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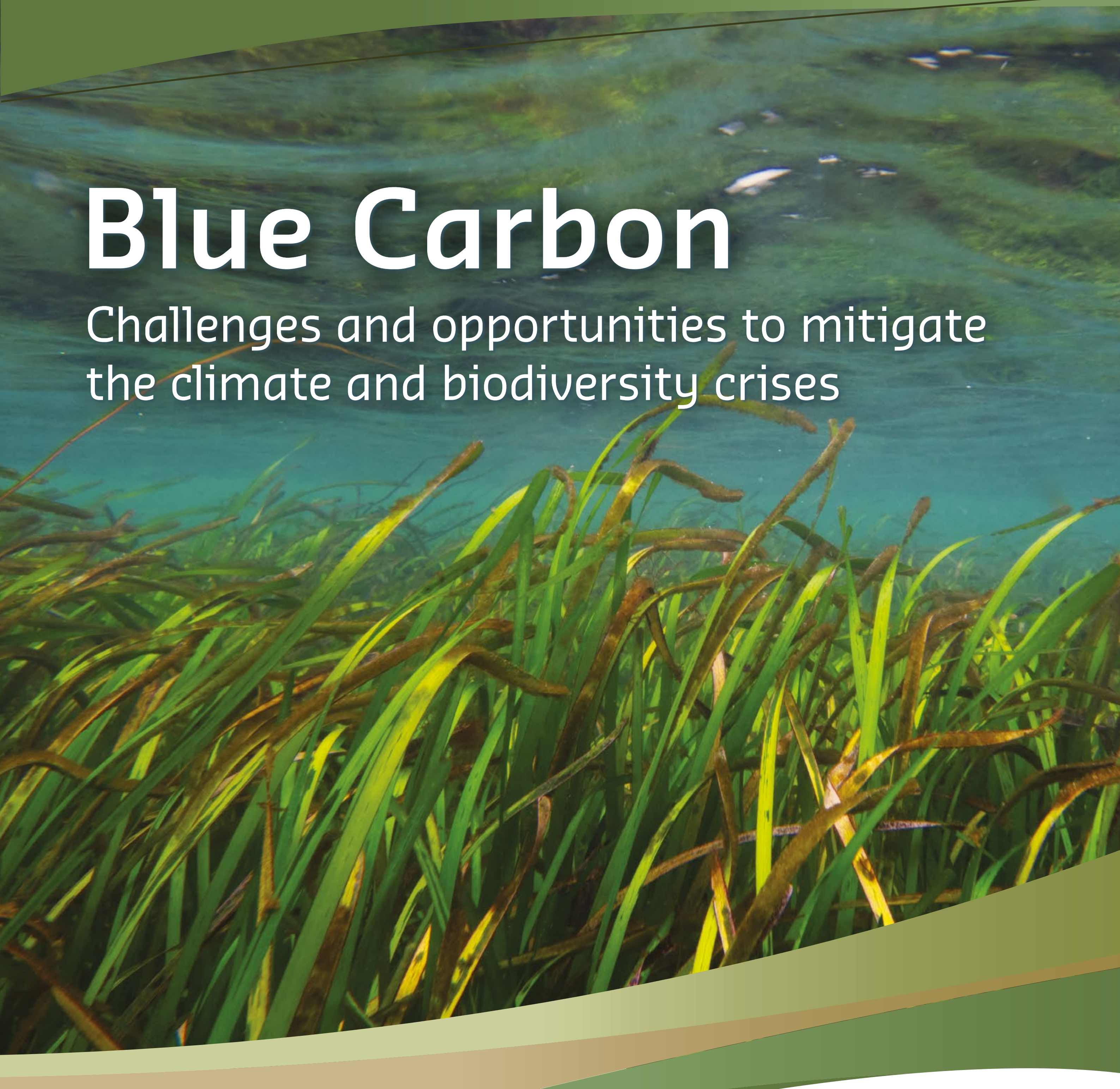

Blue Carbon

Challenges and opportunities to mitigate the climate and biodiversity crises

European MARINE BOARD
Advancing Seas & Ocean Science

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This policy brief is the result of an *ad hoc* Working Group established by the European Marine Board to address Blue Carbon. The list of Working Group members and reviewers can be found on page 13.

1. What is Blue Carbon?

Blue Carbon was originally defined as the amount of carbon captured and stored by coastal and marine living organisms (Nellemann *et al.*, 2009) and focused on coastal vegetated ecosystems with rooted vegetation, such as tidal marshes, mangroves and seagrasses. These ecosystems have high carbon burial rates per unit area and accumulate carbon in their soils and sediments. Now, the Intergovernmental Panel on Climate Change (IPCC) AR6 glossary[1] defines Blue Carbon as: "Biologically driven carbon fluxes and storage in marine systems that are amenable to management", and it also highlights that there is current debate regarding the application of the Blue Carbon concept to coastal and non-coastal processes and ecosystems other than coastal vegetated ecosystems, including the open Ocean. Thus, an expanded definition of Blue Carbon ecosystems includes shelf and offshore marine sediments, which can also store and sequester[2] carbon. The deep Ocean, whales and fish stocks have also been discussed for their role in enhancing carbon sequestration and climate mitigation via the biological carbon pump. Similarly, kelp forests and habitats formed by calcifying organisms (e.g. maerl and shellfish) have been discussed for their Blue Carbon potential.

In this document we define Blue Carbon ecosystems as coastal vegetated ecosystems with rooted vegetation and marine coastal, continental shelf and offshore sediments. The most important issue is the long-term storage of carbon.

