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Final report

Potential of Blue Carbon for global climate change mitigation

by:
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Abstract: Potential of Blue Carbon for global climate change mitigation

Achieving climate neutrality primarily requires reducing greenhouse gas (GHG) emissions. However, in addition it requires measures to absorb CO_2 from the atmosphere and storing carbon in the long term to balance unavoidable residual emissions. A key measure available for countries to achieve this is to maintain and enlarge natural carbon sinks. In this respect, measures to protect and restore coastal ecosystems such as mangrove forests, seagrass meadows and tidal marshes are attracting growing attention as they are important natural marine carbon sinks and store a lot of carbon per unit area in their sediments. Therefore, they are often referred to as "Blue Carbon ecosystems" (BCE). Although the term "Blue Carbon" (BC) is not yet uniformly defined, it is becoming more and more prominent in international climate policy and is being discussed in the context of the (voluntary) carbon market, among other things. This study provides an overview of the use of the term BC in scientific literature and international reports in order to derive a working definition of BC and criteria for identifying BC measures (Chapter 2). In the following chapters we summarize and critically assess positive contributions and limits of the global climate mitigation potential of BCE (Chapter 3) and present a summary of the discussions and the future role of BC in international climate policy (Chapter 4). In Chapter 5, the visibility of BC emissions and removals in national GHG inventories is summarized. Based on these analyses, Chapter 6 provides conclusions and recommendations for the future use of the term BC and summarizes its potential contribution to global climate mitigation.

Kurzbeschreibung: Das Potenzial von „Blue Carbon" für den globalen Klimaschutz

Das Erreichen der Klimaneutralität erfordert in erster Linie eine Verringerung der Treibhausgasemissionen (THG). Darüber hinaus sind aber auch Maßnahmen zur CO_2-Aufnahme aus der Atmosphäre und zur langfristigen Speicherung des Kohlenstoffs erforderlich, um die unvermeidbaren Restemissionen auszugleichen. Eine wichtige Maßnahme, die Staaten zur Verfügung steht, um dies zu erreichen, ist der Erhalt und die Ausweitung natürlicher Kohlenstoffsenken. In diesem Zusammenhang finden Maßnahmen zum Schutz und zur Wiederherstellung von Küstenökosystemen wie Mangrovenwäldern, Seegraswiesen und Salzmarschen zunehmend Beachtung, da sie wichtige natürliche marine Kohlenstoffsenken sind und in ihren Sedimenten viel Kohlenstoff pro Flächeneinheit speichern. Daher werden sie oft als "Blue Carbon Ökosysteme" (BCE) bezeichnet. Obwohl der Begriff "Blue Carbon" (BC) noch nicht einheitlich definiert ist, gewinnt er in der internationalen Klimapolitik immer mehr an Bedeutung und wird unter anderem im Zusammenhang mit dem (freiwilligen) Kohlenstoffmarkt diskutiert. Die vorliegende Studie gibt einen Überblick über die Verwendung des Begriffs BC in der wissenschaftlichen Literatur und in internationalen Berichten, um daraus eine Arbeitsdefinition von BC und Kriterien zur Identifizierung von BC-Maßnahmen abzuleiten (Kapitel 2). In den folgenden Kapiteln werden die positiven Beiträge und die Grenzen des globalen Klimaschutzpotenzials von BCE zusammengefasst und kritisch bewertet (Kapitel 3) sowie eine Zusammenfassung der Diskussionen und der zukünftigen Rolle von BC in der internationalen Klimapolitik präsentiert (Kapitel 4). In Kapitel 5 werden die Sichtbarkeit von BC-Emissionen und -Entnahmen in nationalen Treibhausgasinventaren zusammengefasst. Auf der Grundlage dieser Analysen werden in Kapitel 6 Schlussfolgerungen und Empfehlungen für die künftige Verwendung des Begriffs BC gegeben und sein potenzieller Beitrag zum globalen Klimaschutz zusammengefasst.

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BC	Blue Carbon
BCE	Blue Carbon ecosystem
CAR	Carbon accumulation rates
CBD	Convention on Biological Diversity
CO_2	Carbon dioxide
COP	Conference of the Parties
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
DIC	Dissolved inorganic carbon
DOC	Dissolved organic carbon
EEZ	Exclusive economic zone
EU	European Union
EU-ETS	EU Emissions Trading System
GHG	Greenhouse gas
IPCC	Intergovernmental Panel on Climate Change
ITMOs	internationally transferred mitigation outcomes
UNCLOS	United Nations Convention on the Law of the Sea
MPA	Marine protected area
NbS	Nature-based solutions
NDC	Nationally Determined Contributions (in Paris Agreement)
NET	Negative emission technologies
NIR	National GHG inventory reports
N_2O	Nitrous oxide (laughing gas)
OM	Organic material
PIC	Particulate inorganic carbon
POC	Particulate organic carbon
RBP	Results-based payments
UNEA	United Nations Environment Assembly
UNFCCC	United Nations Framework Convention on Climate Change

1 Introduction

The Paris Agreement set the goal to limit the increase in global average temperature to below 2°C and to pursue efforts to keep this increase to a maximum of 1.5°C. To achieve this goal, increased efforts in defining and implementing effective measures to avoid and reduce greenhouse gas (GHG) emissions are required. However, the measures and targets set by countries to date in their Nationally Determined Contributions (NDCs) are not sufficient to comply with the 1.5°C temperature limit and to achieve climate neutrality[1] in the long term (UNFCCC 2021). In 2020, the European Union (EU) passed the European Climate Law (EU 2021), which set the goal of achieving climate neutrality by 2050. Specifically, this means that GHG emissions across all EU Member States should be net zero by 2050.

Achieving climate neutrality primarily requires the reduction of GHG emissions. This entails taking measures in all major economic sectors, addressing our overconsumption of resources and protecting ecosystems from degradation and the release of stored carbon. However, we will not realistically be able to eliminate all emissions, and a certain amount of unavoidable residual emissions will remain, e.g. from agriculture. Achieving climate neutrality will additionally require measures to absorb CO_2 from the atmosphere and the storage of carbon in the long term. The key measure available for countries to achieve their climate neutrality targets is to maintain and enlarge natural carbon sinks to balance the unavoidable residual emissions.[2] Natural carbon sinks refer to ecosystems, on land and in the ocean, which absorb CO_2 from the atmosphere over a period of time, e.g. via photosynthesis, and then store the carbon in chemical compounds (IPCC 2013). Globally, ocean and terrestrial carbon sinks absorbed about 50 % of anthropogenic CO_2 emissions annually from 2012 to 2021 (about 6 Gt C/year) (Friedlingstein et al. 2022).

Within the ocean, carbon is absorbed, stored and released in numerous different processes. There is both organic and inorganic carbon in the ocean. About 95 % of the carbon that circulates in it (37,000 Gt C) is dissolved inorganic carbon (DIC), which is primarily dissolved CO_2, bicarbonate, carbonate and carbonic acid (Friedlingstein et al. 2022). Only a small proportion of carbon is stored as organic carbon (700 Gt C), mainly as dissolved organic carbon (DOC), which are very small organic molecules such as proteins, carbohydrates, or lipids. Even less carbon (3 Gt C) is stored in the biomass of marine organisms and their decaying matter (dead biomass, particulate organic carbon (POC)) (Hansell et al. 2009; Friedlingstein et al. 2022). Another substantial amount of carbon is stored in ocean sediments (1750 Gt C, Friedlingstein et al. 2022), which can be organic and inorganic carbon (including particulate inorganic carbon (PIC)).

