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Nature-Based Solutions: Blue Carbon

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Blue Carbon
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Acronyms

CCE	Circular Carbon Economy
CO2	Carbon Dioxide
CO2-E	Carbon Dioxide Equivalents
EEZ	Exclusive Economic Zone
FAO	Food And Agriculture Organization
GHG	Greenhouse Gas
IPCC	Intergovernmental Panel On Climate Change
MPA	Marine Protected Area
MSP	Marine Spatial Planning
NBS	Nature-Based Solutions
NDCS	Nationally Determined Contributions
NGO	Non-Governmental Organization
PES	Payments For Ecosystem Services
SDGS	Sustainable Development Goals
UNEP	United Nations Environment Program
UNESCO	United Nations Educational, Scientific And Cultural Organization
UNFCCC	United Nations Framework Convention On Climate Change

Executive Summary

Blue Carbon habitats (the definition is currently limited by the United Nations Framework Committee on Climate Change to mangroves, seagrass, tidal marsh) provide nurseries for marine life and extraordinary benefits to the communities that live alongside them. Blue Carbon habitats are also in severe decline. Meanwhile, global carbon dioxide emissions continue to rise and Nature-based Solutions for sequestering carbon are in short supply. Blue carbon is a concept that governments can include in their national greenhouse gas inventories, and that companies may be able to invest in at a scale that dwarfs philanthropic donations to marine conservation. However, the science of Blue Carbon is in its infancy, with gaps in evidence and quantification. The techniques to develop, verify and monitor Blue Carbon projects and their impact on Sustainable Development Goals globally are still emerging.

A widespread international attention on Blue Carbon ecosystems arises as a cost-effective Nature-based Solution for climate change mitigation and adaptation, owing to their potential to play an important role in a Circular Carbon Economy. Blue Carbon ecosystems are not only characterized by their rapid organic carbon sequestration over long-term periods of time and their capacity to protect against sea level rise, severe storms and other climate change impacts, but also by the multiple benefits they provide for human wellbeing.

Despite their critical role, Blue Carbon habitats are in severe decline induced both by climatic and anthropogenic threats. The risk of additional greenhouse gas emissions from degrading ecosystems, but also the potential of restoring historic losses offer multiple opportunities for enhanced carbon sequestration and/or avoided greenhouse gas emissions throughout management of threatened Blue Carbon ecosystems. The restoration and conservation of Blue Carbon ecosystems contributes to Reduce (when conservation leads to reduced emissions) and Remove (when restoration leads to increased sequestration) mitigation options towards achieving a net-zero emission world using the Circular Carbon Economy Approach, while contributing to achieve several Sustainable Development Goals listed in the United Nations Agenda for Sustainable Development, through their co-benefits, particularly for developing countries.

Blue carbon is a concept that governments can include in their national greenhouse gas inventories and Nationally Determined Contributions towards achieving climate change mitigation targets defined under the United Nations Framework Convention on Climate Change. It is envisaged that the implementation of Blue Carbon projects, including both conservation and restoration actions, will increase exponentially worldwide over the UN Decade of Ecosystem Restoration (2021-2030), fuelled by the billions of dollars investment predicted after the 26th Conference of the Parties (COP26). However, critical science and policy advances are required to facilitate the large uptake and scalability of Blue Carbon projects. Knowledge of historical and contemporary Blue Carbon ecosystem extent together with spatially explicit maps of carbon storage and modeling efforts are crucial to aid the identification of cost-effective Blue Carbon projects in terms of carbon abatement potential, feasibility and associated risks, keeping in mind that local implementation assists climate change adaptation efforts, but only large-scale projects will have a relevant impact on the global carbon cycle.

This report seeks to explore the global scale and opportunity for Blue Carbon habitats to act as a Nature-based Solution for climate change mitigation and adaptation, and to highlight the co-benefits and trade-offs with Sustainable Development Goals. It also examines more innovative, thus very promising forms of Blue Carbon such as macroalgae that have been largely overlooked by science and policy until recently. Several examples of successful and on-going Blue Carbon projects around the world are hereto provided, aiming to shed light on research gaps, implementation methodologies, funding and additional co-benefits of Blue Carbon projects. The widespread uptake of Blue Carbon projects will require the advancement of new technologies and activity types, but also the quantification of risks associated with the permanence of carbon once a Blue Carbon project is implemented.

Finally, the authors explore the emerging blue carbon market and the potential for its further development. Carbon crediting schemes and associated methodologies for accounting should aim at reducing the costs of project implementation and monitoring to increase the associated cost-benefit ratio. Improved modelling of Blue Carbon resources and increased scientific evidence, showcasing change in carbon fluxes under different management scenarios, can contribute to this goal, by reducing the costs of project implementation and the uncertainties stemming from current carbon credit schemes. As voluntary carbon markets become regulated and the ambition and necessity for net zero emissions accelerate, it is imperative that the value of co-benefits provided by Blue Carbon habitats are incorporated into carbon market accounting systems.

Recommendations

Foreseen guidelines for enhancing the future of Blue Carbon as a Nature-based Solution for climate change mitigation and adaptation, and towards achieving Sustainable Development Goals are summarized below:

- Stronger collaboration between the scientific community, the corporate sector, government bodies and Non-Governmental Organizations to support research, data collection and financing instruments related to Blue Carbon projects.

- Improved mapping of historic and contemporary extent of Blue Carbon ecosystems, together with spatially explicit maps of carbon storage to aid the identification of hotspots for targeting and facilitating the implementation of Blue Carbon conservation and restoration projects.

- Cost-benefit assessments of different Blue Carbon project activities.

- Advancement of new technologies and identification of project activities that entail low implementation cost and large carbon abatement to facilitate Blue Carbon project uptake.

- Increase of scientific evidence of emissions reduction and carbon sequestration enhancement, and associated risks to carbon permanence across multiple Blue Carbon project activities at different spatial and temporal scales.

- Inclusion of seaweed aquaculture in the portfolio of Blue Carbon actions to further boost mitigation and adaptation efforts.

- Development of simple but robust carbon crediting schemes and associated methodologies linked to national inventories and Nationally Determined Contributions to reduce implementation costs and associated uncertainties in carbon accounting to enhance Blue Carbon project uptake.

- Development of Payments for Ecosystem Services that embed e.g., climate change adaptation, biodiversity, reduced pollution and human well-being co-benefits, in conjunction with carbon credits, to boost the cost-benefit and large-scale uptake of Blue Carbon projects.

- Inclusion of Blue Carbon projects’ implementation in the national marine spatial plans of the countries across Exclusive Economic Zones.

Introduction: What is Blue Carbon?

In order to hold the rise in global average temperatures, additional solutions beyond emission reductions are required to meet net-zero emissions targets (Livingston and Rummukainen, 2020). Among the climate change mitigation pathways identified by the Intergovernmental Panel on climate Change (IPCC), Nature-based Solutions (NbS) arise as cost-effective alternatives compared with current carbon storage technologies. NbS focus on the conservation and restoration of ecosystems for climate change mitigation and adaptation, and constitute a key mechanism to achieve the Sustainable Development Goals (SDGs) set up by the United Nations to attain a better and more sustainable future for all (United Nations, 2017).

Blue Carbon ecosystems (i.e., tidal marshes, mangrove forests, seagrass meadows and macroalgae forests, among others; Figure 1) are highly productive habitats that rank amongst the most treasured ecosystems on Earth. They are widespread across the coastlines around the world, extending over 8,000 million km2 (Figure 2). Blue Carbon ecosystems constitute natural carbon sinks and provide multiple co-benefits, including support of biodiversity and human wellbeing, and coastal protection against erosion and sea level rise (Figure 3).

Blue Carbon ecosystems occupy more than 0.5% of the sea bottom, but sequester more than half of the biological carbon captured worldwide (Duarte et al., 2005) (Table 1). A widespread international attention on Blue Carbon ecosystems arises as NbS develop owing to their potential for rapid organic carbon (C) sequestration over long-term periods of time, the risks of greenhouse gas (GHG) emissions from threatened ecosystems, and the potential of restoring historic losses in their extent.

Figure 1. Blue Carbon ecosystems: seagrass meadows (top left), mangrove forests (top right), tidal marshes (bottom left) and macroalgae (bottom right). Credits: Thanos Dailianis (top left); Karina Inostroza (top right and bottom left); Scott Bennett (bottom right).

Figure 2. The global distribution of marine forests (i.e., tidal marsh, mangrove, seagrass and kelp ecosystems) around the world. Maps: tidal marsh, mangrove and seagrass distributions from The Blue Carbon Initiative (https://www.thebluecarboninitiative.org/); kelp distribution from Filbee-Dexter and Wernberg (2018).

Figure 3. Blue Carbon (BC) benefits. BC ecosystems act as carbon sinks, thereby assisting in climate change mitigation, while providing multiple co-benefits for climate change adaptation (e.g., coastal protection), as well as for the health and well-being of coastal communities (e.g., pollution reduction, fisheries enhancement).

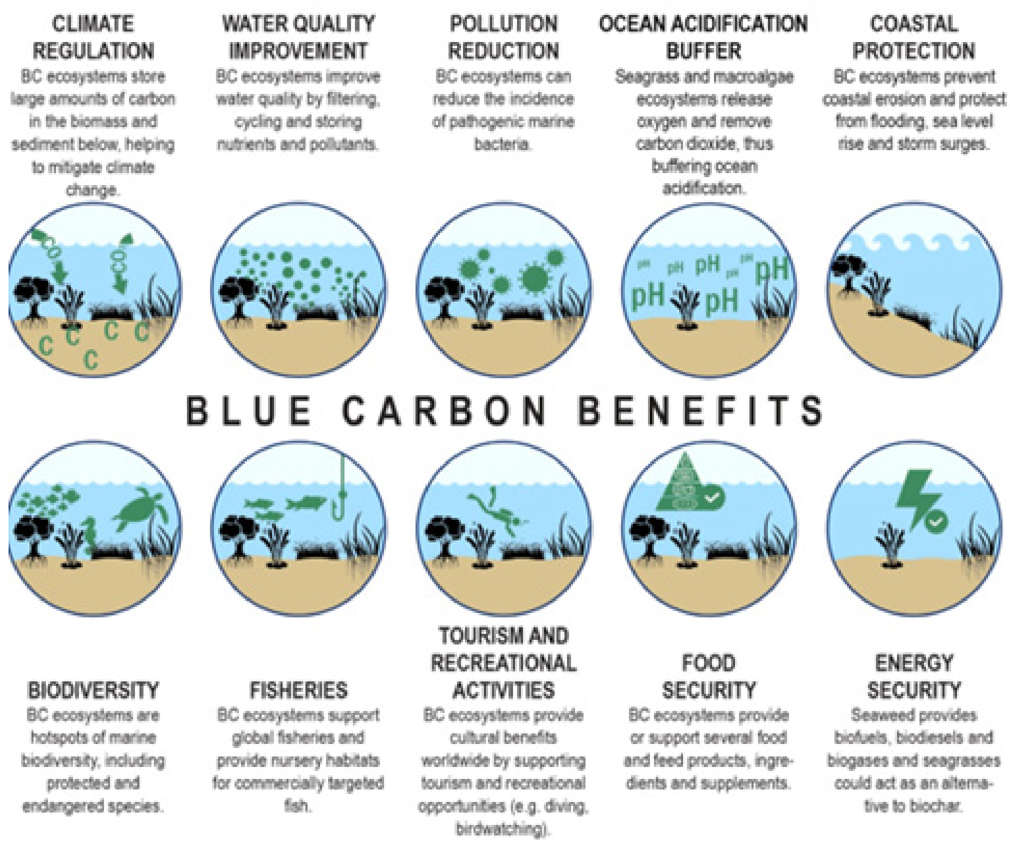


Table 1. Global extent, loss rates and carbon storage potential in the soil and biomass of Blue Carbon ecosystems. N.A. = not available. 1 Tg = 1,000,000 Mg.