The amount of carbon taken up by Blue Carbon ecosystems varies according to habitat, sediment type, location, water depth, and organisms involved, which in coastal systems include plants. The presence of plants in coastal ecosystems provides a natural way to capture carbon through photosynthesis, and over time some of the carbon captured by these plants gets stored in the sediment around the plant roots where it may be sequestered for centuries. The burial of carbon within sediments and around the root structures is influenced by the diversity of plants (and their root structures), although how this burial process varies is not well understood. In the absence of plants in shelf and offshore sediments, the burial of carbon is driven by the supply of carbon, which may be from coastal sources or the overlying water and the respective sedimentation or accumulation rate in the food web. Blue Carbon research to date tends to focus on organic carbon[3], although coastal inputs of inorganic carbon to the shelf, and the large sedimentary inorganic carbon stocks are also Blue Carbon.

2021 United Nations Decade
2030 of Ocean Science
for Sustainable Development

This Policy Brief and its recommendations support the UN Decade of Ocean Science for Sustainable Development (Ocean Decade) in the following ways: It highlights knowledge needed to support the Societal Outcomes 2. **A healthy and resilient Ocean**, 3. **A productive Ocean**, 4. **A predicted Ocean** and 5. **A safe Ocean**. The Policy Brief also addresses the following Challenges[4] of the Ocean Decade: Challenge 5 by specifically focusing on the opportunities and uncertainties of how to **unlock Blue Carbon ecosystems as a solution to climate change;** Challenge 2 by highlighting the need to **protect and restore** Blue Carbon ecosystems and their biodiversity; Challenge 3 by showing the importance of rebuilding carbon rich Blue Carbon ecosystems to sustainably **feed the global population**; Challenge 4 by describing the **knowledge needed for an equitable and sustainable Ocean economy**; Challenge 6 by highlighting the importance of Blue Carbon ecosystems in contributing to building **resilient coasts and Ocean**; and Challenges 7 and 8 by describing the **sustained observations needed** to understand Blue Carbon ecosystems and the models required to include Blue Carbon in the **Digital Twin of the Ocean**.

This Policy Brief and its recommendations support the EU Mission: Restore our Ocean and Waters. It addresses Objective 1: **Protect and restore marine and freshwater ecosystems** by describing the opportunities and issues related to the protection and restoration of Blue Carbon ecosystems; and Objective 3: **Make the sustainable blue economy carbon-neutral and circular**, by highlighting the importance of the protection of Blue Carbon ecosystems for a future carbon neutral and circular Europe.

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[1] https://apps.ipcc.ch/glossary/searchlatest.php

[2] **Carbon sequestration** is the long-term storage of carbon (>100 years). Conversely, **carbon storage** usually refers to carbon stored in a habitat or ecosystem for shorter time periods (<100 years).

[3] Organic carbon is the carbon originally manufactured from carbon dioxide (CO_2) by photosynthesis; it can be dissolved or particulate. Inorganic carbon includes the various forms of CO_2 dissolved in seawater, such as carbonate (CO_3^{2-}) and bicarbonate (HCO_3^-).

[4] https://oceandecade.org/challenges/

Credit: Angel Muñiz Piniella

Mangrove forest in Grand Cul-de-Sac Marin de la Guadeloupe, France.

2. The benefits of Blue Carbon ecosystems

Expanding and protecting Blue Carbon ecosystems has been proposed as a Nature-based Solution[5] to complement climate change mitigation efforts on land (Pörtner *et al.,* 2023). The protection, restoration and sustainable management of Blue Carbon ecosystems may also benefit marine biodiversity at the coast and in the open Ocean. The locations that are identified as important for protecting marine and terrestrial biodiversity are often characterised by high carbon storage and a large capacity for ongoing carbon sequestration. In addition, securing and rebuilding carbon-rich ecosystems can stabilise livelihoods, protect coasts, and support other societal needs such as food security from the Ocean. However, the rate and effectiveness of Nature-based Solutions such as Blue Carbon conservation and restoration, i.e. the capacity of terrestrial and Ocean ecosystems to capture carbon dioxide (CO_2) and store carbon, is constrained by the space available and by ecosystem productivity. Under climate change, this can be limited by the loss of space at the coast due to sea-level rise (coastal squeeze), and in both terrestrial and Ocean ecosystems by the negative impacts of warming and other changes (e.g. drought, hypoxia) that can impact the rate of biological functions.

To effectively manage carbon-rich terrestrial and Ocean ecosystems, strategies are needed that both mitigate climate change and maximise co-benefits. Strengthening efforts to keep global warming close to 1.5°C above pre-industrial levels is fundamental to avoid the worst impacts of warming and maintain the capacity of Blue Carbon ecosystems to sequester carbon, which will in turn support long-term climate stabilisation. Following the IPCC[6] and UN Framework Convention on Climate Change (UNFCCC[7]) rationale, warming of 1.5°C represents a threshold in the transition from 'safe' to 'dangerous' climate change, but even warming of 1.5°C will weaken Nature-based Solutions such as Blue Carbon ecosystems. As temperature rises beyond 1.5°C, the ability of these systems to mitigate climate change will become further compromised. Current "Nationally Determined Contributions"[8] would warm the world between 2.2 and 3.5°C by 2100 (IPCC, 2023). If we do not keep warming below the threshold of 1.5°C, these carbon sinks[9] may progressively turn into carbon sources, which would exacerbate the climate problem and harm biodiversity, with knock-on effects for food security, society, etc. A well-connected network of protected areas that enables genetic connectivity and the ability of species and biomes[10] to move under climate change will be needed to halt and reverse biodiversity loss and strengthen climate resilience. Optimised

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[5] The United Nations Environmental Program (UNEP), defines Nature-based Solutions as actions to protect, conserve, restore, sustainably use and manage natural or modified terrestrial, freshwater, coastal and marine ecosystems which address social, economic and environmental challenges effectively and adaptively, while simultaneously providing human wellbeing, ecosystem services, resilience and biodiversity benefits (https://wedocs.unep.org/20.500.11822/39752)

[6] https://www.ipcc.ch/

[7] https://unfccc.int/

[8] Nationally Determined Contributions or NDCs, are countries' self-defined national climate pledges under the Paris Agreement.

