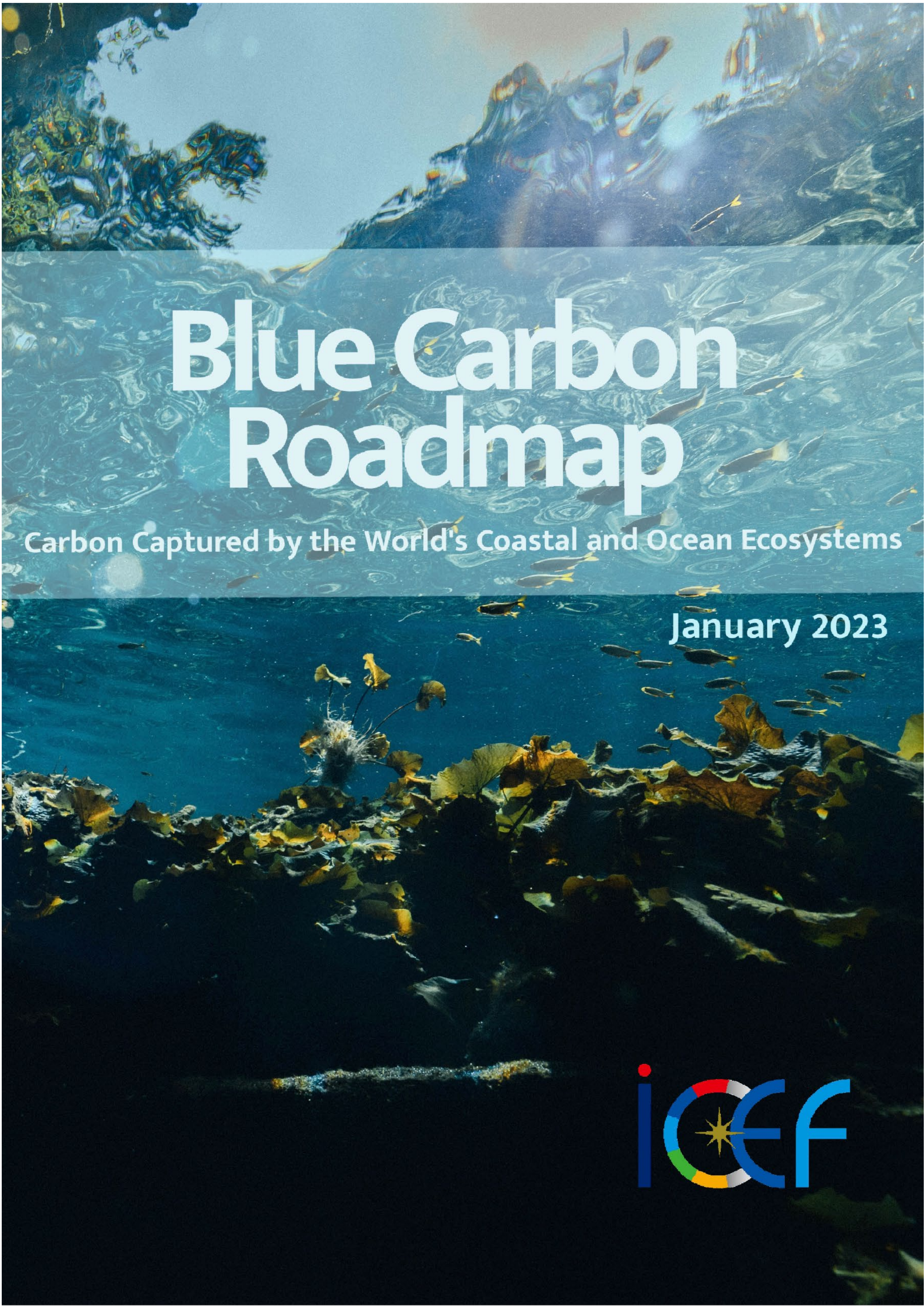

Blue Carbon Roadmap

Carbon Captured by the World's Coastal and Ocean Ecosystems

January 2023

ICEF

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Executive Summary

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Climate change action to limit global warming to 1.5 °C above preindustrial levels has come too late to wait. Rapid and effective emission reductions must be achieved through technological innovation, intersectoral and multisectoral collaboration, and international cooperation. Simultaneously, examining the carbon sequestration capacity of coastal and ocean coastal ecosystems and taking action to maintain, restore, and rehabilitate these ecosystems are important.

The carbon absorbed and sequestered by coastal vegetation, such as mangrove forests, seagrass beds, and salt marshes, is called coastal blue carbon. The sequestration potential per unit area and sequestration time of coastal blue carbon are higher than those of terrestrial forests. Expectations are high for its use as a nature-based solution (NbS) and as a negative emission technology (NET). Large macroalgae (seaweed) beds and macroalgal cultivation, which have been attracting attention in recent years as new candidates for blue carbon, have yet to establish a unified international scientific methodology. Nevertheless, the scientific knowledge is accumulating, and methodologies have been developed in Japan and around the world.

In addition to its mitigation function, blue carbon is expected to benefit local communities, thus attracting worldwide attention. Blue carbon will introduce various synergistic benefits, such as coastal defense, biodiversity maintenance, water purification, and cultural use value, which are also related to climate change adaptation. As an action that links global and local needs and an activity that prompts mitigation, human, and biodiversity “triple benefits,” Blue Carbon Projects are attracting considerable anticipation.

In this roadmap, Chapter 1 introduces the development of blue carbon in international policy and scientific forums, such as the United Nations Framework Convention on Climate Change (UNFCCC) and IPCC, and Chapter 2 describes the scientific understanding of mangrove forests, seagrass beds, and salt marshes in the context of blue carbon, as well as macroalgal beds and farming, which are gaining salience for their significant blue carbon potential. Chapter 3 introduces existing technologies and those expected to be developed in the future to produce, protect, measure, and use blue carbon ecosystems and their products, especially from macroalgal farming. Chapter 4 describes the points to be considered in terms of international treaties, institutional requirements, and environmental impacts when expanding Blue Carbon Projects to scale. Finally, Chapter 5 describes the current status and potential development of the Blue Carbon Credit as an economic tool necessary to make the Blue Carbon Project a sustainable action and maximize its potential.

Through the above, we envisage that this roadmap will help recognize the gap between the current status of Blue Carbon and the goals to be reached within the next few decades and provide a roadmap on filling that gap from scientific, technological, policy, and economic aspects.

Chapter 1
Introduction

“Blue Carbon” is a relatively new term coined in a 2009 report compiled primarily by the United Nations Environment Program (UNEP) [8]. Even before the term was coined, international research and discussion on the coastal and oceanic carbon cycle existed. However, within a decade, a recapping of knowledge on blue carbon and significant progress in international research and policy has been observed. This introductory chapter will describe the evolution of ocean carbon cycle and blue carbon research and concepts in the international community and then present the structure and objectives of this roadmap.

(1) Development of Blue Carbon

First, we look at the brief discussion of CO_2 sinks before the term "blue carbon" was coined and the developments in the UNFCCC and IPCC since the publication of the Blue Carbon Report in 2009 (Table 1.1). Research on carbon sequestration in coastal ecosystems, which is connected to the concept of blue carbon, has been available since the 1800s. As long-term observations of atmospheric CO_2 concentrations began to reveal increments in atmospheric CO_2 concentrations, research on the measurement of CO_2 concentrations in the ocean and the role of the ocean and coastal zones in the carbon cycle became increasingly active. By contrast, seagrass beds, salt marshes, and mangrove forests, which are active carbon cycle sites in coastal areas, have been declining worldwide due to population growth and development in coastal areas.

The 2009 Blue Carbon report is the result of a movement to conserve and restore seagrass beds, salt marshes, and mangrove forests, which are important carbon sinks and resources for coastal communities. Since 2009, scientific knowledge on the three ecosystems of seagrass beds, salt marshes, and mangrove forests has been reorganized and their coverage by the IPCC and UNFCCC has dramatically increased, leading to a significant rise in interest from countries, academia, and NGOs.

In relation to Table 1.1, we outline the treatment of carbon sinks and storage under the UNFCCC (a) and then summarize the science and policy developments around the UN system since 2009 (b).

(2) Sink and Reservoir under the UNFCCC

The UNFCCC, adopted in 1992, declares that “All Parties, taking into account their common but differentiated responsibilities and their specific national and regional development priorities, objectives, and circumstances, shall: Promote sustainable management, and promote and cooperate in the conservation and enhancement, as appropriate, of sinks and reservoirs of all greenhouse gases not controlled by the Montreal Protocol, including biomass, forests, and oceans as well as other terrestrial, coastal and marine ecosystems” in Article 4, paragraph 1(d).

The calculation and accounting scope of “Sink” and “Reservoir” have become remarkably comprehensive and inclusive since the Kyoto Protocol (COP3/1997). In Kyoto Protocol, the scope of “Sink” was only "from direct anthropogenic land use change and forest activities" and the activities were limited to “new plantations and reforestation, deforestation, and (on an optional choice) forest management[9] since 1990.” In Doha Climate Gateway (COP18/CMP8/2012), “forest activities” became mandatory from the optional choice, and “Re-flooding of wetlands (peatlands)” was added as an optional choice from the 2nd commitment period of Kyoto Protocol (2013–2020). The prevailing view is that the scope should cover all land use, land-use change, and forestry (LULUCF)-related carbon stock changes from the perspective of equity and completeness under certain scientific and social rules[10].

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8 Nellemann, C., Corcoran, E., Duarte, C. M., Valdrés, L., Young, C. D., Fonseca, L., & Grimsditch, G. (2009). Blue Carbon: The Role of Healthy Oceans in Binding Carbon. UN Environment, GRID-Arendal.

9 Farmland management, grazing land management, vegetation restoration.

10 The projects related to sink activities under the Clean Development Mechanism (CDM), established as one of the Kyoto Mechanisms (flexibility measures), were allowed only for "afforestation and reforestation.”

Table 1.1. Brief history of Blue Carbon and relevant concepts

Year	Main Scientific and Political Events regarding Blue Carbon Concepts
1841	J.B.A. Dumas, a French chemist, published "Leçon sur la Statique Chimique des Etres Organisés" ("The Chemical and Physiological Balance of Organic Nature," discussed scientifically about Marine Carbon Cycles[11].
1914	Boysen-Jensen P., a Danish botanist, provided the first estimate of the contribution of Blue Carbon (seagrass) in carbon storage and burial.
1981	S.V. Smith proposed the role of marine macrophytes in sequestering CO_2 and suggested the overlooked role of seagrasses and macroalgae.[12]
1992	Adoption of the United Nations Framework Convention on Climate Change (UNFCCC), entered into force in 1994, in which the ultimate objective lies in the stabilization of the greenhouse gas (GHG) concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. The meaning of "Sink" is defined as "Any process, activity or mechanism which removes a greenhouse gas, an aerosol or a precursor of a greenhouse gas from the atmosphere" and "Reservoir" as "a component or components of the climate system where a greenhouse gas or a precursor of a greenhouse gas is stored."
1997	Kyoto Protocol was published, obligating the Annex I Parties to reduce their GHG emissions for the commitment period based on 1990 (at COP3).
2005	The true-up period of the 1st commitment period of the Kyoto Protocol was decided as 2008–2012.
2009	United Nations Environment Program (UNEP) published "Blue Carbon: The Role of Healthy Oceans in Binding Carbon" in January 2009, which first coined the term "Blue Carbon."
2010	Cancun Agreements published, pledged the Annex I Parties to declare the quantified economy-wide emission reduction targets for 2020 and submit the annual GHG inventory and progress reports (COP16/COP6).
2012	Doha Climate Gateway published, the true-up period of the 2nd commitment period of the Kyoto Protocol was decided as 2013–2020 and the scope of sinks expanded (LULUCF). Japan, Russia, Canada, and New Zealand left, while the EU, Norway, Australia, and Switzerland joined (COP18/CMP8).
2013	IPCC Task Force on National Greenhouse Gas Inventories "2013 Supplement to the 2006 Guidelines for National Greenhouse Gas Inventories: Wetlands" ("Wetlands Supplement") was accepted at the 37th Session of IPCC held in Batumi, Georgia in October 2013.
2015	The Paris Agreement was published, indicating all parties to promote the conservation and enhancement of sinks (COP21). Article 5.1 states "Parties should take action to conserve and enhance, as appropriate, sinks and reservoirs of greenhouse gases as referred to in Article 4, paragraph 1 (d), of the Convention, including forests." All parties (regardless of whether Annex I or non-Annex I) will proceed with the calculation, reporting, and verification of GHG inventories under a common mechanism while retaining a certain degree of flexibility to consider the capabilities and experience of non-Annex I parties.
2018	An IPCC special report on the impacts of global warming of 1.5 °C (SR15) projected that "intact wetland ecosystems can reduce the adverse impacts of rising sea levels," "intensifying storms by protecting shorelines, and their degradation could reduce remaining carbon budgets by up to 100 $GtCO_2$" and "under 1.5°C of warming, natural sedimentation rates are projected to outpace SLR, but other feedbacks, such as landward migration of wetlands and the adaptation of infrastructure, remain important" in each medium confidence level.
2019	An IPCC "Special Report on the Ocean and Cryosphere in a Changing Climate" ("SROCC") released in November 2019. The Report addresses the improvement of conservation and management of blue carbon ecosystems, which absorb, fix, and sequester carbon dioxide in coastal areas, as a climate change mitigation strategy using marine ecosystems.
2021	The IPCC and the IPBES, providing scientific advice to the UNFCCC and UN CBD, respectively, released their first joint report examining the Climate-Biodiversity nexus[13]. Blue Carbon actions are highlighted in this report as holding a high potential to contribute to climate and biodiversity goals while contributing to human well-being at a moderate cost and with minimal or no unintended consequences.

*The lines in blue are directly related to blue carbon.

(3) Blue Carbon in the Global Discourse

a) UNEP" Blue Carbon: The Role of Healthy Oceans in Binding Carbon" published in January 2009

The term "Blue Carbon" was first coined in a United Nations Environment Program (UNEP) report "Blue Carbon: The Role of Healthy Oceans in Binding Carbon" published in January 2009[14] complied by the experts at GRID-Arendal in collaboration with the UN Food and Agricultural Organization of the United Nations (FAO) and the United Nations Educational, Scientific, and Cultural Organization International Oceanographic Commissions and other scientists.

The report highlights the carbon fluxes and storage in marine systems. In contrast to the carbon absorbed and sequestered by terrestrial forests and vegetation ("Green Carbon"), this report depicts the importance of coastal

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[11] Gordon A. Riley.(1994). The Carbon Metabolism and Photosynthetic efficiency of the Earth as a whole, American Scientist, 32(2),129-134

[12] Smith, S. V. Marine macrophytes as a global carbon sink. Science 211, 838–840 (1981).

[13] Pörtner, H.O., Scholes, R.J., Agard, J., et al.. 2021. IPBES-IPCC co-sponsored workshop report on biodiversity and climate change; IPBES and IPCC

[14] See *supra* note 7

ecosystems in the carbon cycle and catalyzed to draw attention to the necessity and urgency of halting the decline of the coastal ecosystem. Additionally, the ocean, which is the interconnected body of saline water that covers 71% of the Earth's surface, contains 97% of the Earth's water and provides 99% of the Earth's biologically habitable space.
The report scientifically presented that more than 50% of the carbon dioxide produced on the Earth is absorbed by the ocean and covers ~360 million square kilometers, half of which is stored in the soil, especially in seagrass beds, salt marshes, and mangrove forests, which cover only 0.5% of the ocean's surface area (Figure 1.1).

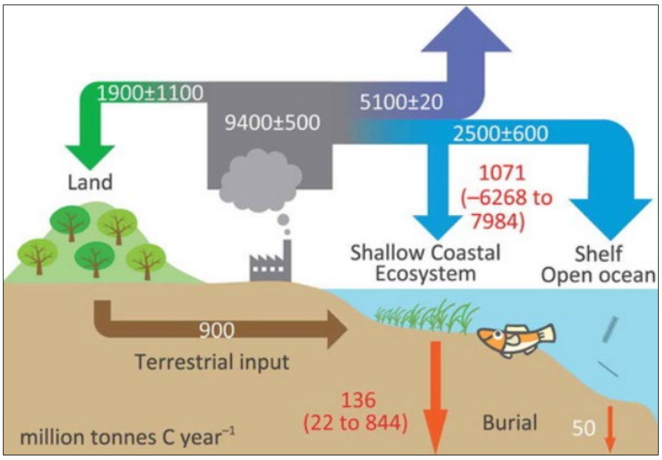

Figure 1.1. Global "Green Carbon" and "Blue Carbon" Cycling[15]

The coastal Blue Carbon ecosystems have high carbon burial rates on a per unit area basis and accumulate carbon in their soils and sediments. The flow of carbon (in various forms, as carbon dioxide (CO_2), carbon in biomass, and carbon dissolved in the ocean as carbonate and bicarbonate ions) is cycling through the atmosphere, hydrosphere, ocean, terrestrial and marine biosphere, and lithosphere. If degraded or lost, then coastal blue carbon ecosystems are likely to release some of the carbon back into the atmosphere.

The climate mitigation effectiveness of other natural carbon removal processes in coastal waters, such as macroalgal ecosystems and proposed nonbiological marine CO_2 removal methods, is small or currently has high associated uncertainties. Macroalgal aquaculture warrants further research attention.

b) IPCC Wetlands Supplements in 2013

The IPCC Task Force on National Greenhouse Gas Inventories published the "2013 Supplement to the 2006 Guidelines for National Greenhouse Gas Inventories: Wetlands" ("Wetlands Supplement"), which constitutes an important scientific milestone in the development of blue carbon.

In 2010, UNFCCC invited the IPCC to undertake further methodological work on wetlands, focusing on the rewetting and restoration of peatland, with a view to filling in the gaps in the 2006 IPCC Guidelines for National GHG as Inventories. The work on the production of the Wetlands Supplement was conducted in 2011–2013 over four Lead Author meetings and two rounds of review followed by a round of written comments by governments. The IPCC Government and Expert Reviews of the Final Draft of the Wetlands Supplement were held in August and September 2013. The Overview Chapter of the Wetlands Supplement was adopted, and the entire report was accepted at the 37th Session of the IPCC (IPCC 37) held in Batumi, Georgia, in October 2013.

During the multistage review process, which was first conducted by experts and then by governments and experts, expert reviewers, and governments are invited to comment on the accuracy and completeness of the scientific, technical, and socioeconomic contents and the overall balance of the drafts.

The IPCC developed the inventory methodological guidance on wetlands, including default emission factor values. Typical

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[15] Tomohiro Kuwae & Stephen Crooks (2021) Linking climate change mitigation and adaptation through coastal green–gray infrastructure: a perspective, Coastal Engineering Journal, 63:3, 188-199, DOI: 10.1080/21664250.2021.1935581

management practices for organic matter and wet soils related to blue carbon are shown in Figure 1.2. Chapter 4 of the guidelines provides guidance on methodologies for estimating carbon stock changes and CH_4 emissions from mangrove forests, tidal marshes, and seagrass meadows in coastal wetlands and N_2O emissions from aquaculture in coastal wetlands.

CO_2 and GHG emissions (or absorption) are expressed as the product of the area covered by the activity (called activity data) and the emission (absorption) factor. The amount of activity can be regarded as the distribution area (above a certain coverage) of blue carbon ecosystems found within the area covered by the activity in the case of conservation, rehabilitation, or restoration activities. The absorption coefficient is the amount of CO_2 absorbed per unit area by the target ecosystem.

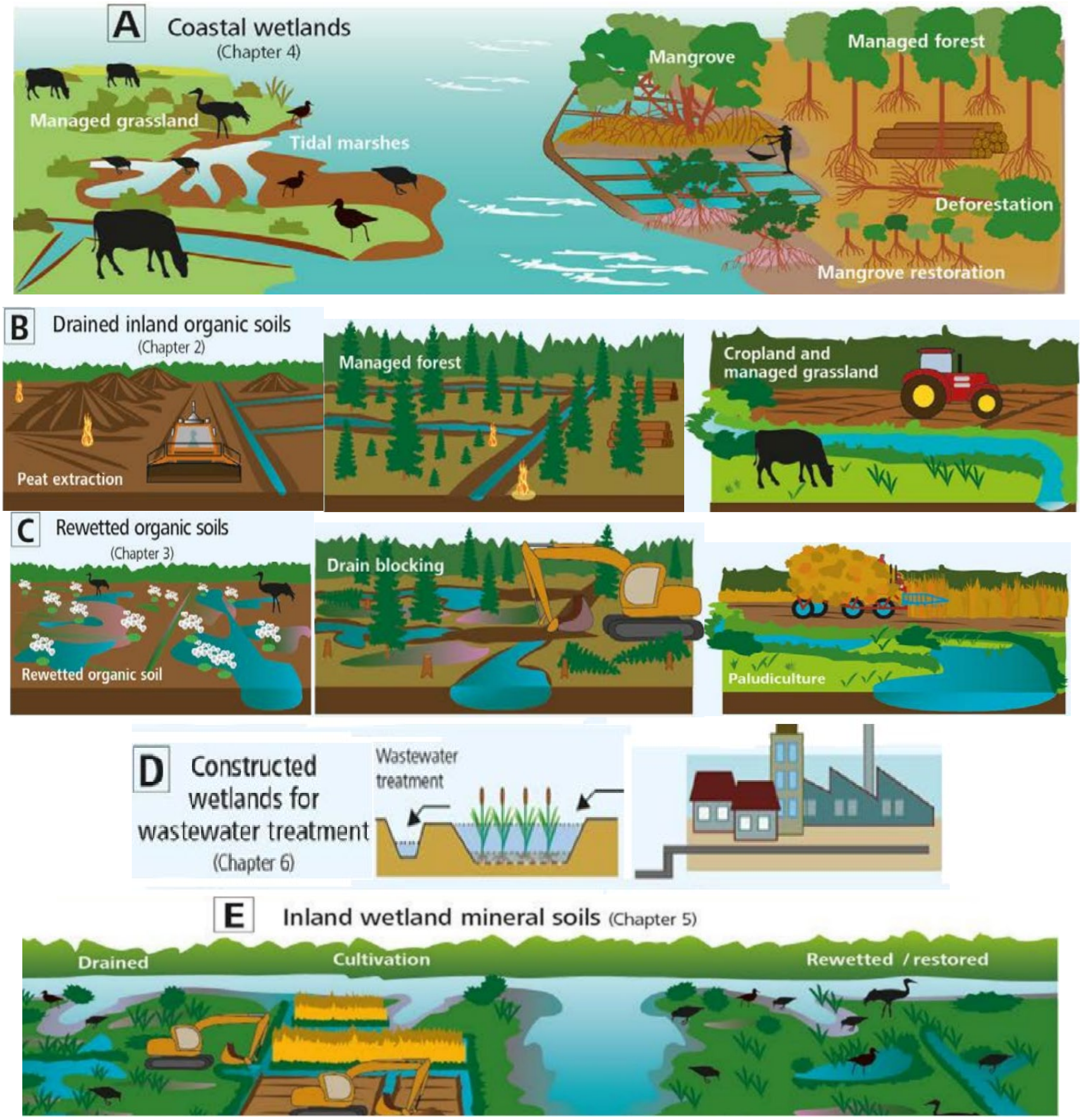

Figure 1.2. Typical management practices on organic and wet soils[16]

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[16] IPCC (2014). 2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands. IPCC, Switzerland

c) IPCC SROCC in 2019

The IPCC “Special Report on the Ocean and Cryosphere in a Changing Climate” (“SROCC”)[17] released in 2019 was an important scientific milestone. This report addresses the improvement of conservation and management of blue carbon ecosystems, which absorb, fix, and sequester carbon dioxide in coastal areas, as a climate change mitigation strategy using marine ecosystems.

In the report on Blue Carbon, the adaptation responses (A), the impacts (I), and the expected benefits (B) in coastal ecosystems within physical, ecological, social, governance, economic, and knowledge categories are indicated as listed in Table 1.2 (A “+” sign indicates robust evidence and a “-“ indicates medium evidence. Dark blue cells indicate high agreement and light blue indicates medium agreement (denoted by the presence of a sign). A systematic evaluation of the adaptation responses of blue carbon was conducted based on scientific validity as of 2019.

Table 1.2. Blue Carbon Adaptation Responses (A), Impacts (I), and Benefits (B)

Adaptation(A)/Impacts(I)/Benefits(B)	Coastal Communities			Built Infrastructure			Fisheries & Aquaculture			Coastal Tourism			Government			Health		
	I	A	B	I	A	B	I	A	B	I	A	B	I	A	B	I	A	B
1. Physical Category																		
(A) Supporting physical processes (I) Coastal physical processes disrupted (B) Physical process supported	■ -		■ -	■ -	■ -	■ +	▨ +	▨	■ -	■ +	▨	■ -	■ +		■ +			
(A) Hard engineering responses (I) Catchment physical processes disrupted (B) Coastal infrastructure resilience increased											▨							
(A) Soft engineering responses & buffers (I) Coastal infrastructure damage (B) Improved infrastructure functionally										▨				▨ -				
(A) Integrated hard & soft engineering (I) Disruption of urban systems (B) Increased structural heterogeneity														▨ -				
2. Ecological Category																		
(A) Ecosystem restoration and protection (I) Ecosystem degradation and loss (B) Ecosystem/ecological resilience supported	■ +	▨ -	■ +	■ +	■ +	■ +	■ -			▨	▨	■ -		■ -	▨			
(A) Bioengineering (I) Biodiversity and genetic diversity loss (B) Physical processes supported							■ -	▨										
(A) Assisted evolution & relocation (I) Habitat range shifts (B) Coastal infrastructure resilience increased		▨ -								■ -								
(A) Nature-based solutions (I) Sublethal species impacts (B) Increased biodiversity				▨ -														
Social Category																		
(A) Improving access to/storage of natural resources (I) Decreased access to ecosystem services (B) Access to sustainable ecosystem services			■ -			■ +			■ -									
(A) Sustainable resource use (I) Livelihood impacts (B) Improved socioeconomic services														▨				
(A) Maintaining or switching livelihoods (I) Increased food insecurity (B) Improved employment and livelihoods						▨												
(A) Community participatory programs (I) Public health risks increased (B) Improved health					▨													
Knowledge Category																		
(A) Better monitoring and modeling (I) Uncertainty for decision makers (B) Informed decision-making tools					▨													
(A) Integrating knowledge systems																	■ –	
(A) Stakeholder identification, outreach, and education					▨													

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17 https://www.ipcc.ch/site/assets/uploads/sites/3/2022/03/SROCC_FullReport_FINAL.pdf (accessed on January 8, 2023)

d) High-Level Panel for a Sustainable Ocean Economy (Ocean Panel) in December 2020

In 2018, Norway co-chairing with Palau led the launch of a high-level panel for a sustainable ocean economy (Ocean Panel), comprising the leaders of maritime nations. Participating countries as of November 2022 include the following 17 countries: Norway, Palau, Japan, Australia, Canada, Chile, Fiji, Ghana, Indonesia, Jamaica, Kenya, Mexico, Namibia and Portugal, the UK, France, and the USA.

Through its December 2020 High-Level Panel Leaders' Document, the Ocean Panel is committed to managing 100% of the ocean area under national jurisdiction sustainably with guidance from the Sustainable Ocean Plans by 2025. The panel urged all coastal and ocean states to join in this commitment to manage all ocean areas under national jurisdiction sustainably by 2030.

Sixteen blue papers and special reports were published by the Ocean Panel. One of the reports was "The Ocean as a Solution to Climate Change: Five Opportunities for Action[18]," which highlighted blue carbon (described as coastal and marine ecosystems) as one of the five ocean-based solutions for climate change. Assessment revealed that ocean-based mitigation measures could contribute 4%–12% and 6%–21% by 2030 and 2050, respectively, to limit temperature increase to within 1.5 °C since the Industrial Revolution.

In the long term, the contribution of ocean-based renewable energy is expected to become substantially large by 2050 due to the expected increase in the scale of offshore wind power generation. However, when considering the next decade until 2030, the potential for conservation and restoration of blue carbon ecosystems is relatively large (0.9 $GtCO_2e$ yr^{-1}), accounting for up to 25% of total ocean-based solutions.

e) IPCC AR6 Synthesis Report (late 2022 or early 2023)

The IPCC is currently in its Sixth Assessment cycle; the AR6 Synthesis Report (SYR)[19] will be finalized in late 2022 or early 2023. The AR6 SYR is based on the content of the following three Working Groups Assessment Reports: WGI – The Physical Science Basis; WGII—Impacts, Adaptation, and Vulnerability; WGIII—Mitigation of Climate Change (Table 1.3 and the three Special Reports: Global Warming of 1.5 °C, Climate Change and Land, and the Ocean and Cryosphere in a Changing Climate).

The first section, namely "Current Status and Trends," covers the historical and present period. The second section, namely "Long-term Climate and Development Futures," addresses projected futures up to 2100 and beyond. The final section, namely "Near-term Responses in a Changing Climate," considers current international policy timeframes and the time interval between now and 2030–2040.

Table 1.3. IPCC AR6 Synthesis Report Contents

Synthesis Report of AR6 (Synthesis Report)
Comprising two parts: a Summary for Policymakers (SPM) of 5 to 10 pages and a Long Report of 30 to 50 pages. Approval and distribution of the AR6 Synthesis Report are expected in early 2023. 21 Nov–15 Jan 2023 SYR Final Government Distribution.
Working Group I Report (Physical Science Basis)
Addressing the most up-to-date physical understanding of the climate system and change, bringing together the latest advances in climate science, and combining multiple lines of evidence from paleoclimate, observations, process understanding, and global and regional climate simulations.
Working Group II Report (Impacts, Adaptation, and Vulnerability)
Assessing the impacts of climate change from a worldwide to a regional view of ecosystems and biodiversity and of humans and their diverse societies, cultures, and settlements. This report considers their vulnerabilities and the capacities and limits of these natural and human systems to adapt to climate change and thereby reduce climate-associated risks together with options for creating a sustainable future for all through an equitable and integrated approach to mitigation and adaptation efforts at all scales.
Working Group III Report (Mitigation of Climate Change)
Assessing all aspects of mitigation, including technical feasibility, cost, and the enabling environments that would allow measures to be

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[18] Hoegh-Guldberg. O., et al. 2019. ''The Ocean as a Solution to Climate Change: Five Opportunities for Action.'' Report. Washington, DC: World Resources Institute. Available online at http://www.oceanpanel.org/climate (accessed on January 8, 2023)

[19] According to IPCC procedures, the SYR should "synthesize and integrate materials contained within the Assessment Reports and Special Reports" and "should be written in a non-technical style suitable for policymakers and address a broad range of policy-relevant but policy-neutral questions approved by the Panel." The report comprises two parts: a Summary for Policymakers (SPMs) of 5 to 10 pages and a Long Report of 30 to 50 pages.

taken. Enabling environments cover policy instruments, governance options, and social acceptability. Synergies and tradeoffs with adaptation measures as well as co-benefits, risks, and links to sustainable development are of increasing interest. Taking a near-term perspective relevant to decision makers in the government and the private sector and a long-term perspective that helps identify how high-level climate policy goals might be met.

In the Working Group I Report (Physical Science Basis), the SROCC discussions mentioned Blue Carbon as one of the carbon dioxide removal (CDR) methods and current potentials are shown below (Table 1.4). Therefore, the feasibility of open ocean fertilization and alkalinization approaches was negligible due to their inconclusive influence on ocean carbon storage on long time scales, unintended side effects on marine ecosystems, and associated governance challenges. The assessment of blue carbon ecosystems concluded their minimal contribution to global atmospheric CO_2 reduction but emphasized that the benefits of protecting and restoring coastal blue carbon extend beyond climate change mitigation.

Table 1.4. Characteristics of various Carbon Dioxide Removal (CDR) methods including Blue Carbon[20]

Methods (Category Methods)	Status (TRL*)	Cost (USD t CO_2^{-1})	Mitigation Potential ($GtCO_2\ yr^{-1}$)	Nature of CO_2 Removal Process/Storage Form Description	Time Scale of Carbon Storage (Factors that Affect Carbon Storage Time Scale)	Termination Effects
Category I: Enhanced biological production and storage on land (in vegetation, soils, or geologic formations)						
Afforestation, reforestation, and forest management (Biological/Organic)	(8–9)	0–240	0.5–10	Store carbon in trees and soils by planting, restoring, or managing forests	Decades to centuries (disturbances (e.g., fires, pests), extreme weather)	None
Soil carbon sequestration (Biological/Organic)	(8–9)	45–100	0.6–9.3	Use agricultural management practices to improve soil carbon storage	Decades to centuries (Soil and crop management)	None
Biochar (Biological/Organic)	(6–7)	10–345	0.3–6.6	Burn biomass at high temperature under anoxic conditions to form biochar and add to soils	Decades to centuries (Fire)	None
Peatland restoration (Biological/Organic)	(8–9)※	Insufficient Data	0.5–2.1※	Store carbon in soil by creating or restoring peatlands	Decades to centuries (Peatland drainage, fire, drought, land-use change)	None
Bioenergy with carbon capture and storage (BECCS) (Biological/Inorganic)	(5–6)	15–400	0.5–11	Production of energy from plant biomass combined with carbon capture and storage	Potentially permanent –analogous to direct air carbon capture with carbon (Leakage)	None
Category II: Enhanced biological production and storage in coastal and open ocean						
Ocean fertilization (Biological/Organic)	1–2	50–500	1–3	Fertilize upper ocean with micro (Fe) and macronutrients (N, P) to increase phytoplankton photosynthesis and biomass and deep ocean carbon storage through the biological pump	Decades to millennia (ocean stratification and circulation; efficiency of carbon sequestration in deep ocean)	Uncertain
Artificial ocean upwelling (Biological/Organic)	-	-	-	Pump nutrient-rich deep ocean water to the surface to increase carbon uptake and storage through the biological pump	Centuries to millennia (ocean circulation; dissolved inorganic carbon content of upwelled waters)	Warming beyond temperatures experienced if artificial ocean upwelling had not been deployed
Restoration of vegetated coastal ecosystems (Blue Carbon) (Biological/Organic)	(8–9)※	Insufficient Data	0.5–2.1※	Manage coastal ecosystems to increase net primary production and store carbon in sediments	Decades to centuries if functional integrity of ecosystem maintained (Land-use change of coastal ecosystems, extreme weather (e.g., heatwaves and sea level change)	None
Category III: Enhanced geochemical processes on land and in ocean						
Enhanced weathering (Geochemical/Inorganic)	3–4	50–200 (24–578)	2–4 (<1–95)	Spread alkaline minerals on land to remove atmospheric CO_2 in reactions that form solid minerals chemically (carbonates and silicates) that are stored in soils or in the ocean	10,000 to 10^6 years (Storage in soils or ocean)	None
Ocean alkalinization (Geochemical/Inorganic)	1–2	40–260	1–100	Increased CO_2 uptake via increased alkalinity by deposition of alkaline minerals (e.g., olivine)	10,000 to 100,000 years (Carbonate chemistry; ocean stratification and circulation)	Higher rates of warming and acidification than if alkalinization had not begun (under a high emission scenario)
Category IV: Chemical						
Direct air carbon capture with storage (DACCS) (Chemical/Inorganic)	6	100–300 (84–386)	5–40	Direct removal of CO_2 from air through chemical adsorption, absorption or mineralization, and storage underground in deep ocean or in long-lasting usable materials	Potentially permanent (Leakage)	None

* TRL means “Technology Readiness Level”. (※) is the total amount of Peatland restoration and Restoration of vegetated coastal ecosystems.

