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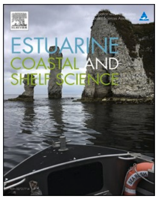

Blue Carbon potential in Germany: Status and future development

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ABSTRACT

Climate change and biodiversity loss are global challenges that need to be addressed through a combination of measures. However, political and societal action has not yet kept pace with the urgency of these challenges. Marine carbon sequestering habitats ("Blue Carbon habitats") are globally recognized for their role in climate change mitigation and for their co-benefits and ecosystem functions, e.g., as habitat providers. In Germany, research on the Blue Carbon potential of coastal and marine ecosystems has gained momentum in recent years. However, a synergistic approach with an inclusive decision-making process is crucial to ensure political action. Current challenges are considerable knowledge gaps and the limited accessibility and transferability of existing data. Funding of research projects at different administrative levels impacts coordination, output and visibility. Here, we present a general overview of existing knowledge and identified knowledge gaps in Blue Carbon research and focus on potential Blue Carbon ecosystems (BCEs) of the German coast. Furthermore, we identify windows of opportunity and provide actionable recommendations at the science-policy-society interface by examining the current framework for Blue Carbon in Germany. Based on this, ongoing research can be further prioritized and funded in order to simultaneously strengthen the political decision-making process. The results of this study, supported by the lessons learned from a case study on the German coast, recommend a two-pronged strategy to not only avoid additional release of already stored carbon through ecosystem conservation and sustainable governance and management, but also to increase net carbon storage through (re-)establishing BCEs.

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1. Introduction

Against the backdrop of global climate change and the loss of biodiversity, there is an increased need to understand roles and contributions of coastal and marine ecosystems and habitats. Coastal ecosystems and their ecological function provide a range of valuable ecosystem services (Barbier et al., 2011; Liquete et al., 2013; Nellemann et al., 2009). Coastal vegetated ecosystems (CVEs), like mangrove forests, salt marshes and seagrass meadows, can mitigate climate change processes by capturing and storing carbon as biomass and within sediments and soils over long time scales (Nellemann et al., 2009; IPCC, 2022). Carbon stored in marine ecosystems is referred to as Blue Carbon (BC) with regional CVEs being important coastal BC ecosystems (BCEs) (Nellemann et al., 2009; Williamson and Gattuso, 2022). Blue Carbon as nature-based solution for climate mitigation aims to avoid or mitigate greenhouse gas emissions by conserving and restoring marine carbon- and biodiversity-rich habitats (Nellemann et al., 2009). As such, BC is seen as carbon dioxide removal (CDR) which according to the latest assessment report of the Intergovernmental Panel on Climate Change is needed to offset residual emissions and achieve the internationally targeted net-zero scenario (IPCC, 2022).

For northern Europe, salt marshes and seagrass meadows have been defined as such relevant coastal BCEs (Nellemann et al., 2009; Duarte et al., 2005; Lovelock and Duarte, 2019). Research has primarily focused on these ecosystems, given their relatively high efficiency for carbon storage (Maxwell et al., 2023; Pollmann et al., 2021). However, in recent years, several studies have explored the BC potential of other marine systems (Lovelock and Duarte, 2019; Filgueira et al., 2019; HELCOM, 2021; Jurasinski et al., 2018; Krause-Jensen et al., 2018; Macreadie et al., 2019), such as unvegetated soft sediments, macroalgae (e.g., kelp forests), biogenic reefs (e.g., mussel and oyster reefs), the role of marine organisms (e.g., fish) in these marine systems, effects of outwelling from BCEs for marine C storage, and coastal transition zones such as non-tidal peatlands along the Baltic Sea coast. Protecting these ecosystems from degradation and spatial loss will avoid the release of very large amounts of stored carbon from the associated sediments and soils (Pendleton et al., 2012). Further, restoration of BCEs will increase carbon dioxide removal over time as well as increase local biodiversity in those habitats (Greiner et al., 2013; Frigstad et al., 2021). The important role of BCEs for climate mitigation is broadly recognized, whereas the feasibility of achieving quantifiable and secure negative emissions from restoration is still under debate (Williamson and Gattuso, 2022). In the light of fighting both crises at the same time, research into marine carbon sequestration and storage has received immediate scientific and political attention in the last decade (Macreadie et al., 2021; Merk et al., 2022). Estimates of carbon storage indicate that more than 30 Gt of (organic) carbon are stored over 1.85×10^6 km^2 of BCEs globally (Macreadie et al., 2021). In contrast to other (technical) approaches to ocean-based carbon removal, where potential side effects to the ocean environment need to be closely examined first, conservation and restoration of BC on an ecological scale provides immediate positive effects (Quevedo et al., 2023; Gattuso et al., 2021). However, in densely populated and heavily utilized areas, such as the German coasts, these ecological aspects are overshadowed by conflicts of interest and economic factors, making it crucial to consider the societal and political landscape.

BCEs are directly and indirectly integrated into the global environmental governance framework (Röschel and Neumann, 2023), however it is not specified how states ought to approach their restoration. On the EU level, a new regulation which introduces the necessary framework for ongoing habitat improvement, is the Nature Restoration Law (NRL (European Parliament, 2024; Hering et al., 2023). With aims to integrate biodiversity preservation and climate change mitigation (Art. 1 NRL), the NRL addresses the ongoing deterioration of nature and unfavorable habitat status within the Natura 2000 network identified by the EU Commission's State of Nature report (European Environment Agency, 2020). It distinguishes itself by emphasizing targets, deadlines, and a specific focus on ecosystem restoration, surpassing conventional conservation legislation (Hoek, 2022). The steps and timetables proposed in the NRL provide a clear reference for a German strategy for the formulation of comprehensive nature restoration plans. Together with Germany's 2023 Federal Action Plan on Nature-Based Solutions for Climate and Biodiversity (ANK, Aktionsprogramm Natürlicher Klimaschutz (BMUV, 2023)), synergies between restoration, conservation and climate mitigation strategies in Germany could be strengthened. To move forward with such a national restoration plan (Mengis et al., 2023; European Environment Agency et al., 2021), collecting and visualizing existing knowledge as well as prioritizing open questions is crucial.

This study aims to provide a first summary of BCEs specifically in Germany and within the national environmental policy regime. Here, we provide an overview of the function of carbon sequestration in national (coastal) BCEs as well as of potential (coastal) BCEs of the German North Sea and Baltic Sea. Further we summarize the state of scientific knowledge and related knowledge gaps that need to be addressed in order to I) integrate BC into a comprehensive national climate strategy and II) evaluate how existing BC potential can be enhanced through, e.g., management and restoration activities. We highlight windows of opportunities within the BC policy framework towards the conservation and restoration of BC environments on the sub-national, national and supranational level (European Commission et al., 2023a, 2023b). By outlining and acknowledging the range of open questions on this relatively new topic in Germany in the context of climate mitigation measures, our study helps to guide integrated and interdisciplinary approaches across ecosystems to understand and reveal underlying processes and their positive or negative effects on organic matter (OM) remineralization and/or carbon storage. Here a case study of salt marsh restoration on the German Wadden Sea Coast exemplifies first steps for the practical implementation for enhancing BC in Germany.

2. General principles: carbon capture and sequestration in marine ecosystems

CVEs are characterized by different compositions of vegetation and, thus, they manifest as different types of habitats and ecosystems such as mangrove forests, seagrass meadows or coastal marshes. Nevertheless, even though they are different, general BC drivers and factors apply to all (Fig. 1).

1) CO_2 is captured via photosynthesis and incorporated into above-ground (leaves, plants) and below-ground plant material (roots, rhizomes) (Rullkötter et al., 2006; Akam et al., 2020)
2) Particulate organic carbon (POC) is trapped and captured by the vegetation, enabling a constant burial of organic carbon (C_{org}) through vertical soil development, which is also influenced by varying rates of sea-level rise.
3) Low rates of microbial OM degradation under reducing soil and sediment conditions (Mcleod et al., 2011; Froelich et al., 1979; Canfield and Des Marais, 1991).

The greater part of the vegetation in temperate ecosystems dies off seasonally (this does not apply to mangrove forests or most tropical seagrass beds) and is subsequently remineralized, or transported to adjacent ecosystems, or further into other marine and coastal areas (Rullkötter et al., 2006; Santos et al., 2021; Duarte and Krause-Jensen, 2017).

However, a proportion of the dead biomass is buried *in situ* and is microbially degraded, releasing CO_2, or is stored for decades, centuries or longer. Part of this (autochthonous) carbon is sequestered in deeper sediments or soil due to slower remineralization rates under anoxic conditions compared to the degradation under oxic conditions. Remineralization leads to the formation and outwelling of alkalinity/dissolved inorganic carbon (DIC) (Froelich et al., 1979) which may lead to the *in situ* formation of authigenic carbonates (Akam et al., 2020; Van