[9] A carbon sink is anything that absorbs more carbon than it releases.

[10] Biomes are naturally occurring communities of flora and fauna occupying a major habitat.

marine spatial planning needs to build on critical research to strengthen Blue Carbon ecosystems and their long-term role in climate stabilisation and safeguarding marine biodiversity (Pörtner *et al.,* 2023). For more information on how to build coastal resilience see Villasante *et al.,* (2023).

Nature-based Solutions have the potential to tackle both climate mitigation and adaptation challenges at relatively low-cost while delivering multiple additional benefits for people and nature (Seddon *et al.,* 2020). However, the application of Nature-based Solutions cannot be used as justification to allow for continued greenhouse gas emissions. The maximum mitigation provided by coastal Blue Carbon systems is around 2% of our current rate of global emissions (Bindoff *et al.,* 2019) and there are several reasons why it could be much less (Williamson & Gattuso, 2022). Thus, while Blue Carbon ecosystems cannot be used as a substitute for drastic and immediate emissions reductions, the substantial overall carbon storage capacity of Blue Carbon and high carbon terrestrial ecosystems will be important to stabilise climate in the long-term by binding, and thus lowering atmospheric CO_2 from residual emissions over decades to centuries and beyond. The conservation and restoration of Blue Carbon ecosystems will thus be needed to secure the long-term success of climate mitigation strategies and other co-benefits.

3. The role of the Ocean in the carbon cycle

Beyond the formation of Blue Carbon ecosystems, the Ocean is vitally important in climate change mitigation. Through gas exchange with the atmosphere, transport and equilibration of dissolved CO_2 across Ocean layers, and in response to increasing atmospheric CO_2 levels, the Ocean currently takes up about 25% of all CO_2 emissions each year (or 2.9 billion tonnes of carbon per year, see Figure 1). This uptake is controlled by the Ocean's ability to absorb CO_2 from the atmosphere, and transport and store it in the deep Ocean though Ocean currents and the Biological Carbon Pump (see next paragraph). However, the Ocean's ability to absorb CO_2 from the atmosphere will diminish with increasing amounts of CO_2 dissolved in seawater due to higher emissions and changes in water chemistry. In addition, the CO_2 dissolved in seawater can be released back into the atmosphere through Ocean currents and mixing, on timescales that generally depend on the depth of the water mass in which the dissolved CO_2 is stored (see Figure 2). For example, CO_2 that has reached the deep Ocean will not return to the atmosphere for 1,000 years or more, while CO_2 dissolved in the surface Ocean will equilibrate with the atmosphere within several months to years.