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[20] IPCC (2021). Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press.

In the Working Group II Report (Impacts, Adaptation, and Vulnerability) and the Working Group III Report (Mitigation of Climate Change), which are both based on the SROCC discussions, the impacts and the mitigation and restoration potentials were analyzed for three coastal Blue Carbon ecosystems as shown below (Table 1.5).

Table 1.5. Impacts on organic carbon storage and burial rates in mangroves, salt marshes, and seagrass.

		Mangroves	Salt marshes	Seagrasses
Sea Level Rise	Landward expansion by vegetation	+C	+C	+C
	Coastal squeeze	−C	−C	−C
	Loss of low-lying or submerged land or vegetation	−C	−C	−C
	Human adaptation to increase accommodation space	+C	+C	
Extreme Storms	Erosion, loss of area, subsidence	−C	−C	0 to −C
	Enhanced sedimentation	+C	+C	+C
	Vegetation damage and mortality	−C to +C		−C
Warming	Increased productivity	+C		+C
	Vegetation mortality			−C
	Increased decomposition of soil	−C	−C to +C	
	Poleward expansion of mangroves	+C	−C	
	Poleward expansion of seagrasses			+C
	Poleward expansion of bioturbators	ΔC		
	Change in dominant species	ΔC		
Rising concentrations of atmospheric CO_2	Increased productivity of some species	ΔC	ΔC	+C
	Biodiversity loss	−C		
Altered precipitation	Vegetation mortality	−C		
	Reduced productivity	−C	−C	
	Increased productivity	+C		+C
	Increased remineralization	−C	−C	
	Low-salinity events			0 to −C

"+C" indicates potential positive effects on blue carbon stocks, "−C" indicates potential negative effects, "0" indicates no effects, and "ΔC" indicates positive potential or negative effects.

Blue Carbon data (e.g., carbon accumulation and sequestration rates) vary widely depending on the climatic and sedimentary conditions of each region. Additionally, the quantification of their overall mitigation value is difficult due to the variable production of CH_4 and N_2O uncertainties considering the provenance of the accumulated carbon and the release of CO_2 by biogenic carbonate formation in seagrass ecosystems.

The median costs of CDR methods are estimated as 240, 30,000, and 7800 USD per tCO_2 for mangroves, salt marsh, and seagrass management, respectively. Currently, estimated cost-effectiveness (for climate change mitigation) is generally remarkably low. The total potential carbon sequestration rate through blue carbon CDR is generally estimated in the range 0.02–0.08 $GtCO_2$ yr^{-1}[21]. Gattuso et al. (2021)[22] estimated the theoretical cumulative potential of coastal blue carbon management to be 95 $GtCO_2$ by 2100 considering the maximum area that can be occupied by these habitats and historic losses of mangrove, seagrass, and salt marsh ecosystems.

The blue carbon science has evolved, thereby encompassing different scientific fields, engaging actors at various scales, and emerging in multiple international climate change discussions since its conception in 2009 based on a recent assessment of peer-reviewed and gray publications (Quevedo et al., accepted). As presented in Table 1.6, the blue carbon research has progressed from potential blue carbon payments to quantifying blue carbon stocks from 2009 to 2015. These years also focused on understanding and investigating carbon dynamics in coastal ecosystems. The years 2016 to 2018 had witnessed a growth of mapping blue carbon ecosystems across the world using various technologies. This information has paved the way to the emergence of multidisciplinary approaches in blue carbon research, particularly toward their management and restoration. Consequently, this phenomenon led to an increase in social and policy-driven investigations in 2021. However, challenges in bringing blue carbon to market and project implementations in the international arena remain despite the progressive development.

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[21] Babiker, M., G. Berndes, K. Blok, B. Cohen, A. Cowie, O. Geden, V. Ginzburg, A. Leip, P. Smith, M. Sugiyama, F. Yamba (2022). Cross-sectoral perspectives. In IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press. Based on Wilcox, J., P.C. Psarras, and S. Liguori (2017). Assessment of reasonable opportunities for direct air capture. Environ. Res. Lett., 12(6).

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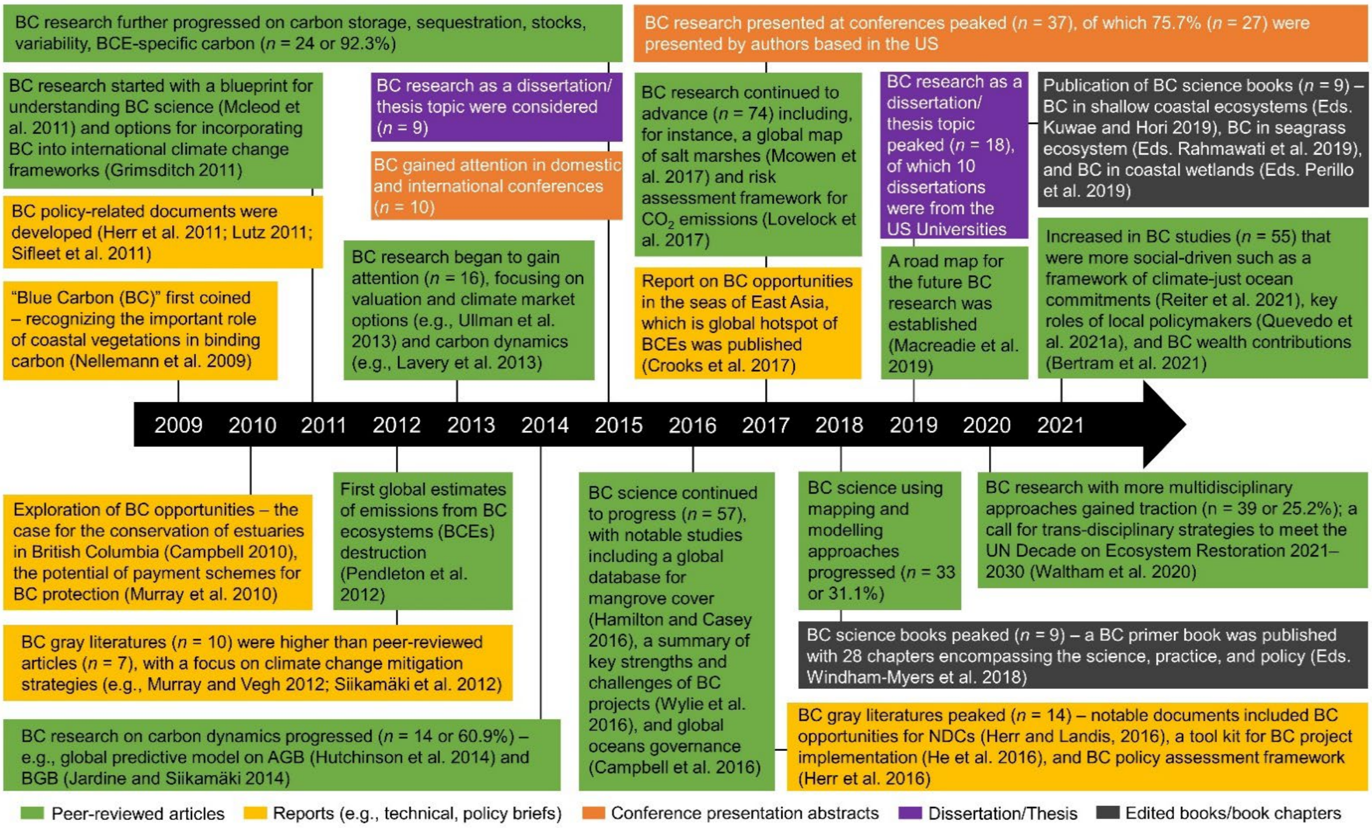
Thus far in the introduction, we have examined the evolution of the blue carbon debate, mainly in the international policy arena. This roadmap aims to examine the potential for progress on Blue Carbon over the next 10 to 30 years. Chapter 2 summarizes the current state of scientific knowledge on Blue Carbon, which is the basis for policy trends, with a particular emphasis on natural macroalgal beds and macroalgae cultivation, which have been the focus of increasing attention in recent years. Chapter 3 summarizes the current status and future prospects of methods for quantitatively evaluating the existing amount, dynamics, and sequestration rate of blue carbon, technologies for protecting and increasing blue carbon through conservation, restoration, and creation, and technologies for utilizing blue carbon, especially macroalgae. Chapter 4 describes the institutional, legal, and ethical considerations and potential challenges in promoting the Blue Carbon Project, particularly considering large-scale macroalgal aquaculture. Chapter 5 summarizes mitigation measures and the potential for carbon credits in the event of progress in blue carbon conservation, restoration, and creation. We conclude with recommendations for future consideration after examining the above discussion.

Table 1.6. Timeline and progress of Blue Carbon research since its conception in 2009



BC research further progressed on carbon storage, sequestration, stocks, variability, BCE-specific carbon (*n* = 24 or 92.3%)

BC research presented at conferences peaked (*n* = 37), of which 75.7% (*n* = 27) were presented by authors based in the US

BC research started with a blueprint for understanding BC science (Mcleod et al. 2011) and options for incorporating BC into international climate change frameworks (Grimsditch 2011)

BC policy-related documents were developed (Herr et al. 2011; Lutz 2011; Sifleet et al. 2011)

"Blue Carbon (BC)" first coined – recognizing the important role of coastal vegetations in binding carbon (Nellemann et al. 2009)

BC research as a dissertation/ thesis topic were considered (*n* = 9)

BC gained attention in domestic and international conferences (*n* = 10)

BC research began to gain attention (*n* = 16), focusing on valuation and climate market options (e.g., Ullman et al. 2013) and carbon dynamics (e.g., Lavery et al. 2013)

BC research continued to advance (*n* = 74) including, for instance, a global map of salt marshes (Mcowen et al. 2017) and risk assessment framework for CO_2 emissions (Lovelock et al. 2017)

Report on BC opportunities in the seas of East Asia, which is global hotspot of BCEs was published (Crooks et al. 2017)

BC research as a dissertation/ thesis topic peaked (*n* = 18), of which 10 dissertations were from the US Universities

A road map for the future BC research was established (Macreadie et al. 2019)

Publication of BC science books (*n* = 9) – BC in shallow coastal ecosystems (Eds. Kuwae and Hori 2019), BC in seagrass ecosystem (Eds. Rahmawati et al. 2019), and BC in coastal wetlands (Eds. Perillo et al. 2019)

Increased in BC studies (*n* = 55) that were more social-driven such as a framework of climate-just ocean commitments (Reiter et al. 2021), key roles of local policymakers (Quevedo et al. 2021a), and BC wealth contributions (Bertram et al. 2021)

Exploration of BC opportunities – the case for the conservation of estuaries in British Columbia (Campbell 2010), the potential of payment schemes for BC protection (Murray et al. 2010)

First global estimates of emissions from BC ecosystems (BCEs) destruction (Pendleton et al. 2012)

BC gray literatures (*n* = 10) were higher than peer-reviewed articles (*n* = 7), with a focus on climate change mitigation strategies (e.g., Murray and Vegh 2012; Siikamäki et al. 2012)

BC research on carbon dynamics progressed (*n* = 14 or 60.9%) – e.g., global predictive model on AGB (Hutchinson et al. 2014) and BGB (Jardine and Siikamäki 2014)

BC science continued to progress (*n* = 57), with notable studies including a global database for mangrove cover (Hamilton and Casey 2016), a summary of key strengths and challenges of BC projects (Wylie et al. 2016), and global oceans governance (Campbell et al. 2016)

BC science using mapping and modelling approaches progressed (*n* = 33 or 31.1%)

BC research with more multidisciplinary approaches gained traction (n = 39 or 25.2%); a call for trans-disciplinary strategies to meet the UN Decade on Ecosystem Restoration 2021–2030 (Waltham et al. 2020)

BC science books peaked (*n* = 9) – a BC primer book was published with 28 chapters encompassing the science, practice, and policy (Eds. Windham-Myers et al. 2018)

BC gray literatures peaked (*n* = 14) – notable documents included BC opportunities for NDCs (Herr and Landis, 2016), a tool kit for BC project implementation (He et al. 2016), and BC policy assessment framework (Herr et al. 2016)

*Notable publications and significant contributions in blue carbon research are reflected on the basis of the review of 1179 documents (peer-reviewed and gray publications)[23]

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[23] Quevedo, J. M. D., Uchiyama, Y., & Kohsaka, R (2023). Progress of blue carbon research: 12 years of global trends based on content analysis of peer-reviewed and "gray literature" documents. Ocean and Coastal Management. Accepted.

Chapter 2

Scientific Understandings of Blue Carbon

(1) Criteria for Inclusion as actionable Blue Carbon Ecosystems

Blue Carbon has multiple definitions. Established and emerging areas in scientific and political fields currently exist in the climate change mitigation and conservation measures using Blue Carbon. Lovelock and Duarte (2019)[24] summarized the assessment of disciplines and criteria for inclusion as actionable Blue Carbon based on the current status of the science or policy (Table 2.1). Mangrove forests, tidal marshes, and seagrass meadows are established Blue Carbon ecosystems because they often have high carbon stocks, support long-term carbon storage, offer the potential to manage GHG emissions, and support other adaptation policies. Some marine ecosystems do not meet key criteria for inclusion within the Blue Carbon framework (e.g., oyster and coral reefs). Others are potential emerging Blue Carbon but have gaps in scientific understanding of carbon stocks or greenhouse gas fluxes. Moreover, potential for management or accounting for carbon sequestration (macroalgae and phytoplankton) is currently limited.

In addition to the blue carbon ecosystems already defined as actionable, this roadmap will primarily focus on natural and cultivated macroalgae: mangrove forests, salt marshes, and seagrass beds. Despite their exclusion in the IPCC Guidelines, we focus on natural and farmed macroalgae because scientific knowledge has dramatically accumulated in recent years and their quantitative potential is estimated to be sufficiently large to be manageable by humans.

Table 2.1. Criteria for Inclusion as actionable Blue Carbon Ecosystem (adopted from Lovelock and Duarte, 2018)

	Scale of GHG removals or emissions are significant	Long-term storage of fixed CO_2	Undesirable anthropogenic impacts on the ecosystem	Management is practical/possible to maintain /enhance C stocks and reduce GHG emissions	Interventions have no social or environmental harm	Alignment with other policies: mitigation and adaptation
Mangrove	Yes	Yes	Yes	Yes	Uncertain	Yes
Tidal Marsh	Yes	Yes	Yes	Yes	Uncertain	Yes
Seagrass	Yes	Yes	Yes	Yes	Yes	Yes
Macroalgae	Yes	Uncertain	Yes	Yes	Uncertain	Yes
Salt Flats (Sabkhas)	Uncertain	Uncertain	Yes	Uncertain	Uncertain	Uncertain
Freshwater Tidal Forest	Uncertain	Yes	Yes	Yes	Uncertain	Uncertain
Phytoplankton	Yes	Uncertain	Uncertain	Uncertain	Uncertain	No
Coral Reef	No	No	Yes	No	Uncertain	Yes
Marine Fauna (fish)	No	No	Yes	No	Uncertain	No
Oyster Reefs	No	Uncertain	Yes	No	Yes	Yes

The use of phytoplankton as a climate change mitigation strategy has been proposed since the first ocean fertilization experiments were conducted in the 1990s. A hypothesis indicates the existence of ocean areas with sufficient macro nutrients, such as nitrogen and phosphorus in the surface seawater but few phytoplankton due to a lack of micronutrients, especially iron. Thirteen major experiments have been conducted since the 1990s to date, and the evidence that large amounts of fixed carbon reach the deep ocean is ambiguous[25]. Various adverse effects have been indicated, including the potential occurrence of harmful algal blooms. In 2008, the UN Convention on Biological Diversity (CBD) decided to place a moratorium on all marine fertilization projects, except for small-scale ones in coastal waters. Five years later, the London Convention on Marine Pollution adopted rules for assessing marine fertilization research.

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[24] Lovelock Catherine E. and Duarte Carlos M (2019).Dimensions of Blue Carbon and emerging perspectives. Biology Letters.

[25] Tollefson, J (2017). Iron-dumping ocean experiment sparks controversy. Nature 545, 393–394.

Marine Fauna (including fish, marine mammals, and invertebrates) influence the carbon cycle of the ocean through a range of processes, including consumption, respiration, and excretion. The net carbon sequestration benefit from marine fauna, once allowance is made for respiration over the lifetime of the animal, respiration and carbon output from the species feeding on feces and carcasses before final burial in the seafloor, remains uncertain. Marine Fauna activity can stimulate production by plants (Lapointe et al., 2014[26]) and phytoplankton, leading to sequestration of 0.0007 $GtCO_2e$/year (Lavery et al., 2010[27]). Populations of vertebrates are an important component of the carbon cycle in ocean ecosystems (Schmitz et al., 2018[28]), including predators, which can regulate grazers (Atwood et al., 2015[29]) and may be given consideration when developing policies to secure nature-based carbon functions.

Other coastal ecosystems that are considered Blue Carbon ecosystems include tidally influenced forests. For example, bald cypress and *Melaleuca* forests, which can have enormous soil carbon stocks in their soils, have been markedly reduced in cover. Sabkhas, which comprise high intertidal salt flats dominated by microbial mats and can be extensive in arid environments, may also be candidates for Blue Carbon-based conservation despite the currently limited information on C stocks and fluxes and on their role in adaptation to climate change.

(2) Established Blue Carbon Ecosystem (Mangrove, Salt Marsh, and Seagrass)

Mangrove, salt marsh, and seagrass ecosystems (Figure 2.1) fall within the IPCC definition of “wetlands” and mangroves are often classified as “forests” (and therefore often included in national forest inventories), enabling their inclusion within GHG accounting guidance of the IPCC. The IPCC provided emission factors (CO_2, CH_4, and N_2O) for land-use change in coastal wetlands for activities that result in loss and conversion or those leading to restoration. Mangroves, where they are included in national forest inventories, may also be included in existing GHG reduction schemes, such as Reduced Emissions from Deforestation and Degradation and fostering conservation (REDD+).

Subsequent use of the term has focused on carbon-accumulating coastal habitats structured by rooted plants, such as mangroves, tidal salt marshes, and seagrass meadows, which are relatively amenable to management (Lovelock and Duarte, 2019[30]). Comparisons across the full range of freshwater and saline wetland types are assisted by standardized approaches (Vázquez-González et al., 2017[31]).

A total of 20%–50 % of global blue carbon ecosystems have already been converted or degraded, leading some analysts to conclude that restoring wetlands can offer 14 percent of the mitigation potential needed to hold global temperature to below 2°C above the preindustrial period (Griscom et al., 2017[32]). Rates of mangrove loss have declined from 2.1%/year in the 1980s (Valiela et al., 2001[33]) to 0.11%/year in the past decade (Bunting et al., 2018[34]) due to improved understanding, management, and restoration (Lee et al., 2019[35]). However, mangrove areas still emit an estimated 0.007 $GtCO_{2e}$/year (Atwood et al., 2017[36]). Rates of loss and degradation of seagrass cover are between 2% and 7%/year mainly

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[26] Gea-Izquierdo, G., Bergeron, Y., Huang, J. G., Lapointe-Garant, M. P., Grace, J. & Berninger, F.(2014). The relationship between productivity and tree-ring growth in boreal coniferous forests. Boreal Env. Res. 19: 363–378.

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[30] Catherine Lovelock and Carlos M Duarte (2019). Dimensions of Blue Carbon and emerging perspectives. Biology Letters. Vol. 15. Issue 3. Royal Society

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[35] Lee, S.Y., Hamilton, S., Barbier, E.B. et al. Better restoration policies are needed to conserve mangrove ecosystems. Nat Ecol Evol 3, 870–872 (2019).

[36] Trisha B. Atwood, Rod M. Connolly, Hanan Almahasheer, Paul E. Carnell, Carlos M. Duarte, Carolyn J. Ewers Lewis, Xabier Irigoien, Jeffrey J. Kelleway, Paul S. Lavery, Peter I. Macreadie, Oscar Serrano, Christian J. Sanders, Isaac Santos, Andrew D. L. Steven & Catherine E. Lovelock (2017). Global patterns in mangrove soil carbon stocks and losses. Nature Climate Change volume 7, 523–528

due to pollution of coastal waters (Waycott et al., 2009[37]). Emissions are estimated at 0.05 to 0.33 $GtCO_{2e}$/year (Pendleton et al., 2012[38]), although gains in cover have recently been observed in Europe (de los Santos et al., 2019[39]). Global rates of salt marsh loss are uncertain (1%–2% per year), but losses are estimated to be responsible for 0.02 to 0.24 $GtCO_{2e}$/year (Pendleton et al., 2012). The area covered by blue carbon ecosystems is equivalent to only 1.5% of terrestrial forest cover; however, their loss and degradation are equivalent to 8.4% of CO_2 emissions from terrestrial deforestation because of their high carbon stocks per hectare (Griscom et al., 2017).

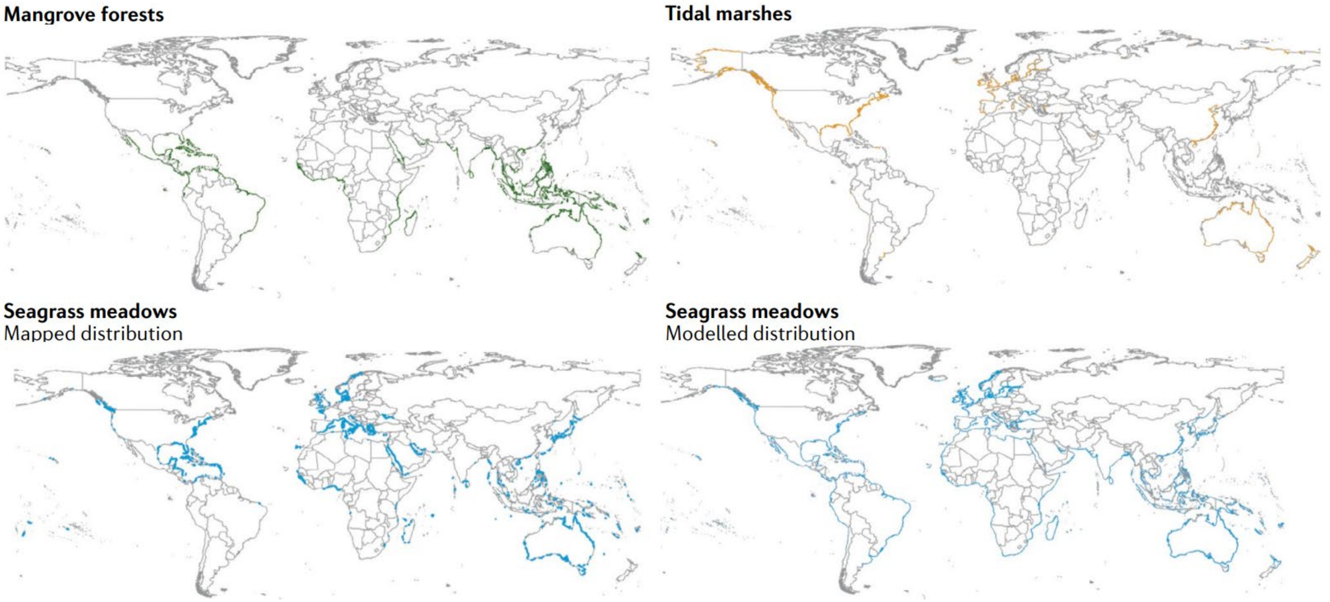

Figure 2.1. Global Distribution of the Established Blue Carbon Ecosystem[40]

The area of mangroves and salt marshes may also be adversely affected by sea level rise in some regions (Lovelock et al., 2015) but could expand in others (Schuerch et al., 2018[41]), increasing their mitigation benefits. Sea level rise will affect habitat areas for all coastal vegetated ecosystems as well as their mitigation potential (Schuerch et al., 2018). The impact of sea level rise on these ecosystems will be strongly influenced by the following: human activities (e.g., sediment supply, land-use changes, population, and seawall defenses), the effects of climate change on adjacent ecosystems (such as coral reefs, mudflats, or barrier islands), and GHG emissions from freshwater wetlands (Luo et al., 2019[42]). Extreme events could also reduce the effectiveness of restoration. Small-scale macroalgae cultivation is considered low risk; however, a large-scale expansion of the industry requires a considerable understanding of impacts and the balance of environmental risks and benefits that macroalgae cultivation projects can offer (Campbell et al., 2019[43]). In addition to climate change, marine and coastal ecosystems are also vulnerable to failure due to socioeconomic factors, including inadequate and inappropriate incentives (Lee et al., 2019). Similar to those developed for forests (Chhatre et al., 2012[44]), social safeguards should also be established.

The estimated mitigation potential of coastal and marine ecosystems (Figure 2.2) is via the two main pathways.

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[42] Luo, M., Huang, JF., Zhu, WF. et al(2019). Impacts of increasing salinity and inundation on rates and pathways of organic carbon mineralization in tidal wetlands. Hydrobiologia 827, 31–49.

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1. Conserving and protecting blue carbon ecosystems, which involves stopping the loss and degradation of these ecosystems, thus avoiding direct land-use change emissions and additional emissions from alternative land use, such as agriculture.
2. Restoration and expansion of degraded blue carbon ecosystems, which involves rehabilitating the soil and associated organisms, thereby restoring their ability to sequester and store carbon.

The World Economic Forum (2021)[45] illustrated the mitigation potential of land-based ecosystems to blue carbon ecosystems. The mitigation potential of restoring green carbon ecosystems, notably forests, is generally high, while that of blue carbon ecosystems per unit area is substantially high.

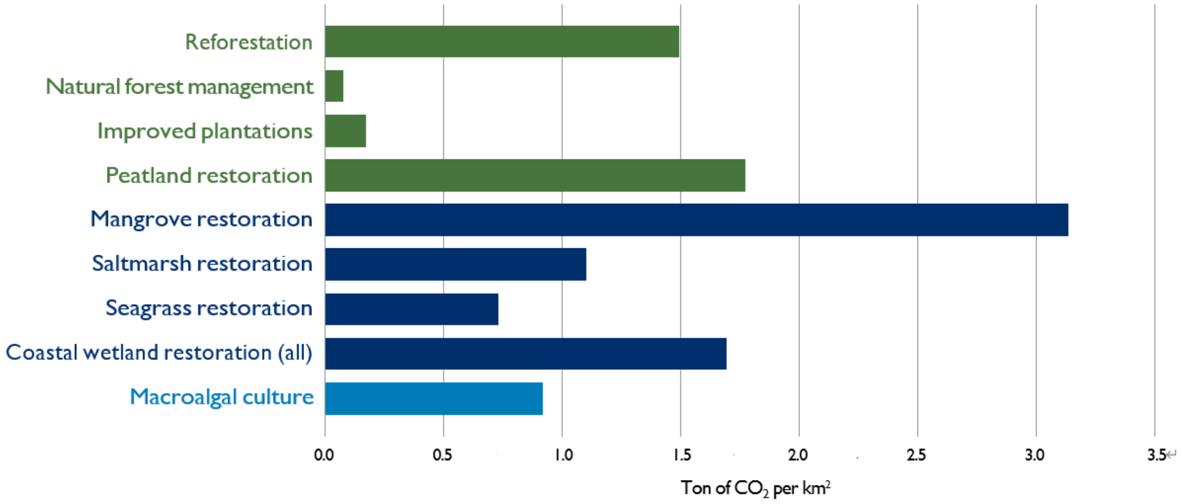

Figure 2.2. Mitigation Potential per Unit Area of Restoring Land-based and Marine Ecosystems

Achieving high levels of mitigation through conservation and restoration is dependent on increased investment in protection, restoration, and enabling the expansion of ecosystem cover where sea level rise provides new opportunities. However, ambitious conservation and restoration targets must be considered within local socioeconomic contexts to prevent perverse outcomes (Lovelock and Brown 2019). Efforts to restore blue carbon ecosystems are growing in number, area, and success (Unsworth et al., 2018[46]; Lee et al., 2019[47]; Gittman et al., 2019[48], Kuwae and Hori, 2019[49]) but remain relatively small scale in most instances (An exception is the 589 km^2 of salt marsh restoration in the United States between 2006 and 2015, Gittman et al., 2019[50]).

Estimates of CO_2 emissions associated with prevented anthropogenic degradation of mangrove, salt marsh, and seagrass ecosystems are sensitive to uncertainties in global cover and loss rates (2%–7%/year), which is particularly the case for seagrass (Table 2.2). Estimates of salt marsh area and its losses (1%–2%/year) are also uncertain (McOwen et al., 2019[51]). Losses of mangrove ecosystems have slowed in the last decades (Table 2.2); thus, emissions associated with their losses have also declined compared to those estimated by Pendleton et al. (2012). The range in potential mitigation that could be achieved through restoration of mangroves, salt marshes, and seagrass ecosystems varied with the level of effort and investment. Low-end estimates of mitigation that could possibly be achieved through restoration by 2050 are 0.2 $GtCO_2e$/year, reflecting limited restoration activities and success (Table 2.3).

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Table 2.2. Global Extent and Loss Rates of Blue Carbon Ecosystems[52]

Ecosystem		Areal Cover (square km)	Recent Rates of Loss (% Year)
Mangroves		138,0000	0.11
Salt Marshes		55,000	1–2
Seagrasses		325,000	2–7
Macroalgae		3,540,000	Unknown

Information on the dynamics of GHGs other than CO_2 (CH_4 and N_2O) in the established blue carbon ecosystems. Some studies suggest that mangrove forests are net sources of CH_4 globally, and the CH_4 emissions can offset C burial in mangroves by 20 %[53]. In contrast, some mangrove forests are sinks for N_2O[54]. However, no concurrent measurements of CO_2, CH_4, and N_2O at relevant temporal and spatial scales are unavailable, and future research is needed.

Table 2.3. Summary of Mitigation Potential from Blue Carbon Ecosystems
(Coastal and Marine Ecosystem) by 2030 and 2050

Mitigation Option	Description	Mitigation Potential 2030 (GTCO2E/YEAR)	Mitigation Potential 2050 (GTCO2E/YEAR)
Conservation: potential mitigation from halting loss and degradation of ecosystems (avoided emissions)	Mangroves	0.02–0.04	
	Salt/tidal marshes	0.04–0.07	
	Seagrasses	0.19–0.65	
	Macroalgae	Knowledge gaps currently too large	
Restoration: potential mitigation from restoring and rehabilitating ecosystems and organisms	Mangroves	0.05–0.08	0.16–0.25
	Salt/tidal marshes	0.004–0.01	0.01–0.03
	Seagrasses	0.01–0.02	0.03–0.05
	Macroalgae	Knowledge gaps currently too large	
Increased macroalgae production via aquaculture	–	0.01–0.02	0.05–0.29
End overexploitation of the ocean to support recovery of biodiversity and increase biomass	–	Knowledge gaps currently too large	
Total	–	0.32–0.89	0.50–1.38

(3) Natural and Farmed Macroalgae

Macroalgae can also be regarded as coastal blue carbon (Krause-Jensen et al., 2018[55]; Raven, 2018[56]). However, their climate mitigation potential is currently assessed separately because of differences in their carbon processing than the established Blue Carbon ecosystems.

The most extensive and productive coastal vegetated ecosystems are globally formed by macroalgae, which are a diverse group, including brown algae (e.g., kelps), red algae, and green algae. Though with large uncertainty, the areal extent of macroalgae is estimated to be 3.5 million km^2 of coastal regions (Table 2.2). The global distribution of kelp forests is provided in Figure 2.3.

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[52] Global Mangrove Watch (2018); Bunting et al. (2018) (mangroves); McOwen et al. (2018) (salt marsh cover); Bridgham et al. (2006) (salt marsh loss); Unsworth et al. (2018) (seagrass cover); Duarte et al. (2008), Waycott et al. (2009) (seagrass loss); Krause-Jensen et al. (2016) (macroalgae cover).

[53] Rosentreter, J. A., Maher, D. T., Erler, D. V., Murray, R. H. & Eyre, B. D. CH_4 emissions partially offset 'Blue Carbon' burial in mangroves. Sci. Adv. 4, eaao4985 (2018).

[54] Erler, D. V. et al. Applying cavity ring-down spectroscopy for the measurement of dissolved nitrous oxide concentrations and bulk nitrogen isotopic composition in aquatic systems: correcting for interferences and field application. Limnol. Oceanogr. Methods 13, 391–401 (2015).