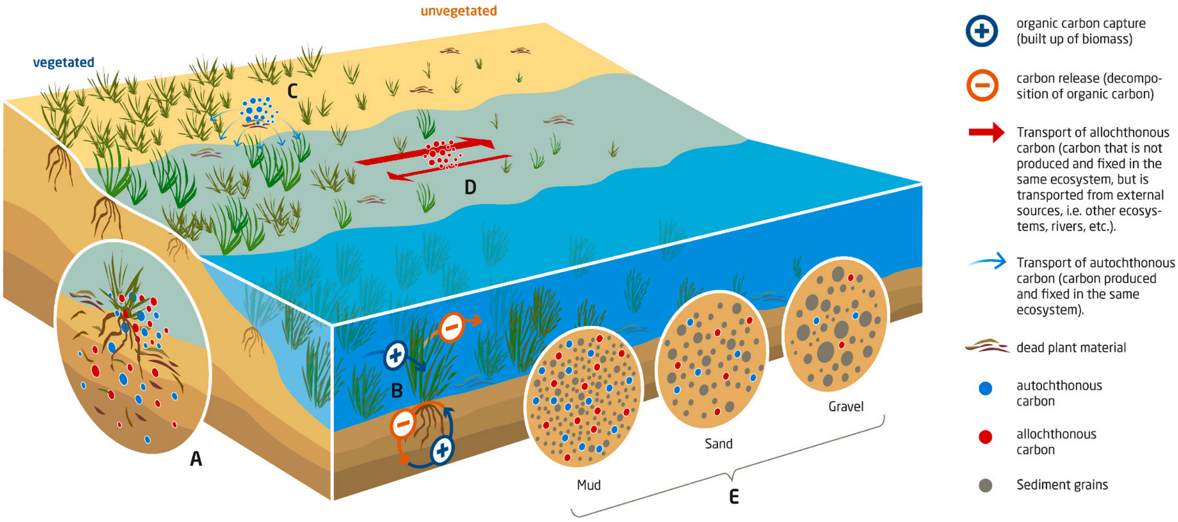


Fig. 1. Blue Carbon (BC) drivers and relevant factors. (A) Vegetation: three-dimensional structures such as stems and leaves reduce flow velocity, increasing sedimentation and particle accumulation. This process captures both autochthonous and allochthonous carbon, allowing a steady burial of C_{org}. The primary long-term storage in the context of BC occurs in deeper layers. **(B)** CO_2 is captured via photosynthesis and incorporated into above-ground 3D-structures and below-ground structures (roots, rhizomes). Carbon is partly released back through organic matter decomposition. In the sediment/soil, where less exchange through, e.g., currents occur, these processes are more locally connected than above-ground. **(C)** Part of the dead biomass is buried in situ and is degraded, with some of the carbon being locally stored in deeper sediments/soils due to reduced remineralisation rates under anoxic and/or highly saline conditions (autochthonous carbon) **(D)** A proportion of this carbon is remineralised or is transported to adjacent ecosystems or further into other marine and coastal areas, whereas the most recalcitrant material, is being transported without being degraded (transport of allochthonous carbon). **(E)** Fine-grained sediments, such as mud, tend to have higher organic carbon contents than coarser-grained sediments, such as sand or gravel. The ratio between autochthonous and allochthonous carbon differs depending on the sediment type. We would expect to see more allochthonous carbon in fine-grained sediments such as mud because material that has been transported between ecosystems (allochthonous carbon) is more likely to have reduced in size than material that has not been transported between ecosystems (autochthonous carbon).

Dam et al., 2022) and potentially influences the pH of coastal areas (Reithmaier et al., 2023). Above ground three dimensional structures of the vegetation (plant components like stem and leaves) reduce the flow velocity and increase sedimentation. Particles (including C_{org} and C_{inorg}) are removed from the water column by the vegetation and accumulate (Mueller et al., 2023; Koch et al., 2006; Mateo et al., 1997), forming and representing an additional allochthonous carbon pool.

In addition to active carbon capture through high primary production and reduced decomposition of organic matter, dense vegetation in CVEs prevents resuspension of deposited sediments and stabilizes the benthic environment. Coastal sediments or soils can contain several-thousand-year-old peat layers, thereby, upon degradation, linking the past with the present carbon cycle. Therefore, the preservation of existing carbon stores in sediments or soils is an effective measure to avoid additional release of carbon from the deposits of CVEs (IPCC, 2022; Duarte et al., 2013; Fourqurean et al., 2012).

The amount of carbon deposited in CVEs depends on factors such as plant species composition, plant primary production, particle accumulation rate (Mcleod et al., 2011; Chmura et al., 2003), and the distance to terrestrial carbon sources. The processes involved in carbon capture and burial operate over time-scales of hours to months (Bax et al., 2021; Pessarrodona et al., 2023). The amount of captured carbon and longevity of storage depends on sediment type, dry bulk density, sedimentation rates, microbial activity, and on environmental conditions such as, e.g., temperature, oxygen conditions and current speed. All factors are subject to natural and anthropogenic variability, e.g., altering flooding frequency and changing salinity zones due to sea level rise in coastal areas, changes in local climate conditions, and events whirling up sediments like storms or bottom fishing activities (Pollmann et al., 2021; Hansen et al., 2017; Kirwan and Megonigal, 2013; Saintilan et al., 2013; Valéry et al., 2004). As carbon sequestration happens over time-scales of centuries to millennia (Duarte et al., 2005; Bax et al., 2021; UNFCCC, 2022), the BC potential of marine ecosystems is mainly assessed within the (underlying) sediments or soils on which the described CVEs grow.

Fine-grained sediments (mud) become usually anoxic within a few mm depth and are usually characterized by higher C_{org} contents compared to coarse-grained sediments (e.g., sand) (Bockelmann et al., 2018; Delafontaine et al., 1996; Diesing et al., 2017). Under oxic conditions that prevail at the sediment surface, carbon is rapidly remineralized (Rullkötter et al., 2006; Froelich et al., 1979; Berner, 1981). In coarse coastal sediments or soils, where advective transport dominates, oxygen may reach several cm into the sediment or soil. Muddy sediments are dominated by diffusive fluxes, leading to oxygen depletion in shallow depth as oxygen supply can't keep up with the oxygen consumption. Further downward, the organic matter degradation (under anoxic conditions) continues at slower rates (Canfield and Des Marais, 1991; Al-Raei et al., 2009; Jørgensen, 1982; Keil, 2017) using other electron acceptors such as nitrate (NO_3^-), manganese (Mn) and iron (Fe) oxides or sulfate. In principle, high sedimentation rates "dilute" the organic matter content, but may also bury organic matter faster into those depths that are oxygen-depleted (Al-Raei et al., 2009; Böttcher et al., 2000; DeFlaun and Mayer, 1983; Llobet-Brossa et al., 1998, 2002). Therefore, higher sedimentation rates usually enhance carbon preservation (Tyson, 2001).

Except for permeable tidal surface sediments during low tide, marine sediments and coastal sediments and soils are typically permanently water-saturated and low in dissolved oxygen compared to drained sediments or soils (de Beer et al., 2005). As a result, microbial decay of organic matter is slow, enabling long(er)-term carbon storage (Mcleod et al., 2011; Froelich et al., 1979; Canfield and Des Marais, 1991).

In general, the functioning of carbon sequestration in coastal and marine habitats is a complex cycle influenced by multiple factors. Some of these general principles are still being examined, e.g., the interaction between inorganic and organic carbon cycles and processes that could counteract carbon storage potential (Van Dam et al., 2021), the role of inorganic carbon (Turrell et al., 2023), the relevance of non-CO_2 greenhouse gas emissions in the C-budget of BCEs (Asplund et al., 2022; Al-Haj and Fulweiler, 2020; Rosentreter et al., 2023) and overall the impact of climate change on (re-established) BCEs in the future.

These open questions make precise accounting of the amount of Blue Carbon stored both on the short and long-term within the different CVEs, very difficult. This calls for new approaches including both *in situ* data and the modelling potential of impact scenarios on carbon stores (Dam et al., 2024).

New and ongoing studies globally focus on quantitatively and qualitatively describing the locally relevant processes. Model simulations for North Sea sediments e.g. found that the majority of fresh C_{org} reaching the seafloor undergoes natural "resuspension-transport-deposition cycles" until finally being remineralized (ca. 87 %), with bioturbation causing 25–30 % of this remineralization. Bioturbation however also contributes to a downward transport of C_{org}, potentially increasing the long-term carbon storage in deeper sediments. Together with C_{org} consumption by macrobenthos this results in a total estimated C_{org} accumulation of around 1.5 ± 1.1 Mg km^{-2} yr^{-1} in the North Sea (Zhang et al., 2024).

With an increasing number of variables added to the overall carbon budget of CVEs like photosynthetic activity, active particle trapping, higher biodiversity representing an increase in CO_2 turn over processes and influence by seasons and tides, the exact quantification of local carbon sequestration gets more challenging. A general prediction of the relative contribution of certain processes to the overall carbon sequestration potential is therefore not possible.

In the following sections, we examine the long-term carbon storage potential and provide estimates of Germany's BC inventory (Table 1). However, as emphasized throughout, the available data are often fragmented and based on estimates.

3. Blue Carbon in German coastal and marine ecosystems

Factors such as the amount of carbon captured, the origin of this carbon (allochthonous vs. autochthonous), physical oceanography, sediment or soil characteristics and the remineralization rate influence the long-term carbon storage potential of BCEs (Hansen et al., 2017; Novak et al., 2020; Verduin and Backhaus, 2000; Mueller et al., 2019a, 2019b; Lavery et al., 2013). Knowing these factors along with the extent covered by the ecosystems as well as their resilience with regard to, e.g., climate change allows an assessment of the carbon storage potential of BC in Germany. It further supports possible protection and optimization measures as required in a national restoration plan, i.e. the NRL or German Marine Strategy. Classical BCEs in Germany are represented by coastal marshes and seagrass meadows. However, other natural systems that contribute to BC storage are also discussed, both globally and in Europe, and are typically referred to as non-classical BC ecosystems (IPCC, 2022). In the following sections, the long-term carbon storage potential of non-vegetated marine sediments is discussed before the classical BCEs in Germany, in order to first illustrate the distribution of different underlying sediment types in the German coastal and marine ecosystems. As a rough quantitative overview see available first data for German coasts in Table 1.

3.1. *Non-vegetated marine sediments*

The long-term storage of organic carbon in marine non-vegetated sediments accounts for only about 5 % of the total carbon inventory in BC systems, while the rest is recycled (Legge et al., 2020). Nevertheless, partly due to their large spatial extent (Diesing et al., 2017; Leipe et al., 2011), shelf seas such as the North and Baltic Sea are considered to play an important role in the storage of carbon (Graves et al., 2022), including carbon that was taken up by marine organisms from the atmosphere (Chen and Borges, 2009; Winogradow and Pempkowiak, 2014). The seabed of the German Exclusive Economic Zone (EEZ) covers 41,034 km^2 in the North Sea and 15,507 km^2 in the Baltic Sea (Al-Haj and Fulweiler, 2020). One key ecosystem for BC research in the North Sea is the Wadden Sea, the largest tidal flat system in the world with largely undisturbed natural processes enabling significant local mud deposition (Colina Alonso et al., 2024). The German sector of the Wadden Sea covers an area of about 4030 km^2 (based on nautical chart/topographic data, data from NLPVW & LKN SH, 2015–2016).

The German North Sea is mainly characterized by shallow water depths (mean depth of 32 m, maximum of 71 m depth (GEBCO, 2022)), a wide tidal range, wind-induced turbulence and often high current

Table 1
Overview of available quantitative data on total area, carbon storage and carbon sequestration rate of (potential) Blue Carbon ecosystems in Germany (see list of references below the table).

