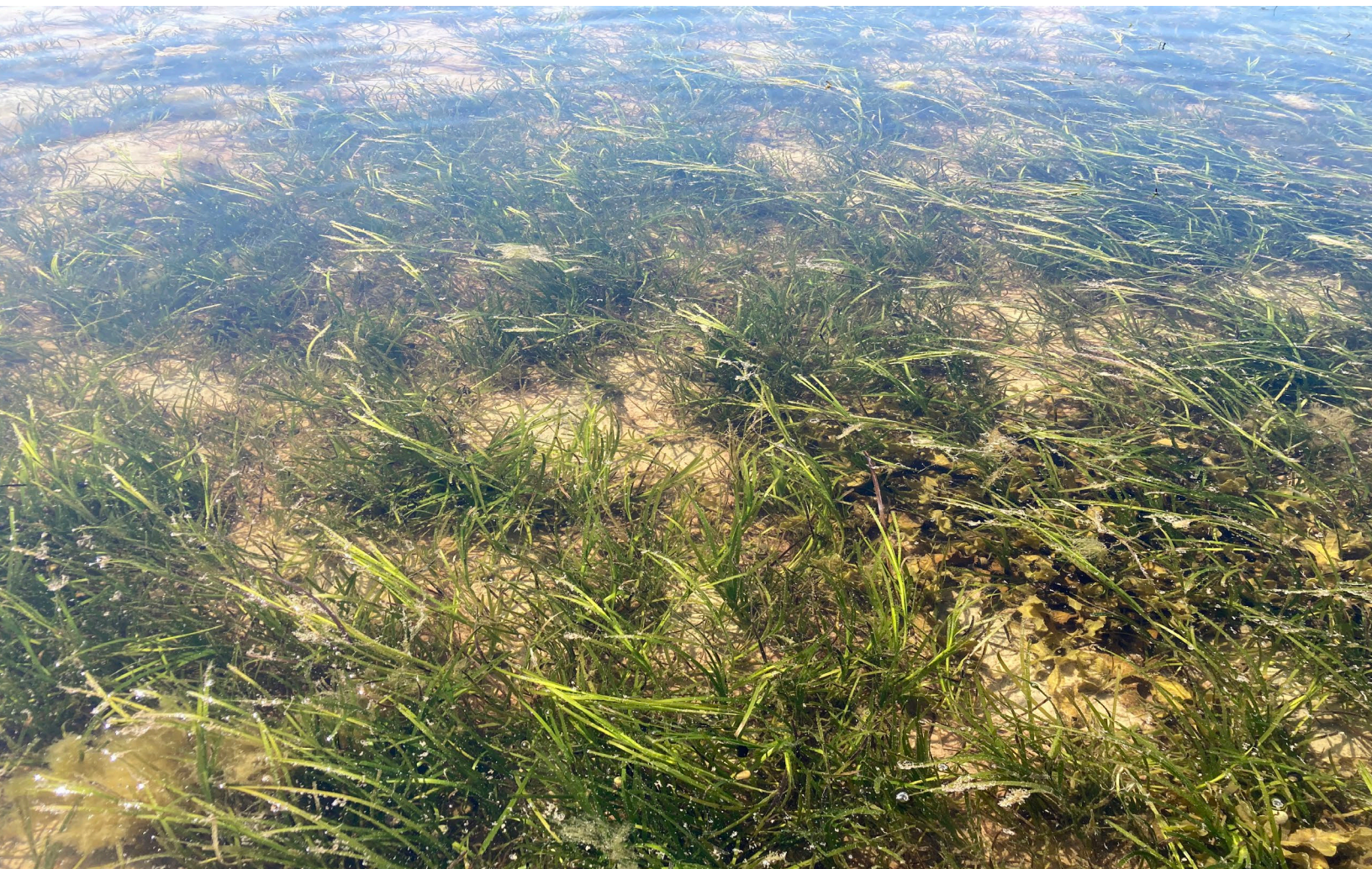


Carbon accumulation rates and protected area networks for Europe's saltmarshes and seagrasses meadows



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Data availability

The compiled dataset is available here:

<https://sdi.eea.europa.eu/catalogue/srv/api/records/f87b5f3f-d3e2-47fa-902f-a49ab340d298>

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Summary

Saltmarshes and seagrass meadows underpin multiple ecosystem functions but have experienced major losses due to human pressures. Halting losses and supporting recovery through protection and restoration therefore offer benefits for biodiversity, coastal protection, and long-term retention of nutrients and carbon (blue carbon). Although blue carbon has received major attention over the past decade, a synthesis of long-term organic carbon accumulation rates (CAR) of European saltmarsh and seagrass habitats along with their protection status is lacking. We reviewed the literature to address this knowledge gap. We compiled 265 and 88 observations of saltmarsh-, and seagrass CAR, respectively, across the NE Atlantic Ocean (197 and 26 obs.), the Mediterranean Sea (36 and 55 obs.) and the Baltic Sea (32 and 7 obs.), with seagrass CAR representing the three native genera, *Posidonia* (43 obs. of *P. oceanica* endemic to the Mediterranean Sea), *Cymodocea* (12 obs.) and *Zostera* (32 obs.), as well as the introduced *Halophila* (1 obs.). Saltmarsh CAR was consistently higher than seagrass CAR, but data also showed marked regional and habitat-specific differences. Median saltmarsh CAR was almost similar in the NE Atlantic ($86.9\text{gC m}^{-2}\text{ y}^{-1}$) and the Mediterranean ($88.3\text{gC m}^{-2}\text{ y}^{-1}$) but only about half in the Baltic ($47.0\text{gC m}^{-2}\text{ y}^{-1}$). Median seagrass CAR was highest in the Mediterranean ($29.8\text{gC m}^{-2}\text{ y}^{-1}$), lower in the NE Atlantic ($24.5\text{gC m}^{-2}\text{ y}^{-1}$) and much lower in the Baltic Sea ($0.8\text{gC m}^{-2}\text{ y}^{-1}$), partly reflecting that median CAR among genera was about 50% higher for the expanded meadows of *Posidonia* ($30.8\text{gC m}^{-2}\text{ y}^{-1}$) in the Mediterranean Sea compared to *Zostera* ($19.6\text{gC m}^{-2}\text{ y}^{-1}$) and *Cymodocea* ($19.5\text{gC m}^{-2}\text{ y}^{-1}$). Median CAR of non-*Posidonia* seagrasses and Baltic saltmarshes fall below IPCC's Tier 1 emission factors (seagrass: $43\text{gC m}^{-2}\text{ y}^{-1}$, tidal marsh: $91\text{gC m}^{-2}\text{ y}^{-1}$), implying a need to adjust those to avoid overestimation of the climate benefit of European blue carbon strategies. Our review showed that current protection schemes cover most of Europe's saltmarsh area and associated CAR (74.2-98.6% across regional seas, least for the Baltic Sea) whereas seagrass meadows are less covered (57.7-64.7%). In addition to expanding the protection coverage for seagrasses, it is necessary to increase the efficiency of protection and reduce stressors because the habitats are still suffering losses. Rethinking and expansion of the designation of protected saltmarsh and seagrass areas are also required to safeguard these ecosystems in the future where sea level rise is projected to inundate and squeeze most of Europe's current saltmarsh areas, which therefore also require space and protection in landward direction.

1 Introduction

The protection and restoration of saltmarshes and seagrass meadows are seen as multifaceted nature-based solutions because these habitats offer benefits for biodiversity, coastal protection, nutrient and carbon retention in their sediments (e.g. Howard et al. 2023). The role of vegetated coastal habitats for carbon accumulation was highlighted with the concept of “blue carbon” (Nellemann et al. 2009), defined by IPCC as “all biologically-driven carbon fluxes and storage in marine systems that are amenable to management” (IPCC 2019) and included as natural climate solutions in the 2013 Wetland supplement to the IPCC guidelines for national greenhouse gas inventories (IPCC 2014). Several international and EU environmental policy measures target the protection and restoration of these coastal vegetated ecosystems, including the Kunming-Montreal Global Biodiversity Framework adopted under the auspices of the Convention on Biological Diversity and, at the European Union scale, the Habitats Directive, the Water Framework Directive, the EU Biodiversity Strategy for 2030 and the Nature Restoration Regulation among others. In addition, some national frameworks also foresee mitigation activities in coastal wetlands as part of their National Determined Contributions (Herr and Landis, 2016). Despite the multiscale and growing policy initiatives targeting blue carbon habitat conservation, there are still many knowledge gaps concerning the annual carbon accumulation rates (CAR) of saltmarsh- and seagrass habitats across Europe as well as the proportion of these habitats and their associated CAR which is currently covered vs. uncovered by spatial protection measures in the European regional seas, i.e. the Mediterranean Sea, the Northeast (NE) Atlantic Ocean, the Baltic Sea and the Black Sea.

There are four indigenous European seagrass species: *Posidonia oceanica*, endemic to the Mediterranean Sea, *Cymodocea nodosa* distributed in the Mediterranean Sea and the NE Atlantic Ocean, and the *Zostera* species *Z. noltei* and *Z. marina* (including the narrow-leaved variant *Z. angustifolia*) occurring in all European seas, with *Z. marina* being the globally most extended of all seagrass species and extending furthest north (Green and Short 2003; den Hartog et al. 2006). The Mediterranean Sea also has two exotic seagrasses: *Halophila stipulacea*, which was introduced via the Suez Canal more than a century ago (Por, 1978) and has recently spread into the Atlantic Ocean, and *Halophila decipiens*, discovered (in Greece) in 2018, likely introduced through shipping activities (Gerakaris et al., 2020). Despite their multiple ecosystem functions, seagrass distributions and trends over time are still insufficiently quantified with only a fraction of the global habitat having been surveyed, due to the methodological challenges of observing and mapping these vast underwater habitats (Dunic et al. 2021). The surveys of European seagrasses indicate that the seagrass area has suffered major losses since the late 19th century, equivalent to approximately 1/3 at the European scale and 19% at the global scale although with a tendency towards recent stabilization (de los Santos et al. 2019; Dunic et al. 2021). The reported major loss drivers, based mainly on descriptive rather than inferential evaluation, are coastal development, poor water quality and disease while better management is helping counteract the losses (de los Santos et al. 2019; Dunic et al. 2021).

Here we use the general term saltmarsh to cover a variety of habitat types at the European scale, including classifications under the European Environment Agency’s EUNIS (European Nature Information System; ‘A2.5 Saltmarshes and coastal reed beds’) and habitat classes under the European Union’s (EU’s) Habitats Directive Annex I (‘1310 Salicornia and other annuals colonizing mud and sand’, ‘1320 *Spartina* swards (*Spartinion maritimae*)’, ‘1330 Atlantic salt meadows (*Glauco-*

Puccinellietalia maritimae’, ‘1410 Mediterranean salt meadows (*Juncetalia maritimi*)’, ‘1630 Boreal Baltic coastal meadows’). These habitats, also referred to as coastal marshes, coastal wetlands, coastal grasslands, tidal marshes and seashore meadows (Vehmaa et al. 2024), are diverse and widespread productive coastal wetlands linking land- and sea ecosystems across microtidal and macrotidal coastlines (Davidson 2016; Yando et al. 2023; Vehmaa et al. 2024). Because they are only partly inundated, their area extent is much better known than that of seagrasses and has recently been successfully assessed through the use of remote sensing satellite imagery (Mcowen et al. 2017; Campbell et al. 2022; Murray et al. 2019 and 2022), although inconsistent nomenclature in the Nordic region implied that e.g. Norway only recently realised that they also have coastal marshes (Vehma et al. 2024 and references therein).

Since around year 1900, 63% of coastal natural wetlands are estimated to have been lost at the global scale and 71% at the European scale (Davidson 2014), mainly due to conversion to arable land infrastructure through diking and draining (Gedan et al. 2009). Satellite-based assessments show continued area losses (Campbell et al. 2022) partly offset by gains, with 27% of changes associated to direct effect of human activities, such as conversion to agriculture and restoration (through reestablishment of natural hydrology), and the rest related to coastal processes and climate change (Murray et al. 2022). Sea level rise and associated coastal squeeze is projected to cause major future loss of coastal marsh area (Canal-Vergés et al. 2025; Schuerch et al. 2025).

To assess the carbon sequestration potential of European seagrasses and saltmarshes, data on long-term organic carbon (OC) accumulation rates (CAR) in their sediments is needed, as this is the primary compartment for long-term OC storage. Despite growing interest in blue carbon, most research has focused on measuring OC sediment stocks, the total amount of OC accumulated down to a specific depth, rather than CAR, the rate of accumulation of OC. Stocks provide insufficient information because they do not reflect the time it took to accumulate the OC while CAR reflects the timeframe and quantifies the rate at which these habitats accumulate OC in their sediments. For OC to be considered “long-term captured” before degrading and re-entering the atmosphere, it must remain stored for climatically significant periods, generally considered to be at least 100 years. Yet, CAR alone remains an insufficient proxy for true sequestration and net climate mitigation, which also require tracing the origin of the soil OC to verify it was fixed from atmospheric CO₂ via habitat photosynthesis, and quantify net GHG fluxes (CH₄, N₂O) to ensure the habitat provides net negative emissions (Don et al. 2023). Therefore, while long-term CAR indicates *potential* OC sequestration, which cannot be asserted without these additional assessments, it currently is the most widely available metric for a large-scale assessment of OC sequestration potential. The most recent reviews of CAR for saltmarshes and seagrasses (Mcleod et al. 2011; Ouyang and Lee, 2014) need update, as a significant amount of new data has been released since their publication but has not yet been compiled and analysed. It is also important to identify how updated CAR values compare with CAR-based emission levels in IPCC’s guiding document for quantifying and reporting national GHG emissions and removals related to land-use changes of coastal wetlands. IPCC applies so-called Tier 1 emission factors, which are the general factors to be used unless country-scale- or more local scale information is available (IPCC 2014). Spatial protection of saltmarsh- and seagrass habitats through the management of human activities to reduce pressures (in situ and distant) that caused and still are causing habitat loss would preserve and even increase blue carbon habitat areas and associated CAR. This would underpin the continued capacity of these habitats to accumulate and

store OC, helping prevent loss of the already accumulated OC stocks while also supporting the many other ecosystem functions of these habitats. The European network of protected areas (PAs) includes sites designated under the Habitats Directive Natura 2000 framework, national programs and Regional Sea Conventions (HELCOM for the Baltic, OSPAR for the Atlantic Ocean, SPAMI for the Mediterranean Sea). While EU MPA network assessments have indicated that spatial protection effort has been increasing over the last decade in line with the targets set by international and EU environmental policy drivers, there is yet no overview of the extent of spatial protection that overall network provides to saltmarshes and seagrasses present in EU waters and their associated CAR. Because saltmarshes and seagrasses grow in neighbouring habitats at the land-sea boundary and constitute an important part of the coastal mosaic of habitats (Smith et al. 2024), efficient protection strategies should ideally straddle across and beyond both habitat types jointly so as to enable an ecosystemic conservation effect to the benefit of all habitats contained in the land-sea continuum. The interconnection of deteriorating conservation status from one habitat to another adjacent one, in the absence of sound conservation measures, has been described by several authors. For example, the loss of seagrass meadows can increase the erosion of saltmarsh habitats (Nardin et al. 2018) and draining of saltmarshes can increase the runoff of nutrients and coloured dissolved organic matter and thereby hamper the seagrass beds (Valiela and Cole, 2002; Preston et al. 2025). Nevertheless, there is, to our knowledge, no overview of the joint protection of saltmarshes and seagrasses at the European scale.

The main aims of this study were twofold. The first main aim was, based on a compilation of data from the literature, to quantify CAR in European seagrasses and saltmarsh sediments, including variability between regions, habitats and seagrass genera, and to identify potential predictors of these differences. To increase the relevance of the findings for climate mitigation and comparability across habitat types, seagrass genera, and regional seas, our focus was on long-term CAR estimates, aiming to represent a period as close as possible to the past 100 years, and to compare the values to IPCC's Tier 1 emission factors for saltmarshes and seagrasses. The second main aim was to define the extent of each blue carbon habitat that is included in the currently established PA network and that is therefore potentially object of protection measures, and quantify the fraction of habitat areas and associated CAR that currently extend outside of the protected area network and that therefore remain unprotected. This aim was achieved by combining CAR data with habitat distribution maps and overlaying them with maps of the extent of protected areas.

2 Methods

2.1 Study area and spatial data sets

We focus on the European regional seas, which include the Northeast Atlantic Ocean, the Baltic Sea, the Black Sea and part of the Mediterranean Sea. We largely use the delimitation of marine areas applied in previous Marine Protected Areas (MPA) network assessments under the European Environment Agency's (EEAs) European Topic Centres (ETC's; ETC/ICM and ETC/BE; Table 1). However, since saltmarshes and some shallow seagrass habitats are distributed in transitional or marine waters between land and the marine coastal baseline, the base assessment area was extended by calculating a 50km buffer stretching landward from the coastline/baseline and manually adjusting the new boundaries where the automatized buffer tool was unable to carry out the landward extension of the base assessment area. The resulting extended assessment area is illustrated for a portion of the Baltic Sea to visualise the inclusion of PAs over the transitional waters that would otherwise have been excluded from the base assessment area considered for other strictly marine PAs (Figure 1A).