BLUE CARBON ECOSYSTEMS	EXTENT (KM2)	GLOBAL CARBON STOCKS IN BIOMASS (TGC)	GLOBAL CARBON STOCKS IN SOILS (TGC)	GLOBAL CARBON BURIAL RATE IN SOILS (TGC YR-1)	RECENT RATES OF LOSS (% YR-1)
TIDAL MARSH	54,950J	N.A.	860 G–1,350G	28–70L	1-2
MANGROVE	81,500A–152,400C	1,750E–3,900F	2,600B–6,400D	5–16L	0.16-0.39
SEAGRASS	316,300K–1,646,800H	75.5I–151I	3,760G–21,000G	10–308L	2-7
MACROALGAE	6,073,000M	N.A.	N.A.	61–268N	0.0018 (ONLY FOR KELP)
TOTAL	6,525,750–7,927,150	1,825–4,051	7,220–28,750	104–662	

a) Hamilton, S. E. & Casey, D. Creation of a high spatio-temporal resolution global database of continuous mangrove forest cover for the 21st century (CGMFC-21). Glob. Ecol. Biogeogr. 25, 729–738 (2016).

b) Atwood, T. B. et al. Global patterns in mangrove soil carbon stocks and losses. Nat. Clim. Chang. 7, 523–528 (2017).

c) Spalding, M., Kainuma, M. & Collins, L. World Atlas of Mangroves. (Earthscan, 2010).

d) Sanderman, J. et al. A global map of mangrove forest soil carbon at 30 m spatial resolution. Environ. Res. Lett. 13, 55002 (2018).

e) Simard, M. et al. Mangrove canopy height globally related to precipitation, temperature and cyclone frequency. Nat. Geosci. 12, 40–45 (2019).

f) Hutchison, J., Manica, A., Swetnam, R., Balmford, A. & Spalding, M. Predicting Global Patterns in Mangrove Forest Biomass. Conserv. Lett. 7, 233–240 (2014).

g) Macreadie, Peter I., Micheli DP Costa, Trisha B. Atwood, Daniel A. Friess, Jeffrey J. Kelleway, Hilary Kennedy, Catherine E. Lovelock, Oscar Serrano, and Carlos M. Duarte. “Blue carbon as a natural climate solution.” Nature Reviews Earth & Environment 2, no. 12 (2021): 826-839.

h) Jayathilake, D. R. M. & Costello, M. J. A modelled global distribution of the seagrass biome. Biol. Conserv. 226, 120–126 (2018).

i) Fourqurean, J. W. et al. Seagrass ecosystems as a globally significant carbon stock. Nat. Geosci. 5, 505–509 (2012).

j) Mcowen, C. J. et al. A global map of saltmarshes. Biodivers. Data J. 5, (2017).

k) UNEP-WCMC, S. F. T. Global distribution of seagrasses (version 6.0). Sixth update to the data layer used in Green and Short (2003). Cambridge UN Environ. World Conserv. Monit. Cent. (2018) doi:http://data.unep-wcmc.org/datasets/7

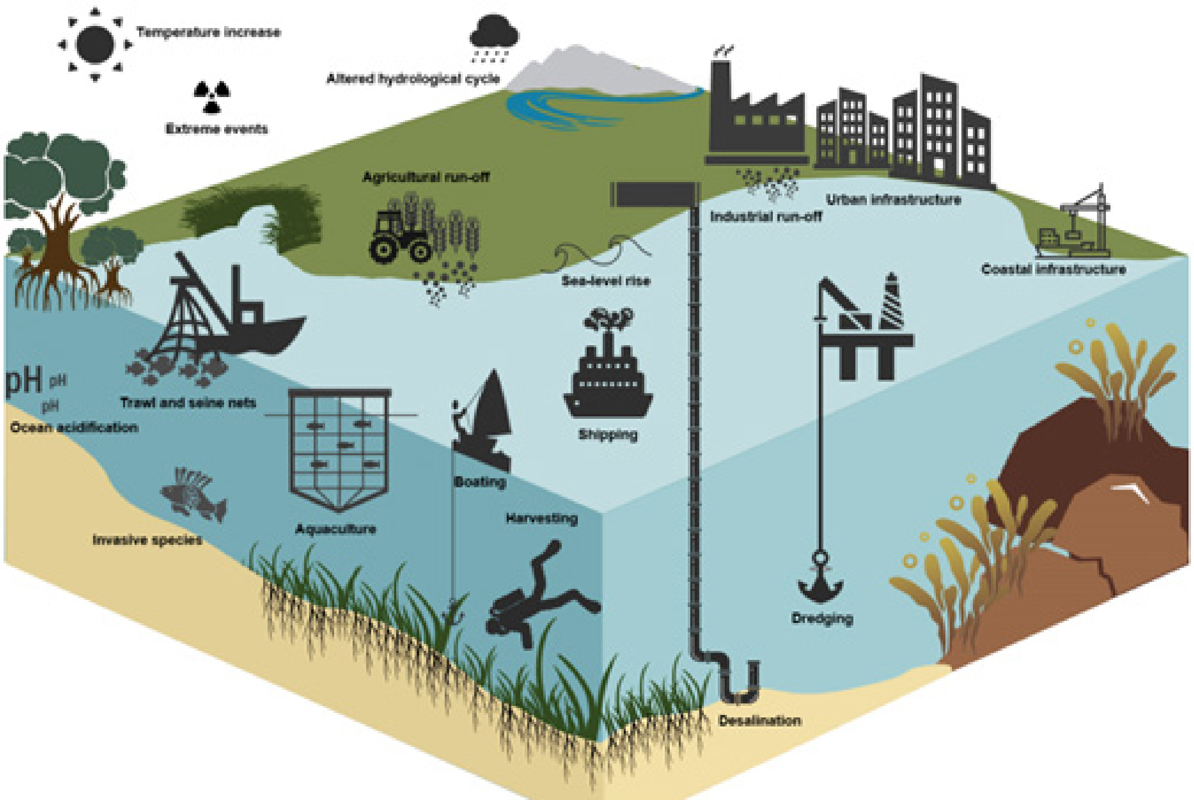
l) Duarte, C.M., 2017. Reviews and syntheses: Hidden forests, the role of vegetated coastal habitats in the ocean carbon budget. Biogeosciences, 14(2), pp.301-310.

m) Duarte et al 2022. Global estimates of the extent and production of macroalgal forests. Global Ecology and Biogeography.

n) Krause-Jensen and Duarte 2016. Nature geoscience
Sources for habitat loss: UNEP, 2020 (seagrass extent); Duarte et al. (2008), Waycott et al. (2009) (seagrass loss); Woodwell et al., 1973, McOwen et al., 2017 (tidal marsh extent); Duarte et al., 2008 (tidal marsh loss); FAO, 2020. Global Forest Resources Assessment 2020: Main report. Rome (mangroves extent); Hamilton et al., 2016 (mangroves loss); Krause-Jensen and Duarte, 2016 (macroalgae extent); Krumhansl et al., 2016; Wernberg et al., 2019 (kelp loss)

Regrettably, about 50% of the global extent of Blue Carbon ecosystems has been lost due to anthropogenic disturbances, which resulted in GHG emissions and the loss of their role in C burial (Duarte et al., 2013). The threats to Blue Carbon ecosystems are numerous, and include climatic threats (e.g., sea level rise and global warming), as well as direct and indirect anthropogenic disturbances (e.g., trawling, coastal development and eutrophication) (Figure 4). Humans and Blue Carbon ecosystems thrive in coastal areas, with 10% of the world's population living along coastlines and exerting severe impacts on coastal landscapes, whereas about 40% of the global population live in coastal communities and depend on ocean, coastal and marine resources (https://www.un.org/sustainabledevelopment/wp-content/uploads/2017/05/Ocean-fact-sheet-package.pdf).

Figure 4. Threats to Blue Carbon ecosystems. Threats include both climatic threats: (i) temperature increase; (ii) altered hydrological cycle; (iii) extreme events; (iv) sea-level rise; (v) ocean acidification and (vi) invasive species, as well as threat induced by anthropogenic activities including: (vii) agricultural run-off, (viii) urban and (ix) coastal infrastructure; (x) industrial run-off; (xi) shipping; (xii) desalination; (xiii) dredging; (xiv) harvesting; (xv) boating; (xvi) trawling; and (xvii) aquaculture.



Thus, stopping the loss of Blue Carbon ecosystems through conservation, and reversing losses throughout restoration will contribute to avoid GHG emissions from extant C stores and will restore their C sequestration capacity (Figure 5). The restoration and conservation of Blue Carbon ecosystems contributes to Reduce (when conservation leads to reduced emissions) and Remove (when restoration leads to increased sequestration) mitigation options towards achieving a net-zero emission world using the Circular Carbon Economy Approach (KAPSARC, 2021), while contributing to several SDGs apart from SDG 14 – Life below water, as indicated in Figure 6.

Figure 5. Diagram showing carbon cycling in contrasting management scenarios of coastal and marine ecosystems. Panel A showcases anthropogenic activities linked to coastal development and industrial activities (e.g., prawn aquaculture, logging, land fill, and tidal flow restriction for sugar cane farming) that result in greenhouse gas emissions. Panel B showcases a pristine coastal wetland environment, with tidal marsh, mangrove, seagrass, macroalgae and phytoplankton sequestering carbon dioxide (CO2) throughout photosynthesis and acting as natural C sinks.

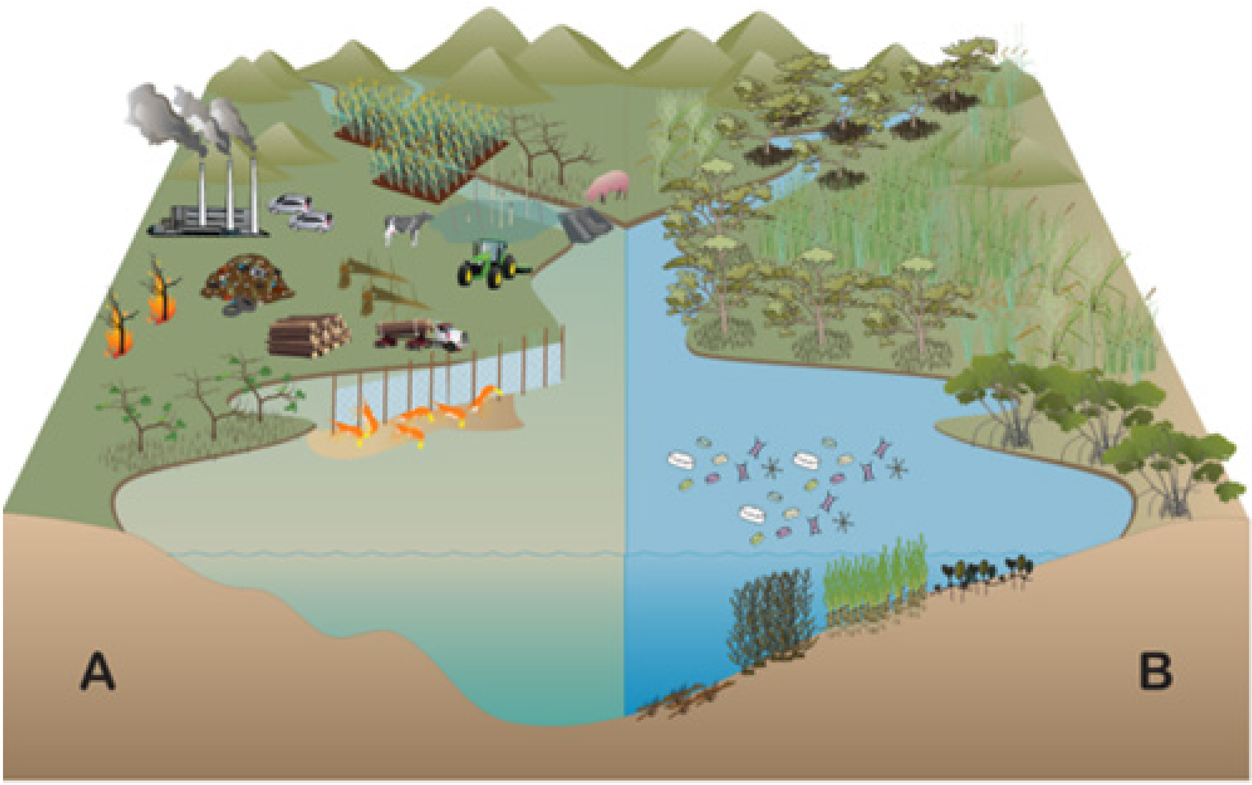
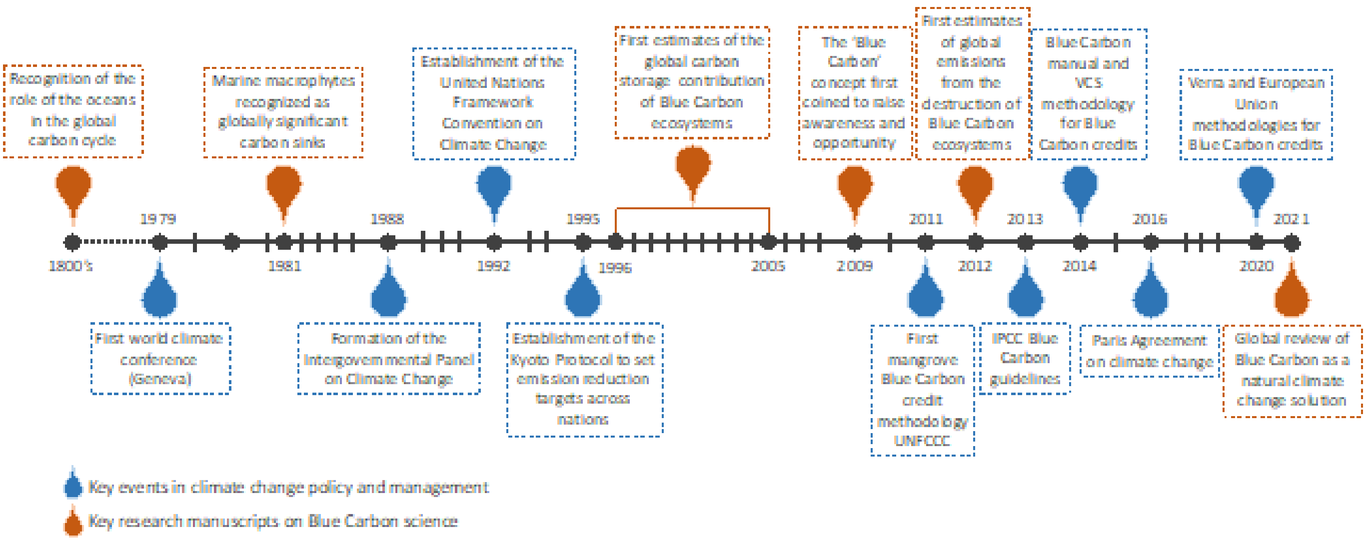


Figure 6. Diagram showing the contribution of Blue Carbon (BC) ecosystems to the achievement of Sustainable Development Goals (SDGs). BC projects contribute not only to SDG14 – Life below water, through C storage, but to almost all other SDGs through the multiple co-benefits they provide.

