

Study on the seabed's natural carbon sequestration capacity and related impacts from seabed-disturbing activities

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Acronyms

AIS	Automatic Identification System – High frequency satellite system primarily for the avoidance of collisions
BCP	Biological Carbon Pump
CFG	Core Fishing Ground
CPZ	Carbon Protection Zone
CSZ	Carbon Sensitivity Zone
DBD	Dry Bulk Density
EEZ	European Economic Zone
EMODnet	European Marine Observation and Data Network
GFW	Global Fishing Watch – Data collated on fishing activities
ICES	International Council for the Exploration of the Sea
IPCC	International Panel on Climate Change
MSFD	Marine Strategy Framework Directive
MSFD_BBHT	Marine Strategy Framework Directive – Broad Benthic Habitat Types
OC	Organic Carbon
OWF	Offshore Wind Farm
SAR	Swept Area Ratio – A value for the number of times per year a certain area of the seabed is disturbed by fishing gear or dredges (unitless - m^2 per m^2 per year)
SVR	Swept Volume Ratio – The volume of sediment disturbed per area per unit of time (as m^3 per m^2 per year).
VMS	Vessel Monitoring System – for fisheries enforcement and management

Glossary

Aeolian – Derived by wind. So aeolian sediments are the result of wind erosion and deposition in the sea.

Biological carbon pump – the ocean's natural, biologically driven process that transfers carbon from the atmosphere and surface waters into the deep ocean and seafloor sediments. Small amounts of this carbon make it to deeper areas, where it can be considered 'sequestered'.

Blue Carbon (IPCC, 2019) – 'All biologically-driven carbon fluxes and storage in marine systems that are amenable to management can be considered as blue carbon'.

Carbon accumulation – Accumulation of carbon is described in terms of organic or inorganic carbon added to stores (temporary or permanent), per unit of time, per unit area.

Carbon fixation – is the biological process by which organisms convert inorganic carbon (primarily carbon dioxide from air and water) into organic compounds, notably through photosynthesis.

Carbon pump – natural processes that transfer carbon dioxide from the Earth's atmosphere into the deep ocean and seafloor sediments. Usually, the solubility pumps and biological pumps are described where large amounts of carbon (in various forms, DIC, DOC, POC, PIC) are transferred through systems. Both pumps can result in carbon being 'sequestered' as it is described in the present study, locked away from atmospheric circulation into carbon sinks.

Carbon Sensitivity Zone – an area of high organic carbon density, derived from the 75th percentile of values in the North Sea, which are vulnerable to disturbance.

Carbon sequestration – the process of capturing and storing atmospheric carbon dioxide (CO_2) to mitigate global climate change. Sequestration of carbon occurs over timescales which have a significant and lasting impacts on atmospheric circulation, the long-term removal of CO_2 . Long-term is usually defined as between 10's-100's of years but the longevity is usually specified by authors or modellers.

Carbon sink – is any system, natural or artificial, that absorbs more carbon dioxide from the atmosphere or water than it releases. By storing (sequestering) this carbon in sediments (sinks) it reduces the concentration of greenhouse gases in the atmosphere, helping to mitigate global climate change.

Carbon storage – Here, carbon storage refers to those temporary stores such as those within biomass of kelp, seagrass. A carbon store may have a duration of 0-50 years depending on the habitat.

Erosion – the vertical loss of substrate at a specific location

Inorganic Carbon – Refers to the bi-products of cellular respiration, in most eukaryotes this will be the production of CO_2 , but inorganic carbon compounds also include carbonate ions (carbonate and bicarbonate) and calcium carbonate (CaCO_3).

OC% – The percentage of organic carbon in a sample, usually directly from the analytical instrument. Samples are often freeze dried, or treated directly so the value is reported as percentage dry weight (% dw) or wet weight (% ww).

OC Density – A measurement of organic carbon by *volume* of sediment. OC density can be calculated using the known OC% multiplied by the bulk density of the sample expressed in units of mass (e.g., kg) per unit of volume (e.g., m^3).

Organic Carbon – Refers to carbon which is found in organic compounds, generally carbohydrates, lipids, proteins and nucleic acids. Organic carbon accumulates in sediment stores through decomposition processes, hydrodynamic deposition, burial and can be deposited by glacial retreat.

Sediment accumulation – The volume of sediments added to a region per unit of thickness (cm) per unit of area (m^2) per unit of time (yr).

Solubility pump – Atmospheric gases (carbon dioxide, nitrogen and oxygen) dissolved into seawater are transported by ocean currents, thermohaline circulation and surface winds. Carbon dioxide is dissolved as dissolved inorganic carbon (DIC) in various forms. The majority of CO_2 is dissolved in colder water, at the poles, where mixing can occur and it is incorporated into deep water circulation currents.

Executive Summary

Purpose and scope

European seabed sediments constitute one of the planet's largest long-term carbon stores, but their contribution to climate mitigation remains incompletely quantified and is not yet fully incorporated into marine policy or management. The report addresses this gap by reviewing the state of knowledge, mapping organic carbon stocks and accumulation across European seabed habitats, analysing the effects of seabed-disturbing activities, testing spatial management scenarios, and identifying legal and technical options for the European Union and its Member States. Its central objective is to improve understanding of the natural capacity of European seabed habitats to remove carbon from seawater and retain it, and of the extent to which human activities may impair that function.

The report distinguishes vegetated coastal “blue carbon” systems, principally seagrasses and macroalgal habitats within the study's marine scope, from the much more extensive organic carbon stores held in seabed sediments. Saltmarshes, wetlands and transitional-water ecosystems are outside the study. Although vegetated habitats occupy a small area, they can store and accumulate high quantities of carbon per unit area while supporting biodiversity, food webs, coastal resilience and other ecosystem services. Offshore sediments generally contain less carbon per unit area but cover vastly greater areas and may retain carbon over much longer periods. Both therefore matter, but they require different evidence, accounting and management approaches.

The analysis combines literature review, habitat and sediment mapping, carbon-density models, observations, fishing-pressure datasets and scenario modelling. It focuses particularly on the upper 0.1 metres of sediment, where recent organic carbon is most exposed to physical disturbance. It uses European Nature Information System habitat classifications and Marine Strategy Framework Directive regions to organise the assessment. Six published models of sediment organic carbon density are compared, alongside newer MPA Europe outputs and sample-based datasets. Fishing activity is represented through ICES, OSPAR and Global Fishing Watch sources and converted, where possible, into measures of swept area and swept volume that reflect the frequency and depth of contact with the seabed.

Distribution and accumulation of seabed carbon

Organic carbon in marine sediments originates from several interconnected sources. Phytoplankton production supplies material across broad marine areas; seagrasses, kelp and other macroalgae provide locally important inputs; and rivers deliver terrestrial organic matter. Once deposited, carbon may be buried and preserved, consumed or remineralised by organisms, resuspended and transported, or returned to dissolved inorganic carbon and potentially to the atmosphere as carbon dioxide. The balance depends on sediment type, oxygen conditions, hydrodynamics, depth, biological activity, carbon quality and the frequency of physical disturbance.

Fine-grained, muddy and depositional sediments are generally the most important stores because they trap organic particles and can protect them from rapid degradation. Sublittoral sediments and deep-sea beds consequently represent the principal sedimentary habitats of interest. Seagrass meadows can enhance deposition, reduce resuspension and accumulate substantial carbon in the sediments beneath them. Macroalgal forests are highly productive and export organic material, although tracing where that material is ultimately buried remains difficult. The report emphasises that stock, accumulation and sequestration are not interchangeable concepts: a large existing stock does not necessarily indicate a high present-day

accumulation rate, and disturbance of a stock does not mean that all disturbed carbon is immediately emitted to the atmosphere.

Available estimates reveal important regional patterns, but also major uncertainty. Carbon-rich deposits are associated with muddy continental-shelf environments, enclosed and semi-enclosed seas, deeper depositional zones and some vegetated coastal habitats. However, the six carbon-density models differ substantially in predicted values and spatial distributions, especially in the southern North Sea and Barents Sea. Models rely on different observations, depths, sediment classifications, spatial predictors and resolutions, and they cover European sea basins unevenly. Agreement is strongest in some well-sampled North Sea areas and weaker across the Mediterranean and Black Sea. This divergence is not a minor technical issue: the choice of carbon map materially changes estimates of the amount and location of carbon exposed to disturbance and the apparent benefit of particular management scenarios.

Evidence on accumulation and sequestration is still less complete than evidence on stocks. Published accumulation rates vary widely between coastal, shelf and abyssal settings. Sediment accumulation can help predict carbon accumulation, but carbon density alone is an imperfect proxy. The report therefore cautions against presenting mapped stocks as verified additional carbon removals or treating avoided disturbance as directly equivalent to avoided atmospheric emissions. Robust climate accounting requires information on burial rates, carbon provenance and lability, the counterfactual condition without intervention, permanence, leakage or displacement, and the eventual fate of disturbed material.

Human pressures and the significance of bottom fishing

Natural processes such as storms, waves, currents, bioturbation and sediment transport continually rework the seabed. Human activities add pressures through bottom-contact fishing, dredging, aggregate extraction, construction, cables and pipelines, offshore energy, anchoring, aquaculture, navigation and potentially seabed mining. Their effects vary greatly in intensity, depth, duration, recurrence and spatial footprint. Some developments cause severe but localised disturbance during construction; others may subsequently stabilise an area or exclude more extensive pressures.

Bottom-contact fishing is the dominant anthropogenic pressure identified. Its estimated spatial footprint is roughly eight times that of the next most extensive seabed disturbance examined. Mobile gears repeatedly penetrate, mix and resuspend surface sediments across large areas, often at intervals too short for carbon stores or benthic communities to recover. The effect depends on gear type, penetration depth, sediment characteristics, fishing frequency and the degradability of the exposed carbon. Dredging for shellfish and aggregates can be intense but is more geographically limited. Wind farms, cables, pipelines and fixed infrastructure have direct construction footprints, yet their net long-term effect may be smaller and may even include local protection where bottom fishing is excluded.

The report estimates “carbon disturbed,” rather than claiming that the same amount becomes carbon dioxide. Disturbance makes organic matter more available for degradation and may reduce long-term burial, but some material is redeposited and preserved elsewhere, some was already relatively resistant to decomposition, and only a portion of remineralised carbon will exchange with the atmosphere. Hydrodynamic transport, sediment oxygenation, microbial processes and water-column buffering all influence the outcome. Recent process-based studies provide more realistic representations of degradation, resuspension, redeposition and air-sea exchange, but they remain geographically limited. Expanding these models is essential if sediment protection is to generate credible quantified climate benefits.

Management scenarios and principal results

Four spatial approaches were tested: removing bottom fishing from existing Marine Protected Areas; excluding it from operational and planned offshore wind-farm zones; protecting carbon-sensitive zones defined by high sediment carbon density; and restricting bottom fishing to core fishing grounds. The scenarios extend approaches developed for the North Sea across European waters using the new MPA Europe carbon map and alternative carbon and fishing datasets. They are exploratory rather than forecasts. They assume simplified responses and do not fully represent fleet adaptation, displacement, changes in effort, target species, economic incentives or ecological spillover.

Removing bottom-contact fishing from existing MPAs reduced estimated organic carbon disturbance by approximately 10-30%, depending on the carbon and fishing datasets used. This demonstrates that designated biodiversity areas already offer an immediately available delivery mechanism, but also exposes the limited protection afforded where damaging fishing remains permitted. Offshore wind-farm exclusions produced smaller overall reductions because their footprint is more restricted, though local benefits may be important and could partly offset construction disturbance.

Carbon-sensitive zones directly target areas of high carbon density and can provide substantial protection, but their performance is particularly dependent on the reliability of the underlying maps. They may overlook lower-density areas with high current accumulation rates or especially vulnerable carbon, and high-carbon zones may not coincide with the most heavily disturbed areas. They should therefore complement, rather than replace, biodiversity-based protection and should be revised as data improve.

Restricting activity to core fishing grounds produced the largest modelled reductions in several combinations. When Global Fishing Watch data defined those grounds, estimated disturbance fell by as much as 75%. This reflects the concentration of fishing effort and suggests that spatial rationalisation could protect large areas while retaining activity in the most important fishing locations.

It also represents the scenario with potentially the greatest socio-economic consequences and displacement risk. If excluded effort simply moves into carbon-rich or previously lightly disturbed sediments, some gains could be lost. Conversely, recovery within closed areas may improve biodiversity, fish populations and catch per unit effort around their boundaries, reducing the effort needed over time. The outcomes therefore depend on accompanying effort controls, fleet behaviour, alternative gears, compliance and adaptive review.

Across all model combinations, a consistent result is that reducing bottom-fishing pressure in MPAs and other spatially managed areas decreases estimated carbon disturbance and is also likely to benefit seabed integrity and biodiversity. The analysis supports action but not false precision. Differences between carbon models, incomplete Mediterranean and Black Sea fishing data, uncertainties in gear classification and penetration depth, and the simplified treatment of carbon fate mean that scenario percentages should be treated as indicative ranges. The strongest near-term policy case is for precautionary pressure reduction in locations where carbon value, ecological sensitivity and disturbance clearly overlap.

EU policy and legal relevance

The report positions blue and seabed carbon at the intersection of climate mitigation, biodiversity recovery, ecosystem resilience and sustainable use of marine space. The European Green Deal and Biodiversity Strategy for 2030 establish the overarching direction. The Nature Restoration Regulation creates binding, time-bound requirements to restore marine habitats in poor condition and recognises restoration's

contribution to climate mitigation and adaptation. The Marine Strategy Framework Directive provides the principal operational framework through assessments, definitions of Good Environmental Status, environmental targets, monitoring and programmes of measures.

Seabed carbon is especially relevant to MSFD Descriptor 6 on sea-floor integrity and Descriptor 1 on biodiversity. Carbon storage can be treated as evidence of benthic ecosystem function: activities that damage sediment structure and compromise long-term carbon retention also affect habitat condition, ecological processes and resilience. Carbon-related functional indicators could support assessment of the extent and severity of physical disturbance under Descriptor 6, while Descriptor 1 and 6 results could help target restoration. Links also exist with eutrophication, contaminants and water quality because these pressures affect habitat condition, productivity, oxygenation and carbon preservation.

The European Ocean Pact, prospective Ocean Act and revision of marine governance offer an opportunity to integrate blue carbon more coherently, reduce fragmented reporting and strengthen sea-basin coordination. Maritime Spatial Planning can bring carbon-risk information into decisions on fisheries, protected areas, renewable energy, ports, cables, extraction and restoration. The Common Fisheries Policy and the EU Marine Action Plan provide routes for managing mobile bottom-contact gears, particularly in MPAs. Environmental and strategic assessments can prevent or mitigate damage from projects and plans by considering carbon stocks, sequestration functions, cumulative effects and restoration feasibility.

Regional Seas Conventions - OSPAR, HELCOM, the Barcelona Convention and the Bucharest Convention - are essential because sediment processes, habitats and human pressures cross national boundaries. They can develop shared baselines, indicators, thresholds, monitoring methods and transboundary priorities. Sea-basin and macro-regional initiatives can align projects and finance, particularly where individual states have limited data or capacity. At international level, protecting seabed carbon supports the Kunming-Montreal Global Biodiversity Framework, including the use of ecosystem-based and nature-based approaches to reduce climate impacts on biodiversity.

Policy recommendations

The report proposes eight mutually reinforcing recommendations. First, bottom-contact fishing should be excluded from blue-carbon-relevant areas through a targeted, risk-based and adaptive approach. Priority should be given to locations where reliable evidence shows overlap between mobile gears and carbon-rich or vulnerable habitats. Measures should include monitoring, review, compliance and management of displaced effort, together with support for less disturbing techniques where feasible.

Second, the EU should develop carbon-sensitive zones as a complementary management category alongside MPAs. These zones would make climate-regulation functions visible in spatial planning and permitting, including outside areas selected primarily for biodiversity. Initial designation should focus on high-confidence locations and be subject to rolling evidence review rather than fixed permanently on uncertain maps.

Third, environmental impact assessment and strategic environmental assessment should explicitly address blue and seabed carbon. Relevant plans and projects should evaluate stock disturbance, loss of accumulation or storage function, cumulative pressures, the fate of resuspended carbon, alternatives, mitigation and restoration. This is particularly important for dredging, aggregate extraction, ports, coastal construction and seabed infrastructure.

Fourth, the EU needs formal, progressively harmonised carbon monitoring and reporting within marine governance. Minimum requirements should cover habitat extent and condition, sediment carbon stocks where feasible, accumulation and vulnerability, pressure layers and time series capable of detecting deterioration or recovery. EMODnet, Copernicus Marine, national programmes, ICES, the Joint Research Centre and research infrastructures can support interoperable, decision-grade products.

Fifth, blue carbon action should be aligned with implementation of the Nature Restoration Regulation and the MSFD. Restoration planning and marine-status assessment should use common ecological and pressure evidence, recognise climate-regulation functions and avoid parallel, disconnected reporting systems. This would allow biodiversity recovery, seabed integrity and climate objectives to be delivered through a coherent management logic.

Sixth, Regional Seas Conventions and sea-basin cooperation should be strengthened as implementation platforms. Basin-specific methods, thresholds and priorities are preferable to fragmented national approaches and can respond to contrasting ecological conditions and evidence gaps across the Atlantic, Baltic, Mediterranean and Black Seas.

Seventh, knowledge gaps should be treated as implementation priorities rather than reasons for inaction. Immediate needs include better observations and mapping outside the North Sea, improved estimates of accumulation and sequestration, information on carbon origin and degradability, realistic models of disturbance and recovery, and stronger linkage between ecological and activity data. Policy should proceed in phases, with monitoring designed to test assumptions and update management.

Eighth, socio-economic transition measures are needed from the outset. Spatial restrictions affect fisheries and other marine users and will be more durable if developed through engagement, predictable planning, support for alternative gears and practices, and targeted mitigation where justified. Managing displacement is essential: exclusion without effort management may transfer pressure rather than reduce it.

Implementation priorities and safeguards

The report's findings imply a practical sequence for implementation. In the near term, authorities should combine existing habitat, carbon and pressure layers to identify high-confidence overlap zones, beginning with well-studied basins and sites where mobile bottom-contact fishing is recurrent. Existing MPAs should be screened first because their biodiversity objectives and governance structures provide an established basis for action. Management plans should state whether bottom-contact gears are permitted, specify the ecological and carbon rationale for restrictions, and establish enforceable spatial rules. Offshore renewable-energy planning should similarly assess both direct construction effects and indirect changes caused by fishing exclusion or displacement, rather than assuming that development is automatically beneficial or harmful to seabed carbon.

At the same time, a common technical framework should define what is being measured. Stock estimates should specify sediment depth, units, spatial resolution and uncertainty. Accumulation and sequestration should be reported separately, and claims about avoided emissions should disclose assumptions concerning degradation, transport, redeposition, water-column chemistry and atmospheric exchange. Carbon maps should carry confidence classifications so that decision-makers can distinguish robust hotspots from model-dependent predictions. Observations should be designed to improve weakly sampled regions and sediment types rather than repeatedly concentrating effort in already well-described parts of the North Sea.

Monitoring should link pressure, state and response. Vessel-position data and gear characteristics are needed to establish the frequency and depth of disturbance; sediment sampling and habitat observations are needed to detect changes in carbon stocks and benthic condition; and process measurements are needed to determine whether exposed carbon is degraded, redeposited or retained. Before-after-control-impact designs, long-term reference sites and coordinated restoration pilots would allow management effectiveness to be tested. Results should feed back into periodic revisions of carbon-sensitive zones, fisheries measures and restoration priorities.

Governance must also address additionality and permanence. Protection of an intact carbon store primarily avoids a risk of future loss; restoration may increase accumulation, but benefits can take years to emerge and can be reversed by renewed disturbance or deteriorating water quality. Any use in carbon certification or finance should therefore apply conservative baselines, transparent uncertainty deductions, long monitoring periods and safeguards against double counting with biodiversity or national climate commitments. The report supports development of such methods but does not conclude that present datasets are sufficient for widespread generation of tradable credits.

Finally, decisions should be evaluated against multiple outcomes. Carbon is an important ecosystem function, but it should not displace biodiversity, food security or community considerations as the sole optimisation criterion. Areas with modestly mapped stocks may have high ecological value or current accumulation, while a carbon-rich site may be less vulnerable if it is naturally dynamic or already inaccessible to damaging activity. The strongest interventions will protect carbon and habitat together, reduce cumulative pressures, maintain legitimate uses where compatible, and distribute transition costs fairly. This multi-objective approach is consistent with ecosystem-based management and reduces the risk that uncertain carbon estimates are given disproportionate weight.

Overall conclusion

The report establishes a strong case for treating seabed carbon as a material component of European marine governance, while drawing a careful boundary between evidence of carbon disturbance and proof of atmospheric emissions or additional removals. Bottom trawling is the clearest and most extensive manageable pressure. Existing MPAs offer an immediate route to reduce disturbance; carbon-sensitive zoning can improve targeting; and concentrating fishing in core grounds may generate larger benefits if socio-economic impacts and displacement are responsibly managed.

The immediate policy objective should be to preserve carbon-rich and carbon-vulnerable seabeds while recovering biodiversity and sea-floor integrity, not to overstate uncertain climate credits. Action should begin where the evidence is strongest, combine protection with restoration and pressure reduction, and be embedded in MSFD implementation, the Nature Restoration Regulation, fisheries management, Maritime Spatial Planning and regional cooperation. At the same time, the EU should invest in harmonised observation, process-based modelling and monitoring, reporting and verification capable of converting today's indicative risk maps into reliable management and climate-accounting tools. A staged and adaptive approach offers the most credible path: act now on clear risks, measure outcomes, refine methods and expand protection as confidence improves.

1. Introduction

Seabed sediments represent one of the largest long-term carbon stores on Earth. Because of their important role in the carbon cycle (Visser, 2025), there is growing interest in quantifying these stores, the rates at which carbon is added to and released from them. Carbon within biologically driven fluxes and stores in the ocean is referred to as “blue carbon” (Glossary). (Howard et al., 2023) . The term includes coastal vegetated blue carbon habitats such as saltmarshes, seagrass beds and kelp forests (Laffoley & Grimsditch, 2009). Here, we refer to coastal vegetated blue carbon systems as blue carbon but given the current debate around the inclusion of open ocean carbon cycles within blue carbon frameworks, we refer to seabed sediment carbon stores as seabed carbon (IPCC, 2018).

The surface layers of marine sediments typically contain carbon that has been recently fixed by photosynthetic organisms. Key sources include phytoplankton and coastal vegetation such as kelp forests, seagrass meadows, and saltmarshes, together with organic matter carried from land by rivers. In recent years, new spatial datasets and scientific evidence have improved knowledge on the amount of carbon stored in seabed sediments, how quickly it accumulates, and how long it is likely to remain there.

Seabed habitats are highly interconnected. Fine sand and muddy sediments in shallow coastal waters are particularly effective at capturing and storing organic carbon, which originates from plankton production, seaweed beds, and terrestrial inputs. Initial studies around Europe (e.g., Legge et al. 2020) are beginning to clarify the dynamics of coastal carbon budgets.

The general aim of the study is to improve the understanding of the natural capacity of different types of seabed habitats in European marine waters to sequester the carbon present in the sea water and the potential negative effects of seabed-disturbing anthropogenic activities on this capacity. This involved mapping carbon storage across European waters, investigating how human activities affect these stores and suggesting technical options for policy-relevant recommendations to better protect them. The results are intended to provide policymakers with evidence to identify where management is most needed, and what measures may be most effective to protect and enhance the role of seabed sediments in long-term carbon storage.

The study comprised three main tasks:

- Reviewing the existing literature, information and data to provide a state of current knowledge regarding the natural capacity of the seabed in European marine waters to sequester carbon, and the impacts of interactions of human activities with this capacity;
- Estimating the carbon sequestration rates of different seabed habitats in various scenarios based on the information and data gathered; and
- Formulating a set of appropriate recommendations for measures that could be taken by the Commission and/or Member States to prevent or mitigate the most serious impacts from seabed-disturbing activities, taking into account the existing EU legal and policy framework and international commitments.

2. Literature Review, Data Processing and Seabed Carbon Mapping

2.1 Blue carbon habitats

The increasing focus on the role that carbon stored and regularly accumulated in seabed sediments may have in the global carbon cycle, and thus its role in climate science (Sala *et al.*, 2021), has led to intense focus in the physical and biological processes that regulate the processes involved. There are several definitions of 'blue carbon'. Here we apply the IPCC definition as 'all biologically driven carbon fluxes that are amenable to management.' (IPCC, 2018). We refer to coastal vegetated blue carbon systems as saltmarshes, seagrasses and include kelp and other macroalgae in our definition, but given the current debate around the inclusion of open ocean carbon cycles within blue carbon frameworks, we refer to seabed sediment carbon stores as seabed carbon (IPCC, 2018). Considering that microalgae and plankton blooms are in most cases beyond management, they fall outside of the definition of blue carbon as well, and instead within biological carbon pumps (BCP).

Given that coastal blue carbon habitats represent between 0.5-1% of the global marine sediment surface area, coastal blue carbon habitats store a much greater *proportion* of carbon (per surface area) (Burrows *et al.*, 2024) than in marine sediments globally (Duarte *et al.*, 2013). Therefore, offshore sediments contribute less to the total global ocean carbon sequestration potential than coastal blue carbon habitats per unit area. Additionally, carbon present in coastal vegetated systems (seagrass and saltmarshes), while potentially comprising half of all carbon in ocean sediments (Duarte *et al.*, 2005), may not be stored as long as that in seabed sediments, being relatively easily released back into the atmosphere by disturbance of such habitats. Carbon stored biomass and buried in the structure of the plants in blue carbon ecosystems may therefore be seen as part of the short-term surface carbon cycle and not stored over geological timescales (Diesing *et al.*, 2024).

2.2 Seabed carbon

Here we review the scientific evidence and available sources of data around natural processes of carbon accumulation in seabed sediments, the role of such accumulation in the dynamics of ocean and atmospheric carbon cycles) and the resulting immediate impacts on seabed ecosystems. Potential processes of anthropogenic seabed disturbance are also reviewed. Emerging knowledge and data gaps, and any implications of methods adopted for measuring and modelling seabed carbon processes are identified throughout the review. The major sources of data as maps and observations are listed and have been processed in preparation for development of the scenarios outlined in this section.

The review begins with geographical descriptions of the seabed around Europe as classified under the EUSeamap project into EUNIS categories, and the predicted distribution of organic carbon content (as % and as gC/m² in the top 0.1m of sediment) across Marine Strategy Framework Directive regions from recent modelling efforts (MPA Europe). Processes of carbon accumulation in sediments are reviewed and the distribution of modelled and observed carbon stores across EUNIS seabed classes shows the relative importance of each habitat type as carbon accumulators, subsequently used to guide choices of habitats for further focus. Impacts on stored carbon and the rates of accumulation of carbon on the dynamics of seabed sediment systems around Europe both natural and anthropogenic are considered.

2.3 Carbon stocks and sequestration capacity across European seabed habitats

2.3.1 EUNIS Classification of European habitats

Marine habitats are classified by the European Nature Information System (EUNIS) as code A habitats being those that are directly connected to the ocean (Davies *et al.*, 2004). Habitats within A are classified by their substratum (Table 1). EUNIS codes occurring in EUSeamap 2023 (Vasquez *et al.*, 2023) across the MSFD Benthic Broad Habitats (MSFD_BBHT) are given in Section 8, Table S7.

Table 1: EUNIS level 2 classifications of code A habitats used in this study

Missing here are A7 (pelagic water column) and A8 (ice-associated marine habitats) as these classifications are not considered to contribute to long-term carbon storage in the same way as seabed habitats. EUNIS habitats are mapped in Figure 1.

Code	Habitat Zone and definition	Description	Main Biota
A1	Littoral rock	Littoral refers to the area of the shore which is between mean low and high astronomical tide marks. Exposed to air at low tide and submerged at high tide. All rocky hard surfaces within this zone are classified here.	A variety of intertidal algae, barnacles, molluscs and other invertebrates
A2	Littoral sediment	All Soft sediment habitats (coarse A5.1, sand A5.2, mud A5.3) which are located along the shore between the lowest and highest astronomical tide marks.	Infauna, diatoms, multiple macrophytes are found here including <i>Nanozostera noltii</i> (dwarf seagrass) and some algal species.
A3	Infralittoral rock and other hard substrata	The infralittoral is the shallow sub-tidal zone where algae grow immediately below the littoral. This zone extends below the Mean Low Water Springs (MLWS) and is usually permanently submerged, apart from extreme low water tides.	Seaweeds including kelp forests, kelp parks and associated epifauna. Communities on hard substrates can include bryozoans, hydroids, molluscs and other invertebrates.
A4	Circalittoral rock	The circalittoral begins where the infralittoral ends. The boundary between the infralittoral and circalittoral regions is determined by light availability and subsequent biological communities that persist. It can vary in turbid or clear waters. At level 3 this region is classified into high (A4.1), moderate (A4.2) and low energy (A4.3) habitats	Usually sessile invertebrates including sponge communities, mixed turf and crustose communities (A4.21, Echinoderms, <i>Sabellaria</i> reefs (A4.22, deep mussel beds (A4.24) Brachiopods and Ascidians.
A5	Sublittoral sediment	While infralittoral and circalittoral are sub-divisions of the sublittoral. Soft sublittoral sediments are all grouped by grain dynamics. Coarse A5.1, sandy A5.2, muddy A5.3 and mixed A5.4. The infra and circa littoral distinctions occur in lower-level classifications.	Infauna including polychaetes, bivalves, cnidarians and echinoderms. Epifauna Since many sub-tidal seagrasses occur below the littoral <i>Zostera marina</i> beds are classified here (A5.533) as are biogenic reefs (A5.6)
A6	Deep-sea bed	Mixed substrata which fall into the deep sea, can include multiple sediment types, communities and different deep-sea fauna.	Deep-sea fauna which includes holothurian communities, polychaetes and abyssal fauna.

2.3.2 EUNIS marine habitats chosen for this study

Each of the habitats listed in Table 1 has numerous sub-categories. The organic carbon stores are primarily within sublittoral sediments and deep-sea bed sediments. Littoral rock and sediments are outside the scope of this study, therefore habitats A1-A2 are not discussed¹. This means that saltmarsh, littoral seagrass species (such as *Zostera noltii*, *Ruppia maritima*) and saline reedbeds are not included. Instead, this study does include those sublittoral and infralittoral biogenic habitats that contribute to carbon cycles (kelp forests and seagrass beds). These plants fix CO₂ as part of coastal carbon cycles as well as forming three-dimensional structures that support enhanced biodiversity by provision of habitat and contribute material to marine food webs (Burrows *et al.*, 2024; Krause-Jensen *et al.*, 2022a). As such, the focus on infralittoral rock and other hard substrata (A3) will involve macroalgal forests which have different, species-specific preferences to low, moderate and high energy environments in Atlantic, Baltic and Mediterranean areas (A3.1-6, Table 2). These can be grouped and treated as a single unit 'A3'. Habitats where organic carbon accumulates comprise the sublittoral (infralittoral, circalittoral, bathyal) muddy sediments (Table 2).

The focus of this report is on seabed habitats up to and beyond the continental shelf limits in European seas. Those substrata fall within the EUNIS classification of A5 and A6, being permanently water covered and mobile (A5) or classified as deep-sea bed (Davies *et al.*, 2004).

Table 2: EUNIS habitats which are sources of organic carbon by providing substrata for seaweeds (A3) and where organic carbon accumulates (B4² to B6)

As for infralittoral rock habitats, sediment habitats are subdivided by the regional seas, and in turn all these physical habitats are divided into biotopes characterised by their dominant fauna and flora. A full breakdown of biotopes is available from <https://eunis.eea.europa.eu/habitats> and <https://www.marlin.ac.uk/habitats/eunis>.