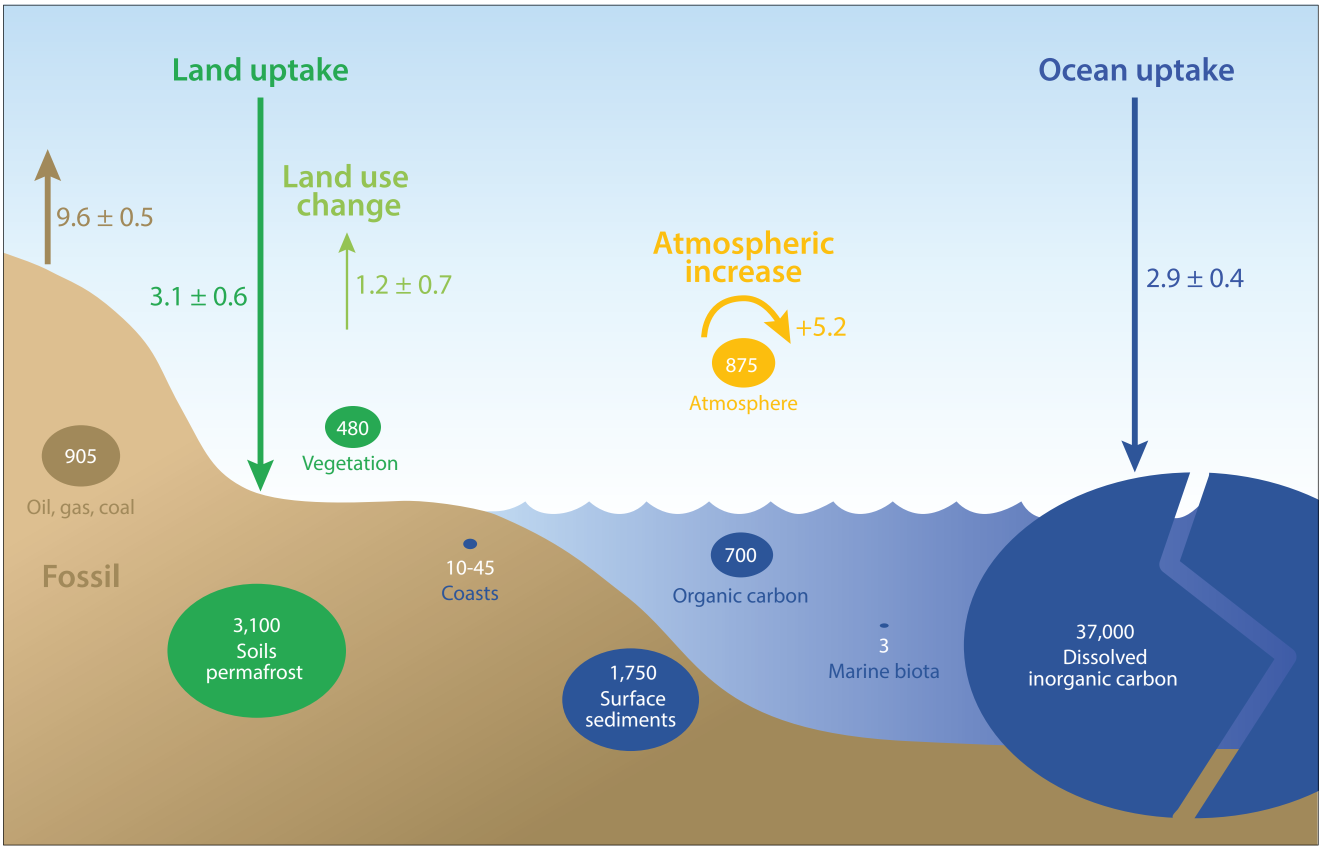

Figure 1. The global carbon cycle in billion tonnes of carbon for the decade from 2012 to 2021 (adapted from Friedlingstein *et al.,* 2022 (CC-BY 4.0)). Circles represent carbon reservoirs and arrows indicate annual exchange fluxes between the reservoirs. Note the dissolved inorganic carbon pool is not to scale.

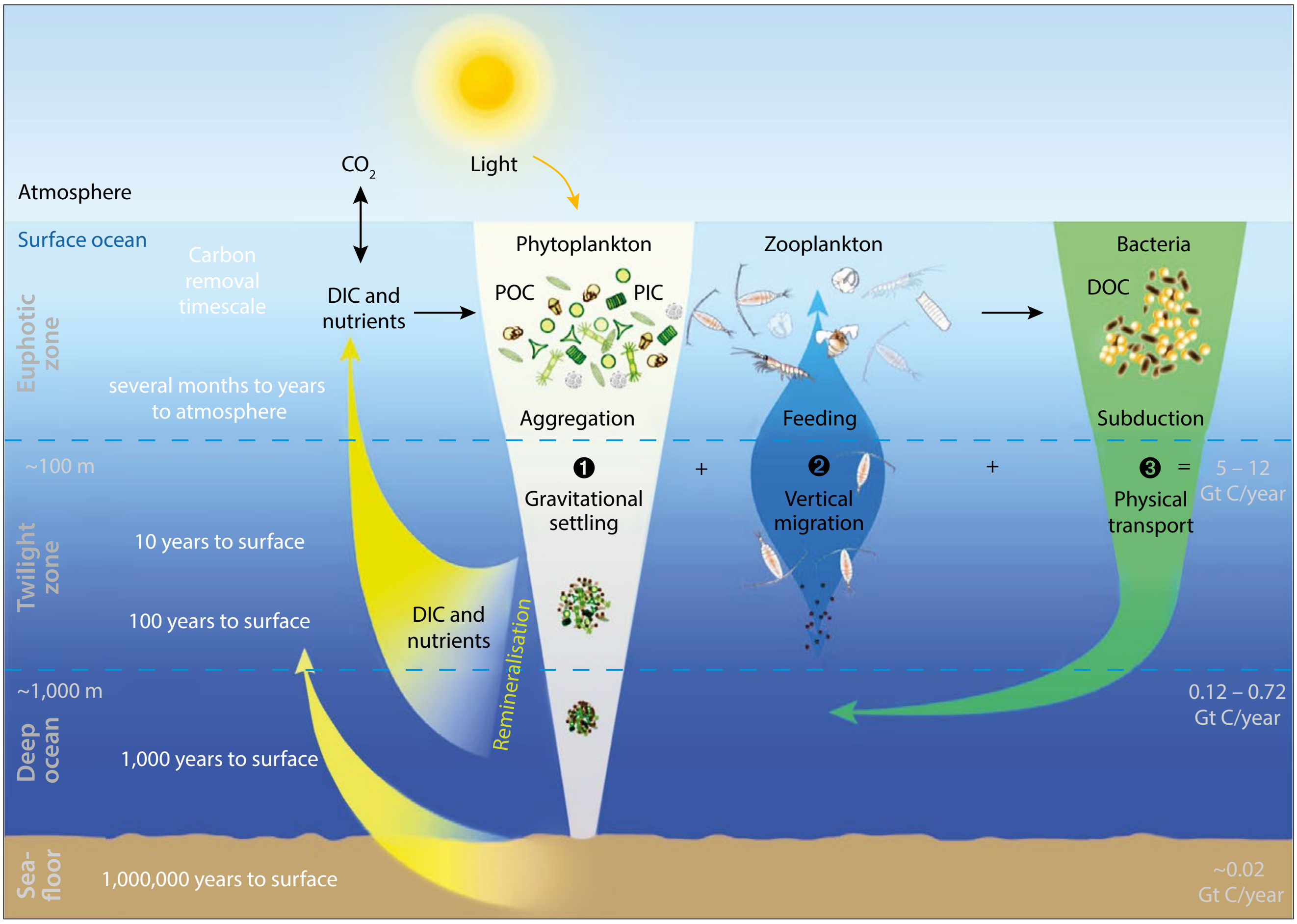

Figure 2. The mechanisms and carbon storage timescales of the Biological Carbon Pump (adapted from Iversen (2023); CC-BY 4.0). 1) Production of Particulate Organic Carbon (POC) and Particulate Inorganic Carbon (PIC) and transport to the deep Ocean by gravitational settling, 2) vertical migration of zooplankton that graze in the surface and metabolise the ingested carbon at depth (faecal pellet production, respiration), and 3) subduction of Dissolved Organic Carbon (DOC) and suspended POC and PIC via physical mixing processes. POC is converted back to Dissolved Inorganic Carbon (DIC) and nutrients by bacterial remineralisation at depth. The depth of remineralisation determines how long the carbon is removed from the atmosphere. Note: Although not depicted in this picture, the Biological Carbon Pump includes all living organisms that move carbon around the Ocean, including whales, fish and kelp.