Current status: Timeline and steps for Blue Carbon science

The role of the oceans in the global C cycle and climate control has been recognized for decades, with emphasis on the contribution of phytoplankton in C cycling since the 19th century (Riley, 1944; Figure 7). The relevance of marine macrophytes as global C sinks was highlighted in the journal Science in 1981 (Smith, 1981), and shortly after, the scientific community contributed the first estimates of the global contribution of Blue Carbon ecosystems to C storage (Duarte and Cebrián, 1996; Duarte et al., 2005). The establishment of the IPCC in 1988, and the formation of the United Nations Framework Convention on Climate Change (UNFCCC) in 1992 together with the establishment of the Kyoto Protocol in 1995 to bind nations to reduce emissions, reflected the scientific, social and political awareness of the need to take action against the increasingly tangible impacts of climate change.

Figure 7. Timeline showing the historic evolution of the Blue Carbon concept, with key events that contributed to advance Blue Carbon science, management and policy.



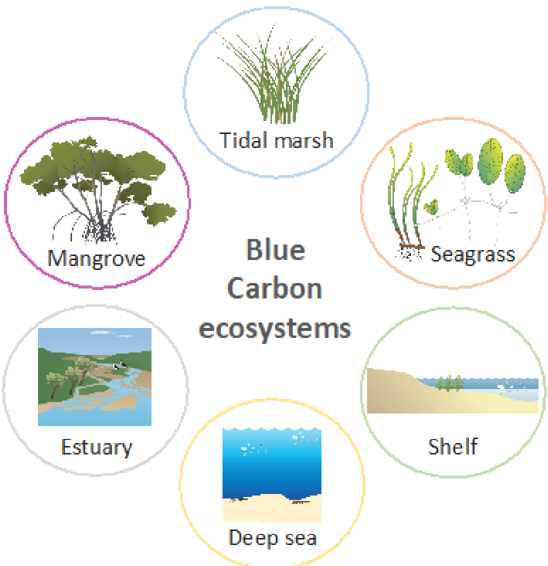
Current status: Timeline and steps for Blue Carbon science

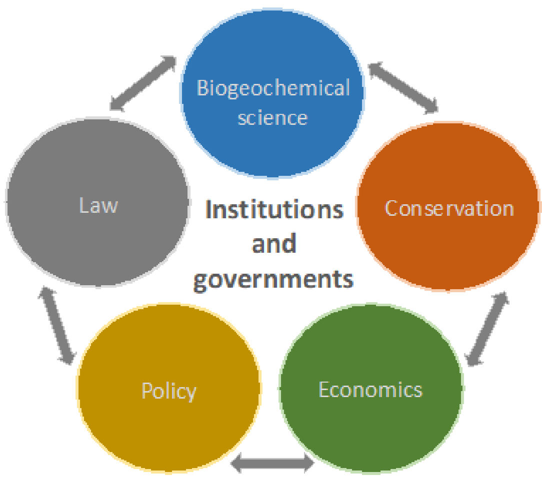
The term Blue Carbon was coined in 2009 to raise consciousness on the need to conserve and restore degrading marine and coastal ecosystems for climate change mitigation, and the preservation of the vital ecosystem services they provide (Nellemann et al., 2009), which together with the publication of another influential report (Laffoley and Grimsditch, 2009), contributed to rapidly advance Blue Carbon science and policy over the past two decades (Box 1). The interest and involvement of government agencies and Non-Governmental Organizations (NGOs) in Blue Carbon also contributed to push forward the political agenda. The first estimates of global GHG emissions from the conversion and degradation of Blue Carbon ecosystems (Pendleton et al., 2012) provided the basis to evaluate its climate and economic implications.

Box 1 The inception and evolution of the Blue Carbon concept

The inter-agency collaboration among United Nations Environment Program (UNEP), Food and Agriculture Organization (FAO) and United Nations Educational, Scientific and Cultural Organization (UNESCO), and Professor Carlos M. Duarte produced a report in 2009 that coined the term Blue Carbon to raise consciousness on the need to conserve and restore degrading marine and coastal ecosystems for climate change mitigation, and the preservation of the vital ecosystem services they provide (Nellemann et al., 2009). The initial definition embedded ecosystems that fall within the IPCC classification of ´wetlands´ (i.e., tidal marshes, mangroves and seagrasses) and therefore, they were readily actionable in policy frameworks due to the alignment with other policies for climate change mitigation and the existence of robust scientific evidence showcasing that conservation and restoration actions result in enhanced C sequestration and/or avoided GHG emissions. The Blue Carbon definition reported by Nellemann et al. (2009) also included coastal and marine habitats that play a key role in the ocean carbon cycle (i.e., estuaries, the continental shelf and the deep sea).

The Blue Carbon concept embeds multiple fields, entailing networks among biogeochemical sciences, conservation, economics, policy and law across multiple coastal and marine ecosystems. As a result, the Blue Carbon concept is evolving fast due to its complex nature and the rapid growth driven by the large potential of Blue Carbon as a Nature Climate Solution and the imperative need to take climate change action. The Blue Carbon concept aims at exploring and exploiting all potential options for ocean-based NBS for climate change mitigation. The evolution of the Blue Carbon concept includes the inclusion of new ecosystems (e.g., macroalgae, supratidal forests, salt flats, mud flats and phytoplankton), and activities and processes (e.g., farming and sequestration of C beyond the boundaries of photosynthetic ecosystems). It is envisaged that during the 2020s, science will support the implementation of multiple conservation, restoration and creation projects based on Blue Carbon ecosystems worldwide towards achieving scalable and meaningful climate change mitigation contributions.

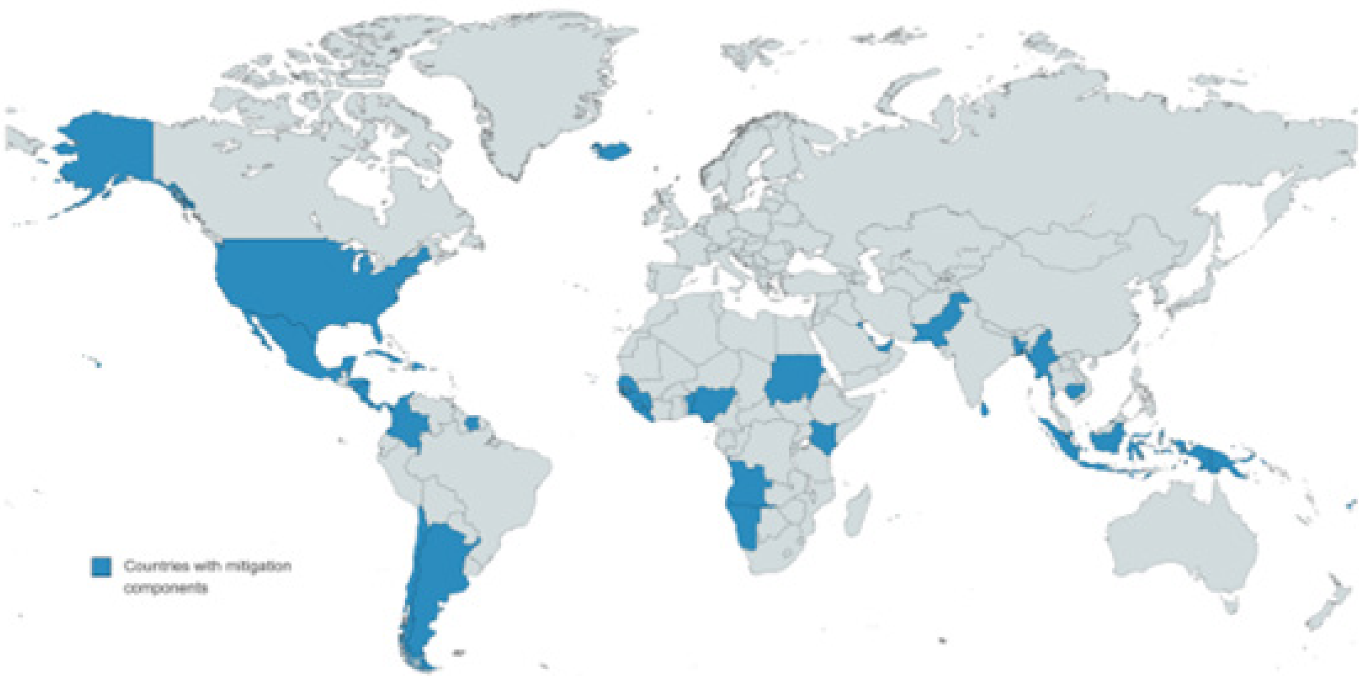




Current status: Timeline and steps for Blue Carbon science

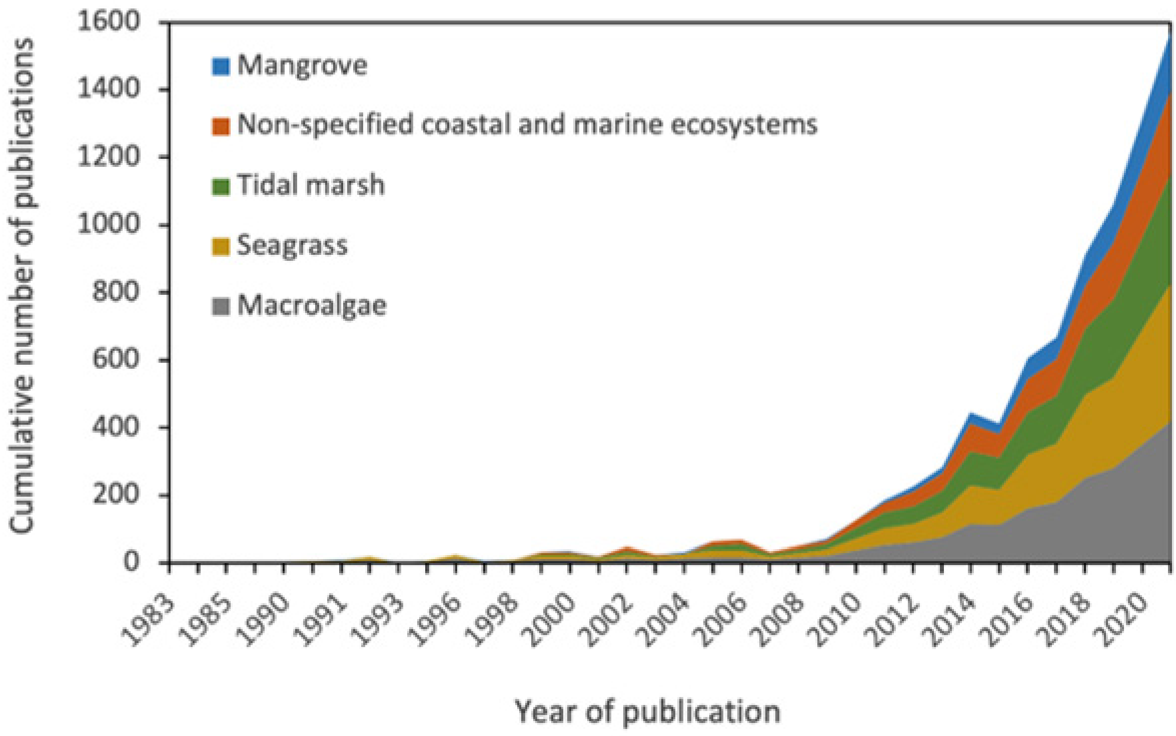
The release of the first Blue Carbon manual for measuring, assessing, and analysing Blue Carbon by the International Blue Carbon Initiative (Howard et al. 2014) also contributed to translate complex Blue Carbon terms into a friendly version that enhanced the uptake by developing countries, where the vast majority of Blue Carbon opportunities exist. The inclusion of Blue Carbon into IPCC guidelines in 2013 (IPCC, 2014) constituted a major milestone, enabling coastal nations to account for Blue Carbon as part of their Nationally Determined Contributions (NDCs) under the UNFCCC Paris Agreement (Figure 8), aiming at embedding a portfolio of actions to reduce emissions and remove GHG from the atmosphere.

Figure 8. Global map showing the countries that included Blue Carbon ecosystems (i.e., mangroves, seagrasses, tidal marshes, and other coastal ecosystems) as Nature-based Solutions (NbS) towards mitigating GHG emissions in their Nationally Determined Contributions (NDCs) (in blue) in October 2021 (Lecerf et al., 2021). 46 countries: Angola, Antigua and Barbuda, Argentina, Bahrain, Bangladesh, Barbados, Belize, Benin, Brunei Darussalam, Cape Verde, Cambodia, Chile, Colombia, Costa Rica, Cuba, Dominican Republic, Fiji, Guinea, Guinea Bissau, Honduras, Iceland, Indonesia, Kenya, Kuwait, Liberia, Maldives, Mauritius, Mexico, Myanmar, Namibia, Nicaragua, Nigeria, Pakistan, Panama, Papua New Guinea, Saint Lucia, Senegal, Seychelles, Sierra Leone, Singapore, Sri Lanka, Sudan, Suriname, Tonga, United Arab Emirates, and United States. Map created using http://www.mapchart.net.