Code	Description	Code	Description
A3	Infralittoral rock and other hard substrata	B6	Infralittoral mud
A3.1	Atlantic and Mediterranean high energy infralittoral rock	D6	Offshore circalittoral mud
A3.2	Atlantic and Mediterranean moderate energy infralittoral rock	E6	Upper Bathyal mud
A3.3	Atlantic and Mediterranean low energy infralittoral rock	F6	Lower bathyal mud
A3.4	Baltic exposed infralittoral rock		
A3.5	Baltic moderately exposed infralittoral rock		
A3.6	Baltic sheltered infralittoral rock		

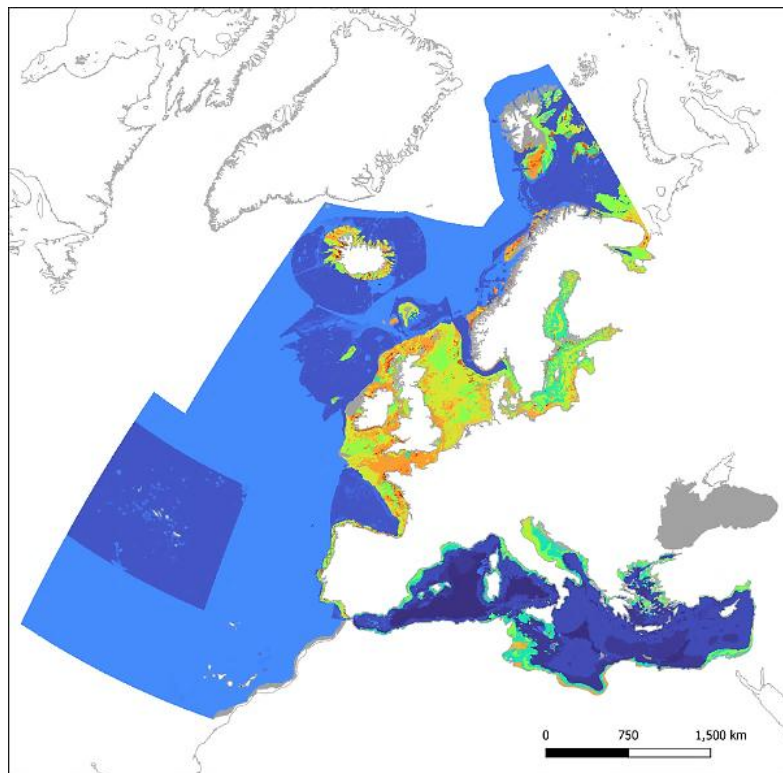
Anthropogenic activities which impact these different habitats have varying levels of severity, ranging from those that have an immediate effect, after which communities can recover, to continuous or more lasting effects. Studies have found that low impact activities include waste disposal, hydrocarbon extraction, marine research and communication cables. Most current studies agree that bottom trawling (and its various forms) is much wider in terms of the extent of its impact, even in deeper regions (Benn *et al.*, 2010).

¹ From the tender description: *The study shall not cover wetlands, saltmarshes and other fresh and transitional water ecosystems. Sediments associated with seagrass beds and macroalgal forests (often referred to as 'Blue Carbon' ecosystems), are meant to be included, however they are not expected to be the focus of the study given their relatively small extent.*

² B4 Coastal and seabed shores - intertidal was outside of the scope of this study.

Figure 1: EUSeamap habitats and their European Nature Information System (EUNIS) classifications

EUSeaMap habitat predictions and their EUNIS classifications are largely based on seabed acoustic information (e.g. backscatter, side-scan sonar and multibeam echosounder data), combined with bathymetric, physical and environmental variables.



EUNIS code	
A3 Infralittoral rock and other hard substrata	A5.35 or A5.36 Circalittoral sandy mud or Circalittoral fine mud
A3.1 Atlantic and Mediterranean high energy infralittoral rock	A5.36 Circalittoral fine mud
A3.2 Atlantic and Mediterranean moderate energy infralittoral rock	A5.37 Deep circalittoral mud
A3.3 Atlantic and Mediterranean low energy infralittoral rock	A5.38 Mediterranean biocoenosis of muddy detritic bottoms
A3.4 Baltic exposed infralittoral rock	A5.39 Mediterranean biocoenosis of coastal terrigenous muds
A3.5 Baltic moderately exposed infralittoral rock	A5.39 or A5.46 or A5.38
A3.6 Baltic sheltered infralittoral rock	A5.39 or A5.47
A4 Circalittoral rock and other hard substrata	A5.43 Infralittoral mixed sediments
A4.1 Atlantic and Mediterranean high energy circalittoral rock	A5.434 [Limaria hians] beds in tide-swept sublittoral muddy mixed sediment
A4.12 Sponge communities on deep circalittoral rock	A5.435 Oyster beds on shallow sublittoral muddy mixed sediment
A4.12 or A4.27 or A4.33	A5.44 Circalittoral mixed sediments
A4.2 Atlantic and Mediterranean moderate energy circalittoral rock	A5.45 Deep circalittoral mixed sediments
A4.26 or A4.32	A5.46 Mediterranean biocoenosis of coastal detritic bottoms
A4.27 Faunal communities on deep moderate energy circalittoral rock	A5.47 Mediterranean communities of shelf-edge detritic bottoms
A4.3 Atlantic and Mediterranean low energy circalittoral rock	A5.529 Facies with [Ficopomatus enigmaticus]
A4.33 Faunal communities on deep low energy circalittoral rock	A5.535 [Posidonia] beds
A4.4 Baltic exposed circalittoral rock	"A5.5353 Facies of dead ""mattes"" of [Posidonia oceanica]"
A4.5 Baltic moderately exposed circalittoral rock	A5.6 Sublittoral biogenic reefs
A4.6 Baltic sheltered Circalittoral rock	A5.61 Sublittoral polychaete worm reefs on sediment
A5 Sublittoral sediment	A5.611 [Sabellaria spinulosa] on stable circalittoral mixed sediment
A5.13 Infralittoral coarse sediment	A5.612 Sabellaria alveolata on variable salinity sublittoral mixed sediment
A5.14 Circalittoral coarse sediment	A5.62 Sublittoral mussel beds on sediment
A5.15 Deep circalittoral coarse sediment	A5.625 [Mytilus edulis] beds on sublittoral sediment
A5.23 Infralittoral fine sands	A5.631 Circalittoral Lophelia pertusa reefs
A5.23 or A5.24 Infralittoral fine sand or Infralittoral muddy sand	A6 Deep-sea bed
A5.23 or A5.33 or A5.34 Infralittoral fine sands or Infralittoral sandy mud or Infralittoral fine mud	A6.11 Deep-sea rock
A5.24 Infralittoral muddy sand	A6.2 Deep-sea mixed substrata
A5.24 or A5.33 or A5.34 Infralittoral muddy sand or Infralittoral sandy mud or Infralittoral fine mud	A6.3 Deep-sea sand
A5.25 Circalittoral fine sand	A6.3
A5.25 or A5.26 Circalittoral fine sand or Circalittoral muddy sand	A6.4 Deep-sea muddy sand
A5.26 Circalittoral muddy sand	A6.5 Deep-sea mud
A5.26 or A5.35 or A5.36 Circalittoral muddy sand or Circalittoral sandy mud or Circalittoral fine mud	A6.51 Mediterranean communities of bathyal muds
A5.27 Deep circalittoral sand	A6.51 or A6.511 or A6.4
A5.27 or A5.37 Deep circalittoral sand or Deep circalittoral mud	A6.511 Facies of sandy muds with Thenea muricata
A5.33 Infralittoral sandy mud	A6.52 Communities of abyssal muds
A5.33 or A5.34 Infralittoral sandy mud or Infralittoral fine mud	A6.61 Communities of deep-sea corals
A5.34 Infralittoral fine mud	A6.611 Deep-sea Lophelia pertusa reefs
A5.35 Circalittoral sandy mud	Not assigned

2.3.3 Carbon stocks across the European seabed

EUSeamap EUNIS habitats (Figure 1) and MSFD regions (Figure 2) spatial polygon data were projected and rasterized to the same coordinate system (ESPG 3035), extent and grid cell size as the predicted carbon models. This allowed rapid summaries to be made for each region and subregion (Table 3). The same approach allows sequestration capacity to be summarised across these MSFD regions and subregions.

Europe-wide maps of carbon content of sediment have been produced using data from sediment organic carbon studies and measurement programmes across Europe, collated into the Euro-Carbon database (Lønborg *et al.*, 2025) compiled as part of the *MPA Europe Horizons Europe* project. Similar global databases exist, such as the CCN Data Library ([Data | Smithsonian Environmental Research Center](#)) curated by the Smithsonian Institution. The EU carbon database is more resolute and comprehensive across the study area for the present study.

The Euro-Carbon dataset (Lønborg, *et al.*, 2025) has 61,352 entries for carbon-related characteristics of marine sediments around Europe from 11,425 unique locations. Data are from bare sediments (46308 entries from 10946 locations), saltmarshes (10,746 from 260 locations) and seagrass meadows (4,233 from 198 locations). Locations are strongly skewed towards coastal areas: 5855 locations < 5km from the coast, 1,952 locations > 5km from the coast and 3,903 locations on land, likely in coastal saltmarshes or lagoons not classed as sea on coastal maps. Key variables used in analyses of carbon content of sediments are 'Organic Carbon (%)' (61306, hereafter %OC) and 'Dry bulk density (g/cm³)' (18,281 data, 454 bare sediment locations, DBD) with the product of %OC and DBD giving the carbon density of sediments in kgC/m³ and carbon content per unit area when integrated over a specified depth (usually 0.1m).

Figure 2: MSFD regions and subregions (coloured) and the larger NE Atlantic regional seas

Includes countries within the European Economic Area (EEA) and the United Kingdom EEZ.

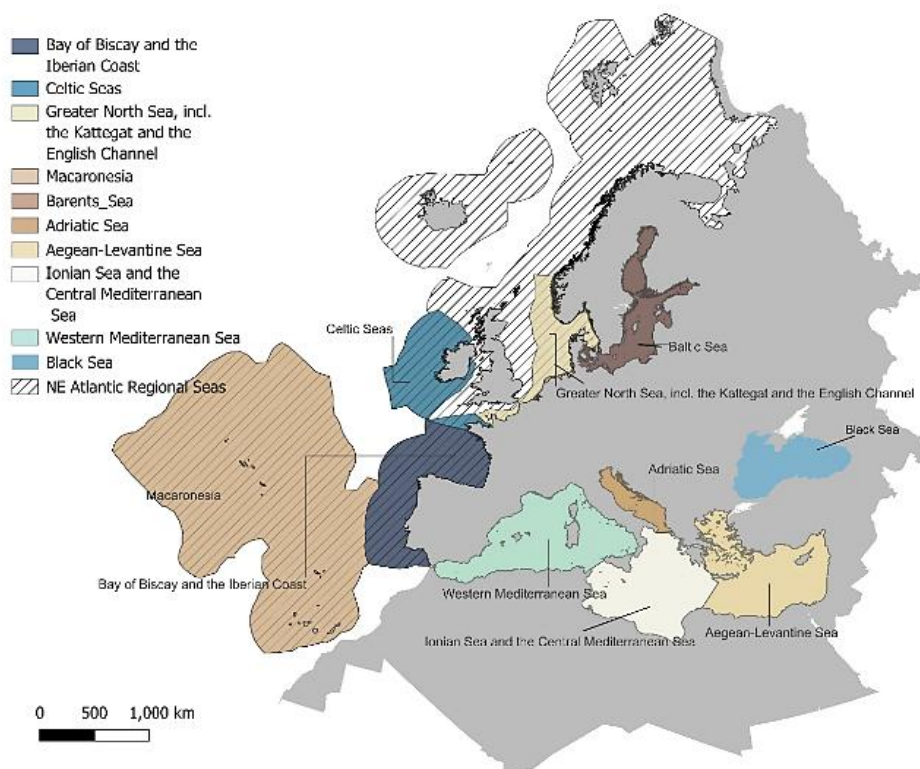


Table 3: Summary of sediment carbon stocks for MSFD subregions

The total area of each habitat subregion is shown as 1000s of km². Average predicted carbon density is shown as kg/m². Carbon stocks are expressed in Mt as the product of average carbon density and total area of each subregion. A full list of data sources is provided in Section 8, Table S1.

Sub-region code	Subregion Name	Region	Region Name	Area km ² x 1000	C kg/m ²	%OC	Mt OC
ABI	Bay of Biscay and the Iberian Coast	ATL	North East Atlantic Ocean	803	0.33	0.20	263
ACS	Celtic Seas	ATL	North East Atlantic Ocean	533	0.44	0.25	233
AMA	Macaronesia	ATL	North East Atlantic Ocean	3763	0.15	0.07	575
ANS	Greater North Sea, incl. the Kattegat and the English Channel	ATL	North East Atlantic Ocean	388	0.49	0.51	191
GNA	Greater North Atlantic	ATL	North East Atlantic Ocean	8914	0.31	0.25	2733
BAL	Baltic Sea	BAL	Baltic Sea	391	0.51	0.80	199
BLK	Black Sea	BLK	Black Sea	422	0.54	0.32	227
MAD	Adriatic Sea	MED	Mediterranean Sea	139	0.71	0.53	99
MAL	Aegean-Levantine Sea	MED	Mediterranean Sea	757	0.39	0.17	297
MIC	Ionian Sea and the Central Mediterranean Sea	MED	Mediterranean Sea	773	0.29	0.11	224
MWE	Western Mediterranean Sea	MED	Mediterranean Sea	845	0.42	0.14	352

These data have been used to model the percentage of organic carbon of sediments by weight at 1km resolution across European seas (36°W - 42°E, 25 - 85°N) using the statistical associations between %OC and a range of pre-disturbance environmental predictors (Figure 3) using the boosted regression tree machine learning approach (xgboost, Chen *et al.*, 2025). Predictors included bathymetry, diffuse attenuation, distance to shore, landscape geomorphic features, oxygen, river runoff, salinity, seawater speed, slope, temperature max, temperature min (from Bio-Oracle 3.0 Assis *et al.*, 2024), and wave fetch (Burrows, 2020). We do not apply fishing effort data here as this is considered an impact and not a predictor of %OC.

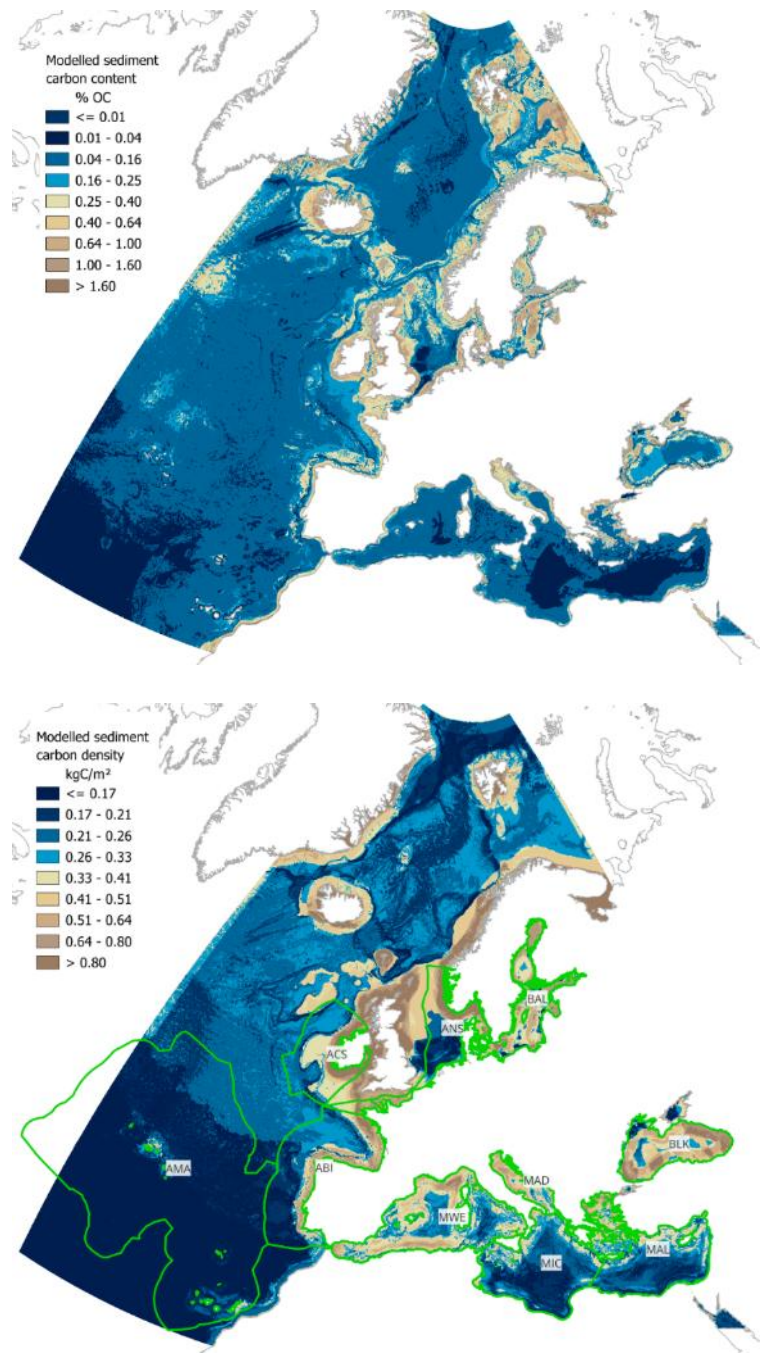
Wave fetch emerged as the most important contributor with least organic carbon in areas of high wave fetch and most in areas of low fetch, likely reflecting the proximity to terrestrial sources of carbon and the effects of waves of particle resuspension in shallow waters (<20m depth). The model explained 53% of the deviance in observed %OC. Higher percentages of organic carbon were predicted close inshore (top) and in areas of the Barents Sea, North Sea, Baltic Sea, Adriatic Sea, and the Black Sea. Greater model uncertainty (Figure S1) showing greater discrepancy between modelled and observed values of %OC was seen in coastal areas and in areas of the North Atlantic, Baltic Sea and Black Sea.

A similar model was developed to predict carbon stocks (kgC/m² for 0.1m depth) using data from locations with direct estimates of organic carbon density obtained from %OC and DBD measures from the same

sediment samples (Figure 5 bottom) (Lønborg, Graversen, Addamo, Assis, *et al.*, 2025). Data used for this model were however from a more limited and spatially restricted set of locations (454, Figure S3) that were biased towards certain areas (282 in the Norwegian Trench versus 32 in the Mediterranean, for example). The resulting map was broadly reflective of expected large-scale trends in carbon stocks, but with spatial details that were less highly resolved than for %OC and other similar models of carbon stocks in European areas, such as those for the UK EEZ (Smeaton *et al.*, 2021), the North Sea (Diesing *et al.*, 2017a; Diesing, 2021), albeit being very different (much lower) than the European part of a global estimation of sediment carbon stocks (Atwood *et al.*, 2020).

Figure 3: Modelled organic carbon content of seabed sediments.

Top: Estimated percentage of organic carbon. Bottom: Carbon density in kgC/m^2 (from Lønborg *et al.*, 2025). Outlines of MSFD Subregions are shown in the lower plot (see Figure 2).



Uncertainty in each of these predicted maps (%OC and kgC/m²) was calculated using refitting of models using bootstrapped samples of the model training datasets. Greater uncertainty in %OC (Figure S1) was evident in deep ocean sediments, around coastal habitats in Svalbard and Norway, and especially in the middle of the Baltic Sea. Least uncertainty for %OC was seen at more southerly latitudes in the Mediterranean and Macaronesia subregion, the southern North Sea and in deeper parts of the subarctic North Atlantic.

Uncertainty in sediment organic carbon density (Figure S2) was also generally lower at more southerly latitudes but tended to be higher overall along coastlines and shelf areas where organic carbon density was predicted to be higher. The reduced sediment carbon density in the southern North Sea was predicted with lower uncertainty relative to surrounding areas. Higher uncertainty occurs in areas where there is higher modelled sediment OC, the more certain values are where predicted OC is lower. This is not necessarily related to the lack of samples but more closely to the magnitude of the prediction.

Confidence in patterns seen in predictive maps of percentages and densities of sediment carbon should be seen as following the quantity of data for each region being described, with high confidence where data is plentiful and the model predictions match observations well, in an analogous way to the IPCC principles (Mastrandrea *et al.*, 2011). For Europe, measurement data on %OC are well distributed all across the model domain (Figure S3 left) but this is not so for data on organic carbon density (Figure S3 right). Predicted estimates of sediment organic carbon density where direct observations are rare or absent should be treated with caution.

These maps of predicted carbon content of seabed sediments are used here to describe the potential distribution of organic carbon stocks across European seabed habitats and, by association, carbon sequestration capacity (CAR) alongside the limited direct measurements available in the literature (see section 2.3.4).

The total amount of organic carbon stored in the top 0.1 m of seabed sediment, calculated as the product of total area and carbon density, is mostly scaled by the area of each subregion. The area of the predicted model beyond MSFD regions ('Greater North Atlantic'), that of not overlapped by MSFD regions (Figure 3), is much the largest area (8.9M km², almost 2% of the global ocean 361 M km²) and consequently holds the greatest stock of over 2700 Mt. Stocks vary widely among MSFD regions, with total organic carbon (OC) ranging from under 100 Mt (the Black Sea) up to over 575 Mt in Macaronesia, despite the relatively low carbon density in the latter region. Density values range from 0.15 kg/m² in Macaronesia to 0.71 kg/m² in the Western Mediterranean, largely reflecting the proportion of low-density bathyal areas in each region. Percent organic carbon content also differs substantially, from low levels (0.07%) in deep ocean regions (AMA) and the deep basins of the Mediterranean (0.11% to 0.17% in MIC, MWE and MAL) through intermediate levels in open coastal and shelf seas (0.20% to 0.50% in ABU, ACS and ANS) to high values in enclosed seas (0.8% in the Baltic Sea and 0.53% in the Adriatic).

Mediterranean Sea

Just over 2.5 M km² in area, the Mediterranean basin is split into four sub-regions: the Western Mediterranean Sea (MWE), the Ionian Sea and the Central Mediterranean (MIC), the Adriatic Sea (MAD) and the Aegean-Levantine Sea (MAL) (Figure 3). The majority of seabed habitats (Table 3, Table S6) in the Mediterranean are in the fine mud, sandy mud, or muddy sand classification ranges (A). Around the mainland and island coasts are predominantly sands and *Posidonia* meadows are common within the sand and sandy

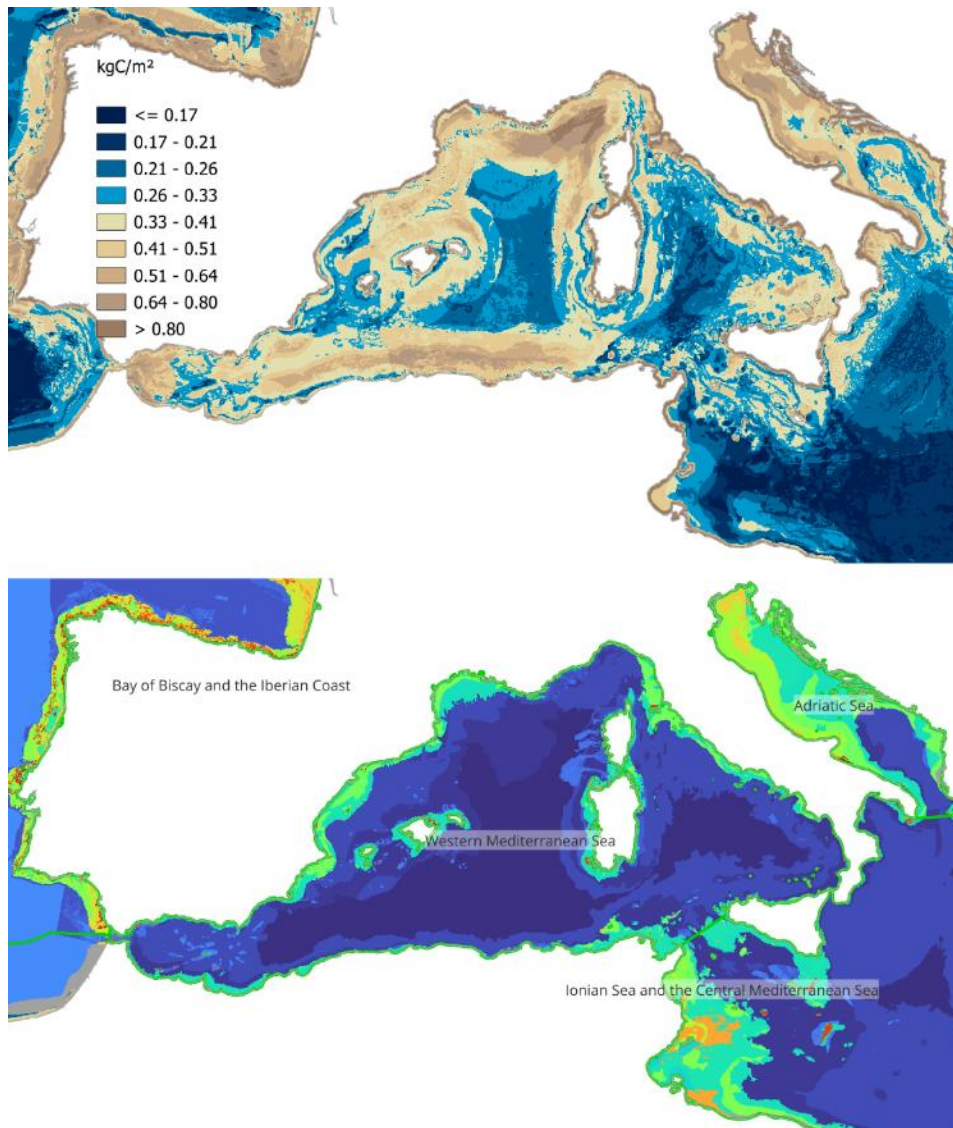
mud areas of the infralittoral and upper circalittoral. Sources of information for this and each other regions as published scientific literature and in online data repositories (such as PANGAEA, <https://www.pangaea.de/>) are detailed in the Euro-Carbon (Lønborg, Graversen, Addamo, Pedersen, *et al.*, 2025) and summarised in Supplementary Table S6. 1730 records in the Euro-Carbon dataset fall within the Mediterranean Sea (Supplementary Figure S3).

Western Mediterranean

As in other parts of the Mediterranean, organic carbon in the western Mediterranean forms a greater proportion of the sediment in immediately coastal areas (Figure 4) in areas of sublittoral sands and muds (EUNIS A4), but with a predicted high carbon density region in deeper habitats (EUNIS A5) off North Africa (Table S6: 102Mt (10.2×10^9 kg) in EUNIS A6.51, 97Mt (9.7×10^9 kg) in A6.52). No observations of OC density lie in this predicted region, with consequent low confidence in the model prediction (Figure S2).

Figure 4: Modelled organic carbon density (kg/m^2) for the western Mediterranean (top) and (bottom) EUNIS seabed habitats

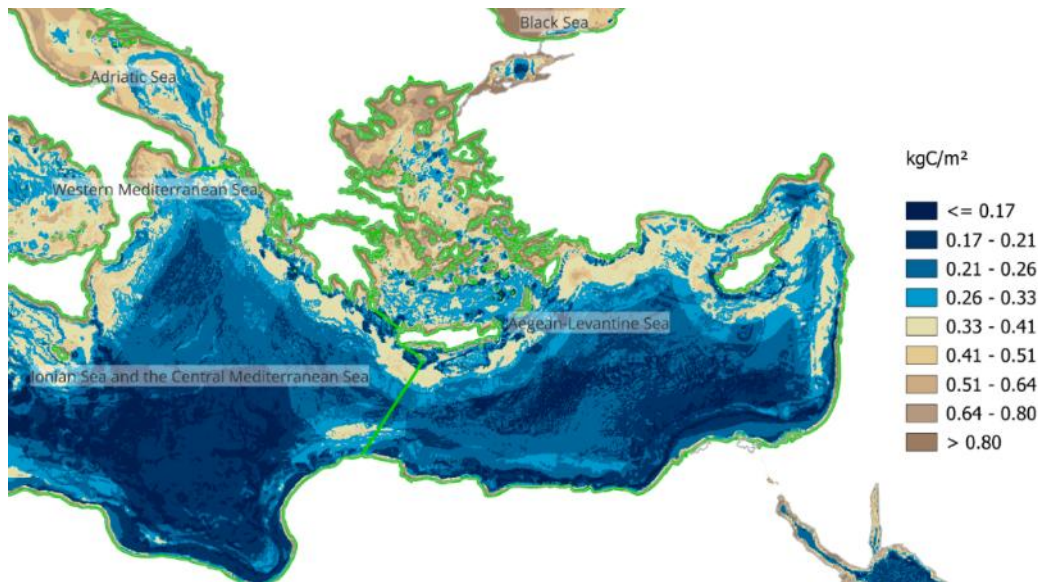
Legend as Figure 2



Eastern Mediterranean

The pattern of organic carbon density in the eastern Mediterranean (Figure 5) is dominated by the difference between low carbon deep sediments and high carbon shallow ones. A high carbon density area in the southern Adriatic can be considered with medium to high confidence given the greater frequency of samples in this regional sea (Figure S3) than in other parts of the Mediterranean and contributions from the Po River.

Figure 5: Modelled organic carbon density (kgC/m^2) for the eastern Mediterranean

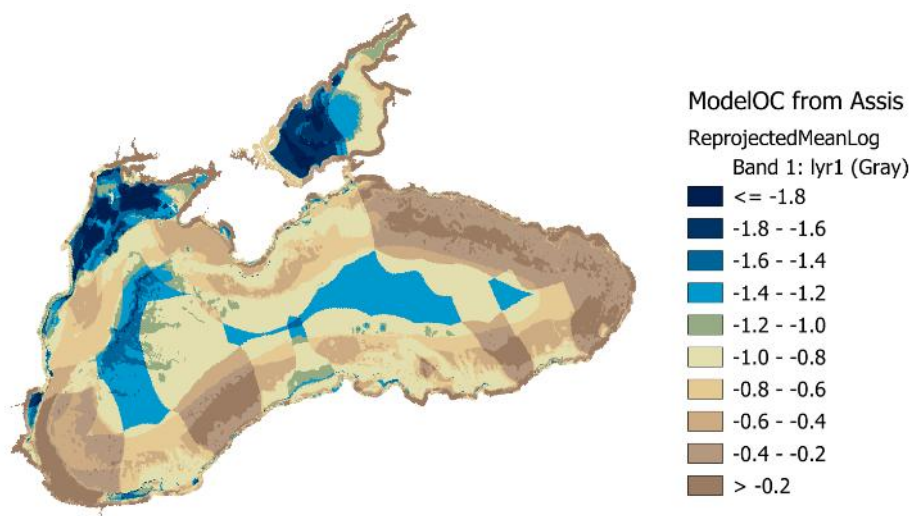


Black Sea

Predicted patterns of organic carbon density in the Black Sea seem to be dominated by model artefacts generated by the overlap of predictor variable layers and are characterized by relatively high uncertainty (Figure S1). Percentage organic carbon in the Black Sea, however, is much better represented by observations in the Euro-Carbon dataset (Figure S3), with higher organic content in more immediately coastal areas (Figure 5) than predictions of organic carbon density (Figure 6) suggest.

Figure 6: Modelled organic carbon density (as log base e kgC/m^2) for the Black Sea.

No EUSeamap data is available for the region.

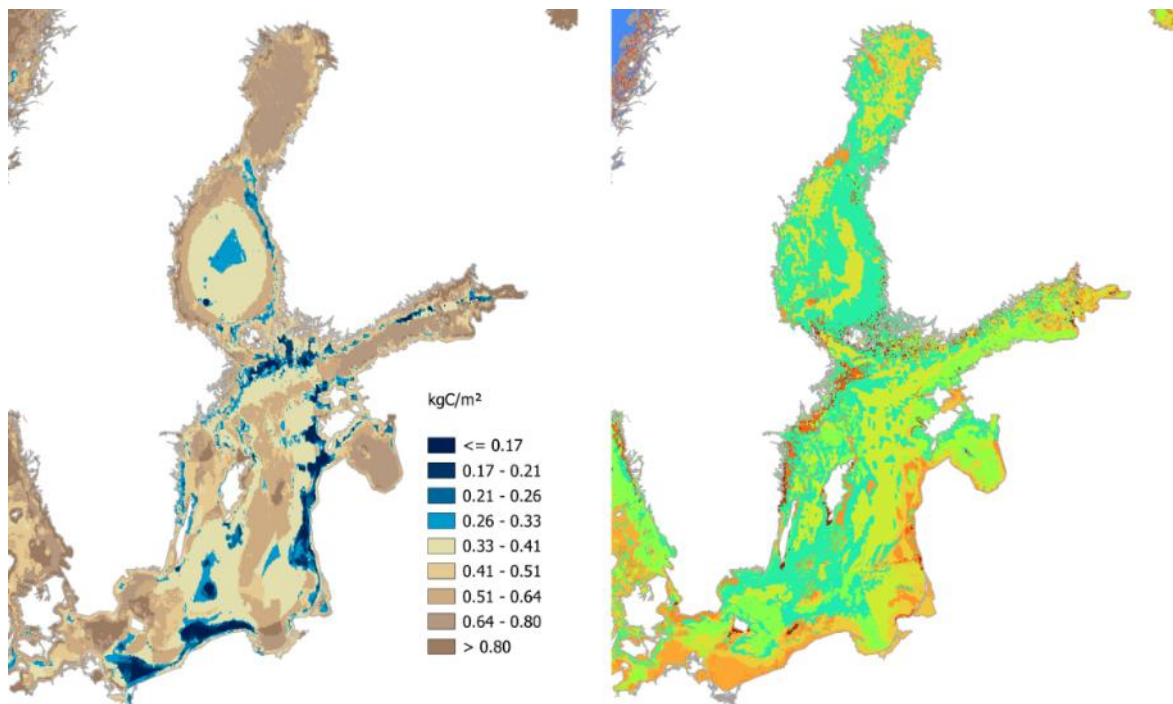


Baltic Sea

The Baltic Sea has the highest predicted value of average predicted carbon content of sediments (Table 4) with high predicted values of %OC in sediments and carbon density in the central region. While absolute values of uncertainty in %OC (Figure S1) and carbon density (Figure S2) are similarly high, the greater frequency of %OC measurements lend greater confidence to the mapped estimates of %OC than carbon density.