The transport of organic carbon from the surface to the deeper Ocean and the seafloor is known as the Ocean's Biological Carbon Pump (BCP): a complex mechanism representing the fluxes and storage of carbon produced by living organisms (Figure 2). The BCP is mainly driven by phytoplankton taking up CO$_2$ from the seawater and converting it into organic carbon (i.e. photosynthesis) in the sunlit surface of the Ocean (the euphotic zone). Part of this carbon escapes recycling in the euphotic zone food web and either sinks, or gets transported down to the twilight zone through vertical animal migrations or physical mixing. In the twilight zone, most of the organic carbon is converted back into CO$_2$ and nutrients (a process called remineralisation). As a consequence, only a small fraction of the exported carbon will reach deep waters, where it can be stored for 100 years or more before upwelling[11] returns it to the surface Ocean and the atmosphere. An even smaller fraction of this carbon exported from the euphotic zone reaches the seafloor where some of it is remineralised in sediments, and the remainder is stored in sediments for hundreds to millions of years. The BCP thus lowers CO$_2$ in the surface Ocean resulting in the drawdown of atmospheric CO$_2$ and its storage on time scales that are climatically significant (Figure 2). This makes the BCP and the organisms therein an important element in building Blue Carbon ecosystems.

Despite the importance of the BCP as a climate regulator, there are still many uncertainties. The uncertainty in the estimates of the amount of carbon exported from the surface annually, for example, is almost as large as current annual CO$_2$ emissions from fossil fuel burning (9.6 ± 0.5 billion tonnes of carbon/year, Figure 1). Uncertainty also exists about the role of the so-called Carbonate Counter Pump (CCP), which involves the formation, settling, and dissolution of calcium carbonate shells by biota (referred to as PIC, Particulate Inorganic Carbon in Figure 2). The CCP increases CO$_2$ in surface waters, countering the CO$_2$ sequestration by the BCP (Neukermans *et al.*, 2023), while shell dissolution in the deeper Ocean and the sediments reduce CO$_2$, helping to neutralize excess CO$_2$. The extent to which climate change affects the functioning of the BCP and the CCP, and which climate feedbacks this will lead to are currently unknown. To improve our understanding of the BCP and CCP, and to reduce uncertainties in the Ocean carbon budget, we

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[11] Upwelling is a process in which deep, cold water rises toward the surface (see https://oceanservice.noaa.gov/facts/upwelling.html).

need better observations of carbon stocks, fluxes, and process rates. These efforts should include the role of ecosystems in supporting species such as whales (Pearson *et al.,* 2023) and fish (Pinti *et al.,* 2023) in strengthening the natural carbon cycle, through natural mechanisms of Ocean fertilisation (e.g. by whale excrements). Enhanced observations will in turn allow us to better parameterise carbon processes (e.g. remineralisation, fragmentation, sinking) in carbon cycle models. A well devised monitoring and observation network and well parameterised models are necessary to provide the knowledge necessary to verify the storage potential and management of Blue Carbon ecosystems, and for the robust, evidence-based carbon accounting process, which is needed for National Carbon Accounting and for the European Union (EU)'s Emissions Trading System (EU ETS)[12].

Balancing global and regional carbon budgets[13] and understanding the flow of organic and inorganic carbon is important for the UNFCCC stock-taking activities towards meeting the goals of the Paris Agreement, for CO_2 removal and for Nature-based Solutions such as Blue Carbon. However, the marine carbon cycle is complex, and the coastal carbon budget specifically has large uncertainties. Lateral transport of carbon from land through river systems, uptake by marine ecosystems, burial of carbon in the sediments and transport through Ocean currents are among the key processes which complicate regional carbon budgets even in well-observed shelf sea regions.

Therefore, long-term carbon sequestration in Blue Carbon ecosystems like coastal, offshore or shelf sediments have received increased attention. Over geological timescales, the CO_2 taken up in seawater and sequestered by plants has buried around 10-45 billion tonnes of carbon in coastal zones and 1,750 billion tonnes of carbon in the Ocean's seabed sediments (Figure 1). The carbon buried in deep-water sediments is not as sensitive to climate change as the carbon in the water column or in coastal/shelf sediments, making it an ideal storage place for excess anthropogenically emitted carbon for multiple centuries.

Effective management of different marine habitats will help to protect the integrity and storage of carbon stocks, which may include banning deep-sea mining or restricting bottom trawling. Bottom trawling[14] and dredging[15] might release the carbon that is stored in the surface layers of the sediment into the water column where it could be partially remineralised by bacteria and subsequently re-released into the atmosphere (if it is carbon that can be broken down quickly by microorganisms). However, we currently lack reliable estimates of carbon loss from the seabed to make robust global projections (Hiddink *et al.,* 2023).

In parts of the Ocean, nutrient supply is a major limiting factor for primary production, which has been used as rationale to suggest that man-made Ocean fertilisation could be used to enhance the BCP by stimulating phytoplankton productivity in the euphotic zone. Theoretically, this could increase the uptake of atmospheric CO_2 and remove it for long enough to help with climate mitigation, although there are likely to be adverse biological and ecological consequences. As highlighted in Box 1, the London Convention and London Protocol[16] prohibits Ocean fertilisation except for research.