The exponential increase in scientific evidence supporting the key role of Blue Carbon ecosystems in carbon storage worldwide (Figure 9), and the development of methodologies for carbon credit accounting linked to Blue Carbon conservation and restoration projects, showcases that the term Blue Carbon has been consolidated throughout the years and its role in climate change mitigation and adaptation has now reached international prominence. Currently, there are ongoing discussions to include more ecosystems besides seagrasses, tidal marshes and mangroves, under the Blue Carbon umbrella. A plethora of opportunities for climate change mitigation and SDGs initiatives encompassing a growing number of emerging Blue Carbon ecosystems is arising. In fact, in 2015 it was first proposed to include seaweed aquaculture as a Blue Carbon activity (Erlania and Radiarta, 2015), followed by a more detailed evaluation from a scientific point of view in 2017 (Duarte et al., 2017). Furthermore, carbon storage by large marine animals such as whales was proposed in 2010 (Lavery et al., 2010) and more novel options, including carbon storage by oyster reefs (Fodrie et al., 2017) and avoided trawling (Sala et al., 2021) are being discussed among scientists and policymakers.

Figure 9. Exponential growth in Blue Carbon research from 1983 to 2021. Number of cumulative publications addressing carbon storage in mangrove, tidal marsh, seagrass, macroalgae and other non-specified coastal and marine ecosystems across the past four decades. Adapted from Macreadie et al. (2021).



Blue Carbon resources, management and specificities

Tidal marshes

Key facts

- Tidal marshes are primarily found in estuaries along the coasts of Arctic, temperate and subtropical coastal lagoons, embayments, and low-energy coastlines.
- Within the tidal marsh community, there are often clear carbon storage patterns across inundation and salinity gradients.
- They sequester carbon at a rate ~55 times faster than tropical rainforests.
- Despite their importance, global mapping of tidal marshes has been undertaken in only 43 countries, yielding a total habitat extent that represents just 14% of the potential global area.

Tidal marsh ecosystems are among the most abundant, fertile, and accessible coastal habitats on earth (Gedand et al., 2009). Tidal marshes occur worldwide, but are primarily found in intertidal settings of estuaries along the coastlines of Arctic, temperate and subtropical coastal lagoons, embayments, and low-energy open coasts (Macreadie et al., 2019). The vegetation of a tidal marsh consists of halophytic (salt-tolerant) herbs, grasses and low shrubs adapted to regular or occasional tidal inundation (McOwen et al., 2017). Within the tidal marsh community, there are often clear patterns of zonation, typically linked to inundation and salinity, that drive differences in carbon storage (McOwen et al., 2017). Despite their importance, global mapping of their extent is at its onset, with areas reported for only 43 countries, yielding a total habitat extent of ~55,000 km2, which represents just 14% of the potential global area (Macreadie et al., 2019; McOwen et al., 2017). Tidal marsh coverage is well documented for Canada, Europe, USA, South Africa and Australia, but remains mostly unknown for regions such as Northern Russia, Africa and South America (Macreadie et al., 2019; McOwen et al., 2017). Therefore, producing accurate estimates of the global extent of tidal marshes is crucial to assess their global carbon storage and to identify habitats in need of protection and restoration.

Habitat loss

The minimum global rate of loss of tidal marsh area is estimated at 1–2% per year (Duarte et al., 2008), resulting in the loss of 25–50% of the global tidal marsh extent since the 1880s (Macreadie et al., 2013; Barbier et al., 2011). Tidal marshes' position at the land-sea interface poses significant threats stemming from human activities, including land reclamation for agriculture or development, altered hydrology and nutrient pollution. Furthermore, environmental changes driven by climatic forces such as increasing air and sea surface temperatures, spread of invasive species, and rising sea levels are impacting tidal marshes and their capacity to act as carbon sinks (Chmura, 2013). Effective management for tidal marsh conservation and restoration should account for present and future stressors acting at multiple spatial and temporal scales.

CO2 removal capacity

Tidal marshes are one of the most powerful carbon sinks on the planet. They bury at a rate ~55 times faster than tropical rainforests, and rank amongst the most significant terrestrial C sinks (Macreadie et al., 2013). Globally, C stocks tidal marshes are estimated at 860–1,350 Tg C (Macreadie et al. 2021), and their global carbon burial rates (28–70 Tg C yr-1) (Duarte, 2017) are within the range of those in tropical rainforests (53 ± 9.6 Tg C yr-1) (Macreadie et al., 2013). Above-ground biomass C accounts only for 1% of total C stores in tidal marshes (Alongi, 2020), thus leaving the majority of sequestered carbon in the soil, which can be several meters deep. It is estimated that 0.02–0.24 billion tons of carbon dioxide equivalents (CO2-e) are emitted each year to the atmosphere following the destruction of tidal marsh ecosystems (Pendleton et al., 2012).

Protection and restoration

The conservation and wise use of wetlands, including tidal marsh ecosystems, is promoted by international legal instruments and policy frameworks, such as the Convention on Wetlands of International Importance, the Ramsar Convention and the Convention on Biological Diversity 2. However, the percentage of global tidal marsh extent falling within protected areas remains undefined. Tidal marsh restoration approaches involve removing invasive vegetation and herbivores, changing the marsh elevation, and planting the desired species, but also restoring tidal flow through the removal of manmade barriers including dikes, dams and levees. Restoration of tidal marshes is now also included among NbS strategies including climate adaptation planning (Arkema et al., 2013; Barbier, 2014). Examples of successful tidal marsh restoration projects can be found worldwide, for example the recovery of 0.22 km2 of degraded tidal marshes in Huelva, Spain (Box 2).

Co-benefits

Tidal marshes provide a wide range of ecosystem services, including the support of coastal fisheries by acting as habitats for juvenile fish (Baker et al., 2020), while constituting biodiversity hotspots and food resources for coastal communities, and creating habitat for birds and other animals of commercial interest (Chmura, 2013). Tidal marshes act as a sink for nutrient runoff, thereby reducing nitrogen input to estuaries and diminishing the risk of toxic algal blooms and marine dead zones (Chmura, 2013). Furthermore, they are an effective NbS that protects the shoreline from erosion, flooding and storm surges, and are increasingly being used as protective measures with significant advantages over "hard" engineering solutions (e.g., breakwaters, groins, seawalls), in terms of cost and sustainable development. Efforts are emerging to use tidal marsh conservation and restoration in carbon offset programs, similar to the efforts to reduce emissions from deforestation and forest degradation in developing countries (REDD+), creating further economic co-benefits contributing to the SDGs (Chmura, 2013).

Mangroves

Key facts

- Mangrove forests are highly productive and sequester more carbon per unit area than any other tropical ecosystem, land or sea.
- Mangroves occur in 118 countries worldwide, but ~75% of total coverage is located within just 15 countries, most of them found in Asia.
- Vast areas of mangroves were lost over the 20th century; however, the rate of mangrove conversion decreased dramatically in the 21st century due to conservation efforts.
- 42% of mangroves are now located in protected areas, although the levels of actual protection these provide can be variable.

Mangroves are among the most well described and widely studied wetland communities in the world, and they receive considerably more attention in the media compared with tidal marsh and seagrass ecosystems (Duarte et al., 2013). Mangroves are a taxonomically diverse group of about 70 tree, shrub, and fern species (with at least 25 genera and 19 families) that grow in anoxic and saline soils mostly along sheltered, tropical coasts (Ellison et al., 2020). The global area of mangroves has been estimated in 81,500–152,400 km2 (Spalding et al., 2010; Hamilton and Casey, 2016), with a distribution across 118 countries. However, ~75% of total mangrove area is located within just 15 countries, most of them found in Asia, with ~23% found in Indonesia alone (Macreadie et al., 2019; Giri et al., 2011).

Habitat loss

Mangrove deforestation and disturbance of organic rich soils can release more CO_2 per hectare than deforestation of any other forest type (Hamilton et al., 2016). Over a quarter of the original mangrove cover has already been lost since the late 19th century. Total mangrove extent during the second half of the 20th century declined at rates 1–3% per year, mainly due to aquaculture, land use change and land reclamation (Valiela et al., 2009). Erosion, sea level rise, hurricanes and drought, which are exacerbated by climate change, are also leading to the die-off and loss of mangroves. It is estimated that between 2000 and 2016, 80% of the global losses induced by human activities occurred within six Asian nations mainly linked to aquaculture activities to support economic development (Goldberg et al., 2020). However, since the beginning of the 21st century, mangrove loss rates decreased to 0.16–0.39% per year (Hamilton et al., 2016), showcasing the implementation of conservation initiatives and sustainable practices in developing countries (Macreadie et al., 2019).

CO_2 removal capacity

Mangroves are one of the top three carbon-capturing ecosystems on Earth, sequestering mainly in their soils and distinctive root systems, which rise in lattices above the ground and water. Globally, mangroves store 1,750–3,900 Tg C in their biomass (Simard et al., 2019) and 2,600–6,400 Tg C in their soils (Atwood et al., 2017; Sanderman et al., 2018), with a global soil C burial rate estimated at 5–16 Tg C per year (Duarte, 2017). Although the extent of mangrove forests is relatively small compared with that of seagrass and macroalgae, the global mangrove C stocks are one order of magnitude greater than in other Blue Carbon ecosystems. About 0.09–0.45 billion tons of CO_2-e are emitted each year to the atmosphere following the destruction of mangrove ecosystems (Pendleton et al., 2012). On the other hand, it is estimated that global emissions from mangrove loss will reach 2,390 Tg CO_2-e by the end of the century (2020–2100) (Adame et al., 2021) reflecting the need for increasing conservation schemes. The restoration of recently lost mangrove could eventually restore 260 Tg CO_2-e into the biomass and avoid a further 1,100 Tg CO_2-e, through soil stabilization.

Protection and restoration

Avoiding further degradation of mangroves is of paramount importance to avoid fuelling CO_2 emissions. Currently some 42% of all remaining mangroves fall within legally designated protected areas, albeit recognizing that the levels of actual protection provided can be variable (Spalding et al., 2021). Such areas range from small, locally managed sites to nationally governed forests, such as the Sundarbans — which are protected across almost all its extent in both Bangladesh and India. South America is the region where over 74% of mangroves fall within protected areas, whereas this percentage is 13% for East Asia and only 9% for the Pacific islands. Unfortunately, global change maps demonstrate that mangrove losses still occur in protected areas (Spalding et al., 2021). The start of the UN Decade of Restoration, and partnerships such as the REDD+ Initiative and the Global Mangrove Alliance are seeking to increase mangrove area by 20% by 2030, while the Bonn Challenge has commenced and resulted in the acceleration of restoration and rehabilitation projects worldwide (Friess et al., 2019). Restoration projects vary across activities aiming at facilitating the natural regeneration to reforestation or the re-establishment of hydrological connectivity and sediment inputs. However, many of the projects have not been successful, mostly due to improper site selection, incorrect matching of species, the use of inadequate techniques and of failure to resolve socio-economic and institutional barriers to effective restoration.

Co-benefits

Mangroves have long been recognized by coastal communities as a critical ecosystem because of their numerous benefits. Apart from acting as carbon sink, mangroves conform NbS against erosion, storms and floods, via wave attenuation achieved over mangroves' roots, trunks and canopy. A 100-metre mangrove strip is considered to reduce wave heights by 13–66%, which can save lives during major storms (Van Wesenbeeck et al., 2019). Also, mangrove forests have the capacity to keep pace with sea level rise and to avoid inundation through vertical accretion of sediments (Lovelock et al., 2015). At the same time, mangroves regulate sediment and water quality, by taking up pollutants and nutrients, and provide habitat for a broad range of birds and threatened species such as Bengal tigers (Sills et al., 2020). Indeed, in many countries, over 80% of small-scale fisheries rely on mangroves and 4.1 million fishermen operate in mangrove forests worldwide (Spalding et al., 2021). Mangroves are also important for national tourism industries and community recreation (Ahmad et al., 2021). A recent study published a survey of data from TripAdvisor reporting almost 4,000 mangrove "attractions" in 93 different countries and territories (Spalding et al., 2018).

Seagrass meadows

Key facts

- Seagrass ecosystems cover only 0.1 to 0.5% of the ocean floor, but act as highly efficient carbon sinks storing up to 18% of the world's carbon in marine sediments.
- The global seagrass area has decreased by ~29% since first reported in 1879, and only 26% of seagrass meadows fall within Marine Protection Areas (MPAs).
- There is a lack of proper mapping and monitoring of seagrass extent around the world.
- Restoration projects have been proven successful at a 10–20 years' timeframe, but their success is strongly connected to robust management schemes and transboundary cooperation.
- Seagrass meadows provide co-benefits that contribute to climate change mitigation and adaptation, improving the resilience of coastal communities and contributing to a sustainable ocean economy.