[55] Dorte Krause-Jensen, Paul Lavery, Oscar Serrano, Núria Marbà, Pere Masque and Carlos M. Duarte(2018). Sequestration of macroalgal carbon: the elephant in the Blue Carbon room. The Royal Society Biology Letters. Vol.14 (6)

[56] John Raven (2018). Blue carbon: past, present and future, with emphasis on macroalgae. The Royal Society Biology Letters. Vol.14(10).

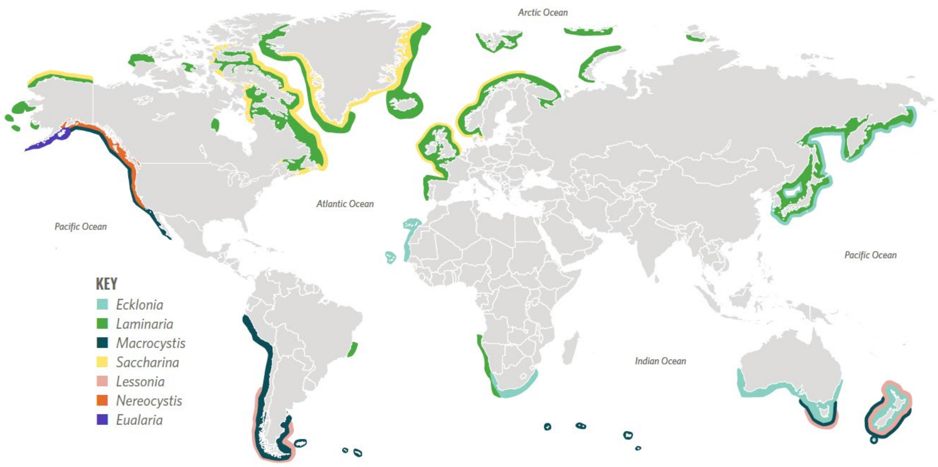

Figure 2.3. Global distribution of kelp forests[57]

Macroalgae are mainly attached to rocks or occasionally free-floating. They lack root structures that would sequester and trap soil carbon, which indicates that the climate mitigation value of wild macroalgae habitats is largely through the export of organic carbon in plant biomass to sinks located in shelf sediments and in the deep ocean (Krause-Jensen and Duarte 2016[58]). Similar to the case in mangroves, salt marshes, or seagrass beds, the loss of macroalgae habitats reduces carbon sequestration but does not result in CO_2 emissions to the atmosphere from sediments below the habitats. Macroalgae carbon sequestration is estimated to be 0.64 (range 0.22–0.98) $GtCO_2e$/year, representing 11 percent of annual global net macroalgae primary production (Figure 2.4; Krause-Jensen and Duarte 2016[59]). Recent studies also underline the large carbon export fluxes of macroalgae (Filbee-Dexter et al., 2018[60]; Queirós et al., 2019[61]; Ortega et al., 2019[62]).

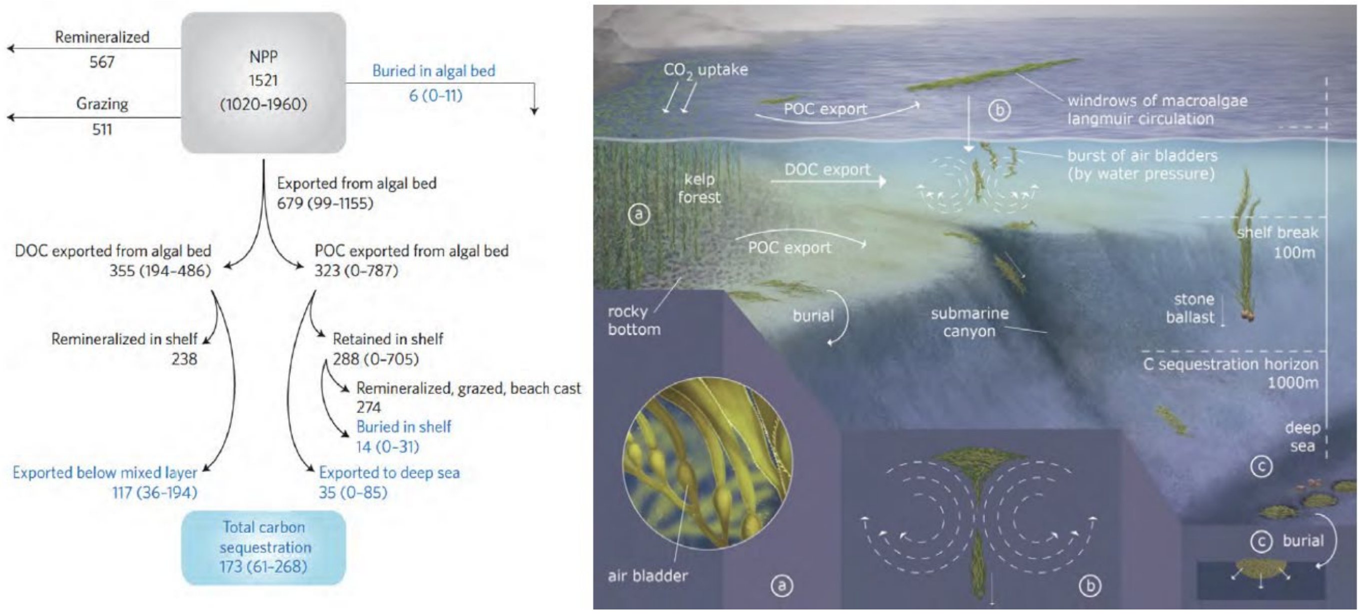

Figure 2.4. Macroalgae Contributions for Climate Change Mitigations[63]

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[57] Eger, A. M. and Wernberg, T. (2022). Introduction. In Kelp Restoration Guidebook: Lessons Learned from Kelp Projects Around the World, (Eger, A. M., Layton, C., McHugh, T. A., Gleason, M., and Eddy, N.), pp 5-9. The Nature Conservancy, Sacramento, CA, USA.

[58] Krause-Jensen, D., Duarte, C (2016). Substantial role of macroalgae in marine carbon sequestration. Nature Geosci 9, 737–742.

[59] Krause-Jensen, D., Duarte, C (2016). Substantial role of macroalgae in marine carbon sequestration. Nature Geosci 9, 737–742.

[60] Karen Filbee-Dexter, Thomas Wernberg(2018). Rise of Turfs: A New Battlefront for Globally Declining Kelp Forests, Bio Science, Vol.68(2),64–76,

[61] Ana Moura Queirós,Nicholas Stephens,Stephen Widdicombe,Karen Tait,Sophie J. McCoy,Jeroen Ingels,Saskia Rühl,Ruth Airs,Amanda Beesley,Giorgia Carnovale,Pierre Cazenave,Sarah Dashfield,Er Hua,Mark Jones,Penelope Lindeque,Caroline L. McNeill,Joana Nunes,Helen Parry,Christine Pascoe,Claire Widdicombe,Tim Smyth,Angus Atkinson,Dorte Krause-Jensen,Paul J. Somerfield(2019). Connected macroalgal-sediment systems: blue carbon and food webs in the deep coastal ocean. Ecological Society of America Ecological Monographs. Vol89(3)

[62] Ortega, A., Geraldi, N.R., Alam, I. et al.(2019). Important contribution of macroalgae to oceanic carbon sequestration. Nat. Geosci. 12, 748–754

[63] Krause-Jensen, D., Duarte, C. Substantial role of macroalgae in marine carbon sequestration. Nature Geosci 9, 737–742 (2016). https://doi.org/10.1038/ngeo2790

Overall assessment of the global change rate of macroalgae habitats is unavailable and the net area is lost; thus, kelps (brown canopy-forming macroalgae) are estimated to have experienced a global average annual loss rate of ~0.018%/year over the past 50 years, demonstrating large geographic variability (Wernberg et al., 2019[64]). The protection and restoration of wild macroalgae habitats also hold potential for GHG emission mitigation, but knowledge gaps are currently too large to estimate the potential contribution due to the unknown extent of lost macroalgal habitats that could be restored. Moreover, methods and success rates of restoration and protection measures (including sustainable harvest methods) must be explored and reviewed.

Policy recognition of the mitigation benefits of coastal ecosystems requires quantitative information on their actual and potential carbon uptake and storage at the local and national scales within an international framework for carbon accounting. Proposals to apply carbon accounting to the amount of refractory (poorly soluble) dissolved organic carbon (DOC) produced by macroalgae and the amount of seafloor deposition and burial and deep-sea transport of organic matter derived from macroalgae are underdeveloped. As a national project (March 2021–March2025), models in Japan are being developed to evaluate seafloor deposition and burial, deep-sea transport of organic carbon, and refractory organic matter production for natural and farmed macroalgae by function and region to evaluate CO_2 absorption.

Evidence that macroalgae produce highly refractory compounds and that organic carbon may be buried in sediments or transported to the deep sea and thus stored for thousands of years is growing (Figure 2.5). In addition to conserving wild kelp beds, macroalgae aquaculture offers opportunities for climate change mitigation and adaptation. However, macroalgae (and phytoplankton) necessitates a different approach to those typically involved in established Blue Carbon ecosystems because they require management of the future of their carbon production and the locations of carbon accumulation, which may be distant from the production sites (e.g., in water column and deep water).

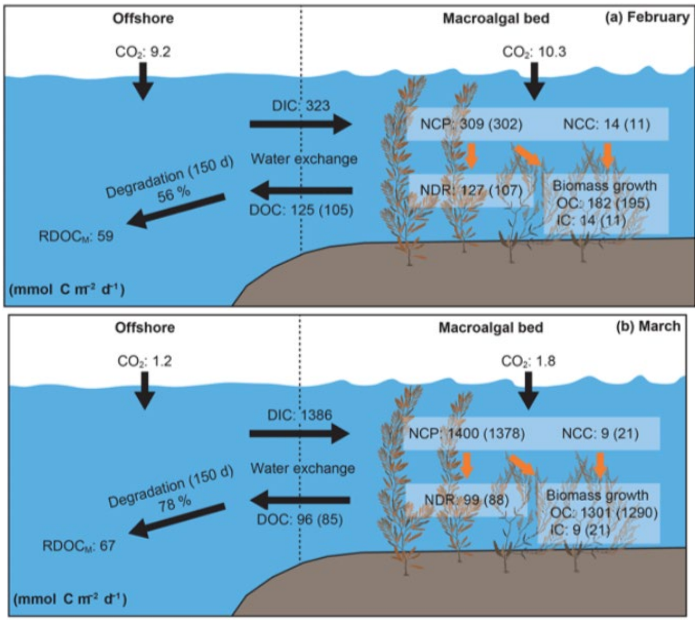

Figure 2.5. Carbon Flows and Macroalgal Community Metabolism[65]

*"NCP" indicates "net community production"; "NCC" indicates "net community calcification"; NDR indicates "net DOC release"; in the macroalgal bed, calculated using the results of field-bag experiments[66].

Macroalgae aquaculture is inherently manageable as a mitigation measure. If linked to biofuel or biogas production, then potential to reduce emissions (as an alternative to fossil fuels); if also linked to carbon capture and storage, then achieving negative emissions may be possible (net CO_2 removal from the atmosphere). Full life cycle analyses are needed to assess

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[64] Thomas Wernberg and Karen Filbee-Dexter(2019). Missing the marine forest for the trees. Mar Ecol Prog Ser 612. 209-215

[65] Watanabe, K., Yoshida, G., Hori, M., Umezawa, Y., Moki, H., & Kuwae, T. (2020). Macroalgal metabolism and lateral carbon flows can create significant carbon sinks. Biogeosciences, 17(9), 2425-2440.

[66] Biomass growth in terms of organic carbon (OC) is calculated by subtracting NDR from NCP. Biomass growth in terms of inorganic carbon (IC) is the same as NCC. DIC and DOC flows via water exchange are estimated by mass-balance modeling. Community metabolism, biomass growth, and DOC outflow indicate the sum of macroalgal and planktonic carbon flows. Carbon fluxes are calculated in units of millimoles per square meter of the surface area of the macroalgal bed per day. RDOCM indicates refractory DOC released by macroalgae.

the energy efficiency of such approaches and the viability of scaling up these approaches to climatically important levels considering associated environmental and socioeconomic implications. A different mitigation option using macroalgae relates to their use as a dietary supplement for ruminants to suppress methane production. *In vitro* studies have provided promising results. However, confidence in this approach as a mitigation option is low because its potential scale of real-world benefits has yet to be quantified.

Rather than accumulate carbon (similar to most wild algal forests), macroalgae farms found in sites over coarse sediment (coarse sand to stony soils) and sites with strong currents export carbon. Carbon accumulation and sequestration below the farm were documented for many types of farms. Remarkably high sedimentation and carbon burial rates were found in farms from Ningde farm (China), Seriwe and Naim Island (Indonesia), and Semporna (Malaysia) and Atlantic Sea Farms (USA).

Two-thirds of the farms demonstrated elevated organic carbon in farm soils (the rest of the farms were placed in erosive, high-energy environments). A total of 75% of farms where sedimentation rates could be resolved showed increased sedimentation rates, accounting for 0.27 ± 0.17 g m^{-2} $year^{-1}$ in soils under farms on average (across all farms). Meanwhile, 75% of farms, wherein carbon accumulation rates could be resolved, accumulated excess carbon compared to reference or before farm operation. Carbon sequestration averaged 2.0 tCO_2 ha^{-1} $year^{-1}$ and increased (compared to reference or before operation) by 1.4 tCO_2 ha^{-1} $year^{-1}$ (max 8.0 tCO_2 ha^{-1} $year^{-1}$) on average. Highest carbon accumulation rates in sites that supported high carbon accumulation rates before operation emphasized the importance of selecting sink sites to maximize macroalgae climate and carbon benefits without causing tradeoffs, such as seabed environmental degradation.

Projections of mitigation from macroalgae farming could reach 0.05–0.29 $GtCO_2e$/year by 2050 (Table 2.3). However, expansion rates of the industry and the production proportion that would be sequestered demonstrate uncertainties. Scaling up macroalgae production via aquaculture offers different potential mitigation pathways.

- Macroalgae products might replace those with a high CO_2 footprint, thereby avoiding emissions (rather than directly contributing to sequestration) in fields, such as food, feed, fertilizers, nutraceuticals, biofuels, and bioplastics (Duarte et al., 2017[67]). The extent of this mitigation pathway is currently unknown.
- Addition of macroalgae to animal feeds might lead to reduced enteric methane emission from ruminants, a potential technology that is currently being explored and may substantially increase the mitigation potential of macroalgae. In vitro experiments have shown that the red alga, Asparaguses taxonomies, can reduce methane emissions from ruminants by up to 99% when constituting 2% of the feed; several other species, including common ones, show a potential methane reduction of 33% to 50% (Machado et al., 2016[68]). The Sea Forest team has currently been attempting to cultivate Asparagopsis at a commercial scale as the first case in the world in Australia and New Zealand.
- Similar to wild macroalgae, farmed macroalgae contribute to carbon sequestration through export of dissolved and particulate carbon to oceanic carbon sinks during the production phase (Duarte et al., 2017[69]).

Two scenarios were considered for estimating the mitigation potential of macroalgae farming by 2030 and 2050. The assumptions underlying the two scenarios are presented below.

1. Macroalgae farming develops at 8.3%/year (the current rate, calculated on the basis of the increase in the farmed and harvested production of green, red, and brown macroalgae between 2000 and 2017) (FAO 2018), 100% of production is assumed sequestered, and farming and processing are assumed CO_2 neutral. Conversion factors from wet weight to carbon are from Duarte et al. (2017).
    - Average annual yield is 1000 tons dry weight/km^2 (current best practices) (World Bank 2016). Estimated production by 2030 (9.4 Mt dry weight/year, equivalent to 2.3 megatons of carbon/year [MtC/ year)] and 2050 (49.3 Mt dry weight/year, equivalent to 12.2 MtC/year) would require an area of 9383 and 49,348 km^2, respectively. This finding represents 0.02% and 0.1% of the global area suitable for macroalgal aquaculture

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[67] Duarte CM, Wu J, Xiao X, Bruhn A and Krause-Jensen D (2017) Can Seaweed Farming Play a Role in Climate Change Mitigation and Adaptation? Front. Mar. Sci. 4:100.

[68] Machado, L., Magnusson, M., Paul, N.A. et al(2016). Dose-response effects of Asparagopsis taxiformis and Oedogonium sp. on in vitro fermentation and methane production. J Appl Phycol 28, 1443–1452.

[69] Duarte CM, Wu J, Xiao X, Bruhn A and Krause-Jensen D (2017) Can Seaweed Farming Play a Role in Climate Change Mitigation and Adaptation? Front. Mar. Sci. 4:100.

(estimate based on suitable temperature and nutrient conditions, Froehlich et al., 2019[70]).

2. Macroalgae farming develops at 14%/year from 2013 onward (rate assumed in a scenario developed by the World Bank, 2016), 100% of production is assumed sequestered, and farming and processing are assumed to be CO_2 neutral. Conversion factors from wet weight to carbon are from Duarte et al. (2017). Average annual yield is 1000 tons dry weight/km^2 (current best practices) (World Bank 2016), leading to a production of 324 Mt dry weight/ year, which is equivalent to carbon assimilation of 80 MtC/ year by 2050.
    - The scenario of a 14% annual increase in production provides an upper limit of the sequestration potential by 2030 and 2050; it is further assumed that farming could proceed at this increase rate without meeting constraints before 2050. An even high production estimate of 10 billion tons dry weight/year was recently proposed (Lehahn et al., 2016[71]), indicating that the estimated upper limit of macroalgae production is realistic.
    - The assumption that 100% of the macroalgae harvest is sequestered is highly unlikely because macroalgae are farmed for economically profitable purposes other than carbon sequestration. Energy is also required in the production process. However, carbon sequestration through export of the “non seen production” during farming will contribute to the sequestration potential (Duarte et al., 2017).

Recent estimates suggest that this export may constitute 60% of what is eventually harvested (Zhang and Kitazawa, 2016[72]). Assuming that 25% of the macroalgae export is sequestered (Krause-Jensen et al., 2016[73]).

Farms must not harm wild blue carbon ecosystems (mangroves, seagrasses, saltmarshes, and macroalgae) to maximize the mitigation benefit of macroalgae farming. Conversely, sustainable macroalgae farming may have the advantage of reducing the harvest of wild macroalgae.

Research on the dynamics of GHGs other than CO_2 in natural macroalgal beds and farms is necessary. Recent studies have shown that the Baltic Sea macroalgae *Fucus vesiculosus* releases methane equivalent to 28%–35% of the annual CO_2 uptake by this macroalgae[74]. Future studies should consider the process of CH_4 release by macroalgae to constrain the potential of blue carbon effectively.

(4) Mitigation in the Open Ocean

(a) Ocean Fertilization[75]

Current net primary production by marine phytoplankton is estimated to be 58 ± 7 GtC Cyr^{-1}, equal to 212.86 ± 25.69 $GtCO_2$ Cyr^{-1}; this estimated value is similar to terrestrial primary production and around six times larger than anthropogenic emissions. However, over 99% of the biologically fixed carbon returns to the atmosphere over a range of timescales.

The direct method of increasing marine productivity involves adding land-derived nutrients that may currently limit primary production, particularly iron. This approach has been investigated experimentally by modeling and observing natural system behavior. Experimental studies to date have shown that primary production can be occasionally enhanced by the addition of iron.

Difficulties arise in demonstrating the timescale of additional carbon removal and obtaining information on the consequences of the fertilization for other marine ecosystem components, including ocean acidification and other

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[70] Halley E. Froehlich, Jamie C. Afflerbach, Melanie Frazier, Benjamin S. Halpern (2019). Blue Growth Potential to Mitigate Climate Change through Seaweed Offsetting. Current Biology. Vol 29 (18),3087-3093.

[71] Yoav Lehahn, Kapilkumar Nivrutti Ingle, Alexander Golberg (2016). Global potential of offshore and shallow waters macroalgal biorefineries to provide for food, chemicals and energy: feasibility and sustainability. Algal Research, Vol17, 150-160.

[72] Junbo Zhang, Daisuke Kitazawa (2016). Assessing the bio-mitigation effect of integrated multi-trophic aquaculture on marine environment by a numerical approach. Marine Pollution Bulletin, Vol 110 (1), 484-492.

[73] Krause-Jensen, D., Duarte, C (2016). Substantial role of macroalgae in marine carbon sequestration. Nature Geosci 9, 737–742.

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[75] Wingard, G.L., Bergstresser, S.E., Stackhouse, B.L., Jones, M.C., Marot, M.E., Hoefke, K., Daniels, A. and Keller, K. (2019). Impacts of Hurricane Irma on Florida Bay Islands, Everglades National Park, USA. Estuaries and Coasts, 1-20., GESAMP (2019). High level review of a wide range of proposed marine geoengineering techniques. (Boyd, P.W. and Vivian, C.M.G., eds.). (IMO/FAO/UNESCO-IOC/UNIDO/WMO/IAEA/UN/UN Environment/UNDP/ISA Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection).
Rep. Stud. GESAMP No. 98, 144 p

potential side effects. Modeling studies indicate that the climatic benefits could be relatively short-lived. Furthermore, public and political acceptability for ocean fertilization is low. Ocean iron fertilization is regulated by the London Protocol, with amendments prohibiting such an action unless constituting legitimate scientific research authorized under permit. There are additional governance constraints for the Southern Ocean where ocean iron fertilization is theoretically considered to be most effective.

Open ocean fertilization by macronutrients (e.g., nitrate) has also been proposed, with modeled potential for gigaton-scale carbon removal. Similar technical and governance considerations apply with regard to the quantification of mitigation benefits the monitoring of potential adverse impacts and the political acceptability of large-scale deployment. This approach would also involve high costs because of the remarkably large quantities of required nutrients.

Recent reviews of the scope for using natural processes in the open ocean for climate mitigation are provided. The summary assessment provided herein is limited to direct and indirect biologically based approaches, consistent with the scoping of this report and the major governance constraints on the large-scale application of open ocean interventions.

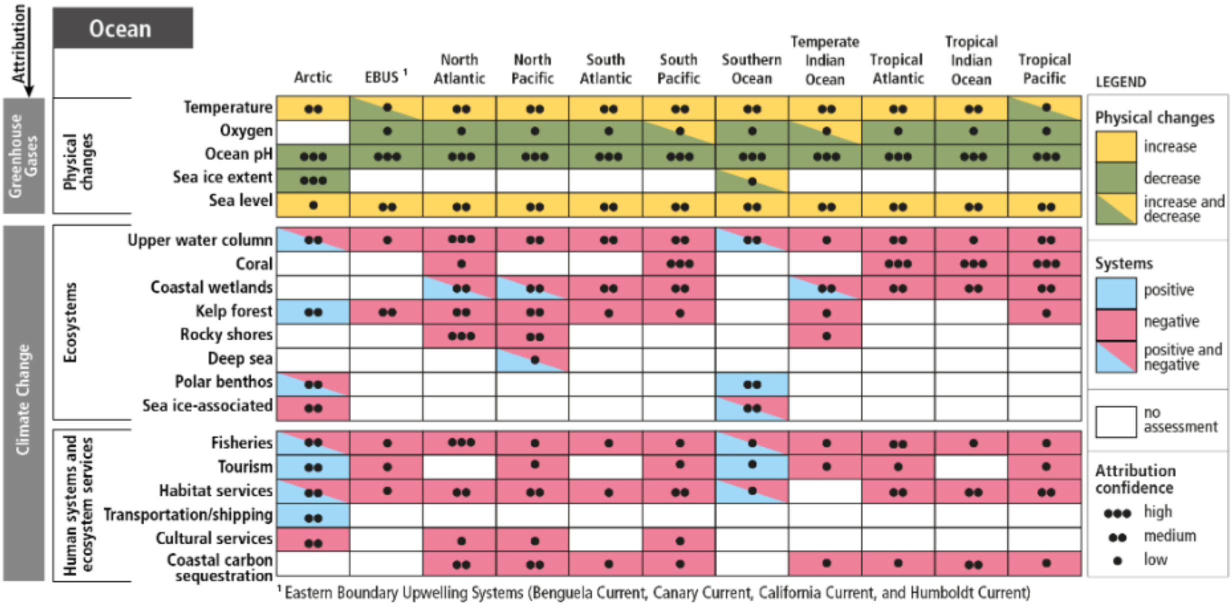
(b) Increasing Upwelling

The indirect method of enhancing marine productivity uses physical devices to increase upwelling, thereby raising the supply of a wide range of naturally occurring nutrients from deep water. This technique risks releasing additional CO_2 to the atmosphere, reducing its potential for climate mitigation. Other undesirable climatic consequences, including disruption of regional weather patterns and long-term warming rather than cooling, may also be observed if enhanced large-scale upwelling is deployed.

Confidence that such open ocean manipulations provide a viable mitigation measure is low due to the many technical, environmental, and governance issues relating to marine productivity enhancement by either direct fertilization or upwelling.

(5) Climate Change Adaptation Effects

(a) Climate Change Impacts for the Ocean



Ocean		Arctic	EBUS [1]	North Atlantic	North Pacific	South Atlantic	South Pacific	Southern Ocean	Temperate Indian Ocean	Tropical Atlantic	Tropical Indian Ocean	Tropical Pacific
Physical changes	Temperature	🟨 ●●	🟨🟩 ●	🟨 ●●	🟨 ●●	🟨 ●●	🟨 ●●	🟨 ●●	🟨 ●●	🟨 ●●	🟨 ●●	🟨🟩 ●
	Oxygen		🟩 ●	🟩 ●	🟩 ●	🟩 ●	🟨🟩 ●	🟩 ●	🟨🟩 ●	🟩 ●	🟩 ●	🟩 ●
	Ocean pH	🟩 ●●●	🟩 ●●●	🟩 ●●●	🟩 ●●●	🟩 ●●●	🟩 ●●●	🟩 ●●●	🟩 ●●●	🟩 ●●●	🟩 ●●●	🟩 ●●●
	Sea ice extent	🟩 ●●●						🟨🟩 ●				
	Sea level	🟨 ●	🟨 ●●	🟨 ●●	🟨 ●●	🟨 ●●	🟨 ●●	🟨 ●●	🟨 ●●	🟨 ●●	🟨 ●●	🟨 ●●
Ecosystems	Upper water column	🟦🟥 ●●	🟥 ●	🟥 ●●●	🟥 ●●	🟥 ●●	🟥 ●●	🟦🟥 ●●	🟥 ●	🟥 ●●	🟥 ●	🟥 ●●
	Coral			🟥 ●			🟥 ●●●			🟥 ●●●	🟥 ●●●	🟥 ●●●
	Coastal wetlands			🟦🟥 ●●	🟦🟥 ●●	🟥 ●●	🟥 ●●		🟦🟥 ●●	🟥 ●●	🟥 ●●	🟥 ●●
	Kelp forest	🟦 ●●	🟥 ●●	🟥 ●●	🟥 ●●	🟥 ●	🟥 ●		🟥 ●			🟥 ●
	Rocky shores			🟥 ●●●	🟥 ●●				🟥 ●			
	Deep sea				🟦🟥 ●							
	Polar benthos	🟦🟥 ●●						🟦 ●●				
	Sea ice-associated	🟥 ●●						🟦🟥 ●●				
Human systems and ecosystem services	Fisheries	🟦🟥 ●●	🟥 ●	🟥 ●●●	🟥 ●	🟥 ●	🟥 ●	🟦🟥 ●	🟥 ●	🟥 ●●	🟥 ●	🟥 ●
	Tourism	🟦 ●●	🟥 ●		🟥 ●		🟥 ●	🟦 ●	🟥 ●	🟥 ●		🟥 ●
	Habitat services	🟦🟥 ●●	🟥 ●	🟥 ●●	🟥 ●●	🟥 ●	🟥 ●●	🟦🟥 ●		🟥 ●●	🟥 ●●	🟥 ●●
	Transportation/shipping	🟦 ●●										
	Cultural services	🟥 ●●		🟥 ●	🟥 ●		🟥 ●					
	Coastal carbon sequestration			🟥 ●●	🟥 ●●	🟥 ●	🟥 ●		🟥 ●	🟥 ●	🟥 ●●	🟥 ●

LEGEND

Physical changes
🟨 increase
🟩 decrease
🟨🟩 increase and decrease

Systems
🟦 positive
🟥 negative
🟦🟥 positive and negative

☐ no assessment

Attribution confidence
●●● high
●● medium
● low

[1] Eastern Boundary Upwelling Systems (Benguela Current, Canary Current, California Current, and Humboldt Current)

Figure 2.6. Observed Regional Impacts from changes in the Ocean[76]

Ocean and cryosphere changes particularly impact islands and coasts with cascading and compounding risks for both extreme events: for example, marine heat waves, tropical and extratropical storms, associated storm surges, and heavy precipitation; slow onset changes, such as the retreat of glaciers and ice sheets, sea ice and permafrost thawing, sea level

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[76] IPCC (2019). IPCC Special Report on the Ocean and Cryosphere in a Changing Climate. Cambridge University Press.

rise, and ocean warming and acidification. The scientific analysis of the impacts was described in the above part of IPCC SROCC in 2019, which featured each sea area as shown below (Figure 2.6). Some ocean indexes are expected to emerge earlier than others and could therefore be used to prioritize planning and building resilience.

Low-lying islands and coasts are particularly at risk from climate-related changes to the ocean and the cryosphere, whether urban or rural, continental or island, at any latitude and regardless of development level, which has the potential to increase the level of loss and damage experienced by local coastal livelihoods significantly (e.g., fishing, logistics, or tourism). For example, accelerating sea level rise will combine with storm surges, tides, and waves to generate extreme sea level events that affect flooding, shoreline changes, and salinization of soils, groundwater, and surface waters. Sea level rise will also combine with ocean warming to accelerate permafrost thawing in the Arctic. Ocean acidification will combine with ocean warming and deoxygenation to impact benthic and pelagic organisms, associated ecosystems (e.g., coral reefs, oyster beds), and top predators, with subsequent impacts on the abundance and distribution of species and the ecosystem services benefiting human societies.

Nearly 50% of the preindustrial, natural extent of global coastal wetlands has been lost since the 19th century[77]. Such a reduction in wetlands is primarily caused by non-climatic drivers, such as alteration of drainage, agriculture development, coastal settlement, hydrological alterations, and reductions in sediment supply. Local factors are driven by regional processes, such as extensive coastal urbanization, human-induced sediment starvation (and implications on subsidence), degradation of vegetated coastal ecosystems (e.g., mangroves, coral reefs, and saltmarshes), lack of long-term integrated planning, changing consumption modes, and conflicting resource use and socioeconomic inequalities. These factors are vehicles of increasing exposure and vulnerability at multiple scales.

Large-scale mortality events of mangroves from “natural causes” have also occurred globally since the 1960s; ~70% of this loss has been attributed to low frequency, high-intensity weather events (such as tropical cyclones (45%)) and climatic extremes (such as droughts, SLR variations, and heat waves). The compounding effects of heat waves, hypersaline conditions, and increased turbidity and nutrient levels associated with floods have negatively changed the composition and biomass of co-occurring seagrass species.

Substantial evidence supports with high confidence that warming and salinization of wetlands due to SLR are causing shifts in the distribution of plant species inland and poleward, such as mangrove encroachment into subtropical salt marshes or seagrass meadows contraction at low latitudes. Plants with low tolerance to flooding and extreme temperatures are particularly vulnerable and may be locally extirpated. The flooded area of salt marshes can become a mudflat or be colonized by considerably tolerant, invasive species whose expansion is favored by combined effects of warming, rising CO_2, and nutrient enrichment. The loss of vegetated coastal ecosystems causes a reduction in carbon storage with positive feedback to the climate system. SLR and warming are expected to continue to reduce the area of coastal wetlands, with a projected global loss of 20%–90% by the end of the century depending on emission scenarios. High risk of total local loss is projected under the RCP8.5 emission scenario by 2100, especially if landward migration and sediment supply are constrained by human modification of shorelines and river flows.

(b) Climate Change Adaptation Effects of Blue Carbon

The Blue Carbon ecosystem conservation and restoration activities can help the ecosystem (including local communities and human residents) cope with changes in response to climate change and reduce damage. Consequently, this approach leads to the implementation of blue carbon ecosystem restoration as NbSs, especially to addressing the impacts of climate change and other societal challenges. Specifically, blue carbon ecosystems provide protection from storms and sea level rise, prevent shoreline erosion, regulate coastal water quality, provide habitat for marine life including commercially

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[77] Highly context-specific territorial and societal dynamics have resulted in major changes at the coast, for instance the growing concentration of people and assets in risk prone coastal areas, and the degradation of coastal ecosystem services such as coastal protection and healthy conditions for coastal fisheries and aquaculture. Local drivers of exposure and vulnerability include, for example, coastal squeeze, inadequate land use planning, changes in construction modes, sand mining and unsustainable resource extraction, as well as loss of Indigenous Knowledge and Local Knowledge. Poor planning can combine with coastal population growth and climate-related ocean change to create maladaptation. Betzold, C. and I. Mohamed (2016).Seawalls as a response to coastal erosion and flooding: a case study from Grande Comore, Comoros (West Indian Ocean). Regional Environmental Change, 17 (4), 1077-1087., Ratter, B. M. W., J. Petzold and K. M. Sinane (2016). Considering the locals: coastal construction and destruction in times of climate change on Anjouan, Comoros. Natural Resources Forum, 40 (3), 112-126., Juhola, S., E. Glaas, B.-O. Linnér and T.-S. Neset (2016).Redefining maladaptation. Environmental Science & Policy, 55, 135-140., Magnan, A. K. et al.(2016). Addressing the risk of maladaptation to climate change. Wiley Interdisciplinary Reviews: Climate Change, 7 (5), 646-665.

important fish species and endangered species, and provide food security for coastal communities (often describing these adaptation effects as “blue carbon co-benefits”).

For example, soft protection systems were found to exhibit effectiveness in reducing wave heights at 62%–79% for salt marshes, 36% for seagrass meadows, and 31% for mangroves[78]. Arguing that coral reefs can provide comparably higher wave attenuation benefits to artificial defenses such as breakwaters, and reef defenses for reducing coastal hazards can be enhanced cost effectively on the order of 1/10th[79]. If applied place specific and adequate (e.g., use of indigenous rather than exotic species[80]), then ecosystem-based measures are usually considered low-regret in that they can stabilize the coastal vegetation and protect against coastal hazards while simultaneously enhancing the adaptive capacity of natural ecosystems[81].