The main focus of this study is on coastal ecosystems, such as mangrove forests, seagrass meadows and tidal or salt marshes. Public interest in coastal ecosystems has significantly increased in recent years due to their high relevance as natural carbon sinks. These are often referred to, including in this report, as “Blue Carbon ecosystems (BCE)” (IUCN 2021; IPCC 2019d). Likewise, the term “Blue Carbon” (BC) is increasingly being used, albeit without a uniform definition, in the context of carbon storage in marine ecosystems (Lovelock and Duarte 2019). BCEs continuously exchange carbon (CO_2, DIC, DOC, PIC, POC) with the atmosphere, the hinterland (mainly through rivers) and the coastal ocean (Figure 1). But it is their substantial capacity to sequester and store carbon in the biomass and sediments that makes them one of the most efficient natural carbon sinks on earth. BCEs are of great importance because of their high

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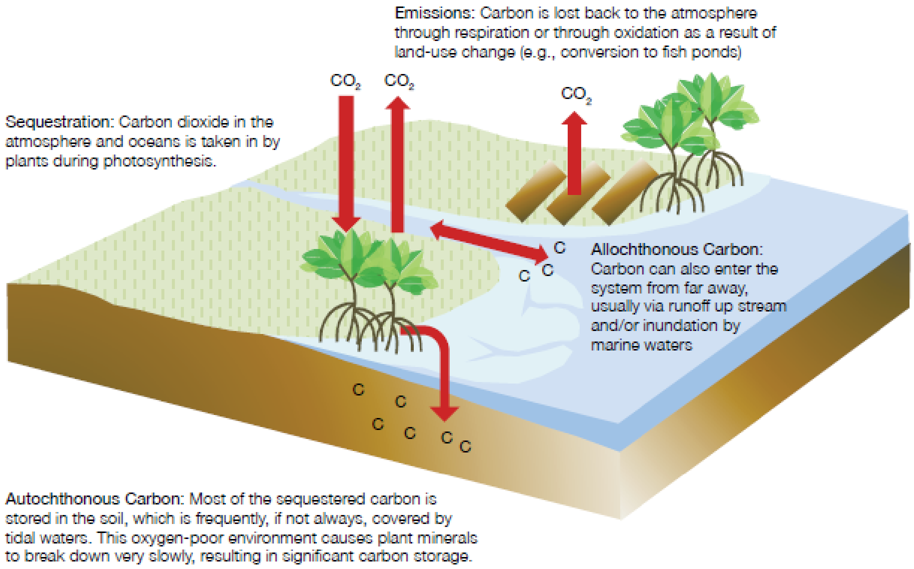
[1] Climate neutrality means that net zero greenhouse gas emissions are achieved by balancing the emissions and their removals so they are equal.

[2] Technical solutions to remove CO_2 from the atmosphere, such as direct air capture are being developed as well, but are not the focus of this report.

carbon storage per unit area in their sediments. In the top metre of the sediment, carbon storage of mangroves has been estimated at 280 t C/ha, 250 t C/ha for tidal marshes, and 140 t C/ha for seagrass meadows (Pendleton et al. 2012).

Figure 1: Mechanisms by which carbon moves out and into Blue Carbon ecosystems.



Emissions: Carbon is lost back to the atmosphere through respiration or through oxidation as a result of land-use change (e.g., conversion to fish ponds)

Sequestration: Carbon dioxide in the atmosphere and oceans is taken in by plants during photosynthesis.

Allochthonous Carbon: Carbon can also enter the system from far away, usually via runoff up stream and/or inundation by marine waters

Autochthonous Carbon: Most of the sequestered carbon is stored in the soil, which is frequently, if not always, covered by tidal waters. This oxygen-poor environment causes plant minerals to break down very slowly, resulting in significant carbon storage.

Source: Illustration by Howard (2014).

In addition to carbon sequestration, coastal ecosystems are important habitats for many different species and provide numerous ecosystem services such as fish nurseries, nutrient cycling and protection against flooding (Li et al. 2018; Mitsch et al. 2015). However, an estimated 50 % of coastal ecosystems have been destroyed or degraded since the 20th century, especially during the past 50 years (Li et al. 2018). The main causes are conversion to aquaculture and agricultural use. Coastal ecosystems are also destroyed by trawling for fish and the development of coastal infrastructure. Increased nutrient inputs from agriculture and negative impacts on hydrodynamics also contribute to the loss and degradation of coastal ecosystems (Macreadie et al. 2017; Pendleton et al. 2012). Especially, the disturbance and destruction of the carbon rich marine sediments can cause substantial amounts of emissions. Approx. 2.4 % of the ocean is classified as highly protected marine protected areas (MPA) where commercial fishery is prohibited and other extractive activities are minimized. Atwood et al. (2020) conclude that at most 2 % (48 Gt C) of the global marine carbon stocks are protected from harmful interventions that lead them to emit the stored carbon.

This study presents an overview of the global climate mitigation potential of blue carbon and critically discusses the challenges of the monitoring and reporting of carbon fluxes in BCE. Firstly, the use of the term BC in scientific literature and international reports is analysed in order to derive a working definition of Blue Carbon and criteria for identifying Blue Carbon measures (Chapter 2). This working definition and the criteria for related measures inform the scope of the subsequent chapters. Chapter 3 critically assesses positive contributions and limits of the global climate mitigation potential of BCE. Chapter 4 provides an overview of the discussions and the future role of Blue Carbon in the international climate policy. In Chapter 5, the visibility of Blue Carbon emissions and removals in GHG inventories is summarized. Based on these analyses, Chapter 6 provides conclusions and recommendations for the future use of the term BC and critically summarises its potential contribution to global climate mitigation.

This study is carried out as part of the project entitled “Climate mitigation measures in coastal regions and waters - Accounting, crediting and financing of Blue Carbon measures” (2022-2024) and is commissioned and financed by the German Environment Agency (Umweltbundesamt). It serves as the scientific basis for subsequent studies in the project which will analyse and discuss the role of market-based approaches in financing the protection and restoration of BCE.

To assess the relevance of BC and BCE for climate mitigation, it is important to clarify the respective terminology.

Important terminology

Allochthonous carbon

Carbon that was originally sequestered in a location other than where it is ultimately stored. In coastal ecosystems, for instance, allochthonous carbon may have been sequestered by terrestrial plants in their biomass and then transported to coastal areas by rivers.

Autochthonous carbon

Carbon that is locally sequestered by plants in coastal ecosystems and subsequently stored in both living and dead biomass. A significant proportion of this biomass goes into the sediment, contributing to long-term carbon storage.

Carbon pool

Carbon pools refer to components of an ecosystem such as living or dead biomass, litter and soil that can store carbon. Carbon pools are dynamic: their carbon storage can increase by, for example, continuous carbon sequestration or decrease by, for example, the release of CO_2 due to decomposition of dead biomass. A carbon pool can therefore be qualified as a carbon sink or an emission source depending on their net carbon fluxes.

Carbon sequestration

Carbon sequestration describes the process of CO_2 (or other forms of carbon) removal from the atmosphere or water, e.g. via photosynthesis and the storage of carbon in chemical compounds like the biomass of seagrass or the wood of a mangrove tree on climatically significant time scales (decade to century) (IPCC 2019c). To quantify carbon sequestration, it must be related to a specific time period. If a sequestration rate is qualified as “net,” it does account for the carbon losses of the relevant carbon pool.

Carbon sink

Carbon sinks temporarily or permanently remove more CO_2 from the atmosphere or water than they release. Carbon sinks store carbon in pools. A seagrass meadow is a carbon sink, if all its carbon pools (living biomass and sediment) sequester more carbon than they release. As a carbon sink a seagrass meadow can built up a carbon stock.

Carbon stock

Carbon stock describes the total amount of organic carbon stored in an ecosystem (all relevant carbon pools) or in a carbon pool at a certain moment in time or as a mean value over a timespan. For example, the total carbon stock of a seagrass meadow would consist of the carbon stored in the seagrass biomass and in the seagrass sediment (soil). Carbon stock describe the “vulnerability potential” – the amount of carbon that could be released if the ecosystem is destroyed.

2 Definition and criteria of Blue Carbon and Blue Carbon measures

There is currently no scientifically or politically agreed definition of BC. The term was originally coined in a rapid assessment report by the United Nations Environment Programme, which stressed the important role of oceans in binding carbon and described the atmospheric carbon that is captured by marine living organisms and stored in sediments of vegetated coastal ecosystems like mangrove forests, tidal marshes and seagrass meadows (Nelleman et al. 2009). The term was used to distinguish between carbon sequestered by marine plants ("Blue Carbon") and by land plants ("green carbon"), both removing "brown carbon" from the atmosphere, which refers to emissions stemming from the burning of fossil fuels. The term "Blue Carbon" has appeared in more than 1.7 million scientific publications since 2009[3] (e.g. Mcleod et al. 2011; Lovelock und Duarte 2019; Macreadie et al. 2019; Pendleton et al. 2012; IUCN 2021; Herr and Landis 2016) and appears in publications of the Intergovernmental Panel on Climate Change (IPCC 2019d) as well as those of non-governmental organisations (e.g. WWF 2012). As with Nelleman et al. (2009), the term is predominantly used in connection with carbon sequestration in coastal ecosystems of mangroves, seagrass meadows and tidal marshes.

In recent years, there has been increasing interest in the use of BC as an umbrella term for ocean-related climate mitigation measures (IPCC 2019b). It is especially used in the context of coastal ecosystems and their potential to achieve national climate goals (Herr and Landis 2016; Taraska 2018). These ecosystems are often referred to as "BCEs" or "coastal Blue Carbon" (Macreadie et al. 2019; IUCN 2021; Mcleod et al. 2011; Green et al. 2021; Coelho and Tavonvunchai 2022; IPBC 2021; Macreadie et al. 2019). Another context in which the term BC is increasingly used is the generation of carbon credits for the voluntary carbon market (e.g. Blue Carbon Buyers Alliance 2021).