Ecosystem/Habitat	est. total area [km^2]	C_{org} in sediment [$kgCm^{-2}$] *1 m depth*	C_{org} sequestration rate [$gCm^{-2}yr^{-1}$]
German North Sea			
Coastal marshes	196.7[a]	12.2–21.7 (Mueller et al., 2019a)	75.64–165.6 (Mueller et al., 2019a)
Coastal sediments	4030.2[b]	N.A.	N.A.
Biogenic reefs	23.5 (Folmer et al., 2017)	N.A.	N.A.
Seagrass	190.9 (KÜFOG GmbH and Steuwer, 2020; Dolch et al., 2020)	N.A.	24 (Mengis et al., 2022)
Macroalgae	11.1 (Stahl et al., 2024)	N.A.	370 (in biomass) (Stahl et al., 2024)
Subtidal sediments	41,034[c]	N.A.	22.5 (Helgoland mud area) (Müller et al., 2024)
German Baltic Sea			
Coastal marshes	50.2[d]	1.76–88.6 (Reet) (Buczko et al., 2022)	N.A.
Coastal sediments	103.7[e]	2.4 ± 3.6 (Stevenson et al., 2023)	N.A.
Biogenic reefs	N.A.	N.A.	N.A.
Seagrass	269.1[f] (Schubert et al., 2015)	7.6 ± 1.6 (Stevenson et al., 2023)	39.4 (Mengis et al., 2022)
Macroalgae	N.A.	N.A.	N.A.
Subtidal sediments	15,507[c]	N.A.	N.A.

References.
[a] Monitoring data NLWKN (2014–2017), monitoring data LKN SH (2021): FFH habitat types 1310, 1320, 1330.
[b] Based on nautical chart/topographic data, data from NLPVW & LKN SH, 2015–2016.
[c] Data German Federal Agency for Nature Conservation online: www.bfn.de/nationale-meeresschutzgebiete (March 24, 2025).
[d] Monitoring data LUNG MV (2005–2021), monitoring data LLUR SH (2012–2020): FFH LRT 1310, 1330.
[e] Monitoring data Lung MV (2011–2021), monitoring data LLUR SH (2012–2020): FFH LRG 1140.
[f] Monitoring data LUNG MV 2017.

velocities. Sands with low C_{org} content dominate in the German Bight (Fig. 2) (de Haas et al., 1997; Diesing et al., 2021). The German North Sea sediments are often mixed and reworked due to the combination of the prevailing environmental conditions, leading to a fairly complete mixing of the water column during wind and storm conditions. The material is usually resuspended several times before final deposition, which means that the organic particles are subject to an enhanced oxic degradation. Therefore, carbon accumulation rates are close to zero over most areas (Diesing et al., 2021), resulting in C_{org} contents (POC dry wt %) of 0.1 % (Southern Bight) to 1.9 % (south east of the Helgoland mud area) or 2 % (TOC dry wt%) (southern part of the Helgoland mud area) respectively in sediments of the German North Sea (de Haas et al., 1997; Müller et al., 2024). Outside of the German part of the North Sea a first estimate (Diesing et al., 2017) of POC storage in the top 10 cm of subtidal sediments of the north west European shelf is 0.48 (0.21–0.79) kgC m^{-2}. The major carbon deposition center of the North Sea (outside of Germany) is the Norwegian Trough (Skagerrak), accounting for about 87 % of the total C_{org} accumulation in the total North Sea because of low current velocities and high sedimentation rates of fine sediments (Diesing et al., 2017; de Haas et al., 1997). In the German North Sea, the area of particular interest for BC research for non-vegetated sediments is the Helgoland mud area, since this is a major offshore mud sink in the North Sea with an annual C_{org} burial flux of 22.5 gC m^{-2} yr^{-1} (Müller et al., 2024).

The German Baltic Sea is also very shallow (mean depth of 18 m, maximum of 47 m (GEBCO, 2022)), with mostly silty sediments (Fig. 2) that are richer in organic material than sediments of the North Sea (Leipe et al., 2011). Outside of the German Baltic Sea average accumulation rates of 22 ± 10 g C_{org} m^{-2} yr^{-1} were determined for the Bornholm Deep (south western Baltic Sea, Denmark) (Winogradow and Pempkowiak, 2014). The C_{org} content (POC dry wt%) varies from 0.1 % in shallow, sandy areas to 16 % in deep, muddy, suboxic to anoxic areas (e.g., Gotland Basin, Sweden) (Leipe et al., 2011). For the top 10 cm of Baltic Sea sediments, the modelled C_{org} storage amounts to 0.83 ± 0.09 kgC m^{-2} (Scheffold and Hense, 2020). There are currently no studies on the C_{org} content specifically in the German EEZ. However, there are no anoxic areas present in the German EEZ which could potentially show C_{org} contents as high as in the Gotland Basin. Areas of particular interest to BC research for non-vegetated sediments in the German Baltic Sea are therefore the deep muddy basins (e.g., Kieler, Lübecker and Mecklenburger Bay, and Arkona Basin).

The potential of annual carbon sequestration and total carbon storage in marine sediments, as well as the origin of organic matter stored in the German EEZ, have not yet been determined in detail for neither the Baltic Sea nor the North Sea. Furthermore, long-term carbon storage in marine sediments is currently mainly considered as C_{org} pools. For a holistic picture, C_{inorg} pools and carbon fluxes need to be investigated too (Leipe et al., 2011; Winogradow and Pempkowiak, 2014). Additionally, microphytobenthos is an important stabilizer of marine sediments in shallow coastal waters. In shallow coastal areas, its productivity can be greater than the productivity of the water column. Thus, mud and sandflats may seem to be devoid of photosynthesizing plants, but due to the carbon fixation of these microalgae and bacteria this is not the case. Middelburg et al. (2000) have shown that the carbon fixed by microphytobenthos can enter all heterotrophic components. Indeed, it has been shown repeatedly that microphytobenthos can play a central role in carbon flow in coastal sediments. In the context of its potential role in carbon sequestration, it is imperative that it is included in future intertidal and coastal carbon considerations.

To be able to estimate the BC potential of non-vegetated marine sediments, in the sense of the conservation of, e.g., carbon-rich habitats under national restoration plans in Germany, the following knowledge gaps need to be addressed: Absence of comprehensive data of the extent of relevant sediment types, carbon stocks (C_{org} and C_{inorg}) and sequestration rates, non-CO_2 greenhouse-gas dynamics and factors influencing them. Several national projects are working on first estimates on the missing data (see supplementary data S1). This basis is crucial to plan and implement future management and conservation plans for BC stocks in marine sediments within the German EEZ as well as on the coasts through protection measures. Marine sediments are named in Annex II in the EU NRL and fall within the monitoring of the Habitats Directive (Council Directive, 1992) as well as of the Marine Strategy Framework Directive (MSFD).

3.2. *Coastal marshes*

Coastal marshes are highly productive ecosystems at the interface between land and sea and are characterized by distinctive flora and fauna. They include salt, brackish, and freshwater marshes, with habitats such as tidal flats, estuaries and shallow coastal waters generally considered adjacent to vegetated coastal marshes. All these habitats are relevant to BC, albeit studied to varying degrees, especially in Germany. Coastal marshes are studied on a broader scale than tidal flats simply because they store more carbon per unit area.

Salt marshes are the most common type of coastal marshes along the German Wadden Sea on the North Sea coast and cover a small portion along the German Baltic Sea coast (Fig. 3). For Wadden Sea marshes only, initial evidence suggests that in these habitats, allochthonous carbon accounts for the majority of the long-term sequestered carbon (Mueller et al., 2023) with an input of approx. 1.84 Mt yr^{-1} and mud sedimentation rates up to a magnitude higher than in the basins of the Wadden Sea (Colina Alonso et al., 2024). Autochthonous carbon contributes comparatively little to this pool (Mueller et al., 2019a, 2019b; Granse et al., 2024). Salt marshes are subject to regular flooding, which

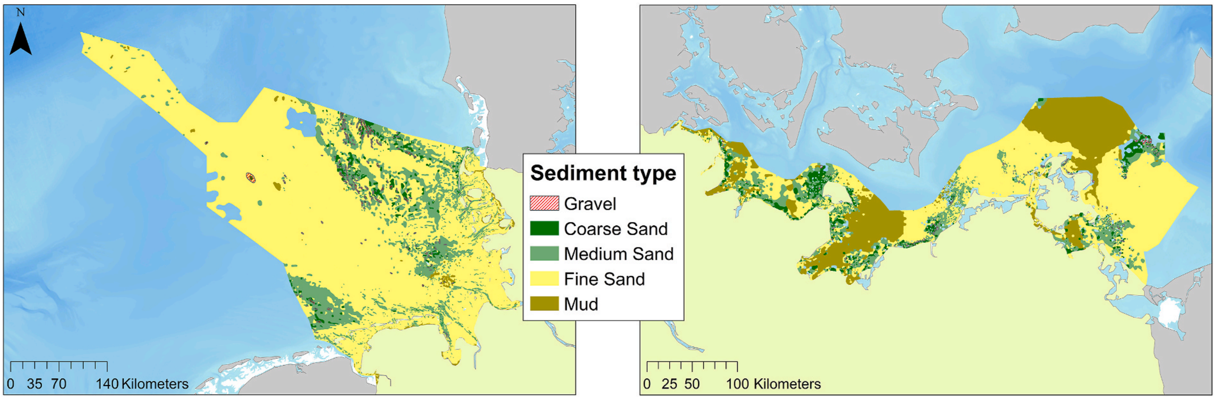


Fig. 2. Distribution and type of marine sediments for the German North Sea (left) and the German Baltic Sea (right). Left part of the Figure based on Laurer and Zeiler, (2014). Right part of the Figure based on BSH, (2016).