Coastal and oceanic adaptation responses are greatly complicated by the presence of competing interests (either between user groups, communities, or nations), where considerations other than climate change need to be incorporated into cooperation agreements and policy. The deployment of either built or natural protection systems or adopting a “wait and see” approach, is subject to the social acceptance of these approaches in communities. Similarly, the willingness to move away from climate change impacted zones is dependent upon a range of other socioeconomic factors, such as age, access to resources, and crime. Adaptation to climate change includes a range of nonclimatic and social variables that complicate implementation of adaptation plans.

In coastal communities and in most other sectors, despite consensus on the importance of cooperation in tackling climate change, adaptation progress may be hampered by competing economic interests and worldviews, which can be compounded by limited climate change knowledge. Thus, another critical factor that limits climate change adaptation through a blue carbon framework is the lack of awareness of communities or relatively low perceptions of this particular benefit. For example, local communities in the Philippines and Indonesia were surveyed for blue carbon ecosystem service awareness and results showed relatively low level of awareness[82]. Thus, improving community participation and integrating knowledge systems (local, traditional, and scientific) is necessary to support coastal community adaptation responses, for better co-production of knowledge, improved community awareness and better-informed, and cohesive coastal communities. Social responses should include increasing climate change awareness and improving participatory decision making through bottom-up approaches. Additionally, community organization for action and engagements with local management authorities is highly encouraged because local people actively participate in management activities with proper information[83]. Climate change adaptation capacity is shaped by historical path dependencies, local context, and international linkages, while action is influenced by science, research partnerships, and citizen participation. Thus, locally context-specific data to guide appropriate adaptation response should be integrated although, this remains a knowledge gap.

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Chapter 3

Current and Future Technologies to Scale the Blue Carbon

This chapter describes technologies to measure or track, regenerate, conserve, and create blue carbon to use its products. Areas where research and development are expected to be conducted in the future are also presented in this chapter.

(1) Technology to Measure and Track

The ability to parameterize sequestration accurately and cost-effectively from blue carbon ecosystems using standardized methods must be improved. Relatively unknown physicochemical pathways in the blue carbon cycle, including carbonate production and dissolution, alkalinity (carbonate and bicarbonate in seawater) export, and the exports of the blue carbon to deep ocean sinks, must be explored but may have globally significant implications.

The area and activity of each blue carbon ecosystem must be accurately determined. Several methods to determine the area, including satellite imagery, drones, underwater drone photography, ground truth by diving operations, and biologging, are available. Each method has its strengths and weaknesses, and an appropriate combination is necessary. In addition, technologies to aggregate data and perform calculations on the cloud and technologies to extract blue carbon from images automatically using AI are necessary (Figure 3.1).

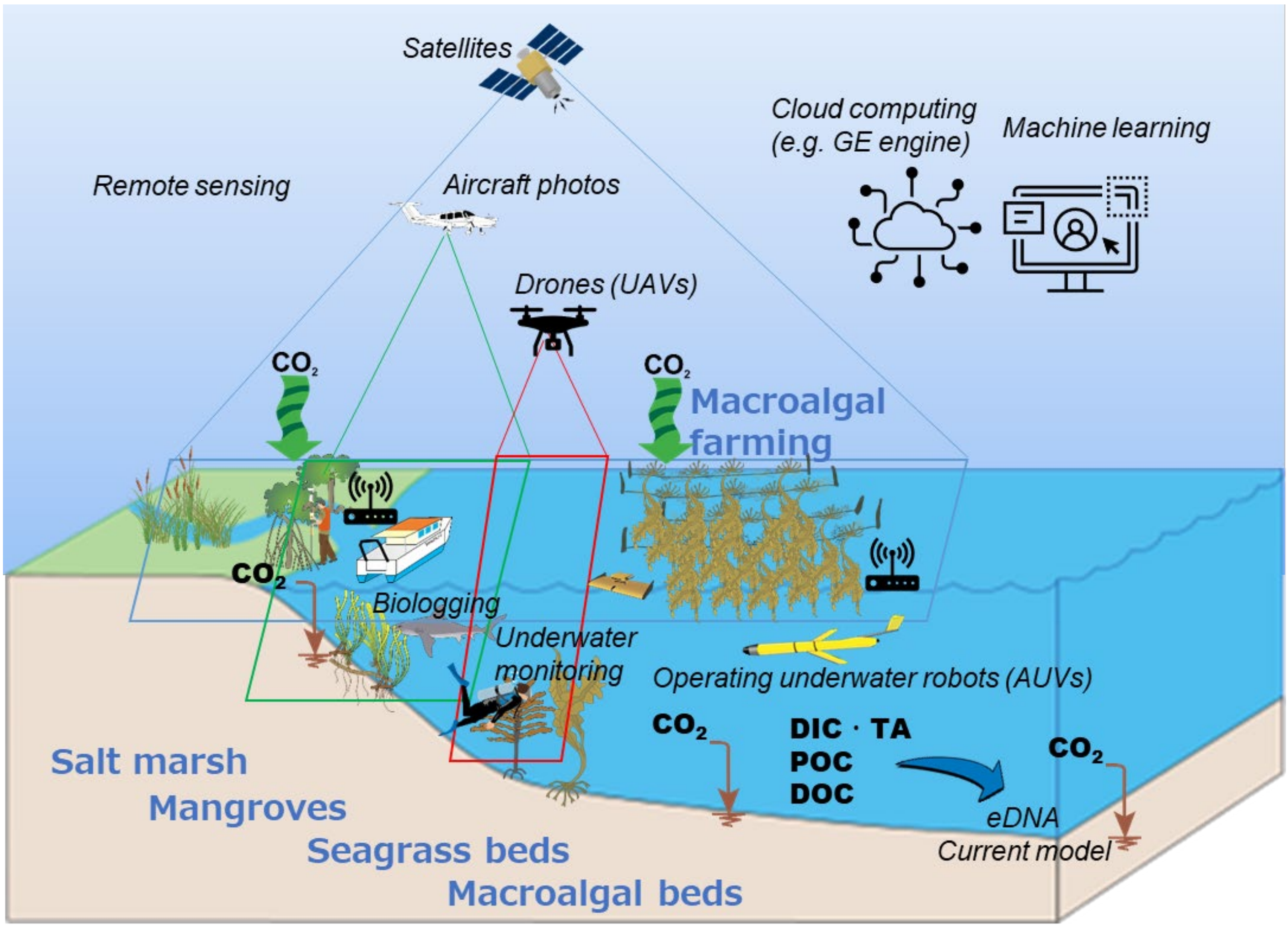

Figure 3.1. Observation technology and analytical tools to improve the parameterization of blue carbon.

The use of machine learning methods and data integration of optical and synthetic aperture radar data is increasing in the mapping and monitoring of blue carbon (BC) ecosystems. The use of drones in combination with machine learning methods is also promising for BC monitoring when applied to salt marshes[84] and seagrass beds[85]. A new approach to displaying seagrass and its surroundings on a map has also been developed by combining the cloud computing power of Google Earth Engine, free satellite imagery, and machine learning[86]. This approach has resulted in a new method to map seagrass distribution and its changes, mapping the seagrass beds of *Posidonia oceanica* in the Aegean Sea, Greece, with an overall accuracy of 72% for ~2510 km^2. An excellent review of remote sensing monitoring of BC ecosystems is also available[87]. Remote sensing from the air can be adapted for monitoring macroalgal farming, but the development of methods from the sea using operating underwater robots (so-called AUVs) has also begun[88].

Visual and camera imaging by Stand-Up Paddleboard, waterborne drones, and onboard and scuba-diving are effective for ground truthing, which is the field data necessary to validate remote sensing. Biologging using tiger sharks and sea turtles can also be an effective monitoring method for some ecosystems. A recent paper reported that at least 66,000 km^2 and up to 92,000 km^2 of seagrass habitat is identified by utilizing recently obtained movement data from tiger sharks on the Bahama Banks[89].

Scientific investigations are needed on slightly understood pathways, such as alkalinity transport from mangroves to the ocean[90,91], transport of dissolved and suspended form carbon from seagrass and macroalgal beds[92], mangroves[93], and cultivated macroalgae to the deep sea, and understanding the interaction between carbonate sediments and BC[94]. Tracking exported BC using environmental DNA (eDNA) in marine sediments and water samples[95] and utilizing recent high-resolution shelf-scale current models [96] should further be developed to assess exports of macroalgae (‘‘allochthonous’’ BC) from coastal habitats to deep ocean sinks.

(2) Technology to Create

When creating BC ecosystems, cases in which reforestation is conducted by planting trees (such as mangroves) or shallow areas that have been lost due to land reclamation or some reasons, are created by artificial materials to create macroalgal and seagrass beds. In some cases, ecological engineering technology is used to create macroalgal beds by creating varieties that are tolerant to high temperatures. In some cases, macroalgae is cultivated together with fish and bivalve mollusks through integrated multitrophic aquaculture (IMTA).

Several manuals and guidelines have been published by international organizations and others on the ecological

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restoration of mangrove forests[97]. We will defer to these publications for details. However, the following general rules are presented.

- Abiotic parameters, such as hydrodynamic, topographic, and physicochemical conditions of the target area, should be understood.
- Natural colonization should be prioritized by restoring favorable hydrological conditions.
- Mangrove planting should be conducted in a manner acceptable to the local community only when natural colonization is impossible.
- Transplantation will be performed by selecting appropriate species to the abiotic conditions within the intertidal zone.
- Appropriate post-planting monitoring should be conducted.

Similarly, manuals on restoration have been published for seagrass beds[98], salt marshes[99], and kelp forests[100]. As with mangrove forests, the guiding principle is to first identify the factors or abiotic parameters surrounding the degraded seagrass beds responsible for the degradation if the factors can be eliminated and addressed to promote natural recovery and only if natural recovery cannot be achieved even after addressing the factors to plant appropriate seagrass or marsh species actively. Preliminary identification of factors will also be important in establishing project baselines.

Japan has many projects to restore macroalgal beds using artificial structures. Activities to restore kelp beds are currently conducted in the coastal areas of Hokkaido, where underwater kelp forests have become barren by herbivores, using steelmaking slag[101]. A project is also underway to measure the creation of macroalgal beds by attaching macroalgae to wave-dissipating blocks while reducing manufacturing costs by 20% and CO_2 emissions by 43% using copper slag mortar for the blocks. In sea areas where three-dimensionality or rugosity has been lost and macroalgal restoration has not progressed, restoring macroalgal beds or kelp forests using artificial reefs and structures while considering the environmental risks may be necessary.

Biotechnology is also being developed for the restoration of underwater forests. One example is the development of technology for perennial macroalgae, such as *Ecklonia cava* and *Eisenia bicyclis*, in which mother algae are collected before the disappearance of macroalgal beds and “free-living gametophyte technology” is used to enable seedling production of large macroalgae at any time. In Japan, efforts are underway to restore underwater forests by combining such seedling production with artificial reefs.

Macroalgal cultivation methods that utilize man-made structures used for other purposes are also being considered. For example, the use of floating or bottom-set offshore wind farm facilities for macroalgal cultivation purposes has been proposed[102]. Moreover, IMTA, a kind of aquaculture that combines primary producers, primary consumers, and secondary consumers, is attracting attention (Figure 3.2). For example, research is also underway to enable bivalves, sea cucumbers, and macroalgae to utilize nutrients from salmon[103], sea bream, and yellowtail aquacultures, respectively. Studies indicated that commercializing IMTA faces challenges; however, the inclusion of climate change mitigation as an option can add values and is worth considering.

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[97] Mangrove Restoration: the key elements to be considered in any restoration project. Technical guide, Pôle-relais zones humides tropicales, 2018; Claudia Teutli-Hernández, Jorge A. Herrera-Silveira, Diana J. Cisneros-de la Cruz, Daniel Arceo-Carranza, Andrés Canul-Cabrera, Pedro Javier Robles-Toral, Oscar J. Pérez-Martínez, Daniela Sierra-Oramas, Karla Zenteno, Heimi G. UsBalam, Eunice Pech-Poot, Xavier Chiappa-Carrara, Francisco A. Comín. 2021. Manual for the ecological restoration of mangroves in the Mesoamerican Reef System and the Wider Caribbean. Integrated Ridge-to-Reef Management of the Mesoamerican Reef Ecoregion Project - MAR2R, UNEP-Cartagena Convention, Mesoamerican Reef Fund. Guatemala City, Guatemala.

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[101] Steelmaking slag is a byproduct of the reduction and refining process that produces steel from iron ore, in which silica (SiO_2) and other non-iron components are melted and combined with lime (CaO).

[102] Stelzenmüller, V., Gimpel, A., Gopnik, M., Gee, K. (2017). Aquaculture Site-Selection and Marine Spatial Planning: The Roles of GIS-Based Tools and Models. In: Buck, B., Langan, R. (eds) Aquaculture Perspective of Multi-Use Sites in the Open Ocean. Springer, Cham.

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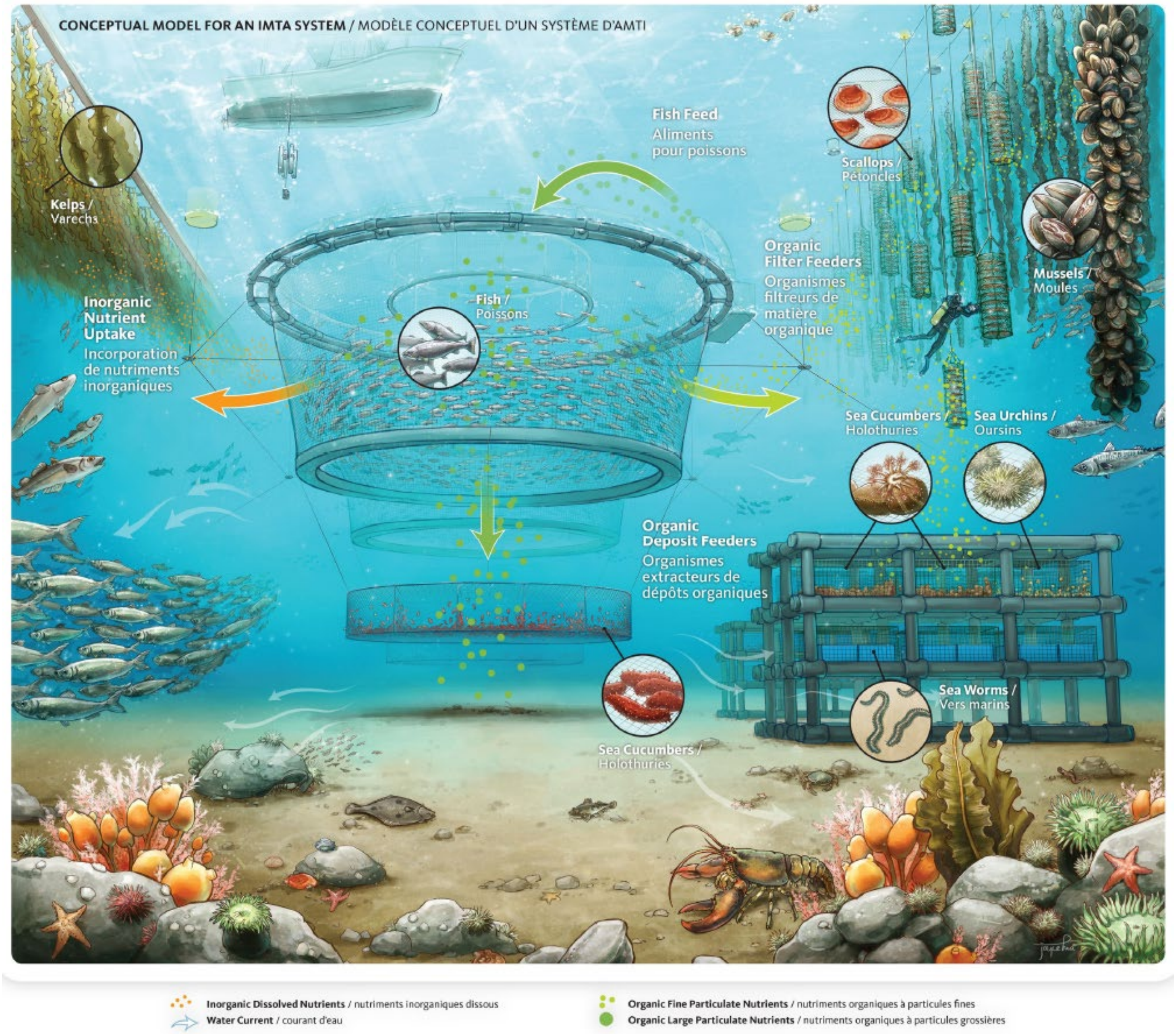

Figure 3.2. Conceptual model for an Integrated Multitrophic Aquaculture (IMTA) System[104]

The search for precocious macroalgae and their artificial cultivation is also currently underway. In Sagami Bay, Japan, research to find a fast-growing, precocious species of *Ecklonia cava*, which normally takes a year and a half to grow, is ongoing; this species has been found to grow in approximately six months, which is one-third the normal time. Artificial cultivation technology for this macroalgae is also under development[105]. Solutions are also being considered for the promotion of blue infrastructure, which can lead to the creation of BC ecosystems, as well as integrated land and sea approaches to promote eco-engineering or NbSs (Box 1).

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[104] https://www.dfo-mpo.gc.ca/aquaculture/sci-res/imta-amti/index-eng.htm (accessed on January 8, 2023)

[105] https://www.pref.kanagawa.jp/docs/kb2/prs/r5306312kajime.html (accessed on January 8, 2023)

Box 1. Eco-engineering and blue infrastructure

The application of ecological engineering principles to build coastal defense structures that "mimic" natural coastal areas, including dynamic coastal landforms (such as beaches, barrier islands, and dunes) and coastal vegetation (such as mangroves, seagrasses, dune vegetation, saltmarshes, and kelp forests), continues to increase. Steven et al. (2020[106]) illustrate the co-benefits of implementing blue infrastructure and the advantages and disadvantages of each form of infrastructure (Figure 3.3, Table 3.1).

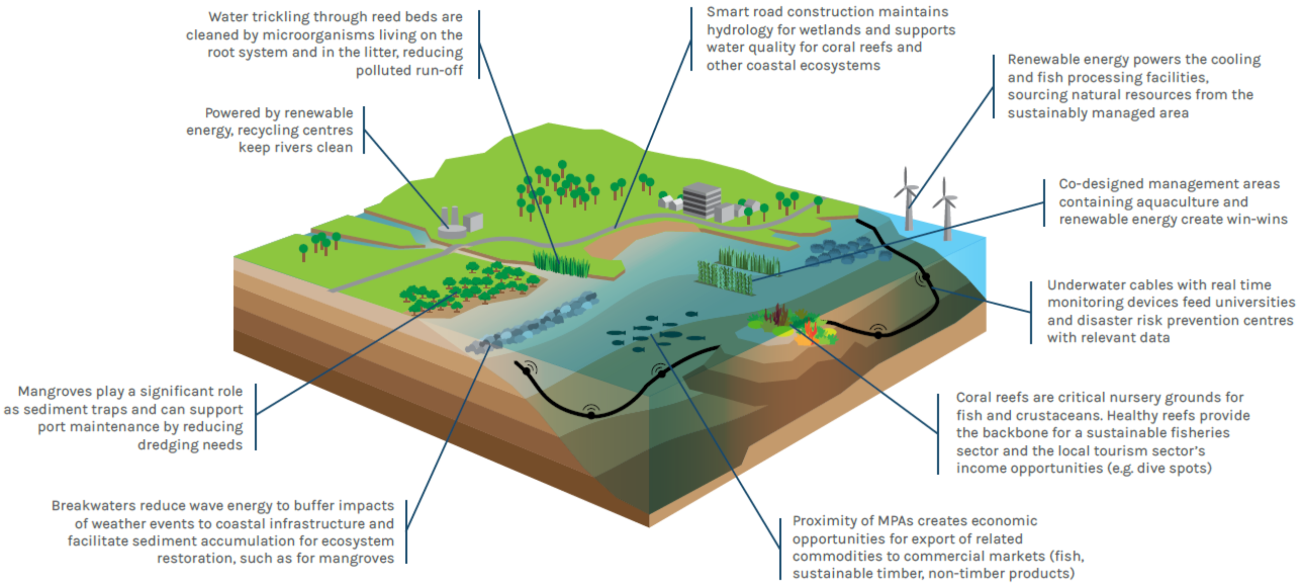

Figure 3.3. Benefits of Implementing Blue Infrastructure[107]

Kuwae and Crocks (2020) suggested the implementation of green and gray[108] hybrid infrastructure to add multifunctionality to coastal infrastructure. Reducing costs and appropriately quantifying green infrastructure functions and monetizing the co-benefits, which currently have underestimated value because quantifying multifunctionality is difficult, is necessary to improve cost-effectiveness. In addition, practitioners must quantitatively confirm that cost-effectiveness is better with green infrastructure than without it in relation to real projects and explain the quantitative benefits of green infrastructure to doubtful stakeholders regarding its efficacy and profitability.

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[106] Kelleway, J. J., Serrano, O., Baldock, J. A., Burgess, R., Cannard, T., Lavery, P. S., Lovelock, C. E., Macreadie, P. I., Masqué, P., Newnham, M., Saintilan, N. and Steven, A. D. L.(2020).A national approach to greenhouse gas abatement through blue carbon management, Global Environmental Change, Vol. 63.

[107] Thiele, T., G. Alleng, A. Biermann, E. Corwin, S. Crooks, P. Fieldhouse, D. Herr, N. Matthews, N. Roth, A. Shrivastava, M. von Unger and J. Zeitlberger (2020). Blue Infrastructure Finance: A New Approach, Integrating Nature-based Solutions for Coastal Resilience. Gland, Switzerland: International Union for Conservation of Nature

[108] gray means the traditional coastal infrastructure typically built with concrete and steel

Table 3.1. Eco-Engineering advantages and disadvantages compared with traditional coastal infrastructures[109]

	Advantages	Disadvantages
Traditional Coastal Infrastructure typically built with concreate & steel	Significant expertise on the design and building of such approaches at large scales exists Decades of experience with implementation Excellent understanding of the function of these approaches and the level of protection provided by different types of structures built to specific engineering standards Infrastructure can withstand a storm event as soon as it is constructed	Does not adapt with changing conditions, such as weakening of sea level rise with time, and has a built-in lifetime Disrupt longshore coastal sediment transport and cause downdrift coastal erosion Cause coastal habitat loss and have negative impacts on the ecosystem services provided by nearby coastal ecosystems May sustain additional damage during small storm events Only provides storm protection benefits when a storm is approaching; no co-benefits accrue in good weather Needs continuous monitoring and regular maintenance Barrier to dispersal and movement of fauna and flora, resulting in loss of ecosystem connections
Natural and Hybrid Infrastructure	Capitalizes on best characteristics of built and natural Allows for innovation in designing coastal protection systems Provides some co-benefits in addition to coastal protection Provides a higher level of confidence than natural approaches alone Possible use in areas with minimal space to implement natural approaches alone Balances conservation with development	Data on the current performance of these systems are limited Does not provide the same benefits given by natural systems Additional research is needed to design the best hybrid systems Growing but limited expertise in the coastal planning and development community on which approaches to use Hybrid systems can still have some negative impacts on species diversity due to their built part Uncertainty in cost-effectiveness and long-term performance Permission for hybrid projects can be a more difficult process than for built projects Response to native species colonization is unpredictable
Ecosystem Restoration	Provides many co-benefits in addition to coastal protection, including fishery habitat, water quality improvements, and carbon sequestration and storage, and offers these benefits to coastal communities all the time, not only during storm events Ecosystem grows strong with time as established Demonstrates self-recover potential after a storm or other disturbance events Maintain pace with sea level rise Cheap to construct Increased CO_2 storage capacity in created, maintained, or restored ecosystems; reduction of urban heatwave island effect; improvement in water quality Can enhance tourism, recreational, and local employment opportunities included in establishment and maintenance Enhances the natural environment and implicit value Saves raw materials and improves public health	Development of best practices for restoring ecosystems according to a set of starting criteria is needed Provides variable levels of coastal protection (nonlinearity of the provisioning of coastal protection benefits) depending on the ecosystem, geography, and the type and severity of storm events; additional research is needed to understand effectivel the estimation or prediction of the provided coastal protectio Establishing restored ecosystems can take a long time; therefore, the natural systems can provide the necessary leve of coastal protection Possibly requires a substantial amount of space to implement natural approaches (such as ecosystem restoration or protection of existing ecosystems), which may be impossible i highly urban or industrial contexts Uncertainty in cost-effectiveness and long-term performance Permitting for natural projects can be a more difficult process than for built projects Uncertainty over responsibility for ownership and maintenance Uncertainty in assessing levels of risk for insurance cover and premiums for coastal assets

(3) Technology to Protect

The description of technologies to protect BC ecosystems will focus on macroalgal beds, wherein feeding damage is a major problem. Seagrass beds are also occasionally observed to be damaged by fish and sea turtles, and the same measures may be required as for macroalgal beds.

Various factors that contribute to the decline of macroalgal beds, including feeding damage by fish and sea urchins (Figure 3.4), deterioration of water quality, and increments in water temperature, are available. Considering measures for the deterioration of water quality and rise in water temperature, such as the aforementioned land-sea integrated eco-engineering and adaptation through seedling production, is necessary. By contrast, for sea urchins in particular, various measures have been attempted with some success. Macroalgal feeding damage by sea urchins is widespread worldwide, and its countermeasures include physical culling, chemical culling, exclusion, and predator protection[110].

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[109] Thiele, T., G. Alleng, A. Biermann, E. Corwin, S. Crooks, P. Fieldhouse, D. Herr, N. Matthews, N. Roth, A. Shrivastava, M. von Unger and J. Zeitlberger (2020). Blue Infrastructure Finance: A New Approach, Integrating Nature-based Solutions for Coastal Resilience. Gland, Switzerland: International Union for Conservation of Nature

[110] See *supra* note 100

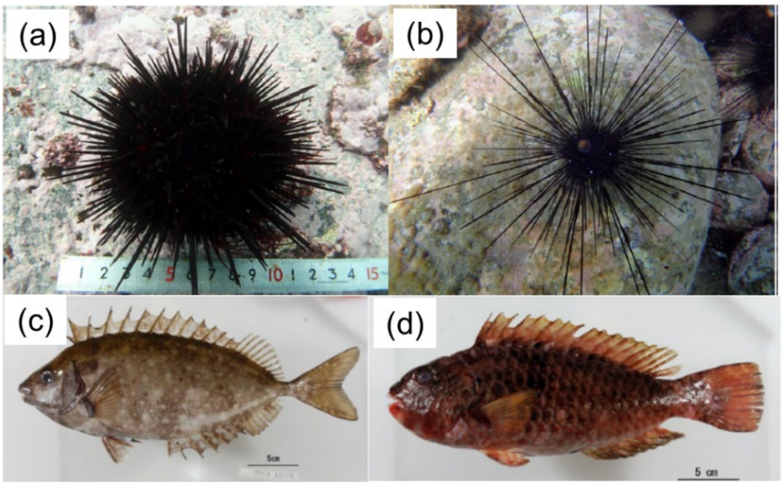

Figure 3.4. Typical herbivores: (a) *Mesocentrotus nudus*, (b) *Diadema setosum*, (c) *Siganus fuscescens*, and (d) *Calotomus japonicus.* Photos are taken from the "Isoyake taisaku guidelines (the sea desertification control guidelines)[111]."

In physical culling, sea urchins are destroyed underwater by scuba or free diving using a variety of tools. In chemical culling, quicklime is applied to seawater, creating a strong base that destroys the sea urchins. Exclusion removes herbivores from the macroalgal beds, and the removed herbivores may be stocked and raised elsewhere, such as in marine areas or in land-based facilities. Predator protection is a way of using natural processes to protect predators of herbivores, such as fish, lobsters, and sea star, to exert top-down controls. In many cases, such predators have been depleted by human harvest. Therefore, this approach will be effective through the establishment of marine protected areas or reserves.

Each method has its strengths and weaknesses considering labor, cost, temporal and spatial range of effectiveness, environmental side effects, and social acceptability.

(4) Technology to Use

Mangrove wood is used for firewood, charcoal, and poles for building materials in Southeast Asia, Africa, and South America, respectively. In Malaysia, mangroves are used for poles and charcoal through the management of separate conservation and utilize areas on a 30-year rotation; thus, it is recognized that carbon neutrality can be achieved through silvicultural activities[112]. Industrial use of seagrasses and salt marsh plants is limited. Examples of seagrass used as organic fertilizer are available. Macroalgae have a variety of industrial uses and have potential for further development. Macroalgal aquaculture offers significant potential for developing low-carbon alternatives for food, feed, and many other applications. Macroalgae are not only utilized as food but also provide benefits, such as climate change action, food security, health and welfare, and clean energy, through their use as feed, drug discovery, and fiber (Figure 3.5).

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[111] https://www.jfa.maff.go.jp/j/gyoko_gyozyo/g_gideline/attach/pdf/index-34.pdf (in Japanese)

[112] Wolswijk, G., Barrios Trullols, A., Hugé, J., Otero, V. (2022) Satyanarayana, B.; Lucas, R.; Dahdouh-Guebas, F. Can Mangrove Silviculture Be Carbon Neutral? Remote Sens. 2022, 14, 2920. https://doi.org/10.3390/rs14122920

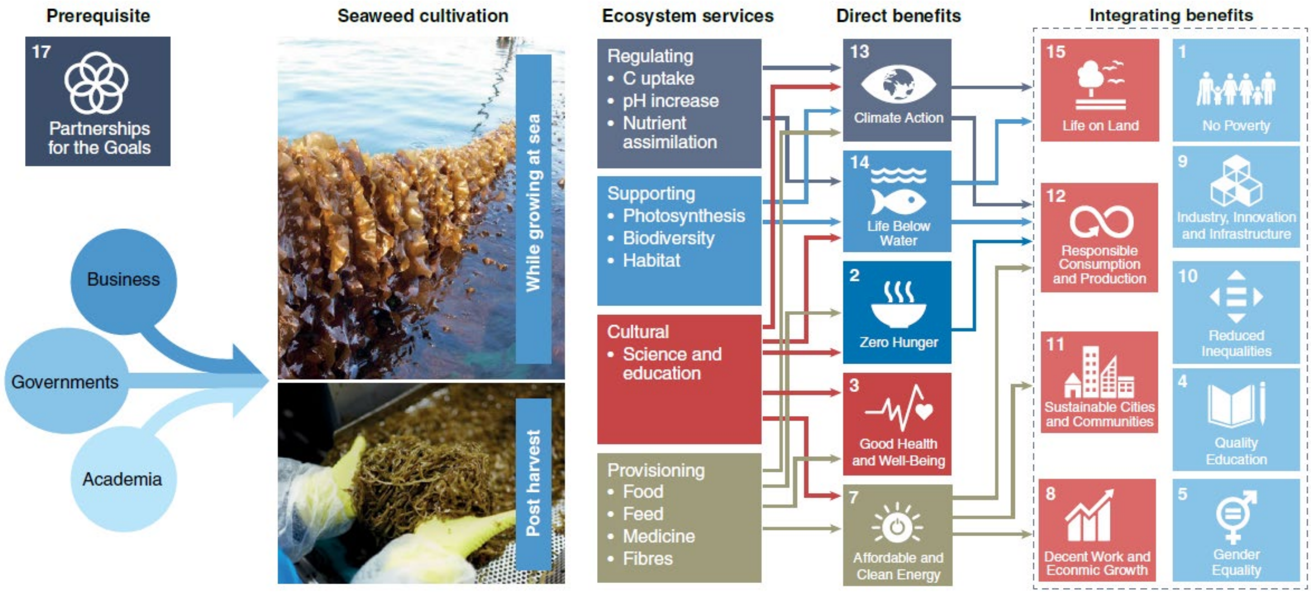

Figure 3.5. Various ecosystem services and benefits of macroalgae utilization[113]

Japan has a long history of using macroalgae since ancient times. For example, the Taiho Ritsuryo, a legal system enacted in 701, mentioned that red seaweed nori and other macroalgae were paid to the Imperial Court as a tax. In 720, the macroalgae *Sargassum* was mentioned in the "Nihon shoki," a Japanese Chronicle or a history book. In the oldest anthology of Japanese poetry, the Manyoshu, which was compiled in 759, mentioned macroalgae in more than 100 out of 4500 poems in total.

Most farmed macroalgae are currently used for human consumption (90% of production), either directly or as additives. The latter are mainly hydrocolloids, such as agar, alginates, and carrageenans, which are used as viscosity modifiers in the food and pharmaceutical industries[114]. Macroalgae are an essential part of the human diet, providing macro and micro nutritional elements, antioxidants, fiber, and healthy fatty acids that contribute to reducing the risk of various diseases[115]. Food use alone would have to increase to 150 MtFW at present and 187 MtFW in 2050 of macroalgal production (assuming populations of 7.8 and 9.7 billion, respectively) to bring the world population's consumption of macroalgae in line with that of the current Japanese population (5.3 gDW d^{-1}). Future demand for macroalgal products would be even high if macroalgal hydrocolloids used in the food industry, which currently account for over 54% of global macroalgal production, are included. Regular monitoring of toxic elements in macroalgae is necessary because they can accumulate toxic elements from the environment[116]. This practice is required for all foods.

Macroalgae provide an opportunity to produce sustainable, nonherbivorous forages for farmed animals. Arguably, replacing fish oil and meal in animal diets with seaweed aquaculture products in feeds is essential for the development of sustainable animal aquaculture on the scale needed to feed a growing population sustainably. The use of some macroalgae in fish diets has positive effects on fish growth and immune systems. However, the formulation of fish diets from macroalgae (either directly or indirectly using them as small invertebrate food and as feed) has not been implemented at any scale and remains an opportunity for the future. Realizing this opportunity will require considerable research and development (R&D) to optimize macroalgae as a substitute for fish meal and oil.