Figure 7: (Left) Modelled organic carbon density (kg/m²) for the Baltic Sea and (Right) EUNIS seabed habitats

Areas of relatively low predicted density can be seen in southern coastal areas corresponding with infralittoral fine sand, mud or sandy mud habitat classes (A5.23, orange), while higher predicted carbon density areas in the central west Baltic are areas of circalittoral mixed sediments (A5.44, teal).



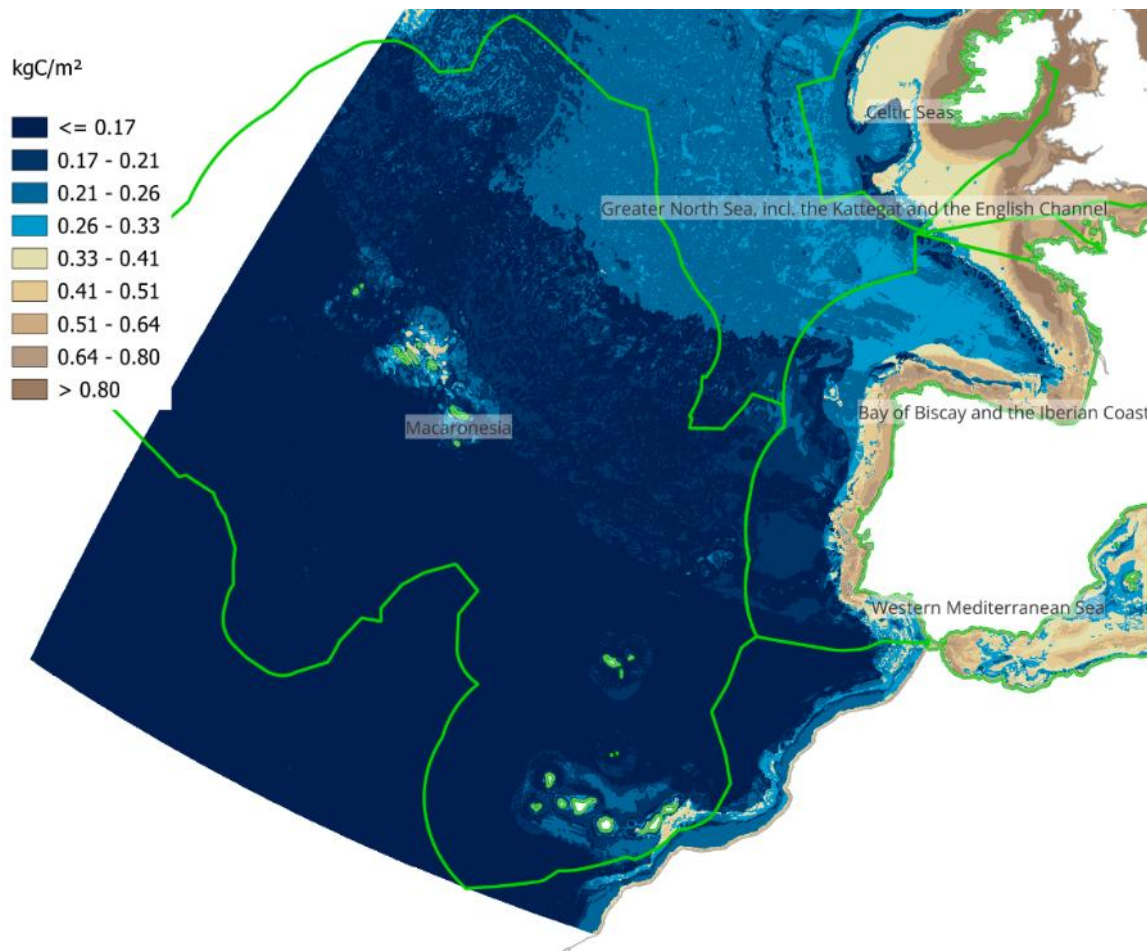
Greater carbon density predicted for mixed sediments is inconsistent with the general trend of greater organic carbon storage in fine muddy sediments and is likely to have resulted from the relatively poor performance of the predictive model in this region, as also seen in the Black Sea (Figure 6). This further suggests that either the seabed classification used does not capture the expected patterns of carbon content of sediments or that the model needs additional data to perform well in the Baltic.

Northeast Atlantic: Bay of Biscay and the Iberian Coast (ABI), Macaronesia (AMA)

These Northeast Atlantic MSFD regions span areas of offshore islands surrounded by low carbon density sediments to relatively high predicted carbon along narrow areas of continental shelves along coastlines of the Iberian Peninsula and western France (Figure 8). As in other regions, confidence in predicted %OC is much higher than for carbon density because of the absence of measurements of density in the region (Figure S3).

Figure 8: Modelled Organic carbon density (kg/m^2) for the Northeast Atlantic Ocean (ABI, AMA)

Northeast Atlantic: Celtic Seas (ACS), Greater North Sea, incl. the Kattegat and the English Channel (ANS). Here the predicted maps of %OC and carbon density are quite different, with high density carbon areas ($>0.6 \text{ kg/m}^2$) extending across the continental shelf to the shelf break (Figure 11).



Northeast Atlantic Ocean (ACS, ANS)

The North Sea is the most studied and modelled area for organic carbon content of sediments and their sequestration capacity. Modelling studies by Diesing and co-authors (Diesing *et al.*, 2017a; Diesing *et al.* 2021; Diesing *et al.*, 2024; Stephens & Diesing, 2015) using similar methods to Lønborg *et al.* (2025) produced similar results to the Euro-Carbon generated model (Figure S4). Low carbon density in the southern North Sea emerged from both sets of modelling effort.

Northeast Atlantic: Beyond MSFD regions

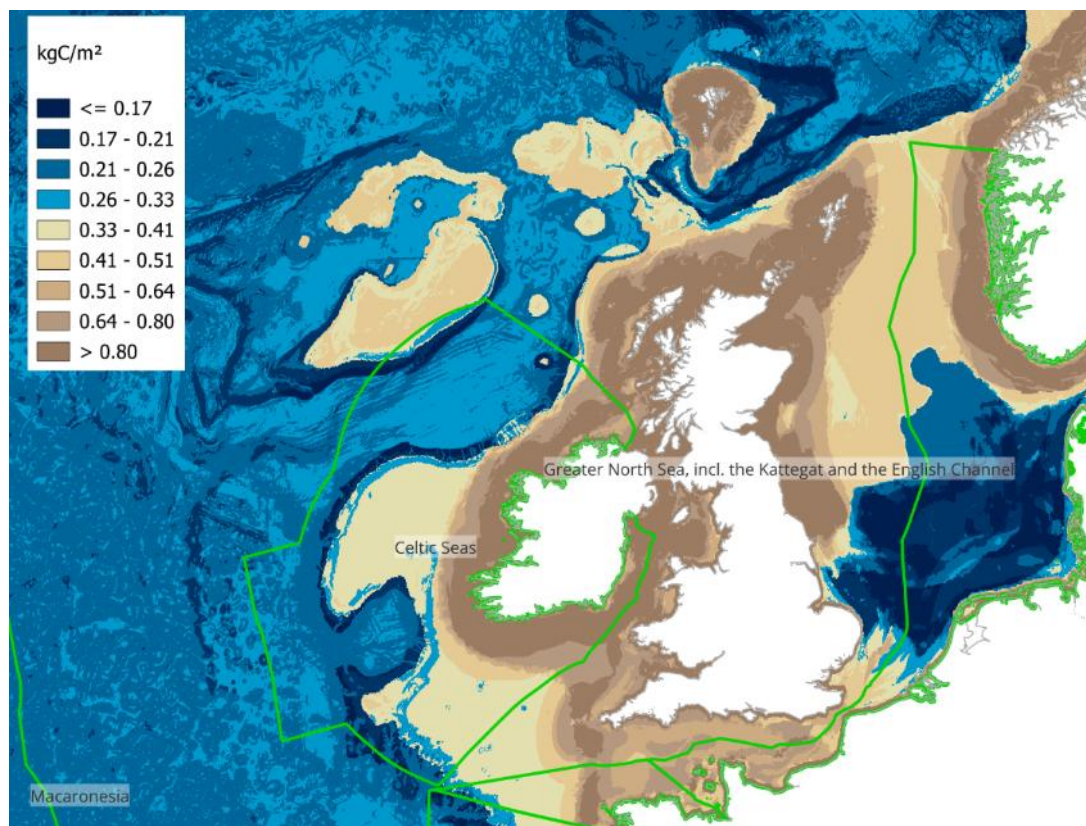
A significant proportion of the Northeast Atlantic is not included within the MSFD regions (Figure 5). Some of this area is within the EEA, but not all of it falls within the EU (Norway and UK for example). One of the most studied regions across the whole of Europe is the North Sea, with multiple data points and key peer reviewed articles which are relevant (Black *et al.*, 2022a; Diesing *et al.*, 2017b; Diesing, *et al.* 2021; Porz *et al.*, 2024a; Smeaton *et al.*, 2021).

2.3.4 Carbon accumulation in sediments

Compared with relatively simple estimation of the proportion of organic carbon material in sediments, the estimation of area-specific rates of accumulation of carbon in sediments ($\text{gC/m}^2/\text{yr}$) requires a more

comprehensive set of measurements from sedimentary material. Estimated accumulation rates of carbon derive from sedimentation rates expressed as the increase in sediment depth in mm/yr and the carbon density of existing sediments, if newly added material has a similar content of carbon to the sediment to which it is added.

Figure 9: Modelled organic carbon density (kg/m²) for the Northeast Atlantic Ocean (ACS, ANS)



Carbon density (as gC/m³ or gC/m² to a specific depth, usually 10 cm) requires knowledge of dry bulk density (DBD) of the sediment itself, often built on assumptions about the porosity of the sediment, and the percentage of organic carbon in that sediment (Diesing *et al.*, 2017a; Smeaton, *et al.*, 2021).

Sediment accumulation rates are generally assessed with radioactive dating methods using ²¹⁰Pb (Arias-Ortiz *et al.*, 2018) or ¹⁴C (Ausín *et al.*, 2021) that assess the age of deposited material as a function of depth, albeit with sometimes differing results (Ausín *et al.*, 2019) thought to be due to transport of organic and inorganic sediment fractions from different sources, where carbon may derive from older such as from nearby terrestrial sources (Smeaton & Austin, 2022). Combining these measurements gives the carbon burial rate (gC/m²/yr). Stahl *et al.* (2004). For example, at 4850-m depth in the Porcupine Abyssal Plain, ¹⁴C dating of foraminifera sampled just below the mixed layer (7 cm) of surface sediments gave a sedimentation rate of 6.1 cm/ky for that location, which combined with a 0.25 % content of organic carbon by weight (sedOC) and a dry bulk density (DBD) estimate of 0.74 g/cm³ (7.4x10⁻⁴kg/cm³) gave an estimate of carbon burial rate (BFc) as 0.03 mmolC/m²/d, equivalent to 0.13gC/m²/yr (1.3x10⁻⁴kg/m²/yr). Thus, BFc = Sedimentation rate × DBD × sedOC.

An earlier review of carbon accumulation rates in northwest Europe (Table 4), focussed on seas around the UK (Burrows *et al.*, 2014). It showed that accumulation rates reported on coastal and shelf sediments using

the same approaches were generally much higher than that for abyssal sediments, typically upwards of 35 gC/m²/yr (3.5x10⁻⁴kg/m²/yr) for sandy mud areas (de Haas & van Weering, 1997) and potentially >100 gC/m²/yr in anaerobic sediments, as in the Baltic Sea – North Sea transition area (Jørgensen *et al.*, 1990). Richspots of carbon burial occur in fjordic systems such as those on the west coast of Scotland (Smeaton, *et al.*, 2021), where rapid accumulation of buried carbon (57 gC/m²/yr, 5.7x10⁻⁴kg/m²/yr) in glacially deepened basins has likely resulted in greater storage of carbon since the end of the last glaciation (13.5kya) than the entire North Sea.

Table 4: Varying accumulation rates calculated in literature across coastal, shelf and abyssal sediments

Region	Accumulation rate	Unit description	Reference
Sediments in abyssal plain	0.13gC/m ² /yr	grams of carbon per m ² per year	Stahl <i>et al.</i> , 2004
Sandy mud areas (NW Europe)	35 gC/m ² /yr	grams of carbon per m ² per year	Burrows <i>et al.</i> , 2014
Muddy anaerobic areas (NW Europe)	>100 gC/m ² /yr	grams of carbon per m ² per year	Burrows <i>et al.</i> , 2014
Fjordic systems (NW Europe)	57 gC/m ² /yr	grams of carbon per m ² per year	Smeaton <i>et al.</i> , 2021

While the Euro-Carbon dataset (Graversen *et al.*, 2025; Lønborg, *et al.*, 2025) has >61,000 measures of % OC from >10,000 locations, it has only 713 measurements of carbon accumulation rates in sediments (CAR gC/m²/yr) from 68 locations across Europe, restricted to west Scotland, Denmark, a few coastal locations around the Iberian peninsula and some deep sub-Arctic locations in the North Atlantic. More measurements exist for sediment accumulation rate (SedAR mm/yr): 1447 measurements from 184 locations. Diesing *et al.* 's work in the North Sea (2017a) and in the Norwegian Trough (2024) involved spatial modelling of organic carbon content (%OC) and dry bulk densities (DBD) to give mapped organic carbon densities and combining this with a spatial model of sediment accumulation rate to give carbon accumulation rates. This represents the likely state of the art for estimating seabed carbon sequestration rate, albeit not addressing the short- and long-term fate of stored material.

Options for using the CAR data in the Euro-Carbon dataset to map estimated rates across European seabed habitats include:

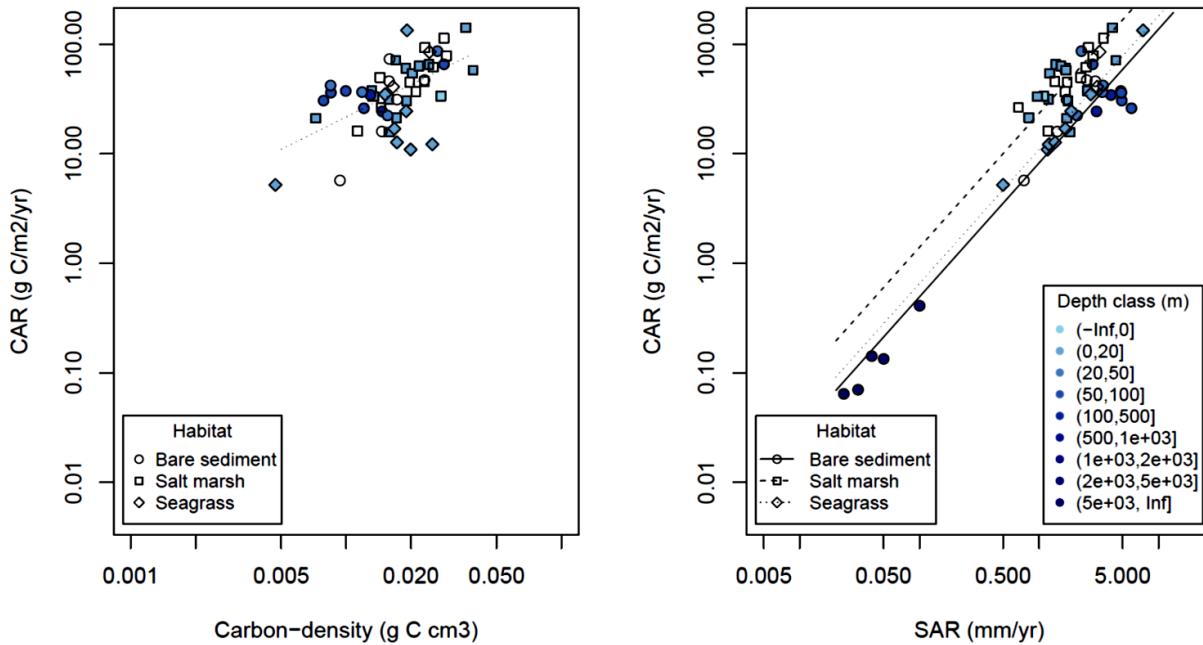
- 1) a fully spatial model of predicted CAR using environmental predictors, as for carbon density in Figure 3 to Figure 8 (as in Diesing *et al.* (2024) $CAR = \%OC_{\text{spatial}} \times DBD_{\text{spatial}} \times SedAR_{\text{spatial}}$; using subscripted text to describe the data type where 'spatial' is spatially modelled data and 'EUNIS, Region' is the average measured rate of CAR in each habitat by MSFD region);
- 2) using spatially integrated average regional CAR rates across EUNIS seabed habitats ($CAR = CAR_{\text{EUNIS,Region}}$);
- 3) using spatially estimated CAR through relationships of observed CAR rates with other mapped indicators of sediment organic carbon content (%OC, density kg/m², environment; $CAR = f(\text{sediment carbon content, plus other environmental predictors})$);
- 4) using spatially modelled SedAR rates and habitat-specific organic carbon density estimates $CAR = \%OC_{\text{spatial}} \times DBD_{\text{EUNIS}} \times SedAR_{\text{spatial}}$, similar to (Smeaton, Hunt, *et al.*, 2021)).

Option (1) is not available at present (8/25) but would be unlikely to be feasible with such limited data. Option (2) is possible but introduces the risk that a single average carbon accumulation rate across a EUNIS habitat may not adequately represent the range of CAR values across the habitats, resulting in potentially

significant overestimation (Burrows *et al.*, 2021) or underestimation of rates. The same limitation may apply if single values for carbon densities for each EUNIS habitat type in the EUSeamap spatial dataset are used to estimate total regional stores (Burrows *et al.*, 2014). Option (3) is feasible but relies on the strength of relationships between CAR and the sediment carbon parameters involved. CAR is directly dependent on organic carbon density (kg/m^2) and sediment accumulation rate (mm/yr), so these measurements are the most important predictors. CAR is positively related to organic carbon density in the Euro-Carbon dataset (Figure 10 left, $R^2=0.32$) but much more strongly related to sediment accumulation rate (Figure 10 right, $R^2=0.95$) (Diesing *et al.*, 2024). This suggests that additional data on sediment accumulation more immediately useful than organic carbon density in improving spatial mapping of CAR, and that option (4), spatially modelled SedAR and %OC plus average DBD for EUNIS habitats, may be possible for the current assessment.

Figure 10: Carbon accumulation rate (left) versus sediment carbon density ($R^2 = 0.32$, $n = 52$ locations), and (right) sediment accumulation rate ($R^2=0.95$, $n=58$ locations)

Symbol colours indicate depth such that darker blue shades are from deeper sample locations, with no shading for sample locations on land, largely saltmarshes ($1\text{gC/m}^2/\text{yr} = 1 \times 10^{-3}\text{kgC/m}^2/\text{yr}$).

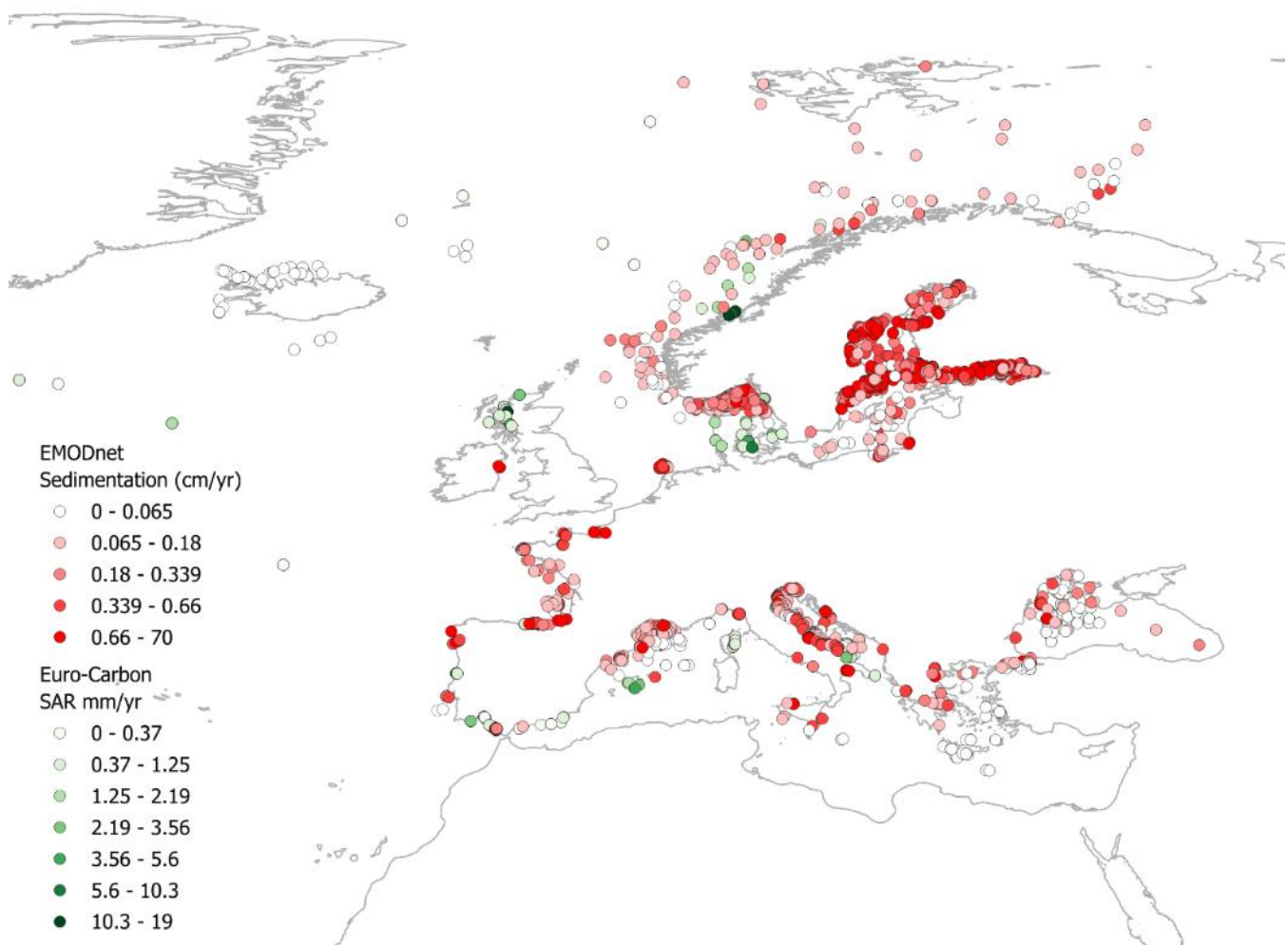


More data on sediment accumulation rates (mm/yr) in addition to those in the Euro-Carbon dataset are available from the European Marine Observation and Data Network (EMODnet) (*European Atlas of the Seas*, n.d.). Together these data are spatially extensive (Figure 11) and may be suitable for spatial modelling as per Lønborg *et al.* (2025) and Diesing *et al.* (2024). A spatially modelled sedimentation rate layer ($\text{SedAR}_{\text{spatial}}$ above) combined with predicted spatial organic carbon density maps from the percentage of organic carbon (OC%) with the dry bulk density of sediments (kg/m^3 , $\%OC_{\text{spatial}} \times \text{DBD}_{\text{spatial}}$) would be a strong route towards a Europe-wide map of carbon sequestration rates of seabed sediments. Accounting for sediment erosion as negative accumulation and the longevity of stored organic carbon in the sediments for a complete picture, this approach (Option (1) above) offers a feasible solution to production of a single spatial map of carbon sequestration at this scale.

2.3.5 Carbon data by EUNIS categorised benthic habitats

Two primary data sources were used to estimate average values of carbon across the different EUNIS habitats in GIS software. The first was the EUNIS marine habitat distribution datasets (available [here](#)) which provides the latest knowledge of the extent of each zone, secondly a compiled dataset from (the Euro-Carbon database, see Graversen *et al.*, 2025). This dataset contains information on organic carbon content of sediments OC including % dry weight and carbon density per unit area (kg/m²).

Figure 11: Sedimentation rates from EMODnet and Euro-Carbon datasets



The point data containing information on carbon were merged with shapefile data and each of the EUNIS categorised seafloor habitats. This allowed calculations of average carbon accumulation by habitat (at the broadest scale).

2.4 Blue carbon habitats

Here we use the IPCC definition of blue carbon as ‘biologically-driven carbon fluxes and storage in marine systems that are amenable to management’ (Fuglestad *et al.*, 2020). This refers to coastal vegetated habitats that store carbon in a relatively stable way in their sediments. The exception to this rule is seaweeds (kelps and other macroalgae) which do not grow in sediments so the production of detritus is considered to be a pathway for carbon storage. These habitats generally sit within the EUNIS codes of A3 – A5 and contain

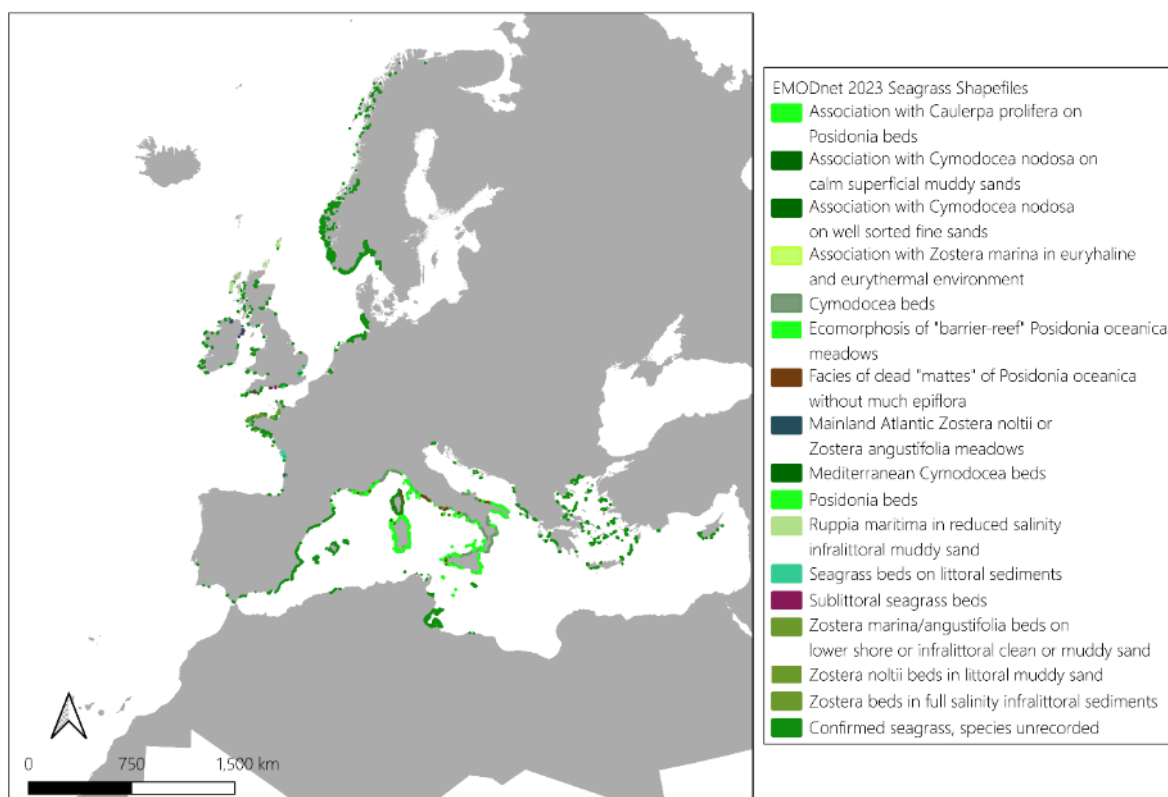
sub-sections which include the relevant substrata and associated communities. By the IPCC definition, coastal seabed sediments only qualify as blue carbon if such areas can be seen as amenable to management. The term 'emerging' habitats is often used for habitats that don't fit the IPCC blue carbon definition (e.g. Howard *et al.*, 2023) but may have an important role in carbon cycling.

2.4.1 Seagrass

The latest available data on seagrass species extent (*P. oceanica*, *Z. marina*, *Z. angustifolia*, *Z. noltii*, *Cymodocea sp*, *Ruppia maritima*) and their associated fauna and flora were downloaded from EUNIS EU Sea Map and EMODnet product catalogues (see Lillie *et al.*, 2021) (Figure 12). These data include aerial extent of mapped seagrass systems.

Figure 12: Extent of different seagrass species across Europe

Colours in this legend are grouped by seagrass species and their associated environmental variables and taxa. Dataset by Lillis *et al.* (2021) and updated in 2023.



Literature which present carbon stocks within the sediments of *P. oceanica* present a range from 6.1-273 kg C m⁻². Various techniques were used across sources including sub-bottom profile imagery within the top 1 m of mattes (Leduc *et al.*, 2023) and carbon flux measurements with in-situ chambers (Gacia *et al.*, 2002). A wide range of studies using different techniques and measuring carbon in sediments from 1 m depth to just cm in some parts was found. In the data included in this study (Euro-Carbon), 7% of the points collected were within seagrass meadows finding on average OC was 2.37 % ± 5.96% median 3.03% slightly lower than saltmarsh sediments but higher than bare sediments in general (Graversen *et al.*, 2025) (Table 5). Variability is also found in published C stocks of *Z. marina* with an overall range of 0.05 – 30 kg C m⁻². Considerable variation in stock below seagrass meadows is documented within and across different studies. For example, the Baltic Sea was found to have lower C content in its *Z. marina* meadows when compared to the Kattegat-Skagerrak region (Billman *et al.*, 2023).

Noticeably within the data, C stores in sediments in *P. oceanica* meadows are reported in kilograms while *Z. marina* in grams, highlighting the elevated C levels in *P. oceanica* sediment stores in the Mediterranean. However, a few places in the range of *Z. marina* report values above 30 kg C m⁻² (in some Norwegian meadows). A wide range of sediment depths are reported ranging from 10 cm to 100 cm, which explains some of the variation in the data. In terms of extent of seagrass meadows, estimates report occurrence rather than non-occurrence such that the area covered is usually an under-estimate (Burrows *et al.*, 2024; Krause-Jensen *et al.*, 2022b; Frascchetti *et al.*, 2024). Many of the shapefiles collated by Lillis *et al.* (2021) are not described and likely represent a combination of *P. oceanica* in the Mediterranean and *Z. marina* from Norwegian Fjord systems (9049.2 km², Table 5), although the dataset is considered to be more complete than that of macroalgae.

Table 5: Literature values where carbon is estimated in *P. oceanica* and *Z. marina* sediments beneath meadows in the Europe

All values were converted from published values into kg or g C m⁻². Equivalent data for sediments in other vegetated habitats (saltmarshes) and in seabed sediments are available in the Euro-Carbon dataset (Graversen *et al.*, 2025), too numerous to list (>60,000 entries) but forming the basis for maps of seabed carbon presented in Figure 3.

Species	kg C m ⁻²	Location	Reference
<i>P. oceanica</i>	6.1 ± 1.4	Mediterranean	Mazarrasa <i>et al.</i> , 2017
<i>P. oceanica</i>	71-273	Mediterranean	Pergent <i>et al.</i> , 2014
<i>P. oceanica</i>	79	NW Mediterranean	Serrano <i>et al.</i> , 2012
<i>P. oceanica</i>	14.6 ± 5.0	Mediterranean	Apostolaki <i>et al.</i> , 2024
<i>P. oceanica</i>	20.2 – 58.7	Corsica – Mediterranean	Leduc <i>et al.</i> , 2023
<i>P. oceanica</i>	32.7	Corsica – Mediterranean	Monnier <i>et al.</i> , 2022
<i>P. oceanica</i> range	6.1 – 273 kg 6,100–2,730,000 t C km ⁻²		
<i>Z. marina</i>	2.414	Norway	(Krause-Jensen <i>et al.</i> , 2022b)
<i>Z. marina</i>	0.627-4.324	Baltic Sea	Röhr <i>et al.</i> , 2016
<i>Z. marina</i>	0.578 ± 0.0043	Baltic Sea	Röhr <i>et al.</i> , 2018
<i>Z. marina</i>	0.725 ± 0.159	Black Sea	Röhr <i>et al.</i> , 2018
<i>Z. marina</i>	1.384 ± 0.241	Eastern Atlantic	Röhr <i>et al.</i> , 2018
<i>Z. marina</i>	4.862 ± 0.741	Kattegatt-Skagerrak	Röhr <i>et al.</i> , 2018
<i>Z. marina</i>	8.793 ± 2.248	Mediterranean Sea	Röhr <i>et al.</i> , 2018
<i>Z. marina</i>	0.635 ± 0.321	Baltic Sea	Billman <i>et al.</i> , 2023
<i>Z. marina</i>	3.457 ± 3.382	Kattegat-Skagerrak	Billman <i>et al.</i> , 2023
<i>Z. marina</i>	0.400 – 30	Norway	Gagnon <i>et al.</i> , 2024
<i>Z. marina</i>	1.547	UK	Burrows <i>et al.</i> , 2024
<i>Z. marina</i>	0.0502– 0.228	Baltic Sea	Jankowska <i>et al.</i> , 2016
<i>Z. marina</i> range	0.05 – 30 kg 500 – 300,000 t C km ⁻²		

This dataset does not include species that are present (previously unmapped) in the Sea of Marmara. The region has recently been mapped and includes records of *Cymodocea nodosa*, *Posidonia oceanica*, *Zostera marina*, and *Z. noltii* covering an area of 0.28 km² (Karadurmuş *et al.*, 2025).