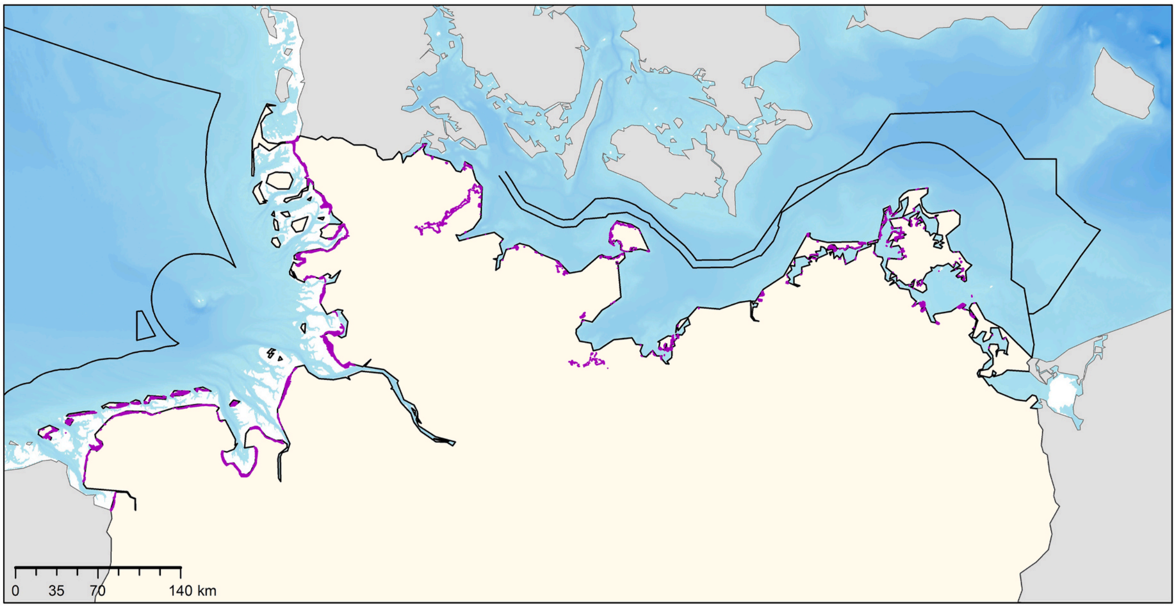


Fig. 3. Distribution map of salt marshes (Directive 92/43/EEC habitat types 1310, 1320 and 1330) along the German North the German North Sea and Baltic Sea coasts, maritime border: German EEZ (Sources: North Sea: Monitoring data NLWKN (2014-2017), monitoring data LKN SH (2021): FFH habitat types 1310, 1320, 1330; Baltic Sea: monitoring data LUNG MV (2005-2021), monitoring data LLUR SH (2012-2020): FFH LRT 1310, 1330), Figure from Koplin et al., (2024).

is a source of external soils and carbon, and their soils are often anaerobic and highly saline. The combination of these factors leads to a suppression of microbial organic matter decomposition, thus enabling carbon preservation and eventually long-term sequestration (Mcleod et al., 2011). However, the influence of anthropogenic drainage systems by, e.g., the use of artificial ditches in salt marshes of the Wadden Sea, likely results in higher than normal drainage rates which, in turn, increase soil aeration and, thus, organic matter decomposition (and associated carbon release) in the upper soil layers (Mueller et al., 2019a; Esselink et al., 2017).

The topsoil of saltmarsh soils contains relatively high densities of organic material, although this is fresh material rather than stored or sequestered carbon. The carbon density decreases with increasing soil depth until it eventually reaches a stable state and can be considered as effectively preserved and long-term sequestered; the depth at which this state is reached varies depending on site hydrology and redox conditions (Mueller et al., 2019b). While a fraction of the topsoil carbon may eventually end up as long-term stored carbon in the subsoil, the carbon stored in the long term is primarily restricted to deeper soil layers (Mueller et al., 2019a). There are several factors affecting the quantity and quality of organic matter throughout the soil column, some of them are: species composition (Schulte Ostermann et al., 2024), the flooding frequency (Butzeck et al., 2015), the distance of the habitat to allochthonous carbon sources, and the availability of electron acceptors (Pollmann et al., 2021). Especially the latter two can be greatly influenced by use and management of the land resources. For the Wadden Sea, at least 50 % of the salt marshes are used for livestock grazing, which can strongly affect plant biomass production, soil microbial activity and carbon sequestration. Studies from the Wadden Sea region suggest a positive impact of livestock grazing on soil carbon sequestration in salt marshes (Mueller et al., 2017, 2019b; Elschot et al., 2015).

Along the Wadden Sea coast, coastal marshes cover about 196.7 km^2, along the Baltic Sea coast about 50.2 km^2 (monitoring data of the German federal states). Measurements for the 1 m-depth soil layer of coastal marshes along the German North Sea coast indicate an annual C_{org} sequestration rate of 75.64–165.6 gC m^{-2} yr^{-1} with a carbon storage potential of 12.2–21.7 kgC m^{-2} (Mueller et al., 2019a). In contrast, for the German Baltic Sea coast, the carbon storage of a marsh colonized by reeds was estimated to vary between 1.76 and 88.6 kgC m^{-2} for the 1 m-depth soil layer (Buczko et al., 2022). To the best of our knowledge, there are no further examples for comparing the measured carbon storage potential between similar coastal marsh types along the German coast. There are also no further examples for comparing different coastal marsh types within the same coastal basin (Mueller et al., 2019b). It is noteworthy that during the preparation of our study, a first step in this direction was achieved, as a compilation of C_{org} for salt marshes on a global scale was carried out (Maxwell et al., 2023).

In Germany and the EU, coastal marshes are already acknowledged as important and conserved habitat types, e.g., under the MSFD and the habitats directive (salt marshes: Directive 92/43/EEC habitat types 1310, 1320, 1330). In the EU NRL they are named as part of Coastal Wetlands under Annex I. To be able to estimate the BC potential of coastal marshes in Germany, also to be included in future national conservation and climate mitigation plans, the following knowledge gaps need to be addressed: absence of comprehensive and high resolution spatial and temporal data on carbon stocks, on sequestration and remineralization rates (OC and IC) as well as on non-CO_2 greenhouse-gas dynamics. Several national projects are working on first estimates on the missing data (see supplementary data S1). With a view on future management regulations, individual assessment of livestock influence on coastal marshes is needed. In relation to climate change effects on salt marshes in the future this includes, e.g., to evaluate promoting carbon storage versus preparing for rising sea levels.

3.3. Seagrass meadows

Seagrass meadows can form large, dense beds and, thus, create extensive habitats on a shallow, sedimentary seafloor from which many associated species benefit (e.g., food, shelter, settlement of sediment) (Bell, 1989; Bertelli and Unsworth, 2014; Ford et al., 2010; Heck and Thoman, 1981; Heck et al., 2003; Larkum et al., 2006; Nacken and Reise, 2000). They are highly productive, represent biodiversity hotspots and form an important cornerstone of the food web of the German seas (Larkum et al., 2006; Horn et al., 2021; Orth et al., 1984). The common seagrass *Zostera marina* L. is the dominant seagrass species in the Baltic Sea (Kuhwald et al., 2021), whereas habitat requirements for the dwarf eelgrass *Z. noltii* Hornem differs and it dominates populations in the Wadden Sea of both Lower Saxony (KÜFOG GmbH and Steuwer, 2020) and Schleswig-Holstein (Dolch et al., 2013), the south-east and north-west sectors of the German North Sea, respectively. In the German Wadden Sea, seagrass meadows cover about 191 km^2 and their distribution is limited to intertidal and sheltered locations (Fig. 4) (Dolch et al., 2017). In comparison, about 269 km^2 of the German Baltic Sea's sublittoral regions are covered by seagrass meadows, large and dense beds are found especially in sheltered bays (Fig. 4) (Kuhwald et al., 2021; Schubert et al., 2015).

Both *Zostera* species structure starkly different meadows (e.g., density and canopy height), which can significantly influence the carbon storage potential (Greiner et al., 2013; Duarte et al., 2013; Ribaudo et al., 2016; Röhr et al., 2018). The flow-reducing influence of the seagrass vegetation depends, among others, on the structural characteristics of the grass meadow (e.g., canopy height, and shoot density) (Gacia et al., 1999; Jankowska et al., 2016). Thus, the structural differences between *Z. marina* and *Z. noltii* result in clear variances, in terms of biomass per unit area between the Baltic and North Sea seagrass meadows both above and below ground, with biomass of Baltic seagrass meadows exceeding that of the populations found in the North Sea (Schubert et al., 2015). In terms of C_{org} storage, there is currently no available data for the seagrass meadows of the North Sea, while there are datasets available for the Baltic Sea, e.g., a stock of approximately 1.9 ± 0.4 kgC m^{-2} was calculated for the first 25 cm of the sediment layer (Stevenson et al., 2023). From this stock, 12 % corresponds to autochthonous sources, whereas 88 % of the C_{org} stock originates from allochthonous sources (phytoplankton and macroalgae). Relics of terrestrial peatland material deposited approximately 6000 years BP during the last deglaciation, represent an unexpected and significant storage of C_{org}. The Baltic Sea, in comparison to the North Sea, has comparatively finer sediments, less hydrodynamic energy (currents and waves), more efficient capture of allochthonous organic material through higher seagrass complexity, and the relics of terrestrial peatlands. These factors, in combination with the lower biomass per unit area of the North Sea suggest a generally lower storage potential per unit area for seagrass areas in the North Sea. However, the increased occurrence of seagrass meadows in the Wadden Sea through favoring natural spread or reintroduction as a nature-based solution will alter hydro-morphodynamic conditions in favor of sediment, and therefore potentially also carbon, accumulation (Jacob et al., 2023).

In Germany, seagrass beds are monitored as one environmental parameter for the assessment of the ecological condition of coastal areas within the framework of the MSFD and EU WFD. In the EU NRL they are named as part of Group 1 (seagrass beds) under Annex II, being an important ecosystem also for the implementation of the future National Marine Strategy (NMS) of the German government. In order to be able to define substantial recovery and restoration plans with respect to their BC potential along the German coasts the following knowledge gaps need to be addressed: Lack of comprehensive data in terms of extent of seagrass meadows (specifically in the subtidal areas in the Baltic Sea), carbon stocks and sequestration rates, non-CO_2 greenhouse-gas dynamics and the local effect of seagrass restoration on BC sequestration potential. Interaction between inorganic and organic carbon within local carbon cycles could counteract carbon storage potential (e.g., calcification in ecosystems). With regard to changing environmental factors such as temperature and nutrient loads also the impact of climate change effects on (re-established) seagrass meadows need to be included into future restoration plans. Several national projects are working on first estimates on the missing data (see supplementary S1) (Koplin et al., 2024).

3.4. Non-classical Blue Carbon ecosystems

The two ecosystems described in the previous sections (marshes and seagrass meadows) are referred to as classical BCEs. Some non-classical BCEs include intertidal and subtidal benthic habitats (e.g., biogenic reefs), mudflats, mesophotic habitats, and macroalgal forests (Bax et al., 2021; James et al., 2024), with the latter currently being of great interest in nature-based CDR research, also in Germany. In the German North Sea, relevant distributions of macroalgae forests in this context are mainly represented as kelp forests and found around the island of Helgoland (Bartsch and Tittley, 2004; Pehlke and Bartsch, 2008; Stahl et al., 2024). Another possibly relevant macroalgae, *Fucus* spp., also grows in the intertidal zone at Helgoland and can be found along almost the entire sublittoral Baltic Sea coast (Bartsch and Tittley, 2004; Johannesson et al., 2011).

