosystems naturally rich in carbon. This includes introducing and using standardised units to document carbon values and understanding how they relate to nations' existing responsibilities in EEZs and the High Seas under UNCLOS, to ensure that carbon management is provided in the new Treaty agreement under negotiation at the UN.
- We must broaden the scope of what is considered blue carbon to all carbon rich coastal and marine ecosystems and act to protect them. Currently the working definition of 'blue carbon' is restricted to the exceedingly small minority of coastal and marine carbon-rich ecosystems that qualify under UNFCCC. This is overplaying the sequestration/atmospheric links which is inadvertently focusing blue carbon as only 'a climate issue', and thereby directly undermining efforts, which must urgently happen now, under the CBD, using management tools such as MPAs and other spatial measures. Also, by looking at blue carbon habitats only for their blue carbon climate mitigation benefits loses sight of the majority of other benefits they can provide which may bolster the case to designate areas as MPAs.
- Recognition that the priority to act, as already agreed in the SDGs, is on protecting and restoring the resilience and functioning of carbon in natural systems – and that this explicitly includes the ocean.
- Act to better manage human activities in MPAs, as well as the wider coastal and shelf-seas, that disrupt, damage, or destroy natural carbon sinks, reservoirs, and sequestration and storage processes. Bottom contact fisheries, for example, are by far the biggest contributor to damaging marine carbon sinks and need new regulation to protect all blue carbon habitats from bottom contact fisheries that directly damage the seabed.

There is a compelling case to answer for action to protect the resilience and functioning of ocean ecosystems rich in carbon. Current action on blue carbon, whilst welcome, is too slow and too restricted in scope. There is now an urgent need to level the policy playing field across the land/sea divide, to recognise carbon in coastal and marine systems just as has been done on land, and to act urgently to protect such carbon stocks.

The emphasis moving forward should be to use all relevant existing policy mechanisms across UN Conventions and other regional and national agreements, and to use what we already know, to act in a far more coordinated and comprehensive manner to protect all blue carbon ecosystems and reservoirs at the coast and in the ocean. This approach, centred around MPAs and OECMs but with wider measures delivered through Marine Spatial Planning, should form the centre of a renewed no-regrets combined approach to tackling the climate and biodiversity crises, which is long overdue.

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