Macroalgae has also traditionally been used as a supplement to livestock feed in coastal areas, and this practice is currently gaining renewed attention. Inclusion of macroalga in livestock diets may contribute to the protein and energy requirements of livestock, provide beneficial bioactive compounds that may improve the production and health of

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[113] Duarte, C.M., Bruhn, A. & Krause-Jensen, D. A seaweed aquaculture imperative to meet global sustainability targets. *Nat Sustain* **5**, 185–193 (2022). https://doi.org/10.1038/s41893-021-00773-9

[114] Mazarrasa, I., Olsen, Y. S., Mayol, E., Marbà, N. & Duarte, C. M. Rapid growth of seaweed biotechnology provides opportunities for developing nations. Nat. Biotechnol. 31, 591–592 (2013).

[115] Holdt, S. L. & Kraan, S. Bioactive compounds in seaweed: functional food applications and legislation. *J. Appl. Phycol.* **23**, 543–597 (2011).

[116] http://extwprlegs1.fao.org/docs/pdf/eri42405.pdf

monogastric and ruminant livestock[117], and contribute to a significant reduction in methane emissions from ruminants[118].

The amount of Sargassum (mainly two species, *Sargassum natans* and *Sargassum fluitans*) drifting ashore in the Caribbean and west African region has dramatically increased, adversely affecting the marine environment, the fishing and tourism industry, and the health of the local population. Together with the government and local authorities, programs to collect and remove drifting *Sargassum* have been initiated with the support of FAO[119] to develop policies, standards, and incentives. Simultaneously, FAO is promoting the repurpose, commercial use, and creation of employment and income through the development of guidelines for the use of *Sargassum*. Moreover, *Sargassum* is already currently used to make bricks, shoe soles, soaps, plant stimulants, and paper, and its conversion to renewable energy, bioplastics, and compost is considered. Isolated compounds are known to exhibit a variety of biological activities, such as analgesic, anti-inflammatory, antioxidant, anti-tumor, anti-bacterial, and anti-viral, and are expected to be utilized in the medical field. For example, antioxidants in *Sargassum fluitans* are effective in inhibiting liver cirrhosis[120].

The development of technology to utilize macroalgae (especially kelp) for carbon capture and sequestration in the ocean is also currently considered. This technology can be used as a CO_2 removal technology (CDR) by efficiently increasing the number of macroalgae, especially kelps, through photosynthesis and transporting CO_2 from the ocean surface to the deep sea or into sediments[121]. Some companies are actually conducting demonstrations of this technology. The keys to future large-scale applications of this technology involve the following: potential increase in amount of carbon absorbed by macroalgae compared to that of carbon already fixed by phytoplankton, possibility of reducing the cost to approximately $100 per metric ton, possibility of coordinating with other industries when occupying ocean areas on a large scale, and potential detrimental effect on the environment in the areas where the biomass can be transported and stored. Environmental assessment in lifecycles should also be considered for the industrial use of macroalgae farming (Box 2).

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117 Makkar, H. P. S. et al. Seaweeds for livestock diets(2016). a review. Anim. Feed Sci. Technol. 212, 1–17.

118 Kinley, R. D. et al(2020). Mitigating the carbon footprint and improving productivity of ruminant livestock agriculture using a red seaweed. J. Clean. Prod. 259, 120836.

119 https://www.fao.org/fao-stories/article/en/c/1617549/ (accessed on January 8, 2023)

120 Quintal-Novelo C, Rangel-Méndez J, Ortiz-Tello Á, Graniel-Sabido M, Pérez-Cabeza de Vaca R, Moo-Puc R. A *Sargassum fluitans* Borgesen Ethanol Extract Exhibits a Hepatoprotective Effect *In Vivo* in Acute and Chronic Liver Damage Models. Biomed Res Int. 2018 Dec 20;2018:6921845. doi: 10.1155/2018/6921845. PMID: 30671467; PMCID: PMC6317085.

121 National Academies of Sciences, Engineering, and Medicine. 2022. A Research Strategy for Ocean-based Carbon Dioxide Removal and Sequestration. Washington, DC: The National Academies Press. https://doi.org/10.17226/26278.

Box 2. Life cycle environmental impacts of macroalgal farming (plastic ropes, CO_2 release during drying) (van Oirschot et al., 2017)[122]

LCA is a well-established tool to clarify the environmental performance of product (and production) systems by quantifying their cradle-to-grave (or gate) contribution to a range of impact categories. Some LCA studies have been conducted with a focus on specific aspects of macroalgae supply chains (for instance, wild harvests and valorization strategies, photobioreactor cultivation and oil extraction, macroalgae biorefinery, and production of biofuels from cultivated macroalgae biomass).

Large-scale commercial macroalgae cultivation has not yet taken place in Europe; thus, the possible design of the infrastructure and the drying subsystems are relevant outcomes of this exploratory LCA. The drying process provides a large contribution to all impact categories, with the exception of human toxicity and fresh water ecotoxicity.

The possible design of the macroalgae cultivation infrastructure subsystem, more importantly of their permanent infrastructure in the marine environment, is therefore first comprehensively described. The results for the biomass and proteins yields are then presented, followed by a description of the drying process.

It particularly dominates ozone layer depletion due to emissions of methane and ethane compounds from the burning and refining of light fuel oil for production of heat. Other dominated impact categories include abiotic depletion, climate change, photochemical oxidation, and acidification.

The majority of nonrenewable CED also is attributed to the drying process. Considering the drying process, the relative contribution toward impacts notably remains exactly the same regardless of the single or dual layer configuration.

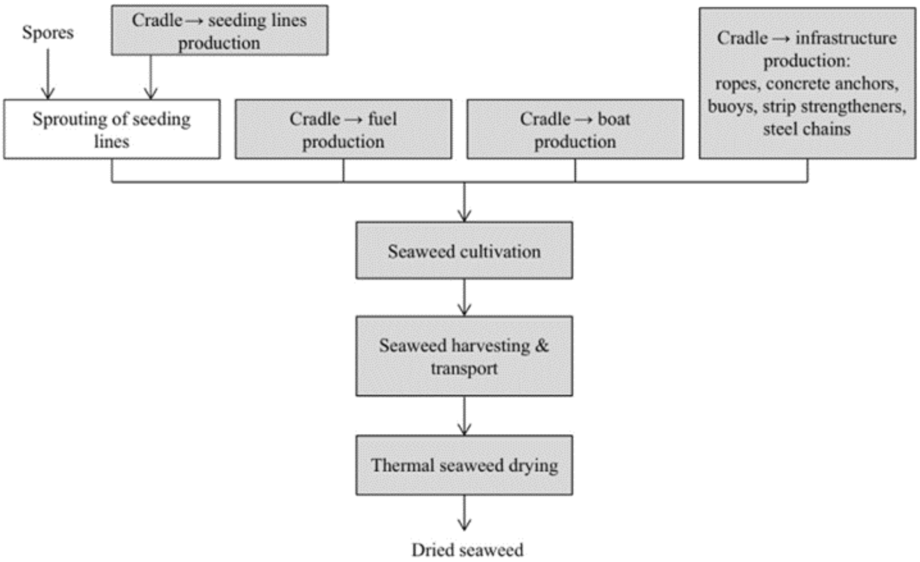

Figure 3.6. Dried macroalgae production system[123]

The stack diagram shows the relative contributions of each infrastructural component for the single and dual layer configurations. The chains provide the highest contribution, followed by the ropes, anchors, buoys, and strip strengtheners.

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[122] Roel van Oirschota, JeanBaptiste E. Thomasc,, Fredrik Gröndahlc, Karen P.J. Fortuina, Willem Brandenburgd, José Pottinga,b,e (2017).Explorative environmental life cycle assessment for system design of macroalgae cultivation and drying.

[123] Roel van Oirschota, JeanBaptiste E. Thomasc,, Fredrik Gröndahlc, Karen P.J. Fortuina, Willem Brandenburgd, José Pottinga,b,e (2017).Explorative environmental life cycle assessment for system design of macroalgae cultivation and drying.

Table 3.2. Eco Invent process applied for calculating environmental outputs of the reference dried macroalgae production systems.

Economic inputs used	Life	Input characteristics	Source of input Information	Quantity of input used				Eco Invent v3.0 process applied to calculate environmental outputs
				Single layer	Dual layer	Single layer	Dual layer	
Seeding lines	1 Year	Polypropylene, 2 mm ø, 0.0014 kg/m	Author measurement	0.00021 ton/ 100 m of longline/y	0.00021 ton/100 of longline/y	= 0.016 ton/ tonprotein/ 20y	= 0.022 ton/ tonprotein/20 y	“Fleece, polyethylene terephthalate/RER, at plant/ RER,” adjusted through the following: (a) replacing production of polyethylene granulate by polypropylene granulate; (b) adding a polypropylene end of life incineration scenario
Cultivation and infrastructure rope	5 Years	Polypropylene, 22 mm ø,0.22 kg/m	Touwfabriek Langman BV	0.030 ton/100 m of longline/5 y	0.028 ton/100 m of longline/5 y	= 0.46 ton/ tonprotein/ 20 y	= 0.58 ton/ tonprotein/20 y	
Chains	20 Years	Chromium steel, 19 mm ø, 8.3 kg/m	Author calculation	0.048 ton/100 m of longline/20 y	0.024 ton/100 m of longline/20 y	= 0.18 ton/ tonprotein/ 20 y	= 0.12 ton/ tonprotein/20 y	Chain manufacturing: “Product manufacturing, average metal working/kg/RER” Steel production: 55.5% recycled “Steel, electric, chromium steel 18/8, at plant/RER U” and 44.5% virgin “Steel, converter, chromium steel 18/8, at plant/ RER U” based on scrap average in European steel
Anchors		Concrete, rectangular block, 1000 kg	Author assumption	2.033 ton/100 m of longline/20 y	1.017 ton/100 m of longline/20 y	t = 7.9 ton/tonprotein/20 y	= 5.3 ton/ tonprotein/20 y	“Concrete block, at plant/kg/DE”
Small buoys		Polyvinyl chloride, 0.31 m ø, 1.2 kg/buoy	Chandelry World Ltd.	0.011 ton/100 m of longline/20 y	0.0055 ton/100 m of longline/20 y	= 0.043 ton/ tonprotein/ 20 y	= 0.028 ton / tonprotein/20 y	“Polyvinyl chloride, granulate, at plant/RER” PVC “Blow molding/RER” for manufacture of buoys and strip strengtheners
Large marker buoys		Polyvinyl chloride, 0.59 m ø, 4.1 kg/buoy						
Strip strengtheners		Polyvinyl chloride, 1.98 kg per rod	Author calculation	0.054 ton/100 m of longline/20 y	0.054 ton/100 m of longline/20 y	= 0.021 ton/ tonprotein/ 20 y	= 0.028 ton/ tonprotein/20 y	“Disposal, polyvinyl chloride, 0.2% water, to municipal incineration/CH”
Transport	n/a	5 × 20 km return trips for delivery of seeding lines and monitoring 1× loaded barge with harvest 10 km	Author calculation Validated by pilot researchers Seafarm	246 tkm/100 m of longline/20 y	138 tkm/100 m of longline/20 y	= 955 tkm/ton protein/20 y	= 951 tkm/ton protein/ 20 y	Barge production, operation & maintenance: at “Transport, barge/RER”
Thermal drying of macroalgae biomass		85% moisture content of S. latissima 83% moisture content at start of drying 22% moisture content at end of drying	Schiener et al. Author assumption Scoggan et al.	15 tons/100 m of longline/20 y (of evaporated water)	11 tons/100 m of longline/20 y (of evaporated water)	= 59 tons/ tonprotein /20 y (of evaporated water)	= 59 tons/ tonprotein/20 y (of evaporated water)	“Maize drying/CH”

The sensitivity analysis of the total environmental impacts of dried macroalgae production systems for the single layer cultivation configuration.

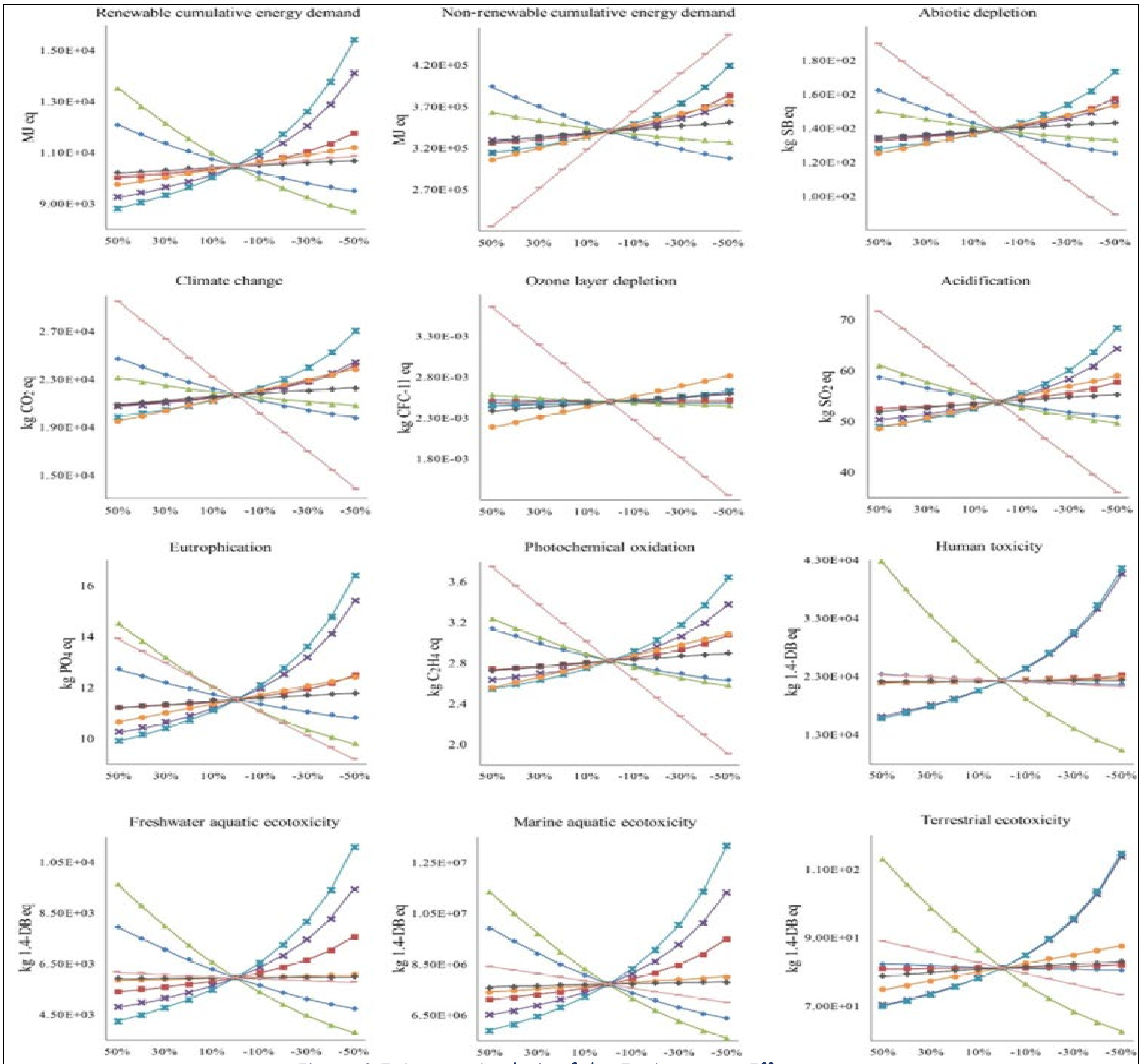

Figure 3.7. Impact Analysis of the Environment Effects

The impacts of both reference systems are represented by the “0” on the x-axis, the other % shows the influence of changing input values compared to the reference system for rope diameter (blue), rope replacement frequency (red), chain diameter (green), infrastructure replacement frequency (purple), biomass yield (emerald blue), water loss during harvest (orange), water content of outgoing biomass (gray), and the specific moisture extraction rate (SMER) of the biomass dryer (pink).

Chapter 4
Policy and Institutional Requirements

Large-scale promotion of BC will require a place in the nationally determined contributions (NDC) of the Paris Agreement and inclusion in the inventories reported by each country to the UNFCCC. Consideration must also be given to meeting the requirements for promoting high-quality carbon credits. In addition, when large-scale macroalgal aquaculture is developed, new considerations for treatment under existing international conventions and environmental impact assessments are reasonable. This chapter explains the aforementioned points.

(1) Blue Carbon and Nationally Determined Contribution ("NDC") and National GHG inventories
A) General

Mangrove, salt marsh, and seagrass habitats are widely recognized as BC ecosystems with mitigation potential. More than 150 countries have at least one of these ecosystems; 71 countries have all three and 74 countries mention such coastal wetlands in their NDCs to the Paris Agreement. However, the incorporation of BC into NDC reveal significant differences in the situation in each country (Table 4.1). Gallo et al. (2017)[124] reported that 27 countries include BC in their NDCs.

Table 4.1. Status of NDCs and inventories on wetland guidelines in major countries[125]

Countries	Handling of Blue Carbon in NDCs/Inventory Calculation Status
Australia and USA	Included in the numerical targets of the NDC. Calculated BC in the inventory based on 2006 and wetland guidelines.
Antigua and Barbuda, Bahrain, UAE, and the Philippines	Referencing to sinks by BC but not yet reflected in the numerical targets and not yet calculated in the inventory.
Guinea, Bahama, Angola, Burundi, Haiti, and Senegal	They include forests as well as mangroves in their mitigation measures (Angola also includes wetlands). However, the calculations are based on the 1996 guidelines, and soil is excluded from the calculations (Senegal uses the 2006 guidelines but soil is excluded from the calculations). Therefore, the numerical targets do not yet reflect this phenomenon.
Bangladesh	Forests, including mangroves, are involved in the mitigation measures. However, the entire LULUCF sector is not included or reflected in the numerical targets.
Suriname, Sri Lanka, and El Salvador	Forests, including mangroves, are included in the mitigation measures but are not a GHG emission reduction type target.
Iceland	The decision to exclude them in the numerical targets of the NDC is made. Wetland restoration is included as a mitigation measure and refers to the restoration of peatland from degradation; thus, it should not be interpreted as a blue carbon target.

The following is a brief examination on the situation in several countries with some background information.

B) Australia

Australia ranks second in the world in seagrass beds (52,051 km^2), mangrove forests (9,780 km^2), and salt marshes (13,259 km^2), making it a major "BC country." The establishment of the International Partnership for Blue Carbon, which was spearheaded by the Australian government during COP21 in 2015 during the adoption of the Paris Agreement, is believed to reflect this BC potential and their political will. Australia is also one of the few countries in the world that has incorporated BC into its National GHG inventory using the IPCC wetland guidelines (2013). Australia reports net emissions associated with mangrove forest harvesting and regeneration, salt marsh conversion, and seagrass dredging.

Commonwealth Scientific and Industrial Research Organization (CSIRO) (2020)[126] drew 4 strategies and 17 actions to reframe policy debates on biodiversity conservation, climate change adaptation and mitigation, and sustainable use of natural resources to address conflicts and tradeoffs associated with the use and management of ecosystem services and invest in blue infrastructure and ocean finance (Table 4.2).

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[124] Gallo, N. D., D. G. Victor, and L. A. Levin (2017). Ocean commitments under the Paris Agreement. Nature Climate Change 7(11):833-838.

[125] Based on Mai Fujii and Atsushi Sato (2020).Current Status and Issues Related to "Blue Carbon" under the United Nations Framework Convention on Climate Change. Ocean Policy Studies. No.14.

[126] Steven, A.D.L., Appeaning Addo, K., Llewellyn, G., Vu, T.C. et al. (2020). Coastal Development: Resilience, Restoration, and Infrastructure Requirements. Washington, DC, World Resources Institute.

In January 2022, the Australian government announced tidal reinstatement as the first methodology for the Blue Carbon Project under the emissions reduction fund (ERF)[127] through the accumulation of study results by CSIRO and other organizations. The ERF of Australia allows earning of Australian Carbon Credit Units (ACCUs) by projects that remove or modify tidal flow restriction mechanisms and introduce tidal flow to an area of land. This condition results in the rewetting of fully or partially drained coastal wetland ecosystems and the conversion of freshwater wetlands to brackish or saline wetlands[128]. This approach will result in the acquisition of ACCUs for the restoration of coastal wetland ecosystems due to project activities. The project can contribute to carbon emission control through three components: carbon sequestration in soil, carbon fixation in above- and below-ground biomass, and emissions avoided through the introduction of tidal currents.

Table 4.2 CSIRO's 4 Strategies and 17 Actions of CSIRO regarding climate action and biodiversity conservation

1	Protect: Protection strategies use regulations and area-based management to designate where and how much of specified activities can and cannot occur in coastal environments and in the adjacent catchment and legislate areas for conservation, such as marine protected areas (MPAs) or implement area, habitat, and species-specific conservation plans.
2	Mitigate: Mitigation strategies aim to reduce local stressors caused by human action through the use of technology, regulation, and the promotion of stewardship to minimize the introduction of pollutants and the overexploitation of resources or activities that will otherwise harm coastal environments.
3	Adapt: Adaptation strategies explicitly consider the coastal social–ecological system and are implicitly related to resilience; adaptation leads to resilience, which is a property needed for having the capacity to adapt (Nelson 2011). They use principles of ecosystem-based adaptation and ecological engineering to incorporate natural infrastructure into existing gray infrastructure, relocate at-risk activities and populations away from the coast, and also use incentives to change behaviors and practices.
4	Repair: Repair strategies seek to restore damaged ecosystems by rebuilding the composition and/or function of lost or fragmented habitats, restoring (reinstating) the natural hydrology, sediment and nutrient balance entering and cycling through coastal ecosystems or by assisted evolution.

C) The United States of America

The US included the wetland in the numerical targets of the NDC, calculating the National GHG inventory based on IPCC 2006 and IPCC wetland guidelines. The United States of America accounts for the world's largest area of salt marshes (18,849 km^2). The Blue Carbon in the US has recently been promoted through several wetland restoration projects led by a nonprofit organization called Restore America's Estuaries (RAE). The Herring River Estuary Restoration Project is a carbon offset project that is being tested as a demonstration of a voluntary carbon market initiated in 2016. REA, along with the US EPA, National Oceanic and Atmospheric Administration, which maintains a Restoration Atlas (NOAA), and others, established the coastal wetland carbon working group in 2016 and began studying the inclusion of BC ecosystems in the US GHG inventory. Consequently, coastal wetlands were incorporated into the National GHG emissions and sinks for the first time in the world in 2017.

Seagrass restoration efforts have been underway along Virginia's Eastern Shore coast for the past 20 years. Therefore, over 9000 acres of seagrass beds have been restored and NGOs and local research institutions are preparing to launch a BC credit program for seagrass with the state[129].

D) People's Republic of China

Coastal BC ecosystems have been the focus of considerable attention in China in recent years as a mitigation and adaptation measure. People's Republic of China has lost an estimated 9236–10,059 km^2 of BC ecosystems such as mangroves, salt marshes, and seagrass beds from 1950 to the present, and currently reports 1326–2149 km^2 of natural and 2–15 km^2 of regenerated or created ecosystems[130]. Macroalgae cultivation, on the other hand, is estimated to cover 1252–1265 km^2, about the same size as natural BC ecosystems. Annual CO_2 absorption is estimated to be 151.8 × 1000 t-CO_2 for seagrass beds, 960-2720 × 1000 t-CO_2 for salt marshes, and 399 × 1000 t-CO_2 for mangroves[131].

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[127] https://www.cleanenergyregulator.gov.au/ERF/Pages/News%20and%20updates/News-item.aspx?ListId=19b4efbb-6f5d-4637-94c4-121c1f96fcfe&ItemId=1043

[128] https://www.bluecarbonlab.org/blue_carbon_accus/#:~:text=The%20Emissions%20Reduction%20Fund%20(ERF,technologies%20to%20reduce%20their%20emissions

[129] https://www.pilotonline.com/news/environment/vp-nw-seagrass-blue-carbon-program-20220205-ake65u7pzbbkbbkipe7rjihacm-story.html

[130] Wu et al. (2020) Opportunities for blue carbon strategies in China. Ocean & Coastal Management
Volume 194, 15 August 2020, 105241

[131] http://eascongress2018.pemsea.org/wp-content/uploads/2018/12/S1.1-Blue-Carbon-Policy-andStrategy-Development-in-China_ZPeng.pdf

In recent years, China has become the world's largest producer of macroalgae with 18 million tons, far ahead of second place Indonesia's 10 million tons[132], and including macroalgae farming as a source of BC has received considerable interest. By contrast, as macroalgae cultivation grows in scale, investing in anchor systems with buoyancy adjustment functions is necessary to cultivate macroalgae in offshore areas where waves and other factors create a high-energy environment.

In Wenzhou City's Dongbang District, a new technology is being demonstrated in *Sargassum fusiform* aquaculture. The creation of carbon credits for such additional investment aims to contribute to the sustainability of the aquaculture business. In addition, cultivated macroalgae is currently mainly used for food but has a limited mitigation effect because the macroalgae is converted back to CO_2 during consumption. Macroalgae yields must be used for biofuel production, long-lasting products, and residues for biochar production for soil improvement to maximize climate change mitigation through macroalgae farming. Some reports include research on BC ecosystems, monitoring and standardization/regulation, and promotion of international cooperation as part of the vision for marine cooperation in the Belt and Road Initiative.

E) Republic of Indonesia

Indonesia also has vast BC ecosystems. With ~31,000 km^2 of mangrove forests, its mangroves account for 20% of the world's total[133]. Estimations revealed that Indonesia's mangroves can sequester and store 3 billion tons of mangrove BC and their conservation can reduce emissions by 0.2 $GtCO_2e$ per year or 30% of the country's annual land-based emissions. Meanwhile, seagrass beds in Indonesia are estimated to be around 30,000 km^2, with carbon sequestration potential of roughly 5.62–8.40ton C per hectare per year. In addition, after the above-mentioned China, Indonesia is the second largest producer of macroalgae aquaculture in the world.

As an example, for the BC program in the country, the "Indonesia Blue Carbon Strategic Framework" has been formulated for the "National Medium-Term Development Plan (RPJMN) 2020–2024," which is currently implemented by the agencies in charge of development and planning, marine policy, fisheries, and natural resource conservation. The framework aims to address key strategic issues for BC in Indonesia, such as the policy, science, outreach and communication, learning sites, and sustainable financing.

The Presidential Decree also sets a goal of restoring 1.82 million hectares of mangrove ecosystems by 2045, with a numerical target of 60,000 hectares to be restored annually to achieve this goal. Indonesia aims to integrate BC into the National GHG inventory. Mangrove forests in Indonesia are currently declining with several pressures of degradation identified across the country such as land use conversion, increasing management efforts. This phenomenon can also be observed for seagrass conservation for their BC potentials[134].

F) Japan

Japan has seagrass beds, salt marshes, mangrove forests, and macroalgae beds of 620, 470, 30, and 1,720 km^2, respectively, with an estimated total annual CO_2 absorption of 1320–4040 × 1000 t-CO_2. These figures are on the same scale as those of China. However, the difference is that the macroalgae beds of Japan are mainly natural macroalgae beds while those of China are farmed.

Japan does not include marine areas in its GHG inventory and does not calculate coastal wetlands in accordance with its wetland guidelines. The Blue Carbon Study Group, comprising academic experts and related organizations, was established in 2017 to overcome the aforementioned situation and focused on research, such as estimating CO_2 absorption by BC ecosystems. Based on the results of the study group, the "Promotion of Efforts to Utilize Blue Carbon Ecosystems: Establishment of a Study Group on the Role of Blue Carbon in Contributing to Global Warming Prevention" was established in 2019 as a national study group led by the Marine and Environment Division of the Port and Harbor Bureau of the Ministry of Land, Infrastructure, Transport, and Tourism, and concrete studies are underway to utilize BC as a sink.

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[132] FAO. 2020. The State of World Fisheries and Aquaculture 2020. Sustainability in action. Rome.

[133] Mark Spalding, Mami Kainumaand Lorna Collins(2010). World Atlas of Mangroves.London, Washington D.C.,Earthscan

[134] Jay Mar D. Quevedo, Kevin Muhamad Lukman, Yaya Ihya Ulumuddin, Yuta Uchiyama, Ryo Kohsaka (2023). Applying the DPSIR framework to qualitatively assess the globally important mangrove ecosystems of Indonesia: A review towards evidence-based policymaking approaches. Marine Policy, Volume 147, 2023, 105354.

The committee is currently working on specific studies to utilize Blue Carbon as a sink. Furthermore, the Japan Blue Economy Association (JBE) was established in July 2020 as a corporation authorized by the government (competent minister) using the scheme called Collaborative Innovation Partnership. In particular, JBE is conducting R&D on the role of BC ecosystems as CO_2 sinks and on the design of a new system for the assessment, certification, and issuance of BC credits to accelerate efforts toward climate change mitigation and adaptation in other coastal and marine areas. Under the JBE, R&D and social demonstrations related to BC, including natural and cultured macroalgae, are underway. From the fiscal year 2020 onward, a BC credit system called J-Blue Credit® has been established, and the certification, issuance, and management of credits are conducted[135]. To date, projects at 22 sites have been certified, generating a total of over 3800 tons of credits. In response to this trend, discussions are underway across ministries and agencies in the country to incorporate BC into the GHG inventory.

G) The Bahamas

On June 7, 1997, the Government signed the Ramsar Convention on Wetlands to have a comprehensive wetland policy that clearly outlines the guidelines and objectives for the protection of wetlands. This policy can be used by those responsible for the administration of existing laws and regulations related to wetlands as a guideline to ensure their sustainable management. It also serves as a guide for activities that may be carried out in and around wetlands.

Since 2015, the government has reestablished and rehabilitated Davis Creek in Andros to improve sequestration potential as the mitigation route of the Land Use, Land Use Change and Forestry (LULUCF) sectors. The mangrove forest areas have been conserved and recovered, and the seagrass beds, reefs and mangroves are protected and rehabilitated.

Following the discovery of the largest seagrass meadow in the ocean (up to 92,000 km^2 in size[136]), the government of Bahamas issued a Carbon bill[137] and established a carbon market to release credits to investors against the conservation of areas at risk of this seagrass meadow.

H）Republic of Colombia

Mangroves dominant the ecosystem of both the Pacific and the Caribbean coastlines of Colombia covering 6,500 km^2 were described as the most luxuriant and wettest of the Americas,[138] and as carbon-rich-tall tidal forests.[139] The seagrass beds in the Colombian Caribbean cover 43,223ha. The mangroves continue to decline in many areas due to increase of industrial and artisanal salt pans as well as agricultural fields.

Colombia ratified the Paris Agreement by Act 1844 of 2017, which also set a series of longer-term climate targets, including 2030 GHG emission reduction goal of 20% which was updated to 51% below BAU in December 2020, and to reduce black carbon emissions by 40% compared to 2014 levels by 2025. This target translates to 2030 emissions level of 169.44 million tCO^{2}e, implying a net reduction of 176 million tCO^{2}e.[140]

A recently launched blue carbon finance project for the first time considers not only the carbon that mangrove trees store in their trunks and leaves, but also the carbon they sequester in their soils. Developed by Conservation International and partners — including Colombia's Marine and Coastal Research Institute (INVEMAR) and the country's Environmental Authority — the project creates a long-term funding opportunity that is expected to conserve and restore mangroves in

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[135] T. Kuwae, Watanabe, A., Yoshihara, S., Suehiro F., Sugimura, Y. (2022) Implementation of blue carbon offset crediting for seagrass meadows, macroalgal beds, and macroalgae farming in Japan. Marine Policy,138, 104996

[136] Gallagher, A.J., J. W. Brownscombe, N. A. Alsudairy, A. B. Casagrande, C. Fu, L. Harding, S. D. Harris, N. Hammerschlag, Wells. Howe, A. Delgado Huertas, S. Kattan1, A. S. Kough, A. Musgrove, N. L. Payne, A. Phillips, B. D. Shea, O. N. Shipley, U. R. Sumaila, M. S. Hossain, and C.M. Duarte. 2022. Tiger sharks support the characterization of the world's largest seagrass ecosystem. *Nature Communications* 13, 6328 (2022).

[137] The Commonwealth of The Bahamas Office of The Prime Minister the Climate Change and Carbon Market Initiatives Bill (https://opm.gov.bs/climate-change-and-carbon-market-initiatives-bill/)

[138] West, R. C. (1956). Mangrove swamps of the Pacific coast of Colombia. Ann. Assoc. Am. Geogr. 46, 98–121.

[139] Hamilton, S. E., and Friess, D. A. (2018). Global carbon stocks and potential emissions due to mangrove deforestation from 2000 to 2012. Nat. Clim. Chang. 8, 240–244.

[140] IETA (2021) Carbon Market Business Brief Colombia

Cispatá, an 11,000-hectare (27,000-acre) mangrove forest along Colombia's Caribbean coast. Scientists there used a simple but effective system for measuring the carbon locked away in the tropical sediment: Wading into the mangroves, they used a special pipe to extract soil one to three meters deep. The soil's carbon content was then analyzed in a lab.

With its carbon stores fully calculated by the Verified Carbon Standard and the Climate, Community & Biodiversity Standards, the most widely used programs for certifying emissions reductions, the Cispatá forest can now be valued for its climate benefits and included in carbon markets. This critical step opens a path for other blue carbon ecosystems around the world to be added to those markets.[141]

I）United Arab Emirates

The UAE's coastal carbon ecosystems include mangrove swamps (150 km^2), seagrass beds (5500 km^2), salt marshes and algal mats, as well as associated blue carbon ecosystems such as coastal sabkha.