Therefore, it is necessary to develop a definition of BC and criteria that ensure that activities promoted with the term BC make a positive contribution to climate mitigation and provide both environmental and social co-benefits (Lovelock and Duarte 2019). The IUCN (2021) definition of BC differentiates between coastal and oceanic Blue Carbon. The latter describes the carbon stored in deep ocean waters and sediments by marine organisms like phytoplankton and chemical processes. Like other BC definitions (Mcleod et al. 2011; Green et al. 2021), they mention relevant marine carbon pools (sediment, biomass) which indicate important carbon fluxes.

Against this background, the following working definition of BC, which takes into account the marine origin of the carbon and important pools, is derived for this report:

Blue Carbon refers to the carbon captured by marine organisms and stored in living and dead biomass as well as in organic compounds in the sediment.

The IPCC (2019b) BC definition also includes all biologically-driven carbon fluxes and storage in marine systems, but additionally adds the condition that they should be "amenable to management". This is a very important aspect that shows that measures related to BC can have an impact on carbon fluxes and storage in marine ecosystems. Such measures that aim to manage BC fluxes (BC measure) should have a positive effect on climate mitigation and meet the following criteria.

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[3] Google Scholar search using "Blue Carbon" for the period 2009 to 2023 (search was made on the 28th July 2023).

Criterion 1): The BC measures reduce anthropogenically-caused emissions and positively affect net carbon capture and storage in a marine ecosystem in a time frame of at least several decades. The duration of carbon storage should be significant for climate protection and therefore last for at least several decades.

Carbon storage in plant biomass lasts for years to decades (short-term) whereas carbon in marine sediments can remain stored for millennia (long-term) (Mcleod et al. 2011). Especially measures to protect and restore mangrove forests, seagrass meadows and tidal marshes (BCEs) have been proven to reduce GHG emissions, positively affect carbon removals and protect sediment carbon stocks (O'Connor et al. 2020; Lovelock and Duarte 2019). For example, a drained and diked salt marsh used as cropland was restored by reintroducing its natural tidal regime in the USA. After four years, the carbon accumulation rate[4] (CAR) was twice as high as in comparable natural tidal marshes. This is because the restored salt marsh was 0.5 to 1m below the elevation of the adjacent natural marsh. Hence, it can continuously accumulate carbon in the sediment until its former sediment elevation is reached. This leads to higher rates of carbon accumulation compared to natural tidal marshes (Poppe and Rybczyk 2021). In contrast, restoration or protection of coral reefs probably do not contribute to additional carbon sequestration, although corals participate in photosynthesis via a symbiotic alga (Howard et al. 2017). Due to the coral's calcification process, they are currently considered to have net CO_2 emissions (Frankignoulle et al. 1995). That is why within this study preservation, restauration and sustainable management of coral reefs are not considered BC measures.

Criterion 2): To meet criterion 1 of BC measures, they must be accompanied by an appropriate monitoring of carbon fluxes. BC measures must be accompanied by a continuous monitoring to demonstrate (I) significant carbon uptake and (II) carbon storage in the habitat as well as (III) the influence of human activities on carbon sequestration.

Tracking carbon fluxes in aquatic environments is a challenge compared to terrestrial ecosystems. DOC and DIC travel far in liquid environments and the location of carbon fixation is not necessarily the location of carbon storage. For example, macroalgae which can form ecosystems like kelp forests are the most productive marine organisms in terms of net primary production. But a significant proportion of the carbon stored in their biomass is drifted to other ecosystems (Krause-Jensen et al. 2018). Macroalgae do not form rhizomes or grow on sediments like seagrass where organic carbon could be stored. However, their contribution to sediment carbon stocks in mangrove forests, seagrass meadows and tidal marshes can be significant (Krause-Jensen et al. 2018). For example, up to 50 % of the carbon stored in seagrass sediments originates from macroalgae and other primary producers (Stevenson et al. 2022; Kennedy et al. 2010) (see also chapter 3). Hence, macroalgae can be considered as significant donors for BC in coastal ecosystems. Additionally, recent studies suggest that macroalgae also contribute to carbon stored in deep sea sediments, where it can remain for long time periods, e.g. over 1,000 years (Ortega et al. 2019; Krause-Jensen and Duarte 2016). The question of whether measures to enhance macroalgae ecosystem should be included in BC schemes is still under debate as the carbon fixed in the biomass is not stored in the habitat of origin. Additionally, little is known about what really happens with the carbon fixed by macroalgae (IUCN 2021; Lovelock and Duarte 2019; Krause-Jensen et al. 2018; Ortega et al. 2019). Macroalgal ecosystems are a good example of the need for all relevant carbon fluxes to be closely monitored in order to detect the impact of human intervention on carbon sequestration. To effectively enhance the long-term storage of carbon absorbed by macroalgae, it is important to implement measures beyond their natural habitats, including the safeguarding of deep-sea sediments as well as coastal ecosystems

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[4] The carbon accumulation rate describes the amount of carbon that is newly stored, e.g. in the sediment of the salt marsh, during a defined time period.

(Krause-Jensen et al. 2018). Since the long-term storage of carbon taken up by macroalgae does not take place in their habitat but depends on other ecosystems, the conservation, restoration and sustainable management of macroalgae are not considered BC measures in this study.

To ensure that BC measures also deliver additional benefits for biodiversity and society, **criterion 3)** states that BC measures must be aligned with the concept of nature-based solutions (NbS).

Nature-based solutions for climate mitigation have gained increasing interest under the United Nations Framework Convention on Climate Change (UNFCCC) process (Reise et al. 2022) and were even included in the decision text of the 27th Conference of the Parties (COP27) in 2022 (UNFCCC 2022a). In addition, the Fifth Session of the United Nations Environment Assembly (UNEA-5) emphasized the important role that NbS play in the response to climate change and adopted the following definition: nature-based solutions are "*actions to protect, conserve, restore, sustainably use and manage natural or modified terrestrial, freshwater, coastal and marine ecosystems, which address social, economic and environmental challenges effectively and adaptively, while simultaneously providing human well-being, ecosystem services and resilience and biodiversity benefits*" (UNEP 2022). The agreed NbS definition of the UNEA-5 is identical in content to the one reached in the UBA review study on NbS for climate mitigation by Reise et al. (2022). The study also formulated six characteristics of NbS (Table 1) which BC measures must meet.

Protecting and restoring coastal ecosystems foster the supply of many other ecosystem services. They host high biodiversity and support the livelihoods of millions of people by providing food resources. Approx. 90 % of marine fisheries depend on coastal wetlands, e.g. as nursery habitats (Hinrichsen 1998). Moreover, coastal ecosystems provide protection against flooding events, sea-level rise and coastal erosion (Nelleman et al. 2009; Barbier et al. 2011; Himes-Cornell et al. 2018; Mitsch et al. 2015). They additionally deliver important cultural ecosystem services (Rodrigues et al. 2017). Hence, the careful management of coastal ecosystems is of high importance and measures aiming to enhance climate mitigation in BCE (BC measures) require a thorough ecological and social assessment.

Since measures with regard to coral reefs do not contribute to climate action and carbon absorbed by macro algae is not primarily stored within its habitat, measures regarding both ecosystems cannot be considered NbS for climate action. Nevertheless, protection, restauration and sustainable management of these ecosystems address other societal challenges. Coastal reefs are among the most biodiverse marine ecosystems and their protection contributes to the preservation of marine biodiversity. Also, coral reefs serve as important coastal protection from storms and erosion (Howard et al. 2017) and therefore can promote nearby seagrass ecosystems (Watanabe and Nakamura 2019). Thus, whilst interventions with regard to coral reefs and macro algae are not considered BC measures in this study, they should be promoted as coastal nature preservation. The assessment of measures in coastal ecosystems is summarized in Table 1:

Table 1: **Overview of whether restoration, protection and sustainable management of coastal ecosystems can meet the criteria for Blue Carbon measures.**

		Restoration, protection and sustainable management in coastal ecosystems				
Criteria for Blue Carbon measures		**Mangroves**	**Seagrass meadow**	**Tidal marshes**	**Macroalgae, e.g. kelp**	**Coral reef**
Climate mitigation effect	Enhancement of CO_2 removal with measures is possible	Yes	Yes	Yes	Yes	No
	Long-term carbon storage in sediments	Yes	Yes	Yes	Uncertain	No
Characteristics of nature-based solutions according to Reise et al. 2022	Alignment with natural ecosystem processes	Yes	Yes	Yes	Yes	Yes
	Benefit biodiversity	Yes	Yes	Yes	Yes	Yes
	Support natural adaptability of the ecosystem	Yes	Yes	Yes	Yes	Yes
	Consider local economic and social conditions and use native species	Yes	Yes	Yes	Yes	Yes
	Provides numerous (co-)benefits for people and the environment	Yes	Yes	Yes	Yes	Yes
	Address societal challenges and enhance human well-being	Yes	Yes	Yes	Yes, but not climate mitigation (duration of carbon storage is unclear)	Yes, but not climate mitigation (calcification process causes CO_2 emissions)

Data sources: Howard et al. 2017; Lovelock and Duarte 2019; Macreadie et al. 2021.