Box 1. Legal Mandates

The EU has anchored climate neutrality by 2050 into law[17] through a range of measures, including in the open Ocean. This requires understanding and quantification of the storage and fluxes of carbon in marine ecosystems as well as understanding climate-driven impacts, including ecosystem tipping points. Beyond Blue Carbon, interest in solutions for the climate crisis, such as Carbon Capture and Storage (CCS) in sub-seabed aquifers and Ocean-based Carbon Dioxide Removal (CDR) such as iron fertilisation and ocean alkalinisation, is also increasing, but there is very little regulation or understanding of their trade-offs and impacts. Carbon capture is regulated by the London Convention and London Protocol, which prohibits Ocean fertilisation except for research[18]. In addition, the EU is party to the Convention on Biological Diversity (CBD), which requires that no climate-related geo-engineering activities that may affect biodiversity should take place until there is an adequate scientific basis on which to justify such activities. It also requires that appropriate consideration be given to the associated risks for the environment and biodiversity, as well as the possible social, economic, and cultural impacts.

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[12] https://www.consilium.europa.eu/en/policies/green-deal/fit-for-55-the-eu-plan-for-a-green-transition/

[13] A carbon budget is the accounting of sources and sinks of carbon, similar to the balance of income and expenses.

[14] Fishing practice that herds and captures animals by towing a net along the Ocean floor https://www.fisheries.noaa.gov/national/bycatch/fishing-gear-bottom-trawls.

[15] Act of removing silt and other material from the bottom of the sea https://oceanservice.noaa.gov/facts/dredging.html.

[16] https://www.imo.org/en/KnowledgeCentre/IndexofIMOResolutions/Pages/LDC-LC-LP.aspx

[17] https://climate.ec.europa.eu/eu-action/european-climate-law_en

[18] https://www.imo.org/en/OurWork/Environment/Pages/OceanFertilization-default.aspx

4. Examples and benefits of Blue Carbon ecosystems in Europe

The earliest and best-understood examples of Blue Carbon are in mangroves. Although there are no mangroves in mainland Europe, they are prevalent in the tropical and subtropical territories of the EU. Salt marshes and seagrass meadows are also part of the "traditional" Blue Carbon ecosystems which have been extensively researched, and these two ecosystems are found extensively around the coastlines of mainland Europe. Their conservation and restoration can protect the carbon they store and can enhance their ability to take up and sequester carbon, providing a Nature-based Solution to partially mitigate climate change.

In the Mediterranean Sea, seagrass meadows dominated by a species called *Posidonia oceanica*, play an important role in storing carbon[19], and this carbon sometimes comes from other plants (called macroalgae) that grow outside of the meadow itself. In contrast to the *Posidonia* meadows in the Mediterranean, Atlantic seagrass meadows are dominated by a smaller *Zostera* species. In Wales and Scotland, Project Seagrass[20] is using *Zostera* for large scale restoration of degraded meadows to replace lost habitats. Healthy and resilient seagrass meadows are important for carbon storage, but also increase biodiversity, create nursery grounds for many species that live in the larger ecosystem, and alleviate poverty in coastal communities by providing habitat for fish.

Compared to seagrass meadows, salt marshes are always intertidal, forming a link between terrestrial and marine ecosystems. European Atlantic and North Sea salt marshes often fringe natural or grazing grasslands, and experience larger tidal fluctuation than those along the coasts of south Portugal and the Mediterranean Sea. Although salt marshes are the best studied Blue Carbon ecosystem in the United Kingdom and very efficient at burying carbon, the estimates for carbon burial are highly variable, partly due to the huge variability between different salt marsh habitats and locations. Many of the salt marshes in the North Sea were historically drained to reclaim land for farming or habitation, reducing their extent.

Credit: Dimitris Poursanidis / Ocean Image Bank

Posidonia oceanica seagrass meadow with exposed root system (rhizome) and matte, where the sediment is retained and carbon is buried and stored.

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[19] https://medposidonianetwork.com/

[20] https://www.projectseagrass.org/

Credit: Natalie Hicks

Saltmarshes on the Blackwater Estuary in Essex, UK.

Salt marshes and seagrass meadows are vulnerable to sea-level rise, particularly where hard coastal defences such as sea walls restrict their natural inland migration. Restoration efforts of salt marshes may include intentional breaching of the sea defences to allow the sea to reflood these areas, called 'managed realignment'. This is a Nature-based Solution for increasing the capture and storage of carbon, but also to protect against floods and storm surges; increase biodiversity and nursery habitats for many fisheries species; enhance water quality; and remove pollutants and contaminants (Villasante *et al.*, 2023).

In contrast to coastal Blue Carbon habitats, the sediment accumulation rates in offshore marine sediments, including continental shelves, are less well understood, and these contain extensive stores of carbon (Legge *et al.*, 2020). Deeper sediments beyond continental shelves can store two orders of magnitude more carbon compared to coastal ecosystems (as shown in Figure 1), and this is sequestered for a very long time (millennia, as described in section 3).

The efforts we make to conserve and restore European Blue Carbon habitats to mitigate climate change may not produce an immediate result in terms of carbon storage. However, appropriate protection of these habitats does provide additional benefits, some of which may be immediate, such as providing habitats for many species, and increasing the biodiversity and resilience of these ecosystems. Their protection means that the Blue Carbon status of these ecosystems will continue to increase over time, as well as protecting existing carbon stocks from being released, if emissions are reduced at the same time.

5. Uncertainties and questions on Blue Carbon ecosystem conservation and restoration as a climate change solution

It is clear that Blue Carbon has potential globally for climate mitigation by increasing CO_2 removal, long-term carbon storage and supporting long-term climate stabilisation. Yet the core question remains: how confident are we of the magnitude of the climate benefits that could be achieved? For coastal Blue Carbon there are two constraints. First, the limited area that is realistically available for coastal Blue Carbon, determined not just by the suitability of the substrate, but also by existing human uses of coastal environments and the cost-effectiveness of restoration. The geographical limitations are not the same for offshore sediments: in terms of seabed substrate cover and extent, the carbon-rich softer sediments cannot be increased, although wider areas of the seabed could be protected. The second constraint is the high uncertainty around carbon accounting for Blue Carbon ecosystems. Such accounting is needed for reliable monitoring, reporting and verification, and to demonstrate the additional benefits of climate policy actions, yet the scientific knowledge that underpins this is limited[21].

