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Potential of blue carbon for global climate mitigation

As part of the research project FKZ 3722 42 510 0 'Climate protection measures in coastal regions and waters'

1 Introduction

With the passing of the European Climate Law, all EU Member States are required to reduce their emissions to net zero by 2050. However, some unavoidable emissions will remain, such as those from agricultural activities. Therefore, additional measures to absorb CO2 from the atmosphere and to store carbon in the long term will be required.

From 2012 to 2021 ocean and terrestrial carbon sinks have absorbed about 50% of the annual anthropogenic emissions globally, which totals about 6 GtC per year (Friedlingstein et al. 2022). Among marine ecosystems, especially coastal ecosystems like mangrove forests, seagrass meadows and tidal or salt marshes function as highly efficient natural carbon sinks through their high carbon storage per unit area (Pendleton et al. 2012). These are often referred to, including in this report, as "Blue Carbon ecosystems (BCE)" (IUCN 2021; IPCC 2019b). Even though the term "blue carbon" (BC) is increasingly being used, it lacks a uniform definition, in the context of carbon storage in marine ecosystems (Lovelock and Duarte 2019).

In addition to carbon sequestration, coastal ecosystems are of great importance for biodiversity and provide numerous ecosystem services (Li et al. 2018; Mitsch et al. 2015). However, the natural distribution of mangroves, tidal marshes and seagrass meadows has already been drastically reduced by estimated 50% due to human interventions (Li et al. 2018).

This factsheet provides a brief overview of the content of the report "Potential of Blue Carbon for global climate change mitigation" (Reise et al. 2024). It contains the definition of blue carbon and criteria of blue carbon measures, discusses their potential for global climate mitigation and its role in international climate policy and portrays their visibility in national greenhouse gas (GHG) inventories.

2 Definition of blue carbon and criteria of blue carbon measures

The term BC was originally coined in an assessment report by the United

Umweltbundesamt
Section V 2.6 Klimaschutzprojekte – Nationale Zustimmungsstelle UNFCCC
Wörlitzer Platz 1
D-06844 Dessau-Roßlau
www.umweltbundesamt.de/en

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). It was employed to distinguish between carbon sequestered by marine plants ("blue carbon") and by land plants ("green carbon"), both removing "brown carbon" (burning of fossil fuels). To date, no scientific or political agreement on definition of BC exists. A definition that includes the marine origin and the carbon pools of the stored carbon is necessary for identifying the relevant carbon stocks and flows and is derived for this factsheet as follows:

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

Blue carbon measures should have a positive effect on climate change mitigation and their effectiveness can be influenced by management (IPCC 2019a). Therefore, the following criteria should be met:

Criterion 1): Blue carbon 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.

Carbon storage in plant biomass lasts for years to decades whereas carbon in marine sediments can remain stored for millennia (Mcleod et al. 2011). Especially measures to protect and restore mangrove forests, seagrass meadows and tidal marshes have proven to reduce GHG emissions, protect and enhance carbon stocks (O'Connor et al. 2020; Lovelock und Duarte 2019). By contrast, coral reefs are currently considered to have net CO_2 emissions due to their calcification process, which is why measures regarding this ecosystem are not considered in this report (Frankignoulle et al. 1995).

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.

A challenge of blue carbon measures is to track carbon flows from the origin of the carbon fixation to the storage. Some ecosystems are very productive in building biomass, but the carbon included in their biomass is ultimately stored in other ecosystems. Macroalgae for example contribute to about 50% of the carbon stored in seagrass sediments (Kennedy et al. 2010; Stevenson et al. 2022) and possibly also contribute to carbon stored in deep sea sediments for longer periods over 1,000 years (Krause-Jensen und Duarte 2016; Ortega et al. 2019). Since the long-term storage of carbon taken up by macroalgae depends on other ecosystems rather than taking place in their habitat, measures regarding macroalgae are not concerened BC measures. Whilst measures regarding coral reefs and macroalgae are not classified as BC measures in this study, the protection and restoration of these ecosystems is crucial to preserve marine biodiversity as well as ensuring coastal protection.

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).

The concept of NbS for climate mitigation has gained increasing interest and recognition in political debates and in the context of the United Nations Framework Convention on Climate Change (UNFCCC) process and the United Nations Environment Assembly (UNEA) (UNFCCC 2022). The Fifth Session of the UNEA adopted the following definition about NbS: *"[A]ctions 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).

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 including geo-engineering activities. As these are engineered interventions and since there are no effective regulatory instruments and no solid scientific basis on associated risks, these do not qualify as NbS and are therefore not considered BC measures in this study (Decision IX/16, CBD 2008).

In contrast to these engineered interventions, restoring and protecting coastal ecosystems counteract the continuous destruction of carbon-rich ecosystem (IPCC 2019b). 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 und 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 factsheet.