Seagrasses are a highly productive group of flowering plants, consisting of about 60 angiosperm species that adapted to life in the sea more than 30 million years ago, and are permanently or temporarily submerged (Duarte et al., 2013; Hemminga and Duarte, 2000). They are found in shallow waters along the shorelines of every continent except Antarctica (Duarte, 2002). They exist in 159 countries, covering between 0.3 to 1.6 million km2, or about 0.1 to 0.5% of the global ocean (United Nations Environment Programme, 2020; Jayathilake and Costello, 2018). The widespread distribution of seagrass contrasts with other Blue Carbon ecosystems that are geographically restricted to much smaller latitudinal ranges (e.g., mangroves inhabiting mostly tropical regions, and kelp beds and tidal marshes thriving in temperate regions) (Orth et al., 2006). Despite their widespread occurrence across temperate and tropical regions, the global extent of seagrasses is poorly estimated (Duarte, 2017), due to the lack of seagrass mapping, particularly in Africa, Indian Ocean, Indo Pacific region and the western coast of South America (United Nations Environment Programme, 2020). Therefore, producing accurate estimates of the global extent of seagrasses is a pressing milestone to protect the remaining meadows and identify areas for restoration.

Habitat loss

Unfortunately, the total global seagrass area has decreased by ~29% since first reported in 1879 (Waycott et al., 2009), although a reversal in the declining trend of seagrass meadows has been reported for some regions since the 2000s (de los Santos et al., 2019). Multiple stressors are responsible for seagrass decline worldwide, including sediment and nutrient runoff, coastal development, unregulated fishing activities, dredging, aquaculture, overgrazing, invasive species, algal blooms, global warming, storm surges and sea level rise (Orth et al., 2006; Rasheed et al., 2011). As a result, the identification of environmental thresholds that result in seagrass decline is the first step to implement effective management actions that halt current losses.

CO2 removal capacity

Seagrass meadows are highly efficient carbon sinks, storing globally up to 18% of the world's carbon deposited in the seafloor, which is equivalent to 10–308 Tg organic carbon (C) per year or 37–1,130 Tg CO2 equivalents per year (CO2-e) (Duarte, 2017). Seagrasses have millenary soil C stocks that can reach up to several meters in height (Lo Iacono et al., 2008), estimated at 3,760–21,000 Tg C worldwide (Macreadie et al., 2021), which are comparable to those of temperate and tropical forests, mangroves, and tidal marshes (Duarte et al., 2005; Fourqurean et al., 2012). Soil C stocks constitute up to 98% of total C stores in seagrass meadows, which accumulated from the net primary production of the meadows (autochthonous C) and through the trapping of organic particles from adjacent marine and terrestrial ecosystems (allochthonous C) (Kennedy et al., 2010; Serrano et al., 2019). The carbon stored in the above-ground living biomass (e.g., leaves) constitutes only ~2% of the total C pools and it is more prone to grazing, export or decomposition and therefore, it is considered a short-term carbon sink not relevant for climate change mitigation (United Nations Environment Programme, 2020). Furthermore, an estimated 24% of seagrass production is exported and buried elsewhere, indicating that the sole assessment of soil carbon stocks and accumulation rates within seagrass habitats might underestimate the role of seagrass in the global carbon cycle (Duarte and Krause-Jensen, 2017). The capacity of seagrasses to sequester carbon varies among seagrass species, meadow characteristics and environmental conditions. For instance, Posidonia oceanica meadows in the Mediterranean Sea are considered Blue Carbon hotspots, accumulating about three times more than other seagrass species (Fourqurean et al., 2012). It is estimated that 0.05–0.33 billion tons of CO2-e are emitted each year to the atmosphere following the destruction of seagrass ecosystems (Pendleton et al., 2012).

Protection and restoration

Regrettably, most seagrass meadows are not covered by management plans or protected against anthropogenic impacts. The inclusion of seagrass ecosystems in Marine Protected Areas (MPAs) via legislative frameworks (e.g., Natura 2000; Diaz-Almela and Duarte, 2008) is fundamental for their conservation. However, only 26% of recorded seagrass meadows fall within MPA compared with 40% of coral reefs and 43% of mangroves (United Nations Environment Programme, 2020). Seagrass conservation can also be achieved through integrated and cross-sectoral management schemes, such as ecosystem-based Marine Spatial Planning (MSP) that considers and tackles multiple pressures from human activities at the land-sea interface. Restoration of degraded seagrass ecosystems, whether by planting or facilitating natural recolonization, can be effective in reversing biodiversity loss and recovering ecosystem services (United Nations Environment Programme, 2020). Several examples of successful seagrass restoration projects exist, including the restoration of 36 km2 of Zostera marina meadows with seeds in Virginia, United States of America (Box 3). However, although seagrass restoration efforts continue to grow worldwide, improved restoration practices are needed to enhance the success of future programs (Orth et al., 2020; Tan et al., 2020). Emerging techniques for seagrass restoration and transboundary collaborations shed some light for upscaling seagrass restoration into the future.

Co-benefits

Healthy seagrass ecosystems provide numerous co-benefits besides CO2 sequestration with significant ecological and economic values for the environment and the livelihoods of coastal communities (Dewsbury et al., 2016), and constitute key NbS towards climate change mitigation and adaptation and contributing to multiple SDGs. Seagrass meadows improve water quality by filtering, cycling and storing nutrients and pollutants including metals and pathogenic bacteria that can cause coral diseases and seafood contamination (Lamb et al., 2017). In addition, they act as a natural line of defense that protects the shorelines from erosion, flooding and storm surges (Duarte et al., 2013; Ondiviela et al., 2014), contribute to mitigate ocean acidification increasing seawater pH through photosynthesis (Ricart et al., 2021), provide shelter and food for thousands of species, including fish, shellfish and threatened and endangered species, such as dugongs, seahorses and sea turtles, and are key to world fisheries production providing nursery habitat to over one fifth of the world’s largest 25 fisheries (Unsworth et al., 2019), which have a total value of at least €200 million per year in the Mediterranean alone (Jackson et al. 2015). Seagrasses additionally provide cultural benefits worldwide from supporting tourism and sourcing nanoparticles for cancer treatment, to being of spiritual and religious importance (Palaniappan et al. 2015; United Nations Environment Programme, 2020).

Macroalgae

Key facts

- Macroalgae is the most extensive and productive coastal vegetated habitat around the world, growing along approximately one quarter of the world's coastlines.
- Seaweed farming is the fastest growing sector of aquaculture in the world, at 8% increase in extent per year.
- Seaweed provides a wide range of product applications from food and feed products to pharmaceuticals and biogases.
- Scaling-up seaweed aquaculture is highly dependent on area suitability and competition for other marine uses.

Marine macroalgae, better known as seaweed, is classified according to its pigmentation into brown (Phaeophyta), red (Rhodophyta), and green (Chlorophyta) colours (Chan et al., 2006). Brown algae is commonly called kelp and can reach tens of meters in height (Wernberg et al., 2019). Macroalgae is the most extensive and productive coastal vegetated habitat around the world, growing along approximately one quarter of the world's coastlines and occupying 6 million km2 (Duarte et al., 2022). Macroalgae are rich in minerals, vitamins and polysaccharides, with some species also containing larger amounts of amino acids, proteins and fatty acids (Leandro et al., 2020). Macroalgae comprises a vast range of species, with 72,500 species described and many more to be discovered (Guiry, 2012).

Habitat loss

While there is no overall assessment of the global rate of change in seaweed habitat extent, it is estimated that kelps have experienced a global average annual loss rate of approximately 0.018% per year over the past 50 years, with large geographic variability (Krumhansl et al., 2016; Wernberg et al., 2019). Threats to macroalgae include invasive species, sedimentation, bottom trawling, eutrophication, ocean acidification, global warming and marine heatwaves, oil spills, overfishing and overharvesting (Spalding et al, 2019; Krumhansi et al., 2012). Macroalgae are not currently recognized as an official Blue Carbon ecosystem by the UNFCCC policies due to scientific knowledge gaps including the rates of carbon assimilation and the fate of exported macroalgae (Pessarrodona et al., 2018). However, this view has been recently challenged (Hill et al., 2015; Trevathan-Tackett et al., 2015; Moreira and Pires, 2016) and new scientific evidence suggests that seaweeds are globally relevant contributors to oceanic carbon sinks (Krause-Jensen and Duarte, 2016). Hence, the contribution of seaweed to Blue Carbon and climate change mitigation strategies is now being reconsidered (Duarte et al., 2017).

CO2 removal capacity

Seaweed has been previously overlooked within the Blue Carbon framework because it grows on hard surfaces, and therefore the accretion of carbon within macroalgae habitat boundaries is restricted, which contrasts with mangrove, seagrass and tidal marsh ecosystems that accumulate C within the habitat. However, seaweed may be a significant carbon donor to Blue Carbon stocks due to its large net primary production and ability to be transported and stored for centuries in deep sea water and sediments (Krause-Jensen and Duarte, 2016; Duarte et al., 2022). This process also occurs in mangrove, seagrass and tidal marsh ecosystems, but the spatial and temporal scales involved in this C sequestration process makes it difficult obtaining global estimates and deciphering its importance. Recent estimates suggests that macroalgae sequester 61–268 Tg C per year globally mostly through C export and sequestration in the deep sea (Krause-Jensen and Duarte, 2016).

Seaweed aquaculture (farming) is the fastest-growing component of global food production, with a growth rate of 8% per year, and has been proposed as a NbS for climate change mitigation and adaptation, while constituting an alternative to CO2 demanding land-based options for food and fuels (Duarte et al., 2017). Farmed seaweeds, similar to wild seaweeds, contribute to C sequestration through export of dissolved and particulate C to deep sea sinks during the production phase (Duarte et al. 2017). Recent estimates suggest that seaweed farming could prevent 0.05–0.29 billion tons of CO2-e emissions per year by 2050, if a 14% annual increase in seaweed production is achieved (Hoegh-Guldberg, 2019). However, these estimates assume that 100% of the yield would be sequestered, which is highly unlikely, as seaweeds are farmed for many other and more economically profitable purposes that result in CO2-e emissions. When a 25% of the seaweed yield is assumed sequestered, then the projected seaweed aquaculture would have an associated sequestration of 6.7 to 44 Tg CO2 per year by 2050 (Hoegh-Guldberg, 2019). The CO2-e emitted each year to the atmosphere following the destruction of macroalgae ecosystems remains unassessed.

Protection and restoration

Restoration of natural kelp forests is necessary to safeguard the numerous ecosystem services provided by kelp into the future (Duarte et al., 2017) and can be achieved throughout the establishment of protected areas, fishing regulations, sea urchin removals by commercial harvest, as well as identifying and planting species more resistant to global change (Krumhansi et al., 2012). Seaweed aquaculture occupies a minimal fraction of the coastal ocean (0.004%), and its expansion is limited by the availability of suitable areas (Duarte et al., 2017).

Co-benefits

Macroalgae not only can be considered a Blue Carbon sink, but presents numerous co-benefits, both for climate change adaptation and mitigation, but also for society. Kelp forests provide structural habitat, food and shelter for many marine species (Howard et al., 2017), while reducing wave energy and coastal erosion, as well as buffering ocean acidification and avoiding deoxygenation (Duarte et al., 2017). Seaweed products include bio-based, high value molecules, such as pharmaceuticals, nutraceuticals, cosmetics, fertilizers, as well as food and feed products, ingredients and supplements. They also include low-valued commodity energy carrying molecules, such as biofuels, biodiesels and biogases (Chopin et al., 2020). Many of these products might replace products with a higher CO_2 footprint, thereby avoiding emissions, rather than directly contributing to sequestration (Lehahn et al., 2016, Duarte et al., 2017). Furthermore, addition of seaweeds to animal feeds can lead to reduced enteric methane GHG emissions from ruminants (Machado et al. 2016). Seaweed farming constitutes a successful example of gender equity and reduced inequalities, as in most developing countries, the majority of people involved with seaweed farming are women (Msuya and Hurtado, 2017).

Sargassum Forests

Source: Gouvea et al., 2020

Brown seaweeds of the genus Sargassum are the largest canopy-forming algae in tropical and subtropical regions, with a wide global distribution on rocky reefs and as floating stands. Recent research suggests that Sargassum forests store 13.1 Pg C globally, playing a relevant role in the global carbon cycle, and showcasing that their management could help mitigating climate change. However, over the past seven years Sargassum has bloomed in open ocean areas of the North Atlantic and Caribbean, leading to massive quantities on beaches with negative impacts on tourism, human health and coastal ecology. Therefore, specific techniques related to bloom production and management should be fostered.

Emerging Blue Carbon options

Blue carbon accreditation methodologies currently exist for tidal marshes, mangroves and seagrasses. Researchers are trying to explore other ecosystems that could be included under the Blue Carbon concept and to develop new methodologies. These include seaweed, marine fauna including whales and sea otters, as well as bivalves and seabed sediments. Inclusion of these approaches into the IPCC framework requires a holistic or seascape management of the marine environment, while also helping countries to meet NDCs targets laid out in the Paris Climate Agreement (Norris et al., 2021).