There are a significant number of caveats and assumptions that would need to be addressed before an accurate estimate of C content in sediment stores is made underneath seagrass meadows across Europe. Assuming all of the 9049.2 km² represents *Z. marina* and summing the other areas of *Z. marina* would equate to 9122 km² and give a range between 4.6x10⁹ kg C and 2.7x10¹² kg C (or 2.7 billion t C). Summing the remaining areas which mention *P. oceanica* equates to 5693.3 km² giving a possible range of 3.5x10¹¹ kg C to 1.6x10¹³ kg C (or 15.5 billion t C).

Table 6: EUNIS descriptions and codes for EU blue carbon (seagrass systems)

EUNIS description	EUNIS Code	km ²
Not described within EMODNET dataset		9049.2
<i>Posidonia</i> beds	A5.535	5054.2
<i>Cymodocea</i> beds	A5.531	964.2
Facies of dead "mattes" of <i>Posidonia oceanica</i> without much epiflora	A4.5613	611.4
Seagrass beds on littoral sediments	A2.61	27.6
<i>Zostera marina/angustifolia</i> beds on lower shore or infralittoral clean or muddy sand	A5.5331	13.3
Mainland Atlantic <i>Zostera noltii</i> or <i>Zostera angustifolia</i> meadows	A2.611	11.7
<i>Ruppia maritima</i> in reduced salinity infralittoral muddy sand	A5.5343	7.8
Association with <i>Cymodocea nodosa</i> on well sorted fine sands	A5.53132	4.1
Sublittoral seagrass beds	A5.53	3.7
<i>Zostera</i> beds in full salinity infralittoral sediments	A5.533	3.1
<i>Zostera noltii</i> beds in littoral muddy sand	A2.6111	1.4
Association with <i>Zostera marina</i> in euryhaline and eurythermal environment	A5.533	0.2
Association with <i>Cymodocea nodosa</i> on calm superficial muddy sands	A5.53131	0.2
Association with <i>Caulerpa prolifera</i> on <i>Posidonia</i> beds	MB6525	0.1
Mediterranean <i>Cymodocea</i> beds	A5.5313	0.0
Ecomorphosis of "barrier-reef" <i>Posidonia oceanica</i> meadows	A5.5351	0.0
Total		15752.2

2.4.2 Macroalgae

Macroalgae have historically been omitted from blue carbon frameworks given that the large brown canopy forming kelps and furoids do not grow on soft sediments, have no root systems and therefore burial of organic carbon (and subsequent sequestration) is precluded in these ecosystems. However, more recent analysis of the production of detritus by these systems has shown that the amount and fate of macroalgal detritus has shown that they export a significant amount of OC to adjacent habitats and regions of the seafloor (Filbee-Dexter *et al.*, 2024). This detritus is in the form of particulate and dissolved organic carbon and considered to be out of atmospheric circulation once it is transported to depths in the ocean (below 200 m in Filbee-Dexter *et al.*, 2024).

However, this on the time scale considered, with sequestration being defined as when carbon is transferred below the permanent pycnocline (ca.1000 m). In this case ventilation is driven by the global thermohaline

circulation (turnover time >1000 yrs). The surface Mixed layer (the layer exchanging with the atmosphere) varies on the seasonal scale and can be deeper than 200 m in winter (Dall'Olmo *et al.* 2016, Nat Geosciences). Carbon storage by macroalgae is in the form of standing stock biomass, and some larger kelps have high rates of production. Significant amounts of annual production (NPP) can be exported from kelp habitats (approximately 70 %, see Pessarrodona *et al.*, (2022)).

Macroalgae inhabit rocky coastal shorelines from the intertidal to the sublittoral zones across a wide range of exposure variables. The dominance of species in Europe ranges from large canopy forming kelps such as *Laminaria hyperborea* (A3.11-323) on infralittoral rock of the northern parts of Scandinavia, the UK and more northern parts of France to macroalgae represented by Fucales (Phaeophyceae) of the genus *Cystoseira sensu lato* canopies (including the genera *Cystoseira*, *Ericaria*, and *Gongolaria*, Molinari-Novoa and Guiry (2020)), (A3.132) largely represented at Mediterranean scale, since they colonize rocky seabed from the intertidal to >50 m depth (Hereu *et al.*, 2008) and whose known distribution in the Mediterranean extends over 30% of rocky coasts (Fabbrizzi *et al.*, 2020). Despite an increasing interest of the structural and functional role of this group, data on the full extent and distribution of *Cystoseira* s.l. canopies are still limited, concentrated to just a few species and spatially confined. There is currently a call for improving mapping and monitoring of all *Cystoseira* forests (Fabbrizzi *et al.*, 2020) as well as developing a better understanding of the threats they face (Verdura *et al.*, 2023). Recent efforts have been made to compile available datasets and modelled distributions (Figure 13) which have large gaps and remain a work in progress as they are not represented in EMODnet Seabed Habitats, especially for the Mediterranean Sea.

Studies that estimate productivity of macroalgae in the Mediterranean are quite consistent, with some finding the seaweed species are more productive than the seagrass in the region (*P. oceanica*, Table 8).

Table 7: Summary of the results of some of the studies that estimate productivity of macroalgae in the Mediterranean

Place	Species	kg C m ² yr ⁻¹	Reference
Mediterranean	<i>Gongolaria rayssiae</i>	0.074	Mulas <i>et al.</i> , 2022
Mediterranean	<i>Cystoseira zosteroides</i>	0.081	Ballesteros, 1990
Mediterranean	<i>Cystoseira caepitosae</i>	0.18 – 0.29	Ballesteros, 1990
Mediterranean	<i>E. amentacea</i>	0.14	Cannarozzi <i>et al.</i> , 2023
Mediterranean	<i>P. oceanica</i>	0.13	Pergent-Martini <i>et al.</i> , 2021

Additional studies from Kvile *et al.* (2022) who modelled the potential extent of kelp forests using boosted regressions tree models (BRT) and available quantitative data on important kelp species and biomass estimate that within the Nordic countries (Norway, Svalbard, Denmark, Greenland, Iceland, Faroe Islands, Sweden and Finland) estimated a total of 9,366 km² of kelp forests in northern Europe. Whole of the UK estimates have been placed at 7,776 km² using MaxEnt models (Burrows *et al.*, 2024), while other publications have attempted to use global distribution models at 0.5° spatial resolution to estimate biomass (Filbee-Dexter *et al.*, 2024). The incomplete datasets being compiled by Lillis *et al.* (2021) equate to just under 400,000 km² of habitat within the A3.11-323 EUNIS habitat descriptions (Supplementary materials). In modelling the exported POC to areas deeper than 200 m, Filbee-Dexter *et al.* (2024) found that the United Kingdom, Norway, France, Italy, Spain, Iceland and Portugal combined have seaweed forest areas of ~104,000 km², which export just over 5 Tg C yr⁻¹ to deeper (>200 m) ocean parts. The contribution to long-term carbon

stores by seaweed beds forests depends upon the ultimate fate of this POC and is still an area of research with many uncertainties (O'Dell *et al.*, 2025). Most detritus will be consumed within adjacent ecosystems or areas of the seafloor before it is buried or exported.

Figure 13: Extent of macroalgae where data are available

Data are still being compiled, and the process is explained by (Lillis *et al.*, 2021). This dataset exposes large regions where modelled extents of macroalgae are not included in both the Mediterranean Sea and the west coast of Norway (not to scale).



Standing stock of Laminariales kelp forests is more widely researched estimated at 3.3 t C ha^{-1} by O'Dell, (2022) although gradients of kelp stand density decrease with depth, light attenuation and can increase with wave exposure in certain areas (Gundersen *et al.*, 2021). Recent work on the topic shows that kelp forests in Portugal store up to 16,500 tC in 5189 ha of standing stock (3.1 t C ha^{-1} , or $3.1 \times 10^5 \text{ kg/km}^2$) (Franco *et al.*, 2025), slightly lower than the overall average measured by Gundersen *et al.*, (2021) at 4.8 t C ha^{-1} ($4.8 \times 10^5 \text{ kg/km}^2$).

Although these systems occur along large portions of European rocky coastlines, considerable effort is still needed to characterise their distribution over broad spatial scales and across environmental gradients such as temperature, substrate type, turbidity and human pressures. Within the literature, estimates of seaweed distribution are often modelled based on a small portion of their actual range that has been studied and recorded. The range of models used result in an equally wide range of extent estimates and large areas remain mapped to low spatial resolution. Nonetheless, these ecosystems play a significant role in the turnover of organic carbon in coastal zones and store carbon in their biomass (standing stock). In the studies presented here, standing stock of kelps could hold $3.1\text{--}4.8 \text{ t C ha}^{-1}$ ($3.1\text{--}4.8 \times 10^5 \text{ kg/km}^2$) across a region of 10.5 million hectares equating to between $32.6\text{--}50.4 \times 10^9 \text{ kg C}$ ($8.9\text{--}13.7 \times 10^9 \text{ kgCO}_2\text{e}$). But without an accurate understanding of the true extent of these systems estimates of carbon standing stock, contributions to adjacent sediments and long-term sequestration rates will remain highly uncertain.

2.4.3 Threats to blue carbon stores

In studies on *P. oceanica* human pressures reduced C burial rates when compared to sites without these pressures (Mazarrasa *et al.*, 2017). The widespread use of crop protectants and herbicides is thought to reduce the photosynthetic performance of seagrasses (Bastegaard & Brodersen, 2025).

In a site impacted by a 400 t yr⁻¹ fish farm in the Mediterranean, the effluent turbidity was shown to decrease the extent of *P. oceanica* (as it regressed from the edge of the cages) but also to decrease the capacity to respire effectively and accumulate carbon in sediments (Apostolaki *et al.*, 2011). Small Scale fisheries (SSF) are rarely quantified, but recent studies have found that they could be responsible for the annual loss of over 500 m² *P. oceanica* meadows in the Mediterranean just within one protected area (Silvestrini *et al.*, 2024; 2025). Studies in the United States have found that eelgrass meadows are impacted significantly by the timing of mechanical oyster harvesting (Boardman & Ruesink, 2024). Oyster dredging still occurs in parts of Europe including Denmark, France and Spain while in Norway and Sweden oysters are handpicked (Dias *et al.*, 2025).

In *Z. marina* restoration sites, plants may be up-rooted by large animals, such as the European green crab *Carcinus maenas* (Petersen *et al.*, 2025). While *P. oceanica* is in danger of being replaced by faster growing, lower biomass species such as *Halophila stipulacea* with potential implications for carbon stores (Beca-Carretero *et al.*, 2024a).

A slow steady increase in average temperatures may not affect *Z. marina* or *P. oceanica* but sudden prolonged periods of elevated temperatures (heat waves) have been found to reduce reproductive capacity, growth rates, and rhizome elongation (Egea *et al.*, 2024; Ims, 2025). Heat wave events are often associated with harmful algal blooms which can limit light and compete for resources but also trigger sediment C decomposition and increase GHG emissions from sediment stocks (Zuo *et al.*, 2025).

The factors listed above result in increased prevalence of degraded *P. oceanica* systems which have been found to omit more CO₂ than healthy systems fix (Roca *et al.*, 2022). Therefore, the degradation of *P. oceanica* in the Mediterranean represents a threat to a significant amount of C stored in sediments.

Threats to macroalgae in the Mediterranean were discussed by Verdura *et al.* (2023) who identified several anthropogenic pressures including water quality, habitat destruction and climate change (amongst others). The limited baseline knowledge of threats, distribution and overall health of *Cystoseira spp.* was found to hinder understanding of their ecological status. Further threat papers conduct Modified Threat Reduction Assessments (MTRAs) to assess threats to *Cystoseira s.l.* in the Mediterranean such as (Fehér *et al.*, 2024). Threats such as herbivory storms and flooding, tourism and recreational activities, fishing and harvesting, heatwaves, household sewage and temperature extremes were identified within the three study areas. Threats to kelp forest include turbidity and changes in suspended solids, dredging gears on the substrate, organic enrichment, pollution including synthetic compounds and PAH's, climate change and heat waves and a rising sea-levels (Araújo *et al.*, 2016).

2.5 Sediment dynamics and carbon release

2.5.1 Natural processes of sediment disturbance

The burning of hydrocarbons, fossil fuels formed over millions of years from buried organic matter, releases greenhouse gases that drive global warming. Plants on land and in the ocean still capture carbon dioxide from the environment and sequester it in their tissues. Upon their death some of this organic matter is deposited in sediments, including marine sediments.

Estuaries collect significant carbon rich organic matter from terrestrial freshwater runoff, while marine sources emanate from marine plants including seagrasses, seaweeds and phytoplankton (Zonneveld *et al.* 2010). Where the amount of light at the bottom of the water column limits the growth of seagrass and

seaweeds, phytoplankton are the primary producer of organic carbon. Thus, the highest concentrations of organic carbon generally accumulate in muddy sediments near major rivers and where wave action and ocean currents deposit fine sediments, such as in estuaries, fjords and glacial troughs (Blair & Aller, 2012; Diesing *et al.*, 2024; Diesing, *et al.* 2021; R. Keil, 2017; Keil & Hedges, 1993; LaRowe *et al.*, 2020; Smeaton *et al.*, 2016; Smeaton *et al.*, 2021).

While the infralittoral rock (EUNIS A3) that provides a substratum for seaweeds that sequester and convert carbon dioxide into plant biomass, the muddy sediment habitats (EUNIS B6, D6, E6, F6) are where it accumulates (Table 3). The latter habitats occur in wave sheltered shallow estuaries and deep wave sheltered areas.

The disturbance and loss of shallow water seagrass and seaweeds, and associated fauna, due to dredging for scallops, oysters or mussels will reduce the habitats capacity to trap sediments (sedimentation) and subsequently reduce the carbon sequestration processes in the habitats (e.g., O'Neill *et al.*, 2013). Natural processes, including tidal currents, wave action, storms, burrowing and bioturbation benthic animals, resuspend and ventilate sediments which release particulates into the water and lead to oxidation (remineralsation) of organic carbon into carbon dioxide (Neumann *et al.*, 2021; Solan *et al.*, 2019; Teal *et al.*, 2008; Zhang *et al.*, 2019, 2021). These activities both release carbon dioxide (and probably methane and ammonia) from sediments but also draw-down particulate matter into the sediments. Thus, benthic fauna can increase organic carbon concentrations in sediments, though the direction and magnitude of this effect likely depend on factors such as bioturbation mode (Zhang *et al.*, 2024).

2.5.2 The impact of anthropogenic activities on seabed carbon

The flow of sediments from rivers and streams is the dominant geological pathway of organic carbon to the coastal ocean. Throughout the Holocene, and largely due to deforestation, farming and mining, sediment delivery to the European seas increased. However, recent increased awareness of soil management, conversion of agricultural land back to forest, dam construction and river diversion have decreased fluvial delivery significantly (Milliman, 2001).

Some human activities disturb seabed sediments, exposing the OC within them to oxygenated waters and as a consequence, release greenhouse gases back into the water column. Organic carbon is oxidised to carbon dioxide and the release of methane. This report looks at the activities that can disturb these sediment stores of organic carbon in European seas (Table 14). Detailed assessments of the sensitivity of benthic habitats to human pressures, including physical disturbance by trawling and dredging, have been published (Tillin and Tyler-Walters 2014a, b, Tillin *et al.* 2010, Tyler-Walters *et al.* 2001, 2004, 2018, 2023a, b, 2018). These activities are grouped into low, medium and high impact categories based on factors that influence the likelihood of a human activity having an impact on the carbon sequestration capacity of the seabed at a European scale. The impact is judged based on the area affected, while recognising that the frequency and intensity of the impact will have significant effects at local scales. The recovery time will depend on the ability of species to survive, recolonise and grow thereby restoring the system to pre-disturbance conditions.

The fauna of muddy sediments where most organic carbon is stored are adapted to conditions sheltered from water movement. Fauna such as cold-water coral reefs, and mats of hydroids and other benthic epifauna, will have formed colonies over centuries that may have stabilised the seabed sediments. The longevity of burrowing infauna, particularly in colder waters and depths below 200 m, will have lifespans of the order of years to decades. Thus, the physical disturbance of their biotopes will take at least decades to recover (e.g., for the North Sea, Zhang *et al.*, 2024; Kaiser *et al.*, 2006). For example, there has been no

recovery of cold-water coral reefs over 16 years from seabed trawling in the North-East Atlantic, and recovery is estimated to take many decades (Bett *et al.*, 2025).

Any increase in carbon dioxide from the disturbance of the seabed may lead to higher concentrations of carbonic acid. In shallow waters this may not significantly affect pH due to the natural variability of pH in coastal waters (Enevoldsen *et al.*, 2024). However, in the very deep sea, below about 4,000 m depth, the water is naturally undersaturated in carbonate, meaning that it is effectively acidic and any calcareous shells and skeletons are dissolved (Harris *et al.*, 2023). Thus, seabed disturbance below about 3,000 m may alter increased “acidification” in the deep sea. Deep water mixing will ultimately connect CO₂ generated by human activities (CO₂ emissions and carbon-resuspending activities on the seabed) and produce decreased pH in deeper waters

The scale of human impacts on the seabed is significant. Syvitski *et al.*, (2022) report that between 1950 and 2010 human extraction of sediment (aggregates) has increased by more than 2500 %. More recent activities include wind farms, most of which are set into the seabed. These structures will affect water currents and may have a baffling effect that increases sedimentation (de Jong *et al.*, 2020). However, to date there are no data to estimate the significance of this (Watson *et al.*, 2024). By far the largest human impact on the marine seabed is fishery trawling, not only because of its immediate destruction of habitat and mortality of marine wildlife, but also because it is repeated in the same place many times (Zhang *et al.*, 2024). Sala *et al.* (2021) drew attention to the global footprint of fishery trawling, and they provided a first global estimate of its mineralisation of organic carbon into carbon dioxide from seabed sediments. Subsequent critiques and studies have improved these estimates, particularly with regard to the effects of benthic fauna on mineralisation and carbon burial (Atwood *et al.*, 2023, 2024; Bianchi *et al.*, 2024; Black *et al.*, 2022a; Epstein *et al.*, 2022; Epstein & Roberts, 2022; Freitas *et al.*, 2021; Hiddink *et al.*, 2023; Porz *et al.*, 2024b; Pusceddu *et al.*, 2014).

The North Sea is one of the most intensely trawled areas in the European region, it is also a highly studied region, as a result there are numerous studies that model the effects of fishing there (Seidel *et al.*, 2026; Zhang *et al.*, 2024; Porz *et al.*, 2024; Bruns *et al.*, 2023), sedimentation, and the dynamics of organic carbon cycling (Diesing *et al.*, 2025; Müller *et al.*, 2025; de Haas, 2022; de Haas 1997). Zhang *et al.* (2024) showed that trawled areas had more variable and less organic carbon than comparable sediments that are less trawled.

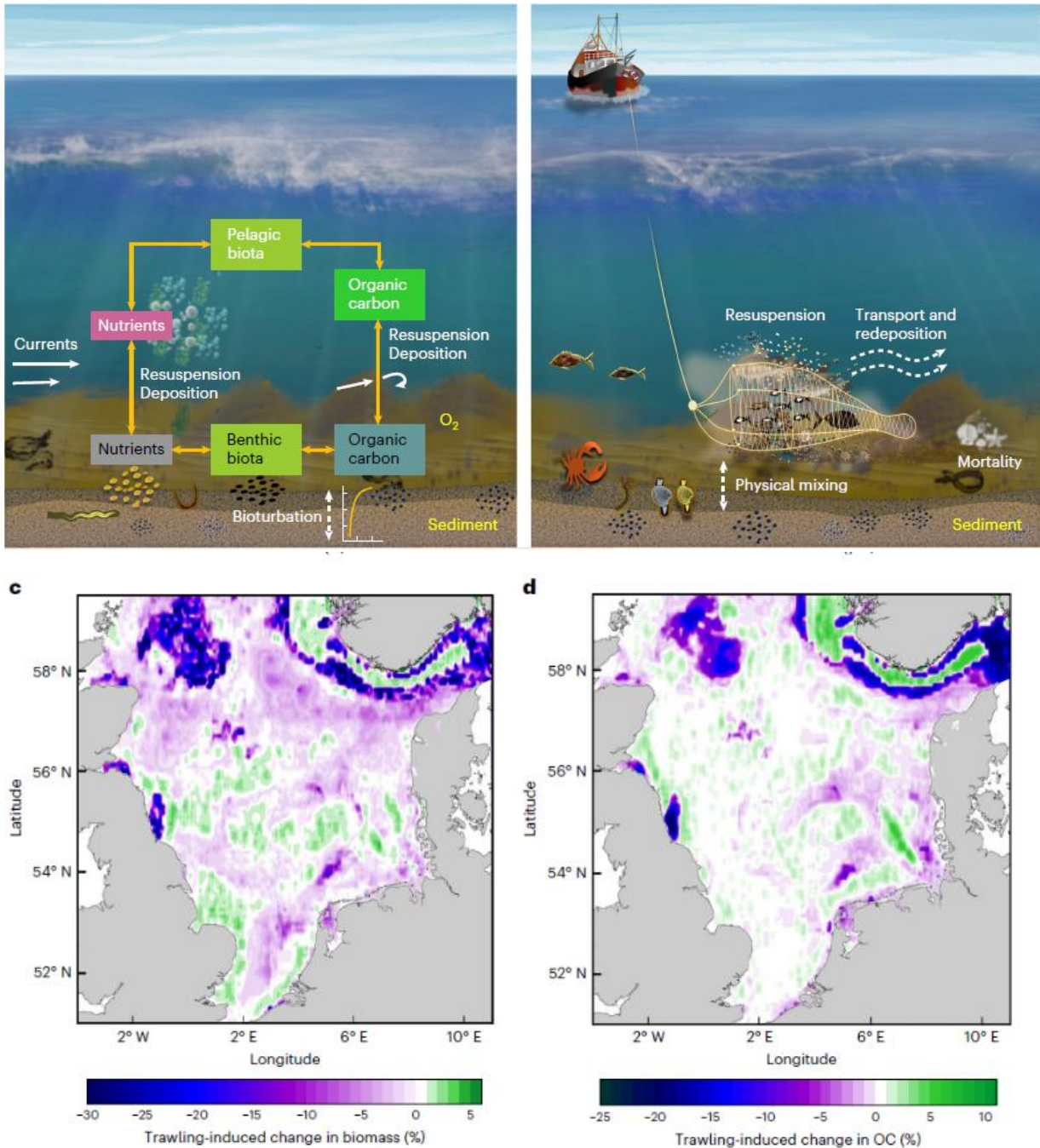
In addition to the immediate exposure and enhanced mineralisation of organic carbon from sediments, the loss of benthic fauna can further reduce the ability of the seabed to capture organic carbon (Figure 16). In their North Sea study area, Zhang *et al.* (2024) attributed the trawling induced loss of up to 30% of the benthic fauna led to reduced carbon storage, especially from muddy sediments which store most organic carbon. In contrast, non-trawled areas had net organic carbon accumulation. They found the net effect of trawling was to reduce the accumulation of organic carbon from $1.5 \pm 1.1 \text{ Mg} \cdot \text{km}^{-2} \cdot \text{yr}^{-1}$ in less trawled areas to $0.4 \pm 1 \text{ Mg} \cdot \text{km}^{-2} \cdot \text{yr}^{-1}$ in heavily trawled ones (Zhang *et al.*, 2024). This suggests that benthic trawling may cause the North Sea to be a net source of carbon dioxide, perhaps $3.67 \text{ MgCO}_2 \cdot \text{km}^{-2} \cdot \text{yr}^{-1}$ (Zhang *et al.*, 2024).

This suggests that benthic trawling may cause the (southern) North Sea to be a net source of carbon dioxide, perhaps $3.67 \text{ MgCO}_2 \cdot \text{km}^{-2} \cdot \text{yr}^{-1}$ (Zhang *et al.*, 2024). However, there is considerable spatial variation in organic carbon deposition and accumulation in sediments, reflecting hydrographic and ecological conditions, meaning that some areas may generally be carbon sources while other (muddy) areas are carbon sinks

(Thomas *et al.*, 2005)(, Kuhn *et al.*, 2010). Furthermore, physical disturbance in organic rich muddy sediments can lower water column pH potentially increasing the local risk of trawling induced seabed acidification in organic-rich areas (Tiano *et al.*, 2021).

Figure 14: The impacts of seabed trawling

Top: infographic demonstrating impacts on organic carbon (OC) stores. Bottom: spatial distribution of sediment property, bottom trawling intensity, and simulated change of benthic faunal biomass (left) and organic carbon content (right) in the North Sea surface sediments due to seabed trawling. From Zhang *et al.* (2024).



3. Scenario Development and Outcomes

No studies of the impacts of human disturbance on seabed carbon to date explicitly focus on the effects of disturbance on natural carbon sequestration rates. Instead, most studies (including this study) examine the role that such disturbance has in resuspending and making such carbon stocks susceptible to redistribution and remineralization, potentially reducing rates of long-term sequestration.

The scenarios developed for this report used methods from existing studies, primarily focused on assessing and quantifying the effects of fishing disturbance on existing sediment carbon stores (Zhang *et al.*, 2024a) from the quantification of the intersection of bottom fishing activities with seabed carbon to determine the volume and mass of carbon disturbed (Diesing *et al.*, 2025; Epstein & Roberts, 2022) through to complete biological, chemical and physical models of carbon dynamics of regional seas (Porz *et al.*, 2024a). The degradability of the carbon disturbed is critically important for understanding the likely rates of consequent remineralization and CO₂ production (Freitas *et al.*, 2021; Hiddink *et al.*, 2023; Smeaton & Austin, 2022) by disturbed material, since oversimplified assumptions about degradation rates lead to potentially misleading projections. Taking account of the lability of carbon to degradation in different sediment types (Black *et al.*, 2022) gives a much better informed assessment of the vulnerability of seabed carbon.

The extent of bottom fishing as a sediment disturbing activity exceeds all other anthropogenic disturbance by a large margin due to the vast spatial coverage involved, such that the effects of other seabed developments like offshore wind farms on seabed are usually measured by the effects of excluding or displacing bottom fishing from the areas of planned or actual development (Porz *et al.*, 2024a), in place of the direct effect of disturbance from that activity. To provide a complete overview, the study also examines the impact of other human activities in section 3.1.4 'Other seabed-disturbing activities' and Table 13.

Increasingly complex but more realistic models of effects of disturbance on seabed carbon demand more data. Most studies to date have centred on the heavily fished North Sea and its bordering areas, using models of seabed carbon density (Diesing *et al.*, 2017; Smeaton *et al.*, 2021) and available datasets on the distribution of fishing activities derived from vessel positioning (VMS automatic identification system, or Vessel Monitoring System, VMS) data (*EMODnet Human Activities, Fisheries, Fishing Intensity*, n.d.), collated by ICES for European Atlantic waters. For the Mediterranean, Black Sea and areas beyond Europe, similar fishing activity information is available from Global Fishing Watch (Kroodsma *et al.*, 2018), derived from AIS vessel positioning information using a machine learning model to estimate the activity of each type of activity.

The assessment presented here produced estimates of the quantity of seabed carbon disturbed by anthropogenic activities across Europe, focussing on the impacts of fishing activity and the reduction of that impact by its exclusion. Effects of restrictions of fishing on sediment carbon disturbance were evaluated in spatial management areas following broad categories used in the North Sea by Porz *et al.* (2024): exclusion of bottom fishing in marine protected areas (MPAs), offshore wind farms (OWFs), carbon sensitivity zones (CSZs, areas of high carbon densities), and by restricting fishing to core fishing grounds (CGFs).

3.1 Spatial data on seabed carbon resources and impacts

3.1.1 Organic carbon density

Several spatial maps of organic carbon density in surface sediments have been produced for Europe with widely varying extents and resolutions (Table 3, Figure 3). These data products broadly divide into (a) those derived from the statistical relationships between observed sediment carbon and spatial predictors such as depth, proximity to land and bottom currents, among others (Atwood *et al.*, 2020; Diesing, 2021, 2024; Diesing *et al.*, 2017; Lønborg *et al.*, 2025), and (b) those derived from more detailed analysis of the underlying sediment characteristics (Folk class assignment, percentage mud, sand and gravel, for example, (Bockelmann *et al.*, 2018; Smeaton *et al.*, 2021; Wilson *et al.*, 2018a).

Organic carbon density layers were obtained from the online repositories associated with each publication listed in Table 8 via links provided at the DOI sources. Reprojection of mapped data to the same coordinate system and resolution as the MPA Europe organic carbon density model allowed comparisons of estimates among layers (Figure 15, 16) and with the recently compiled EURO-Carbon dataset of observations from sediment samples (Graversen *et al.*, 2025) (Figure 16). Data from two studies by Diesing *et al.* (Diesing, 2021; Diesing *et al.*, 2024) were merged for simplicity given the similarity in methods and data used.

Table 8: Sources of mapped organic carbon content of marine seabed sediment in European seas

Measure	Source	Description	Extent	Resolution	Used by
Organic carbon %	Diesing <i>et al.</i> , 2017	%OC (POC)	UK EEZ, North Sea	500 m	Epstein & Roberts 2022
Organic carbon %, density	Wilson <i>et al.</i> , 2018	%OC (POC), kgC/m ² to 0.1 m depth	NW European shelf	0.125 degree	Epstein & Roberts 2022, Khedri <i>et al.</i> , 2024
Organic carbon %, density	Diesing <i>et al.</i> , 2024	%OC (POC), kgC/m ² to 0.1 m depth	Norway and Barents Sea	4000 m	Diesing <i>et al.</i> , 2025
Organic carbon density	Diesing <i>et al.</i> , 2021	kg/m ²	North Sea	500 m	Epstein & Roberts 2022
Organic carbon density	Smeaton <i>et al.</i> , 2021	kg/m ²	UK EEZ	0.01 degree	Epstein & Roberts 2022
Organic carbon density	Atwood <i>et al.</i> , 2020	kg/m ² , Mg/km ² to a depth of 1 m	Global	1 km	Sala <i>et al.</i> , 2021
Organic carbon %, density	Bockelmann <i>et al.</i> , 2018	%OC (POC), kgC/m ² to 0.1 m depth	North Sea	0.01 degree, 1 nm	Porz <i>et al.</i> , 2024 Zhang <i>et al.</i> , 2024
Organic carbon %, density	Lønborg <i>et al.</i> , 2025	kg/m ²	Europe and N Atlantic	0.015 degree	This report

To compare organic carbon density maps, a random subset of 10,000 pixels in the reprojected maps in Figure 5 was used to extract values for shared locations. Correlations of density of organic carbon in overlapping areas (Table 9) showed that maps from studies by Wilson *et al.* (2018), Diesing *et al.* (2021/2024) and Bockelmann *et al.* (2018) were very similar in the North Sea (Figure 16), with all showing high densities of organic carbon in the Norwegian Trough and relatively low densities in the southern North Sea. A similar pattern in North Sea sediments was indicated by the MPA Europe project map (Lønborg *et al.*, 2025, Figure 15e) resulting in a positive but weak correlation between MPA Europe and Wilson *et al.* (2018) values ($r=0.26$) and a stronger correlation between MPA Europe and Bockelmann *et al.* (2018), ($r=0.53$). A major difference in the predicted maps was the predicted high densities of organic carbon in the southern

North Sea in the Atwood *et al.* (2020) map (Figure 15b) not seen in any of the other maps for the region. This discrepancy produced low and even negative correlations between the Atwood *et al.* (2020) map and the other five maps considered (Table 10).

Figure 15: Organic carbon density estimates for Europe

From (a) Wilson *et al.* (2018b), (b) Atwood *et al.* (2020), (c) Diesing *et al.* (2021, 2024 combined), (d) Smeaton & Austin (2021), (e) Bockelmann *et al.* (2018) and (f) the MPA Europe project (Lønborg *et al.*, 2025). All maps were reprojected to the same extent and resolution as the MPA Europe modelled dataset.