Macroalgae fix large amounts of carbon during photosynthesis (Krause-Jensen et al., 2018). However, their distribution in Germany is

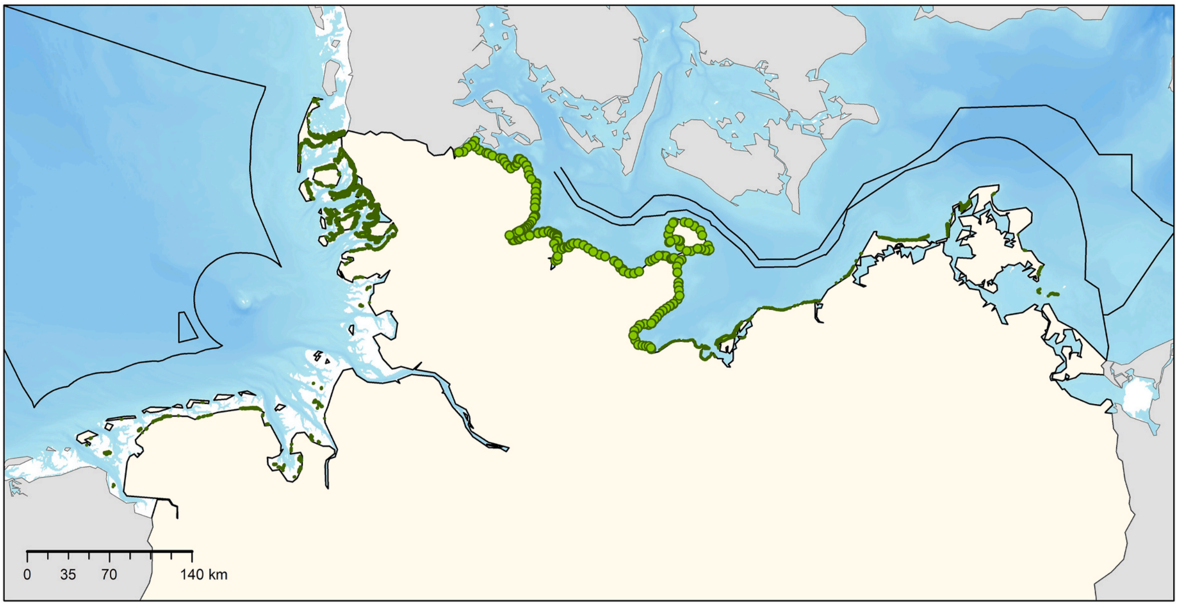


Fig. 4. Distribution map of seagrass meadows along the German North Sea and Baltic Sea coasts, maritime border: German EEZ (Sources: North Sea: KÜFOG GmbH and Steuwer, (2020) ; Dolch et al., (2020)(degree of coverage > 5%); Baltic Sea: Schubert et al., (2015) (point data), monitoring data LUNG MV 2017 (all coverage degrees); Figure from Koplin et al., (2024).

predominantly limited to rocky coasts and shallow reefs, which excludes long-term carbon sequestration in the underlying sediments. Macroalgal detritus can be transported to adjacent deeper habitats or to surrounding habitats with long-term sequestration capacity, such as seagrass meadows or saltmarshes. While this makes it difficult to assess carbon-storage potential for macroalgae forests, the transport of macroalgal detritus suggests macroalgae to act as carbon donors (Hill et al., 2015; Krause-Jensen and Duarte, 2016; Krumhansl and Scheibling, 2012; Queirós et al., 2019). Further difficulties in assessing carbon storage or transport provided by macroalgal forests are related to the uncertainties in calculating storage of macroalgal detritus in sediments, as these require the inclusion of detritus consumption by the detritivorous fauna, the associated remineralization and the local net primary production of the macroalgae (Gallagher et al., 2022), factors for which little or no data are available, as is the case for seagrass and salt marsh detritus.

While presumably of smaller relevance to BC than macroalgal forests, the BC potential of biogenic reefs (e.g., mussel and oyster beds), representing both organic and inorganic depots, is also a current controversially discussed topic (Filgueira et al., 2019; Burrows et al., 2014; Fodrie et al., 2017; Lee et al., 2023). While the formation of calcareous shells releases CO_2 during the process of calcification, particulate inorganic carbon (PIC) can be buried and stored in the sediment for decades, centuries or millennia (Legge et al., 2020; Burrows et al., 2017; Sander et al., 2021). Further, the dissolution of this PIC causes an increase in alkalinity and therefore an uptake of CO_2, possibly also enhancing the sequestration potential in habitats where shells are buried (Wallmann et al., 2022). In addition, mussel beds can have indirect effects on sediment dynamics and consequently enhance carbon burial into the underlying sediment (Sea et al., 2022). To understand the potential of biogenic reefs for the German seas, analyses of processes within existing reefs, but also the consideration of relevant adjacent processes and interactions, are needed (Lee et al., 2023; Filgueira et al., 2015). Biogenic reefs are known to increase biodiversity and are therefore also named as a Directive 92/43/EEC habitat type (1170) as well as in Annex II of the EU NRL. Besides other already well-known ecosystem services supplied by biogenic reefs, they could play a role in long-term carbon storage (Lee et al., 2023). Large knowledge gaps here are still remaining, mostly related to the regional influence of biogenic reefs on the carbon cycle and the surrounding ecosystem.

Several national projects are working on first estimates and collecting missing data also on non-classical BC ecosystems in order to gain a holistic overview of potentials in the German seas (see supplementary S1).

4. Integration of policy, society and research: the implementation of a Blue Carbon Restoration Plan (BCRP)

While BC is emerging as a topic in Germany's environmental policy landscape, global and regional biodiversity conservation and restoration targets for BCEs are still far from being met. Enhancement of BC in Germany requires comprehensive and integrated policy, in addition to scientific knowledge and evidence to inform decision-making and increased societal awareness and interest of Germany's general public in the enhancement of BC. This roadmap reflects on the interaction of policy, society and science and determines windows of opportunity for the comprehensive integration of BC into future decision-making in Germany. The term 'window of opportunity' in reference to governance of BC in Germany refers to a critical period when conditions align favorably to allow for policy changes, e.g., the uptake and integration of BC in German ocean and climate policy. A window of opportunity may emerge when the combination of external and internal pressures allows decision-makers to implement new directions in governance, i.e. enhancing coastal ecosystems for the primary purpose of climate change mitigation (Kingdon, 2013).

Policy action on BC is critically dependent on existing regulations in Germany's complex multi-level governance structure (Boettcher et al., 2023). The aim is to strengthen synergies between existing restoration, conservation, and climate mitigation strategies by implementing a Blue Carbon Restoration Plan (BCRP).

4.1. Policy landscape: windows of opportunity for Blue Carbon enhancement in Germany

Germany is a federal parliamentary republic comprising 16 states, each having its own constitution and being largely autonomous. While Germany's EEZ is governed at the national level, most CVEs are governed under the jurisdiction of Germany's five coastal states (see also *"5. Case study"*). The topic of BC touches upon a multitude of policy topics (e.g., climate, ocean, economy) and therefore the enhancement of BCEs is addressed across multiple entities on federal and national level, further challenging comprehensive governance (e.g., topical fragmentation or doubling of efforts). In addition, Germany, as a Member State of the EU adheres to its supranational environmental policy regime (e.g., European Green Deal) and aims to align its position with other EU Member States in intergovernmental negotiations within the UN System (e.g., nationally determined contributions). The different relevant levels of governance are outlined below, focusing on the national and subnational political levels, as well as the EU level, on which we concentrate our study given the current relevance of the ANK and NRL.

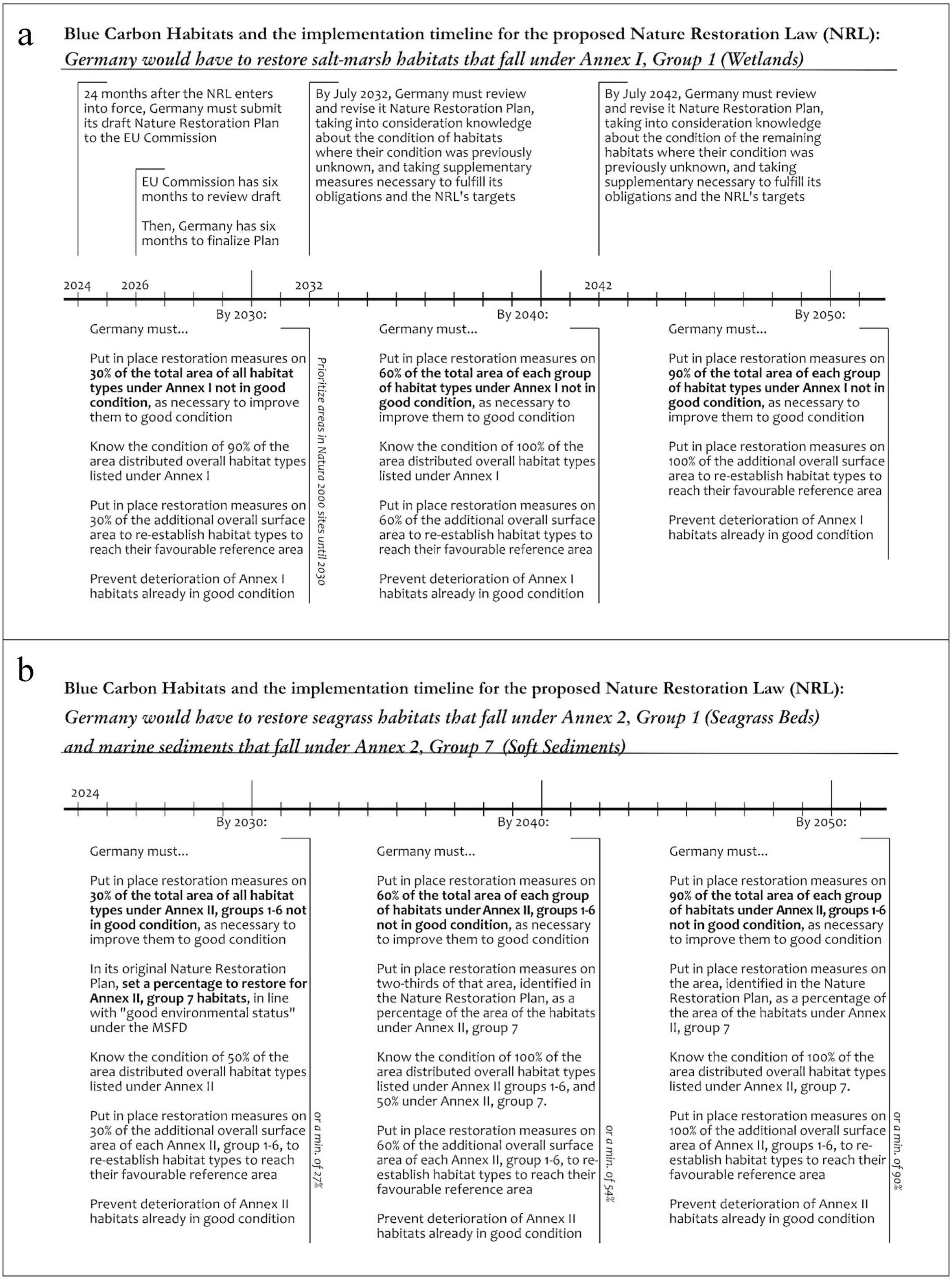
4.1.1. Sub-national/state level

In order to enhance comprehensive management of marine issues across the five coastal federal states the Federal/State Working Group on the North Sea and the Baltic Sea (BLANO, Bund-Länder-Arbeitsgruppe-Nord-und-Ostsee) was established in 2012. BLANO comprises nine working groups and three expert bodies that focus on data collection, evaluation, and action related to marine topics and could also contribute significantly to the national implementation of a BCRP. The establishment of a working group or expert body to explicitly address climate-related issues, including BC, would help to promote cross-cutting policy integration. To achieve this, in addition to the ministries of environment, food and agriculture, digital and transport, the ministry of economy and climate action should be closely integrated into BLANO proceedings.