Marine fauna

Marine fauna (fish, marine mammals, invertebrates, etc.) influence the C cycle of the ocean through a range of processes, that include accumulating and storing C in their bodies by eating phytoplankton and other marine species. When they live and die, they excrete C-rich waste products that either sink to the deep sea or are consumed by other species. Furthermore, their movement between habitats promotes mixing within the water column, contributing to increased phytoplankton production. It was only recently that scientists started to acknowledge that healthy populations of fish and marine mammals have the potential to keep C away from the atmosphere, whereas overfishing of stocks can remove large amounts of Blue Carbon from the ocean. Although there are large data gaps, a first-order assessment estimates that 7,000 Tg CO2-e has accumulated within marine fauna biomass (Bar-On et al., 2018). For instance, it is estimated that if whales were allowed to return to their pre-whaling numbers, they would be able to sequester 1.7 billion tons of CO2 annually, while even a 1% increase in phytoplankton productivity thanks to whale activity would capture hundreds of millions of tons of additional CO2 per year (Chami et al., 2019). On the other hand, there is uncertainty related to the net C sequestration benefit from marine fauna, mostly due to the respiration process during the lifetime of the animals (Norris et al., 2021). In fact, only CO2 fixed through photosynthesis and sequestered over periods of time relevant to climate change mitigation are being considered as NbS by the IPCC. Rebuilding marine life represents a doable Grand Challenge for humanity, an ethical obligation and a smart economic objective to achieve a sustainable future (Duarte et al., 2021), thus estimating the impact of protecting or restoring populations of fish and marine mammals to previous levels on the global C cycle is necessary.

Phytoplankton

Marine phytoplankton include photosynthetic algae and bacteria that fix dissolved inorganic carbon which is then mainly consumed and stored in the biomass of other organisms. It is estimated that they are responsible for ~50 % of global primary production (~50 Gt C/year) (Hilmi et al., 2021). The amount of carbon fixed by phytoplankton and subsequently sequestered varies regionally and temporally, depending on surface water productivity, grazing/microbial degradation, and physical processes such as turbulence (Barnes et al., 2020; Briggs et al., 2020). Most of the carbon fixed by phytoplankton is grazed by zooplankton although viral attack can also release their organic material which is then broken down by other microbes (Breitbart et al., 2018) generating particulate and dissolved organic matter, some of which will end up in deep water masses. The microbial breakdown of organic carbon produced by phytoplankton is estimated to sequester nearly 0.2 Pg C per year (0.74 Pg

CO2-e per year) into the deep sea (Legendre et al., 2015). Fecal pellets, exoskeletons, dead animals and the vertical migrations of open ocean animals also transport the carbon from phytoplankton into the deep sea (Boyd et al., 2019). It is estimated that stimulating phytoplankton production could lead to sequestration of 7 Tg CO2-e per year (Lavery et al., 2010).

Seabed sediments

Seabed sediments cover 350 km2 globally and are estimated to hold 2,000 billion tons of C in the top 1 meter (Atwood et al., 2020), sequestered at a rate of 156 million tons C per year (Smith et al., 2015; Smeaton et al., 2021). Hotspots of C storage in seabed sediments include coastal shelves, shallow seas, productive upwelling areas, fjords and estuaries (Atwood et al., 2020; Sala et al., 2021; Smeaton et al., 2021). As a result, seabed sediments are crucial C reservoirs, and there is considerable theoretical potential to store CO2 in the ocean (McLeod et al., 2011). However, any proposals for ocean-based C storage must consider the substantial risks to the ocean environment and its ecosystems and the associated technical, economic, social, and political challenges. Disturbance of C stores within seabed sediments, such as by bottom-trawling, dredging and offshore construction, can result in GHG emissions. For this reason, only the protection of sedimentary C is hereto considered, whereas geoengineering approaches for C storage in sediments remains outside IPCC frameworks. Recent estimates suggested that disturbance to the seafloor results in an estimated 1.5 Pg of CO2-e emissions for the first year after trawling, and approximately 0.58 Pg CO2-e emissions per year for up to around 400 years (Sala et al., 2021). The implementation of fishing regulations along with ecosystem-based MSP can help alleviating the consequences of seabed disturbances in the C cycle. Seabed C stocks can be protected via the establishment of protected areas. However, currently, only about 2% of global seabed C stocks have such protection (Atwood et al., 2020).

Shellfish reefs

The role of non-photosynthetic and calcifying ecosystems, such as oysters and clams, in capturing C is currently being explored as an alternative Blue Carbon option. There is an ongoing debate of whether shellfish and bivalves act as net CO_2 sources or sinks. As for all living animals, they are sources of CO_2 through the respiration process, but also through the calcification (shell formation) (Lee et al., 2020). However, bivalves such as oysters and mussels act as filter feeders taking particles from the water, ingesting them and depositing them as C-rich faeces that can become sequestered (Lee et al., 2020). Through sediment C accumulation, shellfish reefs may contain significant pools of C. It is estimated that shallow subtidal reefs and tidal marsh fringing reefs could sequester almost 80 tons CO_2-e per ha and year (Fodrie et al., 2017). Recent research suggests that shellfish reefs may increase C sequestration and storage capacity in other habitats, thus providing an indirect mitigation potential (Ridge et al., 2017), while reducing flood risk at a lower cost compared with “hard” infrastructure. Scientific evidence supporting the net C sequestration capacity of calcifying organisms, including corals, is required prior to their inclusion into Blue Carbon schemes. On the other hand, historical mining of the top meter of shellfish reefs may have reintroduced more than 400 Tg C into estuaries (Fodrie et al., 2017), showcasing that the protection of existing reefs is imperative.

Outlook: Global potential of Blue Carbon strategies for climate change mitigation

The protection and restoration of tidal marsh, mangrove and seagrass ecosystems worldwide have the potential to revoke 3% of annual global emissions from fossil fuel combustion (Macreadie et al. 2021). The protection of Blue Carbon ecosystems to avoid further losses in their extent can result in avoided GHG emissions from the decomposition of biomass and soil C estimated at 304 Tg CO2-e per year (ranging from 141-466 Tg CO2-e yr-1), whereas the potential of CO2 abatement throughout restoration has been estimated at 841 Tg CO2-e per year by 2030 (ranging from 621 to 1,064 Tg CO2-e yr-1). Potential for restoration has been estimated in 0.2–3.2 million ha for tidal marshes, 8.3–25.4 million ha for seagrasses and

9–13 million ha for mangroves. These estimates of Blue Carbon climate change mitigation potential only include tidal marsh, mangrove and seagrass ecosystems and thereby, the global potential of Blue Carbon strategies for climate change mitigation can be orders of magnitude larger if seaweed and emerging Blue Carbon ecosystems are included.

Recovering the historic extent of Blue Carbon ecosystems is crucial to achieve the full potential of Blue Carbon as a NbS. Global scale restoration is constrained by several socio-economic factors, in particular when restoration conflicts with the livelihoods and food security of local communities. Other constraints for the recovery of Blue Carbon ecosystems include economical, legal and logistic barriers that can make restoration unfeasible, for example, in urban areas. However, the main anthropogenic activities that caused the loss of Blue Carbon ecosystems worldwide are reversible, including production activities that caused large losses in Asia and America, such as the conversion of rice addies, aquaculture ponds and pasture lands to wetlands.

Although in many cases the historical extent of Blue Carbon ecosystems remains poorly captured, the scientific community developed maps of potential global habitat distribution that can be used to inform restoration initiatives. The identification of hotspots for achieving high C abatement throughout the conservation and restoration of Blue Carbon ecosystems at low cost, either through the implementation of a low-cost activity or the management of habitats with large C storage, is crucial to achieve climate targets over the next decade.

The potential of Blue Carbon as a NbS will largely rely on societal actions. Although restoring and conserving Blue Carbon ecosystems will be a key focus of the UN Decade on ecosystem restoration (2021–2030), critical science and policy advances are required to promote the uptake and scalability of Blue Carbon projects and crediting schemes. Emerging Blue Carbon markets should aim to incorporate the value of co-benefits into financial frameworks to boost the investments required for restoration and conservation.

Figure 10. Representation of potential Blue Carbon projects occurring simultaneously within a coastal site. 1) Demolition of a wall allowed the reintroduction of tidal flow and the regeneration of mangrove forests; 2) Revegetation of mangrove forests with seedlings following a mangrove die-off event; 3) Restoration of seagrass meadows with seeds following a collapse in the ecosystem due to eutrophication; 4) Plantation of mangroves in a previously bare area; 5) Deployment of seaweed farming facilities; 6) Conservation of mangrove ecosystems throughout the banning prawn aquaculture; 7) Wrack harvesting and reintroduction into the ocean; 8) Fencing mangrove ecosystems to avoid the impact of wild pigs. Projects 1 to 3 result in avoided GHG from extant soil C stocks and enhanced C sequestration; projects 4 and 5 result in enhanced C sequestration; and projects 6, 7 and 8 result in avoided GHG emissions. All projects contribute to the Sustainable Development Goals (SDGs) set up by the United Nations to attain a better and more sustainable future for all.

Implementing Blue Carbon Strategies: Case studies of Blue Carbon Projects around the world

Although relatively few ongoing Blue Carbon projects are currently in place, it is envisaged that the number of projects will increase exponentially over the UN Decade of Ecosystem Restoration. Boxes 2 to 4 illustrate some examples of the implementation of Blue Carbon projects as well as its outcomes. Furthermore, indicative ongoing Blue Carbon projects are shown in Figure 11 and briefly described below.

Case studies of completed Blue Carbon Projects

Box 2 Loss and recovery of tidal marsh C sinks following degradation and restoration – Port of Huelva, Spain

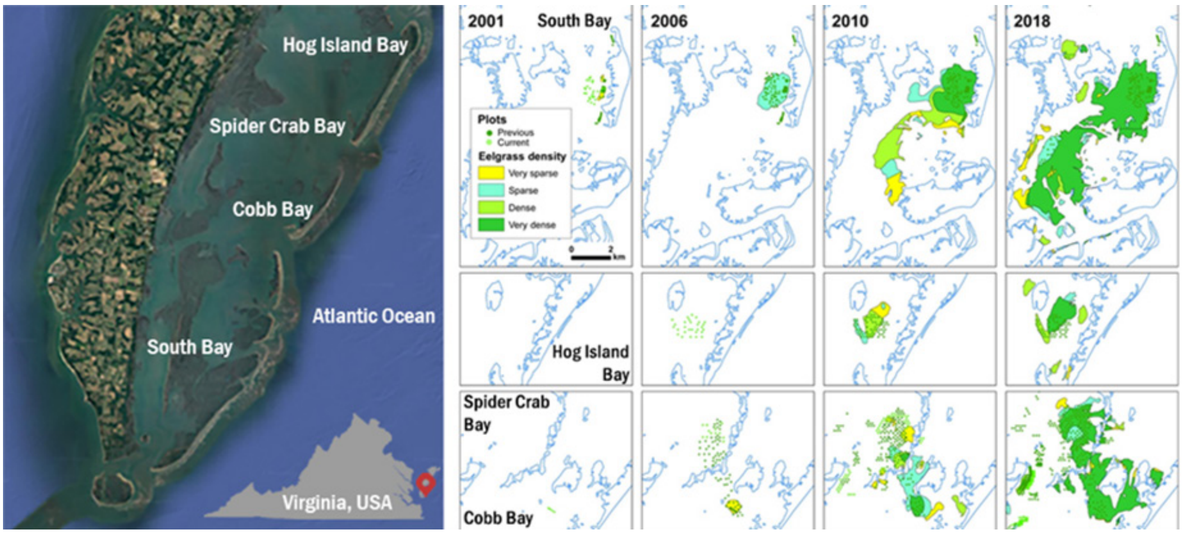
The Port of Huelva is located in the Southwest of Spain, a strategic position with respect to the main international maritime routes. Specifically, its land and inland water service area is located in the estuary of the Odiel and Tinto rivers. Throughout its history, the Port of Huelva has been closely linked to the province's wealth of minerals. It presents continuously growing facilities and traffic, consolidating itself as one of the first Ports of General Interest in Spain. However, Huelva Port is located in an area of great environmental and biological importance protected by international schemes such as Biosphere Reserve, Natura 2000 Network, Natural Site and RAMSAR. The continuous use of the port has led to environmental degradation. In the 1980s and 1990s, different plans were executed to reduce industrial spills. However, there were damaged tidal marsh areas with high rates of erosion that required intervention for environmental recovery, as well as areas without vegetation or dominated by the invasive species Spartina densiflora. The Ecological Recovery project of the port illustrates a successful example of concentrated efforts for over 10 years and a total investment of 27 million euros. The project addressed the environmental recovery of the degraded left bank of the Odiel estuary and the conservation of habitats and their environmental values. More than 100,000 seedlings of the native species Spartina maritima were introduced, with the project covering more than 0.22 km2. The environmental work was complemented with the construction of a pedestrian path of 4 km. The latter has provided citizens with a recreational area of high environmental and social value. The project, first experience in Europe, resulted in the recovery of the native tidal marsh habitat and its associated ecological functions. Also, it led to the creation of a C sink that captures more than 300 tons of C annually, the stabilization of marshes eroded by sea level change, the conservation of protected bird species and the eradication of invasive species. Furthermore, the project increased public awareness through educational programs. The Ecological Recovery project not only positioned the Port of Huelva as an international example of good environmental practice but proved that human activities and conservation could actually coexist if proper management efforts are undertaken.