We acquired spatial datasets on habitat extent and PA-networks for the extended assessment area from various sources (Table 1). The different PA designations were harmonised and coded into three categories:

- 1) Designated Natura 2000 sites (N2000), which includes Sites of Community Importance (SCIs), Special Areas of Conservation (SACs) and Special Protection Areas (SPAs);
- 2) Nationally Designated sites (NDSs), as reported in the EEA database; and
- 3) Regional Sea Convention sites (RSCs), designated under the framework of Regional Sea Convention programs (HELCOM for the Baltic Sea, OSPAR for the Atlantic Ocean, SPAMI for the Mediterranean Sea) (Table S1).

The habitat spatial datasets were elaborated to obtain fit-for-purpose layers of the EU marine/transitional water with seagrass and saltmarsh habitats. These layers were then overlaid with the PA networks to assess the degree to which seagrass and saltmarsh habitats are included in existing PAs at subregional scale.

2.2 Saltmarsh and seagrass distribution

The distribution of seagrass meadows and saltmarshes at the European scale was identified based on available global and European-scale data sources from the UN Environment Programme World Conservation Monitoring Centre (UNEP-WCMC), European Marine Observation and Data Network (EMODnet) Seabed Habitats, and Corine Land Cover (CLC) (Table 1).

Table 1. Description of data and data sources

Data layer	Source (reference or link to data)	Database version (download date)
Assessment area		
EEA marine assessment areas	https://sdi.eea.europa.eu/catalogue/srv/eng/catalog.search#/metadata/a14375b6-13fa-44d2-9e01-f8bee5954dbb	v. 3 (Oct. 2022)
Habitat data		
Global distribution of seagrasses	UNEP-WCMC. Dataset ID: WCMC-013-014 https://data.unep-wcmc.org/datasets/7	v. 7.1 (Mar. 2021)
Seagrass cover (Essential Ocean Variable) in European waters	EMODnet Seabed Habitats https://emodnet.ec.europa.eu/geonetwork/emodnet/eng/catalog.search#/metadata/39746d9c-4220-425c-bc26-7cb3056c36a5	(Sep. 2023)
Global Distribution of Saltmarsh	UNEP-WCMC. Dataset ID: WCMC-027 https://data.unep-wcmc.org/datasets/43	v. 6.1 (Mar. 2021)
CORINE Land Cover 2018 (vector), Europe, 6-yearly	DOI (raster 100 m): https://doi.org/10.2909/960998c1-1870-4e82-8051-6485205ebbac . https://land.copernicus.eu/en/products/corine-land-cover/clc2018#download	2020_20u1 (May 2020)
Designation types		
Nationally designated areas for public access	https://sdi.eea.europa.eu/data/ef77dd7b-e5d0-4b93-81e1-f721b91ec9fe	v. 21 (Jun. 2023)
Natura 2000	https://sdi.eea.europa.eu/data/95e717d4-81dc-415d-a8f0-fecdf7e686b0	Natura2000_v2022 (shp) (2022)
HELCOM MPAs	https://maps.helcom.fi/website/MADS/download/?id=d27df8c0-de86-4d13-a06d-35a8f50b16fa	HELCOM_MPAs_2019_2 (Dec. 2022)
OSPAR Convention MPA	OSPAR carto_amp.ospar_polygon_wdpa_simplified_1729600373_5980 https://carto.mpa.ospar.org/fr/1/ospar.map	(Oct 2024)
SPAMI - Specially Protected Areas of Mediterranean Importance	MAPAMED, the database on sites of interest for the conservation of marine environment in the Mediterranean Sea. MedPAN, UNEP/MAP/RAC-SPA https://data.medchm.net/en/map/279/1/100/0	SPAMIs_wgs84_2020 (2020)

Each dataset had its pros and cons in terms of spatial data attributes (e.g., identification of different species) and/or issues such as duplication of spatial information with minor differences (e.g., spatial shifts due to incorrect original datums, which can lead to habitat duplication) and inconsistencies in spatial information between maps of the same area. To address these issues, we edited the selected original layers and performed basic spatial analysis to create new derived layers, which were used for the spatial assessment.

For creating the saltmarsh layer, the global WCMC saltmarsh layer was clipped to the EU PA assessment regions, and the CLC saltmarsh cells were given priority as CLC provided the most updated distribution of saltmarshes. For creating the seagrass layers the EMODnet seagrass dataset was prioritised over the WCMC because it is derived from field investigations and because it specifies the seagrass species present (Figure 1B). Further details are available in Supplementary materials (S1).

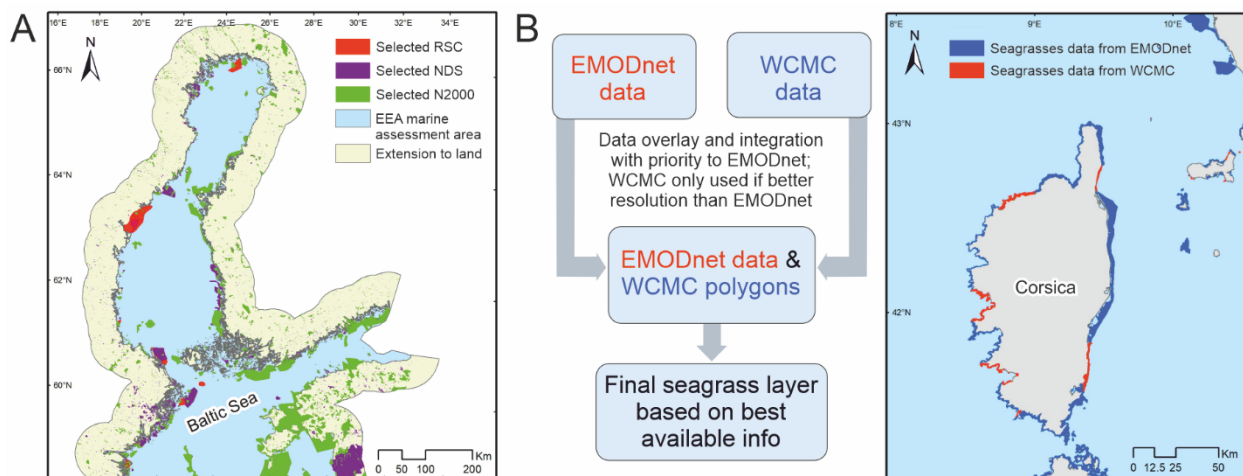


Figure 1. Methodological approach for layer creation. A: Landward extension of the EEA marine assessment area, exemplified for part of the Baltic Sea. The map shows the boundaries of the different PA designations within the assessment area: RSCs areas (designated under the framework of Regional Sea Convention programs; N2000 areas belonging to the Natura 2000 network; NDS areas - Nationally Designated sites. B. Seagrass layer creation process with flow chart and example of a resulting map of seagrass distribution area in the Western Mediterranean Sea (Corsica).

2.3 Overlaying habitat areas with protected areas - preparation of spatial data layers

All the original spatial layers are vector layers, generally shape files. Each layer group (different PA network types and different habitats) could potentially overlap and introduce issues due to superimposition. Superimposition of PAs happens when given areas are protected under more than one protection framework, e.g. designated as both a Natura 2000 site and a nationally protected site. Superimposition for habitats happens when a single area is covered by a mosaic of two or more overlaid habitat types. This overlapping issue complicates accurate calculation of the total surface area any single habitat type or protection network occupies. To overcome these issues and generate spatial datasets not affected by topological issues, each polygon layer was converted into raster grid format that was later used for the spatial computation (details in supplementary materials S2 and Table S1). The cell size was set to 10 meters, chosen to ensure that our spatial datasets are comparable with EEA’s automated spatial JEDI procedures and that the layers could be aligned and snapped to the EEA environmental reporting grid standards. To speed up the analysis, while maintaining the flexibility to conduct a more detailed assessment if needed, the spatial processing was performed at the subregional level, with the key results for habitat percentage and blue carbon (CAR) scenarios later being aggregated and reported at the broader regional scale.

2.4 Carbon accumulation rates (CAR) of European seagrasses and saltmarshes - Literature survey

We conducted a non-systematic literature search, primarily using recent review papers and secondary sources (e.g. Database of blue carbon in European seagrass and saltmarsh habitats version v1, in the meantime updated by Graversen et al. (2024); and Arias-Ortiz et al. unpublished) where relevant data had already been synthesized. Additional papers were found via Google Scholar, using different combinations of keywords such as "blue carbon," "seagrass", "*Posidonia*", "*Zostera*," "*Cymodocea*", "saltmarsh", "marsh", "coastal habitats", "carbon burial/accumulation rate", "210Pb", and "14C" among others. In some cases, CAR were not directly reported, or details on their calculation were missing. In such instances, we extracted raw depth-specific data from tables, figures, supplementary information, or online datasets to estimate CAR. To retrieve detailed raw data from figures, we used PlotDigitizer (<https://plotdigitizer.com/app>), a free online tool that allows users to extract numerical data from images.

The compiled dataset includes comprehensive information on geographic and habitat characteristics, management and environmental factors, detailed CAR data and associated methodological information. CAR is reported in grams of organic carbon per square meter per year ($\text{g OC m}^2 \text{ yr}^{-1}$, with standard deviation), indicating whether values were directly taken from publications or calculated/recalculated. Each record includes the time span used to derive the CAR estimates, the specific calculation procedure, and the dating method used (210Pb, 137Cs, 14C or historical reconstruction). The CAR estimates represent OC accumulation over periods generally spanning the past century, with the central 80% of values (10th-90th percentiles) ranging from 41 to 141 years in saltmarshes and from 50 to 128 years in seagrass meadows. Associated data on sediment accumulation rate (SAR) and mass accumulation rate (MAR) are also included. To ensure data quality, methodological information is also recorded, including aspects on core compression and its correction, the OC analysis method, and the sampling device used, including its dimension.

We calculated CAR values when they were either not reported or were incompatible with our timeframe of about 100 years. This was typically the case for CAR data spanning several hundred years or millennia (e.g., based on 14C dating). In such instances, provided that depth-resolved OC data (OC percentage and either dry bulk density or cumulative mass) and sediment ages were available, we calculated CAR as follows. First, we calculated the OC stock for each discrete sediment layer. We then summed the stocks across layers down to the depth where sediment dating indicated an age closest to 100 years. Finally, we divided the total OC stock at that depth by the age to obtain the rate. The OC stock per layer was derived from OC densities and corrected for compaction when necessary. If compaction had not been measured but was likely significant (e.g., when tubes were inserted by manual hammering), we applied the mass cumulative method (i.e. summing the sediment mass across layers) to estimate OC stocks, provided soil mass data were available. This method is not affected by compaction issues during field core extraction. On a few occasions, studies reported only average MAR or SAR and average OC content or OC density for a section or the entire core, rather than depth-resolved data. In these cases, we estimated OC accumulation by multiplying the reported MAR by the average OC content, or by multiplying the average soil OC density by the sedimentation rate.

In sediment cores, not all layers are typically analysed for OC. Therefore, before calculating OC stocks, missing OC% values were estimated using one of two approaches. If dry bulk density or water content had been measured for all layers and showed a strong relationship with the available OC data, we used that relationship to estimate the missing OC%. Otherwise, we estimated the missing OC% as the average of the layers immediately above and below.

We also recalculated CAR values to approximate a 100-year rate when the original study did not specify key details, such as the time period used for its calculations or to account for suspected errors in the original age-depth models, which included models that lacked a modern surface age (leading to implausibly old dates for recent sediments) and models that failed to apply a marine reservoir effect correction for seagrass samples in ¹⁴C dating.

For saltmarsh sites, when OC was measured indirectly through soil organic matter estimates using the loss-on-ignition (LOI) method, and no site-specific LOI-OC conversion function was available, we applied the general conversion function by Maxwell et al. (2024) for saltmarshes. This formula was derived from 35 studies across various coastal tidal marsh types, covering broad climatic, oceanographic, and geomorphic gradients, and is suitable for regional or larger-scale applications. For seagrasses, no general conversion equation was necessary, as compiled studies using LOI data provided a site-specific conversion function to recalculate CAR estimates.

2.5 CAR from literature review to inform spatial analysis of area integrated CAR (CAR_{int})

CAR estimates were combined with the spatial data layers of seagrass and saltmarsh habitats within and beyond existing PA networks at subregional scale to generate estimates of area-integrated annual CAR (CAR_{int} , Gigagrams * Year⁻¹) per habitat category and the proportion protected by the current PA network for each habitat across each EU subregion. CAR_{int} was estimated from the median, lower (25%) and upper (75%) quartiles of CAR per habitat category multiplied by the respective habitat surface areas by taxonomic typology (only for seagrasses) and geographic region. Because no CAR data was available from the Black Sea, this region was left out of the assessment.

For saltmarshes, the collated CAR data were too scarce to develop the analyses for different saltmarsh habitat sub-categories, so a single estimate was extracted for an overarching saltmarsh habitat type for each regional sea.

For seagrasses, specific CAR values were calculated for the following seagrass species/genera: *Posidonia oceanica* (hereafter *Posidonia*), *Cymodocea nodosa* (hereafter *Cymodocea*), *Zostera marina*, *Z. noltii*, *Z. angustifolia* (hereafter *Zostera*) for each regional sea where they occurred. For the Mediterranean Sea, no CAR data were available for *Zostera*. However, most of the Mediterranean *Zostera* area was confined to the shallow, protected Thau Lagoon, and given the relative similarity also in salinity and temperature, *Zostera* CAR for the Mediterranean Sea was estimated based on a small subset of eight observations of *Zostera noltei* from shallow estuarine habitats in south Portugal and Spain in the NE Atlantic Ocean. For *Halophila*, our compilation had insufficient CAR data (only one observation) for assessments. For *Zostera* in the Baltic Sea we also had a limited CAR data set of seven observations. Similarly, for *Cymodocea nodosa* in the NE Atlantic, only a single data point

was available. Such cases of only few CAR observations for a given habitat at regional sea level increase the uncertainty of the estimate, which should therefore be interpreted with caution. We therefore decided to apply the genus CAR for *Zostera* in the Baltic and *Cymodocea* in the NE Atlantic, based on all European estimates available for each genus, which provide more robust median CAR values but potentially ignores differences in CAR between regional seas.

2.6 Explanatory variables for saltmarsh and seagrass CAR

Candidate explanatory variables for saltmarsh and seagrass CAR variability were selected based on common global drivers identified in previous studies supplemented by additional variables also considered relevant and constrained by the availability of data layers. The selected variables were subsequently analysed for their potential correlation with CAR (see next section).

For saltmarsh CAR we selected the following candidate variables: relative sea level rise (RSLR, which refers to the combined effect of changes in eustatic sea level and vertical land movement), tidal range, and mean annual temperature, wave fetch, distances to high-flow rivers and time span of CAR estimates. We hypothesized positive correlations between CAR and variables facilitating the delivery and settlement of particles (RSLR, tidal range, proximity to high-flow rivers, sheltered settings) and negative correlations with variables promoting erosion (wave fetch) or increasing the likelihood of OC degradation (time span of CAR estimate), while correlations with temperature could be positive (stimulating production) or negative (stimulating degradation).

For seagrass CAR our selected candidate variables were: current speed, light at the seabed, water depth, nutrient concentration, temperature at the seabed, sediment accretion rate (SAR), and time span of CAR estimates. In line with the approach for saltmarsh CAR, we hypothesized positive correlations with variables facilitating the delivery and settlement of particles (sheltered settings, high SAR) or promoting seagrass production (light at the seabed, shallow depth, higher temperature up to a threshold) and negative correlations with variables promoting erosion (current speed), or increasing the likelihood of OC degradation (excess nutrients, time span of CAR estimate, high temperature).

Details on the rationale for the selection of variables is provided in supplementary materials (S5) along with overviews, descriptions and sources of the spatial data used as candidate explanatory variables for saltmarshes (Table S6) and seagrasses (Table S7).

2.7 Data analysis

We used non-parametric Kruskal-Wallis tests to evaluate several key hypotheses, as the data violated assumptions of normality and homoscedasticity. Where a Kruskal-Wallis test yielded a significant result, we conducted post-hoc pairwise comparisons using Wilcoxon rank-sum tests with Benjamini-Hochberg (BH) p-value adjustment to account for multiple comparisons. Specifically, we tested: (i) whether CAR values were higher in saltmarshes than in seagrasses within each region; (ii) whether CAR values in saltmarshes differed among regions, expecting lower values in the Baltic and Mediterranean saltmarshes due to their microtidal nature, especially in the Baltic Sea, where tidal

ranges are extremely small (only a few centimetres); and (iii) whether CAR values in seagrasses differed among genera and among regions. We expected *Posidonia* to show higher CAR than smaller seagrass genera, as it tends to develop highly organic sediments and larger organic carbon stocks (Kennedy et al. 2022), and we anticipated higher CAR in the Mediterranean where *Posidonia* is the dominant seagrass species. We also (iv) tested for correlations between CAR and the hypothesized potential explanatory variables introduced above using linear or exponential quantile regression, with model fits applied to the median (50th) as well as the lower (5th) and upper (95th) percentiles. All statistical analyses were conducted in the free statistical software R version 4.3.0 with a significance level of $\alpha=0.05$.

To estimate the integrated carbon accumulation rate (CAR_{int}) across European seas, we combined observed CAR data with the estimated areal extent of each habitat type and seagrass genus. Specifically, for CAR values, we used the medians and interquartile ranges (25th-75th percentiles) per marine region, because significant differences in CARs were found among these regions for each habitat. These representative CAR values were multiplied by the corresponding available habitat areas within each marine region, both within and outside protected areas, to obtain regional-scale CAR_{int} estimates.