In recent review reports, BC measures are often summarized under ocean-based mitigation or marine negative emission technologies (NET) (National Academies of Sciences, Engineering, and Medicine 2021; Keller 2005; Keller et al. 2022; Lebling et al. 2022) or marine carbon dioxide removal (mCDR). Other NET mentioned in the context of oceans are ocean alkalinization and fertilization as well as artificial ocean down- and upwelling. They aim to technically support biological (algae photosynthesis via fertilization) or chemical (alkalinization) processes to enhance CO_2 absorption from the atmosphere. In 2008, the parties of the Convention on Biological Diversity (CBD) recommended that large scale ocean fertilization activities are to be avoided until there is a solid scientific basis on associated risks and effective regulatory instruments (Decision IX/16). The decision was confirmed and extended to geo-engineering activities in general in 2010 (Decision X/33). Geo-engineering activities specifically target components that control the climate system on a global scale, like carbon dioxide removal, but do not address the cause of climate change directly (Ginzky et al. 2011). They do not qualify as NbS and are therefore not considered BC measures per this study.

In contrast, restoring and protecting coastal ecosystems counteract the continuous destruction of carbon-rich ecosystems (IPCC 2019d). Protection and restoration measures have already been implemented for some time and accordingly there is research and experience on how they can impact the coastal environment and society (Lebling et al. 2022; Lovelock and Duarte 2019). For these reasons and especially because mangroves, seagrass meadows and tidal marshes significantly contribute to carbon sequestration in marine sediments, they are the focus of this report, and we refer to them as BCEs.

3 Short assessment of the global climate mitigation potential of Blue Carbon ecosystems

Research activities on the potential of marine ecosystems for climate mitigation increased as a result of heightened scientific and societal awareness of the issue. Growing knowledge and data on BCE point in particular to the fact that they are among the most efficient natural carbon sinks on earth and that human interventions can help to enhance this sink (e.g. Lovelock and Duarte 2019). The rapidly grown data base on quantification of BC and entailing efforts to develop a carbon market and respective instruments culminated in the calculation of the "Blue Carbon wealth of nations" (Bertram et al. 2021). However, despite improvements in quantifying BC, there are still large uncertainties associated with both the spatial and temporal dimension of BC quantification and the climatic cost-effectiveness of BC measures (Gattuso et al. 2021; Williamson and Gattuso 2022).

The development of an internationally standardized protocol to quantify BC (Howard et al. 2014) contributed strongly to the production of relevant data sets. Although BC quantification is generally expertise- and resource-demanding, the standardized and simplified procedures in the Blue Carbon Manual are a first step towards facilitating the comparability of scientific data on the one hand and reducing cost and effort on the other hand. Triggered by the seminal paper of Donato et al. (2011) on mangrove carbon stocks, numerous studies on carbon stocks of vegetation and soils/sediments have been conducted in mangrove forests, tidal marshes and seagrass meadows all over the globe in the past decade and the current one. Accordingly, our understanding of carbon storage in BCEs is currently based mainly on stock calculations and scenarios of CO_2 release upon loss of BCEs and related organic matter decomposition, and thus how much BCE conservation can contribute to achieving emission reduction targets by avoiding loss and, hence, the release of CO_2 (Jennerjahn 2021)**.** However, stocks do not provide information on actual carbon sequestration, i.e. active CO_2 removal from the atmosphere. In contrast, age dating of sediment cores by measuring radioactive isotopes allows for the determination of sedimentation and carbon accumulation rates (CAR), in ideal cases it even provides a chronology of CAR variation over time. The disadvantages of this method are the high costs and the fact that physical mixing in the intertidal and/or an insufficient inventory of radioactive isotopes do not always allow for robust determinations (Arias-Ortiz et al. 2018). Consequently, the global CAR data set is much smaller compared to stock data sets (Jennerjahn 2021).

Carbon stocks and carbon accumulation rates describe different aspects of carbon sequestration in BCEs, and therefore serve different purposes. A stock provides an assessment of "how much carbon is there" that can be emitted as CO_2 upon BCE degradation and related organic material (OM) oxidation. It is therefore rather a quantitative measure of the "vulnerability potential" of BCE to climate and environmental change. With respect to the present and future role of BCE as a natural carbon sink, it is important to quantify their active carbon sequestration, i.e. actual removal and long-term storage of anthropogenic CO_2, the largest portion of which is the carbon accumulation in sediments. It provides a measure of the climate "mitigation potential" of BCEs (Jennerjahn 2021). Recent synthesis efforts (Jennerjahn 2021; Ouyang and Lee 2014; Sanderman et al. 2018; Macreadie et al. 2021) summarize the current status of carbon stocks and accumulation rates shown in **Fehler! Verweisquelle konnte nicht gefunden werden.** and identify the knowledge and data gaps.

Table 2: Average area, carbon stocks and carbon accumulation rates (CAR) of global Blue Carbon ecosystems.

	Area (10^3 km^2)	Stock (Mg C/ha)	Global stock (Tg C)	CAR (g C/m^2/yr)	Global CAR (Tg C/yr)
Mangrove forests	138[a]-147[b]	361[c] (1324)	3,130[d,e]-12,300[f,g] (11,477-45,100)	233[h] (854)	23[h] (84)
Tidal marshes	55[i]-91[k]	317[l] (11629)	862-1,350[m] (3,161-4,950)	245[n] (898)	14[n] (51)
Seagrass meadows	160[o]-316[p]	140[q] (513)	3,760[m]-8,400[q] (13,787-30,800)	138[r] (506)	22[r] (81)
Total	**353-554**	**/**	**7,752-22,050 (28,424-80,850)**	**/**	**59 (216)**

Data sources: [a]Giri et al. 2011; [b]Bunting et al. 2022; [c]Sanderman et al. 2018; [d]Hamilton and Friess 2018; [e]Ouyang and Lee 2020; [f]Simard et al. 2019; [g]Kauffman et al. 2020; [h]Jennerjahn 2021; [i]Mcowen et al. 2017; [k]Murray et al. 2022; [l]Alongi 2020; [m]Macreadie et al. 2021; [n]Ouyang and Lee 2014; [o]McKenzie et al. 2020; [p]UNEP-WCMC 2021; [q]Fourqurean et al. 2012; [r]Mcleod et al. 2011.

Note: Numbers in brackets denote mass of CO_2.

The quantification of BC on a global scale and in its temporal and spatial dimensions is hampered by scientific and technical constraints, as described below:

1. The variability of carbon stocks and CAR within one type of BCE can be very high, as demonstrated in the case of mangroves in the Indonesian Segara Anakan Lagoon (Kusumaningtyas et al. 2019). The main reasons for this are the local variability of environmental factors such as hydrodynamics and sediment dynamics, nutrient input, and autochthonous (resident) vs. allochthonous (non-resident) carbon input. To obtain robust data, therefore, a representative set of locally collected samples and data is needed, which often does not exist due to a lack of knowledge of the BCE and a lack of resources.
2. In most cases, the source composition of the deposited carbon is not known. In BCEs, some of the stored carbon was originally absorbed by plants in other ecosystems. Hence, it is called allochthonous carbon from, for example, freshwater ecosystems, and the biomass or the dissolved organic carbon was transferred via rivers into the coastal area. Moreover, this carbon fixation in other ecosystems may have happened a long time ago (Williamson and Gattuso 2022). The fraction of allochthonous carbon can be high – up to 70-90%, for example – and vary widely even within one BCE (Kusumaningtyas et al. 2019; Jennerjahn 2020; Ricart et al. 2020). Restoration measures in BCEs that mostly store allochthonous carbon may not result in additional carbon sequestration if the "carbon donor ecosystems" are simultaneously destroyed or degraded. The loss in carbon stocks of "carbon donor ecosystems" needs to be considered when BCE climate impacts are accounted towards a climate target.
3. Carbon stocks and accumulation rates provide a basis for sequestration rates as calculated for GHG inventory reporting (see also section 5), but the loss through export and decomposition in the form of GHG release and dissolved carbon fluxes can be large

and is insufficiently covered by existing data sets in terms of time and space (Al-Haj and Fulweiler 2020; Rosentreter et al. 2021b; Santos et al. 2021).