Sources: https://sustainableworldports.org/project/port-of-huelva-ecological-recovery-project/; https://www.aivp.org/en/good-practices/the-port-of-huelva-spain-restores-the-estuary-and-explains-its-environment/; https://app.puertohuelva.com//recursos/doc/aphuelvamemoria2019/2020/05/28/04-environmental-dimension.pdf

Box 3 Seagrass meadow degradation and restoration – The case study of the Coastal Bays of Virginia, USA

An example of a loss and subsequent successful seagrass restoration was documented in the inshore lagoons of Virginia, USA, along the mid-western Atlantic. The area once supported vast meadows of eelgrass (Zostera marina) meadows that provided numerous ecosystem functions and services, including commercial and recreational activities supporting the local economy. However, in 1933, all eelgrass meadows were eradicated in the Virginia coastal lagoons, due to a slime mould disease along the entire east coast of the United States and the west coast of Europe, combined with a devastating hurricane. The eradication of the meadows led to the total loss of species including the brant goose, and the commercially valuable fishery for the bay scallop. For over 70 years, eelgrass was not documented in the Virginia coastal lagoons, mainly due to seed recruitment limitation, rather than degraded environmental conditions. In 2001, the establishment of a

seed-based restoration where 74 million seeds were broadcast into more than 500 individual restoration plots annually for over 20 years resulted in 36 km2 of restored eelgrass meadows. More than half of the restored meadows occur in just one bay, South Bay, while the remaining 44% is spread among three nearby bays: Cobb, Spider Crab, and Hog Island Bays. The restored meadow removed 4,100 tons of nitrogen through plant uptake and sediment storage and has C stocks and C accumulation rates similar to those of natural meadows, with an estimated 15,000 tons of C being sequestered, which together with the recovery of additional ecosystems services have an economic value estimated at $8 million per year.



Sources: Orth RJ, Lefcheck JS, McGlathery KS, et al. Restoration of seagrass habitat leads to rapid recovery of coastal ecosystem services. Sci Adv. 2020;6(41):1-10. doi:10.1126/sciadv.abc6434; United Nations Environment Programme (2020). Out of the blue: The value of seagrasses to the environment and to people. UNEP, Nairobi; https://www.sciencenews.org/article/seagrass-restoration-project-virginia-ecosystem-rapid-recovery

Box 4 Tidal reintroduction and Blue Carbon restoration at Trinity Inlet (Queensland, Australia)

Between 1971 and 1975, the tropical mangroves forests, tidal marshes and salt flats surrounding the Trinity Inlet in north Queensland, Australia, were drained by construction of floodgates and a bund wall for the production of sugar cane. Approximately 110 ha of drained soils were exposed to erosion leading to a range of environmental issues. The loss of 1.3 m of soil elevation resulted in the loss of 74,800 Mg C ha-1 over 23 years (until 1999). The soil C remineralisation led to an estimated 0.27 Tg of CO2 emissions. The draining of these highly organic soils exposed soil organic carbon to oxygen and microbial attack, which also led to the formation of acid sulfate soils with a pH of 3.2 (Hicks et al., 2003) that reached and damaged adjacent estuaries. The Queensland Government purchased the site in 2000 to reintroduce tidal flow and remediate the site. Although the Trinity Inlet returned to a healthy status thanks to restoration activities, avoided CO2 emissions and enhanced soil organic carbon following restoration remains to be assessed

The picture above (left image) shows the bund walls surrounding the Trinity Inlet built for the production of sugar cane in 1970s that resulted in GHG emissions and acid sulfate soils. The reintroduction of tidal flow in 2000s resulted in the recovery of vegetation by 2021 (right image; source: Nearmap Australia Pty Ltd).

Figure 11. Map showing some of the ongoing Blue Carbon projects around the world. The pins indicate the location of the projects and the icons show the ecosystems targeted for restoration: tidal marshes, mangroves, seagrasses and kelp.

The Sussex Kelp Restoration Project, UK

Since 1987, over 96% of kelp has been destroyed along the Sussex coastline due to the cumulative effects of human pressure, especially trawling. Once healthy, kelp forests occupied 40 km along the Sussex coastline providing shelter, feeding and nursery grounds for many marine species including cuttlefish, lobster, seabream and bass. The Sussex Kelp Restoration Project aims to protect the wider area of 340 km2 from trawling and restore 167 km2 of historical kelp forests through planting activities. The project commenced in 2021 and involves various collaborators including the Sussex Wildlife Trust, the Blue Marine Foundation, the University of Brighton and the University College London (UCL).

Sources: https://www.rewildingbritain.org.uk/rewilding-projects/sussex-kelp-restoration-project; https://sussexwildlifetrust.org.uk/helpourkelp

Apple's restoration of mangroves in Colombia

In 2018, Apple partnered with Conservation International, local government, local communities and conservation organisations in Colombia to protect and restore almost 110 km2 of mangroves. These mangroves are very important for the coastal communities since they protect the shoreline and sustain the communities' livelihoods. The goal is to sequester 1 million tons of CO2 over the project's lifetime. This project is the first to use "Blue Carbon" methodology to rigorously value the entire mangrove system — both above and below the waterline — for its climate mitigation impacts.

Sources: https://www.apple.com/newsroom/2019/04/conserving-mangroves-a-lifeline-for-the-world/

The Blue Carbon Project Gulf of Morrosquillo

Verra has registered in March 2022 "The Blue Carbon Project Gulf of Morrosquillo" in Colombia. The project was developed by Conservation International with the support of South Pole. It seeks to sequester almost 1 million tonnes of CO2 over 30 years by conserving and sustainably managing 75.6 km2 of mangroves, marshes, and associated streams. In parallel, the project tries to strengthen local governance; protect the habitat of several endangered species such as manatees and otters; promote jobs and activities such as bee-keeping and ecotourism; and introduce sustainable food sources such as community gardens.

Sources: https://verra.org/press-release-verra-has-registered-its-first-blue-carbon-conservation-project/

Restoring mangroves in Mozambique

Mozambique has historically suffered from cyclones, including cyclone Eline and the 2000 storm, the longest-lived cyclone on record in the Indian Ocean. The cyclone destroyed homes, fields and nearly 60% of the mangroves in Limpopo's estuary. Suddenly, residents, who relied on these mangroves to support their livelihoods, were not only economically impacted, but also found themselves exposed to coastal flooding and erosion. As a response to this environmental and socio-economic crisis, the community, the Mozambican government and partners launched an effort to restore 50 km2 of mangroves as part of its Mangrove Management Strategy (2020–2022). That's why this project will combine traditional planting techniques with a hydrological method that seeks to let the environment to return to its initial state. A key recent finding from this research is that the active unblocking of creeks reinstates tidal inundation, which has led to a three-fold increase in restoration success.

Sources: https://www.mangrovealliance.org/news/mozambique-research-on-cyclones-and-mangrove-restoration-success/; https://www.unep.org/news-and-stories/story/decades-after-devastating-cyclone-mangroves-are-rebound-mozambique

Building with Nature Indonesia

Indonesia's muddy shorelines have recently suffered from severe erosion and flooding, mainly caused by the removal of a protective belt of mangroves and their replacement by ponds for aquaculture. Other factors include hard infrastructure, river engineering and excessive groundwater extraction. Furthermore, the increased frequency and intensity of storm surges resulted in the exposure of more than 30 million people in Java alone to flooding. As a response, the Building with Nature Indonesia was launched in 2015 to combine mangrove restoration, small-scale engineering and sustainable land use to strengthen coastlines and reduce erosion. The Initiative entailed a passive restoration approach in Demak, where the creation of suitable ecological and socio-economic conditions allowed mangroves to settle on their own. This is achieved by reinstating natural hydrology, sediment dynamics and soil conditions. Planting is only applied in sites where seedlings fail to settle naturally, for example in the absence of a nearby feedstock. Furthermore, permeable dams made of brushwood are being constructed to capture sediment, and to restore the soil balance. Partners include Wetlands International, Ecoshape, the Indonesian Ministry of Marine Affairs and Fisheries (MMAF) and the Indonesian Ministry of Public Work and Housing (PU) in partnership with Deltares, TU Delft, Wageningen University & Research and local communities.

Sources: https://www.wetlands.org/casestudy/building-with-nature-indonesia/; https://www.ecoshape.org/en/pilots/building-with-nature-indonesia/news-resources/

Delta Blue Carbon, Pakistan

Over a number of decades, mangrove forests in the Indus Delta, Pakistan, have experienced massive-scale deforestation and degradation due to a number of contributing factors, including their use as a source of fuelwood, fodder and open range grazing by livestock. The situation has been exacerbated by the reduced supply of fresh water and sediments into the delta area due to human activities upstream. In 2015, the Government of Sindh has launched the Delta Blue Carbon, a 60-years project implemented over an area of 3,500 km2. To date, an area of some 750 km2 has been restored with mangrove plantations. A total area of 2,250 km2 will be planted during the project lifetime. Additional actions include conservation approaches both for mangroves and tidal wetlands within the area. The project is developed through a public-private partnership including the Forest and Wildlife Department and Indus Delta Capital Ltd, a climate and development focused private party.

Sources: https://deltabluecarbon.com/; https://www.trafigura.com/sustainability/case-studies/delta-blue-carbon-the-world-s-largest-blue-carbon-project/

LIFE Recreation ReMEDIES, UK

More than 44% of UK seagrass has been lost since 1936 due to a variety of factors, from seagrass wasting disease to pollution and physical disturbance from activities such as the anchoring, launching and mooring of leisure boats. The “Reducing and Mitigating Erosion and Disturbance Impacts affecting the Seabed”, launched in 2019 is led by Natural England and funded by the EU LIFE program. It is seeking to protect and restore sensitive seabed habitats which are at risk, including seagrass meadows in 5 Special Areas of Conservation (SAC). To support seagrass recovery in these areas, a series of actions are undertaken: surveying and mapping seagrass beds to help inform recreational marine users; conducting studies to better understand how recreational activities impact seagrass; and introducing voluntary no-anchor zones. Furthermore, advanced mooring systems, designed to interact less with the seabed, are also being trialled. The transplantation process has already been completed in Plymouth Sound SAC, where an area of 0.04 km2 is targeted for restoration. In April 2021, 18,200 seed and seeding bags were deployed. The project is now monitored for success and growth rates.

Sources: https://www.gov.uk/government/news/englands-largest-ever-seagrass-planting-hits-new-milestone--2; https://oceanconservationtrust.org/project/remedies-project/

Seagrass Restoration in Florida, USA

More manatees have already died in 2021 (1,101) than any other year in Florida’s history, as biologists point to seagrass loss in the Indian River Lagoon as a catalyst for starvation and malnutrition. Seagrass meadows are threatened by agricultural and industrial run-off in the area. In an effort to increase the numbers of this charismatic megafauna, the Treasure Coast Manatee Foundation and Manatee Observation and Education Center (MOEC) target the restoration of its habitat by planting one acre of seagrass in Moore’s Creek, with a further

half-acre expansion set to be installed later in 2022. Native seagrass planting units will be installed and protected with herbivory exclusion devices for a year. Maintenance and monitoring will be undertaken for three years to increase the plants’ chance of survival.

Source: https://www.stuartmagazine.com/stuart-life/outdoors/planting-hope-for-florida-manatees/

Restoration of tidal marshes in Jamaica Bay, New York, USA

Jamaica Bay is an estuary nearly the size of Manhattan, spanning between Brooklyn and Queens, and it is the largest natural space within New York City. For at least a decade, it has been recognized that Jamaica Bay's tidal wetlands are rapidly disappearing that resulted in the loss of 80% of the historical marshland extent. Without these natural barriers, residents in the Jamaica Bay area become more vulnerable to rising sea levels and extreme events. In a multimillion-dollar effort to reverse the current conditions, state and city agencies and the National Park Service are partnering with NGOs to build "living shorelines", thus restoring a coastal area of 40.5 km2 to be stabilized with sand, rocks and bags of oyster shells, as well as marshes.

Sources: https://www.nytimes.com/2022/04/01/nyregion/jamaica-bay-broad-channel-climate-change.html

Enabling policies: Certifying and financing Blue Carbon projects

The inclusion of Blue Carbon into IPCC guidelines in 2013 enabled nations with EEZs to account for Blue Carbon as part of their NDCs (Figure 8). As part of the Paris Agreement, the Contracting Parties are committed to regularly submit revised NDCs every five years, indicating their national strategies for climate action, and to submit reviewed pledges that are intended to continually increase their ambitions (Art 4.3 and 4.9 of the Paris Agreement). Parties can develop their mitigation efforts that include NbS, thus considering Blue Carbon as an opportunity to target the emissions gap. At the European level, the European Commission adopted in May 2020 the Biodiversity Strategy as one of the most important frameworks under the umbrella of the European Green Deal. This ambitious multilateral framework sets a series of biodiversity goals with new measures to be achieved by 2030, including restoration investments for conservation measures in protected areas that improve deteriorated ecosystems acting C sinks. Therefore, NbS in general and Blue Carbon options are strongly encouraged via this scheme.

The carbon markets

Carbon markets are one of the tools that can contribute to mitigate GHG emissions and are divided in two types: compliance and voluntary markets. Compliance markets are created and regulated by mandatory international, regional, and subnational C reduction schemes such as the European Union's Emissions Trading Scheme (EU-ETS), the Clean Development Mechanism regulated by the Kyoto Protocol and the California Carbon Market. Voluntary carbon markets have developed on the back of the major compliance carbon markets to offer smaller scale projects by lowering transaction costs. As a result, small-scale projects are emerging while companies and individuals are allowed to purchase carbon offsets on a voluntary basis.