This scaling-up approach assumes that the compiled CAR data are representative of the regional variability within each habitat type and seagrass genus and that the available habitat area estimates reflect the current spatial extent of saltmarshes and seagrasses. When seagrass genus data by region were too few for meaningful regional upscaling, which was the case for *Zostera* in the Baltic Sea and *Cymodocea* in the Northeast Atlantic, we used overall genus-specific data for calculation of regional CAR_{int} by genus. Likewise, in the case of *Zostera* CAR in the Mediterranean Sea, we used the earlier-described subset of *Z. noltei* CAR for the upscaling.

Under these assumptions, the resulting CAR_{int} values provide a first-order estimate of the potential carbon accumulation by saltmarshes and seagrasses across the European seas and their subregions. Although a regression-based upscaling approach would have been preferable, this was not feasible within the time constraints of the study. Nevertheless, simple spatial scaling or “back-of-the-envelope” calculations based on representative blue carbon data can yield first-order estimates that are broadly comparable to those obtained from ensemble modelling approaches (e.g., Ladd et al. 2022).

3 Results

3.1 Saltmarsh and seagrass distribution area and protection effort

The study produced a compounded EU saltmarsh distribution map extending over a total area of 3,393.5km², with the largest distribution (1,810km²) in the NE Atlantic Ocean, 1,274km² in the Mediterranean Sea, 237km² in the Baltic Sea and 72.5km² in the Black Sea (Figure 2A, Table S2). The embedded seagrass area (11,450km²) was more than three times larger with the most extensive meadows found in the Mediterranean Sea (7,548km²), 3,096km² in the Northeast Atlantic, and 806km² in the Baltic Sea (Table S2). The seagrass area is represented by the three native European seagrass genera, with *Posidonia* meadows (6,356km²) confined to the Mediterranean Sea, *Cymodocea* meadows (2,131km²) in the Mediterranean Sea and the NE Atlantic, and *Zostera* meadows (1,790km²) primarily in the NE Atlantic and Baltic Sea and with a small area in the Mediterranean Sea. Moreover, the survey included 173km² of *Halophila* in the Mediterranean Sea (Figure 2B, Table S2). These European saltmarsh and seagrass areas extracted from three European-scale data sources, although being relatively large, do not extend across the complete habitat surface area range known across the European territory³ and across the EU. Importantly, no information was available on the extent of seagrass meadows known to occur in EU coasts of the Black Sea, and the considerable distribution of *Z. marina* along the gently sloping Danish coastlines was not completely mapped at the time of the compilation. Other seagrass areas may also be missing as these submerged habitats are challenging to quantify. Nevertheless, the vast areas included should provide a good basis for the European-scale assessment of associated blue carbon and protection levels.

European saltmarshes are almost completely (>90%) covered by PA networks in most regions and subregions, except for the Baltic Sea where PA coverage is about 74% (Figure 2A, Table S3). Seagrass PA coverage is markedly lower but still substantial, with an average of 65%, 63% and 57% of the habitat extent included by PA networks in the Mediterranean Sea, the NE Atlantic Ocean and the Baltic Sea, respectively (Figure 2A, Table S3). At subregion level the Adriatic Sea is the Mediterranean region with least (38%) coverage of seagrasses by PAs (Figure 2B).

A closer look at the protection level among the native European seagrass genera indicates that *Posidonia* (Figure 2C) is better covered by PAs than *Zostera* (Figure 2E) and *Cymodocea* (Figure 2D) in the Mediterranean Sea, while in the NE Atlantic Ocean *Zostera* is better covered than *Cymodocea*. *Cymodocea* is generally least and insufficiently represented in the currently established protected areas (Figure 2D, Table S3). The limited area of the non-native *Halophila* in the Mediterranean Sea happens to be very well covered by PAs (Figure 2E, Table S3).

A regional comparison of the protection designations for saltmarshes in general and for seagrass genera highlights that, overall, the habitats are mostly protected through their inclusion in N2000 sites (Figure 3). In addition, saltmarshes are almost equally protected in all regions through Nationally Designated Sites (NDSs) except for the Adriatic Sea, Celtic Sea, and Black Sea where their inclusion in N2000 is much higher than in NDSs (Figure 3). Seagrasses are mostly protected by N2000 except for *Zostera* in the Aegean-Levantine Sea and *Cymodocea* in the Western Mediterranean Sea,

³ UK areas are excluded because they are not part of the EU

both more protected by NDSs. In some cases, the inclusion in RSCs is almost the same as for NDSs. The total habitat surface area protected by the combined networks can exceed 100% because of the frequent overlaps of the PA designation types (N2000, NDS and RSC) (Figure 3).

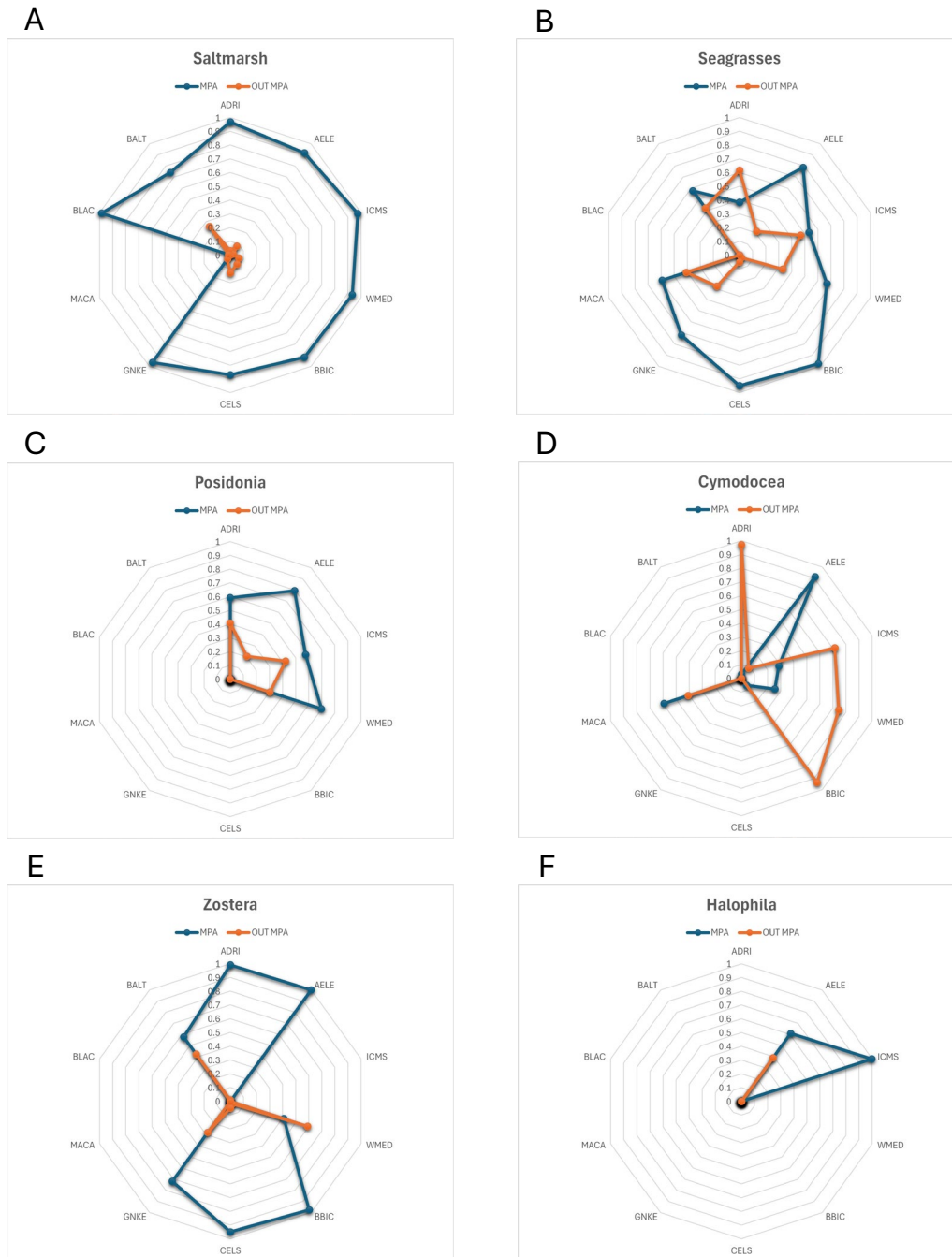


Figure 2. Spatial protection of seagrass- and saltmarsh habitats offered through protected areas (PAs) in European marine regions/subregions. The charts show the fraction of habitat area contained within (blue) and outside (orange) PAs for (A) saltmarshes and (B) seagrasses in general as well as for each of the four seagrass genera (C-F). Marine region/subregions (shown clockwise): Mediterranean Sea (MED) subregions: Adriatic Sea (ADRI), Aegean and Levantine Sea (AELE), Ionian and Central Mediterranean Sea (ICME), Western Mediterranean Sea (WMED), NE Atlantic Ocean (NEA) subregions: Bay of Biscay and the Iberian Coast (BBIC), Celtic Sea (CELS), Greater North Sea incl. the Kattegat and the English Channel (GNKE), Macaronesia (MACA); Black Sea (BLAC) and Baltic Sea (BALT).

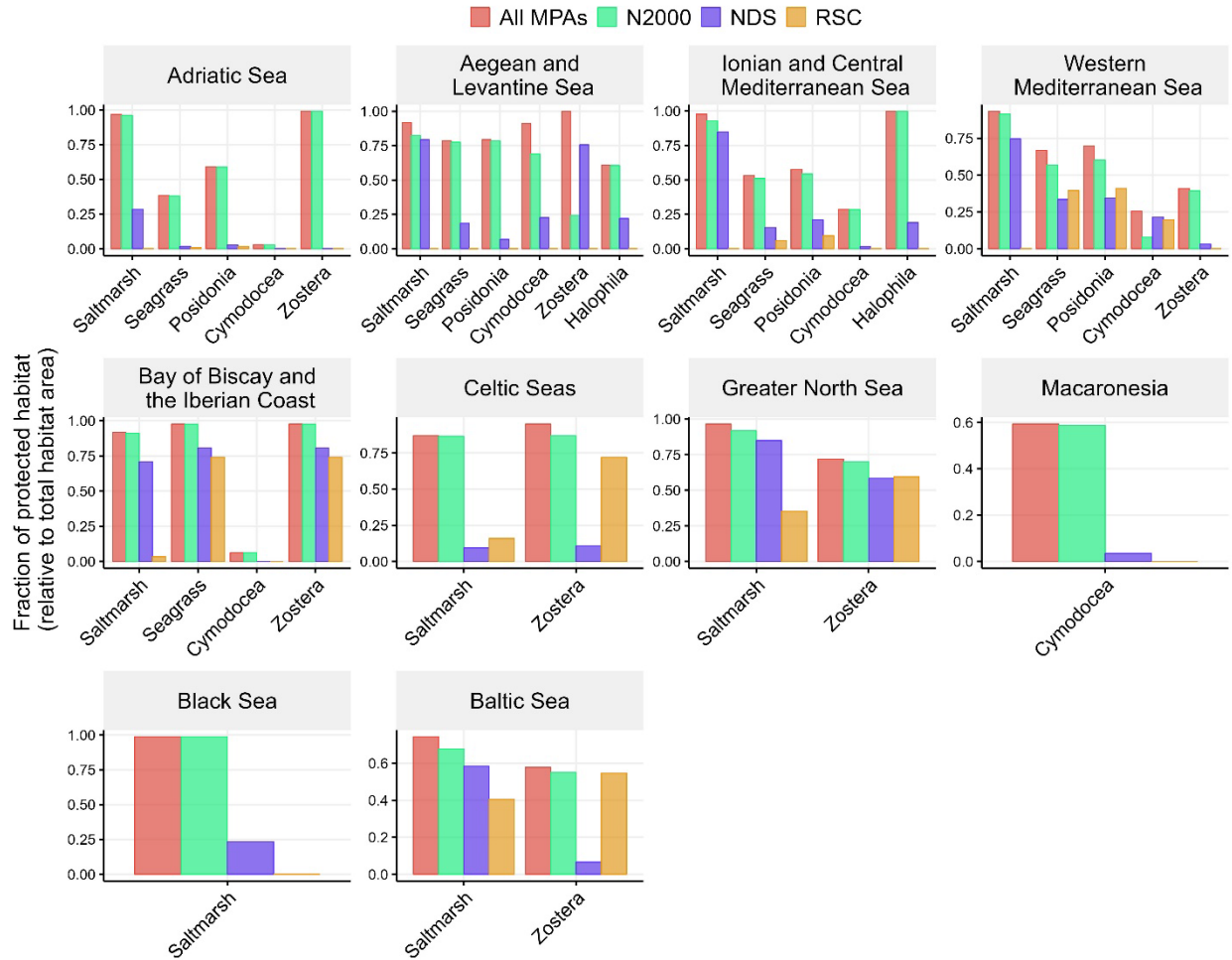


Figure 3. Relative contribution of different protected area (PA) networks to spatial protection of saltmarshes and seagrasses (in general and by genus) by European region/subregion (Upper panel: Mediterranean Sea; Central panel: Northeast Atlantic Ocean; Lower panel: Black Sea (left); Baltic Sea (right)). For each habitat, the first bar (brownish red) represents the fraction of habitat included in combined PAs while the adjacent bars (green, purple and yellow) indicate the fraction included in single PAs (N2000: Natura 2000 sites, NDSs: Nationally Designated Sites reported in the EEA database, RSCs: Regional Sea Convention programs).

3.2 Carbon accumulation rates (CAR)

To ensure comparability, we filtered the data, retaining only the CAR estimates calculated for the time period closest to 100 years per core, with a maximum cutoff of 250 years. This is important because CAR generally decreases over longer timespans due to OC degradation and soil auto compaction over time. Even after filtering (which fully excluded eight sediment cores from *Posidonia* meadows with excessive timespan), the time span used in CAR calculations across Europe ranged from a few decades to ca. 240 years. It slightly varied across habitats, with the central 80% of values (10th-90th percentiles) ranging from 41 to 141 years in saltmarshes and from 50 to 128 years in seagrass meadows.

For saltmarshes, the CAR dataset included 265 observations from 47 publications across 18 countries and 94 locations. Most observations (197) were from the NE Atlantic Ocean, followed by the Mediterranean Sea (36 observations) and the Baltic Sea (32 observations) (Table S4). Median saltmarsh CAR ($79.0\text{g m}^{-2}\text{y}^{-1}$) at the European scale was 2.6 times higher than median seagrass CAR ($24.6\text{g m}^{-2}\text{y}^{-1}$). Saltmarshes consistently exhibited higher median CAR compared to seagrass meadows across all marine regions (Figure 4A, Table S4). This difference was statistically significant in the Baltic Sea ($\chi^2=6.58$, $df=1$, $p=0.010$), NE Atlantic Ocean ($\chi^2=24.9$, $df=1$, $p<0.001$), and Mediterranean Sea ($\chi^2=17.0$, $df=1$, $p<0.001$; Kruskal–Wallis tests).

The lowest median saltmarsh CAR was in the Baltic Sea ($47.0\text{g m}^{-2}\text{y}^{-1}$), while the Mediterranean Sea ($88.3\text{g m}^{-2}\text{y}^{-1}$) and the NE Atlantic Ocean ($86.9\text{g m}^{-2}\text{y}^{-1}$) had similar medians (Figure 4B). NE Atlantic Ocean saltmarshes showed the highest CAR variability, with some rates exceeding $500\text{g m}^{-2}\text{y}^{-1}$. A Kruskal–Wallis test confirmed significant differences in CAR among regions ($\chi^2(2)=12.93$, $p=0.002$), and post-hoc Wilcoxon tests (Benjamini–Hochberg adjusted) indicated that the Baltic Sea differed significantly from both the NE Atlantic ($p=0.001$) and the Mediterranean ($p=0.029$), while no difference was found between the latter two ($p=0.895$).

For seagrasses, the CAR data included 88 observations from 21 publications, across 11 countries and 54 locations. Most of the observations (55) were from the Mediterranean Sea, followed by the NE Atlantic Ocean (26) and the Baltic Sea (7) (Table S4). Across genera, most observations (43) represented *Posidonia*, 32 represented *Zostera*, and 12 represented *Cymodocea*, while there was only one observation for *Halophila*. Median seagrass CAR was highest in the Mediterranean Sea ($29.8\text{g m}^{-2}\text{y}^{-1}$) followed by the NE Atlantic Ocean ($24.5\text{g m}^{-2}\text{y}^{-1}$) (Figure 4A, Table S4) and was remarkably low in the Baltic Sea ($0.8\text{g m}^{-2}\text{y}^{-1}$). A Kruskal–Wallis test revealed significant differences in seagrass CAR among marine regions ($\chi^2(2)=6.97$, $p=0.031$). Post-hoc Wilcoxon tests (Benjamini–Hochberg adjusted) indicated that CAR in the Mediterranean Sea was significantly higher than in the Baltic Sea ($p=0.028$), while differences between the Baltic Sea and NE Atlantic ($p=0.078$) and between the NE Atlantic and Mediterranean ($p=0.398$) were not significant.