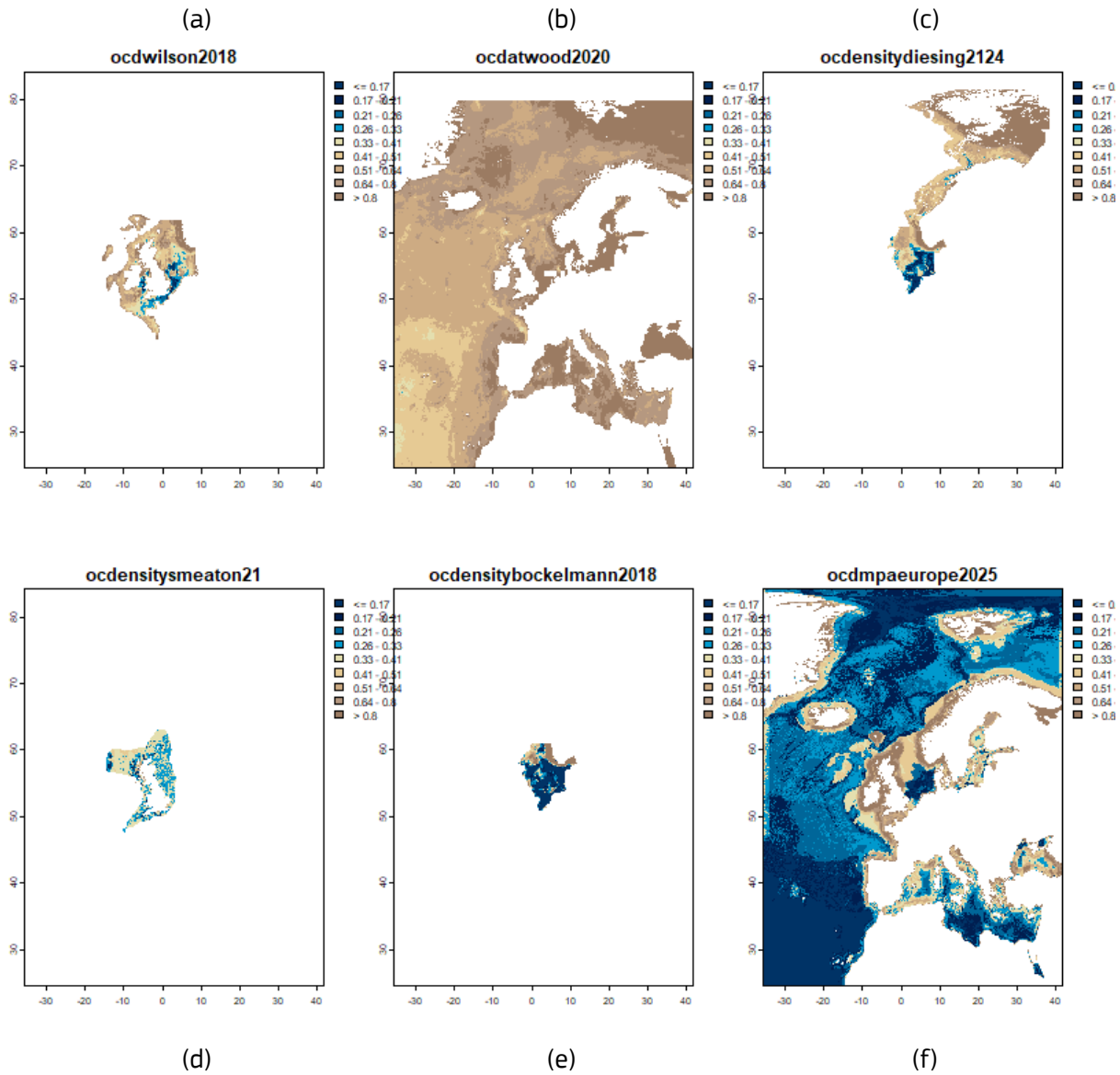
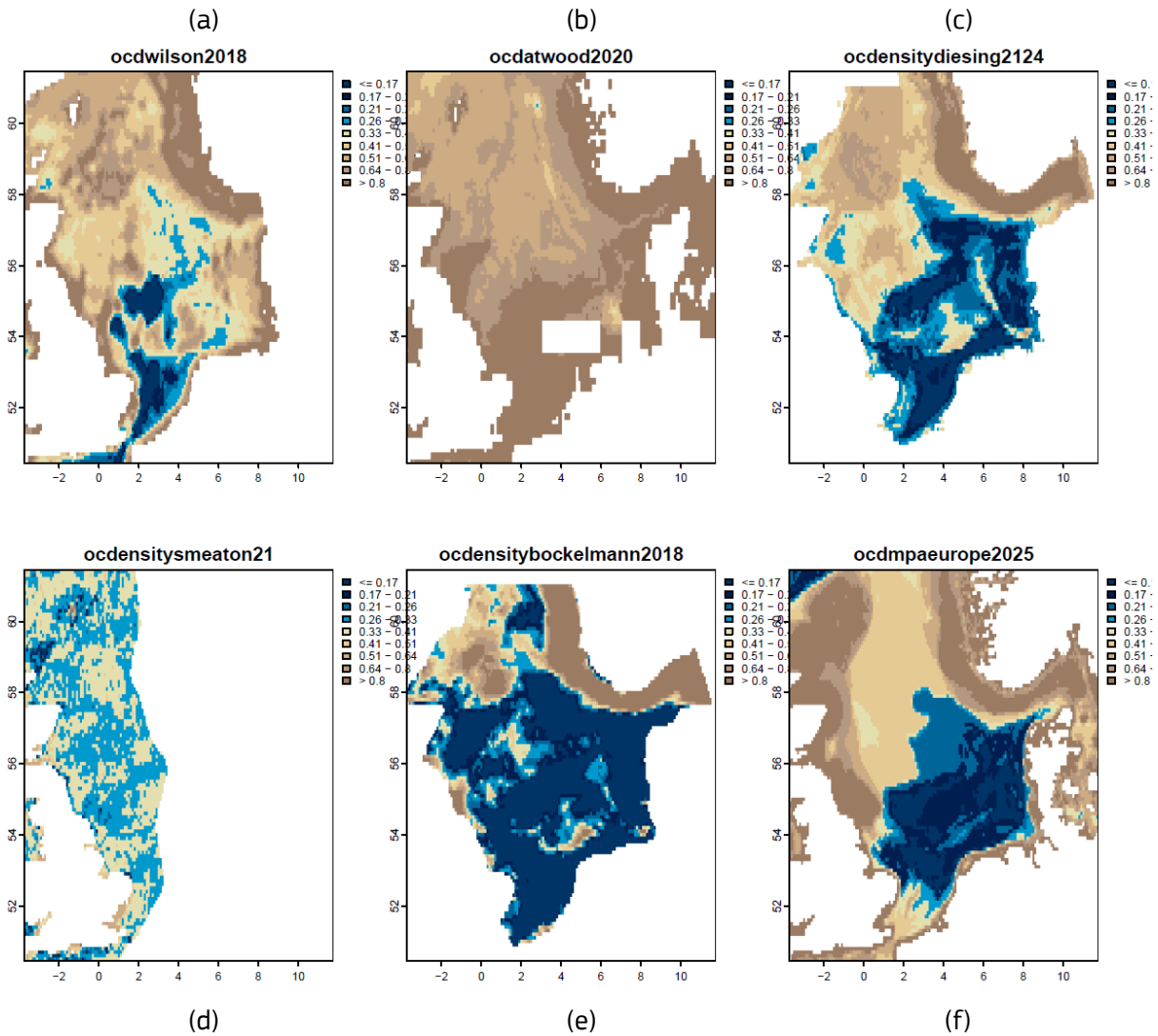


Figure 16: As Figure 15 but for the North Sea area only

Organic carbon density estimates from (a) Wilson *et al.* (2018b), (b) Atwood *et al.* (2020), (c) Diesing *et al.* (2021, 2024 combined), (d) Smeaton & Austin (2021), (e) Bockelmann *et al.* (2018) and (f) the MPA Europe project (Lønborg *et al.*, 2025).



Predicted organic carbon densities widely diverged for the Barents Sea. The Diesing *et al.* (2024) map (Figure 16c) and the Atwood *et al.* (2020, Figure 16b) maps showed relatively high densities in the region (>0.8 kg C/m²) in contrast to the MPA Europe map (16f) where predicted densities were much lower (0.2-0.3 kg C/m²). This difference resulted in negative correlations for predicted carbon values for MPA Europe maps with Atwood *et al.* (2020) and Diesing *et al.* (2021/2024) maps. The organic carbon density map from Smeaton *et al.* (2021) was least similar to the others (Figure 16d).

Table 9: (Left) Correlations among organic carbon density estimates from different sources, based on pairwise complete observations. (Right) Correlations of modelled values with observed values of organic carbon densities at locations of observations (n=832) from the EURO-Carbon dataset (Graversen et al., 2025)

Values are Pearson correlations (r) based on pairwise complete data.

Comparisons among models							Comparison with observations
	Wilson <i>et al.</i> 2018	Diesing <i>et al.</i> , 2021/24	Bockelmann <i>et al.</i> 2018	MPA Europe 2025	Atwood <i>et al.</i> 2020	Smeaton <i>et al.</i> 2021	From 832 location averages
Wilson <i>et al.</i> 2018	1.00	0.68	0.66	0.26	0.14	0.09	0.25
Diesing <i>et al.</i> , 2021/24	0.68	1.00	0.82	-0.16	0.30	0.16	0.22
Bockelmann <i>et al.</i> 2018	0.66	0.82	1.00	0.53	0.13	0.16	0.06
MPA Europe 2025	0.26	-0.16	0.53	1.00	0.39	-0.17	0.54
Atwood <i>et al.</i> 2020	0.14	0.30	0.13	0.39	1.00	-0.07	0.08
Smeaton <i>et al.</i> 2021	0.09	0.16	0.16	-0.17	-0.07	1.00	0.05

Average location-specific organic carbon density values were calculated for 18,373 samples in the EURO-Carbon dataset, giving 832 observations for comparison with model values. Values from the six mapped organic carbon products from the 832 locations and compared with observations (Figure 17, Figure 18, Table 9). As expected, the MPA Europe correlated most strongly with the observations from EURO-Carbon since these observations were used to produce the predictive model (Table 9, $r = 0.54$). Predicted organic carbon density values from Wilson *et al.* (2018) and Diesing *et al.* (2021, 2024 combined) were next most highly correlated with observed values ($r = 0.25$ and 0.22) while values from Bockelmann, Atwood and Smeaton had relatively low correlations with observations ($r = 0.05$ to 0.08).

While correlations between models and observations may be seen as an indication of the confidence that can be associated with the models, such consideration must account for any spatial bias in the observations used to train the models. Spatial coverage in the EURO-Carbon dataset is heavily skewed towards coastal areas, while the other models are likely to have had different spatial distributions of training data that may differently represent the spatial pattern in the model domain.

Figure 17: Modelled organic carbon density estimates for Europe

Comparisons among model estimates for randomly selected locations across Europe.

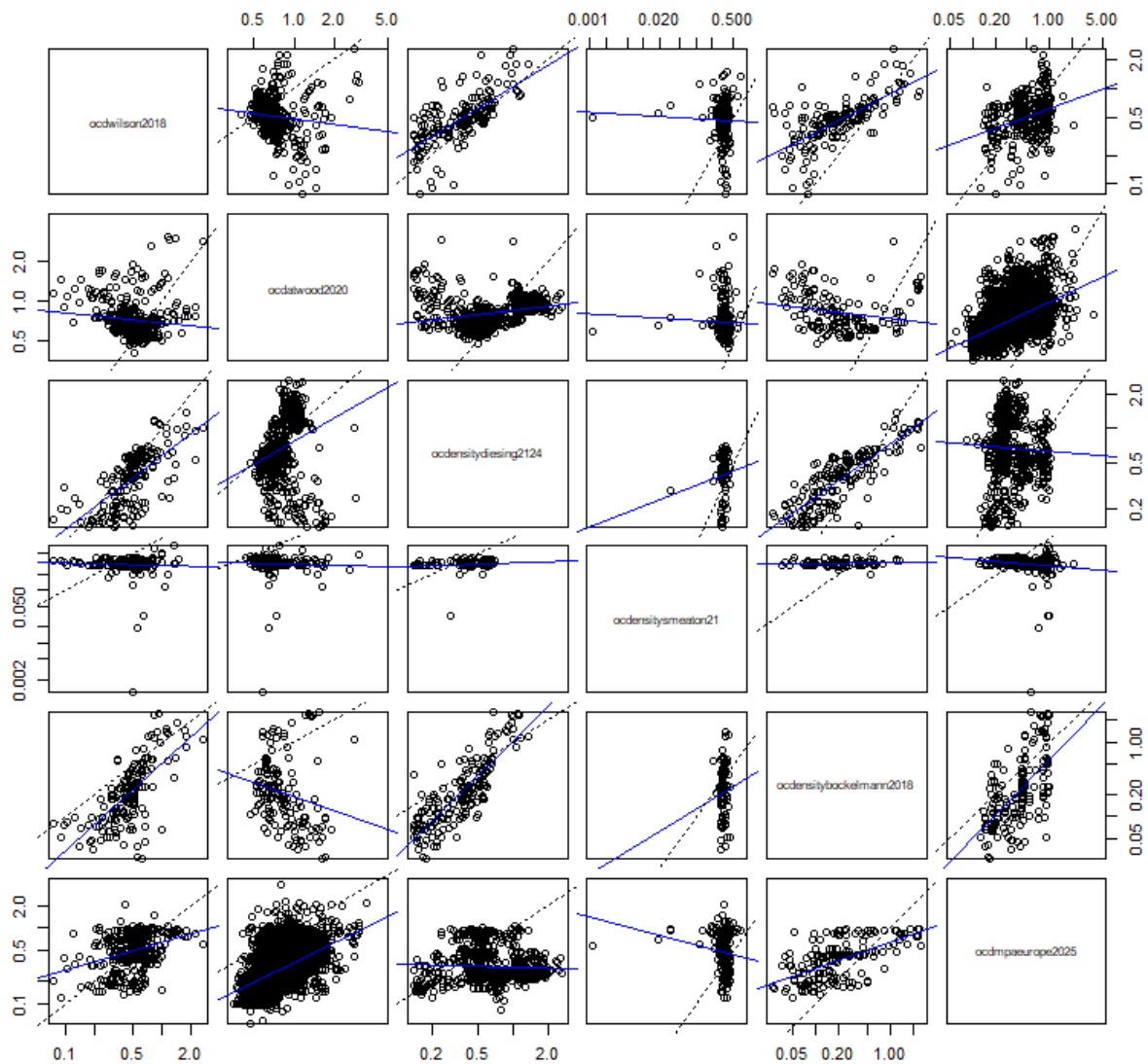
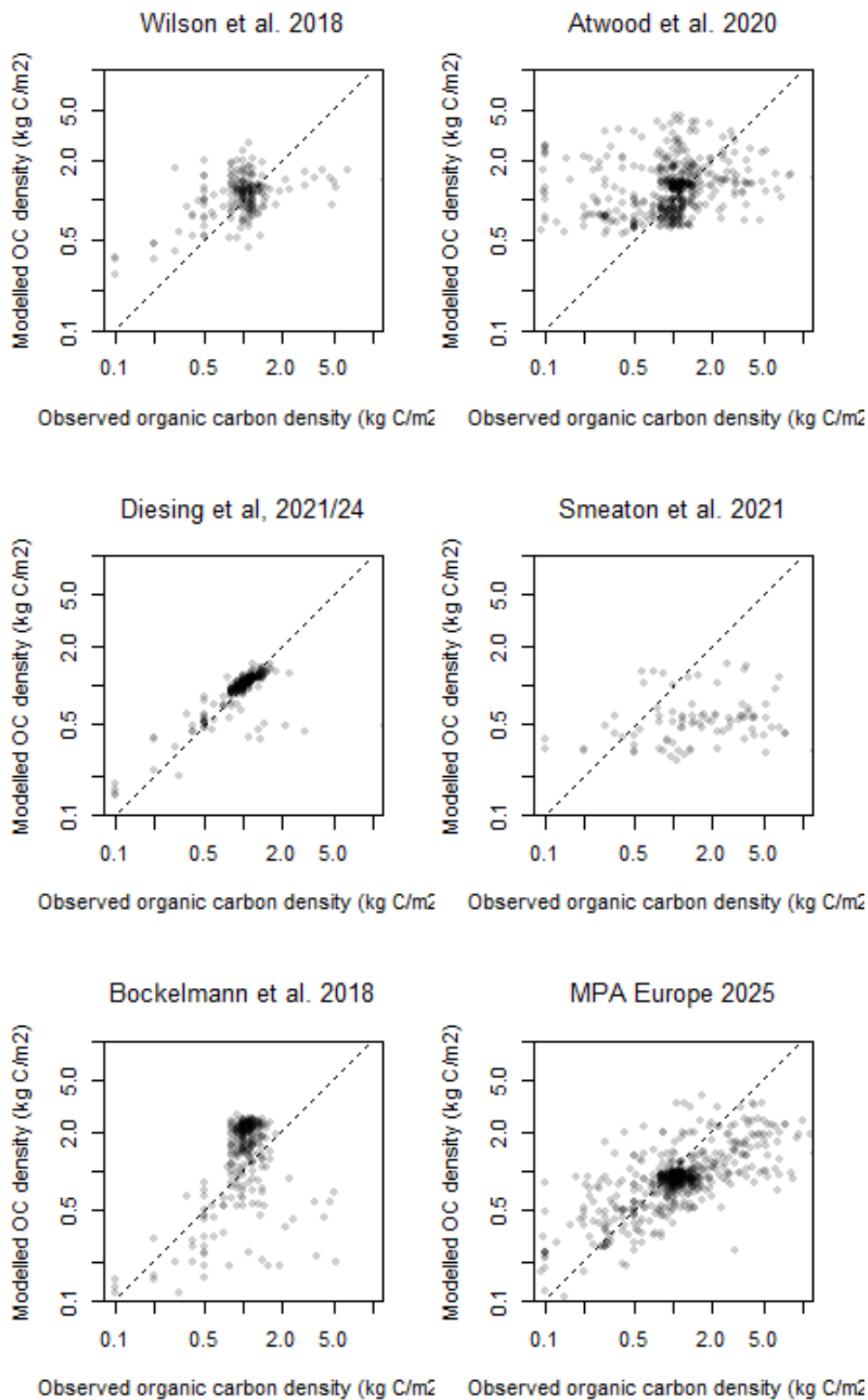


Figure 18: Modelled organic carbon density estimates for Europe

Comparisons among model estimates for randomly selected locations across Europe.



3.1.2 Fishing activity

The footprint of bottom disturbance by fishing has been thoroughly reviewed by Eigaard *et al.* (Eigaard *et al.*, 2017) as part of the EU-funded BENTHIS FP7 'Benthic ecosystem fisheries Impact Study' (Rijnsdorp *et al.*, 2018). In this report, the same approach has been broadly followed using existing and updated datasets on fishing vessels and their estimated effects on seabed carbon stocks.

Vessel hours

Fishing activity is available from two main sources, ICES and Global Fishing Watch (*Global Fishing Watch*, 2025), each derived from AIS, VMS for ICES vessel positioning data and specifying hours spent in reporting areas by vessel type. While individual vessel information can be available, usually anonymised, each source offers aggregated data on vessel hours at a range of suitably high resolutions (ICES, 0.1 dg; GFW, 0.01 and 0.1dg). ICES data reports on seven types of fishing vessels: 'beam trawls', 'bottom otter trawls', 'dredges', 'pelagic trawls and seines', 'static gears' and 'bottom seines'. GFW identifies a larger range of 17 types of vessels, with bottom contacting gear including 'trawlers', and 'dredge fishing'; static gear types including 'fixed gear' and 'pots and traps', and seiner categories as 'purse seines', 'seiners', 'other purse seines', 'other seines', and 'tuna purse seines'. Datasets are presented as aggregated activity over specified time periods. While fishing activities are variable in time and space, for this assessment ICES and GFW activity was used summed over 2020 to 2024, with OSPAR data from 2020 as used by Black *et al.* (2022).

ICES data showed that beam trawling between 2020 and 2024 was restricted to the Celtic Sea (southwest of Ireland), the English Channel and the southern and eastern North Sea (Figure 19). Vessels used bottom otter trawls across the whole European continental shelf, as far as the 500m depth contour (see Figure 20).

Figure 19: ICES vessel effort by fishing gear. Values are hours per year per 0.05 x 0.05 decimal degrees spatial unit

Note that this data is not complete for several countries, including all of the Mediterranean.

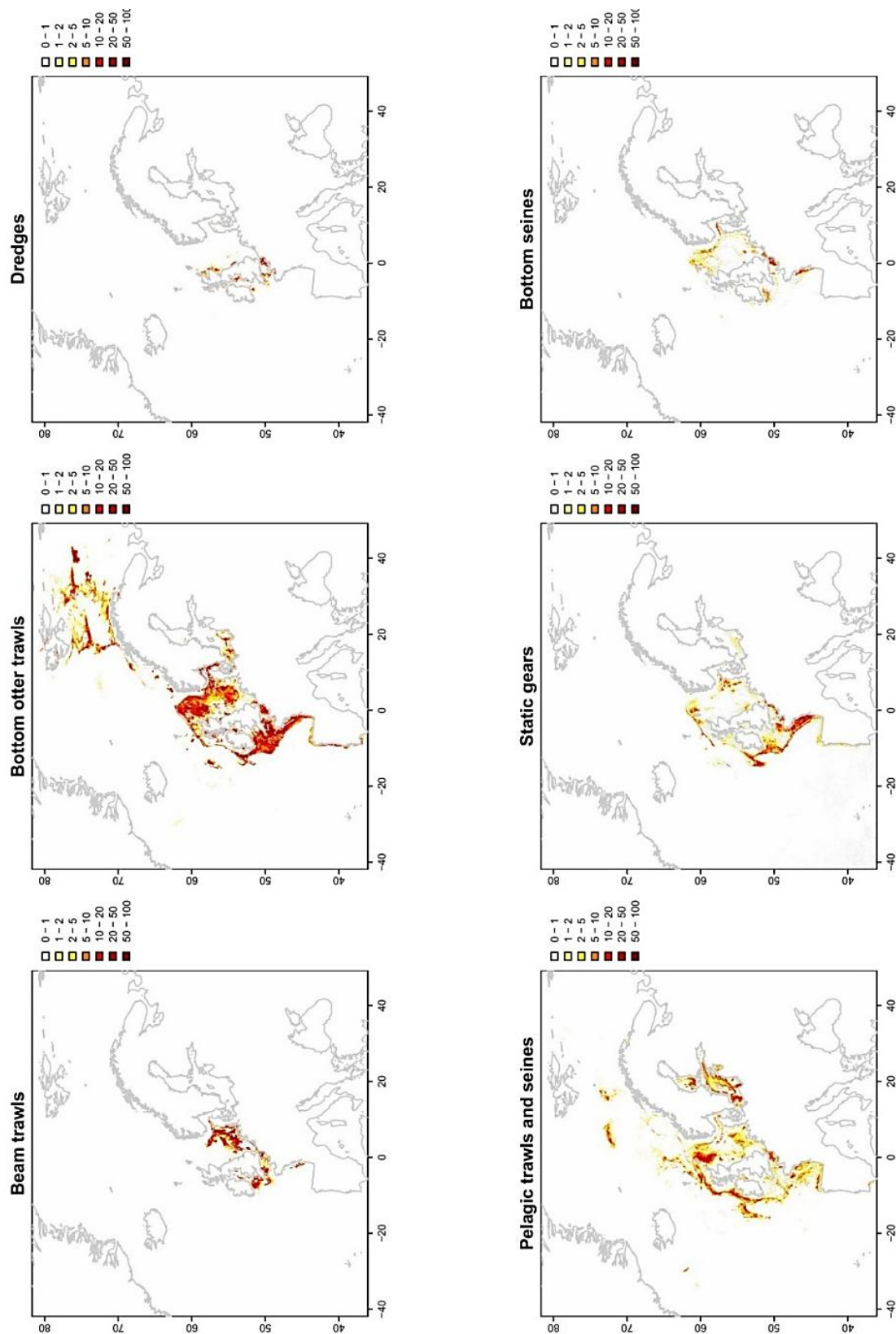


Figure 20: Global Fishing Watch vessel effort by vessel type

Values are hours per year per 0.05 x 0.05 decimal degrees spatial unit.

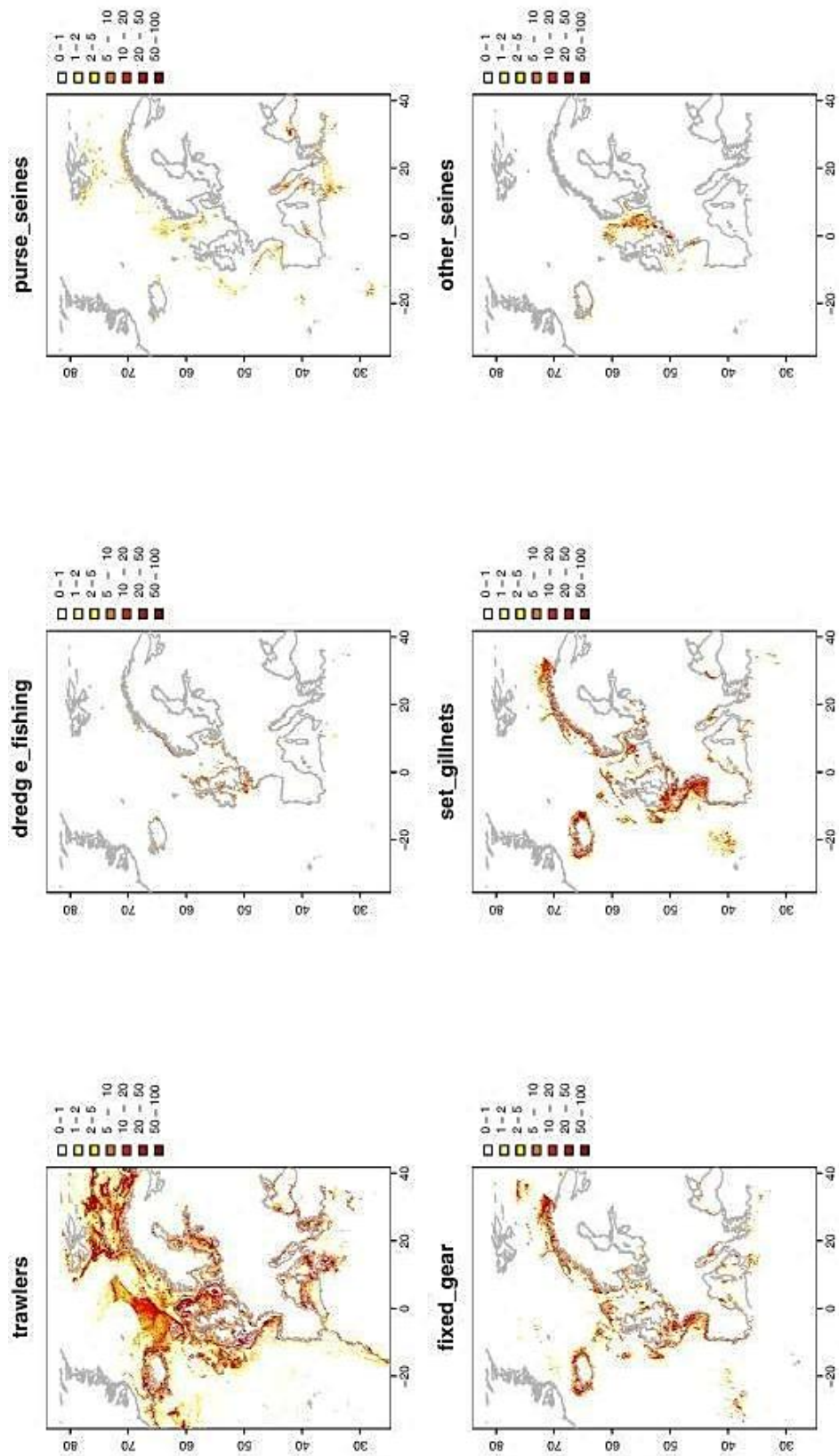


Table 10: Sources of data on fishing activity in European seas

Data set	Global Fishing Watch	ICES fishing data	OSPAR fishing data
Source	Kroodsmma, <i>et al.</i> 2018	EMODnet Human Activities, Fishing	https://odims.ospar.org/
Unit	hrs/unit area by gear type	hrs/unit area by gear type, Swept Area Ratio	hrs/unit area by gear type, Swept Area Ratio
Extent	Global	Atlantic Europe, not Mediterranean	Atlantic Europe, not Mediterranean
Res	0.1 dg	0.05 dg	0.05 dg
Period	2020 to 2024	2020 to 2024	2020
Used by	Sala <i>et al.</i> , 2021, 2024. Porz <i>et al.</i> 2024	Khedri <i>et al.</i> , 2025, Epstein & Roberts 2022, Diesing <i>et al.</i> , 2025, Porz <i>et al.</i> 2024 (gear types)	Black <i>et al.</i> , 2022
Comment	Data from Global Fishing Watch APIs were accessed using r gfwr. Non-commercial use only.	EMODnet Human Activities, Fisheries, Fishing Intensity. Includes Swept area ratio	Includes swept area ratio: surface and subsurface

Swept Area Ratio

Intensity of fishing is more directly described by a measure of the number of times per year that areas of the seabed are disturbed by fishing gear such as trawls or dredges. This is usually expressed by the swept area ratio (SAR). SAR in an area (k) is calculated as the sum of the activity of each type of vessel (j) in that area in hours multiplied by the width of each gear type (w_j), and the vessel speed (v_j) (Hiddink *et al.*, 2026; Porz *et al.*, 2024a; Zhang *et al.*, 2024b):

$$SAR_k = \sum_j \frac{T_{j,k} w_{j,l} v_j}{A_k} \quad (\text{Equation 1})$$

SAR is a unitless rate metric (m^2 per m^2 per year) and is provided by ICES alongside vessel activity data. Global Fishing Watch does not provide SAR data, but recent authors have used GFW vessel use data with proportional data on fishing gears from ICES to produce higher temporal resolution daily datasets (Porz *et al.*, 2024a). With assumptions on the size of fishing gears, using vessel use data permits estimation of SAR across wide areas, including those parts of Europe not presently covered by ICES SAR products: the Mediterranean and Black Seas.

Different sources of data and methods for calculating SAR introduce additional uncertainty in the intensity of seabed impacts. Here, SAR data were used directly from those provided by ICES and OSPAR. Since SAR is calculated using summed activities of individual vessels (using Equation 1), swept area ratio data products used here from ICES and OSPAR, along with that from Zhang *et al.* (2024) correlated with reported vessel use from ICES (Figure 21a) and GFW (Figure 21b). The strength of these relationships demonstrates that, in the absence of specific information on the size and speed of fishing vessels and the gear used, SAR may be synthesised with a relationship between ICES SAR and vessel activity data from GFW. To achieve this,

simple no-intercept linear regression was used to produce a predictive relationship between reported ICES SAR and vessel hours from GFW of each type for the North Sea (Table 11), which was then applied to GFW vessel use data to generate a synthetic GFW SAR. Vessel hours from GFW for trawlers, 'other purse seines' and 'other seines' were strong predictors of ICES SAR, judging by the large t-values and small standard errors for these predictors. The overall R^2 of 0.85 indicates that GFW vessel use may be an adequate predictor of SAR in the North Sea (Figure 22). The relationship between ICES SAR and GFW vessel use was less strong using data for the whole of Europe but still produced a relatively high R^2 of 0.61 (370 degrees of freedom, F-statistic: 114.8 on 5 and 370 DF, p-value: < 0.001).

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Table 11: Function used to create Global Fishing Watch Swept Area Ratio maps for European seas

No-intercept linear regression was used to relate ICES SAR from EMODnet to vessel use from Global Fishing Watch for vessels operating bottom contacting gear in the North Sea. Residual standard error: 0.6117 on 731 degrees of freedom. Multiple R-squared: 0.8493, Adjusted R-squared: 0.8482. F-statistic: 823.8 on 5 and 731 DF, p-value: < 0.001. Estimates are regression coefficients and associated SE, t and P values. GFW combine pelagic and demersal trawlers data and some methods of seine fishing are pelagic so these data sets are not strictly commercial.

GFW vessel use	Estimate	Std. Error	t value	Pr(> t)
Dredge fishing	-0.000042	0.000061	-0.686	0.493
Other purse seines	0.003431	0.000363	9.454	<0.001
Other seines	0.002623	0.000135	19.395	<0.001
Purse seines	-0.000445	0.001806	-0.246	0.806
Trawlers	0.000232	0.000007	32.908	<0.001

Figure 21a: Swept area ratio (SAR) versus vessel use for different classes of fishing vessel from ICES

Data from OSPAR (top), ICES (middle) and Zhang *et al.* (2024). Numbers in plots give R^2 values for linear regressions (dashed lines) of log (SAR) vs log (vessel hours).