4. Methane and nitrous oxide emissions from BCEs are not yet fully understood and need further research. As a consequence, it is unclear how large the effect of methane and nitrous oxide emissions in BCEs is. Some studies suggest that the combined CH_4 and N_2O emissions might be able to offset the CO_2 mitigation impact of BCEs (Rosentreter et al. 2021a; Al-Haj and Fulweiler 2020). However, a recent meta study indicates that the negative effect of methane emissions is much smaller than previously thought (Cotovicz et al. 2024).

Besides these physical uncertainties, there are other obstacles. Those are related to the social implications, governance and financing of BC measures, which do not yet allow the full potential of BC in climate change mitigation to be realised (Macreadie et al. 2022). In sum, BC contributes 59 Tg C/yr or 216 Tg CO_2/yr (Table 2) to climate mitigation, which amounts to <1% of annual global emissions (10,800 Tg C/yr or 39,600 Tg CO_2/yr, Friedlingstein et al. 2022). The estimated potential restoration of BCEs with an area of 18-32 million ha could result in an additional drawdown of 229 Tg C/yr or 841 Tg CO_2/yr, collectively amounting to approx. 3 % of annual global emissions (Macreadie et al. 2021). However, the major portion of this results from actions to counteract the continued degradation of BCEs and thereby protect existing carbon stocks (avoided CO_2 emissions). Hence, the mitigation potential due to additional BC sequestration resulting from management interventions is probably much lower. The contribution of Blue Carbon for climate mitigation is estimated differently by various studies. According to Williamson and Gattuso (2022), it ranges from 0.02% to 6.6% of global annual emissions, which reflects the large uncertainties still present in the quantification of GHG fluxes in BCEs.

Despite the growing awareness of the multitude of ecosystem services provided by BCEs and increasing conservation and restoration efforts, annual area loss rates are still in the order of 1-2 % for tidal marshes (Duarte et al. 2008) and seagrass meadows (Waycott et al. 2009). The magnitude of such loss is smaller for mangrove forests (Friess et al. 2019). While BCEs contribute to climate change mitigation, they are themselves vulnerable to the impacts of climate change, particularly to warming, marine heat waves, sea level rise and an increase in frequency and intensity of extreme weather events (Cooley et al. 2022). However, human activities pose an even greater threat to the existence and wellbeing of coastal BCEs. Major threats are deforestation and conversion to other uses like aquaculture or cropland, pollution, eutrophication, siltation, overexploitation (e.g. timber, fishing), changes in hydrology and subsidence due to extraction of water, oil and gas (Duarte et al. 2008; Kristensen et al. 2017). These threats not only have negative impacts on the resilience and biodiversity of BCEs but can also cause significant emissions. For instance, in China, the emissions of N_2O from aquaculture activities in coastal wetlands were found to exceed the carbon sequestration potential of managed mangroves by a factor of two (Zhao et al. 2022). In conclusion, the effects of ongoing global warming as well as destructive human interference negatively affect the extent and performance of BCEs and hence lower their climate change mitigation potential.

4 The role of Blue Carbon in international climate policy

The definition of the climate system in the United Nations Convention on Climate Change (UNFCCC) encompasses the hydrosphere and therefore oceans (Article 1.3). The sustainable management, conservation and enhancement of oceans, coastal and marine ecosystems are part of the commitments included under Article 4.1(d) of the UNFCCC. Alongside terrestrial ecosystems, oceans, marine and coastal ecosystems are referred to as "sinks and reservoirs not controlled by the Montreal Protocol"[5]. Consequently, this chapter refers to oceans, marine and coastal ecosystems, unless otherwise specified. The UNFCCC establishes obligations for Parties that pertain to their national jurisdictions. In the case of the ocean, countries have jurisdiction over their territorial sea and their exclusive economic zone (EEZ) as defined by the UN Convention on the Law of the Sea (UNCLOS, see also next chapter). Of the two instruments with legal force under the Convention, the Kyoto Protocol, and the Paris Agreement, only the Paris Agreement explicitly mentions oceans. The preamble of the Agreement notes the importance of the "integrity of all ecosystems" and singles out oceans, but not marine or coastal ecosystems. Article 5.1 of the Paris Agreement establishes the obligation for Parties to "take action to conserve and enhance, as appropriate" the sinks and reservoirs included under Article 4.1.(d). However, the article singles out forests as the primary intention behind it for most Parties was to give continuity to the framework for reducing emissions from deforestation and forest degradation in developing countries[6], while not limiting action related to sinks and reservoirs only to developing country parties. Only with the continued advocacy for so-called "ocean action" in relation to climate change, the wider scope of Article 5 is coming into focus.

COP25 in Madrid (2019) mandated one Ocean and Climate Change Dialogue "to consider how to strengthen adaptation and mitigation action". It took place in December 2020 and the discussions have been summarized in an informal report (SBSTA 2021). COP26 mentioned oceans in the Glasgow Climate Change Pact in several ways. It invited the constituted bodies under the UNFCCC and ongoing work programmes to consider ocean-based action in their work and to report back where appropriate. It also extended the ocean dialogue and mandated the Chair of the SBSTA to hold an annual dialogue "to strengthen ocean-based action". The first ocean dialogue under the SBSTA took place in June 2022. COP27 in Sharm el-Sheikh changed the arrangements of the annual dialogue, deciding that Parties will select two co-facilitators for a two-year term. Co-facilitators will consult and decide on the topics for the dialogue and prepare informal summary reports for the COP. The first co-facilitated ocean dialogue took place in June 2023. It focused on coastal ecosystem restoration and BCEs, while also addressing fisheries and issues related to food security. Beyond mandating dialogues, COP27 also encouraged Parties to "consider" ocean-based action in their climate goals, for example in their NDCs, long-term strategies and adaptation communication. Note that the scope of ocean-based action discussed under the UNFCCC goes beyond actions related to the ocean ecosystem and Blue Carbon. It also includes ocean-based renewable energy, ocean-based transport and fisheries and aquaculture (SBSTA 2021).

Dedicated advocacy and diplomacy from Parties and Observers preceded this enhanced attention on the role of oceans under the UNFCCC. In 2015, 23 Heads of State and Government signed the first "Because the Ocean Declaration" before the start of COP21 (Because the Ocean

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[5] The Montreal Protocol regulates the production and consumption of ozone depleting substances. Most of these substances also act as greenhouse gases. Thus, two avoid duplication greenhouses gases already addressed by the Montreal Protocol do not fall under the scope of the UNFCCC.

[6] Decision 1/CP.16 encourages developing countries to reduce emissions from deforestation, reduce emissions from forest degradation, referred to as REDD, but also to conserve forest carbon stocks, sustainably manage forests and enhance carbon stocks, for which the shorthand REDD+ is used.

2015). At the same time, they founded the “Because the Ocean Initiative” to address linkages between climate policies and oceans. The driving forces behind this declaration were the French COP21 presidency and the government of Chile. The declaration highlighted the vulnerability of oceans to climate change as well as their ecological and economic importance. It also stated that oceans would be critical to the implementation of the Paris Agreement and called for an “Ocean action plan” under the UNFCCC. The second “Because the Ocean Declaration” followed at COP22 in Marrakech in 2016, with the signatory countries increasing to 39. Among other things, this declaration called for consideration of oceans at the Global Stocktake and in Parties NDCs, and it stressed the need to “stimulate support for ocean related projects.” The main aim of the third declaration from 2021, focused on calling for an ocean related outcome at COP26 in Glasgow. The declaration currently has 41 signatory countries (Because the Ocean 2024), including the following EU Member States: Belgium, Finland, France, Italy, Luxembourg, Malta, The Netherlands, Romania, Spain and Sweden. Norway and the UK are also signatories.

COP28 marked an important milestone in the implementation of the Paris Agreement as it concluded the first Global Stocktake. Oceans are referenced several times in the operational section of the Global Stocktake outcome under mitigation, adaptation and the way forward (UNFCCC 2024). For example, the COP invites Parties to “preserve and restore oceans and coastal ecosystems and scale (…) ocean-based mitigation actions,” “notes that ecosystem-based approaches, including ocean-based adaptation and resilience measures (…), can reduce a range of climate change risks and provide multiple co-benefits” and “encourages further strengthening of ocean-based action”.