The high CAR level for the Mediterranean Sea seagrasses reflects the dominance of the endemic and largest seagrass species in Europe, *Posidonia oceanica*, for which median CAR ($30.8\text{g m}^{-2}\text{y}^{-1}$) is about 1.6-fold higher than that of the other European seagrass genera, *Zostera* (represented by *Z. marina* and *Z. noltei*, $19.6\text{g m}^{-2}\text{y}^{-1}$) and *Cymodocea nodosa* ($19.5\text{g m}^{-2}\text{y}^{-1}$) (Figure 4C), which have similar median CAR. A Kruskal–Wallis test excluding *Halophila* indicated no statistically significant differences in CAR among seagrass genera ($\chi^2(2)=4.87$, $p=0.088$). Post-hoc Wilcoxon tests (Benjamini–Hochberg adjusted) suggested a tendency for *Posidonia* to have higher CAR than *Zostera* ($p=0.098$), but no significant differences were detected among the other genera ($p>0.36$). In the NE Atlantic Ocean, seagrass CAR data was dominated by *Zostera* (18 of the 19 CAR observations, the last one was represented by *Cymodocea*). The Baltic CAR data was entirely represented by *Zostera* but included only seven observations covering a wide variability (25–75% percentiles of $0\text{--}11\text{g m}^{-2}\text{y}^{-1}$; three observations being zero), making this data insufficient to accurately quantify Baltic seagrass CAR. *Zostera* CAR varied both within and across regional seas with median levels being much higher in the NE Atlantic Ocean ($24.5\text{g m}^{-2}\text{y}^{-1}$) than in the Baltic Sea ($0.8\text{g m}^{-2}\text{y}^{-1}$). However, given the limited number of data points, especially in the Baltic ($n=7$ vs $n=25$ in NE Atlantic), the combined European dataset offers more reliable insights into *Zostera* carbon accumulation capacity.

The marked variability in the spatial distribution of saltmarsh CAR from the Mediterranean Sea to northern Europe is clearly apparent on a map of the region (Figure 5A). Sites with high saltmarsh CAR are primarily concentrated in the NE Atlantic Ocean, particularly in the Netherlands, the Wadden Sea, and the Atlantic coast of France and the United Kingdom. Conversely, low CAR values are widespread in the Baltic Sea, as well as in southern Europe. Compared to saltmarshes, the spatial distribution of seagrass sites is more clustered along the Mediterranean Sea, with generally high CAR values in the Mediterranean Sea but also occasionally in other regions (Figure 5B).

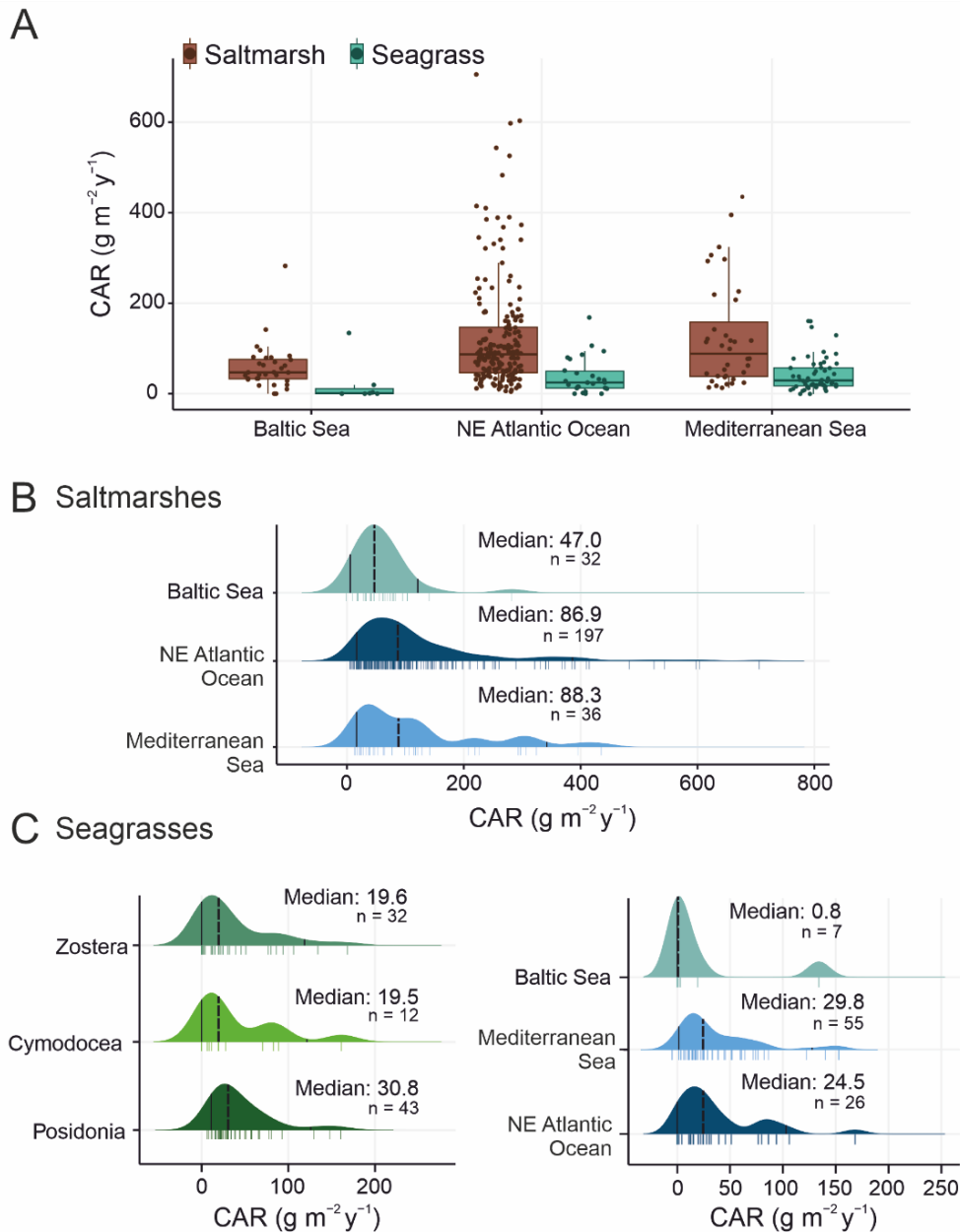


Figure 4. Organic carbon accumulation rates (CAR) in European saltmarshes and seagrasses by marine region and species. A) Boxplot of OC accumulation rates ($\text{g m}^{-2} \text{y}^{-1}$) for saltmarshes and seagrasses across three marine regions (Baltic Sea, Mediterranean Sea, NE Atlantic Ocean). B) Density plots of OC accumulation rates in saltmarshes by marine region, showing median values sample size. C) Density plots of OC accumulation rates in seagrass meadows by seagrass species and marine region, indicating median values and sample size.

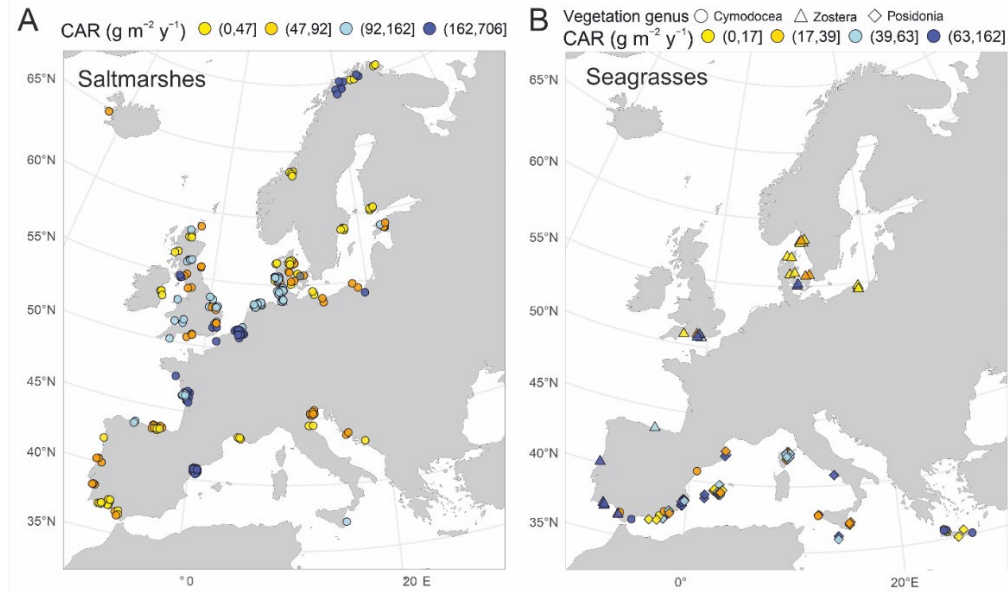


Figure 5. Spatial distribution of organic carbon accumulation rates (CAR) in saltmarshes (A) and seagrasses (B) across Europe. CAR values were averaged by location. Circles are coloured according to CAR ranges ($\text{g m}^{-2} \text{y}^{-1}$), defined by the quantiles of CAR specific to each habitat type and shaped by the seagrass genus.

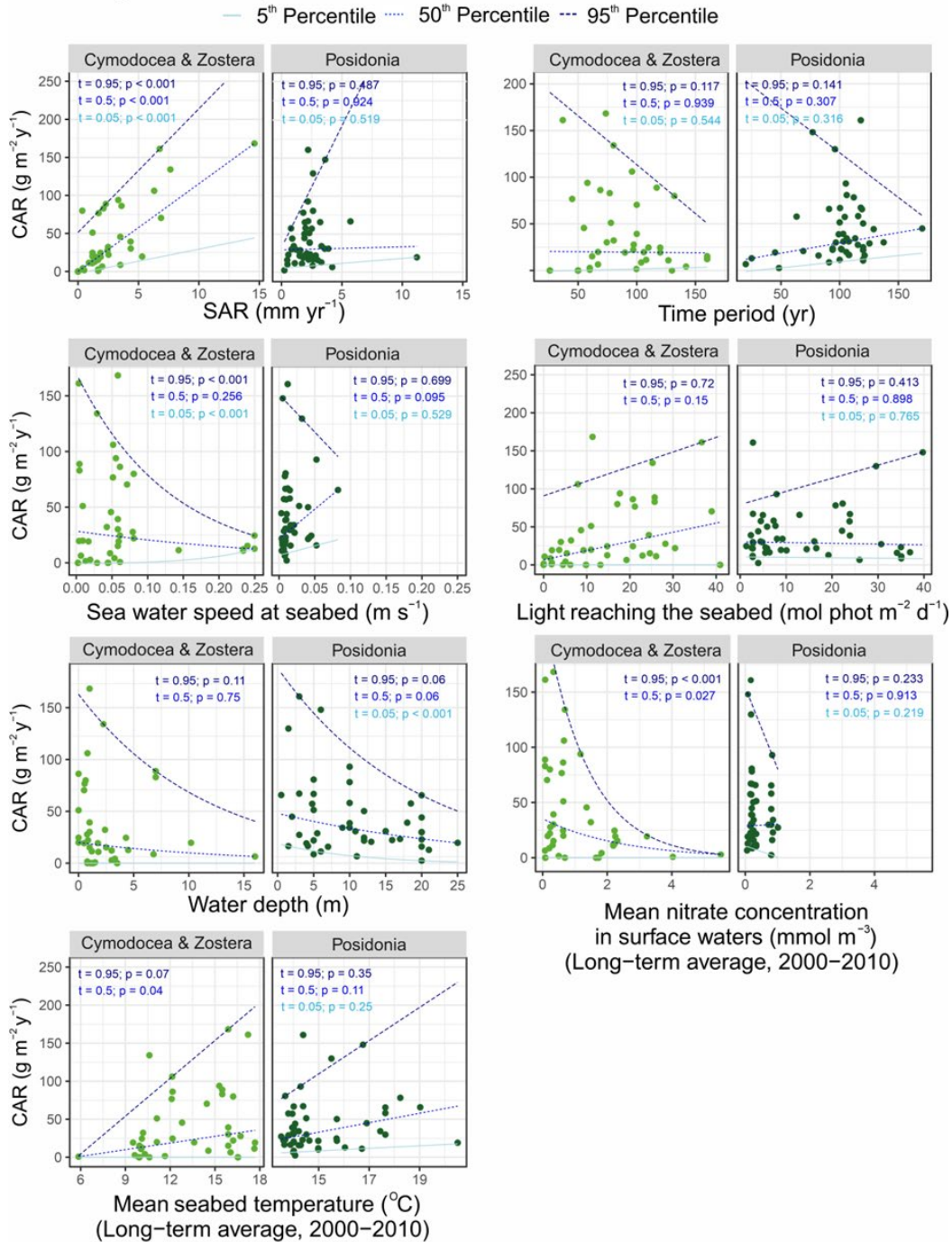
3.3 Correlations between CAR and potential environmental predictors

We used linear and exponential quantile regression for an initial exploration of relationships between CAR and potential environmental predictors, which were derived from spatial data for each study site. In seagrass meadows (Figure 6A), local sedimentation rate was positively correlated with CAR, the correlation being significant across median and extreme quantiles for smaller seagrass species but showing no significant relationship for *P. oceanica*. In contrast, a significant negative exponential relationship between seabed current speed and upper quantiles of CAR for *Cymodocea* and *Zostera* was observed. While light reaching the seabed showed no correlation with seagrass CAR, water depth (a proxy for light availability) was a significant predictor only for *P. oceanica*. Depth showed a strong, negative exponential correlation with lower *P. oceanica* CAR quantiles and a marginally significant one with upper and median quantiles. Other noteworthy trends included a negative exponential relationship between mean nitrate concentration in surface waters and upper- and median CAR for *Cymodocea* and *Zostera* but not for *P. oceanica*. Furthermore, seabed temperature was positively correlated with median CAR, but only for smaller seagrass species. Finally, the time period over which we calculated CAR was not correlated with the CAR values for any seagrass species. This confirms that our effort to limit the timeframe used for calculating CAR to the most recent 100 years was effective in minimizing the influence of the calculation period on seagrass CAR variability.

In saltmarshes (Figure 6B), CAR showed significant correlation with several variables reflecting the physical setting of the sites. Distance to a high-flow river correlated negatively and exponentially with upper and median CAR values. Tidal amplitude (M2 component) had a positive exponential relationship with median and lower CAR values.

Upper 95-percentile and median saltmarsh CAR also showed a positive exponential relationship with relative sea-level rise (RSLR) and upper CAR further showed a negative relationship with wave fetch. The time period over which CAR was calculated was negatively and exponentially correlated with median values of CAR. Lastly, mean annual temperature showed no significant relationship with saltmarsh CAR at any quantile.

A Seagrass CAR predictors



(continues next page)

B Saltmarsh CAR predictors

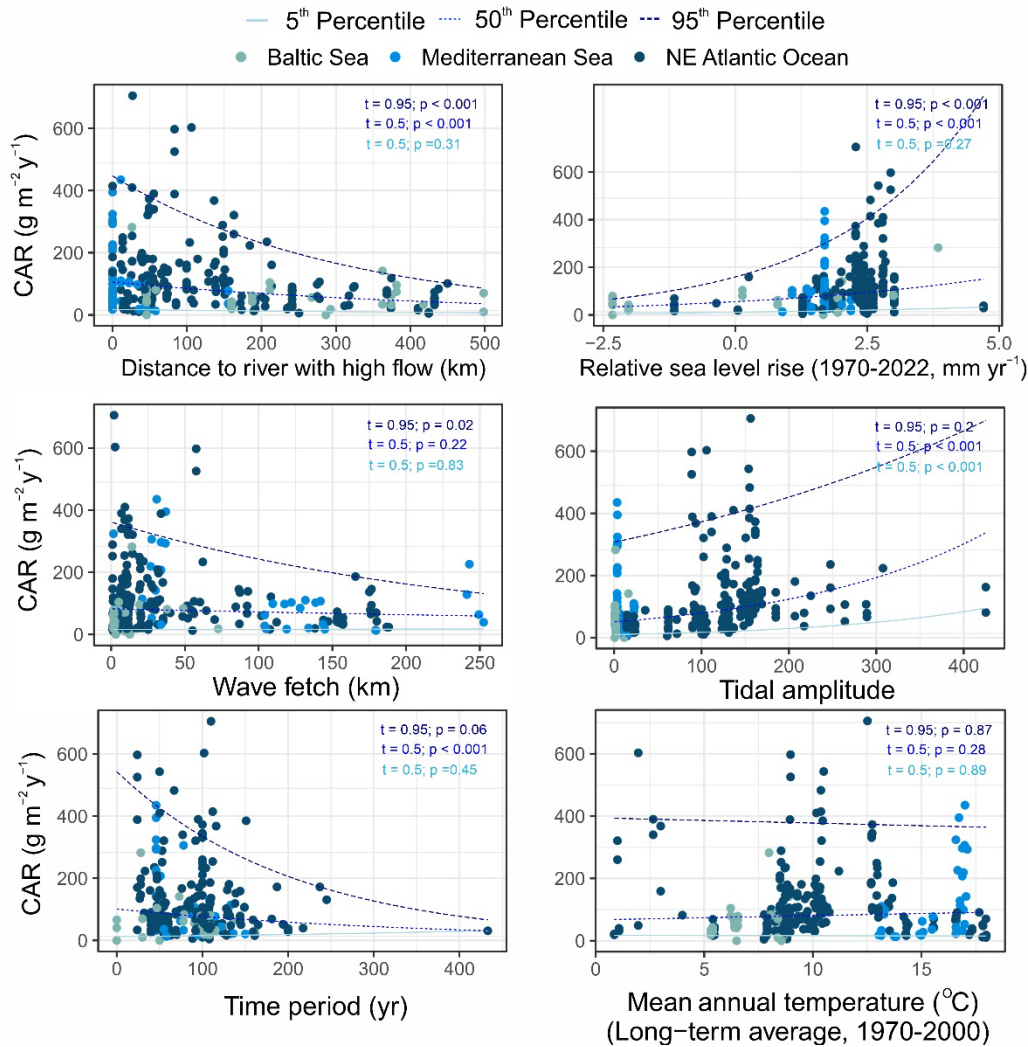


Figure 6. Sediment organic carbon accumulation rates (CAR) in seagrass (A) and saltmarsh (B) as functions of several drivers, including environmental, climatic and methodological (time period used to calculate CAR). Relationships are modelled using either linear or exponential quantile regression, showing the fits for the median (50th) and extreme (5th and 95th) percentiles. P-values are provided for all statistically and non-statistically significant trends. Saltmarsh and seagrass area-integrated CAR (CAR_{int}) within and outside protected areas

Based on the medians and associated range (25-75 quartiles) of the 265 saltmarsh observations, and the 88 seagrass observations by habitat type and species (Figure 4, Table S4) multiplied by the respective available habitat areas (Figure 2, Table S2) we estimated the integrated CAR, CAR_{int} , across protected and non-protected areas of the European seas and their subregions by habitat and seagrass genera (Figure 7, Table S5). In the Mediterranean Sea, CAR_{int} is primarily driven by the widespread *Posidonia oceanica* meadows, which have the highest area-specific CAR of all seagrasses (Figure 7). In the NE Atlantic Ocean, by contrast, the largest contribution to CAR_{int} is from saltmarshes while the Baltic Sea has a similarly low contribution from both habitat types (Figure 7). Based on median CAR data across the habitat areas available for analysis, seagrasses potentially

sequester 225, 76 and 16GgC yr⁻¹ with a protected proportion of 62%, 64% and 58% in the Mediterranean Sea, Northeast Atlantic Ocean and the Baltic Sea, respectively. In comparison, saltmarshes potentially sequester 113, 158 and 11GgC yr⁻¹ with a protected proportion of 94%, 93% and 74% in the Mediterranean Sea, NE Atlantic Ocean and the Baltic Sea, respectively (Figure 7, Table S6).