3 Short assessment of the global climate mitigation potential of blue carbon measures

Growing knowledge suggests that BCE are among the most efficient natural carbon sinks and that human interventions can help to enhance these (e.g. Lovelock und Duarte 2019). Even though improvements in quantifying blue carbon have been made, there are still many uncertainties in spatial and temporal dimensions of blue carbon quantification (Gattuso et al. 2021; Williamson und Gattuso 2022).

The development of an internationally standardised protocol to quantify blue carbon (Howard et al. 2014) contributed strongly to the production of relevant data sets. It is important to note, that our understanding of carbon storage in BCE is currently mainly based on stock calculations and scenarios of CO_2-release upon loss of BCE and related organic matter and thus the avoidance of emissions through BCE conservation (Jennerjahn 2021a). However, stocks do not provide information on the actual carbon sequestration, i.e. active CO_2-removal from the atmosphere. To obtain the variation in carbon accumulation rates (CAR), methods like age dating sediment cores can be used. However, they have high costs and do not always allow robust determinations (Arias-Ortiz et al. 2018). Consequently, the global CAR dataset is much smaller than the global data on stocks (Jennerjahn 2021a).

Carbon stocks and carbon accumulation rates describe different aspects of carbon sequestration in BCE and have different purposes. A carbon stock provides an assessment of "how much carbon is stored" and could potentially be emitted as CO_2 upon BCE degradation. However, it is also important to measure the active carbon sequestration of BCE when assessing their present and future role in climate mitigation. The largest portion of carbon removal and long-term sequestration is the carbon accumulation in sediments which provides a measure of the "mitigation potential" of BCE (Jennerjahn 2021a).

Quantifying blue carbon on a global scale is hampered by the following constraints:

1. **Variability**: stocks and CAR within one BCE can be very high, depending on local environmental conditions (Kusumaningtyas et al. 2019).
2. **Allochthonous carbon**: the source of the stored carbon is unknown in most cases – in BCE some of the stored carbon was originally absorbed by other ecosystems (allochthonous carbon) and may have happened a long time ago (Williamson und Gattuso 2022). The fraction of allochthonous (non-resident) carbon can be high and vary widely even within one BCE (Jennerjahn 2021b; Kusumaningtyas et al. 2019; 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.
3. **Uncertainty**: even though the stock and the accumulation rates can be measured, they only provide a rough basis for sequestration rates, since losses through export and decomposition can be large and are hardly known (Al-Haj und Fulweiler 2020; Rosentreter et al. 2021b; Santos et al. 2021).
4. **Methane and nitrous oxide emissions** from BCE are not yet fully understood and need further research as their impact is unclear. Some studies suggest that methane (CH_4) and nitrous oxide (N_2O) emissions combined might be able to offset the CO_2 mitigation impact (Rosentreter et al. 2021a; Al-Haj und Fulweiler 2020). However, a recent meta study by Cotovicz et al. (2024) indicates that the negative effect of methane emissions is much smaller than previously thought.

Aside from that, there are other obstacles regarding the social implications, governance and finance of BC measures (Macreadie et al. 2022). All together the contribution of BC for climate mitigation is estimated differently by various studies, ranging from 0.02% to 6.6% of global annual emissions, which is reflecting the large uncertainties still present in the quantification of GHG fluxes in BCE (Williamson und Gattuso 2022). It is clearer that most of this comes from protecting existing carbon stocks, not from reducing emissions. This means that the mitigation potential of additional BC sequestration resulting from restauration and management is estimated much lower.

Despite the growing awareness of the multitude of ecosystem services provided by BCE and increasing conservation and restoration efforts, annual area loss rates are still on the order of 1-2% for tidal marshes and seagrass meadows while the order of magnitude of such loss is smaller for mangrove forests (Duarte et al. 2008; Waycott et al. 2009 and Friess et al. 2019).

In conclusion, the effects of ongoing global warming as well as destructive human interference and scientific uncertainty thus pose limits to the mitigation potential which can be achieved through BC measures.

4 The role of blue carbon in international climate policy

The measures and targets set by countries so far in their Nationally Determined Contributions (NDCs) are not sufficient to comply with the 1.5°C temperature limit (UNFCCC 2021). In addition to measures to *reduce* CO_2 emissions, measures to absorb and store CO_2 from the atmosphere are receiving increasing attention.

The preamble of the Paris Agreement notes the importance of the integrity of all ecosystems and singles out oceans, but not marine or coastal ecosystems. Article 5.1 establishes the obligation of parties to protect and enhance sinks and reservoirs.

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 restore and protect coastal ecosystems, oceans and to apply ocean-based mitigation actions because they can reduce risks of climate change and provide many co-benefits.