4.1.2. National/federal level

After federal elections in 2021, the German government put forth a coalition agreement that stated the aim of "enhancing the ocean's natural CO_2 storage capacity through a targeted restoration programme (seagrass meadows, algae forests)". In 2023, Germany published the ANK that recognizes the synergies between nature restoration and climate mitigation. ANK targets specific measures to be achieved by 2026, such as the evaluation of marine carbon inventories and the development of standardized measurement methods, with a total financing budget of four billion euros. The National Marine Strategy (NMS) is set to be published by mid-2025 and will potentially further address these efforts in a synergistic manner as well as multiple aspects of the ocean-climate-nexus in German waters. In addition to financing research projects to close the above-mentioned CVE-related knowledge gaps, the establishment of a national knowledge and data sharing platform to link science with policy is important. Providing policy makers with access to analyzed data on habitat conditions and monitoring status would enhance effective, science-based governance thereof. The ANK's plans to standardize data collection efforts and scientific sampling must allow for national and international comparisons of data and habitats. They must be aligned with stakeholders from all five coastal states, as well as international cross-border cooperation (e.g., with Denmark or the Netherlands). Further, national restoration efforts should integrate carbon sequestration potential of relevant ecosystems and habitats while avoiding additional release of stored carbon by conservation measures (Koplin et al., 2024). The forthcoming NMS is an opportunity to recognize BCEs and marine ecosystems for their climate mitigation potential as well as for their ecological value. The ANK foresees the identification of marine areas with carbon-rich sediments and the development of a possible legal framework for the future designation of climate protection areas (CPAs) (Pogoda et al., 2023). Finally, inclusion of all stakeholders, including the general public (*see "4.2. Societal landscape"*), at appropriate time scales will minimize conflicts, e.g., arising from area-use-competition.

The carbon sequestration potential of German BCEs is rather small in comparison to national emissions. Therefore, a BCRP should consider



Blue Carbon Habitats and the implementation timeline for the proposed Nature Restoration Law (NRL):
Germany would have to restore salt-marsh habitats that fall under Annex I, Group 1 (Wetlands)

24 months after the NRL enters into force, Germany must submit its draft Nature Restoration Plan to the EU Commission

EU Commission has six months to review draft

Then, Germany has six months to finalize Plan

By July 2032, Germany must review and revise it Nature Restoration Plan, taking into consideration knowledge about the condition of habitats where their condition was previously unknown, and taking supplementary measures necessary to fulfill its obligations and the NRL's targets

By July 2042, Germany must review and revise it Nature Restoration Plan, taking into consideration knowledge about the condition of the remaining habitats where their condition was previously unknown, and taking supplementary necessary to fulfill its obligations and the NRL's targets

Germany must...

Put in place restoration measures on **30% of the total area of all habitat types under Annex I not in good condition,** as necessary to improve them to good condition

Know the condition of 90% of the area distributed overall habitat types listed under Annex I

Put in place restoration measures on 30% of the additional overall surface area to re-establish habitat types to reach their favourable reference area

Prevent deterioration of Annex I habitats already in good condition

Germany must...

Put in place restoration measures on **60% of the total area of each group of habitat types under Annex I not in good condition,** as necessary to improve them to good condition

Know the condition of 100% of the area distributed overall habitat types listed under Annex I

Put in place restoration measures on 60% of the additional overall surface area to re-establish habitat types to reach their favourable reference area

Prevent deterioration of Annex I habitats already in good condition

Germany must...

Put in place restoration measures on **90% of the total area of each group of habitat types under Annex I not in good condition,** as necessary to improve them to good condition

Put in place restoration measures on 100% of the additional overall surface area to re-establish habitat types to reach their favourable reference area

Prevent deterioration of Annex I habitats already in good condition

Blue Carbon Habitats and the implementation timeline for the proposed Nature Restoration Law (NRL):
Germany would have to restore seagrass habitats that fall under Annex 2, Group 1 (Seagrass Beds) and marine sediments that fall under Annex 2, Group 7 (Soft Sediments)

Germany must...

Put in place restoration measures on **30% of the total area of all habitat types under Annex II, groups 1-6 not in good condition,** as necessary to improve them to good condition

In its original Nature Restoration Plan, **set a percentage to restore for Annex II, group 7 habitats,** in line with "good environmental status" under the MSFD

Know the condition of 50% of the area distributed overall habitat types listed under Annex II

Put in place restoration measures on 30% of the additional overall surface area of each Annex II, group 1-6, to re-establish habitat types to reach their favourable reference area

Prevent deterioration of Annex II habitats already in good condition

Germany must...

Put in place restoration measures on **60% of the total area of each group of habitats under Annex II, groups 1-6 not in good condition,** as necessary to improve them to good condition

Put in place restoration measures on two-thirds of that area, identified in the Nature Restoration Plan, as a percentage of the area of the habitats under Annex II, group 7

Know the condition of 100% of the area distributed overall habitat types listed under Annex II groups 1-6, and 50% under Annex II, group 7.

Put in place restoration measures on 60% of the additional overall surface area of each Annex II, group 1-6, to re-establish habitat types to reach their favourable reference area

Prevent deterioration of Annex II habitats already in good condition

Germany must...

Put in place restoration measures on **90% of the total area of each group of habitats under Annex II, groups 1-6 not in good condition,** as necessary to improve them to good condition

Put in place restoration measures on the area, identified in the Nature Restoration Plan, as a percentage of the area of the habitats under Annex II, group 7

Know the condition of 100% of the area distributed overall habitat types listed under Annex II, group 7.

Put in place restoration measures on 100% of the additional overall surface area of Annex II, groups 1-6, to re-establish habitat types to reach their favourable reference area

Prevent deterioration of Annex II habitats already in good condition

Fig. 5. Theoretical timelines of the implementation of the EU Nature Restoration law in Germany with regard to the coastal Blue Carbon ecosystem types salt-marshes (a) and seagrass meadows and marine soft sediments (b) (Status as of March 2024).

climate change mitigation and adaptation potential at the same time as importance for conserving and increasing biodiversity when determining which restoration measures to undertake (first). Germany could, for example, give priority for action in areas where salt marshes and seagrass meadows (as well as other potential BC habitats) have the greatest potential for carbon sequestration and simultaneous biodiversity conservation.

4.1.3. Supra-national/EU level

The EU Biodiversity Strategy for 2030 goal of protecting 30 % of terrestrial and marine areas, including BCEs, by the end of the decade is translated into action through several environmental policies. Among those relevant for BC is the EU Habitats Directive, which requires Germany to designate special protection areas as part of the Natura 2000 network to achieve or maintain a 'favorable conservation status' and to monitor and report the status of protected species and habitats to the EU every six years. The German Federal Agency for Nature Conservation (BfN) prepares these reports, while the five federal coastal states develop management plans for each Natura 2000 site which are under their jurisdiction. The MSFD has the objective to achieve or maintain 'good environmental status' in Europe's seas based on 11 indicators, complementing the EU Water Framework Directive (WFD) of inland waters. The German Federal Environment Agency (UBA) is primarily responsible for implementation of the MSFD within the EEZ, while the various ministries and authorities of the five federal coastal states oversee implementation within the 12-mile coastal zone. The new NRL sets multiple binding targets and obligations for listed CVEs (e.g., salt marshes), such as restoring at least 30 % of these ecosystems to good ecological condition (see Fig. 5). The German ANK would transpose the NRL and is put into practice by the Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection (BMUV). Although Germany has decades of accumulated knowledge to support monitoring efforts (Vadrot et al., 2022), coordinating different stakeholders for data collection and assessment is challenging. For comprehensive BC monitoring and management of BCEs in Germany, e.g., under EU legislation, it is important to coordinate and streamline efforts across respective ministries and policy levels. BC restoration and management should encompass a long-term perspective supporting EU and global biodiversity, conservation and restoration goals. Measures need to be tailored to habitat properties including vulnerability to climate change to avoid carbon storage losses over time. Both, ANK and NMS initiatives should be tied to a progress chart for the implementation of the proposed legislation and respective measures. The implementation schedule for the NRL on BCEs (Fig. 5) became legally binding for all EU countries since the law is passed. These (theoretical) timelines shall serve as a guide for national implementation. Under the NRL, states will have concrete milestones for restoring ecosystems to good ecological condition, while retaining flexibility in the means to achieve them. However, appropriate frameworks should be established in the German National Marine Strategy (NMS) for the development, implementation and updating of restoration plans.

Management or restoration plans should give a strategic overview of the estimated carbon sequestration potential of each measure it plans to implement, including "the estimated co-benefits or climate change mitigation and land degradation neutrality associated with the restoration measures over time, as well as wider socio-economic benefits" (Art. 12(2) (j) NRL).