The upper and lower quartile of saltmarsh and seagrasses CAR_{int} per region reflects a large variability of the estimates, spanning up to four-fold and representing a combination of natural variability and measurement uncertainty. In the Mediterranean Sea, CAR_{int} ranges 49-202GgC yr⁻¹ for saltmarshes and 134-436GgC yr⁻¹ for seagrasses. In the NE Atlantic Ocean, ranges are 84-267GgC yr⁻¹ for saltmarshes and 38-154GgC yr⁻¹ for seagrasses. In the Baltic Sea, CAR_{int} ranges 8-18GgC yr⁻¹ for saltmarshes and 2-38GgC yr⁻¹ for seagrasses (Figure 7, Table S5).

Overall, in the NE Atlantic Ocean, only a small proportion of saltmarsh CAR_{int} (7%) and a larger proportion of seagrass CAR_{int} (36%) lies at present, outside of the existing PA network (Figure 7). The Mediterranean Sea has more unprotected seagrass CAR_{int} (38%) than saltmarsh CAR_{int} (6%) while the Baltic Sea shows the opposite pattern with 26% unprotected saltmarsh CAR_{int} and 42% unprotected seagrass CAR_{int}.

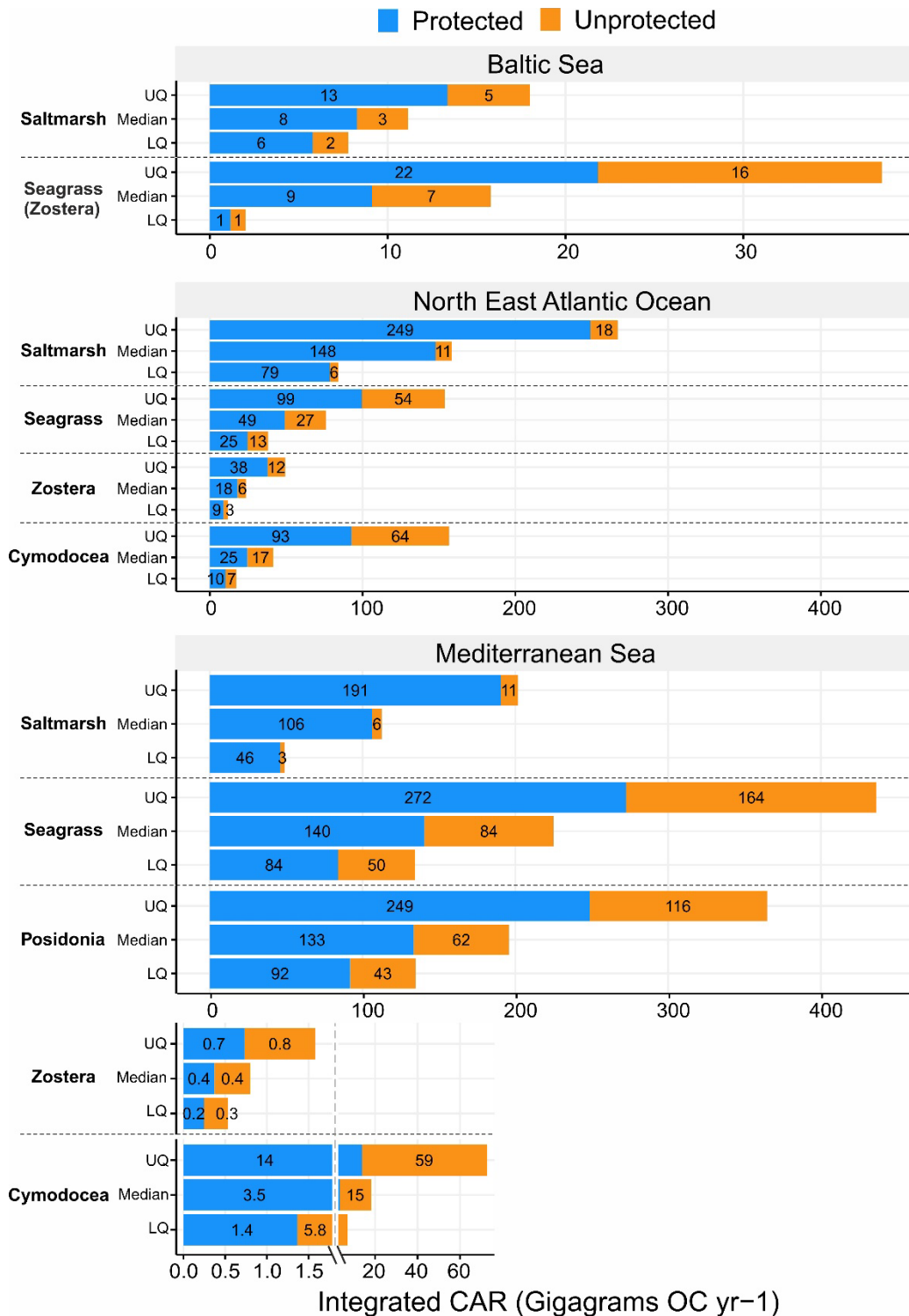


Figure 7. Integrated organic carbon accumulation rate (CAR_{int}, Gigagrams yr⁻¹), based on median, lower quartile (LQ, 25%) and upper quartile (UQ, 75%) CAR per blue carbon habitat type within and outside European PA networks. Note that the X-axis scale for the Baltic Sea is 1/10 of that for the Northeast Atlantic and Mediterranean Sea, - and the latter differs below and above the value 1.5 to improve readability.

4 Discussion

Studies of CAR of saltmarshes and seagrasses have expanded hugely since the seminal blue carbon papers by McLeod et al. (2011) and Duarte et al. (2013), which presented the first global compilations of CAR data across blue carbon habitats. Our updated synthesis offers novel insights on levels and variability of CAR across saltmarsh- and seagrass habitats and genera and their protection across European regional seas. We highlight and discuss the following main findings and their relevance for blue carbon science and policy:

- 1) overall lower CAR of these ecosystems relative to earlier compilations and with marked differences in CAR between habitats, genera and regional seas,
- 2) CAR levels markedly below IPCC Tier 1 values, especially for non-*Posidonia* seagrasses and Baltic saltmarshes, and
- 3) generally high mean coverage of habitat areas by protected area networks at regional sea scale for saltmarshes (74-99%, least for the Baltic Sea) but considerably lower for seagrasses (58-65%); with concrete protection apparently being insufficient for both habitat types given ongoing and projected losses.

4.1 Saltmarsh carbon accumulation rates (CAR) and variability across habitats and regional seas

For European saltmarshes, our updated compilation of 265 observations shows that the overall median saltmarsh CAR ($79\text{g C m}^{-2}\text{y}^{-1}$) is only about half of the median for Europe ($170\text{g C m}^{-2}\text{yr}^{-1}$) reported by Ouyang and Lee (2014), based on 28 observations, and also much lower than the global mean of $218\text{g C m}^{-2}\text{y}^{-1}$ reported by Mcleod et al. (2011) and Duarte et al. (2013) based on 96 sites. This difference is likely partly due to their inclusion of shorter-term accumulation rates, which tend to be relatively high because of a larger contribution of labile organic components compared to longer-term accumulation, which is increasingly limited to more refractory components. The lower CAR of our compilation also reflects a different representation of regions than in the earlier European compilation with a significant contribution of data from Baltic saltmarshes, which have much lower CAR than saltmarshes elsewhere in Europe (Figure 4, Figure 5) and beyond (see e.g. compilation by Leiva-Dueñas et al. 2024). The low CAR of Baltic saltmarsh habitats may reflect the micro-tidal nature of the Baltic Sea and generally younger saltmarshes in this region (Leiva-Dueñas et al. in review). This interpretation is supported by the overall negative correlation observed between CAR and tidal range (with Baltic marshes having the lowest amplitudes) and the positive correlation between CAR and relative sea-level rise (RSLR) (with many Baltic sites experiencing the lowest RSLR). Conversely to Baltic saltmarshes, in the Atlantic saltmarshes, exposed to greater tidal amplitudes, tides deliver more suspended sediments and allochthonous OC, with the regular flooding also promoting the rapid burial of this material (Morris et al. 2002). Historically, the slow rate of RSLR in the Baltic region, caused by isostatic uplift exceeding eustatic rise, has limited the accommodation space needed for vertical marsh growth and carbon burial. Projecting forward, this same geological mechanism ensures that relative sea-level rise will continue to be overall slower in the Baltic than in other regions, presenting a persistent and fundamental constraint on the future carbon accumulation capacity of Baltic saltmarshes.

Across the European saltmarshes, the positive exponential relationship between upper and median CAR and relative sea-level rise (RSLR) reflects a feedback where rising sea levels create vertical accommodation space, enabling greater sediment deposition and organic matter burial during tidal inundation. This process enhances mineral and organic accumulation while reducing decomposition through rapid burial and anoxic conditions, promoting long-term carbon storage. Globally, marshes exposed to rapid RSLR store substantially more blue carbon (1.7-3.7 times more in the upper 20cm and up to 9.1 times more at 50-100cm) than marshes in stable sea-level regions, highlighting RSLR as a major control on blue carbon capture (Rogers et al., 2019).

The generally higher CAR of saltmarshes close to high-flow rivers likely reflects a similar mechanism of allochthonous river material supporting accretion. Conversely, the negative relationship between wave fetch and upper CAR values suggests that high wave energy constrains carbon accumulation by increasing erosion and reducing sediment stability, limiting the capacity of saltmarshes to sustain elevated accumulation rates. Mean annual temperature showed no significant correlation with saltmarsh CAR. This lack of relationship likely reflects the opposing mechanisms through which temperature can influence carbon accumulation (either negatively, by enhancing microbial activity and accelerating organic carbon decomposition, or positively, by stimulating plant productivity; see Supplementary S5). The balance between these processes may vary spatially depending on other environmental factors, which could explain the absence of a consistent overall temperature effect across all sites.

4.2 Seagrass carbon accumulation rates (CAR) and variability across habitats and regional seas

Our overall median CAR for seagrasses in Europe ($24.6\text{g m}^{-2}\text{y}^{-1}$) is also much lower than the estimated global mean for seagrasses ($138\pm 38\text{g m}^{-2}\text{y}^{-1}$) reported 12-14 years ago (e.g. McLeod et al. 2011; Duarte et al. 2013). The main reason for this huge difference is likely a dominance of observations of *P. oceanica* meadows in the previous synthesis, probably in combination with inclusion of data on short-term accumulation, whereas our update has a broader representation of European regional seas and European seagrass genera, although still dominated by observations from the Mediterranean Sea (55 of 88 observations) and *Posidonia* meadows (43 of 88 observations). Our comparison across seagrass genera indeed showed a marked, though non-significant, tendency for higher CAR for *Posidonia* relative to the smaller seagrass genera, *Zostera* and *Cymodocea*. Because our compilation only included one observation of CAR for *H. stipulaceae* (from Apostolaki et al. 2019), our compilation does not contribute any new information for this species. Nevertheless, because future, warmer settings, are expected to favour *H. stipulaceae* over the native seagrasses, it may play an increasing role to maintain seagrass CAR by developing new carbon sinks in bare sediments and colonizing areas currently occupied by *P. oceanica* (Wesselmann et al. 2021).

The efficiency of *P. oceanica* for OC accumulation relative to *Zostera* and other non-*Posidonia* seagrass genera is likely related to its traits and growth form, which support long-term habitat stability, high net primary production, and slow turnover of refractory belowground structures, which form entire reefs of organic carbon (matte) (Duarte and Chiscano 1999; Duarte et al. 2010; Kennedy et al. 2026). Our results align with recent reports of relatively low CAR and with OC stocks (which in

contrast to CAR do not consider the time of accumulation) of *Zostera marina* in the southwestern Baltic Sea (Leiva-Dueñas et al. 2023) and globally (Kennedy et al. 2026). Our findings also align with earlier reports of *P. oceanica* OC stocks exceeding those of *Zostera*, *Cymodocea* and other non-*Posidonia* seagrass genera (Kennedy et al. 2022).

The carbon burial capacity of smaller seagrass meadows correlated positively with higher sedimentation rates, reduced hydrodynamic forces, higher seabed temperatures, and lower nitrate concentrations in surface waters. Such conditions likely reflect sheltered, river-proximal environments where riverine inputs deliver fine sediments with relatively low nutrient loads. In such settings, low hydrodynamic energy and longer water residence times promote sediment deposition and limit resuspension, enhancing the accumulation of mostly allochthonous carbon. Although correlation does not infer causal relationship, the nuances in the correlations suggests that smaller seagrass species, when located in depositional sheltered environments near rivers, are better able to withstand high sediment loads, leading to enhanced carbon burial, although a significant portion of this buried carbon is therefore likely allochthonous in origin. Conversely, strong currents counteract this process by remobilizing sediments and enhancing organic matter oxidation, thereby reducing CAR (e.g. Schaeffer et al. 2025). The negative correlation between *Zostera* and *Cymodocea* CAR and nitrate concentration may reflect that high nutrient concentrations can lead to a greater lability of the seagrass-derived material as well as stimulate sediment microbial processes, both processes leading to increased remineralization of sediment OC (Liu et al. 2017, 2023). High nitrate concentrations could also be linked to enhanced epiphytic growth on seagrass leaves and algal blooms in the water column, which reduce light availability and photosynthetic efficiency, ultimately limiting their carbon accumulation. This is most likely the case for *Zostera* meadows located in the Baltic, where spatial data of nitrate concentration and chlorophyll-a in surface waters correlated positively and strongly (Figure S1). *Posidonia* CAR did not show a negative relationship with nitrate, likely because the meadows in our study are found within a very narrow nitrate range, which is consistent with the species' adaptation to oligotrophic waters. The contrasting responses to seabed temperature, positive for smaller seagrass CAR but absent for *P. oceanica*, may be attributed to the different thermal ranges they inhabit. Smaller species, found in areas from 6 to 18°C, are likely operating below their thermal optimum, making them more sensitive to warming and resulting in higher growth and CAR. The *P. oceanica* meadows, situated in a narrower and warmer range (13-19°C), are likely already near their optimum, limiting the potential for increased growth and CAR with further temperature rise.

For *Posidonia oceanica*, only water depth showed a significant negative relationship with CAR. Because water depth is typically a reliable proxy for seabed light availability, this relationship highlights the essential role of light in enhancing *P. oceanica* productivity and shoot density (Serrano et al. 2014; Pergent-Martini et al. 2021). The absence of a correlation between *P. oceanica* CAR and SAR further supports the interpretation that its carbon accumulation is primarily driven by seagrass productivity (that is, by autochthonous OC inputs) rather than by geomorphological factors that promote higher sedimentation rates, as observed for smaller seagrass species. The fact that CAR correlates with water depth but not with modelled seabed light availability may be due to differences in data resolution. Seabed light availability was derived from a spatial layer with a resolution of approximately 100m², whereas water depth values were taken directly from the site-specific

information reported in the original studies compiled in our dataset. Consequently, water depth better captures local light conditions, likely explaining the observed correlation.

However, for better understanding of drivers of seagrass and saltmarsh CAR, the explorative correlation analyses should be followed up by in-depth analyses of relationships to multiple independent drivers, e.g. through generalised additive model (GAM) analyses, which was beyond the scope of the current report.

4.3 Updated saltmarsh and seagrass CAR in relation to IPCC emission factors

To evaluate the climate change mitigation effect of re-establishing these vegetated habitats, IPCC defines CAR-based Tier-1 emission factors to be used unless country scale- or more local scale information is available. These factors (geometric mean [25%-75% CL]) are 91 [0.7-1.1] g C m⁻² y⁻¹ for saltmarsh habitats and 43 [0.2-0.7] g C m⁻² y⁻¹ (IPCC 2014) for seagrasses.