Regarding to the updated second Nationally Determined Contribution of UAE, submitted in September 2022, more than 3,000 coral fragments have been transplanted, and it is expected that over 10,000 more will be transplanted in the next 10 years. The Fujairah Cultured Coral Reef Gardens project was initiated in 2019 and targets the cultivation of 1.5 million coral reef colonies over five years. The UAE had deployed 4,500 artificial reefs across its marine and coastal zones, and these were being monitored for improved marine life and fish stocks. Additionally, natural rock barriers are being installed in coastal areas across the country in order to recreate natural habitats and breeding grounds for marine species. Taken together, the UAE's efforts to protect and restore coral reefs has the potential to provide jobs and reinforce livelihoods to young people, while helping ensure access to this innovative and emerging sector.

The National Biodiversity Strategy and the National Strategy for Coastal and Marine Environment have been guiding the country's initiatives in environmental conservation and nature-based climate solutions. The National Biodiversity Strategy lays down the framework for establishing a network of protected and effectively managed ecosystems, considering the linking of important areas of biodiversity and ecosystem services. This has entailed biodiversity surveys; issuance of relevant legislation and guidelines; programs to plant and protect native trees; initiatives to protect terrestrial, marine, and freshwater fauna; and designation of new protected areas. Currently, the UAE's 49 protected areas occupy 15.5% of its total territory. The country is developing the UAE Smart Map of Natural Capital to identify biologically rich ecosystems as well as the services they provide.

In the context of climate change, these ecosystems serve both adaptation and mitigation needs. Owing to a range of restoration and conservation efforts implemented since the 1970s, the UAE is amongst the few countries that have proactively expanded their mangrove forest cover. Following the success of the Abu Dhabi Blue Carbon Demonstration Project that has significantly contributed to the understanding of blue carbon stocks in the UAE, the value of these stocks has been incorporated into federal and emirate-level policies. The UAE government is undertaking further field research to determine mangrove soil carbon sequestration rates using radiometric dating techniques. The findings will aid the development of emission inventories and inform coastal management.

To enhance its natural carbon sinks, the UAE has taken an active role in restoring the ecosystems through planting native trees, such as mangroves, which sequester 1,073,696 metric tons of CO_2 in the country annually. During the 26th UN Climate Change Conference (COP26) in Glasgow, the UAE announced its ambition to plant 100 million mangrove seedlings by 2030, significantly increasing the target of 30 million seedlings set in 2020. Further, as part of its efforts to improve the conservation and to build a network of protected areas between 2021 and 2025, the emirate of Abu Dhabi targets the inclusion of a minimum of 20% marine blue carbon habitats within protected areas.

On a global level, the UAE is working on the Mangrove Alliance for Climate (MAC) that seeks to leverage a vast collective of expertise and resources to scale up and accelerate mangrove conservation, restoration, and resilience. Specifically, the members commit to plant, rehabilitate, and restore mangroves within their countries and to support other members in doing the same.

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[141] https://www.conservation.org/blog/in-colombia-a-new-way-to-protect-mangroves-takes-root

J) Kingdom of Saudi Arabia

In the updated first Nationally Determined Contribution submitted to UNFCCC in 2021, the Kingdom declared to implement coastal management strategies to reduce coastal erosion, increase the sinks for blue carbon, maintain related ecosystems and address the threats that climate change poses for marine livelihoods. In October 2021, the Kingdom announced the Saudi Green Initiative, in which they committed to protecting 30% of its terrestrial and marine area by 2030. These goals are well aligned to Vision 2030, the country's unique transformative economic and social reform blueprint as well as to the global Sustainable Development Goals, particularly Goal 14: Life Below Water.

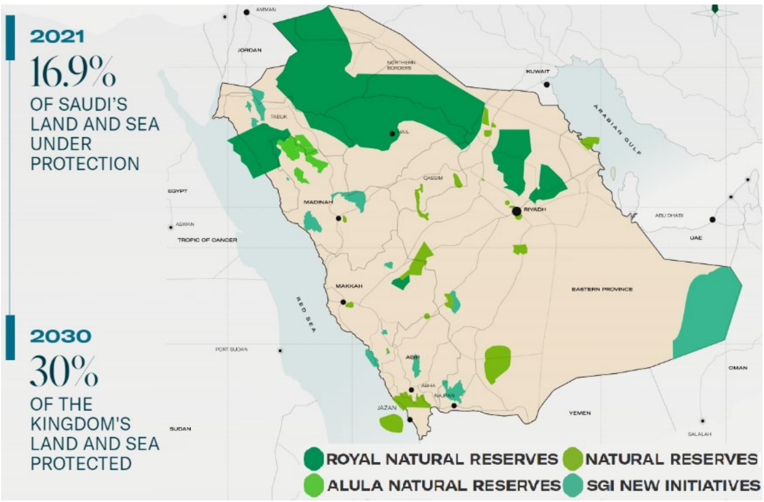

Figure 4.1 Saudi & Middle East Green Initiative Commitment of safeguarding land and sea[142]

The Kingdom has supported the planting of mangrove seedlings along its coasts and strengthened and enhanced the coral reef restoration program throughout the northwestern Arabian Gulf. Saudi Arabia's new generation coral reef restoration technologies accelerator aims to develop innovative technologies that enhance the thermal resilience of coral reefs and provide cost-effective options to scale up reef restoration by bringing together national stakeholders.

Several studies were conducted to estimate the outtake of mangroves and other blue carbons for the Red Sea and the Arabian Gulf. These studies will be utilized in estimating a more accurate blue carbon sink.

K) People's Republic of Bangladesh

The table[143] below shows the ecosystem areas and the estimates of carbon sequestration in vegetated estuaries and coastal habitats of Bangladesh.

Table 4.3 Blue Carbon Habitats of People's Republic of Bangladesh

Habitat	Area(ha)	Tons CO_2-eq/ha/year	Total CO2-eq/year(tons)
Mangroves	441,455	4.73	2,088,082
Saltmarshes	111,585	10.16	1,133,704
Seagrass beds	660,048	10.26	Unknown

Bangladesh's first INDC, submitted in August 2021, proposed for 12 million tons (5%) unconditional reduction in GHG emission from Business-as-Usual scenario by 2030 and a further 24 million tons (10%) conditional reduction in GHG emission with support from the international community taking the base year 2011. As part of the global initiative, Bangladesh is updating the NDC incorporating additional sectors following IPCC guidelines. The updated NDC covers Energy, Industrial Processes and Product Use (IPPU), Agriculture, Forestry, and other Land use (AFOLU) and Waste. For the NDC update, 2012 has been considered as the base year following the Third National Communication of Bangladesh,

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[142] Kingdom of Saudi Arabia "Saudi Green Initiative 2022"

[143] Chowdhury Sayedur et al (2015). Blue carbon in the coastal ecosystems of Bangladesh

which details a comprehensive national GHG emission inventory for 2012. In this NDC update, information to facilitate clarity, transparency and understanding of Bangladesh's NDC in line with the guidelines set out in Katowice decisions (COP24/CMA1) is presented in the form of template in the last part of this document.

The NDC update aims to further mitigation actions that Bangladesh may take to tackle its growing emissions and play its role in global efforts. The NDC calls for a number of mitigation actions that will help limit the country's GHG emissions. These actions will play a key role in realizing the move to a low-carbon, climate-resilient economy and becoming a middle-income country whilst ensuring that it will not cross the average per capita emissions of the developing countries.

L) Republic of India

The updated first NDC, submitted in August 2022, the government set the long-term goal of reaching net-zero by 2070.

Table 4.4 Republic of India NDC Committed Activities

No.	Descriptions
1	To put forward and further propagate a healthy and sustainable way of living based on traditions and values of conservation and moderation, including through a mass movement for 'LIFE'– 'Lifestyle for Environment' as a key to combating climate change.
2	To adopt a climate friendly and a cleaner path than the one followed hitherto by others at corresponding level of economic development.
3	To reduce Emissions Intensity of its GDP by 45 percent by 2030, from 2005 level
4	To achieve about 50 percent cumulative electric power installed capacity from non-fossil fuel-based energy resources by 2030, with the help of transfer of technology and low-cost international finance including from Green Climate Fund (GCF)
5	To create an additional carbon sink of 2.5 to 3 billion tons of CO_2equivalent through additional forest and tree cover by 2030.
6	To better adapt to climate change by enhancing investments in development programs in sectors vulnerable to climate change, particularly agriculture, water resources, Himalayan region, coastal regions, health, and disaster management.
7	To mobilize domestic and new & additional funds from developed countries to implement the above mitigation and adaptation actions in view of the resource required and the resource gap.
8	To build capacities, create domestic framework and international architecture for quick diffusion of cutting-edge climate technology in India and for joint collaborative R&D for such future technologies

Akhand A. et al (2022) [144]collated data on the Indian blue carbon repository (mangroves, seagrasses, and salt marshes) from peer-reviewed literature on carbon stock assessment. The research indicated the blue carbon ecosystems of India could have a collective carbon stock of 67.35 Tg C (mangroves, seagrass, and salt marsh accounting for 67 Tg C, 0.0630 Tg C, and 0.0049 Tg C, respectively). Several studies have ubiquitously measured the spatial extent of mangroves (-4,991 km^2), seagrasses (-517 km^2), salt marshes (290–1,398 km^2) in India.

The study identified that less than half of the total mangrove habitats of India are yet to be sampled leaving a scope of substantial uncertainty in nationwide blue carbon estimates. The spatial extent of India's salt marshes is another aspect that needs to be delineated with a higher confidence level.

M) Arab Republic of Egypt

On June 2022 Arab Republic of Egypt submitted the Egypt's first updated Nationally Determined Contributions. The adaptation policy chooses mainly the accommodation and protection approaches to the risks resulting from climate change by the combination of soft and hard interventions. The government develops the climate resilient Integrated Coastal Zone Management Plan for the North Coast of Egypt, which links the land use development plans, and the coastal protection works over the next 10-15 years.

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[144] Akhand, A., Chanda, A., Jameel, Y. et al (2022). The present state-of-the-art of blue carbon repository in India: a meta-analysis. Sustain Sci.

They have adopted the structural and architectural interventions of the engineering protection work (ex. maritime walls, submersible barriers, soil fixation), the artificial nourishments to compensate for the erosion of beaches and constructions and reinforcements of anti-flood protection structures. From the nature-based approach, they reinforce the sand dune stabilities and the natural defense lines against sea encroachment during storms by the cultivation of wild plants and wooden barriers.

From the point of the tourism, they maintain and expand the protectorates to cover 17% of the national marine and wildlife areas with at least 5% constituting coastal areas. They will assess the degree of fragility and vulnerability of touristic sites, marine and wildlife protectorates, and sites of archaeological value, orienting tourism growth away from environmentally sensitive areas, and implementation of integrated environmental management systems in touristic sites.

N） United Kingdom of Great Britain and Northern Ireland

In December 2020, the United Kingdom of Great Britain and Northern Ireland (the UK) communicated its Nationally NDC to the UNFCCC in line with Article 4 of the Paris Agreement. In the NDC, the UK committed to reducing economy-wide greenhouse gas emissions by at least 68% by 2030, compared to 1990 levels. At COP26 in November 2021, the UK hosted in Glasgow to pursue efforts to limit global temperature increase to 1.5°C. The NDC encompasses emissions and removals from England, Scotland, Wales, and Northern Ireland.

The UK’s vision for the marine environment is for clean, healthy, safe, and biologically diverse ocean and seas. The sustainable use, protection and restoration of the UK’s marine environment is underpinned by the UK Marine and Coastal Access Act (2009), the Environment Act (2021) and Fisheries Act (2020), UK Marine Policy Statement, Marine Strategy, commitment to an ecologically coherent well-managed network of Marine Protected Areas, and Joint Fisheries Statement. Through the UK Marine Strategy, HM Government and Devolved Administrations are working closely together to achieve Good Environmental Status in the UK’s seas.

The Scottish Government has set out a new Blue Economy vision for the sustainable management of Scotland’s seas, establishing long term outcomes to 2045 and including a dedicated climate outcome to support ecosystem health, improved livelihoods, economic prosperity, social inclusion, and wellbeing. New actions to increase protection of the marine environment include delivery of a network of highly protected marine areas by 2026, fishery management measures across the Marine Protected Areas network by 2024 and introduction of a Scottish Wild Salmon Strategy. New evidence is also being delivered through the Scottish Blue Carbon Forum, building upon actions set out in the second Scottish Climate Change Adaptation Program to address Scotland’s marine climate risks.

In November 2019 the Welsh Government published the first Welsh National Marine Plan for the next 20 years to achieve healthy and resilient seas and marine ecosystems, in support of a thriving, sustainable economy.

The Marine Plan for Northern Ireland, published in April 2018, supports the UK Marine Policy Statement, the UK Marine Strategy and the UK’s vision for the marine environment. The sustainable development of Northern Ireland’s marine area is further underpinned by the Marine Act (Northern Ireland) 2013 and the Marine and Coastal Access Act 2009. A second iteration of the Plan is currently being drafted which will take account of the advancements in science, technology, policy, and legislation, particularly in relation to climate change mitigation and adaption including Blue Carbon, Sustainable Fisheries and Offshore Renewable Energy. The Marine Plan for Northern Ireland is expected to be finalized, adopted and published in 2023.

O） Kingdom of Norway (Nordic Area)

The Nordic Blue Carbon Project, funded by the Norwegian Environment Agency, opened the final report[145] regarding the project about the climate adaptation, carbon capture and long-term storage in blue forests in the Nordic region in 2020. The project was led by the Norwegian Institute for Water Research, and cooperated with GRID-Arendal, the Institute of

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[145] Helene Frigstad, Hege Gundersen, Guri S. Andersen, Gunhild Borgersen, Kristina Ø. Kvile, Dorte Krause-Jensen, Christoffer Boström, Trine Bekkby, Marc Anglès d'Auriac, Anders Ruus, Jonas Thormar, Kaya Asdal and Kasper Hancke (2021). Results from the Nordic Blue Carbon Project. TemaNord 2020:541

Marine Research, Aarhus University and Åbo Akademi University. Followers are depended on the final report.

The following map shows the indications of rockweed, kelp, and seagrass (The dotted lines are predicted). Around 5,550 km^2 of rockweed beds are found along most of the coastlines of the Nordic region, but with low coverage in Denmark. Seagrass covers 2600 km^2, a relatively small areal distribution compared to kelp and rockweed, but it is still an important habitat along the coastlines of Norway, Sweden, and Denmark.

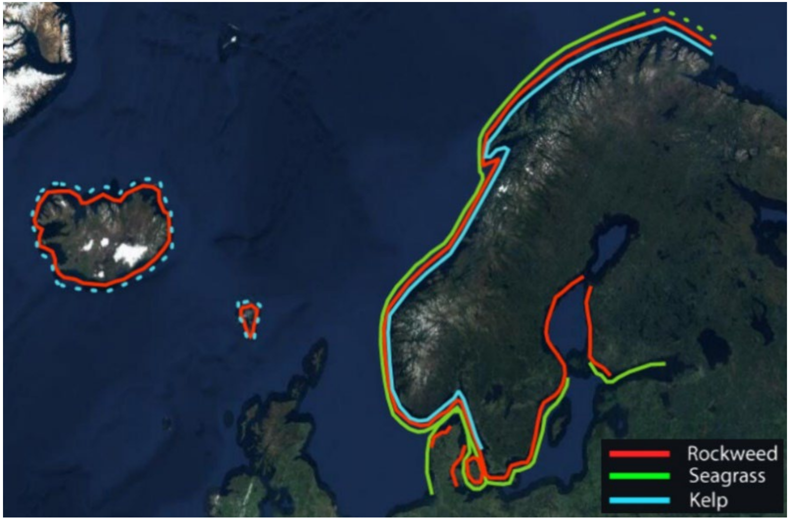

Figure 4.2 Blue Carbon Habitats in Nordic[146]

Kelp forests are the most common of the Nordic Blue Forests, covering approximately 11,000 km^2. They are most widespread along the rocky shores of Norway, Iceland, and the Swedish west coast. There are few to no kelp forests along the Swedish and Finnish coasts. Greenland (as part of Denmark) has potentially large kelp forests, but due to limited data availability, the distribution of Blue Forest habitats has not been estimated there.

The compiled estimates Blue Carbon in Kingdom of Norway are estimated as below. The estimates are predicted or are the weighted average of available data. The 69% of the blue forest are kelp forests, storing 2.7 million tons of CO2, the 19% are rockweed beds, storing 0.8 million tons of CO2 and 12% are seagrass meadows, storing 0.5 million tons of CO2.

Table 4.5 The Compiled estimates Blue Carbon Parameter of Norway[147]

Parameter	Unit	Kelp (SD/Min/Max)	Rockweed (SD/Min/Max)	Seagrass (SD)
Area of Norway				
Area	km2	7,417(-/-/-)	3,090(-/-/-)	90(-)
Net Primary Production (NPP)				
NPP	Million tons FW y-1	49.3(-/24/70)	17.2(0/-/-)	0.5(-)
NPP, C units	Gg C y-1	2,292(-/1,090/4,309)	903(862/-/-)	29(10)
Particulate Organic Carbon (POC)				
POC exported from beds/meadows	Gg C y-1	2,195(-/1,602/5,325)	865(294/-/-)	5(2.3)
POC sequestered on the shelf	Gg C y-1	95(-/59/134)	40(-/-/-)	-(-)
POC sequestered in seagrass meadows	Gg C y-1	-(-/-/-)	-(-/-/-)	3.2(1.3)
POC exported to the deep sea	Gg C y-1	53(-/0/115)	21(-/0/45)	0.8(-)
Dissolved Organic Carbon (DOC)				
DOC exported	Gg C y-1	1,146(-/458/2,750)	181(-/<45/362)	2.0(-)
DOC exported below 1,000m	Gg C y-1	355(107/-/-)	56(42/-/-)	0.7(-)
Total				
Total sequestration	Gg C y-1	503(-/141/601)	117(-/33/139)	4.6(1.3)
Total sequestration	Mill CO2equiv. y-1	1.8(-/0.5/2.2)	0.4(-/0.1/0.5)	0.02(0.005)

* SD: Standard Deviation

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[146] Helene Frigstad, Hege Gundersen, Guri S. Andersen, Gunhild Borgersen, Kristina Ø. Kvile, Dorte Krause-Jensen, Christoffer Boström, Trine Bekkby, Marc Anglès d'Auriac, Anders Ruus, Jonas Thormar, Kaya Asdal and Kasper Hancke (2021). Results from the Nordic Blue Carbon Project. TemaNord 2020:541

[147] Helene Frigstad, Hege Gundersen, Guri S. Andersen, Gunhild Borgersen, Kristina Ø. Kvile, Dorte Krause-Jensen, Christoffer Boström, Trine Bekkby, Marc Anglès d'Auriac, Anders Ruus, Jonas Thormar, Kaya Asdal and Kasper Hancke (2021). Results from the Nordic Blue Carbon Project. TemaNord 2020:541

As the result of the project, they pointed the following knowledges as the knowledge gaps to need for collaborative the Nordic projects:

- Improve distribution mapping and monitoring of Blue Forests.
- Address kye uncertainties in the Nordic Blue Carbon budget, such as the rates of long-term carbon storage.
- Improve collaboration between scientists and policymakers to develop IPCC guidelines for kelp forests.
- Establish greenhouse gas inventories for Blue Forest habitats.
- Research the distribution and function of salt marshes.
- Establish the effects of climate change and other human pressures on Blue Forests.
- Research trophic cascade and other effects of overfishing.
- Develop management measures to improve resilience of Blue Forests.
- Establish methods for successful restoration of Blue Forests.
- Conduct in-field testing of the effectiveness of management measures.
- Map and develop measures to preserve areas of high sedimentation and long-term storage of Blue Carbon in shelf and deep-sea sediments.
- Determine possibilities for using kelp cultivation to increase Blue Carbon biomass and its potential role in climate mitigation.

P）Republic of Fiji

The adverse climate change impacts from the intense floods, and extreme weather events, to rising sea levels and its resultant saltwater intrusion and loss of habitable land has been affected all aspects of life for Fijians – the environment, economy, social development, as well as cultural practices and traditional ways of life. Fiji is facing loss and degradation of vital ecosystems and natural resources, including its coral reefs, coasts, and catchments, on which key sectors of its economy such as agriculture and fisheries are dependent. Further, its critical infrastructure is frequently damaged by the increasing extreme weather events, which are impacting the social well-being, employment and livelihoods of the Fijian people.

Regarding to the first NDC, submitted in December 2020, Fiji sees this NDC update as an opportunity to further support its commitment towards the Paris Agreement by mainstreaming its blue economy ambitions in to its NDC targets through enhanced ocean governance to not only achieve national ocean conservation but also contribute towards enhancing the ocean as a carbon sink.

Through the Implementation of the National Ocean Policy, Fiji will be allocating 30% of its EEZ as Marine Protected Areas and work towards 100% management of its EEZ by 2030. This compliments Fiji’s National Adaptation Plan concurrently its Low Emission Development Strategy, which highlights the need to sustainably manage and protect marine and coastal ecosystems, strengthen their resilience, and restore them when they are degraded. This includes conserving ocean reservoirs as carbon sinks through supporting the restoration, enhancement, and conservation of coastal ecosystems such as mangroves, sea grasses and coral reefs.

Table 4.6 Republic of Fiji's NDC Mitigation targets

No.	Mitigation Targets Descriptions
Target 1	To reduce 30% of BAU CO2 emissions from the energy sector by 2030.
Target 2	As a contribution to Target 1, to reach close to 100% renewable energy power generation (grid connected) by 2030, thus reducing an expected 20% of energy sector CO2 emissions under a BAU scenario.
Target 3	As a contribution to Target 1, to reduce energy sector CO2 emissions by 10% through energy efficiency improvements economy-wide, implicitly in the transport, industry, and electricity demand-side subsectors.
Target 4	As a contribution to Target 1, to reduce domestic maritime shipping emissions by 40%. Adaptation Target
Target 5	To adopt Climate Smart Agriculture practices, with emphasis on the promotion of sustainable practices in crop management, livestock and sugarcane farming Fiji's Updated NDC 2020 and fisheries.
Target 6	To enhance resilience by upgrading, repairing, and relocating existing critical public infrastructure.
Target 7	Develop simplified and standardized early warning and monitoring systems and prioritize nature-based solutions to mitigate the impact of flooding and cyclones.
Target 8	Relocate highly vulnerable communities and implement the concept of 'build back better'.
Target 9	Build strong healthcare system by implementing the 'Guidelines for climate-resilient and environmentally sustainable health care facilities in Fiji'.
Target 10	To conserve natural environment and biodiversity wealth enabling sustainable long-term provision of ecosystem services, including carbon sequestration potential.
Target 11	To plant 30 million trees by 2035.
Target 12	To establish 30% of our Exclusive Economic Zones (EEZ) as Marine Protected Areas and work towards 100% management of our EEZ by 2030 through the implementation of the National Ocean Policy.

The Republic of Fiji National Adaptation Plan in 2018 declared the Adaptation Measures of Biodiversity and the Natural Environment. The national marine ecosystem services have been valued at FJD 2.5 billion per annum. These goods and services provide the biophysical foundation for much economic activity, particularly those vital for the national economy (fisheries, forestry, agriculture, and tourism).

Tourism is of relevance as one of the most important components of the economy. Approximately 40 percent of Fiji's GDP and employment can be traced some to the tourism sector. It supports and provides livelihoods as well as having a vital role in supporting the national balance of payments. For instance, our coral reef ecosystems are one of the most vulnerable ecosystems to climate change and the longer-term outlook for coral reefs in the Pacific is poor.

More immediately, national ecosystems are degrading due to insufficient protection from development-related activities such as unsustainable logging, clearance for commercial developments, infrastructure and agriculture, and over-fishing. This in turn renders them less capable of adapting to climate change impacts, reducing their climate resilience benefits to society. As Fiji's largest income earner, the economic benefits of intact ecosystems to the tourism sector are of paramount importance.

Table 4.7 Republic of Fiji's Adaption Measures

No.	Adaptation Actions Descriptions
Action 1	16.1 Strengthen enforcement of planning and environmental legislative and institutional frameworks, most notably the Environment Management Act and Environment Impact Assessment process.
Action 2	Prioritize and delineate critical areas for protection and sustainable management based on ecosystem services, cultural importance, biodiversity, food security, water security, access and benefit sharing, and importance for adaptation and disaster risk reduction.
Action 3	Gain endorsement of mangrove management plan, implement mangrove rehabilitation projects, and strengthen the regulations regarding mangrove removal and conversion.
Action 4	Assess and monitor the state of coastal ecosystems and protect and enhance the natural coastal defenses.
Action 5	Strengthen the management and monitoring of ecosystems.
Action 6	Regularly update and publish the National Environment Management Strategy and 'State of Environment Reports' on a five-year cycle to inform development and disaster management planning processes at both national and sub-national levels.
Action 7	Integrate green and blue accounting/ ecosystem valuation into the GDP formulation and budget process by 2020.
Action 8	Implement ecosystem-based approaches to adaptation to protect, maintain, and restore degraded habitats with active community,111 NGO and private sector engagement in particular the restoration of critical watersheds, riparian, and coastal zones.
Action 9	Expand 'Tree-Planting Campaign' to encourage voluntary tree and/or mangrove planting activities which are to be conducted as a part of school curriculums, community stewardship and the Corporate Social Responsibility.
Action 10	Implement a national program for the monitoring and management of rivers and watersheds (ridge to reef) to reduce the negative impacts of unsustainable activities linked to logging, river and seabed mining.
Action 11	Identify and map 'climate-vulnerable' species of flora and fauna and their habitat (lifecycle), including connections with the need to control invasive species, and create a national plan and monitoring system to support climate vulnerable species.
Action 12	Increase and mobilize resources available for the implementation, monitoring and enforcement of the National Biodiversity Strategy and Action Plan.
Action 13	Endorse and implement a comprehensive waste management plan for rural and urban areas to reduce the impact of pollution on terrestrial and marine ecosystems and the reliance upon landfill as a waste management option.

(2) Article 6 of Paris Agreement

As governments work on achieving NDCs and cooperative approaches under Article 6 of the Paris Agreement, the benefits and challenges of voluntary carbon markets (VCMs) and work with project investors, developers, and local communities must be considered to understand the implications of different approaches and decisions. Negotiations are underway to clarify the potential implementation of international trading, with authorization being the most controversial issue during the Article 6 consultations at COP 27. Some countries want to retain the right to revoke or modify their authorizations after emission reductions become Internationally Transferred Mitigation Outcomes or are credited as emission reductions under Article 6.4. This condition could undermine the viability of the market mechanism under this article because market participants are markedly concerned regarding the risk of a host country withdrawing its approval of a project. Furthermore, the approach could stall the flow of funds to support emission reduction projects and even undermine the integrity of the already announced Article 6.2 bilateral agreements.

(3) IPCC guideline revision

A BC accounting framework, which includes internationally recognized BC habitats but so far excludes seaweed or macroalgae, has been compiled[148]. Carbon budget methodologies for nearshore macroalgal farming have been

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[148] Ross F, Tarbuck P and Macreadie PI (2022) Seaweed afforestation at large scales exclusively for carbon sequestration: Critical assessment of risks, viability and the state of knowledge. Front. Mar. Sci. 9:1015612. doi: 10.3389/fmars.2022.1015612

considered[149], but carbon sequestration methodology studies for offshore macroalgal farming are still under development. However, macroalgae may sink directly to the storage site through marine afforestation; thus, methodologies to document this transport may be simpler than mapping detritus export and sediment transport pathways from the nearshore environment to offshore sink sites. This timescale may be faster than current pathways for carbon sequestration in macroalgae, which are difficult to track because carbon may be easily monitored and quantified. However, monitoring carbon storage sites and quantifying carbon sequestration in the deep sea remains a challenge.

Biomass accumulation by macroalgae would be relatively simple, but mapping pathways for viable sequestration remains a major challenge for marine afforestation[150]. For any carbon offset project or proposal, providing an accurate methodology for determining the amount of sequestered carbon is critical. The verification methodology must meet international standards for carbon sequestration, such as the United Nations Framework Convention on Climate Change (UNFCCC), must be met to increase the eligibility of ocean macroalgal farming for carbon credits (Michaelowa et al., 2019). This methodology would include criteria around proving additionality, permanence, and accuracy; consideration would need to be provided to incorporating a new international standard for carbon sequestration by natural and farmed macroalgae in the IPCC wetland guidelines or setting a separate international standard.

(4) Requirements for BC projects

The number of BC projects is gradually increasing; in addition to carbon sequestration, institutional design is underway to ensure project quality and promote initiatives that contribute to fair benefit sharing and biodiversity conservation. High-quality BC principles and guidance[151] was released at COP27 held in Egypt in November 2022. The guiding principles are based on the following: the "Quality Assessment Principles for Voluntary Carbon Markets (Core Carbon Principles)[152]" proposed by the Taskforce on Scaling Voluntary Carbon Markets as key points that must be met by projects to avoid climate change and biodiversity crises and advance climate justice and the "Quality Assessment Principles for Voluntary Carbon Markets (Core Carbon Principles)" proposed by the Taskforce on Scaling Voluntary Carbon Markets and the Provisional Claims Code of Practice introduced by the Voluntary Carbon Markets Integrity (VCMI) Initiative[153]. The Core Carbon Principles call for additionality, baseline setting, permanence, avoidance of double counting, and avoidance of adverse environmental and social impacts that BC projects should consider. By contrast, The Code of Practice of VCMI requires carbon credit users to prioritize CO_2 emission reductions before using credits to purchase high-quality credits and report on the transparency of credit use.

Tables 4.3–4.7 summarize the requirements for the restoration and conservation of carbon sinks in actionable BC ecosystems, conservation and restoration of macroalgal beds, macroalgal farming and carbon sequestration, and macroalgal farming and product utilization. Table 2.1 shows the requirements to meet Actionable Blue Carbon criteria.

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[149] Duarte, C. M., Wu, J., Xiao, X., Bruhn, A., and Krause-Jensen, D. (2017). Can seaweed farming play a role in climate change mitigation and adaptation? Front. Mar. Sci. 4, 100

[150] GESAMP (2019). "High level review of a wide range of proposed marine geoengineering techniques".(Boyd, P.W. and Vivian, C.M.G., eds.). (IMO/FAO/UNESCO-IOC/UNIDO/WMO/IAEA/UN/UN Environment/UNDP/ISA Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection). Rep. Stud. GESAMP No. 98, 144 p

[151] https://merid.org/wp-content/uploads/2022/11/HQBC-PG_FINAL_11.8.2022.pdf (accessed on January 8, 2023)

[152] "Taskforce on Scaling Voluntary Carbon Markets Final Report." Taskforce on Scaling Voluntary Carbon Markets, January 2021. https://iif.com/Portals/1/Files/TSVCM_Report.pdf.

[153] Provisional Claims Code of Practice." Voluntary Carbon Markets Integrity (VCMI) Initiative, June 7, 2022. https://vcmintegrity.org/wp-content/uploads/2022/06/VCMI-Provisional-Claims-Code-of-Practice.pdf.

Table 4.8. Solution for the Restoration of the Carbon Sink[154]

Real	Ok
Additionality based on credible baselines	Ok
Monitored, reported, and verified (MRV)	Potentially high costs to monitor and verify carbon sequestered in sediments, especially those of large underwater seagrass
No net harm	Ok
Permanent	Long-term viability is affected by multiple stressors, including climate change (e.g., sea level rise, warming); can account for long-term uncertainty (e.g., buffer system or metric ton/year accounting approach)
Leakage	Ok
Double counting	If on public land or in marine jurisdiction; accounting process outlined by Article 6 of the Paris Agreement prevents most, but not all, cases of double counting but not double claiming
Implementation challenges	Large dependence on upstream or nonlocal environmental factors (e.g., pollution and warming affecting viability of seagrass and macroalgal bed restoration). Large upfront costs before credit issuance
Key new opportunities	Implement latest science-based standard restoration methods to increase project success rates. Consider methodologies to support required upstream interventions (e.g., runoff nutrient load reduction)

Table 4.9. Solution of avoid loss (or conservation) of carbon stock and sink.
(e.g., halt deforestation, development, and pollution)[155]

Real	Ok
Additionality based on credible baselines	Projects can face similar challenges to REDD+ (e.g., additionality depends on assumptions of future socioeconomic incentives and environmental policy; for seagrass, limited data on historical extent)
Monitored, reported, and verified	Ok
No net harm	Ok
Permanent	Depends on continued protection; uncertainty can be addressed with buffer systems
Leakage	Can be an issue for small-scale, fragmented projects
Double counting	Pending further Article 6, excoriations on whether emission avoidance credits (e.g., project-based and/or jurisdictional REDD+) may be internationally traded and counted toward NDCs
Implementation challenges	Typically involves many stakeholders and requires multifaceted community-led development projects to address underlying drivers of destruction and unsustainable use; in some cases, lack of clear ownership or carbon rights within the tidal zone can pose challenges
Key new opportunities	Large-scale jurisdictional approach to facilitate baseline setting, avoid leakage, and address nonlocal upstream threats. Project bundling approach and cost-efficient remote monitoring to decrease verification cost per credit. Consider methodologies to support required upstream interventions (e.g., runoff nutrient load reduction)

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[154] McKinsey & Company, Blue carbon: The potential of coastal and oceanic climate action Nature-based climate solutions in the world's oceans can play an important role in conservation and carbon abatement efforts worldwide, 2022.

[155] McKinsey & Company, Blue carbon: The potential of coastal and oceanic climate action Nature-based climate solutions in the world's oceans can play an important role in conservation and carbon abatement efforts worldwide, 2022.