4.2. Societal landscape: potential barriers, knowledge integration and public participation

Germany's BCRP must carefully balance the ecological, economic, and social functions of ecosystems, as well as their contribution to the sustainable development of the regions and communities concerned (Art. 14(16) (b) NRL). Land-based restoration efforts often face public skepticism, as exemplified by debates over peatland restoration versus agriculture (O'Riordan et al., 2016). In coastal areas, e.g., seagrass meadow restoration must contend with eutrophication, particularly in the Baltic Sea, which requires governance measures to reduce nutrient inputs. The governance of eutrophication is a highly contested policy area in Germany, at least with regard to nutrient inputs from the agricultural sector. In addition, marine restoration measures are facing increasing multiple uses, if not outright "industrialization" (Wolfenden and Penjueli, 2023) of marine space by offshore wind farms and other energy infrastructure, military uses, tourism, as well as fishing. The provision of opportunities for public consultation and participation is widely recommended (for example (Clark, 1994), see also NRL: Art. 14 (20) NRL), and indeed various empirical examples show that under certain contextual conditions, public consultation and participation promote political trust, acceptance and legitimacy of environmental decision-making (Richardson and Razzaque, 2011). A broader public participation with the BCRP could be recommended, e.g., through BLANO-working groups or expert groups that have been limited to researchers until now. However, this is no guarantee for increasing public acceptance, as shown by the recent consultation process in Schleswig-Holstein on the idea of a marine national park (Eisenschmidt Consulting Crew, 2023). More emphasis on (long-term) awareness and knowledge building seems necessary to complement public participation processes (Fink and Ratter, 2024). In addition, different governance approaches and policies may need to be applied to the wider public as opposed to the communities or social groups directly affected by restoration activities. For instance, the commonly used argument of socio-economic benefits of restoration (Aubert and Christopoulou, 2022) does not apply equally to all societal groups, as socio-economic benefits are unequally distributed. Concrete compensation for economic losses, as well as benefits for the provision of ecosystem services to social groups such as farmers, should be discussed openly and with the involvement of these affected groups.

Finally, transdisciplinary research approaches - as currently initiated e.g. by the inter- and transdisciplinary German research missions CDRmare and SustainMare of the German Marine Research Alliance (DAM) - play a role by promoting stakeholder dialogues across disciplines for the co-creation and awareness of relevant knowledge and for triggering social learning processes. Successful formats of knowledge integration within different policy institutions, such as HELCOM, OSPAR or BLANO, will facilitate the identification and implementation of best practices.

4.3. Applied BC research: scientific support and approaches for restoration efforts

Researchers can be key actors in providing critical assessments of governance integration efforts and of implementation barriers for a BCRP. Research will close knowledge gaps and optimize as well as standardize BC monitoring (see also "*3. Blue Carbon in German coastal and marine ecosystems*"). Restoration plans also need to be accompanied by research in order to measure their effects and, if necessary, to adopt changes. Within a BCRP, both active and passive approaches are possible. According to the NRL, active approaches for salt marsh restoration may include removing longitudinal and lateral barriers (such as dikes and dams) and for restoring seagrass meadows actively stabilizing the seabed, reducing and where possible eliminating pressure, or active propagation and planting. Passive measures to favor the natural spread may include reducing stressors and allowing ecosystems to develop their own natural dynamics, for example through the abandonment of harvesting and the promotion of wilderness.

As an example of a practical implementation of these restoration approaches, we present a national case study highlighting a key effort focusing on salt marsh restoration in the Lower Saxony Wadden Sea National Park. The study summarizes the ecological, socio-cultural and coastal protection lessons learned from 30 years of dedicated restoration efforts in the German National Park. In addition, valuable knowledge for policy makers and practitioners worldwide is provided.

5. National case study: salt marsh restoration in the Lower Saxony Wadden Sea National Park: a chance to enhance the blue carbon potential of anthropogenically modified salt marshes

5.1. Policy background

Most salt marshes in Germany are part of the Wadden Sea National Park located along the North Sea Coast of the federal states Lower Saxony, Schleswig-Holstein and Hamburg. In accordance with Federal Nature Conservation Act (BNatSchG § 24) the primary goal of the Wadden Sea National Park is to protect and enable the undisturbed course of natural ecosystem processes wherever possible. With respect to the Blue Carbon potential of salt marshes this means that the Wadden Sea National Park aims at preserving or restoring the *natural* C-sequestration function of salt marshes, resulting from their characteristic hydrological, geomorphological and biochemical processes.

5.2. Assessment of the state of salt marshes

Germany has monitored salt marsh habitats in successive six-year reporting periods, most recently from 2013 to 2018, as part of its reporting obligations under the Habitats Directive (Table 2). Germany has a general obligation to maintain or restore the favorable conservation status of designated salt marsh habitats under the Habitats Directive. Under the EU NRL, Germany will have specific timeframes to implement restoration measures to achieve this objective and to ensure that each habitat type improves to a state where 90 percent of the total area of that habitat type is in good condition. In practice, therefore, any German nature restoration plan will need to include restoration measures to maintain the status of salt marshes that are already in good condition, as well as to improve those salt marshes that are in poor (or unknown) condition.

5.3. Principles of salt marsh management and restoration

Many mainland salt marshes in the Wadden Sea, including those in the Lower Saxony Wadden Sea National Park ("National Park" from now on), have been anthropogenically altered or modified in the past. The primary goal for managing the National Park's salt marshes today is to protect and enhance characteristic habitat processes, such as tidal flooding, sediment deposition, erosion, and succession. However, past human impacts still inhibit natural salt marsh development in many areas. The National Park Authority in Lower Saxony (NPA-LS) actively addresses this challenge through salt marsh restoration, involving singular interventions into the ecosystem. In the long run, such interventions reduce anthropogenic influence on salt marsh processes and habitat properties (Fig. 6 B). Simultaneously, aligning salt marsh development with the National Park's goals provides an opportunity to potentially enhance their BC potential.

The following types of salt marsh restoration methods in the National Park can be a blueprint for approaches within a potential BCRP.

1) **Opening or removing summer dikes** facilitates year-round tidal flooding (Fig. 6 C), enabling the re-establishment of salt marsh vegetation in former summer polders (Rupprecht et al., 2023). Regular flooding reduces soil oxygen, slowing microbial decay of organic matter. Increased inundation with saline water suppresses methane production through sulfate input. The sulfate availability shifts soil microbial communities and methanogens are mostly outcompeted (Poffenbarger et al., 2011). Furthermore, soil deposition increases marsh accretion and introduces allochthonous carbon from marine sources (Mueller et al., 2019a; Koppenaal et al., 2022).
2) **Topsoil removal** lowers the soil surface elevation relative to the mean high tide and thus decreases the impact of artificial structures such as field drains. Consequently, formation of relief and vegetation zonation again align with hydrodynamic conditions and soil deposition patterns (Rupprecht et al., 2023). This measure resets the succession in favor of the pioneer/low marsh vegetation. The BC potential of the newly forming salt marsh is expected to exceed that of the anthropogenically drained marsh in the long-term, however further scientific studies are needed to clarify these processes.
3) **Restoring the natural hydrology** in the salt marsh involves deactivating or reducing the artificial drainage system. Unlike natural salt marshes, anthropogenically modified marshes have an oversized drainage system (Hartmann and Stock, 2019). During the restoration process, field and collector drains are filled or blocked to extend flooding duration (Rupprecht et al., 2023). This, in turn, boosts waterlogging in soils, reducing microbial remineralization and promoting a stable state of carbon, and therefore increased storage, in salt marsh soils (Mueller et al., 2019b).

5.4. Lessons learned from 30 years of salt marsh restoration to prioritize where to take action first

Since the National Park's establishment in 1986, 17 salt marsh restoration projects covering approximately 1000 ha have been completed (Rupprecht et al., 2023). Drawing on over 30 years of experience, the NPA-LS observed successful salt marsh re-establishment following interventions, such as summer dike removal (Fig. 7). This suggests a potential increase in their BC potential over time.

Summer dike openings represent a highly effective restoration measure with minimal operational impact and a significant positive effect on BC potential (Martens et al., 2021). This approach improves ecosystem quality without causing remineralization of carbon stocks due to restoration activities. Besides re-establishing a carbon sink, it is likely to reduce CO_2 and CH_4 emissions in formerly disturbed polders (Kroeger et al., 2017).

However, restored polders often exhibit a low proportion of mudflat and pioneer zones due to unchanged elevation. To address this, combining summer dike openings with topsoil removal can be beneficial (Rupprecht et al., 2023). The latter eliminates artificial drainage structures and initially leads to the development of mudflats and pioneer vegetation in the impact area, followed by lower salt marsh vegetation, within 3–5 years (Rupprecht et al., 2023). Old clay pits, where marsh soil has been excavated for reinforcement of dikes, show the establishment of natural marsh creeks and relief and can serve as a proxy to assess potential long-term development (>30 years) of restoration sites with

Table 2
Overview of total area and respective environmental condition status of coastal marsh habitats in Germany according to the Habitats Directive (Habitats Directive, Article 17 Report, 2013–2018, Coastal Habitats, Germany, All Bioregions).

Habitat	Est. Total Area (km^2)	Est. area in Good Condition (km^2)	% Good Condition	Est. area in Poor Condition (km^2)	Est. area in Unknown Condition (km^2)
1310 - Salicornia and other annuals colonizing mud and sand	27.51	23.85	86.68 %	3.66	0.62
1320 - Spartina swards (*Spartinion maritimae*)	23.31	20.3	87.09 %	3.00	0
1330 - Atlantic salt meadows (*Glauco-Puccinellietalia maritimae*)	262.88	168.99	64.28 %	66.60	29.76