The geometric means (Table S4) of our updated CAR for saltmarsh- and seagrass habitats in Europe lie well below IPCC's Tier-1 emission factors levels, especially for Baltic saltmarshes (21% of tier 1) and non-*Posidonia* seagrasses (*Zostera* 19% of tier 1; *Cymodocea* 27% of tier 1), but also for saltmarshes in general (77% of tier 1) and for *Posidonia* (78% of tier 1). The high IPCC value for seagrass was based on only 6 observations, all for *Posidonia*, which were believed to represent seagrasses in general. Likewise, Baltic saltmarshes were under-represented in the data behind the IPCC values, of which most originated from US saltmarshes, few from Northern Europe marshes and only four from the Baltic Sea (IPCC, 2014). Moreover, the four Baltic observations were from high OC accumulation sites in river basins of the Vistula and Oder rivers, Poland (Callaway et al. 1996).

Our updated saltmarsh and seagrass CAR for European regional seas is therefore important for developing more realistic estimates of the climate mitigation effect of blue carbon strategies at the European scale. Our data also highlights a need to update IPCC emission factors to improve guidance on climate mitigation effects of blue carbon strategies at the global scale. For the latter purpose, our updated European-scale compilation of CAR observations should be extended to a global-scale update.

Carbon accumulation rates in sediments of blue carbon ecosystems have been reported to exceed that of forest soils by 30-40 times (McLeod et al., 2011). Given the increase in data in the meantime, this comparison also needs an update. The CAR estimates for forest soils in the comparison were based on long-term rates over 8,000-10,000 years, whereas much higher rates, in the range of those of blue carbon ecosystems, can happen over shorter timescales, as also mentioned by McLeod et al. (2011). The importance of comparisons of CAR representing the same time scale is highlighted by a recent study estimating that 9% of the initially buried carbon remained stable after 100 years whereas only 0.1% remained after 1000 years (Piñeiro-Juncal et al. 2025). Nevertheless, a comparison of our updated CAR for European saltmarshes (median: 79g C m⁻² y⁻¹) and seagrasses (median: 24.6g C m⁻² y⁻¹), with a few examples for terrestrial forest soils in Europe (15-35g C m⁻² y⁻¹, see below) still indicates that BC habitats can be as efficient or more efficient than terrestrial forest soils in sequestering OC. Hence seagrass CAR is about 1.0-1.6 times higher and saltmarsh CAR about 3-4 times higher than those examples for forest soils., and this is despite those forest soil CAR

relying on methodological approaches based on differences in sediment OC stocks in monitoring plots over shorter periods than 100 years. Hence, French forest soils accumulated $35\text{g m}^{-2}\text{y}^{-1}$ over a 19-year period (Jonard et al. 2017), German coniferous forest soils accumulated $15\text{-}23\text{g m}^{-2}\text{y}^{-1}$ over a ~17-year period (Grüneberg et al. 2014), changes in the OC stocks in Danish forest soils from 1990 to 2005 represented an accumulation of $31\text{g m}^{-2}\text{y}^{-1}$ (Nielsen et al. 2012), while for Swedish forest soils the estimate was $25\text{g m}^{-2}\text{y}^{-1}$ (Berg et al., 2009).

A full assessment of the net climate mitigation effect of blue carbon strategies also requires information on GHG fluxes of methane and nitrous oxide (Rosentreter et al. 2021). The upper limit of methane fluxes decreases from brackish towards more saline settings because sulphate from the seawater allows sulphate-reducing bacteria to outcompete methanogens and thereby limit methane production (Poffenbarger et al. 2011). Accounting for CH_4 and N_2O emissions requires careful consideration, more so for saltmarshes than seagrasses (Neubauer 2014), and is highlighted among uncertainties and challenges in the prediction of climate mitigation through carbon burial in blue carbon ecosystems (Kristensen et al. 2024; Williamson and Gattuso 2022). Moreover, because grazing is a widespread management practice for saltmarshes, it is relevant to also consider GHG emission from cattle for a full understanding of the effect of saltmarsh management practices on climate mitigation (Leiva-Dueñas et al. in review). Overall, region-specific variability in CAR and GHG emissions by blue carbon ecosystems imply that protection and restoration of a given area of saltmarshes or seagrass meadows may have markedly different climate mitigation effect across European regional seas and habitats. Nevertheless, in a comparison among ocean solutions to climate change where blue carbon ecosystems were evaluated as having generally low climate mitigation, their protection and restoration was still categorised as “low regret”-solutions because of their multiple benefits (Gattuso et al. 2021).

4.4 Protection status and perspectives for European saltmarshes and seagrass and their CAR

Our results documented a high level of protected area coverage of saltmarshes and lower levels for seagrass meadows in Europe, with *Posidonia* generally being the best covered by PA's and *Cymodocea* the least covered by PAs among the three native European seagrass genera. Because these patterns were relatively consistent across the European seas, we assume that they are representative although distribution maps were not available for all habitats. The PA habitat coverage of seagrasses, in particular *Posidonia* and *Cymodocea*, is in line with what has been reported through previous assessments for strictly marine assemblages (Agnesi et al., 2017, 2020). The protection coverage is likely driven by the conservation objectives and ecological sufficiency target values resulting from the longstanding implementation process of the Habitat Directive, which addresses the need to protect these assemblages. While saltmarshes and *Posidonia* are specifically protected under the Habitats Directive, other seagrass meadows are, however, only indirectly protected by, e.g., forming part of the habitat type “shallow sandy bay”, which may be the reason for the lower protection coverage of non-*Posidonia* seagrasses. Accordingly, our results indicate that the largest untapped potential for expanding the coverage of European protected area networks to blue carbon habitat areas is to increase the designation of protected saltmarsh areas in the Baltic Sea and of non-*Posidonia* seagrasses in general.

Our results also offer the possibility to evaluate the degree of alignment of the protection of saltmarsh and seagrass habitats in Europe, which, to our knowledge, has not been addressed in earlier studies. The much higher protection level of salt marshes than of seagrasses suggests a potential to increase the alignment. Such alignment has the potential to increase the efficiency of protection because of interdependence and connectivity between saltmarsh and seagrass habitats and neighbouring habitats as e.g. demonstrated for Virginia coastal bays (Smith et al. 2024) and coastal regions in South Australia (Saavedra-Hortua et al. 2023). The interdependence and connectivity between habitats include e.g. export of organic material between habitats, physical protection of saltmarshes by seagrass meadows, nutrient reduction through coastal filtering effects, and trophic interactions. Landscape-scale approaches to coastal ecosystem management that treat coastal mosaics as integrated systems, rather than as isolated habitats therefore have better chances of supporting overall ecosystem functions and resilience compared to approaches that only address blue carbon and only does so for a selected part of the coastal mosaic. Accordingly, Howard et al. (2017) argued that the inclusion of blue carbon in MPAs would promote connectivity between ecosystems within protected landscapes and associated marine areas because of their occurrence at the interphase between land and sea.

Although we identify a high coverage of protected area networks for saltmarsh habitats and some seagrass habitats at the European scale, it is not always clear what such protection implies and whether it is effective and includes reduction of stressors, such as eutrophication and physical disturbance known to cause decline of these habitats (e.g. Arioldi et al. 2007; Davidson 2014; de los Santos et al. 2019). The overall efficiency of protection is clearly insufficient since seagrasses and saltmarshes at global and European scales are still subject to losses outweighing gains, and stressor levels too high to support natural large-scale recolonization (Dunic et al. 2021; Murray et al. 2019 and 2022). This is for example the case for *Zostera* meadows in Denmark, which have suffered major long-term losses and do not show general signs of recovery (e.g. Krause-Jensen et al. 2021).

The effect of projected climate change scenarios on coastal vegetated habitats also calls for rethinking the designation of protected areas. Hence, projected sea level rise leads to inundation and coastal squeeze of current saltmarsh areas in combination with landward migration of the habitats. For example, 45% of the current Danish saltmarsh habitats are expected to be lost by 2120 and to be totally lost over the 22nd century, which is also important at a European level because Danish saltmarshes represent 78% of Europe's continental coastal marshes and 15% of the Atlantic coastal marshes (Canal-Vergés et al. 2025). Similar projections apply to Mediterranean saltmarshes (Schuerch et al. 2025). These projections imply that current protection schemes are entirely insufficient and must be supplemented with extended saltmarsh protection landward to safeguard saltmarshes in the future.

5 Conclusions

Our updated overview of carbon accumulation rates (CAR) of European saltmarshes and seagrass meadows and their protection is based on the best available maps of habitat distribution and protection combined with a compounded bibliographic review of CAR derived from field studies. We demonstrate overall lower CAR of these ecosystems relative to earlier compilations and relative to IPCC tier 1 emission factors, and with marked differences in CAR between habitats, genera and regional seas, which should be considered in blue carbon assessments. We show that the Mediterranean Sea has the highest area-integrated CAR (CAR_{int}) due to the high area-specific CAR of *Posidonia* meadows combined with wide extension of this habitat in the region, while the Baltic Sea has the lowest due to less habitat coverage and lower median CAR.

The current network of PAs covers most of Europe's saltmarshes and a large fraction of Europe's seagrass meadows thereby potentially protecting these important habitats and their ecosystem functions, including CAR. However, our analysis also points at potentials for extending PAs to better cover Baltic saltmarshes and non-*Posidonia* seagrasses. Also, despite apparent protection, European saltmarshes and seagrass meadows still suffer declines due to human pressures, so there is a need to improve management effectiveness and adequacy of the protection. While saltmarshes and *Posidonia oceanica* meadows may be object of direct spatial protection through Natura 2000 sites designated directly for these habitats specifically protected under the Habitats Directive, other seagrass beds (e.g. *Zostera* and *Cymodocea*) may be object of indirect spatial protection when they occur in other marine Habitats Directive habitat complexes for which Natura 2000 sites may be purposefully established (e.g. Mudflats and sandflats not covered by seawater at low tide and Large shallow inlets and bays) thereby leading to differences in observed protected area coverage values at regional scale between one species and another as well as habitat specific conservation measures insisting in the protected area sites. Also, protection schemes must be expanded landward and made part of coastal realignment programs to protect saltmarshes from drowning under projected sea level rise. Overall, we encourage an integrated, land-landscape scale approach to the sustainable management of saltmarsh and seagrass habitats with efficient protection from manageable stressors to limit further losses and facilitate recovery as well as dynamic changes of these habitats under future settings. The associated benefits of such management are multiple, supporting biodiversity, coastal protection, nutrient and carbon retention, and hence extending far beyond a modest climate mitigation effect.

6 References

- Agnesi, S., Mo, G., Annunziatellis, A., Chaniotis, P., Korpinen, S., Snoj, L., Globevnik, L., Tunesi, L., Reker, J. 2017. Spatial Analysis of Marine Protected Area Networks in Europe's Seas II, Volume A, 2017, ed. Künitzer, A., ETC/ICM Technical Report 4/2017, Magdeburg: European Topic Centre on inland, coastal and marine waters, 41 pp.
- Agnesi, S., Annunziatellis, A., Chaniotis, P., Mo, G., Korpinen, S., Snoj, L., Tunesi, L., Reker, J., 2020. Spatial Analysis of Marine Protected Area Networks in Europe's Seas III. ETC/ ICM Technical Report 3/2020: European Topic Centre on Inland, Coastal and Marine waters, 40 pp.
- Airoldi, L., Beck, M.W., 2007. Loss, status and trends for coastal marine habitats of Europe. *Oceanogr. Mar. Biol. Annu. Rev.* 45, 345–405 eBook ISBN 9780429144905.
- Apostolaki, E. T., Vizzini, S., Santinelli, V., Kaberi, H., Andolina, C., Papathanassiou, E., 2019. Exotic *Halophila stipulacea* is an introduced carbon sink for the Eastern Mediterranean Sea. *Sci. Rep.* 9(1), 9643. Doi: 10.1038/s41598-019-45046-w
- Arias-Ortiz, A., Serrano, O., Masqué, P., Lavery, P. S., Mueller, U., Kendrick, G. A., [...], Duarte, C. M. (2018). A marine heatwave drives massive losses from the world's largest seagrass carbon stocks. *Nature Climate Change*, 8(4), 338-344. Doi:10.1038/s41558-018-0096-y
- seagrass carbon stocks. *Nature Clim Change* 8: 338–344. doi:10.1038/s41558-018-0096-y Berg, B., Johansson, M. B., Nilsson, A., Gundersen, P., Norell, L., 2009. Sequestration of carbon in the humus layer of Swedish forests - direct measurements. *Can. J. For. Res.* 39, 962–975. Doi: [10.1139/X09-022](https://doi.org/10.1139/X09-022)
- Callaway, J. C., DeLaune, R. D., Patrick Jr, W. H., 1996. Chernobyl 137Cs used to determine sediment accretion rates at selected northern European coastal wetlands. *Limnol. Oceanogr.* 41(3), 444-450. Doi:[10.4319/lo.1996.41.3.0444](https://doi.org/10.4319/lo.1996.41.3.0444).
- Campbell, A. D., Fatoyinbo, L., Goldberg, L., Lagomasino, D., 2022. Global hotspots of salt marsh change and carbon emissions. *Nature*, 612(7941), 701-706. Doi: 10.1038/s41586-022-05355-z.
- Canal-Vergés, P., Frederiksen, L., Egemose, S., Ebbensgaard, T., Laustsen, K., Flindt, M. R. 2025. Impacts of Sea Level Rise on Danish Coastal Wetlands—a GIS-based Analysis. *Environ. Manage.* 75(4), 1039-1054. Doi: [10.1007/s00267-024-02096-9](https://doi.org/10.1007/s00267-024-02096-9)
- Davidson, E. A., Janssens, I. A. 2006. Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. *Nature*, 440(7081), 165-173. Doi:10.1038/nature04514
- Davidson, N. C. 2014. How much wetland has the world lost? Long-term and recent trends in global wetland area. *Mar. Freshwater Res.* 65(10), 934-941. Doi: [10.1071/MF14173](https://doi.org/10.1071/MF14173)
- Davidson, N. C., 2016. Wetland losses and the status of wetland-dependent species. *In* The wetland book (pp. 1-14). Springer, Dordrecht.
- de Los Santos, C. B., Krause-Jensen, D., Alcoverro, T., Marbà, N., Duarte, C. M., Van Katwijk, M. M., [...], Santos, R. 2019. Recent trend reversal for declining European seagrass meadows. *Nat. Com.* 10(1), 3356. Doi:10.1038/s41467-019-11340-4
- den Hartog, C., Kuo, J. 2006, Chapter 1: Taxonomy and Biogeography of Seagrasses. *In* A. W. D. Larkum et al. (eds.), *Seagrasses: Biology, Ecology and Conservation*, pp. 1-23. © 2006 Springer. Printed in the Netherlands.
- Don, A., Seidel, F., Leifeld, J., Kätterer, T., Martin, M., Pellerin, S., Emde, D., Seitz, D., Chenu, C., 2024. Carbon sequestration in soils and climate change mitigation—Definitions and pitfalls. *G*, 30, e16983. Doi.: 10.1111/gcb.16983