There is often some confusion regarding the terminology for GHG emission units. Carbon assets can be divided into two main categories: The first category includes carbon emission units, which are materialized by an institution in the context of a cap-and-trade mechanism. Each unit represents a right to release GHG equivalent to a tonne of carbon dioxide equivalents (t CO_2-e) into the atmosphere, rather than an actual emission reduction. Depending on the jurisdiction they are often interchangeably called allowances, quotas or amounts. This is notably the case for the Kyoto Protocol's Assigned Amount Units and the European Union Allowances of the EU-ETS. The second category encompasses the carbon emission reduction units, also called carbon credits or offsets. A carbon credit or offset represents the reduction, avoidance or removal of one ton of CO_2-e. These units are materialized by an authority or an independent non-profit organization in the context of a baseline-and-credit mechanism (offsetting mechanism). This process allows emissions to be traded and offset-generating projects to be funded. For a project to generate carbon credits or offsets, it needs to demonstrate that the achieved emission reductions or removals are real, measurable, traceable, permanent, additional and independently verified to globally accepted certification standards.

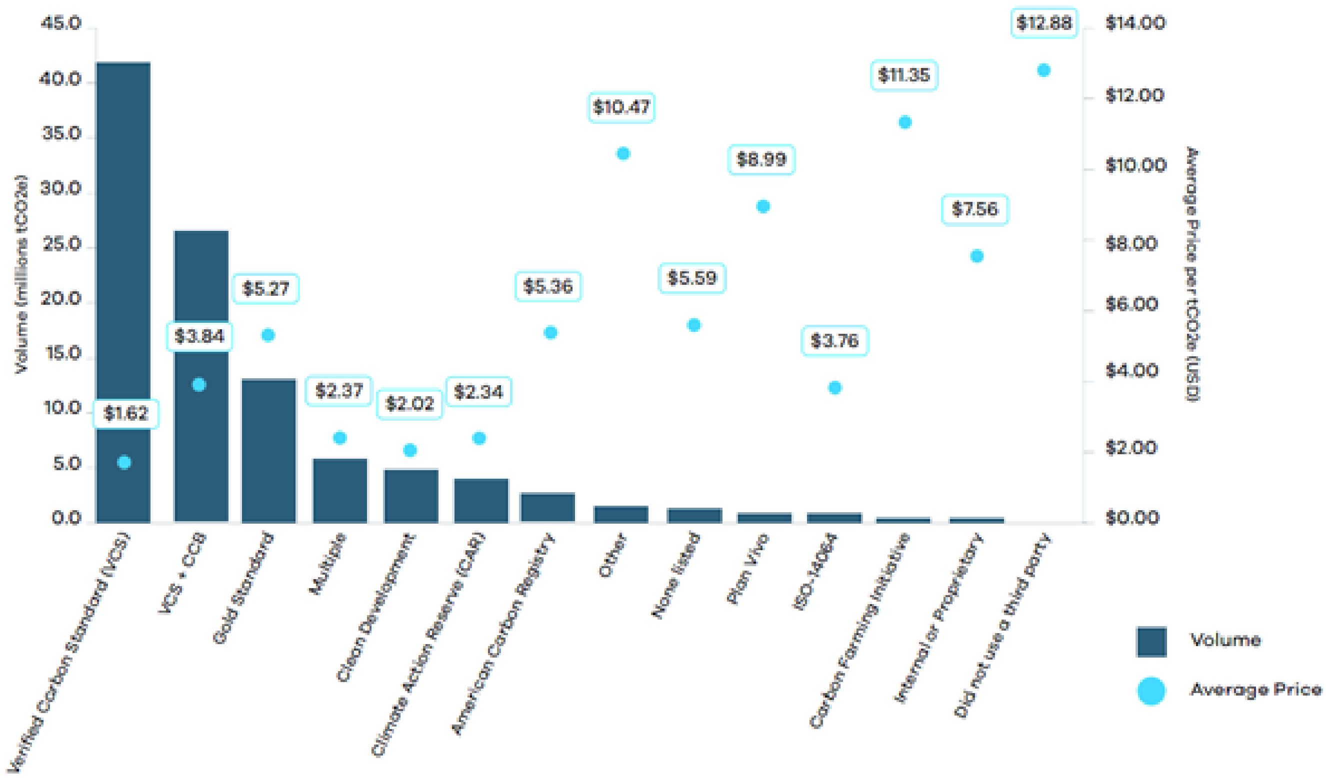
Carbon certification standards establish the framework under which projects can be granted carbon credits. This approach is based on the definition of a hypothetical baseline scenario. The latter could be defined as the most likely scenario in the absence of the project's implementation. Following the establishment of the hypothetical baseline scenario, the GHG emissions related to this scenario are calculated and compared to those induced by the project. The difference of emissions between the baseline and the project scenarios are the ones reduced, avoided or sequestrated by the project.

Enabling policies: Certifying and financing Blue Carbon projects

As far as it concerns compliance carbon markets allowing baseline-and-credit mechanisms, an authority defines the necessary project certification standards for compliance, which are usually very strict. For example, the EU-ETS only allows carbon credits from the Clean Development Mechanism (CDM) and the Joint Implementation (JI), both accepted by the UNFCCC. Voluntary carbon markets are unregulated and for this reason are much more flexible regarding certification standards. There are several standards used including the CDM, but also standards modelled on the principles and sometimes the rules of the CDM, such as the Verified Carbon Standard (VCS), the Gold Standard, Plan Vivo, the American Carbon Registry and the Climate Action Reserve.

The voluntary markets are described by a limited number of participants with pricing being typically negotiated on a bilateral basis between buyers and sellers, leading to considerable variation in prices. Often, a large proportion of the income is taken as fees by market brokers, and hence not paid to the project itself. The current state of the voluntary markets leads to considerable variation in prices (Figure 12). Currently available blue carbon credits are typically priced at $10 - $15 each, though prices as low as $3 or as high as $25 have been observed. Blue Carbon credits are generally higher than the terrestrial ones due to the complexity to implement, smaller scale and multiple co-benefits associated with Blue Carbon projects (Norris et al., 2021).

Figure 12. Average price and volume by voluntary carbon credit standards, 2019. Some of the difference is likely due to specific characteristics in individual projects, but significant variation in prices among the certification standards is observed.



The special issue of double counting

One element that is currently attracts attention is the issue of benefit sharing in Blue Carbon projects. Indeed, since countries account for most of their GHG emissions within their national GHG inventory, any emission reduction happening within the geographical and sectoral boundary of their inventory would be accounted for at the national level. Any third-party entity investing in a Blue Carbon project that reduces GHG emissions would only be able to claim these reductions if it had been deducted from the host country's national inventory. Otherwise, carbon credits are double counted (i.e., counting carbon credits both at the national and at the organization's level).

Risks around Blue Carbon projects

The success of Blue Carbon projects is jeopardised by several risks, including environmental and socio-economic risks which are briefly described below.

Environmental risks

Climate change is anticipated to negatively affect coastal marine ecosystems and their CO2 mitigation potential, turning them from being a net sink of C to a source of C instead (McLeod et al., 2011). Marine heat waves may adversely affect the mitigation contribution from seagrass beds and seaweeds (Arias-Ortiz et al., 2018; Wernberg et al., 2019). Sea level rise will reduce habitat areas for all coastal vegetated ecosystems, and thus their mitigation potential (Lovelock et al., 2015; Saunders et al., 2013; Schuerch et al., 2018). The degree of sea level rise impact will be strongly influenced by the effects of climate change on adjacent ecosystems such as coral reefs (Saunders et al. 2013). Extreme events could also reduce the effectiveness of protection and restoration.

The effects of climate change on macroalgal cultivation are not yet clear (Callaway et al., 2012). Ocean warming may reduce fucoid canopies through physiological stress as well as additional associated pressures from warm-water herbivores (Harley et al., 2012), while increased storm energy and reduced nutrient supply will possibly reduce seaweed aquaculture yields. A greater understanding of impacts and the balance of environmental risks and benefits that seaweed cultivation projects can offer is required (Campbell et al., 2019) before pursuing a large-scale expansion of the seaweed farming industry.

Socio-economic risks

Increased human activities in the coastal zone (e.g., land-use change, population, sediment supply, hydrological modifications) will affect coastal marine ecosystems. For instance, deterioration in water quality may exacerbate the impacts of sea level rise on seagrass (Saunders et al., 2013) and decreased sedimentation from damming of rivers, hydrological modifications and presence of seawalls may negatively affect Blue Carbon stocks in mangroves and tidal marshes (Lovelock et al., 2015; Spencer et al., 2016).

While small-scale seaweed cultivation is considered low risk, a large-scale expansion of the industry requires greater understanding of impacts and the balance of environmental risks and benefits that seaweed cultivation projects can offer (Campbell et al., 2019).

Competition for marine space further compromises the expansion of seaweed aquaculture, which is already limited by the availability of suitable areas (Duarte et al., 2017), requiring MSP approaches that improve synergies and minimize conflicts. Furthermore, the development of a skilled labour force and new technologies (e.g., engineering systems capable of coping with rough conditions offshore) to occupy additional suitable areas for farming is necessary. It is also possible that further growth of seaweed production may drive market prices down (Duarte et al., 2017).

Conservation efforts of coastal marine ecosystems are inherently linked to the establishment of MPA. In 2000, only 0.13 million km2 (Backstrand et al., 2017) or 0.003% of the ocean was protected, but MPA now cover 27.4 million km2 (Hudson, 2017) (7.6% of ocean area) (Duarte et al., 2020). Commitment to long-term management and proper monitoring of MPA are fundamental to achieve conservation goals and avoid further degradation of these ecosystems.

Cost-effectiveness is an important factor while assessing the overall feasibility of a proposed NbS. Conservation of coastal marine ecosystems is considered very cost-effective compared with restoration projects (Gattuso et al., 2018). For example, conserving mangroves to avoid further CO_2 emissions is considerably cheaper than restoring mangroves to enhance CO_2 uptake (4–10 vs. 240 US$ per ton of CO_2-e (Siikamaki et al., 2012; Bayraktarov et al., 2016). Furthermore, cost variability among restoration projects in different geographical locations, highly dependent on labour cost (Bayraktarov et al., 2016) could discourage stakeholders from undertaking such projects.

Useful resources and links

Blue Carbon policy

Coastal blue carbon ecosystems – Opportunities for Nationally Determined Contributions. Policy Brief, available at: https://www.nature.org/content/dam/tnc/nature/en/documents/BC_NDCs_FINAL.pdf

Wetlands: Methodological Guidance on Lands with Wet and Drained Soils, and Constructed Wetlands for Wastewater Treatment, available at: https://www.ipcc.ch/site/assets/uploads/2018/03/Wetlands_Supplement_Entire_Report.pdf

Blue Carbon ecosystems

Out of the Blue: The Value of Seagrasses to the Environment and to People, available at: https://www.unep.org/resources/report/out-blue-value-seagrasses-environment-and-people

Global Forest Resources Assessment 2020: Main report, available at: http://www.fao.org/3/ca9825en/CA9825EN.pdf

The Global Status of Seaweed Production, Trade and Utilization, available at: https://www.fao.org/in-action/globefish/publications/details-publication/en/c/1154074/

Hidden Campion of the Ocean – Seaweed for Europe. Report available at:

Seaweed_for_Europe-Hidden_Champion_of_the_ocean-Report.pdf (seaweedeurope.com)

The Ocean as a Solution to Climate Change: Five Opportunities for Action. Report available at: http://www.oceanpanel.org/climate

Blue Carbon in the United Kingdom. Report available at:

https://www.bluemarinefoundation.com/2022/03/09/uk-blue-carbon-report/

Blue Carbon manuals

Blue Carbon. A Rapid Response Assessment, available at: https://www.grida.no/publications/145

Coastal Blue Carbon: Methods for assessing carbon stocks and emissions factors in mangroves, tidal salt marshes, and seagrass meadows, available at: https://www.thebluecarboninitiative.org/manual

Blue Carbon in Seagrass Ecosystems: Guideline for the Assessment of Carbon Stock and Sequestration in Southeast Asia, available at: https://books.google.es/books?hl=en&lr=&id=KbO-DwAAQBAJ&oi=fnd&pg=PR9&dq=BLUE+CARBON+IN+SEAGRASS+ECOSYSTEM:+Guideline+for+the+Assessment+of+Carbon&ots=ytlb4yGuIv&sig=Z2e-H5qbYnbl8hsVa6ZsB5xoqAGU#v=onepage&q=BLUE%20CARBON%20IN%20SEAGRASS%20ECOSYSTEM%3A%20Guideline%20for%20the%20Assessment%20of%20Carbon&f=false

Useful resources and links

Blue Carbon certified methodologies

Manual for the creation of Blue Carbon projects in Europe and the Mediterranean, available at: https://www.iucn.org/sites/dev/files/content/documents/2021/manualbluecarbon_eng_lr.pdf

Feasibility study the preparation of Blue Carbon offsetting projects in in Andalucía, Spain, available at: https://uicnmed.org/docs/blue-carbon-feasibility-assessment.pdf

Understanding your blue carbon project: Emissions Reduction Fund simple method guide for blue carbon projects registered under the Carbon Credits (Carbon Farming Initiative —Tidal Restoration of Blue Carbon Ecosystems) Methodology Determination 2022, available at: http://www.cleanenergyregulator.gov.au/DocumentAssets/Documents/Understanding%20your%20blue%20carbon%20project%20–%20simple%20method%20guide.pdf

Verified Carbon Standard (VCS), available at: https://verra.org/wp-content/uploads/2022/02/VCS-Standard_v4.2.pdf

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