Table 4.10. Solution of avoid loss of and restore macroalgal beds, including kelp forests[156]

Real	Ok
Additionality based on credible baselines	Limited historical data
Monitored, reported, and verified	Complex due to the dispersal of carbon biomass to nonlocal, allochthonous sinks
No net harm	Ok
Permanent	Limited to fraction of carbon biomass exported to sediments (nonlocal)
Leakage	Ok
Double counting	Similar issues faced by other coastal BC ecosystem projects
Implementation challenges	Large dependence on upstream or nonlocal environmental factors (e.g., pollution and warming), impacts from herbivores (fish, sea urchins) Non-standardized, context-dependent restoration
Key new opportunities	Map extent and trends of kelp ecosystems. Model carbon sequestration of kelp in nonlocal sinks. Develop cost models for restoration

Table 4.11. Solution of the farm and sequester biomass (via sinking)[157]

Real	Ok
Additionality based on credible baselines	Additionality depends on role of limited nutrients in counterfactual scenarios
Monitored, reported, and verified	Requires process monitoring and possibly needs modeling
No net harm	Uncertain ecological impact of large-scale farms and deep-sea sinking
Permanent	Possibly over 100-year duration if sunk below 1000 m
Leakage	Ok
Double counting	Requires clear rules regarding attribution between farm operator and sediment jurisdiction
Implementation Challenges	Unproven technical viability and financial requirements of large-scale or offshore farming
Key new opportunities	Conduct pilot projects to verify sequestration models and study environmental impacts. Develop methods to mitigate impacts on ecology and commerce. Establish policy framework regulating large-scale biomass sinking at sea

Table 4.12. Solution of the farm and harvest biomass (e.g., food consumption, processing as a biofuel)[158]

Real	Ok
Additionality based on credible baselines	Avoided emissions depending on type of displaced product and production process
Monitored, reported, and verified	Requires process monitoring, likely modeling
No net harm	Uncertain ecological impact of large-scale farms and deep-sea sinking
Permanent	Satisfied only for avoided emissions
Leakage	Ok
Double counting	Requires clear rules regarding attribution between operator and sediment jurisdiction
Implementation Challenges	Unproven technical viability and financial requirements of large-scale or offshore farming
Key new opportunities	Conduct pilot projects to verify sequestration models and study environmental impacts. Develop methods to mitigate impacts on ecology and commerce

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[156] McKinsey & Company, Blue carbon: The potential of coastal and oceanic climate action Nature-based climate solutions in the world's oceans can play an important role in conservation and carbon abatement efforts worldwide, 2022.

[157] McKinsey & Company, Blue carbon: The potential of coastal and oceanic climate action Nature-based climate solutions in the world's oceans can play an important role in conservation and carbon abatement efforts worldwide, 2022.

[158] McKinsey & Company, Blue carbon: The potential of coastal and oceanic climate action Nature-based climate solutions in the world's oceans can play an important role in conservation and carbon abatement efforts worldwide, 2022.

(5) Environmental concerns from large-scale macroalgal farming on deep-sea biological communities

Large-scale farming in offshore areas, including the high seas, is considered in the strategy for CDR through macroalgal farming. Therefore, considering the national and international legal frameworks applicable to macroalgal farming is also necessary. Specifically, international legal frameworks, such as UNCLOS, the CBD, the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (London Convention), and the Protocol to that Convention (London Protocol), may be applicable. Macroalgae cultivation activities in territorial waters are mostly regulated similarly as shellfish farming (Billing et al 2021, Wood et al 2017), and explicit regulations regarding sinking macroalgae in the deep ocean are unavailable at any national or international level.

National laws may also apply depending on the implementation method. For example, in the United States, the Outer Continental Shelf Lands Act, National Environmental Policy Act, Endangered Species Act, Coastal Zone Management Act, Marine Protection, Research and Reserve Act, and Clean Water Act may apply[159].

Science cannot currently discern the impacts of large-scale macroalgae sinking in the ocean on marine life or the carbon cycle (Ricart et al., 2022[160]). The ecological carrying capacity of large-scale offshore farming and sinking is unresolved. The consequences for primary productivity in the upper ocean and associated food webs (e.g., from diverting nutrients into large-scale production of macroalgae), as well as the impacts of large macroalgae biomass to deep-sea biological communities (e.g., from oxygen depletion), are largely unknown. Moreover, not all macroalgae ecosystems, farmed or wild, may sequester carbon (Gallagher et al 2022[161]); the storage amount, time, and turnover rate of carbon by sunk macroalgae in the deep ocean, which likely will depend on the location, remains unknown (Siegel et al 2021[162]).

If the objective of farmed macroalgae is to sink it for financial gain through carbon credits, then should the valued biomass be considered waste? Furthermore, comprehensive third-party environmental impact assessments will be crucial. Similarly, accreditors of carbon credits should enforce reliable verification processes and hold companies accountable for the accuracy and precision of carbon removal estimations. Commensurate with emergent scientific evidence, a plural oversight approach that embraces and coordinates the diversity of actors, which include governments, managers, civil society (as consumers and final beneficiaries), and the private sector, is urgently needed. All these factors play a vital role in climate action governance.

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[159] Korey Silverman-Roati, Michael B. Gerrard & Romany M. Webb, Removing Carbon Dioxide Through Seaweed Cultivation: Legal Challenges and Opportunities, Sabin Center for Climate Change Law, Columbia Law School, September 2021 (2021).
Available at: https://scholarship.law.columbia.edu/faculty_scholarship/2980

[160] Ricart, Aurora & Krause-Jensen, Dorte & Hancke, Kasper & Price, Nichole & Masqué, Pere & Duarte, Carlos. (2022). Sinking seaweed in the deep ocean for carbon neutrality is ahead of science and beyond the ethics. Environmental Research Letters.

[161] John Barry Gallagher, Victor Shelamoff, Cayne Layton, Seaweed ecosystems may not mitigate CO2 emissions, ICES Journal of Marine Science, Vol. 79(3),585–592

[162] D A Siegel, T DeVries, S C Doney and T Bell(2021). Assessing the sequestration time scales of some ocean-based carbon dioxide reduction strategies. Environmental Research Letters, Vol16(10).

Chapter 5
Potentials of Carbon Removals by and Credits from Blue Carbon

This chapter outlines the quantitative potential of BC through its conservation, regeneration, and creation and how large the credits could be in the next few decades.

(1) Changes in Market Perceptions of Blue Carbon

Remarkably ambitious carbon prices can help close the gap between pledges and policy and "keep 1.5 alive." Record ETS prices were observed in the European Union (EU), California, New Zealand, and Republic of Korea, among other markets, while several carbon taxes also saw prices hit their highest levels yet. A combination of policy reforms, anticipated changes, speculative investment interests, and broad economic trends, especially in global energy commodity markets, are driving these ETS price spikes. Nonetheless, prices must rise considerably to meet the Paris Agreement temperature goals because less than 4% of global emissions are currently covered by a direct carbon price within the range needed by 2030.

Credits from independent crediting mechanisms dominate the carbon market (Figures 5.1 and 5.2). Driven by corporate commitments, annual VCM value exceeded USD 1 billion for the first time. Compliance demand for carbon credits remains limited despite new rules for international carbon markets under Article 6 of the Paris Agreement provide clarity that may enable future growth.

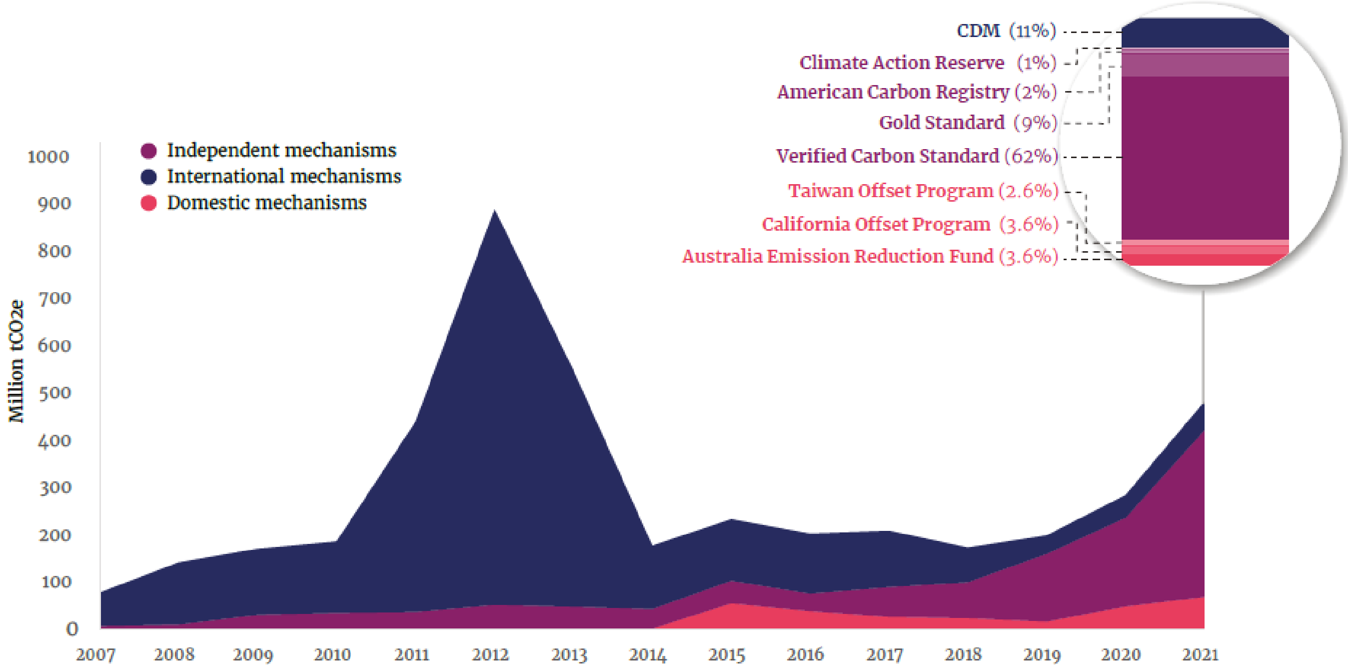

Figure 5.1. Global volume of issuances by crediting mechanism category[163]

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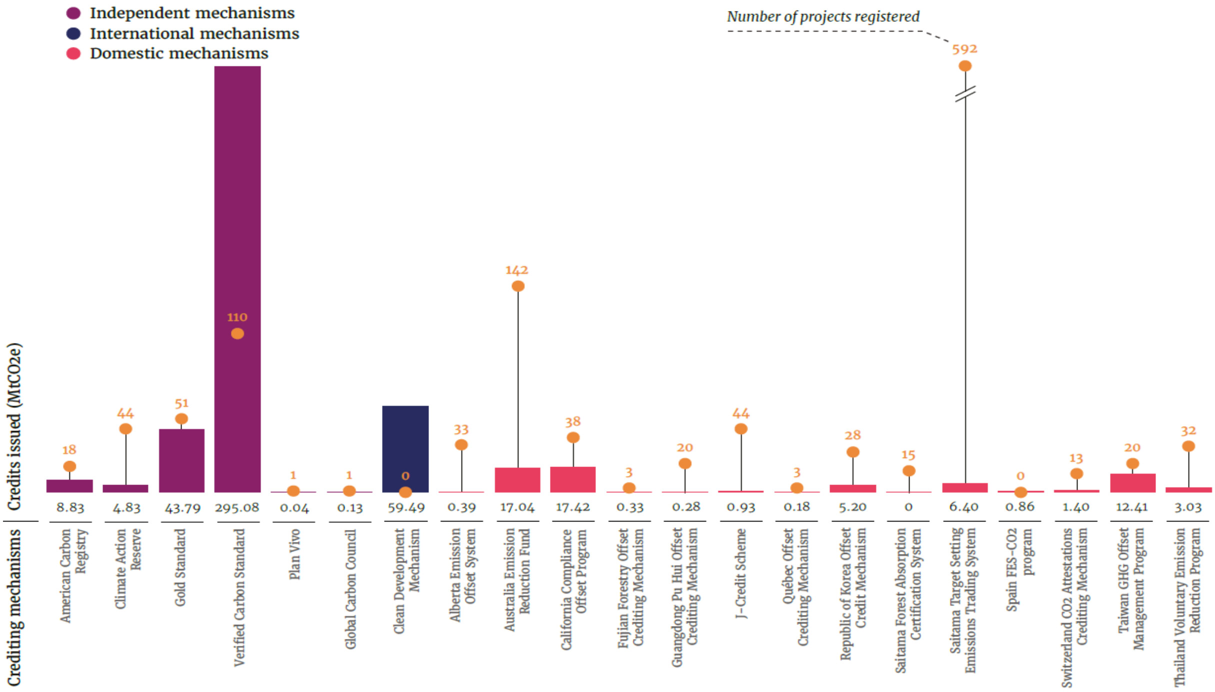
[163] The World Bank International Bank for Reconstruction and Development "State and Trends of Carbon Pricing 2022" (2022)

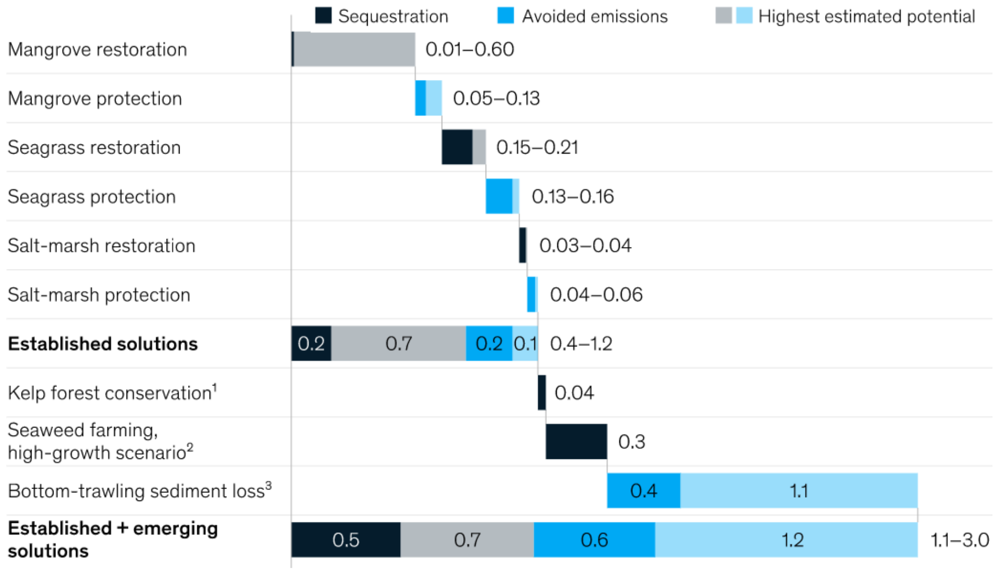


*There is potential for overlap where domestic mechanisms rely on credits initially issued by other existing mechanisms.

Figure 5.2. Credit issuance and number of projects in 2021 by category of mechanisms[164]

(2) Current estimates of carbon removals by blue carbon

With the emergence of the BC market, various entities have published estimates of Potentials of Carbon Removals by and Credits from BC. For example, McKinsey (2022) estimated the scale of blue carbon removals and the cost per solution (Figure 5.3). The report showed that established BC solutions offer abatement of 0.4 to 1.2 metric gigatons of carbon dioxide (GtCO$_2$) per year; emerging solutions could add up to ~1.8 GtCO$_2$ per year for a total of ~3 GtCO$_2$ per year. This potential jumps to ~3 GtCO$_2$ of annual abatement (~7% of total current annual emissions) if the solutions in the emerging category, such as large-scale macroalgae farming and bottom-trawling management, were to be fully confirmed and implemented. Nascent solutions might add another 1 to 2 GtCO$_2$ of annual abatement potential in the long term but the science remains highly uncertain. Annual human emissions are currently around 40 GtCO$_2$ to put these numbers into context.



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[164] The World Bank International Bank for Reconstruction and Development "State and Trends of Carbon Pricing 2022" (2022)

Figure 5.3. Abatement potential from established and emerging BC solutions by 2050, $GtCO_2$ equivalent per year[165]

Moreover, in the estimation of the abatement or conservation potential on a 2050 timeline, the deep dives on kelp reforestation and bottom trawling show how economies of scale in these emerging solutions could help reduce costs. The analysis suggests that around one-third of the total abatement potential would be viable below \$18 per tCO_2 (Figure 5.4). This value is more than the \$5 to \$15 per tCO_2 average price paid in the VCMs but below the \$40 to 100 per tCO_2 paid in the European compliance markets over the past year (February 2021–2022).

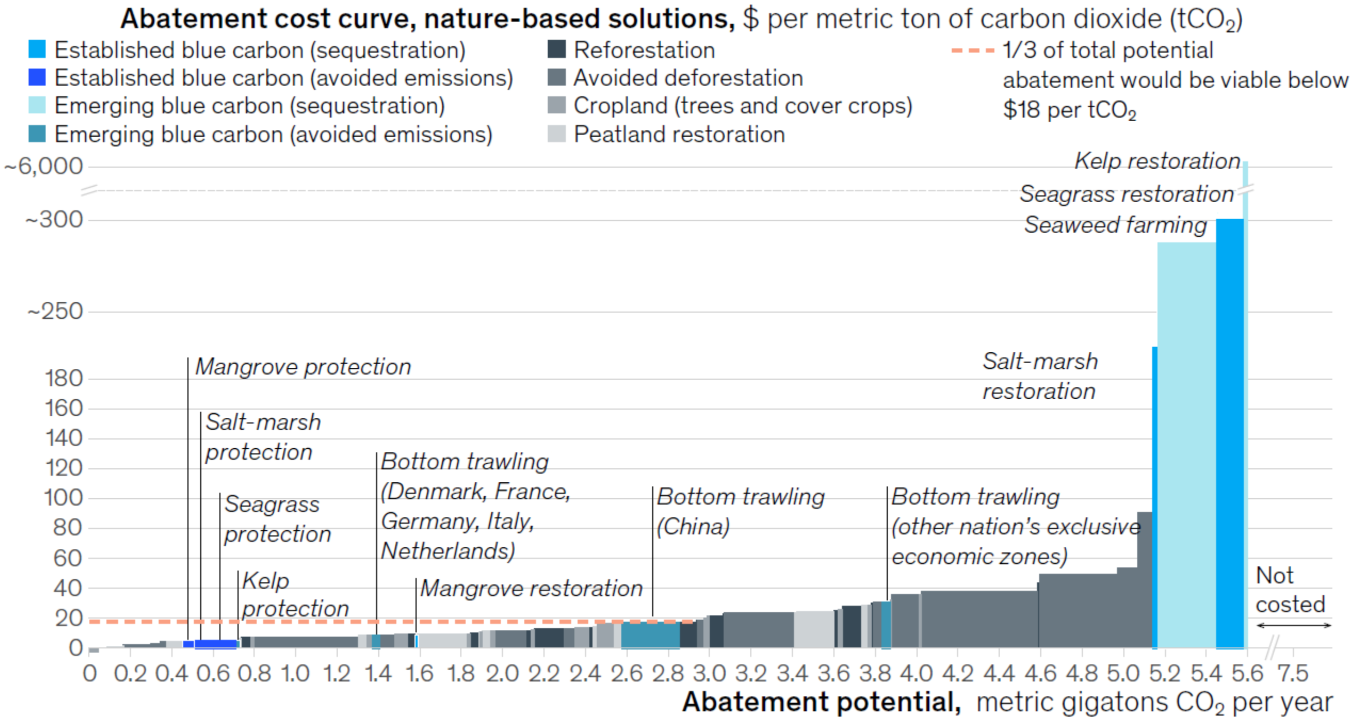

Figure 5.4. Abatement cost curve, nature-based solutions, \$ per metric ton of carbon dioxide (tCO2)[166]

(3) Blue Carbon and Voluntary Carbon Mechanisms

a) Plan Vivo

Plan Vivo generated the world's first carbon credits to the voluntary carbon market (VCM), which are sold to organizations, such as the World Bank in 1997 (Scolel'te Project, Planting trees in Chiapas, United Mexican States, through a collaboration between the University of Edinburgh, El Colegio de la Frontera Sur, other local partners, Table 5.1).

Plan Vivo created proto standard in 2001/2002, the second standard in 2004, the third standard in 2008, the fourth standard in 2013, and the fifth standard in 2022. In 2013, the Plan Vivo-certified Mikoko Pamoja project in Gazi, Kenya, became the world's first Blue Carbon Project by receiving Plan Vivo Certificates for the conservation and restoration of its mangrove forests. The project later won a UN Equator Prize award.

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[165] McKinsey & Company "Blue carbon: The potential of coastal and oceanic climate action (2022). Source: Peter Macreadie et al., "Blue carbon as a natural climate solution," Nature Reviews Earth & Environment, November 2021, Volume 2; Ove Hoegh-Guldberg et al., The ocean as a solution to climate change: Five opportunities for action, World Resources Institute, 2019; Enric Sala et al., "Protecting the global ocean for biodiversity, food and climate," Nature, March 2021, Volume 592; McKinsey analysis

[166] The abatement potential shown for blue-carbon solutions corresponds to the lower-end estimates. An additional 1.9 metric gigatons (Gt) of natural-climate-solutions abatement is not costed (avoided deforestation: 0.95 Gt; peatland restoration: 0.21 Gt; reforestation: 0.36 Gt; cover crops: 0.22 Gt; trees in cropland: 0.11 Gt). This analysis filter out low-feasibility lands (those with high economic returns—ex., >\$45/hectare—from agriculture), which are more likely to be accessed by mechanisms other than voluntary carbon markets. Lower-end estimate of bottom-trawling emission abatement, limited to activity in the top 50 meters of the ocean. The higher-end estimate offers 1.5 Gt at a (lower) average opportunity cost of \$11/tCO2.Macroalgae farming potential based on current cost and implementation growth estimates; chart does not reflect potential cost reductions from technology learning curves and scaling.

Table 5.1. Plan Vivo-certified and under processed (project approved only) Blue Carbon Projects List

Project (Lead Organization/Activity)	Country	Date	Project size
Mikoko Pamoja (ACES/ Mangrove avoided deforestation, Restoration)	Kenya	2013	117 ha
Tahiry Honko (Blue Ventures /Mangrove avoided deforestation, Restoration)	Madagascar	2018	1,200ha
Vanga Blue Forest (ACES/Mangrove avoided deforestation, Restoration)	Kenya	2019	450 ha
Vanga Blue Forest (ACES/ Seagrass conservation)	Kenya	2022	300 ha
Mikoko Ujamaa (Women Against Poverty/ Mangrove avoided deforestation, Restoration)	Tanzania	Approved 2020	1426 ha
Taab Che (Resiliencia Azul/ Mangrove avoided deforestation, Restoration)	Mexico	Approved 2021	10,080 ha
Restoration of Abandoned or Under-utilized Shrimp Farms to Mangroves on Village Owned Land in Southeast Sulawesi (Yayasan Bunga Bakau /Mangrove Restoration)	Indonesia	Approved 2021	4487 ha
Restoration and Protection of Mangroves and Blue Carbon Ecosystems in North Yucatan (CINVESTAV, Sociedad Cooperativa Tulum Sostenible/ Mangrove restoration)	Mexico	Approved 2021	700 ha
Restoration of Mangroves Removed for Shrimp Farms and Firewood in the Gulf of Fonseca (Mangrove restoration / Instituto de Conservacion Foresta Servimos por Naturaleza, CODDEFFAGOLF)	Honduras	Approved 2022	1400 ha

b) Verified Carbon Standard (VCS) (later Verra)

In 2015, the Verified Carbon Standard (VCS) published a methodology (VM0033) that can be adapted to the restoration of seagrass beds and saltmarshes. In September 2020, Verra extended the methodology to the conservation of wetlands (revised VM0007). VM0007 has been used to register the world's first project on the conservation of mangrove ecosystems, including sediments, in Cispatá in the Gulf of Morroquillo, Colombia; the project is supported by Conservation International and Apple. In May 2021, Apple purchased 17,000 tons of CO_2 equivalents (t-CO_2e) to offset its comprehensive carbon footprint for fiscal year 2020. In 2022, a 60-year conservation and regeneration project for 350,000 ha of mangrove forests in Sindh Province, Pakistan, was verified by Verra. Table 5.2 presents the BC projects of Verra.

Table 5.2. VCS Certified and under processed (project approved only) Blue Carbon Projects List

Project (Lead Organization/Activity)	Country	Date	Project size
India Sundarbans Mangrove Restoration (Livelihoods Fund, Danone/Mangrove restoration)	India	2015	4675 ha
Cispatá Bay (Conservation International / Mangrove avoided deforestation)	Colombia	2021	11,000 ha
Community-based Avoided Deforestation Project Guinea-Bissau (Bio Guinea Foundation/Mangrove avoided deforestation)	Guinea- Bissau	2021	35,927 ha
Magdalena Bay (Marvivo/Mangrove avoided deforestation, restoration)	Mexico	2022	222,000 ha
Delta Blue Carbon (Indus Delta Capital/Mangrove avoided deforestation, restoration)	Pakistan	2022	~350,000 ha

c) Blue Carbon Credits in Japan[167]

The three BC credits have been issued in Japan (Table 5.3).

Table 5.3. Current blue carbon (BC) credit schemes

Name (Developer and secretariat / Year)	Estimated project budget & Trading amount	VVB	Approver	Project activities
Yokohama BC Credit (Yokohama City/2015)	5,600,000 JPY (2020) 120.3 t CO_2 (2020)	Not established	Yokohama City	Seagrass meadows (Tier 1) Macroalgal beds Macroalgae aquaculture
Fukuoka BC Credit (Fukuoka City/2019)	1,850,000 JPY (2020) 43.4 t CO_2 (2021)	Not established	Fukuoka City	Seagrass meadows (Tier 3) Macroalgal beds
J-Blue Credit (JBE approved by GoJ/2021)	990,000 JPY (2021) 22.8 t CO_2 (2021)	Established with JBE	JBE	Seagrass meadows (Tier 3) Macroalgal beds

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[167] Tomohiro Kuwae, Atsushi Watanabe, Satoru Yoshihara, Fujiyo Suehiro, Yoshihisa Sugimura(2022). Implementation of blue carbon offset crediting for seagrass meadows, macroalgal beds, and macroalgae farming in Japan. Marine Policy, Volume 138, 104996.

In Yokohama and Fukuoka projects, the BC offset credit scheme is based on the IPCC Guidelines, which outline methodologies for calculating the CO_2 sink capacity of BC ecosystems (mangroves, tidal marshes, and seagrass meadows) and are based on compilations of domestic and international data. Furthermore, in line with the IPCC Guidelines, these methodologies can be used to estimate the CO_2 sink capacities of macroalgal beds and tidal flats throughout Japan.

JBE, established in 2020, has created a system called J-Blue Credit and is promoting demonstrations, such as Blue Carbon Credit audits, certification, trading, and offsets; FY2020 has one project, but the number is gradually expanding to 4 and 21 projects in FY2021 and FY2022, respectively. The number of projects is gradually increasing from 1 in FY2020 to 4 and 21 in FY21 and FY22, respectively. Established methodologies are subject to continuous review and revision by JBE, whereas the methodologies of many domestic and international credit schemes are nearly fixed. A flexible scheme in which methodologies are reviewed and revised considering the rapid progress in science and technology (e.g., area determination using aerial and above-water sailing drones and remote sensing) should improve certainty and reduce costs. However, project management may become increasingly difficult. Simplifying methodologies should help facilitate cost reductions and efficient project development, particularly for small-scale projects, and move the carbon market forward.

(d) Limitations of the size and number of the Blue Carbon Project

New guidance for BC first presents the methodology for conserving BC approved under any major greenhouse gas program released in September 2020 by Verra. Only a few projects have been launched to date. By 2020, five projects were registered under approved methodologies, and all five projects are small scale: compared to 2.4 million tCO_{2e} for other NbS using international standards, the current average project size is 0.3 million tCO_{2e} over the project lifetime. Blue carbon credits are still small in number and scale compared to green carbon credits and is approximately one-hundredth as large in 2020 (Figure 5.5).

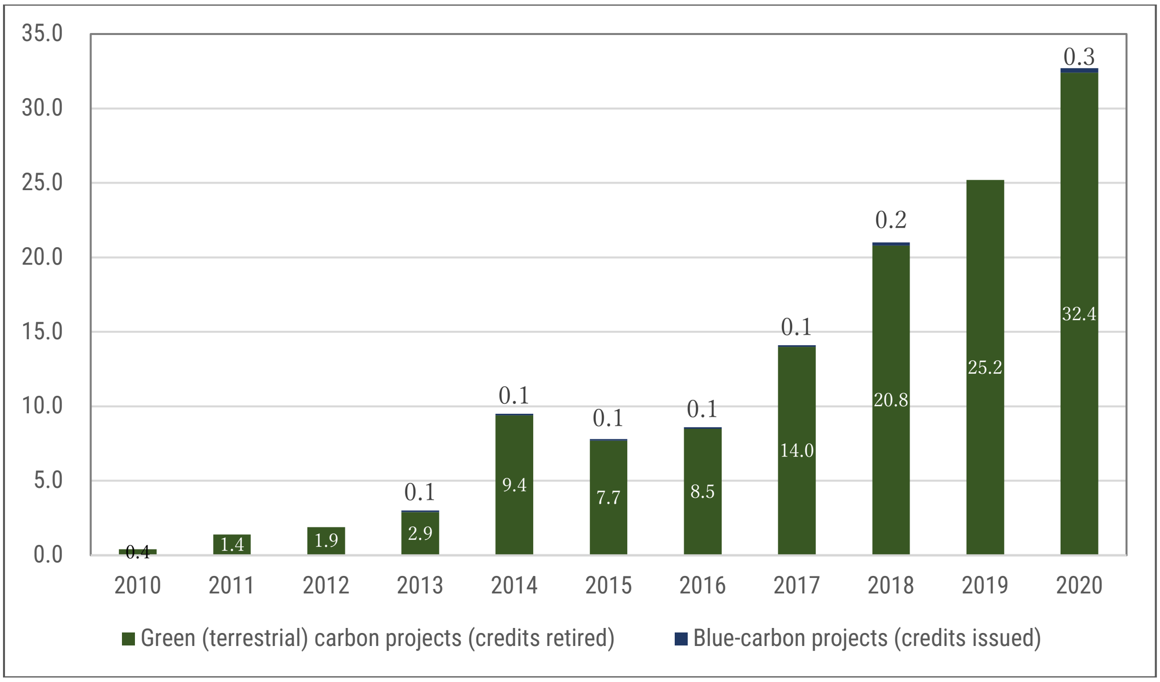

Figure 5.5. Carbon credits issued or retired for nature-based solutions, MtCO2[168]

Nature-based credits are in especially high demand: Forestry and land use transactions more than doubled between 2020 and 2021 with the strengthening of the transparency and quality. Increasing demand for carbon removals has resulted in price increases for these credits. The VCM continues to be strongly diverse, with purchasers placing widely different values on characteristics, such as sector, geography, and perceived co-benefits.

If additional evidence of carbon fixation by macroalgae accumulates in the future, then revising the wetland guideline

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[168] American Carbon Registry; Catherine E. Lovelock and Carlos M. Duarte, 2019; Climate Action Reserve; The Gold Standard; Plan Vivo; Verra

based on such evidence may be an option. The UNFCCC should make a request to the IPCC under the agreement of each country, and the IPCC should develop a methodology by experts.

Box 3. Discussion on blue carbon project requirements

(1) Project Boundary

a) Temporal Boundaries

(I) Peat depletion time (PDT)

Drained peat is subject to oxidation and subsidence and areas with peat at $t = 0$ may lose all peat before the end of the crediting period. The time at which all peat has disappeared or that at which the peat depth reaches a level where no further oxidation or other losses occur (e.g., at the average water table depth) is referred to as the PDT.

(II) Soil organic carbon depletion time (SDT)

Projects that do not quantify reductions of baseline emissions (i.e., those which limit their accounting to GHG removals in biomass and/or soil) need not estimate SDT. SDT for a stratum in the baseline scenario limits the period when the project is eligible to claim emission reductions from restoration and is estimated at the project start date for each stratum.

SDT is conservatively set to zero for project sites drained more than 20 years before the project start date. SDT is also conservatively set to zero, wherein significant soil erosion occurs in the baseline scenario. Considering the estimation of SDT, the accretion of sediment in the baseline scenario is conservatively excluded.

b) Geographic Boundaries

The project proponent must define the geographic boundaries of the project area at the beginning of project activities. The project proponent must provide the geographic coordinates of lands (including subtidal seagrass areas, where relevant) included in the project area to facilitate accurate delineation of the project area. Remotely sensed data, published topographic maps and data, land administration and tenure records, and/or other official documentation that facilitates clear delineation of the project area must be used.

When describing physical project boundaries, the following information must be provided for each discrete area:
Name of the project area (including compartment numbers, local name (if any)):
Unique identifier for each discrete parcel of land:
Map(s) of the area (preferably in digital format):
The project area must be georeferenced and provided in digital format according to VCS rules:
Total area:
Details of land rights holder and user rights.

Land tenure and its intersection with the BC market, such as who “owns” the BC and who has the right to transact carbon credits for a given BC project (the landholder, the project developer, Indigenous groups, or the national/subnational government), is complicated. For example, mangroves often straddle the boundary between privately owned and state-owned land, and seagrasses and macroalgae can exist beyond exclusive economic zones or within countries with conflicting state and national laws.

(I) Ineligible wetland areas

For projects quantifying CO_2 emission reductions, project areas that fail to achieve a significant difference in cumulative carbon loss over a period beyond the project start date are ineligible for crediting based on the reduction of baseline emissions. Thus, these areas must be mapped.

The maximum quantity of GHG emission reductions, which may be claimed from the soil carbon pool, is limited to the difference between the remaining soil organic carbon stock in the project and baseline scenarios after years (total stock approach) or the difference in cumulative soil organic carbon loss in both scenarios over a period of years since the project start date (stock loss approach).

Box 4 Case of Australia

In Australia, tenure issues have been overcome to some extent through contractual agreements whereby parties agree where carbon ownership lies irrespective of underlying property-based rights.

To generate ACCUs from the coastal wetland ecosystems, including the supratidal forests, saltmarshes, mangroves, and seagrass Australian government identified “Carbon Credits (Carbon Farming Initiative-Tidal Restoration of BC Ecosystems) Methodology” as the first BC methodology determination in 2022 and restricted by “The Carbon Credits (Carbon Farming Initiative) Act 2011.” For completeness, the National Inventory Report is not incorporated by reference. Factors have been derived from that document; thus, they have been set out in a manner that does not require reference to the National Inventory Report.