There are many reasons for the uncertainty around carbon accounting (Williamson & Gattuso, 2022). The use of an average value for the burial rate does not consider the large variation in the literature: a 600-fold difference in salt marshes, a 76-fold difference for seagrasses and a 19-fold difference for mangroves, which can only be resolved by the addition of more measurements. Large errors can also occur in site-specific measurements. For example, burrowing animals can disturb sediments, affecting sediment-dating methods and making sediments seem to be accumulating more quickly (or more slowly), and carbon burial rates greater (or smaller) than they actually are. Also, a lot of the carbon buried in coastal sediments (up to 90%) may be land-derived, carried there by rivers and land run-off. Since this terrestrially derived carbon might have been buried anyway, it should not be added to the Blue Carbon climate benefit of the specific site or habitat, even though it provides global benefit as stored carbon from land. Such effects might be countered by the export of plant debris from the Blue Carbon system. However, the fate of such material is very difficult to quantify, and understanding the origin of carbon in these systems would increase our understanding of carbon stocks and flows.

The long-term carbon storage in coastal Blue Carbon ecosystems is made possible by the lack of oxygen in their sediments. However, such conditions also favour the production and emissions of two potent greenhouse gases: methane and nitrous oxide, which have the potential to counteract the climatic benefits of carbon burial. Although technically challenging, greenhouse gas measurements before and after restoration are needed to find out exactly how this varies across restoration timescales and between habitats. The concern around the release of greenhouse gases like methane and nitrous oxide is particularly important for tidal coastal ecosystems, but not as relevant in fully saline environments, such as offshore sediments.

Another key aspect to consider is the long-term integrity of restored and natural Blue Carbon coastal ecosystems. They will need to withstand future climate change impacts such as heatwaves, storms, and sea level rise. In addition, pressures from encroachment and other effects by agriculture, aquaculture, tourism, and other industries, that impacted the restored ecosystems in the first place, might still be there. Long-term integrity is also important to avoid CO_2 emissions driven by the degradation of natural, non-restored coastal Blue Carbon ecosystems, which if degraded or lost are likely to release most of their carbon back to the atmosphere.

Habitats formed by calcifying organisms (such as maerl and shellfish) provide a further complication. These habitats, which usually provide many co-benefits such as habitat provision and supporting biodiversity, can also trap, store and sequester organic carbon under the structures they form. However, they produce CO_2 when they manufacture calcium carbonate, reducing climate benefits. The opposite process (calcium carbonate dissolution, resulting in CO_2 uptake) can also occur. Therefore, sophisticated measurements are needed at each site considered for carbon accounting to determine the importance of these effects and whether these habitats contribute to carbon sequestration. Similarly, there are uncertainties about the carbon sequestration potential of kelp and other macroalgae, which take up CO_2 through photosynthesis, but do not have a root system in sediments where this carbon could become stored. They are therefore not considered Blue Carbon habitats, but some of this carbon does become sequestered in marine sediments, when degraded, detached and decomposed macroalgae are transported by currents and buried in the sediments.

In the polar regions there could be a net reduction in carbon burial due to sea ice melt under climate change and through the loss of sea ice algae, which tend to fall to the bottom in large mats, preserving a large portion of their organic carbon (Faust *et al.,* 2020). Conversely, the loss of sea ice may expose new benthic habitats, which could create new carbon storage capacity. Polar regions may see changes in carbon dynamics, through altered food-webs as the sea ice retreats (Barnes *et al.,* 2021). However, it is not yet known if this will enhance sequestration in the newly exposed benthic habitats.

Further offshore, on the continental shelf, carbon stocks are also not well quantified or understood. Despite recent controversy over whether human activities such as trawling can impact carbon stocks and contribute to carbon emissions (see section 3), there is very little empirical scientific research on the impacts of trawling on carbon dynamics, and sedimentary carbon stocks. Similarly, the quantitative contribution of marine animals (such as whales and fish) to Blue Carbon is also uncertain[22]. Continental shelf systems are under increasing anthropogenic impacts, from fisheries and dredging activities, to installation and decommissioning of energy structures such as wind turbines and oil and gas infrastructure, yet the impact on carbon stocks and sequestration is largely unknown. This makes it challenging to value the carbon, particularly for environmental economic and carbon credit accounting. As in coastal Blue Carbon ecosystems, some of the carbon sequestered

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[21] As highlighted in the EC consultation: https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/13172-Certification-of-carbon-removals-EU-rules_en and in: https://www.cefas.co.uk/media/gdnmduft/ukbcep-evidence-needs-statement_june-23_final.pdf

[22] https://www.edf.org/content/natural-climate-solutions-open-ocean


Credit: Robert Mlinac

Oystercatcher in coastal sediments in Ireland.

on the continental shelf may originate from land and therefore is not considered 'Blue' carbon, although its sequestration still has positive benefits for climate change mitigation. The input of terrestrial-derived carbon likely decreases with distance from the coast. Quantifying the age and origin of sedimentary carbon is difficult but key in understanding the mechanisms behind offshore carbon storage.

All these uncertainties make it very risky to rely on Blue Carbon ecosystems to offset current and continued emissions. Strong governance is needed to avoid loopholes, mis-reporting and perverse incentives that have widely occurred when complex financial incentives have been used as part of UNFCCC's REDD+[23] mechanism under the Kyoto Protocol (West *et al.,* 2020).