The Global Climate Action Agenda[7], which is the stakeholder process related to the UNFCCC process but not part of the formal negotiations, works in thematic areas or sectors. Oceans and Coastal Zones are one of these thematic areas. As for the other areas, a 1.5°C-aligned climate action pathway for 2050 has been put forward. This vision and living document is intended to guide climate action by state and non-state actors. For example, it states that “ocean production and protection go hand-in-hand,”. More than 30% of oceans are protected and the carbon capacity of mangrove forests, seagrass meadows and saltwater marshes was strengthened because “ocean-related natural solutions” became a key component in global mitigation and adaptation efforts. The 2030 “Breakthrough target” proposed by the Action Agenda Climate Champion’s team and allies is to invest USD 4 billion to target protection and restoration of 17 Mha of mangroves (Climate Champions 2024).

56 Parties include a reference to BCEs in their NDCs[8]. The majority of Parties are developing countries (12 from Africa, 24 from Asia-Pacific, 15 from Latin America and the Caribbean). Only 4 developed countries include a reference to BCEs in their NDCs[9]. References can be categorized into three categories: 1) statements related to, e.g. the importance of BCEs and the ocean, as well as expected impacts; 2) proposed policies and measures and 3) targets. NDCs refer to coastal wetlands, marine ecosystems, mangroves, seagrass beds and coral reefs. These references mainly focus on mitigation and adaptation at the same time or are explicitly related to adaptation. In terms of mitigation, Parties refer to carbon sequestration; reducing emissions from ecosystem conversion is less prominent. Another focus is on research and monitoring as countries propose to strengthen research and implement monitoring programmes. The last

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[7] Formally known as the Marrakech Partnership for Global Climate Action.

[8] Key words used to find references in NDCs: ocean, marine, blue, mangrove. 45 countries include more than one reference in their NDC; 11 countries include only one reference.

[9] These four countries are Australia, Canada, the US, and the UK. Australia, the EU, the UK, the Republic of Korea and Norway also state that they intend to use the 2013 IPCC Wetlands supplement for their GHG reporting.

focus is on financing, with references to, for example. the use of public and private funds or payments for ecosystem services. 39 countries have proposed quantified targets. The most common targets relate to the protection or the conservation of ecosystems, which includes strengthening institutional arrangements for protection and management. Seychelles, Timor-Leste, Liberia, Pakistan, United Arab Emirates and Guyana specifically refer to mangrove ecosystems. Targets for restoring mangroves have also been proposed either in terms of trees planted (e.g. UAE) or restored area (Sri Lanka, Samoa, Mozambique, Sierra Leone, Myanmar). The majority of countries include references that can be classified as policies and measures related to BCEs.

24 Parties propose efforts related to research and monitoring. These include the establishment of research facilities or long-term monitoring programmes related to specific ecosystems such as mangroves and coral reefs or on risks, impacts and vulnerabilities. Bahrain, Barbados, Liberia, Panama, Papua New Guinea, Saudi Arabia, Seychelles, and UAE refer to improving knowledge on carbon pools and fluxes in order to include BCEs in GHG inventories. Panama and Papua New Guinea state, they will include blue carbon in their GHG inventories.

Article 6 of the Paris Agreement establishes the rules to enable international carbon market cooperation (Art. 6.2), creates a UN crediting mechanism under UNFCCC supervision, succeeding the Clean Development Mechanism (Art. 6.4) and creates a framework for non-market approaches. Article 6.2. introduces “internationally transferred mitigation outcomes” (ITMOs) which Parties can authorize for three types of uses: NDCs, CORSIA and the voluntary carbon market. Rules are in place to avoid double counting, ensuring environmental integrity through reporting and safeguards. The basis for ITMOs is the quantification of mitigation outcomes. The ability of countries to do so for BCEs in a manner that allows to comply with the reporting and accounting requirements is currently limited (see chapter 5).

Article 6.4. allows for a broad scope of activities and could also encompass “emissions avoidance” and “conservation enhancement” activities. It has not yet been agreed whether this will be the case - a relevant question for those Parties that include conservation of mangroves in their NDC and may seek to generate units with these activities under the 6.4 mechanism.

The UNFCCC process also encompasses research and systemic observation in which inputs by the IPCC are considered. In 2019, the IPCC provided a summary of “best available scientific knowledge” with its “Special Report on the Ocean and the Cryosphere in Changing Climate” (UNEP 2019). For example, it provided an assessment of the impacts and risks expected for BCEs at different levels of global mean sea surface temperature increase relative to pre-industrial levels. Mangrove forests, salt marshes and seagrass meadows, will be exposed to a moderate level of risk and impacts already with an increase of around 2°C (IPCC 2019).

Blue Carbon is also increasingly gaining recognition on the voluntary carbon market. First projects involving BCEs have been developed in the last decade (Wylie et al. 2016), with a substantial number of projects being in the planning or verification process.

Other UN bodies and processes also relate to Blue Carbon. Goal 14 (SDG 14) of the UN Sustainable Development Goals is to “Conserve and Sustainably Use the Oceans, Seas and Marine Resources for Sustainable Development”. The 70th UN General Assembly convened a High-Level UN Conference on Oceans and Seas in June 2017. Also in 2017, under Resolution 71/249 the General Assembly initiated the process for a “legally binding instrument under the United Nations Convention on the Law of the Sea (UNCLOS) on the conservation and sustainable use of marine biological diversity of areas beyond national jurisdiction” (UN 2024). A UN Ocean Conference took place in Lisbon in 2022. It concluded with a declaration (UN 2022) in which, among other things, countries committed to taking measures to strengthen scientific and systematic observation, exchange knowledge and establish partnerships. The declaration also stressed that "implementing nature-based solutions, ecosystem-based approaches for, inter alia, carbon sequestration and the prevention of coastal erosion" can contribute to achieve SDG14. It did not state a commitment to action in this regard. A draft agreement on the legally binding UNCLOS instrument was reached in March 2023, adoption was scheduled for June 2023. The draft agreement specifies rules related to the exploitation of marine genetic resources and establishes "area-based management tools," which include marine protected areas.

The UN Ocean Decade runs from 2021 to 2030. The focus of the decade is to boost the science, funding and partnerships necessary for resilient and sustainably used ocean ecosystems. Action under the Ocean Decade is organized around ten challenges. Two challenges are directly related to Blue Carbon measures: challenge 5 entitled "Unlock ocean-based solutions to climate change," which refers to improving "understanding of the ocean-climate nexus" and finding mitigation, adaptation and resilience; and challenge 2 entitled "Protect and restore ecosystems and biodiversity," which refers to finding "solutions to monitor, protect, manage and restore ecosystems and their biodiversity".

The governments of Norway, Sweden, Korea, Japan, Canada and Portugal provide financial support for the activities of the Ocean Decade (Ocean Decade 2023). An alliance of governments and non-state actors drives the implementation of activities. If successful, the Ocean Decade will allow the value of ocean science to society to become mainstream, make it accessible and contribute to its practical use.

Several international partnerships on Blue Carbon have emerged in recent years. For example, "The Ocean Negative Carbon Emission program," which focuses on research and knowledge creation to develop and evaluate "approaches to enhance carbon sequestration" in the ocean (Once 2024). The "Blue Carbon Initiative" is coordinated by Conservation International, the International Union for Conservation of Nature and Intergovernmental Oceanographic Commission of the United Nations (The Blue Carbon Initiative 2024). This initiative focuses on promoting the restoration and sustainable use of coastal and marine ecosystems.

As of 2007, the EU has an Integrated Maritime Policy under which Member States coordinate ocean and coastal-related policies. The protection and conservation of marine and coastal ecosystems is addressed by the 2008 Marine Strategy Framework Directive (European Commission 2024). This directive requires Member States to present strategies to achieve a good environmental status for their marine ecosystems, for example by reducing eutrophication and maintaining biodiversity. It also requires coordination at regional level with regards to marine protected areas. An example of regional cooperation with a long history is the Baltic Marine Environment Protection Commission, also known as the Helsinki Commission or HELCOM (HELCOM 2024). The Parties to this intergovernmental organisation are Denmark, Estonia, the EU, Finland, Germany, Latvia, Lithuania, Poland, Russia and Sweden. As a regional sea convention, HELCOM aims to protect the Baltic Sea from land, air and sea pollution, conserve habitats, protect biodiversity and ensure the sustainable use of marine resources.

5 Visibility of Blue Carbon in national greenhouse gas inventories

National GHG inventories are the primary tool for monitoring and reporting GHG-emissions and carbon removals of anthropogenic activities in different sectors such as energy, industrial processes, agriculture and land use, land use change and forestry (LULUCF). Under the Paris Agreement, all Parties are required to regularly report emissions and removals, either annually (developed countries) or biennially (developing countries). The reported level of emissions and removals is the basis for measuring progress towards nationally defined climate mitigation targets defined in terms of GHG emissions[10].