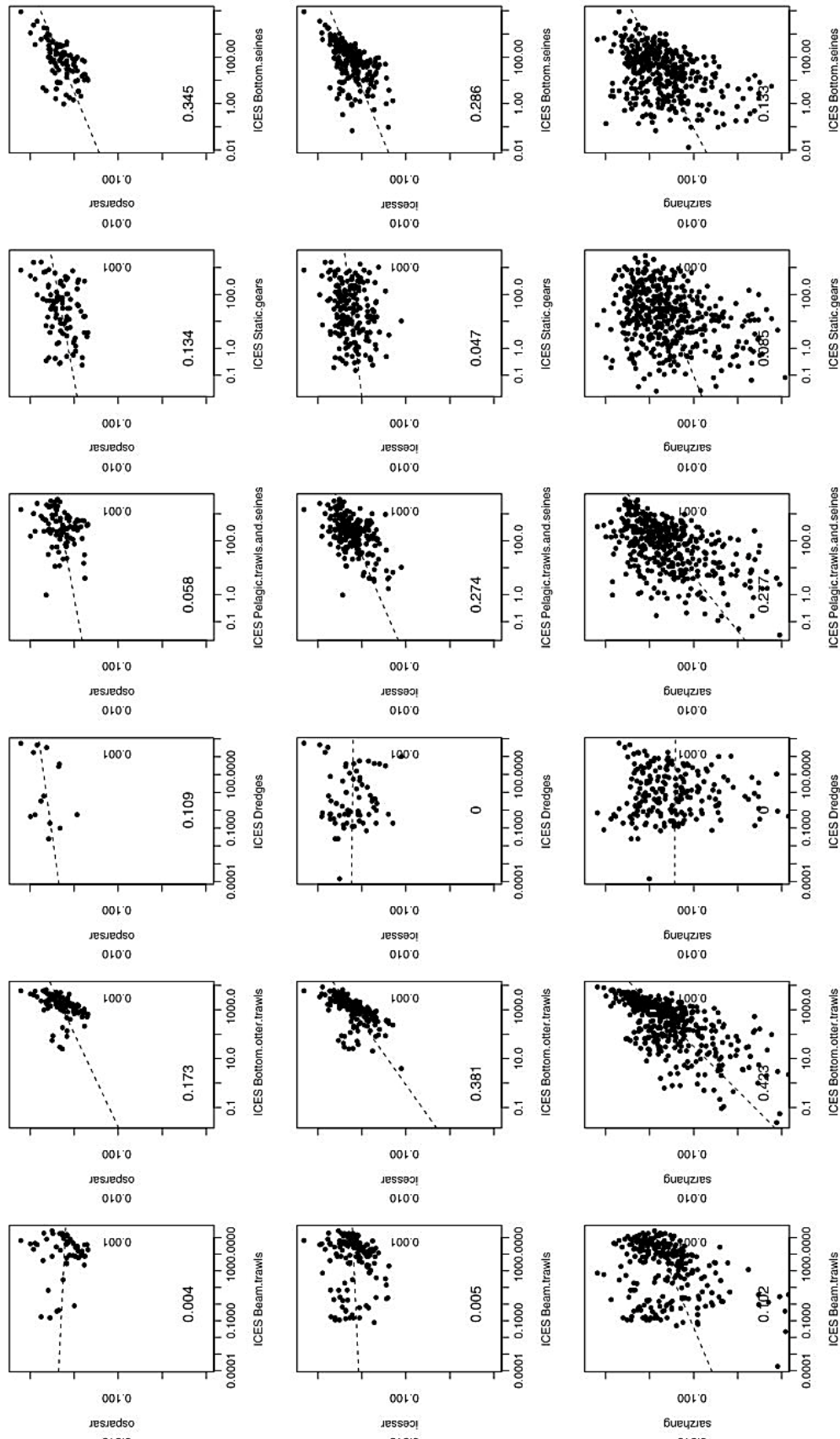


Figure 21b: Swept area ratio (SAR) from OSPAR (top), ICES (middle) and Zhang et al. (2024) versus vessel use from Global Fishing Watch

Numbers in plots give R² values for linear regressions (dashed lines) of log (SAR) vs log (vessel hours).

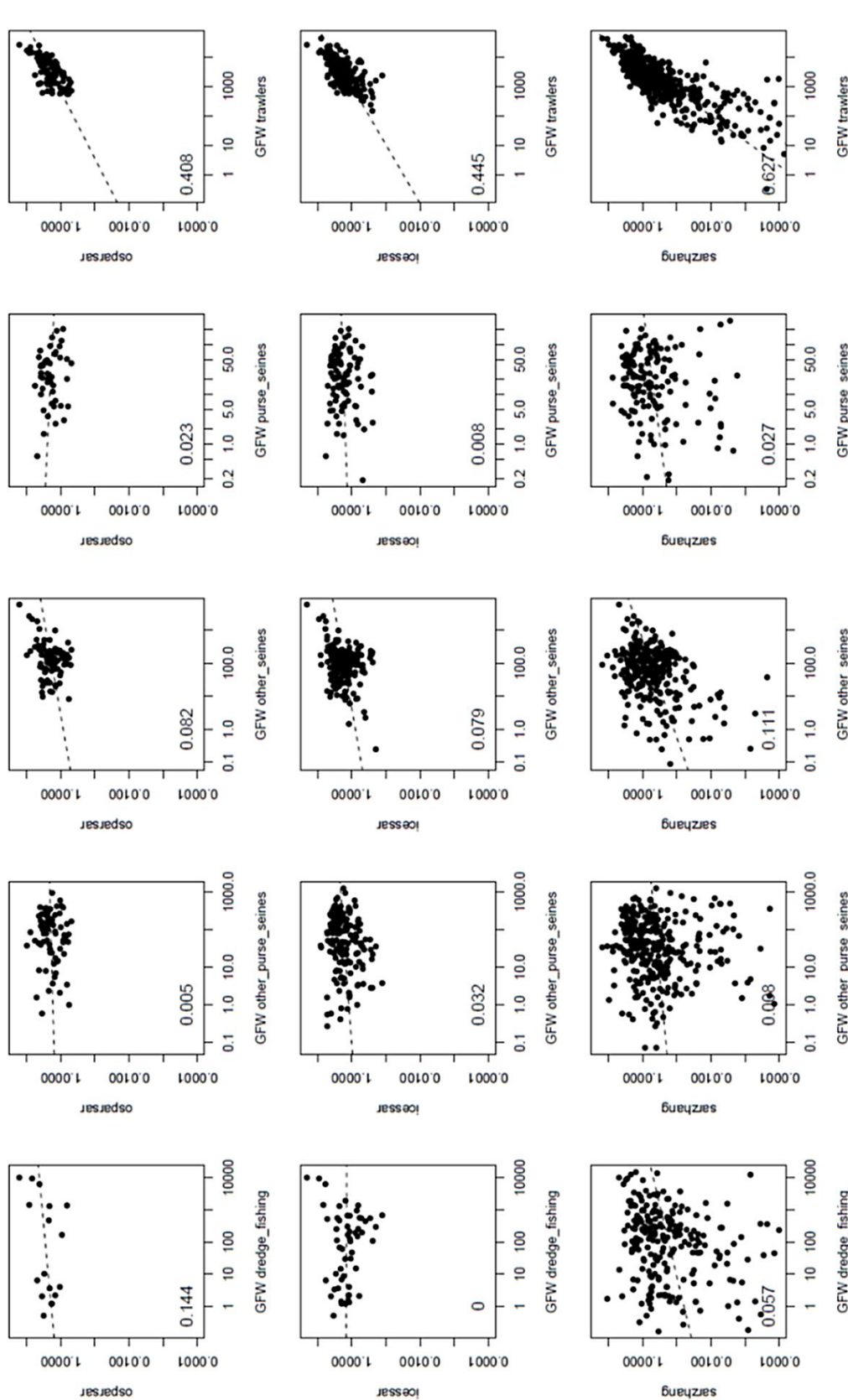
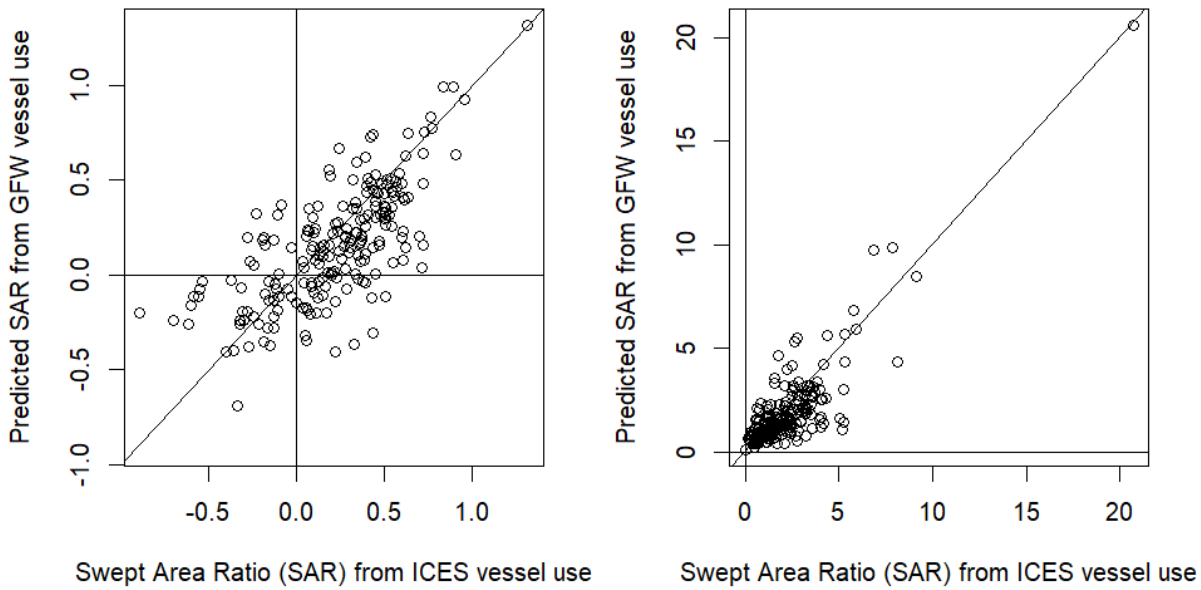


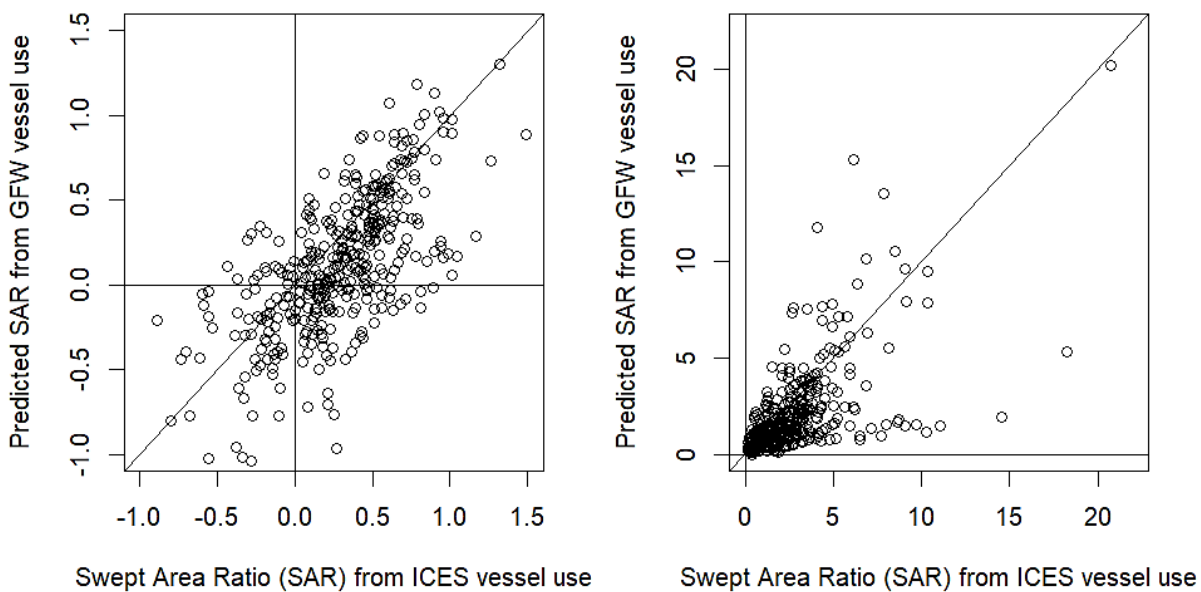
Figure 22: Predicted swept area ratio versus ICES SAR

SAR, as $\log_{10}$ and absolute values in left and right subplots respectively from GFW vessel use (y-axis) using (a) data from the North Sea, (b) all European seas.

(a)



(b)



Swept Volume Ratio

The volume of sediment disturbed per area can be estimated by the product of the total area covered by fishing gear by the depth each gear penetrates the seabed ($d_{j,k}$). This is described as the swept volume ratio, SVR (as m^3 per m^2 per year). Here, SVR has been calculated using data on the proportional incidence of activities of each gear type (j) in that area as a proportion of the total hours spent by all such vessels ($p_{j,k}$) (Figure 25).

Swept area ratio $SAR_{k,l}$ in the area (k) for a specific depth layer (l), if separate layers are recognised, can thus be expressed as:

$$SVR_{k,l} = SAR_{k,l} \sum_j d_{j,k} p_{j,k} \quad (\text{Equation 2})$$

Ideally, SAR and SVR should be quantified using information on individual vessels, but the above approximation may be sufficient for comparisons among areas. Some authors specify differences in gear depth penetration in different sediments (Table 12), with bottom trawls and otter trawl doors going deeper in mud than sand (Khedri *et al.*, 2025; Porz *et al.*, 2024a). Here only effects of fishing on the top 10cm of sediment was considered. Gear depth values used in this assessment were those used by Epstein & Roberts (2022) derived mostly from Hiddink *et al.* (2017).

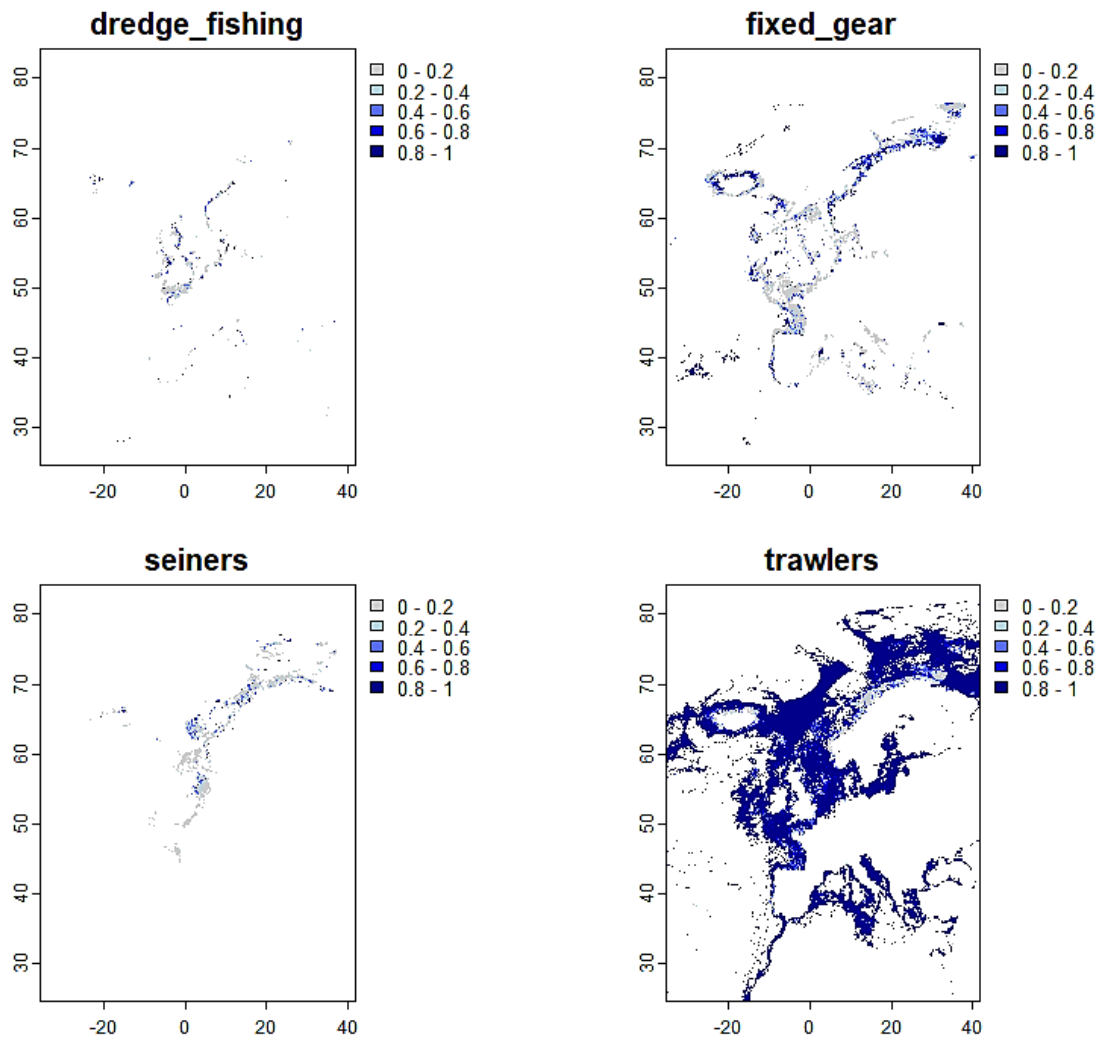
Table 12: Gear penetration depth (d_j in Equation 2) used in recent studies of organic carbon disturbance by fishing

Values used here are those reported as being adopted in the original studies, but see Pitcher *et al.*, 2022 for a review of measurements of trawl impacts worldwide.

Gear type penetration depth	Average depth (cm)				
Study	Epstein & Roberts (2022)	Porz et al. (2024)	Porz et al. (2024)	Khedri et al. (2024)	Khedri et al. (2024)
Sediment type	All	Sand	Mud	Sand	Mud
Otter trawls	2.44	5	10	1.1	2.0
Beam trawls	2.72	10	10	1.9	3.2
Seines	0.50	0	0	0	0
Dredges	5.47	0	0	3.5	5.4
Nephrops trawls	2.44	0			

Expressing fishing effort as the proportion of total vessel hours shows the predominance of beam trawling in the southern North Sea in ICES data (Figure 24), reflecting the pattern in total vessel hours for this activity (Figure 26). Otter trawls were used throughout the remaining shelf waters, with dredging generally restricted to coastal waters of Britain, northern France and Denmark. Static gears were mostly confined to deeper Atlantic waters. Global Fishing Watch data shows similar patterns (25) with the exception of trawling activity in the deeper North Atlantic (see also Figure 27).

Figure 23: Use of fishing gears by fishing vessels, expressed as a proportion of total hours of effort across all types, from ICES data



Patterns in ICES swept volume ratio calculated from SAR, gear penetration depth and the proportion of fishing by each vessel type (SVR, Figure 26), as expected, follow the underlying patterns in swept area and vessel use by beam and otter trawlers. Similarly, patterns in synthesised SVR from GFW vessel use (Figure 29) are broadly similar to those shown by ICES SVR but suggest trawl disturbance in deeper areas, likely due to the lack of distinction between pelagic and benthic fishing activity for trawlers and seiners in the GFW dataset. Deep water seabed disturbance is unlikely since trawl gear is rarely deployed below 1000 m (e.g., (Ragnarsson & Steingrímsson, 2003)) and almost never below 1500 m (Jacquemont *et al.*, 2024). It is also illegal in the EU to trawl deeper than 800 m in the Atlantic and deeper than 1000 m in the Mediterranean. Like swept area, the intensity of disturbance varies over several orders of magnitude, from very light ($0.01 \text{ m}^3/\text{m}^2/\text{yr}$) to much higher values (0.1 to $1.0 \text{ m}^3/\text{m}^2/\text{yr}$) in heavily disturbed areas. The GFW SVR dataset shows high disturbance in coastal areas of the Mediterranean shallower than 1000 m, and particularly intense disturbance throughout the Adriatic.

Figure 24: Proportional use of fishing gears by vessels as a proportion of total hours fishing per reporting area

From Global Fishing Watch data. Trawler and seiners are not split into pelagic and benthic fishing vessels.

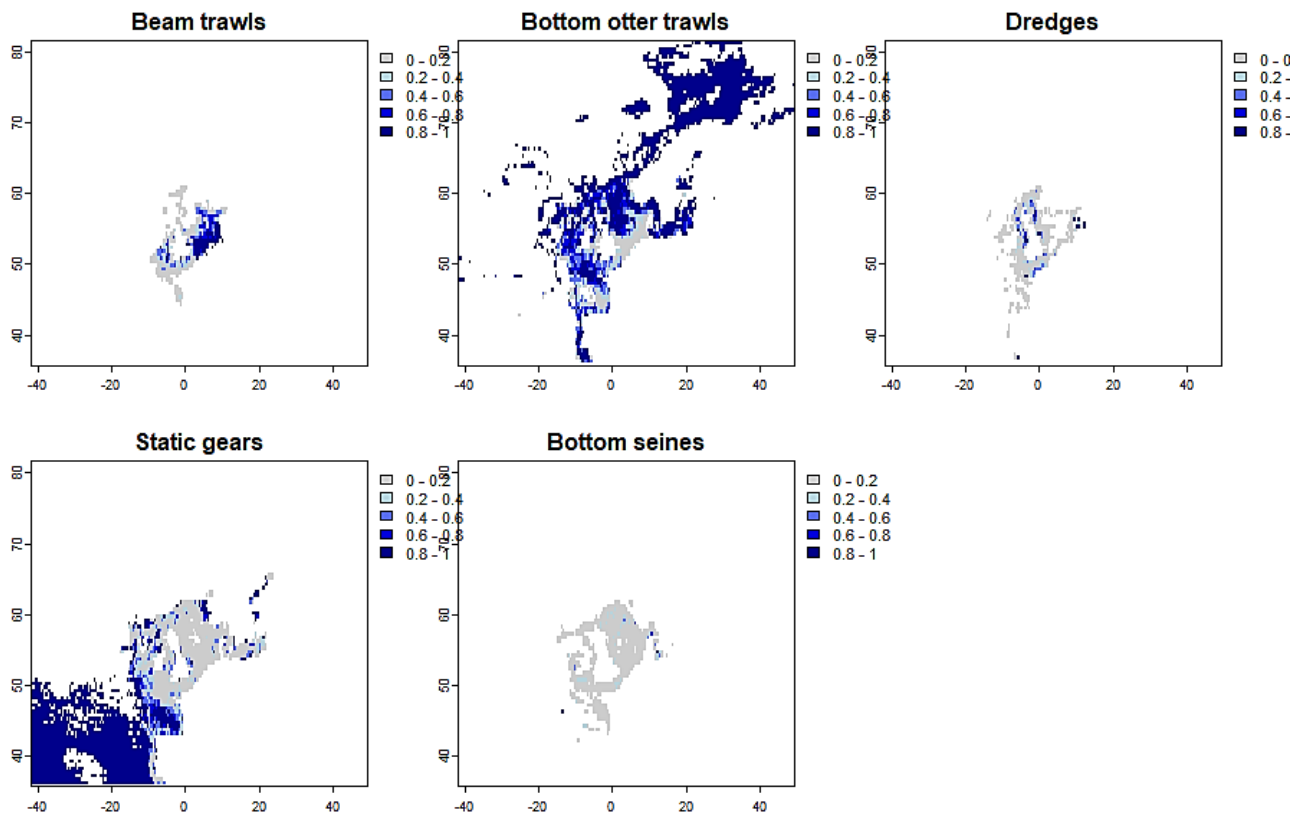


Figure 25: Swept volume ratio from ICES swept area ratio data in the NE Atlantic only

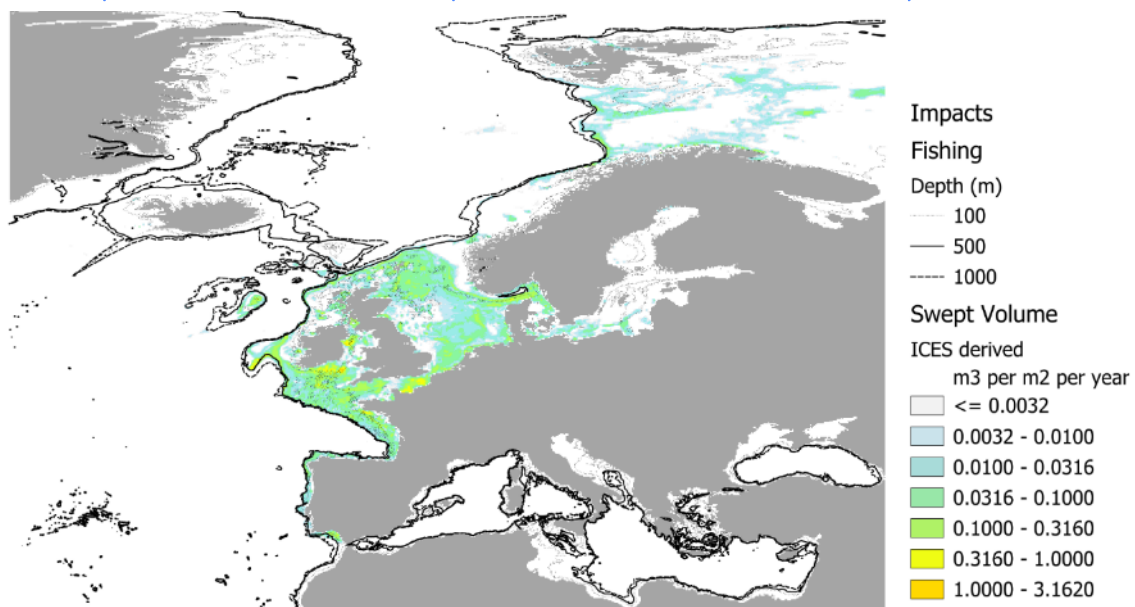
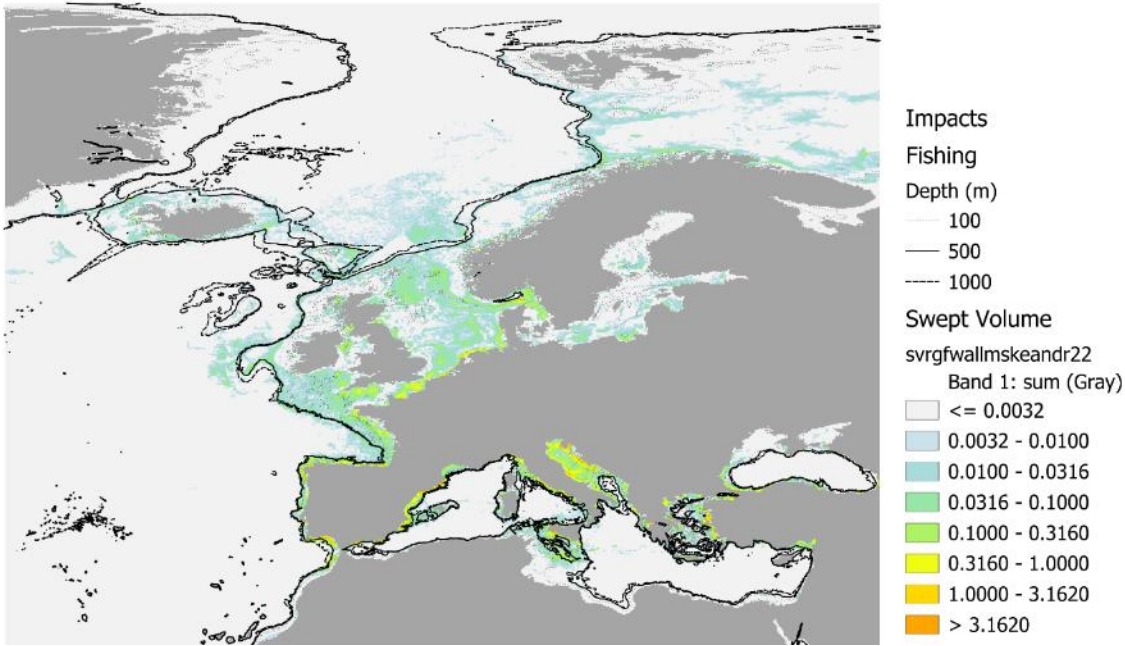


Figure 26: Swept volume ratio from Global Fishing Watch swept area ratio

as synthesised from the relationship between ICES SAR and GFW vessel use data.



3.1.3 Seabed carbon disturbance

The quantity of seabed carbon disturbed per unit area ($\text{kg C/m}^2/\text{year}$) is derived from the product of swept volume ratio (m^3 per m^2 per year) and organic carbon density per unit volume (kg C/m^3). The latter measure is produced by expressing the area-specific carbon density for the top 10 cm of sediment (kg C / m^2) as a per m^3 quantity (OC density) by dividing by the volume of sediment in the top 10cm ($1 \text{ m}^2 \times 0.1 \text{ m} = 0.1 \text{ m}^3$).

$$C_{\text{disurbed},k,l} = \text{OCdensity}_k \times \text{SVR}_{k,l}$$

Combining the six models of organic carbon density with the three datasets of swept area ratio provides a wide range of potential outcomes for the assessment of fishing disturbances (example Figure 27), all sets Figure 33). This set of combinations is used to assess the potential disturbance of organic carbon across the MSFD regions and is used as the basis for estimating the effects of exclusion of fishing from areas of seabed associated with MPAs, offshore wind farms and carbon sensitive zones, and its restriction to core fishing grounds (CFGs).

Similar levels of disturbance can result from the product of low organic carbon density and high swept volume ratio and vice versa. To visualize the separation of these scenarios, organic carbon maps and swept volume maps were classed as low and high by the exceedance of threshold quantiles (75%ile) for each dataset. Where organic carbon density is predicted to be uniformly high across wide regions, such as for the MPA Europe OC map, patterns of disturbance of OC generally follow areas of high fishing intensity (Figure 27).

Greater consistency in the spatial distribution of fishing effort than in OC density produced the consistent classification into high effort areas, but much more variable assignment to high organic carbon disturbance classes. Only the MPA Europe organic carbon density map produced high OC/high disturbance around northern European coastlines of Britain and Ireland. High OC density and high disturbance areas were only consistently predicted (modal class in Figure 29) along the edge of the Norwegian Trench, coasts of eastern

and western Britain, south and west of Ireland and northern and western coasts of France, and parts of the Barents Sea and Baltic Sea. Consistency of assignment to combined disturbance density classes between datasets was not possible to assess effectively for the Mediterranean with only one dataset on fishing intensity (GFW) and two widely differing organic carbon density maps (Atwood *et al.* 2020 and MPA Europe (Lønborg *et al.*, 2025)).

Figure 27: Organic carbon stocks disturbed by bottom fishing

Organic carbon density from MPA Europe and swept volume ratio (a) from ICES estimated, and (b) from Global Fishing Watch data. Values are in kgC/m²/yr.

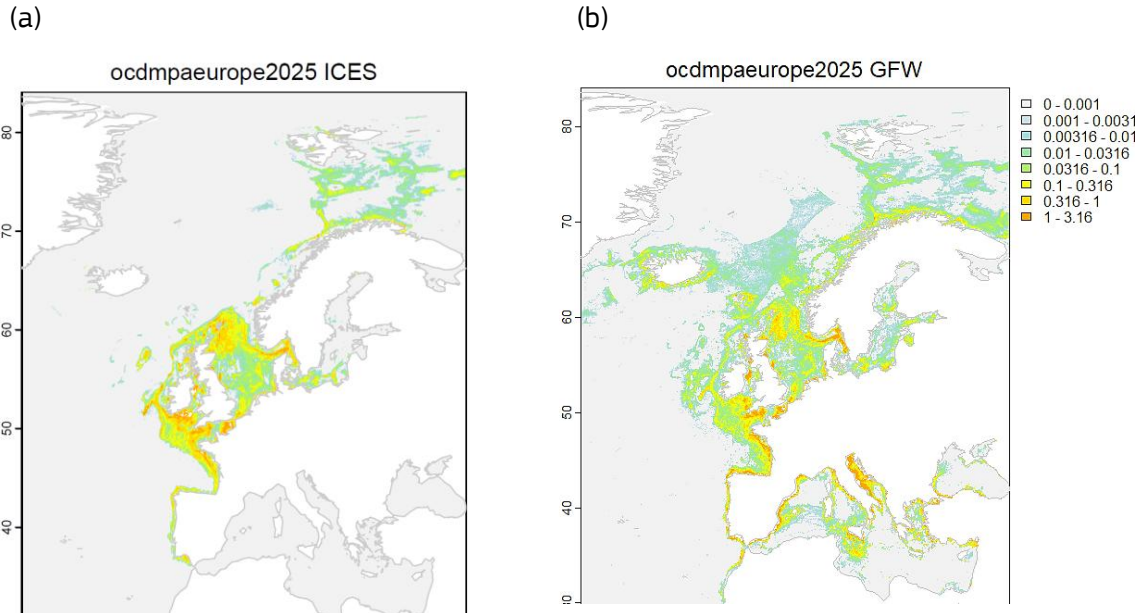


Figure 28: Classification of European seas into areas with combinations of low and high levels of sediment organic carbon densities (MPA Europe) and disturbance by bottom fishing and swept volume

Calculated from (a) ICES and (b) GFW data. Values are 0 (grey): low OC, low disturbance; 1 (yellow): high OC, low disturbance; 2 (blue): low OC, high disturbance; and 3 (red): high OC, high disturbance.