- Duarte, C. M., C. L. Chiscano. 1999. Seagrass biomass and production: a reassessment. *Aquat. Bot.* 65: 159–174. Doi: [10.1016/S0304-3770\(99\)00038-8](https://doi.org/10.1016/S0304-3770(99)00038-8)
- Duarte, C. M., Marbà, N., Gacia, E., Fourqurean, J. W., Beggins, J., Barrón, C., Apostolaki, E. T. 2010. Seagrass community metabolism: Assessing the carbon sink capacity of seagrass meadows. *Global Biogeochem. Cycles* 24. Doi: [10.1029/2010GB003793](https://doi.org/10.1029/2010GB003793)
- Duarte, C., Losada, I., Hendriks, I., Mazarrasa, I., Marbà, N. 2013. The role of coastal plant communities for climate change mitigation and adaptation. *Nat. Clim. Change* 3, 961–968. Doi: [10.1038/nclimate1970](https://doi.org/10.1038/nclimate1970)
- Dunic, J. C., Brown, C. J., Connolly, R. M., Turschwell, M. P., Côté, I. M. 2021. Long-term declines and recovery of meadow area across the world's seagrass bioregions. *Global Change Biol.*, 27(17), 4096-4109. Doi:[10.1111/gcb.15684](https://doi.org/10.1111/gcb.15684)
- Fenchel, T., King, G. M., Blackburn, T. H. 2012. *Bacterial biogeochemistry: the ecophysiology of mineral cycling*. Academic press.
- Fonseca, M. S., Bell, S. S. 1998. Influence of physical setting on seagrass landscapes near Beaufort, North Carolina, USA. *Mar. Ecol. Prog. Ser.*, 171, 109-121. Doi: [10.3354/meps171109](https://doi.org/10.3354/meps171109)
- Gattuso, J. P., Williamson, P., Duarte, C. M., Magnan, A. K. 2021. The potential for ocean-based climate action: negative emissions technologies and beyond. *Front. Clim.*, 2, 575716. Doi: [10.3389/fclim.2020.575716](https://doi.org/10.3389/fclim.2020.575716)
- Gedan, K. B., Silliman, B. R., Bertness, M. D., 2009. Centuries of human-driven change in salt marsh ecosystems. *Ann. Rev. Mar. Sci* 1, 117–141. Doi: [10.1146/annurev.marine.010908.163930](https://doi.org/10.1146/annurev.marine.010908.163930).
- Gerakaris, V., Lardi, P. L., Issaris, Y. 2020. First record of the tropical seagrass species *Halophila decipiens* Ostenfeld in the Mediterranean Sea. *Aquat. Bot.* 160, 103151. Doi: [10.1016/j.aquabot.2019.103151](https://doi.org/10.1016/j.aquabot.2019.103151)
- Graversen, A. E. L., Lønborg, C., Addamo, A. M., Pedersen, S. G., Chemello, S., Alejo, I., [...], Krause-Jensen, D. 2025. A marine and salt marsh sediment organic carbon database for European regional seas (EURO-CARBON). *Data in Brief* 60, 111595. Doi: [10.1016/j.dib.2025.111595](https://doi.org/10.1016/j.dib.2025.111595)
- Green, E.P., Short, F.T. (eds.). 2003. *World Atlas of Seagrasses*. University of California Press, Berkeley, USA. 324 pp.
- Grüneberg, E., Ziche, D., Wellbrock, N. 2014. Organic carbon stocks and sequestration rates of forest soils in Germany. *Global Change Biol.*, 20(8), 2644-2662. Doi: [10.1111/gcb.12558](https://doi.org/10.1111/gcb.12558)
- Herr, D., Landis, E. (2016). *Coastal blue carbon ecosystems. Opportunities for Nationally Determined Contributions*. Policy Brief. Gland, Switzerland: IUCN and Washington, DC, USA: TNC.
- Howard, J., McLeod, E., Thomas, S., Eastwood, E., Fox, M., Wenzel, L., Pidgeon, E., 2017. The potential to integrate blue carbon into MPA design and management. *Aquat. Conserv. Mar. Freshwater Ecosyst.*, 27, 100-115. Doi: [10.1002/aqc.2809](https://doi.org/10.1002/aqc.2809)
- Howard, J., Sutton-Grier, A. E., Smart, L. S., Lopes, C. C., Hamilton, J., Kleypas, J., [...], Landis, E. 2023. Blue carbon pathways for climate mitigation: Known, emerging and unlikely. *Marine Policy*, 156, 105788. Doi: [10.1016/j.marpol.2023.105788](https://doi.org/10.1016/j.marpol.2023.105788)
- Huyzentruyt, M., Belliard, J. P., Saintilan, N., Temmerman, S. 2024. Identifying drivers of global spatial variability in organic carbon sequestration in tidal marsh sediments. *STOTEN*, 957, 177746. Doi: [10.1016/j.scitotenv.2024.177746](https://doi.org/10.1016/j.scitotenv.2024.177746)
- IPCC. 2014. 2013 Supplement to the 2006 IPCC guidelines for national greenhouse gas inventories: wetlands., Hiraishi, T., Krug, T., Tanabe, K., Srivastava, N., Baasansuren, J., Fukuda, M., Troxler, T. [(eds.)]. *IPCC, Switzerland*.

- IPCC, 2019. Annex I: Glossary [Weyer, N.M. (ed.)]. *In: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* [H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 677–702. Doi: 10.1017/9781009157964.010.
- Jonard, M., Nicolas, M., Coomes, D., Caignet, I., Saenger, A., Ponette, Q. 2017. Forest soils in France are sequestering substantial amounts of carbon. *STOTEN* 574, 616–628. Doi: 10.1016/j.scitotenv.2016.09.028
- Kennedy, H. Pagès, J. F., Lagomasino, D., Arias-Ortiz, A., Colarusso, P., Fourqurean, J. W., [...], Duarte C. M. 2022. Species Traits and Geomorphic Setting as Drivers of Global Soil Carbon Stocks in Seagrass Meadows. *Global Biogeochem. Cycles* 36: e2022GB007481. Doi: 10.1029/2022GB007481
- Kennedy, H., Leiva Duenas, C., Lovelock, C., Krause-Jensen, D. 2026. Challenges for carbon crediting in *Zostera marina* (eelgrass) meadows. *STOTEN* 1014, 181314. Doi: 10.1016/j.scitotenv.2025.181314.
- Krause-Jensen, D., Duarte, C. M., Sand-Jensen, K., Carstensen, J. 2021. Century-long records reveal shifting challenges to seagrass recovery. *Global Change Biol.* 27: 563–575. Doi: 10.1111/gcb.15440
- Kristensen, E., Flindt, M. R., Quintana, C. O. 2025. Predicting climate mitigation through carbon burial in blue carbon ecosystems—challenges and pitfalls. *Global Change Biol.*, 31(1), e70022. Doi: [10.1111/gcb.70022](https://doi.org/10.1111/gcb.70022)
- Ladd, C. J., Smeaton, C., Skov, M. W., Austin, W. E. 2022. Best practice for upscaling soil organic carbon stocks in salt marshes. *Geoderma*, 428, 116188.
- Leiva-Dueñas, C., Graversen, A. E. L., Banta, G. T., Holmer, M., Masque, P., Stæhr, P. A. U., Krause-Jensen, D. 2023. Capturing of organic carbon and nitrogen in eelgrass sediments of southern Scandinavia. *Limnol. Oceanogr.* 68(3), 631–648. Doi: [10.1002/lno.12299](https://doi.org/10.1002/lno.12299)
- Leiva-Dueñas, C., Graversen, A. E. L., Banta, G. T., Hansen, J. N., Schrøter, M. L. K., Masqué, P., [...], Krause-Jensen, D. 2024. Region-specific drivers cause low organic carbon stocks and sequestration rates in the saltmarsh soils of southern Scandinavia. *Limnol. Oceanogr.*, 69(2), 290–308.
- Leiva-Dueñas, C., Banta, G. T., Boström, C., Eller, F., Eklöf, J., Andersen, L. H., [...], Krause-Jensen, D. In Review. Low climate benefit of Nordic coastal marshes. *Global Change Biol.*
- Liu, S., Jiang, Z., Wu, Y., Zhang, J., Arbi, I., Ye, F., [...], Macreadie, P. I. 2017. Effects of nutrient load on microbial activities within a seagrass-dominated ecosystem: Implications of changes in seagrass blue carbon. *Mar. Pollut. Bull.*, 117(1-2), 214–221. Doi: 10.1016/j.marpolbul.2017.01.056
- Liu, S., Luo, H., Jiang, Z., Ren, Y., Zhang, X., Wu, Y., [...], Macreadie, P. I. 2023. Nutrient loading weakens seagrass blue carbon potential by stimulating seagrass detritus carbon emission. *Ecol. Indic.*, 157, 111251. Doi: 10.1016/j.ecolind.2023.111251
- Mannino, A. M., Menéndez, M., Obrador, B., Sfrido, A., Triest, L., 2015. The genus *Ruppia* L. (Ruppiaceae) in the Mediterranean region: An overview. *Aquat. Bot.* 124, 1–9 Doi: 10.1016/j.aquabot.2015.02.005
- Maxwell, T. L., Rovai, A. S., Adame, M. F., Adams, J. B., Álvarez-Rogel, J., Austin, W. E., [...], Worthington, T. A. 2023. Global dataset of soil organic carbon in tidal marshes. *Sci Data* 10, 797. Doi: [10.1038/s41597-023-02633-x](https://doi.org/10.1038/s41597-023-02633-x)
- Mcleod, E., Chmura, G. L., Bouillon, S., Salm, R., Björk, M., Duarte, C. M., [...], Silliman, B. R. 2011. A blueprint for blue carbon: toward an improved understanding of the role of vegetated coastal

- habitats in sequestering CO₂. *Frontiers in Ecology and the Environment*, 9(10), 552-560. Doi: [10.1890/110004](https://doi.org/10.1890/110004)
- Mcowen, C. J., Weatherdon, L. V., Van Bochove, J. W., Sullivan, E., Blyth, S., Zockler, C., [...], Fletcher, S. 2017. A global map of saltmarshes. *Biodivers Data J.*, (5), e11764. Doi: [10.3897/BDJ.5.e11764](https://doi.org/10.3897/BDJ.5.e11764)
- Morris, J. T., Sundareshwar, P. V., Nietch, C. T., Kjerfve, B., Cahoon, D. R. 2002. Responses of coastal wetlands to rising sea level. *Ecology* 83(10), 2869-2877. Doi: [10.1890/0012-9658\(2002\)083\[2869:ROCWTR\]2.0.CO;2](https://doi.org/10.1890/0012-9658(2002)083[2869:ROCWTR]2.0.CO;2)
- Murray, N. J., Phinn, S. R., DeWitt, M., Ferrari, R., Johnston, R., Lyons, M. B., [...], Fuller, R. A. 2019. The global distribution and trajectory of tidal flats. *Nature*, 565(7738), 222-225. Doi.: [10.1038/s41586-018-0805-8](https://doi.org/10.1038/s41586-018-0805-8)
- Murray, N. J., Worthington, T. A., Bunting, P., Duce, S., Hagger, V., Lovelock, C. E., [...], Lyons, M. B. 2022. High-resolution mapping of losses and gains of Earth's tidal wetlands. *Science*, 376(6594), 744-749. Doi: [10.1126/science.abm9583](https://doi.org/10.1126/science.abm9583)
- Nardin, W., Larsen, L., Fagherazzi, S., Wiberg, P. 2018. Tradeoffs among hydrodynamics, sediment fluxes and vegetation community in the Virginia Coast Reserve, USA. *Estuarine, Coastal and Shelf Sci.*, 210, 98-108. Doi: [10.1016/j.ecss.2018.06.009](https://doi.org/10.1016/j.ecss.2018.06.009)
- Nellemann, C., Corcoran, E., Duarte, C. M., Valdés, L., De Young, C., Fonseca, L., Grimsditch, G. (Eds). 2009. Blue Carbon. A Rapid Response Assessment. United Nations Environment Programme, GRID-Arendal, www.grida.no
- Neubauer, S.C. 2014. On the challenges of modeling the net radiative forcing of wetlands: reconsidering Mitsch et al. 2013. *Landscape Ecol.* 29, 571–577. Doi: [10.1007/s10980-014-9986-1](https://doi.org/10.1007/s10980-014-9986-1)
- Nielsen, O.-K., Mikkelsen, M. H., Hoffmann, L. 2012. Denmark's National Inventory Report 2012. Emission Inventories 1990-2010 - Submitted under the United Nations Framework Convention on Climate Change 1990-2008. National Environmental Research Institute, Aarhus, 1168.
- Ouyang, X., Lee, S. Y. 2014. Updated estimates of carbon accumulation rates in coastal marsh sediments. *Biogeosciences*, 11, 5057–5071. Doi: [10.5194/bg-11-5057-2014](https://doi.org/10.5194/bg-11-5057-2014)
- Pedersen, M. Ø., Serrano, O., Mateo, M. Á., Holmer, M. 2011. Temperature effects on decomposition of a *Posidonia oceanica* mat. *Aquatic microbial ecology*, 65(2), 169-182. Doi: [10.3354/ame01543](https://doi.org/10.3354/ame01543)
- Pendleton, L., Donato, D. C., Murray, B. C., Crooks, S., Jenkins, W. A., Sifleet, S., [...], Baldera, A. (2012). Estimating global “blue carbon” emissions from conversion and degradation of vegetated coastal ecosystems. *PLoS ONE* 7(9): e43542. Doi: [10.1371/journal.pone.0043542](https://doi.org/10.1371/journal.pone.0043542)
- Pergent-Martini, C., Pergent, G., Monnier, B., Boudouresque, C. F., Mori, C., Valette-Sansevin, A. 2021. Contribution of *Posidonia oceanica* meadows in the context of climate change mitigation in the Mediterranean Sea. *Marine Environmental Research*, 165, 105236. Doi: [10.1016/j.marenvres.2021.105454](https://doi.org/10.1016/j.marenvres.2021.105454)
- Piñeiro-Juncal, N., Mateo, M.A., Leiva-Dueñas, C., Serrano E., Inostroza K., Soler, M., [...], Serrano, O. 2025. Soil organic carbon depth profiles and centennial and millennial decay rates in tidal marsh, mangrove and seagrass blue carbon ecosystems. *Commun.Earth Environ.* 6:504. Doi:[10.1038/s43247-025-02390-2](https://doi.org/10.1038/s43247-025-02390-2)
- Por, F. D. 1978. The influx of Red Sea biota into the Mediterranean by way of the Suez Canal. *Ecological Studies*, 23.
- Poffenbarger, H. J., Needelman, B. A., Megonigal, J. P. 2011. Salinity influence on methane emissions from tidal marshes. *Wetlands*, 31(5), 831-842. Doi: [10.1007/s13157-011-0197-0](https://doi.org/10.1007/s13157-011-0197-0)
- Preston, J., Debney, A., Gamble, C., Hardy, M. J., Underwood, J. C., Garbutt, A., [...] zu Ermgassen, P. S. E. 2025. Seascape connectivity: evidence, knowledge gaps and implications for temperate

- coastal ecosystem restoration practice and policy. *npj Ocean Sustain* 4, 33. Doi: 10.1038/s44183-025-00128-3
- Rosentreter, J. A., Al-Haj, A. N., Fulweiler, R. W., Williamson, P. 2021. Methane and nitrous oxide emissions complicate coastal blue carbon assessments. *Global Biogeochem. Cycles*, 35(2), e2020GB006858. Doi: [10.1029/2020GB006858](https://doi.org/10.1029/2020GB006858)
- Saavedra-Hortua, D., Nagelkerken, I., Estupinan-Suarez, L.M., Gillis, L.G. 2023. Effects of connectivity on carbon and nitrogen stocks in mangrove and seagrass ecosystems. *STOTEN* 896, p.164829. Doi: [10.1016/j.scitotenv.2023.164829](https://doi.org/10.1016/j.scitotenv.2023.164829)
- Saintilan, N., Kovalenko, K. E., Guntenspergen, G., Rogers, K., Lynch, J. C., Cahoon, D. R., [...], Khan, N. 2022. Constraints on the adjustment of tidal marshes to accelerating sea level rise. *Science*, 377(6605), 523-527. Doi: 10.1126/science.abo7872
- Smith, A. J., McGlathery, K., Chen, Y., Ewers Lewis, C. J., Doney, S. C., Gedan, K., [...], Kirwan, M. L. 2024. Compensatory mechanisms absorb regional carbon losses within a rapidly shifting coastal mosaic. *Ecosystems*, 27(1), 122-136. Doi: 10.1007/s10021-023-00877-7
- Schuerch, M., Kiesel, J., Boutron, O., Guelmami, A., Wolff, C., Cramer, W., [...], Vafeidis, A. T. 2025. Large-scale loss of Mediterranean coastal marshes under rising sea levels by 2100. *Commun. Earth Environ.* 6(1), 128. Doi: 10.1038/s43247-025-02099-2
- Serrano, O., Lavery, P. S., Rozaimi, M., Mateo, M. Á. 2014. Influence of water depth on the carbon sequestration capacity of seagrasses. *Global Biogeochem. Cycles*, 28(9), 950-961. Doi: [10.1002/2014GB004872](https://doi.org/10.1002/2014GB004872)
- Trevathan-Tackett, S. M., Kelleway, J., Macreadie, P. I., Beardall, J., Ralph, P., Bellgrove, A. 2015. Comparison of marine macrophytes for their contributions to blue carbon sequestration. *Ecology*, 96(11), 3043-3057. Doi: [10.1890/15-0149.1](https://doi.org/10.1890/15-0149.1)
- Valiela, I., Cole, M. L. 2002. Comparative evidence that salt marshes and mangroves may protect seagrass meadows from land-derived nitrogen loads. *Ecosystems*, 5(1), 92-102. Doi: 10.1007/s10021-001-0058-4
- Vehmaa, A., Lanari, M., Jutila, H., Mussaari, M., Pätsch, R., Telenius, A., [...], Quintana, C. O., 2024. Harmonization of Nordic coastal marsh habitat classification benefits conservation and management. *Ocean Coast Manage* 252 (2024): 107104. Doi: 10.1016/j.ocecoaman.2024.107104
- Wang, J., Yu, G., Han, L., Zhang, J., Sun, M., Krause, S., Liu, C. 2025. Unveiling distribution and drivers of soil organic carbon in coastal China: Salt marshes and tidal flats as major carbon storage contributors. *Ecological Indicators*, 178, 114132. Doi: [10.1016/j.ecolind.2025.114132](https://doi.org/10.1016/j.ecolind.2025.114132)
- Wesselmann, M., Gerdali, N. R., Duarte, C. M., Garcia-Orellana, J., Díaz-Rúa, R., Arias-Ortiz, [...], Marbà, N. 2021. Seagrass (*Halophila stipulacea*) invasion enhances carbon sequestration in the Mediterranean Sea. *Global Change Biol.* 27(11), 2592-2607. Doi: [10.1111/gcb.15589](https://doi.org/10.1111/gcb.15589)
- Williamson, P., Gattuso, J. P. 2022. Carbon removal using coastal blue carbon ecosystems is uncertain and unreliable, with questionable climatic cost-effectiveness. *Front. Climate*, 4, 853666. Doi: [10.3389/fclim.2022.853666](https://doi.org/10.3389/fclim.2022.853666)
- Yando, E. S., Jones, S. F., James, W. R., Colombano, D. D., Montemayor, D. I., Nolte, S., [...], Sergienko, L. 2023. An integrative salt marsh conceptual framework for global comparisons. *Limnol. Oceanogr. Lett.*, 8(6), 830-849. Doi: [10.1002/lo12.10346](https://doi.org/10.1002/lo12.10346)

Supplementary materials

S1. Construction of spatial data layers for saltmarshes and seagrasses

Saltmarshes: The European CLC map was queried to retain only the cells containing saltmarshes (code 421) and these were converted into polygons feature layer. In cases where the WCMC data overlapped with CLC derived polygons or when it contained saltmarsh polygons whose origin attribute information referred to an older CLC version, the WCMC layer was corrected by removing these data so that only the newer CLC polygon extensions were considered for the areas of overlap. After the union of the two layers, any polygon extending beyond the boundary of the newer CLC polygon and originating from the WCMC data polygon were erased if the slivers extended less than 100 m beyond the CLC boundaries.