From 2024 onwards, all parties to the Paris Agreement will submit biennial transparency reports (BTRs) in accordance with the enhanced transparency framework (ETF) which also include national GHG inventories. The ETF builds on previous reporting and review obligations under the UNFCCC and the Kyoto Protocol. BTRs are subject to a review process, in which experts from other countries evaluate the accuracy and completeness of the information provided. All Parties are required to calculate emission sources and removals from multiple sectors by applying IPCC Guidelines for National Greenhouse Gas Inventories. These guidelines already cover management activities in mangrove forests within the LULUCF sector. Guidelines on how to estimate emissions of CO_2, CH_4 and N_2O for activities in tidal marshes and seagrass meadows are part of the 2013 Wetland Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC 2014). The guidelines also provide information on accounting for uncertainties and data gaps in the estimation of carbon stocks and GHG emissions and removals. Currently, there is no obligation to use the methods introduced in the 2013 Wetland Supplement, developed countries are only encouraged to use them. Consequently, measures relating to BCEs are only included in national GHG inventories on a voluntary basis. If countries decide to report activities in BCEs, they must clearly define the extent and location of their activities in these ecosystems to meet their international reporting obligations in the ocean.

This is of particular importance as coastal ecosystems may not occur on areas that are part of the total land area of the country. The 2006 IPCC Guidelines for National Greenhouse Gas Inventories require that the “[n]ational inventories [need to] include greenhouse gas emissions and removals taking place within national territory and offshore areas over which the country has jurisdiction.” (IPCC 2006, p. 8.4). Later supplements and addendums brought no relevant changes.

The extent of countries’ jurisdiction over ocean waters is defined by the United Nations Convention on the Law of the Sea (UNCLOS), an international treaty widely ratified (Silverman-Roati et al. 2022). UNCLOS divides the sea into four different zones:

- territorial sea,
- exclusive economic zone (EEZ),
- continental shelf,
- high sea.

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[10] The Paris Agreement allows Parties to define their own targets. For example, a Party may choose to define a target in terms of an area that will be reforested.

The high sea is outside of any state's jurisdiction and therefore no state may (or must) report GHG emissions and removals.

The territorial sea consists of the first 12 nautical miles (n.m.) of the low water line along the coast that still forms part of the state's sovereign territory. The "coastal country has full sovereign rights over the water and submerged land and the airspace above". Therefore, the obligation of GHG reporting also applies within the territorial sea.

The exclusive economic zone (EEZ), which extends up to 200 n.m., is not part of the country's sovereign territory, but countries can "explore, exploit, conserve, and manage natural resources and undertake other activities for the economic exploitation" (Silverman-Roati et al. 2022, p. 7) in this area. Additionally, countries may claim an extended continental shelf beyond the EEZ but exploitation in such an extended area is limited to resources of the seabed and subsoil, plus sedentary species. Thus, within this zone only carbon pools and fluxes in the seabed may fall under the national jurisdiction and may be covered by the national GHG inventories. In contrast, the waters beyond the EEZ above the extended continental shelf do not fall under the national jurisdiction but are part of the high sea.

In conclusion: the reporting obligations extend to the EEZ, and to certain activities on the Continental Shelf (if claimed). However, according to the 2013 Wetland Supplement (IPCC 2014), these areas beyond the country's sovereign territory are not part of the country's total land area in the GHG inventory. Therefore, if reported, their emissions and removals must be stated separately. This is especially relevant for seagrass meadows, which can be found far from the coastline.

Emissions and removals from anthropogenic activities in tidal marshes, seagrass meadows and mangrove forests are reported in the LULUCF sector. The LULUCF sector is divided in different land use categories: forest land, cropland, grassland, wetlands, settlements and other land. Only emissions and removals from managed lands and changes in land use need to be reported. For example, the area of a tidal marsh is originally classified as wetland. If the tidal marsh area is drained for agriculture use, it is reclassified in the inventory as "Cropland". The emissions and removals are calculated from the annual changes in the different carbon pools. Total carbon stocks are not reported in the national GHG inventories.

The 2013 Wetland Supplement uses a tiered approach to estimate GHG emissions from wetlands, depending on the level of available data and the level of uncertainty associated with the estimates. Tier 1 is the IPCC default method, based on global or regional average emission factors. Tier 2 assessments use a more detailed method that is based on site-specific measurements, while Tier 3 additionally includes specific data of the carbon stocks and carbon flux estimates via repeated measurements or modelling. Since Tier 1 estimates have a high degree of uncertainty, the IPCC recommends using Tier 2 or Tier 3 assessments (IPCC 2014). Currently, the guidelines cover emissions from drainage which is one of the major causes for degradation in coastal ecosystems. But guidance is only available for mangroves and tidal marshes (Table 3). Restoration activities such as rewetting and revegetation are described which are important potential BC measures (Table 3). The most recent update to the 2013 Wetlands Supplement is the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC 2019a). The refinement provides guidance for assessing changes in the soil carbon pool, which is particularly important in cases in which coastal wetland areas are converted to agricultural lands or aquaculture as this can result in significant GHG emissions and losses of carbon stocks.

Table 3Table 3 presents an overview of Tier 1 emission factors available in the 2013 Wetland Supplement (IPCC 2014) for activities causing CO_2-emissions resulting from changes in the carbon pools of mangrove forests, seagrass meadows and tidal marshes as well as non-CO_2-emissions. Guidelines for mangrove forest management are already available under the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC 2006). If mangrove forests fall under the countries forest definition, they are reported under the land use category "Forest land," otherwise they can be included under "Wetlands". Tier 1 default values are not available for all carbon pools and if national data is not available, they do not have to be reported. Hence, only using Tier 1 default data for national reporting can lead to high uncertainties in the emission and removal estimates. Additionally, the Tier 1 emission factors may not be based on statistically significant quantities. For example, Tier 1 emission factors for seagrasses are derived from only six sampling sites (Needelman et al. 2018). However, providing these default data also removes significant barriers to including coastal wetlands in national GHG inventories and can help to increase efforts to improve data and knowledge on the state of coastal wetlands (Green et al. 2021).

Table 3: Activities for which Tier 1 emission factors are available for reporting of non-CO_2 emissions and CO_2 emissions resulting from changes in different carbon pools of mangrove forests (M), seagrass meadows (SM) and tidal marshes (TM)

Activity	Above & below ground biomass	Dead organic matter	Soil carbon (mineral/organic soil)	Non-CO_2
Forest management practices	M	M (if land-use change occurs)	M	-
Extraction, for example for aquaculture or salt ponds	M	M	M, SM, TM	-
Aquaculture use	-	-	-	M, SM, TM (N_2O)
Drainage	M	M	M, TM	-
Rewetting, revegetation and creation	M	-	M, SM, TM	M, TM (CH_4)

Data sources: IPCC 2014, Green et al. 2021.

There is a growing recognition among countries that the protection, restoration, and management of mangrove forests, seagrass meadows and tidal marshes can make a significant contribution to their efforts towards both mitigation and adaptation. As a result, more and more countries are including measures for these BCEs in their NDCs (see section 4). However, despite this increasing recognition of the importance of BCEs, only a limited number of countries are currently reporting GHG emissions from these ecosystems in their national GHG inventories (Green et al. 2021). One reason is the considerable lack of funding and technical capacity to accurately estimate and report GHG emissions, especially in developing countries (Malerba et al. 2023). As a result, many countries either do not report on coastal ecosystems at all or only provide insufficient reports. A brief review[11] of the EU countries' National Inventory Reports revealed that only France reports on mangroves in French Guyana under the land use category

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[11] Review was conducted by searching the National Inventory Reports (NIR, submission in 2022) of the EU member states for coastal wetlands in the Wetland category. NIRs were downloaded from (UNFCCC 2022b) (last checked on 14.05.2023)

of forest land (Tuddenham 30 Jun 2021). However, no coastal ecosystems are currently reported on in the territory of the EU.