The key features of the determination are as listed.

1	The project proponents must remove or modify one or more tidal restriction mechanisms to introduce tidal flow to their project area and use, remove, modify, install, or construct additional necessary infrastructure or drainage infrastructure to manage the subsequent extent of tidal inundation.
2	The land is eligible to be included in a tidal restoration project if either: tidal flow has been excluded or impeded from the land by one or more tidal restriction mechanisms for at least seven years immediately before the project registration application was submitted, or tidal flow has been excluded from the land due to reasons other than a tidal restriction mechanism for at least seven years immediately before the project registration application was submitted and by conducting the eligible project activities the land will be inundated during the 25 year crediting period.
3	The project proponents are required to undertake hydrological mapping as part of the project registration process to ascertain consent and regulatory approval requirements and potential adverse impacts.
4	The project proponents must not conduct prohibited activities and must conduct restricted activities only in accordance with the determination.
5	The project proponents can estimate carbon abatement at intervals of 6 months to 5 years using a modeled approach via the Blue Carbon Accounting Model. No sampling is required under the determination.
6	The determination applies discounts to account for the risks that carbon sequestered by a tidal restoration project is not maintained, or that the coastal wetland biomass that establishes due to the migration of project outside the project area over time.

Particularly, Section 10 (Project Area) and Section 11 (Duty to disclose information relating to project to owners and relevant landholders) of the methodology symbolizes determination.

Section 10 (Project Area)

Section 10 sets out the requirements for determining the boundaries of a project area.

Subsection 10(1) requires that all land identified as impacted land by the project start tidal inundation map (prepared as part of the hydrological assessment) is included in the project area.

Subsection 10(2) requires that the project area must include eligible land.

Subsection 10(3) clarifies that the project area may also include areas of land that are ineligible provided that these areas of land will not be included in CEAs for the project.

Section11 (Duty to disclose information relating to project to owners and relevant landholders)

Section 11 sets out the requirements for project proponents to provide written notices to owners and relevant landholders of land identified by a permanence period tidal inundation map (prepared as part of the hydrological assessment) as land that will be impacted by tidal inundation arising from the eligible project activities (referred to in the Determination as “impacted land”).

Paragraph 11(2)(a) requires that a notice is provided between 35 and 40 days of the commencement of the removal or modification of a tidal restriction mechanism in accordance with paragraph 7(2)(a). This requirement is intended to ensure that relevant landholders are aware when tidal inundation will occur and are provided with sufficient notice to allow any preparations to be made. Paragraph 11(2)(b) outlines the information required to be included in the notification.

The effect of subsection 11(3) is that for the duration of the permanence period for the project, the project proponent must take reasonable steps to inform themselves of the owners and relevant landholders of all land outside the project area that is identified as future impacted land by the most recent permanence period tidal inundation map prepared or revised for the project.

Subsection 11(4) requires project proponents to provide anyone identified under subsection 11(3) with information about the project.

The intent of subsections 11(3) and 11(4) is to ensure that when a change of ownership or operational control of land is identified as future impacted land, the new owner and relevant landholder are provided with adequate information regarding the project within a reasonable timeframe.

c) Carbon Pools

Carbon pools may be deemed de minimis and do not need to be accounted for if the omitted decrease in carbon stocks or increase in GHG emissions jointly amounts to less than 5% of the total GHG benefit generated by the project.

(2) Baseline Scenario

a) Reassessment of the Baseline Scenario

The historic reference period must be extended for this reassessment to include the original reference period and all subsequent monitoring periods up to the beginning of the current monitoring period.

Activity data (in the context of sinks, data on changes in area over time) are unavailable. Absorption and emissions from mangrove forests, salt marshes, and seagrass beds, which are currently considered major BC ecosystems, can be calculated if activity data are available in addition to the Tier 1 absorption factors provided in the wetland guidelines. When countries calculate GHG absorption emissions, many international data are currently used in addition to domestic data to determine the amount of activity. For example, for energy use, the International Energy Agency Energy Balance Table, FAO (Food and Agriculture Organization of the United Nations) International Statistics Database FAOSTAT55 provides data over time. Even if data for a country are lacking, calculating the Tier 1 level is possible using international data as the amount of activity. However, for BC ecosystems, no such international statistics exist, and the creation of data on activity amounts is left entirely to the self-help efforts of individual countries.

Guidance for countries for BC calculation and its incorporation into their NDCs has been published by the Blue Carbon Initiative, and support for methodology development, including data preparation methods, is gradually strengthened. In addition, there are moves toward the development of international data on salt marshes, such as the provision of global data on the area of salt marshes.

(3) Additionality[169]

The project must ensure that the carbon credit project takes place outside of mandated protections, such as national laws, regulations, or other government policies, to demonstrate additionality. A project is additional if (1) it would not have been undertaken without the carbon credit incentive and (2) the benefits (including carbon sequestration) would not have been realized without the project.

Conservation is less costly and provides a large amount of credits because of the considerable amount of protected carbon stocks. However, similar to other conservation credit projects, proving additionality in conservation projects can be difficult because the absence of m negative impacts due to the project intervention must be demonstrated. In conservation projects, establishing baselines and additionality usually involves an analysis of the causes, rates, and patterns of deforestation, degradation, and wetland conversion. Many BC ecosystems face factors of loss caused upstream (e.g., sedimentation and water quality degradation). These factors are often difficult to measure or include in predictions.

In restoration projects, baselines must consider removed emissions (carbon that is taken up as ecosystems are rebuilt, also known as removals) and avoided emissions. If a BC ecosystem is destroyed, then avoided emissions must be considered because carbon-rich soils can emit carbon for up to 20 years. The amount of avoided emissions depends on when the intervention is made for the initial destruction. If the project starts after all the carbon in the soil has been emitted, then the counterfactual hypothetical baseline would have zero avoided emissions, similar to a reforestation project.

(4) Quantification of GHG Emission Reductions and Removals

a) Baseline Emissions

Emissions in the baseline scenario are attributed to carbon stock changes in biomass carbon pools, soil processes, or a combination of these factors. In addition, emissions from fossil fuel use may be quantified where relevant.

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[169] https://merid.org/wp-content/uploads/2022/11/HQBC-PG_FINAL_11.8.2022.pdf (accessed on January 8, 2023)

Estimation of GHG emissions and removals related to the biomass pool is based on carbon stock changes. Estimation of GHG emissions and removals from the SOC pool is based on either various proxy (e.g., carbon stock change, water table depth) or through the use of literature, data, or default factors or models.

Assessing GHG emissions in the baseline scenario includes determining GHG emission proxies/parameters and evaluating their pre-project spatial distribution, constructing a time series of the chosen proxies/parameters for each stratum for the entire project crediting period, and determining annual GHG emissions per stratum for the entire project crediting period.

Current development patterns and plausible future land use changes must be mapped to a scale sufficient to estimate GHG emissions from the baseline scenario. Particular attention must be provided to existing or future construction of barriers to tidal and/or river hydrology and sediment supply from rivers and/or along the coast, as well as barriers that will impair wetland capacity to migrate landwards with sea level rise.

In the case of abandonment of pre-project land use in the baseline scenario, the project proponent must consider nonhuman induced hydrologic changes induced by collapsing dikes or ditches that would have naturally closed over time and progressive subsidence, leading to rising relative water levels, increasingly thin aerobic layers, and reduced CO_2 emission rates. Regarding infrastructure impediments to tidal hydrology, the baseline scenario must consider the current and historic layout of any tidal barriers and drainage systems to derive trends in tidal wetland evolution.

Historic information on the preexisting channel network as determined by aerial photography may serve to set trends in post-project dendritic channel formation in the field. Derivation of such trends must be performed on the basis of hydrologic modeling using the total tidal volume, soil erodibility, and/or expert judgment. Considering hydrological functioning, the baseline scenario must be restricted by climate variables and quantify any impacts on the hydrological functioning as caused by planned measures outside the project area (e.g., dam construction or further changes in hydrology, such as culverts) by demonstrating a hydrological connection to the planned measures.

Natural plant succession, based on the assessment of changes in water table depth, a time series of vegetation composition must be derived *ex ante* according to vegetation succession schemes in the baseline scenario from scientific literature or expert judgment. For example, diked agricultural land will undergo natural plant succession to forests, freshwater wetlands, tidal wetlands, rank uplands, or open water based on the land use trajectory scenario, inundation scenario, proximity to native or invasive seed sources, plant succession trajectories of adjacent natural areas, or possible maintenance consistent with projected future human land use (e.g., pasture, lawn, landscaping).

GHG emissions from disturbed carbon stocks in stockpiles (originating from piling, dredging, and channelization) exposed to aerobic decomposition must be accounted for in the baseline scenario.

The baseline scenario may involve the construction of levees to constrain flow and flooding patterns, the construction of dams to hold water, and/or upstream changes in land surface, leading to intensified runoff. In such cases, the project proponent must account for hydrological processes that lead to increased carbon burial and GHG reductions within the project area using procedures provided in this section.

The subsections below provide guidance considering the methods which may be used to estimate net GHG emissions from soil in the baseline scenario. Project proponents may choose the most suitable method for their project circumstances and data availability. However, default and emissions factors cannot be used in the presence of published data suitable for use in the project area.

b) Project Emissions

Emissions in the project scenario are attributed to carbon stock changes in biomass carbon pools, soil processes, or a combination of these factors. In addition, emissions from organic soil burns and fossil fuel use may be quantified where relevant.

The long-term average carbon stock must be calculated for the baseline and the project scenario. For projects undertaking even-aged management, the time period *n*, over which the long-term average GHG benefit is calculated, involves at minimum one full harvest/cutting cycle, including the last harvest/cut in the cycle. For projects under conservation easements with no intention to harvest after the project crediting period (which must be shown in the project description based on verifiable information), or in case of selective cutting, the time period *n*, over which the long-term average is calculated, is the length of the project crediting period.

Measurements of carbon burial rates show high site-specific variability, which are strongly affected by a wide range of environmental factors for mangroves (Adame et al., 2017; Schile et al., 2017), seagrasses (Lavery et al., 2013), and salt marshes (Kelleway et al., 2017b).

The reliable determination of sediment accumulation rates is a key consideration, with associated uncertainties only partially reflected in the McLeod et al. (2011) estimates presented above. Geochemical-based studies have indicated that seagrass carbon burial may have been markedly overestimated (Johannessen and Macdonald, 2016). These issues are contentious (Johannessen and Macdonald, 2018a; Johannessen and Macdonald, 2018b; Macreadie et al., 2018; Oreska et al., 2018); their scientific resolution is highly desirable.

Lateral transfers are ineffectively quantified. Some of the carbon stored in coastal marine sediments may be recalcitrant carbon from terrestrial or atmospheric sources (and should therefore be excluded) (Chew and Gallagher, 2018), but export of DOC, inorganic carbon, and alkalinity may be considered as additional sequestration (Maher et al., 2018; Santos et al., 2019). Even if well-protected, the permanence of vegetated coastal systems cannot be assumed under future temperature regimes (Ward et al., 2016; Duke et al., 2017; Jennerjahn et al., 2017; Nowicki et al., 2017).

Responses to future SLR are also uncertain and complex (Spencer et al., 2016). However, impacts are not necessarily negative: carbon sequestration capacity may increase where totally new habitats are created (Barnes, 2017) or if salt marshes are replaced by mangroves (Kelleway et al., 2016).

Overall, a combination of conservation and restoration of mangroves, salt marshes, and seagrass habitats can contribute to national mitigation efforts for those countries with relatively large coastlines where such ecosystems naturally occur (Atwood et al., 2017). However, the associated current uncertainties in quantifying relevant carbon storage and flows are expected to be problematic for reliable measurement, reporting, and verification.

c) Emission Reduction

Emission reductions are estimated using a conservative default factor based on fire occurrence and extension in the project area in the baseline scenario. This method avoids the need for direct assessment of GHG emissions from fire in the baseline and the project scenarios.

d) Leakage of Blue Carbon Project

For climate change mitigation, impacts outside the boundary (e.g., activity-shifting leakage, market leakage, ecological leakage, and emissions upstream and downstream (life cycle) of business activities) are generally assumed to be zero unless significant impacts are observed.

The vast potential of nascent BC NbS is offshore, occasionally overlapping and context-dependent jurisdictions and public domains that lack straightforward carbon rights concepts for private property.

The ecological leakage may be achieved by a project design, which causes no alteration of mean annual water table depths or flooding frequency or duration in adjacent areas or limiting such alteration to levels that do not influence GHG emissions. In tidal wetland restoration projects, dewatering downstream wetlands is unexpected if project areas are set sufficiently large to include expected areas of changed hydrology. Procedures for monitoring alterations of water table depth at the project area. The tidal range and sediment delivery experienced by wetlands outside the project area must remain within the system tolerance, which is defined by the high and low tides and regional sediment budget and assessed using hydrological models (and/or empirical analysis) and expert judgment.

Table 5.4. Processes Associated with Ecological Leakage Outside Project Boundary and Related Criteria for their Avoidance[170]

Ecological leakage process outside project boundary	Avoidance criterion
Lowering water table that causes increased soil carbon oxidation	Maintain wetland conditions (e.g., converting from impounded water to a wetland does not cause soil oxidation)
Lowering water table that causes increased N_2O emissions	No conversion of non seagrass wetland to open water
Raising water table that causes increased CH_4 emissions	No conversion of non wetland to wetland
Raising water table that causes decreased vegetation production that causes decreased new soil carbon sequestration	No causation of vegetated to no vegetated (or poorly vegetated) conditions

e) Net GHG Emission Reductions and Removals

(I) Calculation of net GHG emissions reductions

The total net GHG emission reductions project activity is calculated as follows:

$NER_{RWE} = GHG_{BSL} - GHG_{WPS} + FRP - GHG_{LK}$

NER_{RWE} = Net CO_2e emission reductions from the RWE project activity; t CO2e

GHG_{BSL} = Net CO_2e emissions in the baseline scenario; t CO2e

GHG_{WPS} = Net CO2e emissions in the project scenario; t CO2e

FRP = Fire Reduction Premium (net CO2e emission reductions from organic soil combustion due to rewetting and fire management); t CO2e

GHG_{LK} = Net CO_2e emissions due to leakage; t CO2e

For projects claiming reductions of baseline GHG emissions or for conservation and restoration projects where sea level rise may cause a loss of tidal wetland and/or soil organic carbon stocks, the maximum quantity of GHG emission reductions or removals that may be claimed from the biomass and soil organic carbon pool is limited to the net GHG benefit generated by the project years after its start date.

(II) Estimation of uncertainty

The estimation of uncertainty of emissions and carbon stock changes (i.e., for calculating a precision level and any deduction in credits for lack of precision following project implementation and monitoring) must be justified by using a conservative precision. Levels of uncertainty must be known for all aspects of baseline and project implementation and monitoring.

Estimated carbon emissions and removals arising from BC activities have uncertainties associated with the measures and estimates of several parameters. These parameters include the project area or other activity data, carbon stocks, biomass growth rates, expansion factors, and other coefficients. Either as default factors given in the IPCC Guidelines (2006), IPCC-GPG-LULUCF (2003), expert judgment, or estimates based on sound statistical sampling, the uncertainties associated with the estimates of various input data are assumed to be available.

Applying this procedure at an early stage to identify the data sources with the highest uncertainty is good practice to conduct further work to diminish uncertainty.

(III) Calculation of Verified Carbon Units

The project proponent must consider the number of buffer credits, which must be deposited in the pooled buffer account, to calculate the number of verified carbon units. The number of buffer credits, which must be deposited in the pooled buffer account, is based on the net change in carbon stocks.

The percentage of buffer credits to be contributed to the pooled buffer account must be determined by applying each mechanism tool similar to the VCS AFOLU Non-Permanence Risk Tool.

(5) Other Issues

(a) Cost Effectiveness

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[170] VERRA "VM0033 Methodology for Tidal Wetland and Seagrass Restoration v2.0" (2021)

Restoration costs could also be an important constraint for large-scale application. Based on published data from 246 observations, Bayraktarov et al. (2016) estimated median total costs for restoration of one hectare of mangrove, salt marsh, and seagrass habitat to be ~2508, 151,129, and 383,672 in 2010 USD. Each ecosystem had high variability in costs according to the economy of the country where the restoration projects were conducted, and the restoration technique was applied. Assessment of coastal conservation and restoration costs is also given.

(b) Lack of historical data

National governments, international research agencies, and local universities can provide basic forestry information, namely suitable species, management regimes, growth rates, and market information.

In the case of USA tidal wetland and seagrass restoration VCS project, no complete national data sets exist for either tidal wetland loss or restoration in USA for OA[171] and MAP[172], and conservative approximations can be made by examining the data from several sources. All US estuaries face a common set of barriers to tidal wetland restoration, including insufficient funding, lack of willing landowners and community support, and physical and ecological limitations and changes, such as sea level rise (Vigmostad et al 2005). The critical need to provide funding for estuary habitat restoration, including tidal wetlands, and help counter the mentioned socioeconomic factors was recognized in 2000. The United States Congress passed, and President Clinton signed into law, The Estuary Act of 2000, which was passed by the United States Congress and signed into law by President Clinton, authorized $275 million over five years for restoration activities. Seagrass meadow restoration also occurs at a remarkably low level relative to its maximum adoption level provided by the NOAA 2014).

Box 5: Case of USA

(Time Period)

The time period selected for determining the OAy is 2000 to 2013 for the following reasons.

The NEPs began reporting annual activities in 2000 and have been required to do so since 1993 by the Government Performance Results Act. The NEP database captures activities before 2000 as well as those from 2000 forward.

The Estuary Restoration Act was signed into law in 2000. This act made restoring estuaries a national priority and represents a recognition of the growing importance of estuary habitat restoration, including tidal wetlands. Moreover, this act provided funding authorization and appropriations for restoration projects and created a federal interagency council to promote a coordinated federal approach to estuary habitat restoration, forge effective partnerships among public agencies and between the public and private sectors, provide financial and technical assistance for estuary habitat restoration projects, and develop and enhance monitoring and research capabilities. Before 2000, the lack of interagency coordination created sporadic and uncoordinated restoration actions.

Th community-based Restoration Program of NOAA was created in 1999 within its Restoration Center and began funding projects that year with only $500,000 in funding. The creation of this national center for restoration also indicates that a turning point for restoration was anticipated at that time. Since then, annual funding of NOAA for restoration has exceeded over 10 million dollars.

RAE was established in 1997 as a national umbrella organization for regional nonprofit organizations. These organizations identified estuary restoration as an emerging opportunity and established RAE to promote estuary restoration at the national level and provide financial support for new restoration activities. The creation of RAE at this time reflects the need for a national voice to catalyze increased investment in estuary restoration.

Collectively, these milestones represented a sea change in the restoration community, which has markedly increased funding and capacity for restoration activities since the year 2000. Therefore, the time period 2000 to 2013 will capture the preponderance of restoration activities.

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[171] Observed adoption of the project activity. In the project, OA (of tidal wetland restoration excluding seagrass meadows) + OA (of seagrass meadow restoration); The average annual aggregate of tidal wetlands restored from 2000 to 2013 as reported by the 28 National Estuary Programs (NEPs) and their partners in the U.S. Environmental Protection Agency (measured in acreage) and expanded to include restoration activities that occur in a U.S. estuary that is not an NEP + The percentage of seagrass meadow restoration projects compared to other estuary restoration projects funded by NOAA since 2000.

[172] Maximum adoption potential of the project activity. In the project, MAP (of tidal wetland restoration excluding seagrass meadows) + MAP (of seagrass meadow restoration): A portion of the 1991 100-year Coastal Floodplain as determined by the Federal Emergency Management Agency (FEMA) Past tidal wetland losses to shallow open water in Louisiana due to coastal erosion + Tidal wetland losses reported by the U.S. Fish and Wildlife Service (USFWS) from 1991 to 2013.

(Observed Adoption Analysis)

OA for the NEPs was determined through a systematic review of the data sets provided by the EPA for each of the NEPs. The NEP OA calculation is provided in Table 5.5. Once the NEP OA was determined, it is increased by 50% for the Activity Penetration calculation (OAy = NEP OAy × 1.5 = 97,422.17 acres × 1.5 = 146,133 acres) to ensure capture of nonNEP activities.

The NOAA database contains information regarding 2701 habitat projects that have occurred since 2000, and only 120 (4%) are seagrass meadow projects. The database includes numerous habitats (e.g., dunes, in-stream, kelp, mangrove, and oyster reef) as well as numerous activities in wetland habitats (restoration, invasive species removal, and marine debris removal). Only a portion of the 120 seagrass meadow projects would meet the applicability conditions of this methodology. Therefore, including all identified seagrass meadow restoration projects is conservative. The total acreage of estuary habitat restoration projects in the NOAA database is 49,837 acres. Seagrass meadow projects are typically conducted at a smaller scale than other habitat activities; therefore, 4% of the total acreage attributed to seagrass restoration is a conservative assumption. Hence, the OAy for seagrass restoration is 4% of 49,837 = 1,993 acres.

(Maximum Adoption Potential Analysis)

An estimate of the available area for tidal wetland restoration must be established to determine MAPy. The starting point for this estimate is the “Projected Impact of Relative Sea Level Rise on the National Flood Insurance Program” prepared by the Federal Emergency Management Agency.

Table 5.5. Calculation of OAy for the NEPs

	Tidal Wetland Acres Restored				
Estuary Program	2009	2010	2011	2012	4 Year average
Peconic Bay Estuary Program	-	-	-	-	-
Piscataqua Region Estuaries Partnership	-	-	12.00	0.05	3.01
Buzzards Bay National Estuary Program	3.74	-	-	-	0.94
Tillamook Estuaries Partnership	46.00	44.00	16.00	4.40	27.60
Mobile Bay National Estuary Program	137.00	-	6.50	2.00	36.38
Santa Monica Bay Restoration Commission	-	21.00	-	-	5.25
Tampa Bay Estuary Program	142.70	61.28	-	44.54	62.13
Delaware Center for the Inland Bays	26.00	4.00	-	-	7.50
Lower Columbia River Estuary Partnership	-	-	184.00	58.00	60.50
Indian River Lagoon National Estuary Program	1,395.75	21.26	419.00	140.30	494.08
Maryland Coastal Bays Program	64.43	1.80	104.00	189.00	89.81
Galveston Bay Estuary Program	158.00	46.81	407.06	9.00	155.22
New York–New Jersey Harbor Estuary Program	11.00	34.00	65.80	50.00	40.20
Chesapeake Bay Program	622.00	1,005.00	3,775.00	n/a	1,800.67
Puget Sound Partnership	1,277.00	140.00	505.40	101.00	505.85
Charlotte Harbor National Estuary Program	600.50	496.00	795.00	140.00	507.88
San Francisco Estuary Partnership	1,469.00	401.00	3,250.00	983.36	1,525.84
Barataria–Terrebonne Estuary Program	673.58	n/a	35.00	182.00	296.86
Sarasota Bay Estuary Program	516.00	-	30.00	5.00	137.75
Long Island Sound Study	58.65	88.00	42.56	137.70	81.73
Partnership for the Delaware Estuary	1.30	6.50	-	-	1.95
Albemarle–Pamlico National Estuary Program	1.10	4.00	84.20	0.31	22.40
Barnegat Bay Partnership	-	-	-	-	-
Narragansett Bay Estuary Program	63.00	58.00	-	-	30.25
Massachusetts Bays Program	1,442.00	133.00	54.00	21.00	412.50
Casco Bay Estuary Partnership	-	-	-	21.80	5.45
Coastal Bend Bays and Estuaries Program	1,597.00	568.00	351.00	72.00	647.00
Morro Bay National Estuary Program	n/a	n/a	n/a	n/a	n/a
One year average, 2009–2012					6,958.73
2000 to 2013 total estimate = 14 × One year average					97,422.17

FEMA calculated the area of coastal floodplain that would flood under a 100-year coastal flood event for 1990 to be 19,500 mi^2 (12,800,000 acres). A 100-year flood event is defined as a flood that statistically has a 1% chance of occurring in any given year. By definition, the coastal floodplain does not include either upland or existing wetland areas (wetland areas do not flood because they are already regularly inundated). The coastal floodplain substantially comprises former wetland areas that were drained and/or filled and converted to other land uses, such as agricultural, commercial, or residential uses. This area includes only some former tidal wetland areas that were diked or drained for agriculture and other uses (some former wetland areas are no longer in the floodplain because they are now well protected by dikes or levees and therefore are not included in this estimate, which is conservative). Only some of the coastal floodplain areas identified by FEMA are restorable or suitable for wetland creation. However, 33% of this area (4,224,000 acres) is used as a conservative (low) estimate for establishing an estimate of MAPy.

The FEMA estimate was made in 1991 and only includes land areas subject to flooding. Therefore, VCS are also included in the MAPy tidal wetland losses since 1991 and tidal wetlands that have drowned or converted to open water in coastal Louisiana. All these areas are virtually suitable for tidal wetland restoration.

Louisiana wetland losses from 1900 to 1978 are reported to be 901,200 acres (US Department of the Interior 1994). The MAPy estimate does not include Louisiana coastal wetland losses between 1978 and 1986; thus, excluding this area from the MAPy is conservative.

Tidal wetland losses from 1986 to 1997 were reported to be 8450 acres (Dahl 2000). The 1991 to 1997 portion of these losses is assumed to be 4225 acres, a prorated portion of the total.

Tidal wetland losses from 1998 to 2004 were reported to be 32,400 acres (Dahl 2006). Tidal wetland losses from 2004 to 2009 were reported to be 124,290 acres (Dahl 2011).

Data for 2010 to 2013 (four years) are unavailable. We apply the average rate of loss from the previous five-year period, that is, 2004 to 2009, which is 124,290 acres / 6 years = 20,715 acres/year.

Table 5.6. Calculation of Maximum Adoption Potential for tidal wetland restoration (non-seagrass)

Maximum Adoption Potential	Acres
33% of FEMA 1991 Floodplain Estimate	4,244,000
Louisiana Delta Wetland Losses	901,200
Tidal Wetland Losses 1991 to 1997	4,228
Tidal Wetland Losses 1998 to 2004	32,400
Tidal Wetland Losses 2004 to 2009	124,290
Tidal Wetland Losses 2010 to 2013	82,860
Total MAPy (non-seagrass)	5,388,978

Waycott et al. (2009) demonstrated that seagrass meadow habitat losses in the US were 853,845 acres between 1937 and 2006. The primary causes of the loss of seagrass meadows, which include sediment deposition, declining water quality, scarring from vessels, and disease, are typically reversible. Therefore, all areas documented as lost are restorable. Therefore, MAPy for seagrass meadow restoration is 853,845 acres.

(Conclusion)

This project provides the following conclusion based on the presented results: the (1) Activity Penetration Calculation for Tidal Wetlands (non-seagrass): 2.71%; OAy; 146,133 acres/MAPy; 5,338,978 acres and (2) Activity Penetration Calculation for Seagrass Restoration: 0.2%; OAy; 1993/MAPy; 853,845

(c) Complex Transaction

National and local governments can ensure that regulations do not unduly restrict forest management and harvest activities, especially in circumstances where managers subscribe to internationally recognized third-party ESG certification. The regulations should be well defined, enforced transparently, and applied equally to domestic and international owners.

The benefits of including BC investments must exceed the transaction costs of making these investments. Understanding BC investments is complicated. Few investment personnel will have a specific personal education in the field, which is characterized by specialized and often impenetrable terminology. General workers and consultants typically have no knowledge of the field; therefore, obtaining adequate knowledge to provide informed advice is expensive. Plan leadership and boards are justifiably uncomfortable investing in an asset class they do not fully understand; for example, anticipated BC returns are typically reported on a real, unlevered basis, while the practice in the broad private field is to report anticipated returns on a high nominal and levered basis.

Recommendations

The discussions have been summarized, and the short-term (next few years) to long-term (up to 25 years or so) roadmap and barriers to be cleared are summarized in Table 6.1 below for science, technology, economics, and policy aspects.

Table 6.1. Roadmap toward blue carbon implementation

	Short-term (1–3 years) by 2025	Mid-term (2–7 years) until 2030	Long-term (5–25 years) until 2050
Science	· Establish scientific evidence of macroalgal BC, especially in terms of the long-term storage potential. · Other wetland data tailored to each country (IPCC Tier 2) will be developed.	· Supplement to IPCC Guidelines or other international rules will be updated. · Visualization method of co-benefits of BC ecosystems, such as biodiversity, will be developed.	· Visualization method of co-benefits of BC ecosystems, such as biodiversity, will be developed (cont'd). · Environmental impact assessment (EIA) of macroalgal farming in scale.
Technology	· Low-cost sensors (hyperspectral, multispectral, Lidar, UAV, satellites, biologging, cloud computing) will be developed; · R&D of various uses of macroalgal material will be promoted; · Macroalgal farming on multiple scales will be demonstrated; · High-temperature tolerant seeds and seedlings will be developed; · Use of herbivores will be developed.		· Large-scale offshore macroalgal farming will be demonstrated or commercialized.
Economy	· Additional projects on BC Credits on domestic VCM will be developed.	· Additional projects on BC Credits on domestic and international markets (VCM and post-CDM) will be developed.	· Credit mechanisms that consider co-benefits (e.g., biodiversity credits) will be demonstrated. · Commercialization of macroalgal products will be promoted.
Policy (or Social awareness)	· IPCC AR7 scoping will reflect macroalgal BC. · Negotiations to clarify the modalities of Article 6 of the Paris Agreement will be concluded. · Macroalgae and other BC ecosystems will be incorporated into national inventories in many countries. · Laws and markets for carbon trading in each country will be developed. · Registry mechanisms to avoid double counting and overselling (use of blockchain technology) will be developed. · Remarkably ambitious NDCs reflecting BC (2025) will be submitted.	· Consistency with the international legal framework for large-scale macroalgal aquaculture will be built under (e.g., UNCLOS, CBD, and London Protocol); · Consistency with national laws will be built. · Capacity on multidisciplinary areas will be built and mobilized.	· Macroalgae will be included in IPCC wetland guidelines or other international standards and rules.

Recommendation 1: Answers to Fundamental Questions in Blue Carbon Science

Scientific understanding of the impacts of climate change, particularly sea level rise and climatic disturbance, on the distribution, carbon sequestration, and carbon stock of BC ecosystems and their geographic variability, is required. This knowledge is particularly needed as a factor affecting the permanence of BC. An understanding of the global distribution area and its changes from past to present is needed to understand the baseline for established BC ecosystems and macroalgae.

For the accurate estimation of BC, *in-situ* CO_2 gas exchange between the atmosphere and ocean and inorganic carbon production, as well as production and sequestration of organic carbon, must be understood. In addition, combining carbon and nitrogen stable isotopes (^{13}C and ^{15}N), environmental DNA, and high-resolution ocean current models is crucial to understand the origin of organic carbon. In the context of climate change mitigation, knowledge of the dynamics of other GHG gases, such as CH_4 and N_2O, within BC ecosystems, must also be increased.

Many have indicated the diversity and importance of the co-benefits of BC. These co-benefits, especially the effects of enhancing biodiversity (e.g., fish), are often more important to local residents than the carbon value. Developing a system to evaluate such co-benefits scientifically and holistically is crucial.

Momentum from the ongoing UN Sustainable Development Goals, the UN Decade of Ocean Science, and the UN Decade of Ecosystem Restoration should be used to advance the scientific foundation to be built, targeting 2030.

Recommendation 2: Create Blue Carbon Credit projects targeting various ecosystems

Policies, management (conservation, restoration, and creation), and demonstration of BC benefits (including payments) targeting BC ecosystems are still limited. Projects targeting mangroves have increased but those targeting seagrasses, salt marshes, and macroalgae are expected to develop. Projects are recommended to develop Tier 2 or higher assessments using data specific to each country and site. Such assessments in developing countries will be implemented under international cooperation and collaboration.

Scientific knowledge, observational techniques, economic incentives, policies, and governance are lacking in some areas, including that for macroalgae. However, this insufficiency will be partly resolved through effective project implementation, monitoring, and reporting across sectors. Industry, government, and academia are also expected to work together to increase the number of high-quality BC credit cases in the VCM. Moreover, trading rules in the international carbon market must be urgently clarified to be handled under Article 6 of the Paris Agreement, and the value of BC ecosystems must be fairly shared to return the value to local communities.

Recommendation 3: Development of Technologies Related to the Restoration and Creation of Blue Carbon Ecosystems

BC ecosystems and macroalgal beds have been markedly reduced in areas due to anthropogenic impacts and climate change, and investment in various technological developments will be necessary to rebuild these ecosystems by 2050 and bring them back to their pre-degradation state. Technology to mitigate land-based pollution, which is the initial cause of degradation, civil engineering methods (such as blue infrastructure) to restore the lost three-dimensionality or rugosity, and seedling production of macroalgae and seagrass species that are adapted to changing environments while considering genetic diversity, will be necessary. In addition, the development of inexpensive sensors, data sharing on the cloud, and the development of automatic image identification technology using machine learning are required to monitor the outcomes of restoration and creation.

Recommendation 4: Large-scale macroalgal aquaculture projects

Large-scale seaweed farming is expected to be developed not only as a climate change mitigation measure but also in combination with fish farming and industrial use of the products. Along with R&D by research institutions, medium- to large-scale pilot projects in coastal to offshore areas in collaboration with private sector are expected. The transport of DOC and other forms of carbon to other sinks, such as the deep sea, the development of storage mechanisms and industrial utilization technologies for the products, and the coordination of ocean utilization with other industries, such as fishing and shipping (i.e., marine spatial planning, MPA), can be promoted through these projects. Developing various monitoring technologies would also be possible.

Recommendation 5: Establish international rules related to blue carbon

The IPCC wetland guidelines or similar international standards should be updated to include macroalgal BC and other BC related findings. Furthermore, considering large-scale macroalgal farming, which has remarkable potential for carbon sequestration and storage, clarifying how impacts on coastal and deep-sea ecosystems will be handled under the UNCLOS, CBD, and London Convention based on scientific findings, such as environmental impact assessments (EIA), is necessary.

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