Seagrasses: The EMODnet and WCMC layers were integrated, retaining WCMC data in overlaps only where its resolution was better than the EMODnet one (Figure 1B). Spatial data for *Ruppia* were disregarded as this genus is typically not classified as a true seagrass (Mannino et al., 2015; den Hartog and Kuo, 2006) and CAR data for this genus is not available in the scientific literature.

S2. Overlaying habitat areas with protected areas - preparation of spatial data layers

During the rasterization process, a unique numerical code was assigned to each raster grid, code that described the specific habitats or protection statuses present in each cell (see Table S1 for the coding system). By summing the codes of each input raster, 10 final subregional raster layers were generated. In these final raster layers, each cell had a unique code string that fully described all the overlapping features within it (specific habitat type and seagrass genus as well as protection status and protection network). For example, a hypothetical cell containing both *Posidonia* and *Cymodocea* seagrasses, and which is protected under both the Natura 2000 and as a nationally designated site, would be assigned a final code of 110220. This value is the sum of the individual codes for each feature:

Posidonia (10000) + *Cymodocea* (100000) + NDS (20) + N2000 (200) = 110220 (Table S1).

This method allowed to manage all potential combinations of habitats and protection status within a single layer, preventing an overestimation of habitat surface due to the mosaic of different habitats and protection statuses in the original data. Finally, the different layers were used to compute 1) the percentage surface area of seagrass and saltmarsh habitats located inside and outside the PA network(s) of each EU subregion and 2) absolute estimates of CAR (unit) per habitat typology, both across the entire EU region and within the established PAs.

Table S1. Code options used for the grid layers derived from the original vector data for both MPAs and habitats

Codes	Subregion
RSC	2
NDS	20
N2000	200
Saltmarshes	1000
Posidonia	10000
Cymodocea	100000
Zostera	1000000
Halophila	10000000

S3. Saltmarsh and seagrass habitat area and protection level

Table S2. Estimated area extent (km²) by habitat and region.

Habitat	Habitat area (km ²)			
	NE Atlantic	Baltic Sea	Mediterranean Sea	Black Sea
Saltmarsh	1810	237	1274	72.5
Seagrass	3096	806	7548	
- Posidonia			6356	
- Cymodocea	2131		950	
- Zostera	965	806	19	
- Halophila			173	

Table S3. Percent of area protected by habitat and region.

Habitat	Protection extent (% of area)			
	NE Atlantic	Baltic Sea	Mediterranean Sea	Black Sea
Saltmarsh	93.3	74.2	94.4	98.6
Seagrass	64.7	57.7	62.5	
- Posidonia			68.2	
- Cymodocea	59.2		19.1	
- Zostera	76.7	57.7	46.4	
- Halophila			81.1	

S4. Saltmarsh and seagrass CAR

Table S4. Estimated median organic carbon accumulation rate (CAR; $\text{g m}^{-2} \text{yr}^{-1}$) and range (25%-75% quartile) per habitat and EU region. Geometric means are reported for comparison with IPCC Tier 1 levels. N/A indicates that the species is not present in the region. *Refers to Spanish and Portuguese *Zostera* data from the NE Atlantic used in for the Mediterranean due to lacking Mediterranean data.

Habitat	Carbon accumulation rate (CAR, $\text{g m}^{-2} \text{yr}^{-1}$)			
	Median (25-75% quantiles) (Geometric mean) no. of observations (n)			
	Europe	NE Atlantic	Baltic Sea	Mediterranean
Saltmarsh	79.0 (41.1-138.5) (69.9) n=265	86.9 (46.6-146.8) (81.9) n=197	47.0 (32.9-75.9) (18.8) n=32	88.3 (38.3-158.3) (79.8) n=36
Seagrass	24.6 (14.3-57.3) (17.4) n=88	24.5 (12.3-49.7) n=26	0.8 (0.0-11.0) n=7	29.8 (17.8-57.8) n=55
- Posidonia	30.8 (21.2-57.4) (33.5) n=43	NA	NA	30.8 (21.2-57.4) n=43
- Cymodocea	19.5 (8.1-73.5) (11.5) n=12	27.8 (-) n=1	NA	19.3(7.5-76.7) n=11
- Zostera	19.6 (2.5-46.9) (8.4) n=32	24.5 (12.2-51.1) n=25	0.8 (0.0-11.0) n=7	42.4 (28.1-83.4) n=8*
- Halophila	14.8 (-) n=1	NA	NA	14.8 (-) n=1

Table S5. Estimated median and range (25%-75% quartile) of the area-integrated organic carbon accumulation rate (CAR_{int} ; Gg yr^{-1}) per habitat and EU region. N/A indicated that the species is not present in the region. *Refers to Spanish and Portuguese *Zostera* data from the NE Atlantic used for the Mediterranean Sea due to lacking Mediterranean data.

Habitat	Carbon accumulation rate (CAR, Gg yr^{-1})		
	Median (25-75% quantiles)		
	NE Atlantic	Baltic Sea	Mediterranean Sea
Saltmarsh	158 (84-267)	11 (8-18)	113 (49-202)
Seagrass	76 (38-154)	16 (2-38)	225 (134-436)
- Posidonia	NA	NA	196 (135-365)
- Cymodocea	42 (15-157)	NA	18 (7-73)
- Zostera	24 (12-49)	16 (2-38)	0.8 (0.5-1.6)*
- Halophila	NA	NA	NA

S5. Explanatory variables for saltmarsh and seagrass CAR variability

Candidate explanatory variables for saltmarsh CAR variability were selected based on common global drivers identified in previous studies (Wang et al. 2025, Saintilan et al. 2022; Huyzentruyt et al. 2024). Although CAR and SAR values from these studies were computed for shorter time scales (sub-decades to decades, mostly based on surface elevation table - marker horizon data), we can expect the main drivers of longer-term CAR to be similar. The primary drivers identified from the literature are relative sea level rise (RSLR), tidal range, and mean annual temperature. The main and most important driver in these studies was RLSR. RLSR was observed to increase CAR, which was hypothesized to occur through increased tidal flooding and therefore enhanced sediment supply and limited oxygen supply in the sediment under more inundated conditions, reducing organic matter decomposition. Similarly, larger tidal range showed positive relationships with saltmarsh CAR, likely through greater inundation and sediment deposition. The effect of temperature, however, was not clear; while Huyzentruyt et al. (2024) observed a negative relationship with CAR (maybe due to accelerated microbial decay), Wang et al. (2025) stated a positive effect on tidal CAR, which may occur by boosting plant productivity. Although tidal frame position was found to be a relevant driver of saltmarsh SAR and CAR in two of these studies (Saintilan et al. 2022; Huyzentruyt et al. 2024), it was omitted due to time constraints. To these drivers, we added three further candidate variables based on our specific hypotheses. We propose that reduced wave fetch (increased shelter) enhances saltmarsh CAR by facilitating the settlement of fine sediments and minimizing erosion. Similarly, we expect that shorter distances to high-flow rivers boost CAR through periodic inputs of high sediment loads. Finally, we hypothesize that the timespan over which CAR is calculated has a negative effect, with longer periods leading to lower estimates due to processes like organic carbon degradation and compaction.

Seawater current speed and wave exposure strongly influence seagrass carbon accumulation. Higher hydrodynamic exposure reduces seagrass cover, fine particles and sediment organic content by enhancing resuspension and organic carbon export (Fonseca and Bell 1998), resulting in lower CAR in more exposed environments (Leiva Dueñas et al. 2023). Light availability, strongly linked to water depth, is a key control on seagrass OC accumulation. Shallow, well-lit meadows show much higher CAR than deeper, light-limited sites, as greater irradiance enhances seagrass productivity, shoot density, and sediment accretion (Serrano et al. 2014; Pergent-Martini et al. 2021). Nutrient loading can weaken seagrass blue carbon capacity by enhancing decomposition and microbial activity. Elevated nutrients increase leaf nitrogen and labile carbon content, stimulate sediment microbial processes, and reduce sediment OC, leading to greater OC loss and destabilization of stored carbon pools (Liu et al. 2017, 2023). Seabed temperature influences seagrass CAR by affecting both production and decomposition. While warming can enhance plant productivity, it also accelerates microbial OC decomposition, leading to uncertainty about net effects on carbon storage or CAR (Fenchel et al. 2012; Davidson and Janssens 2006; Trevathan-Tackett et al. 2015). Experimental work shows that moderate warming increases remineralization rates in *Posidonia oceanica* sediments up to an optimum (Pedersen et al. 2011), and large-scale heatwaves can cause substantial carbon losses from seagrass meadows (Arias-Ortiz et al. 2018). Sediment Accumulation Rate (SAR) was also considered a CAR driver because SAR controls the physical process of burial. A strong correlation indicates the system's carbon sink is primarily dependent on geomorphological processes and allochthonous sediment supply while a weak correlation indicates greater influence

of seagrass-derived (autochthonous) organic production, emphasizing the role of biological processes in carbon sequestration.

Spatial data description and sources for the hypothesized explanatory variables are provided in Table S6 and Table S7.

Table S6. Spatial properties and sources used as potential explanatory variables for European salt marsh CAR⁴.

Potential covariate and units	Explanation and/or calculation	Spatial resolution	Source
50 year-Relative Sea Level Rise (RLSR, mm/yr)	Relative sea-level rise (RSLR) spatial layer derived from PSMSL tide gauge data (1970-2022) using ordinary kriging interpolation. The interpolation was performed fitting an optimal variogram model to the data.	0.25° (~25km ²)	Permanent Service for Sea Level (PSMSL)
Tidal range (cm)	M2 tide component, which is the principal lunar semidiurnal constituent (12.42 hours) is the most significant tide component across Europe.	1/16 degree (~7km ²)	FES2014 Tide Model
Mean Annual Temperature (MAT, °C)	Mean annual temperature, average for the years 1970-2000.	30-second (~1km ²)	WorldClim version 2.1 (variable BIO 1)
Wave fetch (km)	Summed wave fetch in 32 angular sectors around focal cells, using a model modified from that given in Burrows et al (2012). Wave fetch is the distance to the nearest land in a defined direction. Fetch is calculated up to 5 km from the coastline.	100m ²	Burrows (2020) https://doi.org/10.6084/
Distance to a high-flow river (km)	Distance to the closest river with a long-term average discharge greater than 1,000m ³ and less than 10,000 m ³ . This discharge range captures the largest rivers in Europe. Source data for river locations were derived from the HydroRIVERS polyline dataset.	0.10° (~10km ²)	Lehner and Grill (2013) https://doi.org/10.1002/hyp.9740
Period used to calculate CAR (years)	Point data from dataset compiled in this study.		This study

⁴Table references: Burrows, M. 2020. Wave fetch GIS layers for Europe at 100m scale. figshare. Dataset. Doi:10.6084/m9.figshare.8668127.v1. <https://doi.org/10.6084/m9.figshare.8668127.v1> Lehner, B., Grill, G. 2013. Global river hydrography and network routing: Baseline data and new approaches to study the world's large river systems. Hydrological Processes, 27(15), 2171–2186. Doi: 10.1002/hyp.9740<https://doi.org/10.1002/hyp.9740>

Table S7. Spatial properties and sources used as potential explanatory variables for European seagrass CAR⁵.

Potential covariate and units	Explanation and/or calculation	Spatial resolution	Source
Seawater speed at seabed (m s⁻¹, period 2000–2014)	Marine data layer for present conditions was produced with climate data describing monthly averages for the period 2000–2014, obtained from pre-processed global ocean re-analyses combining satellite and in situ observations at regular two- and three-dimensional spatial grids.	3 minutes (~5km ²)	Bio-ORACLE v3.0 (Assis et al. 2024)
Light reaching the seabed (mol phot m⁻² d⁻¹)	Photosynthetic active radiation (PAR) reaching the seabed, derived by multiplying the fraction of surface light reaching the seabed by the amount of light at the sea surface.	3.75 seconds (~100m ²)	EMODnet Seabed Habitats, derived by ACRI-ST from the European Space Agencies (ESA) MERIS project
Water depth (m)	Point data from dataset compiled in this study.		This study
Mean nitrate concentration in surface waters (mmol m⁻³, period 2000–2014)	Marine data layer for present conditions was produced with climate data describing monthly averages for the period 2000–2014, obtained from pre-processed global ocean re-analyses combining satellite and in situ observations at regular two- and three-dimensional spatial grids.	3 minutes (~5km ²)	Bio-ORACLE v3.0 (Assis et al. 2024)
Mean seabed temperature (°C, period 2000–2014)	Marine data layer for present conditions was produced with climate data describing monthly averages for the period 2000–2014, obtained from pre-processed global ocean re-analyses combining satellite and in situ observations at regular two- and three-dimensional spatial grids.	3 minutes (~5km ²)	Bio-ORACLE v3.0 (Assis et al. 2024)
Sedimentation rates (SAR, mm yr⁻¹)	Point data from dataset compiled in this study.		This study
Period used to calculate CAR (years)	Point data from dataset compiled in this study.		This study

⁵ Table reference: Assis, J., Fernández Bejarano, S. J., Salazar, V. W., Schepers, L., Gouvêa, L., Fragkopoulou, E., [..], De Clerck, O. 2024. Bio-ORACLE v3.0. Pushing marine data layers to the CMIP6 Earth System Models of climate change research. *Global Ecol. Biogeogr.* 33(4), e13813. Doi: 10.1111/geb.13813

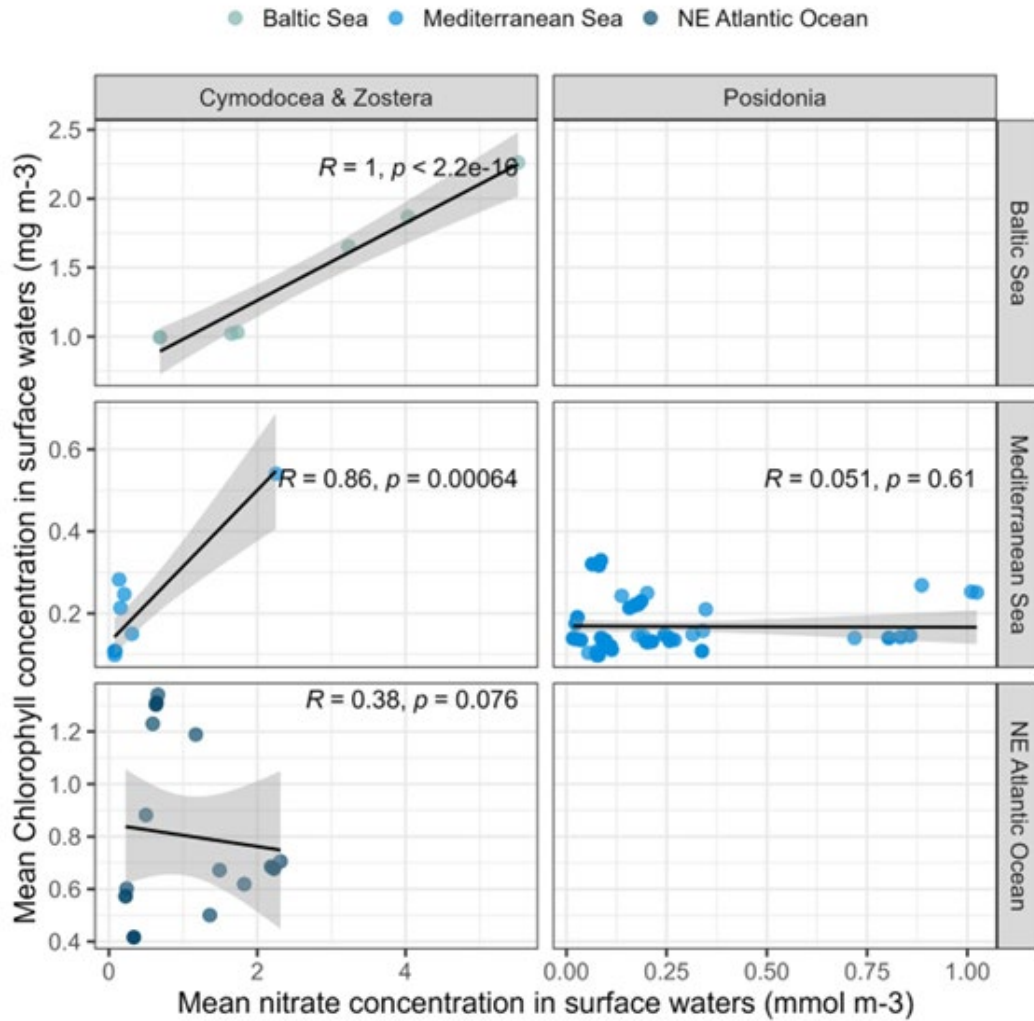


Figure S1. Relationships between mean nitrate concentration and mean chlorophyll-a concentration in surface waters across European regional seas and dominant seagrass genera. Panels show separate relationships for *Cymodocea* and *Zostera* (left) and *Posidonia* (right) within the Baltic Sea, Mediterranean Sea, and NE Atlantic. Black lines represent fitted linear trends with 95% confidence intervals (shaded areas). Reported R and p values correspond to Spearman's rank correlation coefficients.

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