Nevertheless, Blue Carbon ecosystems are much more than carbon sinks: they nurture biodiversity, support fisheries, recycle nutrients, remove contaminants, and coastal Blue Carbon ecosystems also protect communities from storm surges and flooding[24]. Every effort should therefore be made to halt, and wherever possible reverse, the worldwide loss of coastal vegetation, and to effectively manage and protect our offshore habitats sustainably. Blue Carbon ecosystem conservation and restoration does not reduce the urgent need for immediate and ambitious emissions reductions, and over extended time scales will contribute to climate stabilisation and thereby benefit both climate and biodiversity.

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[23] The aim of REDD+ is to encourage developing countries to contribute to climate change mitigation efforts by halting forest loss degradation and reversing it through management, conservation and restoration: https://redd.unfccc.int

[24] See the EMB Position Paper on Coastal Resilience (Villasante *et al.,* 2023) for more information.

6. Summary and Recommendations

The uncertainties around the magnitude of climate benefits of Blue Carbon ecosystems and their global carbon sequestration potential is no reason not to protect them. Although the rate of carbon sequestration and storage is modest, Blue Carbon solutions, whether coastal or offshore, are worth pursuing for the sake of carbon storage, as their long-term contribution to climate stabilisation can be significant once emissions are strongly curtailed. Furthermore, they have many valuable co-benefits such as the ability to harbour rich biodiversity and protecting against flood and storm. Climate change and biodiversity loss are two sides of the same coin and can only be solved together. In the marine realm, this should happen by protecting and restoring Blue Carbon ecosystems.

Blue Carbon solutions have few, if any, disbenefits. Gattuso *et al.,* (2021) qualified the conservation and restoration of Blue Carbon ecosystems as a "low regret action"[25] in their assessment of Ocean-based negative emissions measures. However, protection of Blue Carbon ecosystems cannot be used as an excuse to continue emitting greenhouse gases. Immediate and ambitious emissions reductions are critical for the success of these strategies, as keeping global warming close to 1.5°C is required to maintain the health and long-term functionality of Blue Carbon ecosystems.

In order to address knowledge gaps in Blue Carbon ecosystems, we recommend to:

- **Fund further research to reduce uncertainties about the amount of carbon removed and stored by Blue Carbon ecosystems.** This is essential to maintain reliable, science-based crediting and offsetting systems. It requires guidelines on how to measure the various processes involving the import and export of carbon, uptake and release of greenhouse gases, and socio-economic factors that all occur at local scale. This also needs to be placed in the context of climate change, as rising temperature, sea level, and changes in precipitation may impact the plant and microbial diversity in Blue Carbon ecosystems, directly affecting the balance between carbon uptake and storage, and carbon release.
- **Fund the development of more tailored monitoring and continuous observations of carbon stocks, fluxes, and process rates across various time and space scales to improve our understanding of the global Ocean carbon budget, the biological carbon pumps (BCP, CCP) and sedimentary carbon storage.** This requires an optimally designed network of observatories and sensors in a diverse range of environments to monitor the long-term carbon sequestration of Blue Carbon ecosystems, which will be needed for credible carbon accounting. This could be complemented by the extension of current monitoring programmes to include carbon parameters, providing added value to regular environmental monitoring surveys run by government agencies.
- **Support sustained observations to better parameterise processes (e.g. remineralisation, fragmentation, sinking) in carbon cycle models.** These models will provide a better understanding of the impact of possible future geoengineering or technological options to capture and store greenhouse gases, or to increase the uptake of atmospheric CO_2 and remove it for long enough to provide climatic benefits. Until we have such an observing network and well-enough parameterised models to be sure that these processes will actually enhance carbon sequestration by the Biological Carbon Pump (BCP), it will remain extremely challenging to quantify long-term carbon removal with acceptable accuracy, and to adequately predict and monitor unintended impacts over the large spatial- and timescales at which they would inevitably occur. These efforts should include studying the role of the wider ecosystem in strengthening the carbon cycle, and of the mechanisms through which it contributes to the biological pathways of carbon storage.
- **Fund research to quantify the possible production of methane and nitrous oxide that might arise from coastal restoration efforts over the long term, and the impact that this might have on greenhouse gas emissions.** Although technically challenging, greenhouse gas measurements need to be made before, during and after restoration, and over the longer-term post restoration, to ensure that these coastal Blue Carbon ecosystems do not become net greenhouse gas sources.
- **Fund research to understand the dynamics of offshore carbon stocks and sequestration, and the possible impact of human activities, such as trawl fishing and deep-sea mining.** Despite the controversy over the impact of human activities on the seabed and sedimentary carbon, the impacts of these activities have not been scientifically quantified, including the resuspension of sediment and carbon, and any potential increase in CO_2 emissions, and subsequent implications for carbon storage and sequestration.
- **Promote collaboration between environmental scientists, social scientists and engineers to ensure the integration of Blue Carbon solutions.** Social governance approaches will be required to achieve the many co-benefits of Blue Carbon ecosystems, such as protecting coastlines against flooding through coastal vegetated Blue Carbon ecosystems and reducing the disturbance of offshore sediments by commercial fisheries. All Blue Carbon habitats provide ecosystem services, which can be valued (to improve environmental economics) and management decisions will need to be made on trade-offs. An integrated, interdisciplinary approach will be essential for understanding the environmental, economic and social value of the services within each Blue Carbon ecosystem and for initiating the implementation of sustainable use and protection of these highly valued ecosystems.

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[25] Low-regret adaptation options are those where moderate levels of investment increase the capacity to cope with future climate risks (IPCC).

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Cover Photo: Seagrass meadow (*Zostera marina*) off the Isles of Scilly in England, UK.

Credit: K Miguel Urquizo Richmond

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