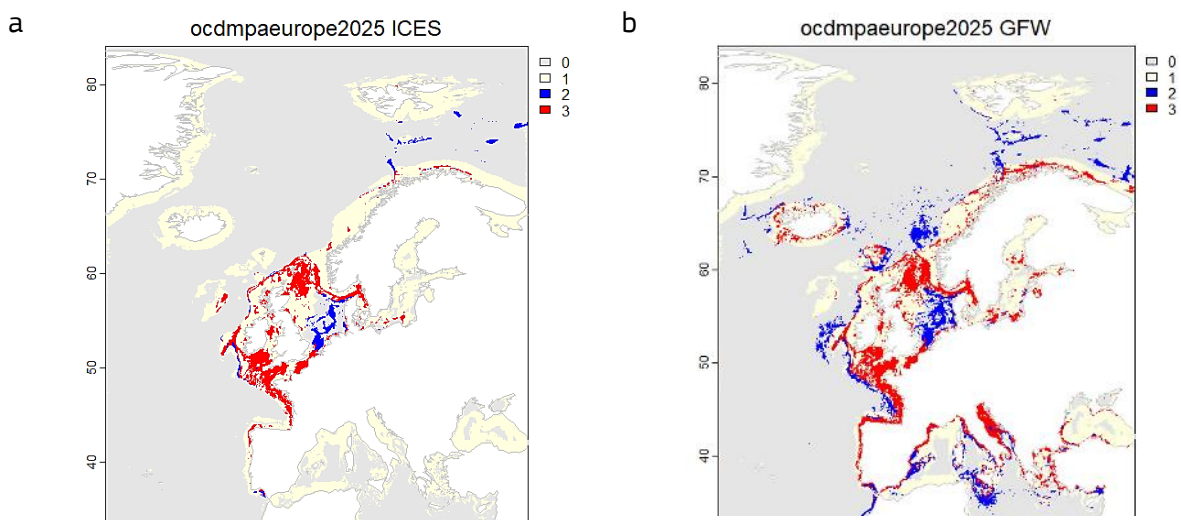


Figure 29: Maximum, minimum and modal vulnerability classes across all 18 combinations of organic carbon and fishing intensity datasets

Classes are 0 (grey): low OC, low disturbance; 1 (yellow): high OC, low disturbance; 2 (blue): low OC, high disturbance; and 3 (red): high OC, high disturbance.

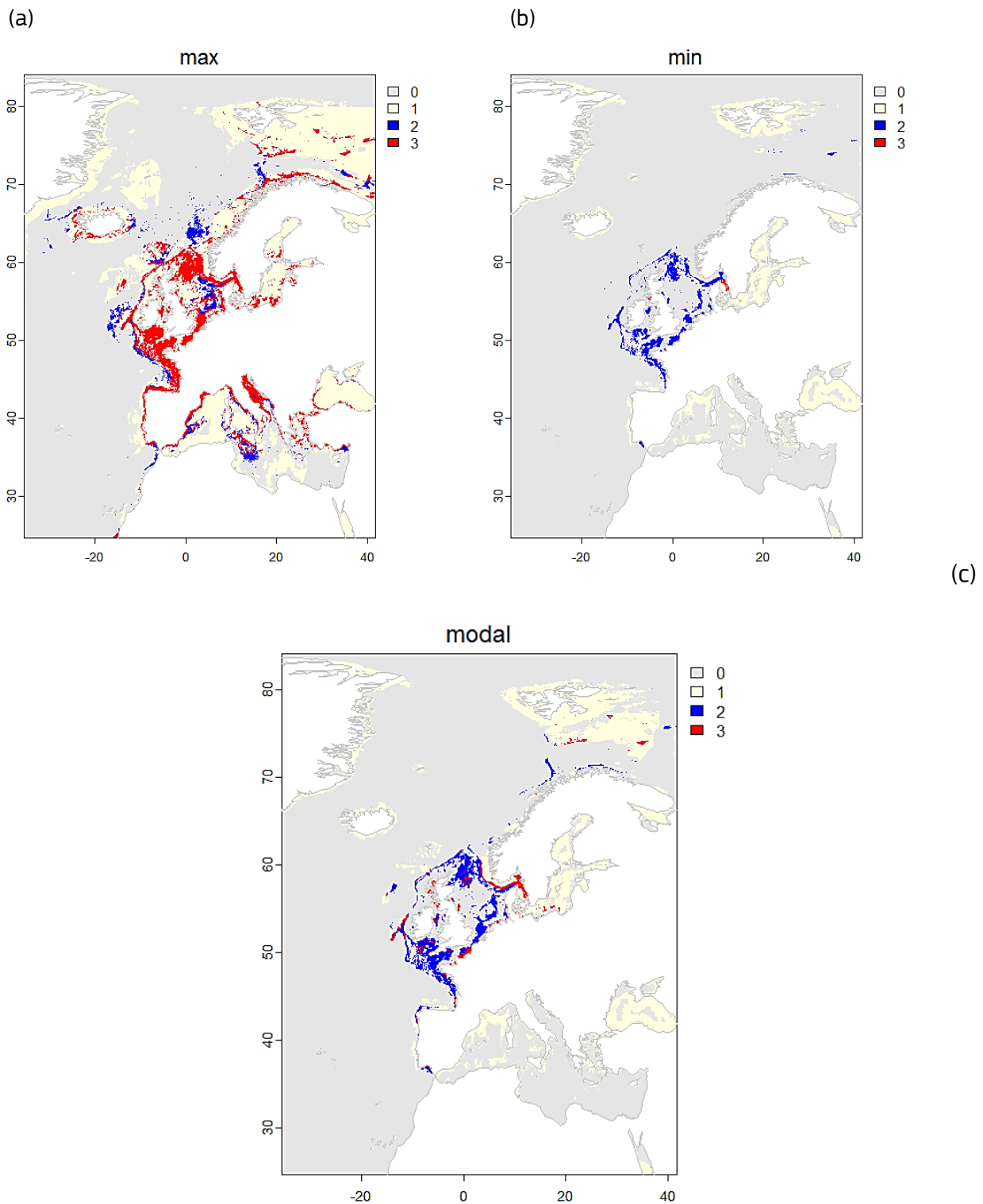


Figure 30a: Organic carbon stocks disturbed by bottom fishing for combinations of organic carbon density models (ocdensitywilson2018 etc.) and swept volume ratio (ICES, OSPAR, GFW)

Values are in $\text{kgC/m}^2/\text{yr}$.

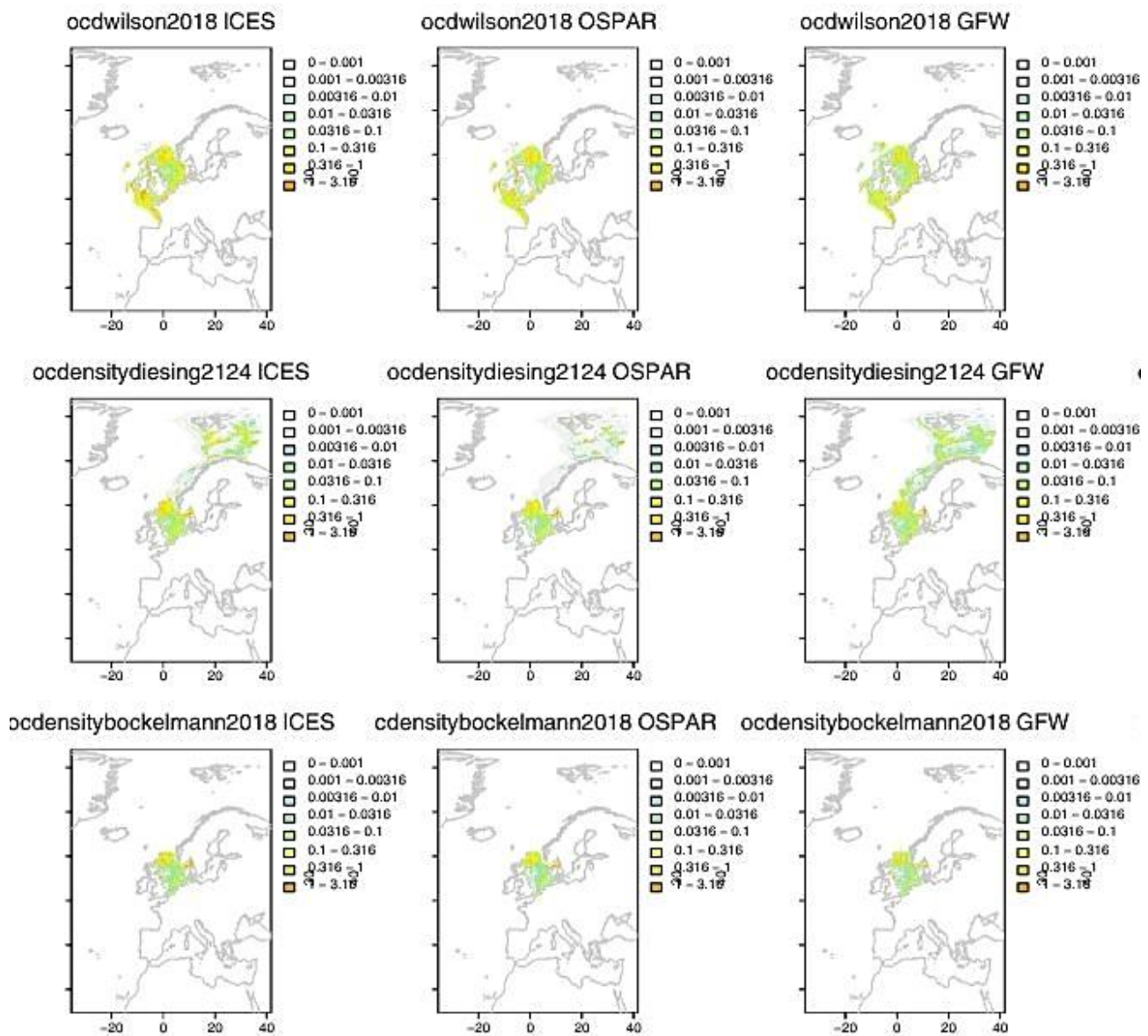


Figure 30b: Organic carbon stocks disturbed by bottom fishing for combinations of organic carbon density models (ocdensitywilson2018 etc.) and swept volume ratio (ICES, OSPAR, GFW)

Values are in $\text{kgC/m}^2/\text{yr}$.

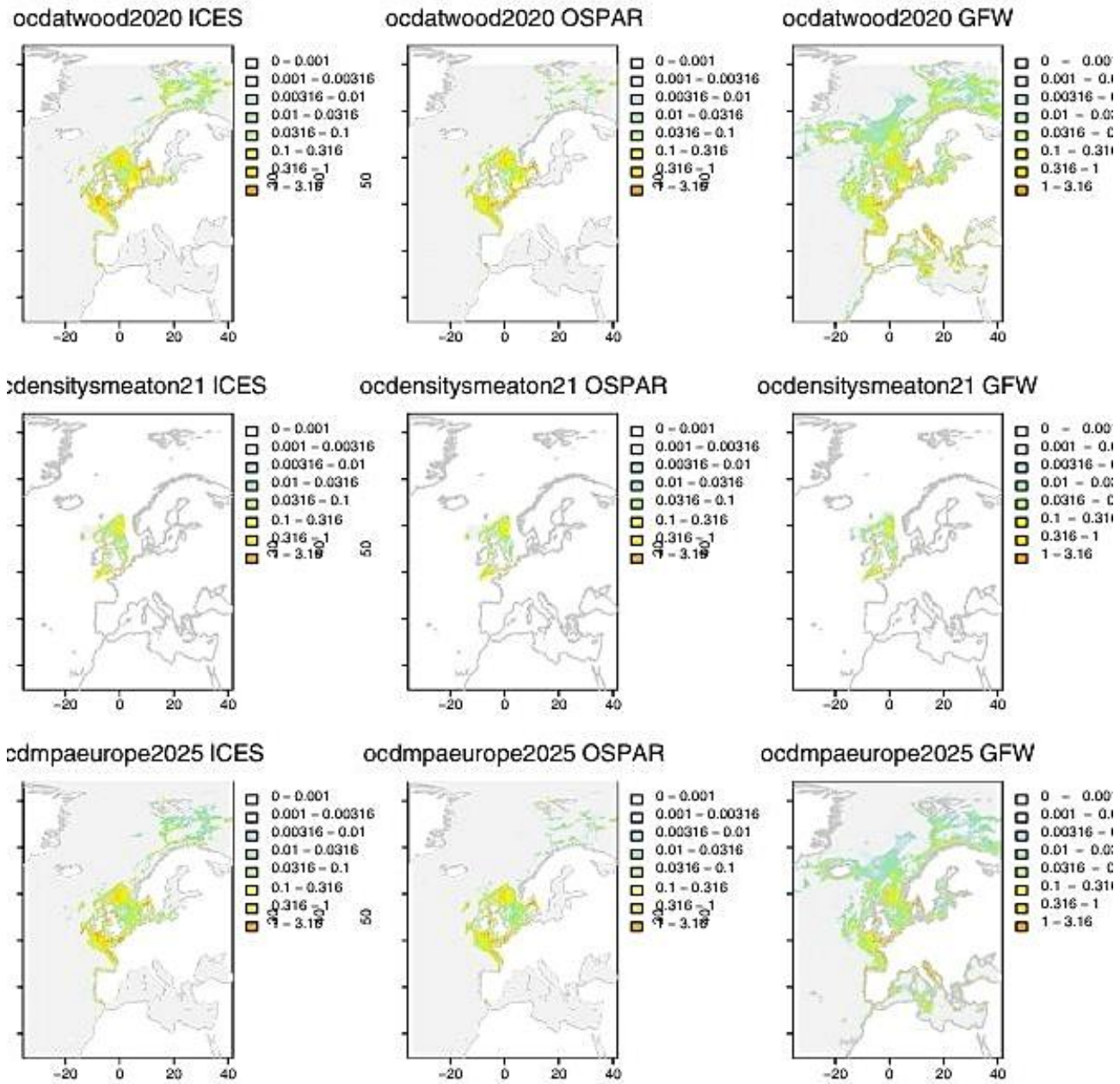


Figure 31a: Classification of European seas into areas with low and high levels of sediment organic carbon densities and disturbance by bottom fishing and swept volume

Calculated from (a) ICES and (b) GFW data. Values are 0 (grey): low OC, low disturbance; 1 (yellow): high OC, low disturbance; 2 (blue): low OC, high disturbance; and 3 (red): high OC, high disturbance. Maps are shown for combinations of organic carbon density models (ocdensitywilson2018 etc) and swept volume ratio datasets (ICES, OSPAR, GFW).

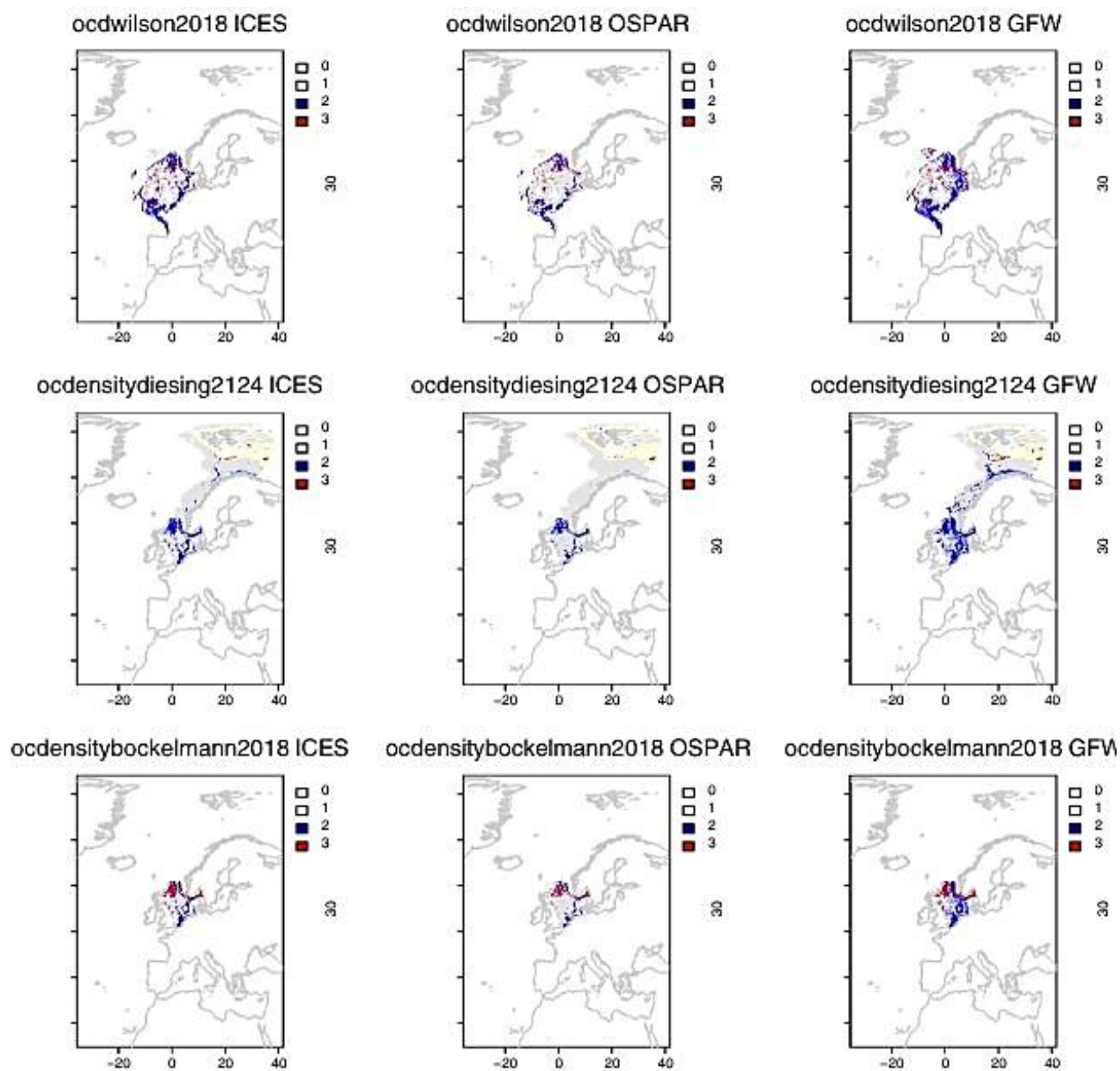
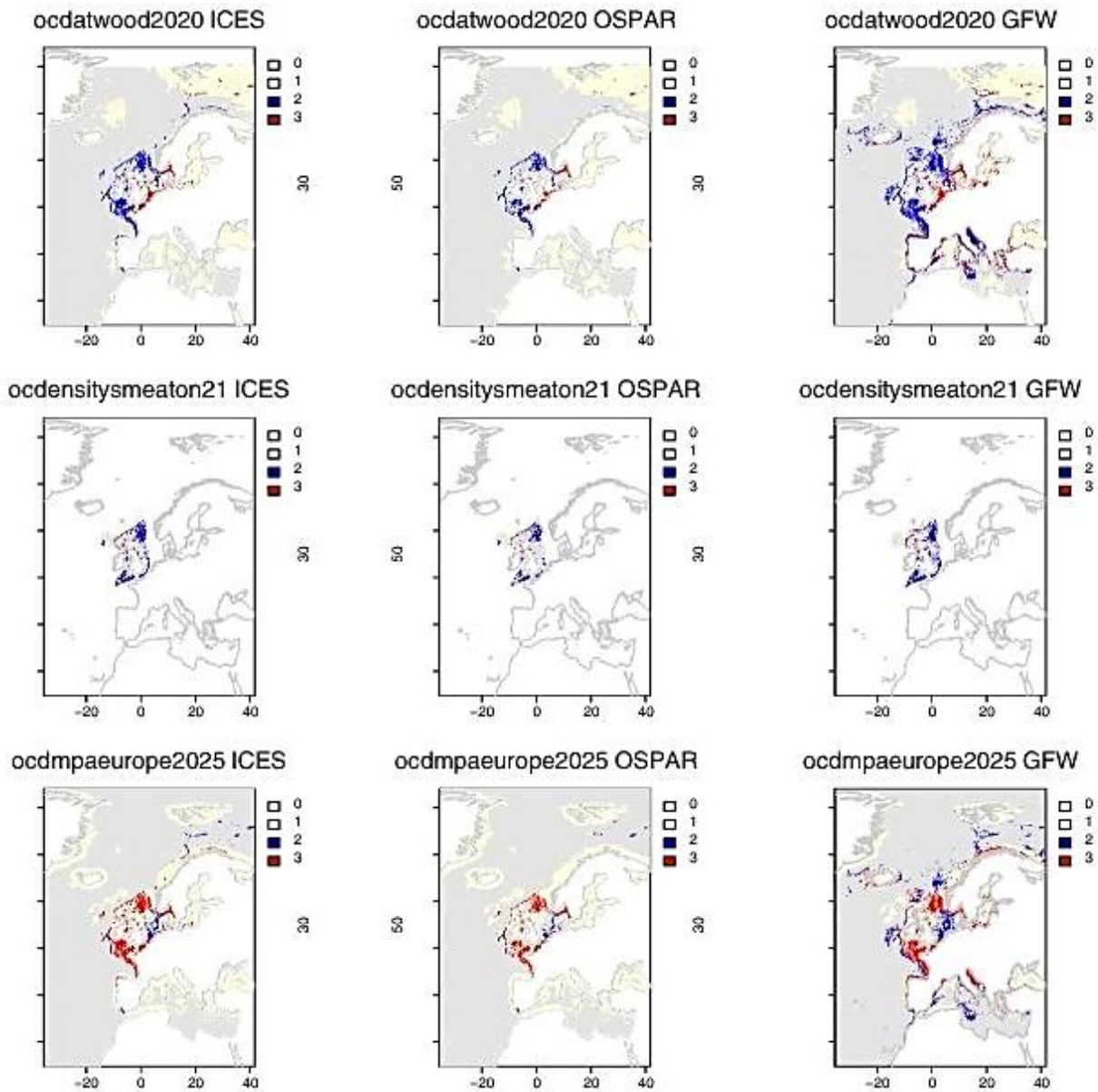


Figure 31b: Classification of European seas into areas with low and high levels of sediment organic carbon densities and disturbance by bottom fishing and swept volume

Calculated from (a) ICES and (b) GFW data. Values are 0 (grey): low OC, low disturbance; 1 (yellow): high OC, low disturbance; 2 (blue): low OC, high disturbance; and 3 (red): high OC, high disturbance. Maps are shown for combinations of organic carbon density models (ocdensitywilson2018 etc) and swept volume ratio datasets (ICES, OSPAR, GFW).



3.1.4 Other seabed-disturbing activities

Several human activities disturb the seabed, potentially impacting the long-term accumulation and storage of organic carbon beyond bottom trawling (Table 13). Data on the spatial extent of these activities were compiled from the EMODnet Human Activities portal and associated datasets. Although the data coverage varies considerably across activities and regions, the compiled estimates indicate that seabed trawling (~1,694,284 km²) has a footprint approximately 1.6 times larger than the next largest disturbance, propeller wash (~1,031,558 km²), and more than 8 times larger than the high-risk shellfish dredging activity (~202,486 km²). A number of key “other activities” which are known to damage the seabed are mapped in Figure 34 using the compiled EMODnet Human Activities datasets. The figure depicts a busy marine space across European Seas, with many of these activities not previously considered for carbon impacts.

It is also recognised that pollution can significantly alter the ecological and biogeochemical processes that support marine and coastal carbon sequestration. Nutrient enrichment, chemical contamination and riverine pollutant inputs can contribute to eutrophication, oxygen depletion, degradation of living blue carbon habitats, altered microbial processes and disruption of benthic sediment-mixing processes that influence organic carbon burial and storage. These effects are complex and context-specific: in some cases, increased organic matter inputs or reduced oxygen may enhance short-term carbon burial, while in others pollution degrades the habitats and sediment processes needed for stable, long-term sequestration. A detailed assessment of these pollution-related effects was beyond the scope of this study, and further work is needed to quantify their implications for blue carbon storage and climate mitigation.

Activities assessed as low-risk or net positive, that is they may result in little or no anthropogenic disturbance of the seabed by excluding activities that disturb sediments, included offshore wind farm infrastructure, cable burial, and aquaculture. These collectively accounted for a substantial area but were considered unlikely to result in net long-term losses of organic carbon and, in some cases, may protect sediments by excluding fishing and increased sedimentation rates. Two activities, coastal infrastructure and seabed mineral mining, could not be adequately estimated from the available datasets. Coastal infrastructure is partially represented by port location data, but this would produce the same estimates as the anchoring and mooring activity, so it has been omitted. Additionally, seabed mining licences are not currently active in European waters and oil and gas and aggregate extraction are already captured as separate activities in Table 13.

Table 13: Estimated spatial footprint (km²) of human activities impacting the seabed in Europe

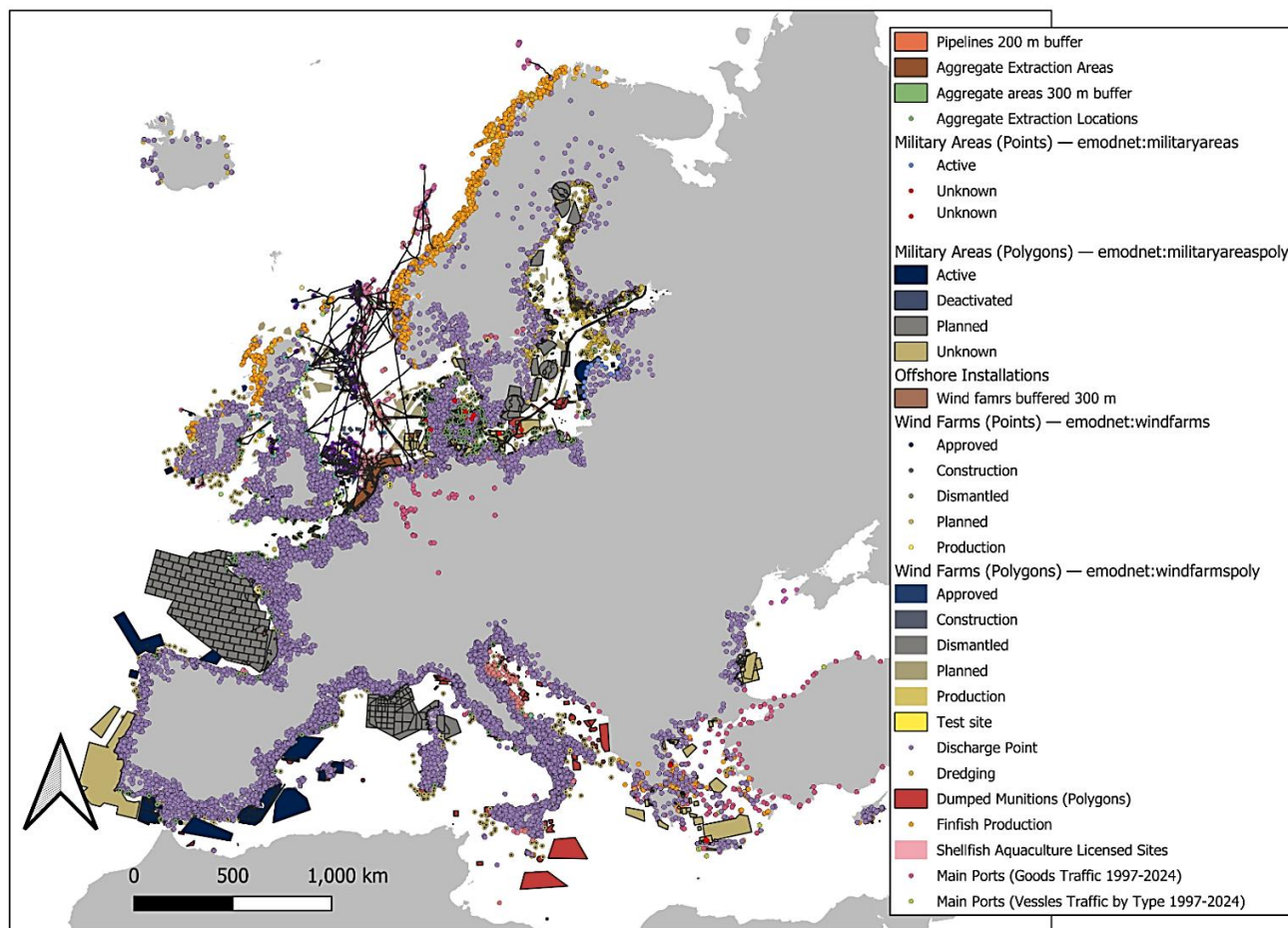
Data compiled from EMODnet Human Activities datasets. The risk categories reflect the likely impact of each activity on long-term organic carbon storage in the seabed.

Activity	Comment	Estimated Area (km ²)	Risk	Countries and regions with data
Seabed trawling for benthic and demersal fish	This activity uses chains and/or beams to disturb the sediment to frighten finfish and crustaceans into the trawl nets. It is repeated at the same location. This exposes the sediments to winnowing by water movements that will release organic matter into the water column.	1,694,284	High	Baltic Sea, Barents Sea, Bay of Biscay and the Iberian Coast, Celtic seas, Faroes, Greater North Sea, Icelandic Waters, Norwegian Sea, Oceanic Northeast Atlantic
Propellor wash	Limited to shallow waters, significant in harbours and marinas.	1,031,558	Low	Albania, Belgium, Bulgaria, Croatia, Cyprus, Germany, Denmark, Estonia, Egypt, Finland, France, Greece, Guernsey, Iceland, Ireland, Ilse of Man, Israel, Italy, Latvia, Lebanon, Libya, Lithuania, Malta, Montenegro, Morocco, the Netherlands, Norway, Poland, Portugal, Romania, Russia, Slovenia, Svalbard & Jan Mayen, Spain, Sweden, Turkey, Ukraine, the United Kingdom
Dredging for scallops, mussels and oysters. By steel dredges or by hydraulic suction	Dredges dig into the seabed to pull up shellfish. This is repeated in the same area. Previously naturally compacted sediments by physical processes and faunal growth are loosened. This exposes the sediments to winnowing by water movements that will release organic matter into the water column.	202,486	High	Baltic Sea, Bay of Biscay and the Iberian Coast, Celtic seas, Greater North Sea, Oceanic Northeast Atlantic
Burial of telecommunications and electricity cables	Minimal and once-off disturbance of seabed. The area may prohibit fishery trawling and protect sediments.	118,037	Low	Denmark, France, the Netherlands, Norway
Dumping of dredged sediment and other materials	Localised but repeated disturbance and may increase sediment accumulation on the seabed.	85,625	Medium	Belgium, Bulgaria, Cyprus, Denmark, Estonia, Finland, France, Germany, Greece, Iceland, Ireland, Italy, Latvia, Lithuania, Malta, the Netherlands, Norway, Poland, Portugal, Russia, Spain, Sweden, the United Kingdom

Activity	Comment	Estimated Area (km ²)	Risk	Countries and regions with data
Dredging of aggregates for construction industry	Generally of coarse, low organic carbon, sediments	25,652	Medium to High	Belgium, Denmark, Estonia, Finland, France, Germany, Ireland, Italy, Lithuania, the Netherlands, Poland, Portugal, Russia, Spain, Sweden, the United Kingdom
Burial of gas and oil pipelines	Minimal and once-off disturbance of seabed. The area may prohibit fishery trawling and protect sediments.	13,296	Low or net positive	Croatia, Denmark, Estonia, Finland, Germany, the Netherlands, Norway, Poland, Russia, Spain (Andalucía), Sweden, the United Kingdom
Construction of wind turbine platforms	Significant but very localised one-time disturbance. The footprint of a wind turbine is typically less than 100 m ²	12,228	Low or net positive	Belgium, Denmark, Estonia, Finland, France, Germany, Ireland, Latvia, Lithuania, the Netherlands, Poland, Spain, Sweden, the United Kingdom
Wind farm infrastructure	The pylons will affect ocean currents in the area, and erosion and deposition of sediments.	6,858	Low or net positive	Belgium, Denmark, Finland, France, Germany, Ireland, Italy, the Netherlands, Portugal, Spain, Sweden, the United Kingdom
Dredging of harbours for navigation purposes	Navigation channels tend to be regularly disturbed by shipping and natural river and ocean currents, and thus, not stable stores of organic carbon.	1037	Medium	Belgium, Bulgaria, Cyprus, Denmark, Estonia, Finland, France, Germany, Greece, Iceland, Ireland, Italy, Latvia, Lithuania, Malta, the Netherlands, Norway, Poland, Portugal, Spain, Sweden, the United Kingdom
Aquaculture	Localised and results in net inputs of organic matter.	238	Low	Cyprus, Denmark, Estonia, the Faroe Islands, Finland, France, Greece, Greenland, Iceland, Ireland, the Netherlands, Norway, Portugal, Spain, Sweden, the United Kingdom
Oil and gas extraction	The drilling site significantly disturbs the sediment with a release of drilling muds on a regular basis. But the physical footprint is in the order of 100s m.	143	Low or net positive	Croatia, Cyprus, Denmark, Germany, Greece (western coast), Ireland, Italy, the Netherlands, Norway, Poland, Spain, the United Kingdom
Anchoring and mooring buoys	Very localised but may be significant at local scales near marinas.	119	Low or net positive	Albania, Belgium, Bulgaria, Croatia, Cyprus, Germany, Denmark, Estonia, Egypt, Finland, France, Greece, Guernsey, Iceland, Ireland, Ilse of Man, Israel, Italy, Latvia, Lebanon, Libya, Lithuania, Malta, Montenegro, Morocco, the Netherlands, Norway,

Activity	Comment	Estimated Area (km ²)	Risk	Countries and regions with data
				Poland, Portugal, Romania, Russia, Slovenia, Svalbard & Jan Mayen, Spain, Sweden, Turkey, Ukraine, the United Kingdom
Coastal infrastructure, marinas, harbours, seawalls	Although its effect on seashore and adjacent habitats is permanent, its impact is local.	No data	Low to Medium	
Seabed mining	The removal of surficial and buried sediments over large areas for extraction of minerals will release particulates into the water and increase carbon dioxide and methane in the water. Most of the particulates will probably be resettled to the seabed as with dredging and seabed trawling.	No data	High	

Figure 32: EMODnet human activities dataset mapped across European Sea



3.2 Scenarios: Effects of exclusion of fishing in designated areas

Given the overwhelming effect of bottom trawling and other mobile fishing gears on seabed disturbance relative to other activities (Table 13), scenarios were developed that excluded fishing activities (SVR = 0) from areas designated as MPAs, where offshore windfarms are planned or in operation (OWFs), from carbon sensitivity zones (CSZs), and that limited sediment disturbance to core fishing grounds (CFGs).