As of 2017, the United States and Australia have started reporting on coastal wetlands in their national GHG inventories, with a focus on net emissions from mangrove regeneration and extraction, conversion of tidal marshes, and aquaculture. In addition, continuous improvements have been made to these inventories, including the consideration of seagrass meadow drainage (Zhao et al. 2022). Utilizing comprehensive inventory reporting in the United States has resulted in an improved ability to identify opportunities for reducing GHG emissions through the restoration of coastal ecosystems (Crooks et al. 2018). Australia has developed a Blue Carbon accounting model (BlueCAM), which is used in the country's voluntary carbon market scheme, the Emission Reduction Fund (Lovelock et al. 2022). BlueCAM is calibrated with Australian data to assess the reduction of GHG emissions and the carbon sinks arising from restoration of coastal ecosystems. The methodology aligns with the IPCC guidelines and can be applied by others with similar ecological conditions (Lovelock et al. 2022). But BlueCAM is not yet applied in the Australian national GHG inventory. Also, Australia does not report restoration activities in coastal ecosystems (Australian Government 2023). While BlueCAM provides a valuable tool for assessing the reduction of GHG emissions and carbon sinks resulting from the restoration of coastal ecosystems, there are still uncertainties in its outputs due to limited availability of site-specific input data. To address this, ongoing efforts in field measurements are needed to improve the accuracy of the model, particularly when it is applied in locations outside Australia (Lovelock et al. 2022).

Lack of data on the past and present area changes and the extent of coastal ecosystems as well as their emissions and removals were also the challenges identified by Zhao et al. (2022) for China to include coastal ecosystems in their national inventory. Hence, it is suggested that emission and removal data is collected from many different locations, salinity conditions and species to improve carbon flux models which can produce estimations and predictions for national GHG inventories (Zhao et al. 2022). Also, incorporating remote sensing data can help to produce better activity data to support higher-tier methods for GHG inventories (Malerba et al. 2023). Research on GHG emission and removals in coastal ecosystems faces different challenges compared to terrestrial environments. For example, the differences in plant species composition and tidal influence can be significant in terms of the magnitude and direction of carbon fluxes and makes coastal ecosystem spatially and temporally complex (Wilson et al. 2018; Windham-Myers et al. 2022). Due to the temporal and spatial complexity and limited data of the carbon fluxes in coastal ecosystems, current models lack predictive power (Windham-Myers et al. 2022).

Another challenge in calculating carbon sequestration in coastal ecosystems is the composition of the carbon stock source, as discussed in Section 3. The exclusion of allochthonous carbon is generally recommended as the carbon originates from terrestrial or other marine sources. Hence, the measurement of allochthonous carbon in coastal ecosystems may overestimate their carbon sequestration potential (Williamson and Gattuso 2022). Further, in addition to foreign carbon inputs, it is crucial to take into account the export of carbon from the ecosystem. These exports could be equal or even higher compared to carbon sequestration in coastal ecosystems (Santos et al. 2021; 2019). These carbon dynamics are still widely unknown as well as the amount of exported carbon that is actually subject to long-term storage in the open ocean and its sediments (Al-Haj and Fulweiler 2020; Rosentreter et al. 2021; Santos et al. 2021). Current methods for assessing carbon fluxes in mangroves, tidal marshes and seagrass meadows, like the default methods under the 2013 Wetland Supplement (IPCC 2014) do not differentiate between autochthonous and allochthonous carbon sources. Also, the Australian model BlueCAM does not discount for allochthonous carbon stored in the sediment. According to Lovelock et al. (2022), allochthonous carbon contributions are small compared to autochthonous carbon contributions in tidal marshes and mangroves in Australia, but can be significant for some seagrass meadows. The Verified Carbon Standard (VCS), a widely used standard for the certification of carbon credits addresses allochthonous carbon in its accounting principle (VCS 2013). The principle dictates that a project can only be credited for sequestering allochthonous carbon in the project scenario if that carbon would have been released into the atmosphere in the baseline scenario. A novel method has been developed to estimate the amount of mineral-protected allochthonous carbon, which involves calculating the percentage of carbon that was present in the mineral matter at the time of deposition, along with the amount of mineral material accumulated in the soil (Needelman et al. 2018). This helps to allocate the part of the allochthonous carbon that is stored long-term in coastal ecosystems.

In summary, official guidelines are provided for all three BCEs (tidal marshes, mangroves, seagrass meadows) that were identified in this report (see chapter 2). But their visibility in national GHG inventories is currently very limited because only a few countries with coastal ecosystems are reporting their emissions and removals. This is mainly due to a lack of funding and a lack of technical capacity for monitoring GHG. Countries that report emissions and removals using default emission factors provided by IPCC (2014) most likely have high uncertainty in their estimations (Needelman et al. 2018; Windham-Myers et al. 2022). Also, carbon fluxes resulting from unmanaged coastal ecosystems, e.g. in strictly protected areas, do not have to be included in the national GHG inventories. There are many methodological, technical, and financial obstacles to provide accurate estimations on GHG emissions and removals for BCEs. The main challenges are:

1. Overcoming the lack of data on the extent and changes in BCE area, especially seagrass meadows and tidal marshes, as well as the status of degraded or revegetated BCE quality by, for example, incorporating remote sensing data.
2. Improvement of databases, e.g. IPCC Emission Factor Database by quantifying GHG emissions and removals associated with different intensity levels of human activities (clearing of vegetation, drainage, burning, restoration) over time, especially in developing countries.
3. Improvement is also needed for carbon stock estimations in BCEs at deeper soil depth (> 1m) for more accurate accounting. Improvement of the quantification of carbon storage in soils additionally requires the measurement of active carbon accumulation, i.e. carbon accumulation rates (CAR).
4. Further research is needed to provide knowledge about the allochthonous carbon inputs from other marine and terrestrial sources and how to report allochthonous carbon correctly in national GHG inventories.
5. Sufficient finance to do research, measurements, and monitoring to prepare national GHG inventories.

6 Summary and conclusions

- The term "Blue Carbon" (BC) was invented to stress the significance of the ocean for the carbon cycle and for the capacity of marine organisms to sequester carbon. For combating climate change, the latter became especially important, and the ocean carbon sink function is increasingly being recognised by policy makers.

- The definition used in this report is: *Blue Carbon refers to the carbon captured by marine organisms and stored in living and dead biomass as well as in organic compounds in the sediment.* Measures targeting to manage BC (BC measure) need to fulfil the following criteria to deliver relevant and sustainable contributions to climate change mitigation:
    - Criterion 1): BC measures must positively affect carbon capture and storage in the marine ecosystem in a time frame of several decades (long-term),
    - Criterion 2): They must be accompanied by a continuous monitoring to demonstrate (I) significant carbon uptake and (II) carbon storage in the habitat as well as (III) the influence of human activities on carbon sequestration and
    - Criterion 3) BC measures must be aligned with the concept of nature-based solutions (NbS) (IUCN 2016; Reise et al. 2022; UNEP 2022).

- Currently, actionable BC measures are ecologically and technically viable in coastal ecosystems of mangroves, seagrass meadows and tidal marshes. They are efficient carbon storing ecosystems and are therefore referred to as "Blue Carbon ecosystems" (BCEs).

- Globally, the potential contribution of the three BCEs to achieve additional significant carbon sequestration is limited. But for some countries that have high shares of coastal ecosystems, they are highly relevant for achieving mitigation and climate adaptation targets.

- BCEs are endangered by, for example, the spread of aquaculture in coastal regions, bottom trawling or pollution, which leads to GHG emission release due to degradation or even total destruction of BCE. Measures to protect and restore BCEs have been proven to reduce GHG emissions. Actions to protect and restore BCEs have many sustainable development co-benefits, especially for protecting biodiversity and adaptation to impacts of climate change like flooding.

- All Parties to the Paris Agreement are expected to provide GHG inventories. The IPCC guidelines for GHG monitoring provide a good basis to include mangroves, seagrass meadows and tidal marshes in national GHG inventory reports. There are methods and emission factors for several activities in these coastal ecosystems.

- The temporal and spatial complexity of coastal ecosystems, coupled with the limited availability of data on carbon fluxes in these environments, leads to significant uncertainties in estimating GHG fluxes and carbon stocks. This is especially true, when default emission factors are applied.

- Due to these methodological, technical, and financial obstacles, the visibility of BC in national GHG emissions reporting is currently very limited because only a few countries with coastal wetlands are able to report their emissions and removals.

- Nevertheless, including coastal ecosystems in national GHG inventories can shed light on the GHG emissions within these ecosystems, thus promoting initiatives to reduce these emissions through restoration and discouraging harmful activities. A dedicated space to address ocean-related climate action has been established under the UNFCCC and countries are increasingly including oceans and coastal ecosystems in their NDCs. Given that oceans are now anchored within the UNFCCC process and the collaborative work prompted by the UN ocean decade, the momentum of ocean climate action is likely to continue.

- The possibility of properly including BCEs in GHG inventories is limited. Efforts to improve this are ongoing. Yet, if a country has expressed an NDC target in terms of an area-based target for ecosystem protection, tracking progress and achievement of NDCs is already possible. It is in this regard that the contribution of mitigation and adaptation measures of BCEs will be captured in the near term.

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