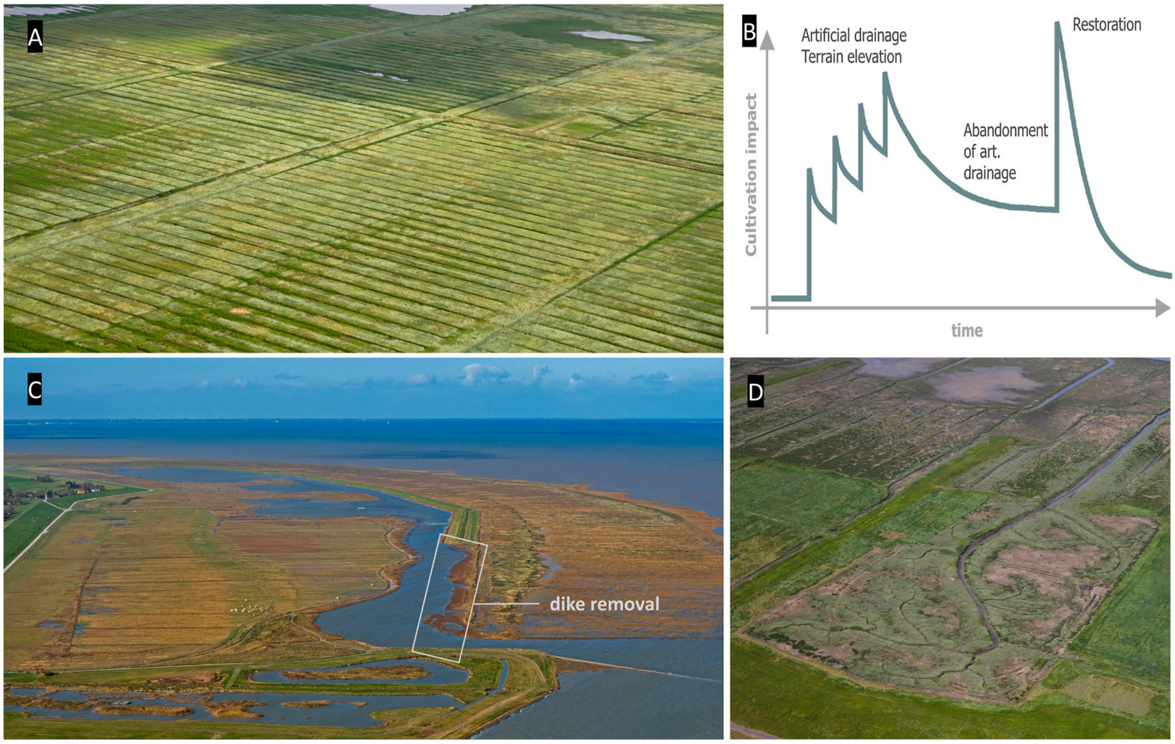


Fig. 6. Salt marsh management and restoration in the National Park: A) typical mainland saltmarsh situation with uniform bed-ditch-structures. B) principal of salt marsh restoration with the goal of reducing cultivation impact on the habitats (© Linders). C) restored polder after dike removal D) Former clay pit, where marsh creeks established after elimination of bed-ditch structures.

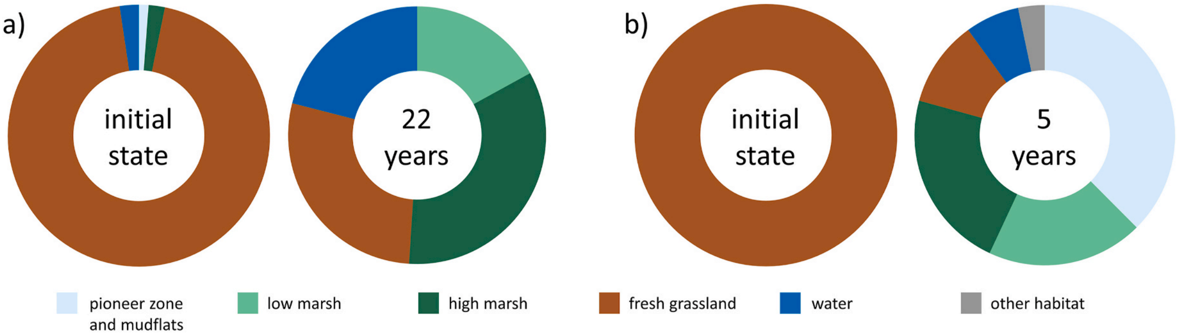


Fig. 7. Habitat development of salt marsh restoration sites prior to and after summer-dike opening. a) Hauener Hooge (monitoring period: 22 years), b) Langwarder Groden (monitoring period: 5 years).

topsoil removal (Fig. 6 D). These old clay pits are currently sampled for predicting the long-term effect of topsoil removal on the carbon storage.

When considering topsoil removal as a method for enhancing BC potential, it is crucial to include the initial and local conditions as a baseline for carbon calculations. E.g., initial carbon remineralization due to topsoil removal might be smaller when applied in polders where grasslands are established than when applied in tidally unrestricted salt marshes. To understand this impact on the net carbon balance in both tidally restricted (e.g., summer polders) and tidally unrestricted marshes, scientific studies are being conducted in collaboration with universities and the NPA-LS.

For rewetting areas that are permanently impacted by former cultivation, thorough planning and construction work is essential for a successful deactivation or reduction of the artificial drainage structures. In the Norderney Ostheller restoration site, shifts in plant communities 12-years post restoration indicate successful rewetting. Ongoing investigations will identify the impact of such measures on the BC potential.

The initial conditions of a restoration site significantly influence its later success of restoration. Key factors, as identified by the NPA-LS, include site morphology, drainage systems, and disturbance duration. While studies on BC in Wadden Sea salt marshes are limited and exclude restoration, embankments, such as summer dike openings are relatively well described and consistently show a significant impact on the BC potential. However, measures, such as reducing artificial drainage or topsoil removal, impacting carbon sequestration, are infrequently studied and involve high uncertainty on the long-term influence on carbon storage. The NPA-LS is actively addressing these knowledge gaps through collaborations with academic partners investigating each restoration measure's impact on Wadden Sea salt marshes. Recognizing the potential symbiosis between promoting habitat quality and enhancing BC, the NPA-LS aims to invest and promote both simultaneously.

5.5. *Societal acceptance: potential barriers, knowledge integration and public participation*

Socio-cultural conflicts with local stakeholders pose a consistent challenge. The mainland salt marshes have deep cultural significance as man-made landscapes, shaped by past generations, creating an emotionally charged conflict when surrendering reclaimed land sites to natural tidal dynamics. Involving local stakeholders is a crucial step in the planning process. However, salt marsh restoration also offers great opportunities for tourism and environmental education, creating a win-win situation for the environment and the economy (Bax et al., 2023). For instance, the 150 ha restoration site "Langwarder Groden" (summer dike opening, topsoil removal) includes a comprehensive nature experience concept, attracting approximately 50.000 visitors annually and gaining full acceptance from local communities despite initial resistance before and during construction.

Reconciliation of salt marsh restoration projects with coastal protection issues is a crucial matter. Salt marshes contribute to coastal protection by promoting wave attenuation and vertical accretion of the dike foreland through sediment trapping and deposition (Barbier et al., 2011; Möller et al., 2014). However, doubts arise among dike managers and associations regarding interference of natural, highly dynamic salt marsh processes such as succession and sedimentary processes with dike safety. Salt marsh restoration thus requires a careful and coordinated strategy, with planning and construction tailored to the local site conditions.

6. Outlook

Germany's Blue Carbon Strategy needs to integrate scientific research, policy coordination and public engagement to improve the restoration and conservation of BCEs. Despite differences in habitat and vegetation, all BCEs share basic carbon sequestration mechanisms. However, critical gaps remain in our knowledge of carbon stock dynamics, sequestration rates, non-CO_2 greenhouse gas emissions, and the resilience of (re-established) BCEs. Addressing these gaps is essential for optimizing future management and regulation of BCEs, informing national restoration plans, and effectively integrating BCE into climate change mitigation strategies. Fragmented governance at the federal, state, and EU levels underscores the need for a Blue Carbon restoration plan that aligns climate action with biodiversity goals. Given the relatively modest carbon sequestration potential of BCEs in Germany, restoration efforts should prioritize areas where carbon storage and biodiversity conservation can be combined as pointed out by the case study in the Lower Saxony Wadden Sea National Park.

The robust support for BC research is exemplified by numerous newly funded projects worldwide. In Germany, it is explicitly included in the coalition agreement, in the ANK and in the designated NMS. Collectively, these initiatives underline (and should result in) a strong commitment to fostering restoration as an integral part of overarching climate and marine conservation strategies. BC ecosystems such as CVEs but also non-classical but potential BC ecosystems, e.g., biogenic reefs provide crucial ecosystem functions and services as biodiversity hotspots and key habitats for a multitude of other organisms (Doolan and Hynes, 2023; Gutiérrez et al., 2011; Smith et al., 2022).

Conservation and restoration of such ecosystems are powerful tools to fight climate change and biodiversity loss. Both are equally important and critical for achieving climate mitigation goals and halting, preventing, and reversing the continuous decrease of biodiversity. These synergies are a chance which must not be underestimated. Seizing this opportunity well can even mean to co-use intact CVEs as living shorelines to improve coastal protection. NbS combined with technical solutions such as dikes are flexible and able to adapt to changing climate conditions (Jacob et al., 2023; Kiesel et al., 2023; Vogelsang et al., 2023).

While Germany has recently published a promising "Federal Action Plan on Nature-based Solutions for Climate and Biodiversity" (ANK 2023 (BMUV, 2023)) it is common sense that climate change mitigation strategies cannot rely on NbS alone: (1) decarbonization must be the priority, (2) conservation of current carbon stocks (regional coastal and marine carbon stocks) and potentials must be explored and measured, (3) relevant CVEs must be expanded and managed to increase CO_2 sequestration potential, as shown in the national case study, while simultaneously supporting these biodiversity hotspots. Successful and sustainable mitigation of climate change is complex and multi-layered. A multi-pronged approach is needed to reach net carbon emissions targets and climate mitigation goals. (Potential) BCEs are not the key to achieving net zero, but they are key ecosystems for enhancing carbon storage processes and biodiversity, as well as providing various co-benefits (Boyd et al., 2024). They are crucial to increasing the resilience of marine habitats and ecosystems to future changes. Germany is moving in the right direction to address the interlinked challenges but needs a temporally and spatially binding framework that a BCRP may provide.

The findings of this study provide valuable lessons to guide other countries as they integrate BC into their national policies. Key scientific, policy and societal considerations need to be addressed to ensure effective implementation. Assessing national blue carbon inventories by identifying missing data and agreeing on standardized scientific methods is crucial to improve the accuracy and comparability of results across regions and internationally. While national regulatory frameworks differ, international directives - such as those at EU level - provide overarching guidance that member states must follow. This study can be seen as a blueprint for how countries can begin to align their policies with these broader directives, promoting a more standardized and coordinated approach to BC management on a global scale. Other countries are encouraged to critically evaluate their own BC policies and adopt best practices for sustainable implementation.

The identified pathways in Germany for integrating BCEs into national climate change strategies and optimizing their management for enhanced carbon sequestration offer a real opportunity to strengthen synergies between nature conservation, restoration and climate change mitigation. Addressing the associated knowledge gaps and leveraging policy opportunities at different levels of governance, while using integrated and interdisciplinary approaches, remains crucial to achieve the goals of realizing the full environmental and climate benefits of BCEs.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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Data availability

No data was used for the research described in the article.

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