In their NDCs, 56 countries, mostly developing countries, include a reference to BC. Some of the references include statements, policy measures, and some even targets. 39 countries have put forward quantified targets, most frequently relating to strengthening institutional arrangements for protection and management. 24 Parties include efforts related to research facilities and long-term monitoring.

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 oversight that succeeds the Clean Development Mechanism (Art. 6.4) and creates a framework for non-market approaches (Art. 6.8). Blue carbon measures could theoretically be included in carbon market approaches under Art. 6.2, but this is limited by the reporting and accounting requirements. Whether only additional carbon sequestration or also emission avoidance or conservation enhancement activities will qualify under Art. 6.4, is still not decided.

Blue Carbon is also increasingly gaining recognition on the voluntary carbon market. First projects involving BCE 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 BC. The sustainable development goal (SDG) 14 for example aims to "conserve and sustainably use oceans, seas and marine resources". The UN General Assembly started 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. A draft for the legally binding UNCLOS instrument was reached in March 2023, adoption is scheduled for June 2023.[1] At the latest UN Ocean conference in 2022, countries agreed to strengthen monitoring and to establish partnerships and exchange knowledge. The declaration also stressed that NbS for carbon sequestration and coastal protection can contribute to achieve SDG 14.

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 BC 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".

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).

5 Visibility of Blue Carbon in national greenhouse gas inventories

1 The High Seas Treaty to protect ocean life was adopted in June 2023. As of May 2025, 115 countries have signed the High Seas Treaty demonstrating their willingness to ratifying it. Out of the 60 countries needed for the Treaty to enter into force, only 21 countries have ratified it until now (https://highseasalliance.org/treaty-ratification/, last accessed: 19.05.2025).

National GHG inventory submissions are the primary important tool to track and report countries progress towards nationally defined climate mitigation targets according to the Paris Agreement. Under the Enhanced Transparency Framework (ETF), established by the Paris Agreement, all countries will submit biennial transparency reports (BTRs) starting in 2024. All countries are required to calculate emission sources and removals by applying IPCC Guidelines. These guidelines already cover management activities in mangrove forests within the land use, land use change and forestry (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) but are not obligatory and consequently only included in national GHG inventories on a voluntary basis. The guidelines also provide information on accounting for uncertainties and data gaps in the estimation of carbon stocks and GHG emissions and removals.

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 (IPCC 2014).

For a correct quantification of emissions and removals, countries need to define coastal wetlands clearly, which is not the case yet. Some coastal ecosystems may not occur on areas that are part of the total land area of a country but in offshore waters governed by that country, which is why the IPCC guidelines require the inclusion of "greenhouse gas emissions and removals taking place within national territory and offshore areas over which the country has jurisdiction" (IPCC 2006).The extent of countries jurisdiction over ocean waters is defined by the UNCLOS, an international treaty widely ratified and part of customary international law. According to this definition, only blue carbon on the seabed of the extended continental shelf (not in the water above it) fall under national jurisdiction and may be covered in the national greenhouse gas inventory.

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. However, only a limited number of countries are currently reporting on GHG emissions from these ecosystems in their national inventories (Green et al. 2021). A brief review of the EU countries' National Inventory Reports revealed that only France reports on mangroves in French Guyana under the land use category of forest land (Tuddenham 30.06.2021).

Reasons for that include the lack of funding and technical capacity for accurate monitoring especially in developing countries (Malerba et al. 2023). Many existing country reports on coastal wetlands are insufficient due to the high complexity of carbon fluxes in coastal ecosystems. As discussed in section 3, the composition of the BCE carbon stocks is another challenge, as the carbon might originate elsewhere than in the BCE. Hence, these import-dynamics must be considered, as well as carbon exports from BCEs. These dynamics are still widely unknown and current methods do not differentiate between the carbon originating from BCEs and carbon originating somewhere else. Moreover, improvement of databases, e.g. IPCC Emission Factor Database and for carbon stock estimations is needed in BCEs at deeper soil depths (> 1m) for more accurate accounting.

6 Conclusion

Blue carbon is a concept that is increasingly being discussed by policymakers in the context of combating climate change. Currently, actionable BC measures are ecologically and technically viable in coastal ecosystems of mangroves, seagrass meadows and tidal marshes. While globally the potential contribution of the three BCEs to achieve additional significant carbon sequestration is limited, for some countries that have high shares of coastal ecosystems, they can be highly relevant for achieving mitigation and climate adaptation targets.

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, e.g. protecting biodiversity.

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.

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Umweltbundesamt
Wörlitzer Platz 1
06844 Dessau-Roßlau
Tel: +49 340-2103-0
buergerservice@uba.de
Internet: www.umweltbundesamt.de

Authors, Institutions

Judith Reise, Cristina Urrutia, Dr. Laura von Vitorelli (Öko-Institut e.V.)

Dr. Tim Jennerjahn (Leibniz Zentrum für marine Tropenforschung)

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