3.2.1 Uncertainty and limitations in scenarios

In this analysis, the primary focus was on uncertainty arising from variation among estimates of organic carbon density and differences between available datasets on fishing activity (e.g., Table 9). Additional uncertainty is introduced through the use of single representative values for gear penetration depth, which may not capture the full variability across fishing gears, sediment conditions, and fishing practices. Further, there is considerable effects of organic carbon resuspension and dispersal from past seabed disturbances (natural and anthropogenic) and sedimentation rate variation (e.g., Zhang *et al.* 2024).

Geographically, most existing studies have focussed on the heavily fished and relatively carbon-rich sediments of the North Sea, where overlapping statistical and process-based models allow medium to high confidence in estimates of carbon stock distribution and disturbance. In contrast, confidence is lower in regions such as the Mediterranean (Atwood *et al.* 2020 and MPA Europe: Lønborg *et al.* (2025)), where only a limited number of models are available and these are largely parameterised using data from other regions (Atwood *et al.* 2020: global data; Lønborg *et al.* 2025, biased towards near coastal areas).

A further and important source of uncertainty relates to the response of fishing effort to spatial exclusions, noting the variability and incompleteness of fishery data for the study area (section 3.1.2). In the present analysis, exclusion scenarios were implemented by removing fishing activity from designated areas without redistribution to other locations. This represents a simplified “no-displacement” assumption and should be interpreted as one endpoint of a range of plausible responses.

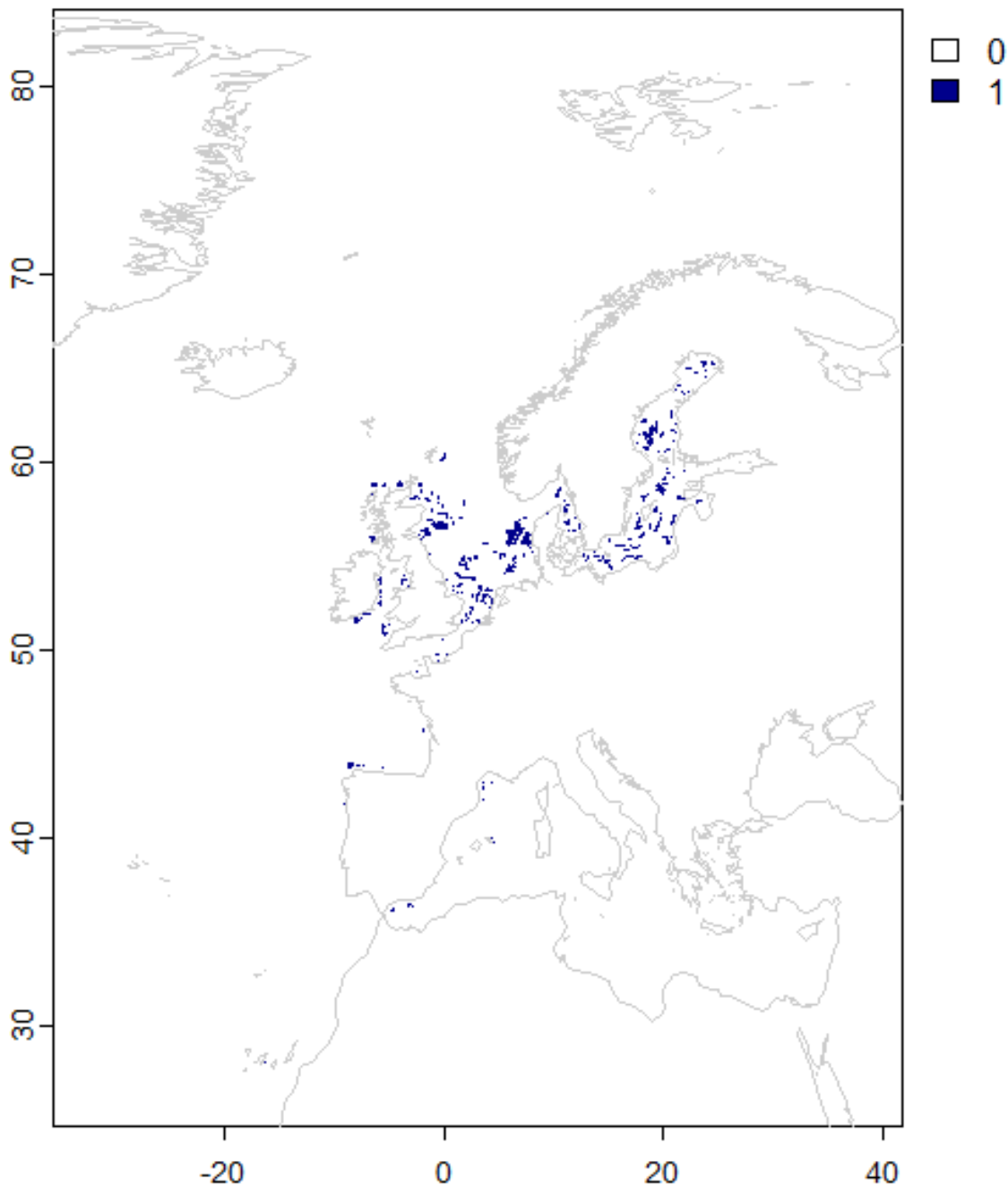
The extent to which fishing effort is displaced following spatial closures remains debated. There is a common but unsubstantiated belief that stopping bottom trawling or dredging in one place moves that effort and has increased negative impacts elsewhere (Costello 2024). There is no evidence this is true. The only study to examine it found the opposite using Global Fishing Watch data they found decreased fishing around no-fishing Marine Protected Areas (McDonald *et al.* 2024). Similarly, there are over 46 examples of spillover benefits to fisheries from MPA (91% from strictly protected) in 25 countries around the world and no examples of any fishery anywhere losing catch due to MPA (Costello 2024). Thus, to provide a seemingly quantitative analysis of fishery displacement could give the false impression that displacement may occur and that the data were adequate to measure it.

3.2.2 Offshore Windfarms (OWFs)

Areas designated for offshore wind farm development were obtained directly from EMODnet as shapefiles. These data are updated annually but include areas that are planned and under construction as well as those currently in operation (Figure 33).

Figure 33: Areas identified for fishery exclusions in European seas associated with operational and planned OWFs

Source EMODnet



3.2.3 Carbon sensitivity zones (CSZs)

Protecting areas for their carbon stocks by excluding fishing from Carbon Sensitivity Zones (CSZs) was explored by Porz *et al.* (2024a). These authors identified such areas as those where the potential remineralization rate of disturbed material was greatest ("We delimit CSZs as areas where the modelled potential OC remineralization rate exceeds $20 \text{ mmol m}^{-2} \text{ d}^{-1}$, corresponding to the top 20th percentile of values in the North Sea"). Such an approach is not possible without running a similar dynamic model to that of Porz *et al.*, so here CSZs were identified as areas of high organic carbon density. Density thresholds for

CSZ designations were derived from 75th percentile of values in the North Sea (Figure 18, Table 14). Using model-specific thresholds allowed for shifts in values for organic carbon density among models. Median values (50th percentile) for organic carbon density in the North Sea varied widely from 0.21 to 0.97 kgOC/m². Threshold 75th percentile values varied from 0.36 to 1.17 kgOC/m².

Table 14: Quantiles for percentiles of modelled values of organic carbon density in the North Sea

Values are given in kg/m². 75th percentile values were used to produce the potential Carbon Protection Zones in Figure 34.

Source \ Percentile	Min	10%	25%	50%	75%	90%	100%	ocmodel
Wilson <i>et al.</i> , 2018	0.06	0.30	0.39	0.52	0.72	1.03	3.06	ocdwilson2018
Atwood <i>et al.</i> , 2020	0.32	0.58	0.63	0.79	1.17	1.78	4.63	ocdatwood2020
Diesing <i>et al.</i> , 2021, 2024	0.12	0.18	0.24	0.39	0.57	0.80	1.43	ocdensitydiesing2124
Smeaton <i>et al.</i> , 2021	0.00	0.29	0.30	0.33	0.36	0.39	1.45	ocdensitysmeaton21
Bockelmann <i>et al.</i> , 2018	0.02	0.07	0.11	0.21	0.43	1.17	3.34	ocdensitybockelmann2018
Lønborg <i>et al.</i> , 2025	0.12	0.19	0.26	0.48	0.84	0.95	4.46	ocdmpaeurope2025

Areas identified as potential CSZs followed the patterns of organic carbon density seen in Figure 18, and as such were quite different for the six different modelled datasets shown in Figure 34. Five of the models showed the Norwegian Trench as a CSZ. The area of the northern North Sea east of Orkney and Shetland was selected by Wilson *et al.* (2018), Bockelmann *et al.* (2018) and Diesing *et al.* (2021 and 2024 combined), while areas west of Britain and Ireland were chosen for the models of Wilson, Smeaton and Lønborg. Coastal areas of the Mediterranean were identified as CSZs by both models that extended to the regions (Atwood and Lønborg).

3.2.4 Core fishing grounds (CFGs)

Restriction of fishing activities to core fishing grounds followed the suggested approach by Porz *et al.* (2024) such that areas were selected where swept area ratios (SAR) were greater than the 90th percentile value (SAR > P90 SAR). This method used SAR data for the North Sea only. Unlike the other three scenarios, MPAs, OWFs, CSZs) where fishing was excluded, Core Fishing Grounds (CFGs) were identified for fishery inclusion with fishing excluded outside of these areas (Figure 34). Organic carbon disturbance from fishing was therefore set to zero outside the CFGs for calculation of the effect of this scenario.

3.2.5 Summary of areas excluded

Areas considered in scenarios for fishery exclusion and inclusion are given in Table 15 (for quantiles of SAR) and Table 16 (sizes of modelled organic carbon domains overlaid by areas of conservation interest), and mapped in Figure 35.

Table 15 - Quantiles for Swept Area Ratio values for the North Sea, where SAR = 1 implies all the area is swept once a year

SAR type	Min	10%	25%	50%	75%	90%	100%	sarmean
GFW predicted SAR	0	0.0000	0.0000	0.0412	0.7868	2.5281	51.3394	0.908991
ICES SAR	0	0.0823	0.3225	0.9856	2.3420	4.4752	65.2861	1.912365
OSPAR SAR	0	0.0257	0.1723	0.8005	2.1892	4.4187	220.2808	1.748439
Zhang <i>et al.</i> 2024	0	0.0000	0.0000	0.0112	0.4600	1.9085	26.0570	0.662388

Figure 34: Carbon Sensitivity Zones (CSZs) considered for exclusion of fishing disturbance

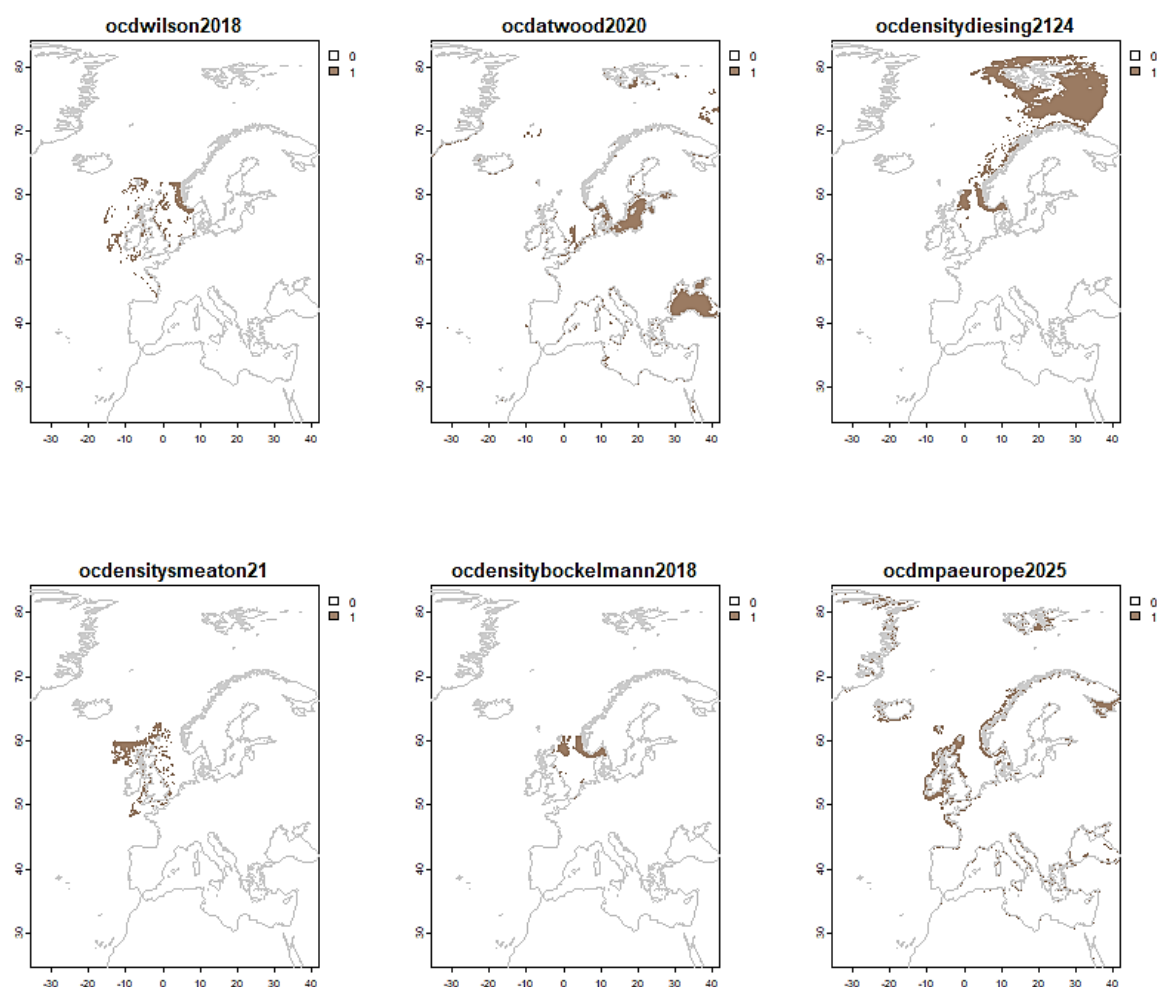


Table 16: Sizes of modelled organic carbon domains overlaid by areas of conservation interest protected and non-protected areas

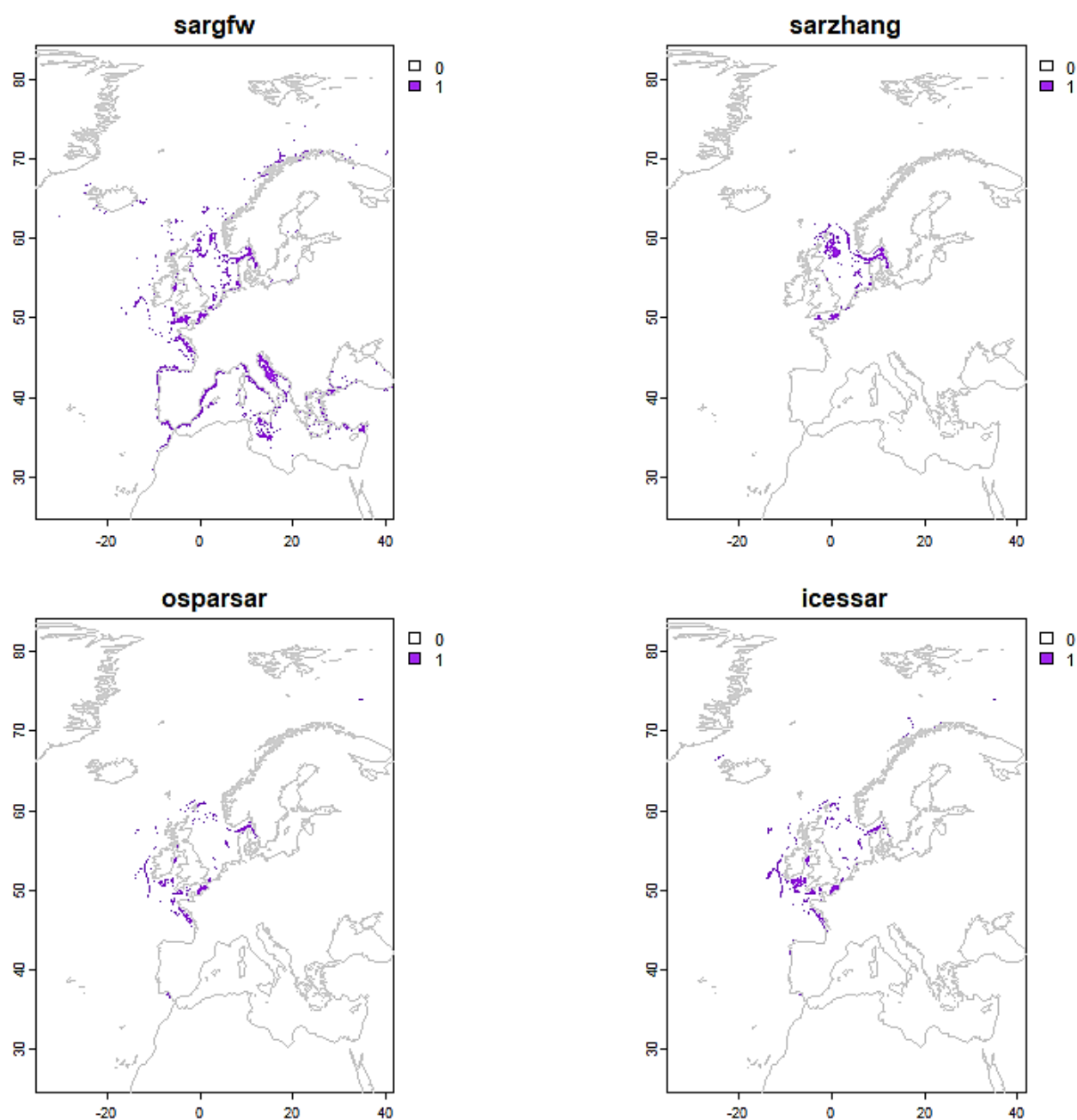
From EMODnet Human Activities, core fishery areas (CFG) (note these are not complete for all of Europe), and high carbon areas (CPZ) across the European seabed in millions km². Total area modelled is 31.7 M km².

Scenario	Not modelled	Not excluded	Excluded area	% excluded*	% coverage
Areas of conservation interest	0.00	30.43	1.28	4.0%	100%
OWFs	0.00	31.61	0.10	0.3%	100%
CFGs: GFW*	13.71	17.31	0.70	3.9%	98%
CFGs: OSPAR*	14.05	17.54	0.13	0.7%	97%
CFGs: ICES*	14.05	17.49	0.18	1.0%	97%
CPZs: ocdwilson2018	30.41	0.99	0.32	24.3%	7%
CPZs: ocdatwood2020	14.17	16.28	1.27	7.2%	96%
CPZs: ocdensitydiesing2124	30.16	0.82	0.74	47.4%	9%
CPZs: ocdensitysmeaton21	30.92	0.51	0.30	36.9%	4%
CPZs: ocdensitybockelmann2018	31.17	0.42	0.13	23.7%	3%
CPZs: ocdmpaeurope2025	13.44	17.17	1.11	6.1%	100%

Note: * Areas of CFGs are areas for confinement of fishing activity, i.e. inclusion rather than exclusion.

Figure 35: Core fishing grounds (CFGs) considered for restriction of fishing activity to protect stored organic carbon.

Selection of areas was based on swept area ratios greater than the 90th percentile values for the North Sea for each data source (Table 15).



3.3 Scenario outcomes

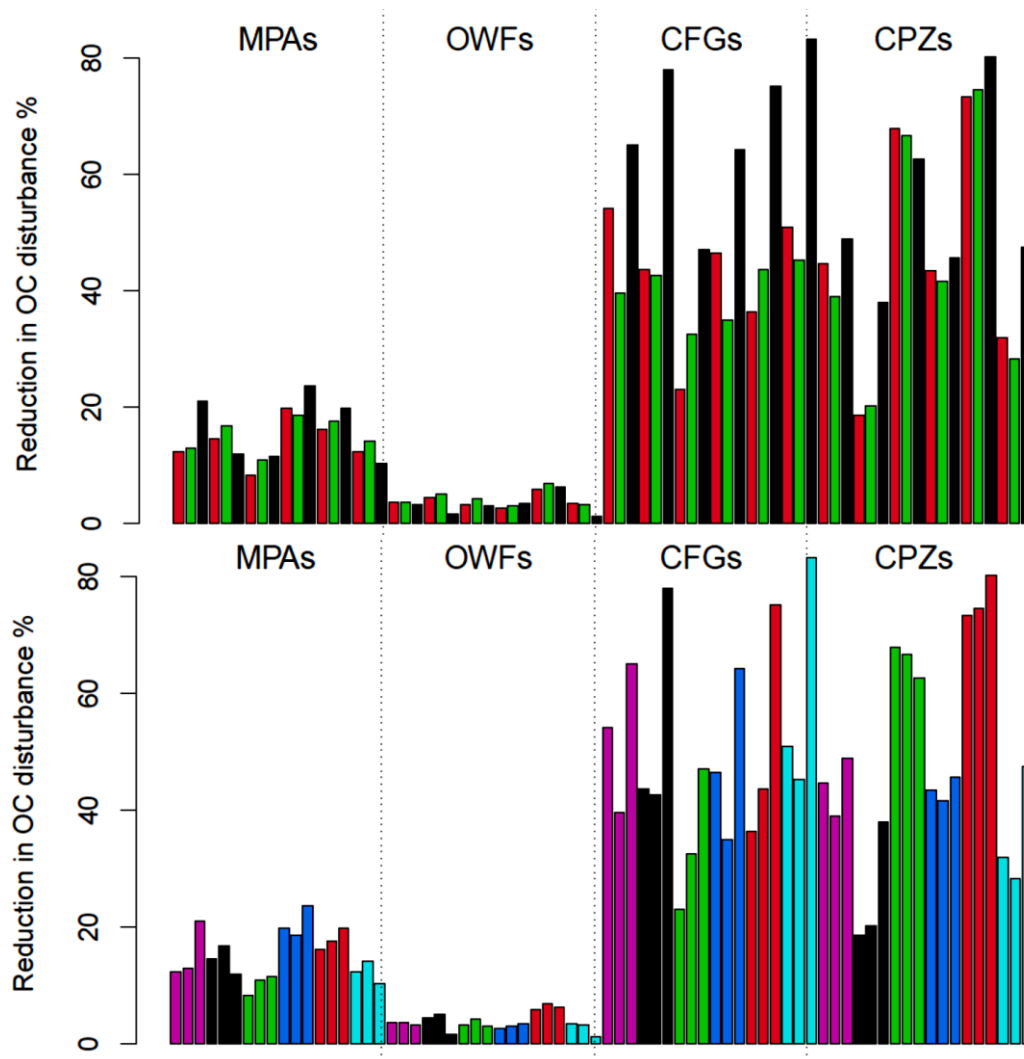
The effects of the four fishery exclusion scenarios (exclusion from MPAs, OWFs and restriction of fishing to CFGs) were evaluated by applying the exclusions to all the 18 mapped estimates of organic carbon disturbed by fishing as combinations (3 x 6) of three fishing activity layers and six organic carbon density maps (Figure 36). In each case, the rate of disturbance in exclusion areas was set to zero kgC/m²/yr. Scenario outcomes were described by summed mass of disturbed organic carbon across all grid cells in each resulting map modified disturbance map. Mass of sediment organic carbon per grid cell masses was calculated by multiplying grid cell values for OC density in the top 0.1m of sediment (kg C/ m²) with grid cell sizes (m², using the R *terra* cell Size function).

Comparison of changes in absolute values of seabed organic carbon disturbed is confounded by the varying spatial extent of each dataset, so effects were expressed as the percentage change in the total carbon disturbed after excluding fishing disturbance from the exclusion area or restricting disturbance to the specified area in the case of restriction to CFGs.

$$\text{Proportional reduction} = \frac{C_{\text{disturbed before exclusion}} - C_{\text{disturbed after exclusion}}}{C_{\text{disturbed before exclusion}}}$$

Figure 36: (top) Reduction in disturbance to organic carbon by exclusion of fishing from MPAs, areas of offshore wind farms (OWFs), core fishing grounds (CFGs) and carbon protection zones (CPZs)

Values are given in Table 14.

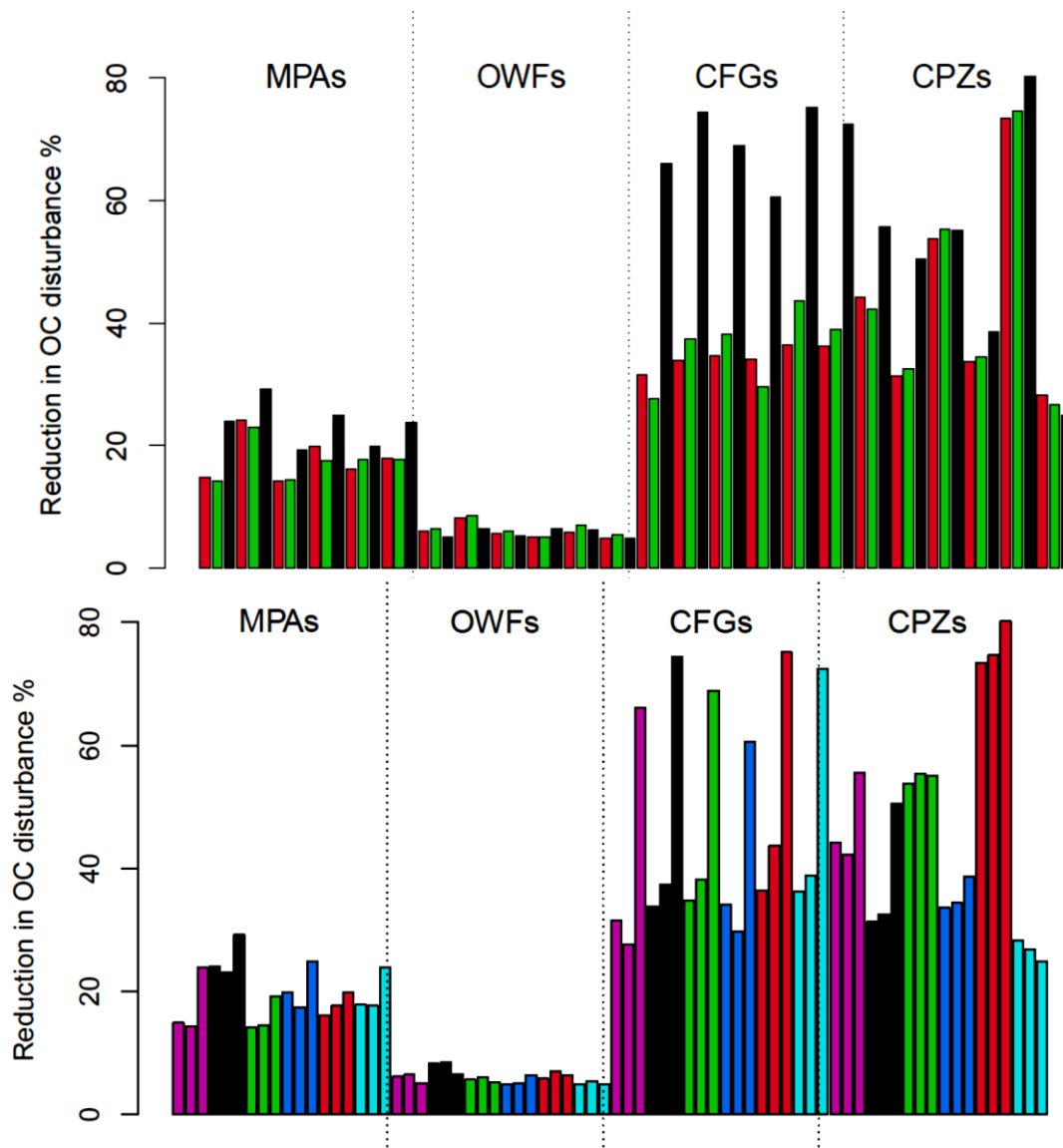


North Sea

Much of the complexity in scenario outcomes described above stems from the very different extents of each dataset on OC and fishing activity. To compare scenarios more effectively, maps of disturbed carbon were cropped to the North Sea only using the extent of the model by Zhang *et al.* (Zhang *et al.*, 2024b). Projected outcomes of fishery exclusions were much more consistent across the combinations of OC density and fishing activity datasets (Figure 37). The relative size of effects of exclusions from MPAs, OWFs, CSZs and CFGs in the North Sea followed the Europe wide outcomes. Exclusion from MPAs resulted in 15-30% reduction in disturbance, while that from OWFs gave a 5 – 9% reduction. Restricting fishing to CFGs reduced disturbance by 28 – 44% using OSPAR and ICES data. Using GFW data to define CFGs gave much larger reductions of 62 – 75% (Table 16). Effects of exclusion of fishing from CSZs on carbon disturbance were as variable as they had been with Europe-wide data, with most of the variation among the different sources of OC data.

Figure 37: As 36 but restricted to North Sea only.

Values are given in Table 16



3.4 Fate of disturbed Carbon

In a rapidly evolving field, the simple (simplistic) assumptions of the above approach may not sufficiently capture the effects of sediment disturbance by fishing on remineralization of sediment organic carbon into CO₂. Under current conditions it is well understood that the upper part of the ocean serves as a significant sink for CO₂, a minor source of CH₄ and CO, and a major source for N₂O (Bange *et al.*, 2024). The processes leading from carbon disturbed and resuspended into the water column to ultimate exchange of CO₂ with the atmosphere are reviewed here.

3.4.1 Degradation

Aerobic microbial degradation (oxidation) of organic matter is the main process which produces CO₂ from suspended material in the ocean. This includes the degradation of methane (Wallenius *et al.*, 2021) and other organic compounds.

3.4.2 Resuspension, transport and redeposition.

Seabed disturbance by bottom-contacting fishing gears leads to the resuspension of surface sediments and associated organic carbon into the water column. This process represents an immediate pathway for the mobilization of previously buried carbon, increasing its exposure to oxygen and enhancing remineralisation to CO₂. However, the fate of resuspended carbon is complex and not limited to direct loss to the atmosphere.

Recent modelling work demonstrates that resuspended organic carbon is subject to hydrodynamic transport and can be redistributed over spatial scales ranging from local to regional. Using a coupled hydrodynamic–sediment–biogeochemical model, Porz *et al.* (2024) showed that resuspended material may undergo multiple cycles of suspension and redeposition before final burial. As a result, disturbance does not uniformly lead to a net loss of sedimentary carbon at all locations.

The impacts of this process are spatially heterogeneous. While trawling leads to a depletion of organic carbon in frequently disturbed, carbon-rich sediments, transported material may be redeposited in adjacent or downstream areas, including deeper or less disturbed environments, where it can contribute to carbon accumulation. This redistribution mechanism can partially offset local carbon losses, although it does not necessarily compensate for increased remineralisation during transport and resuspension phases.

The balance between carbon loss and redistribution depends on several factors, including sediment type, hydrodynamic conditions, and the frequency and intensity of disturbance. Fine-grained, organic-rich sediments are particularly susceptible to resuspension and transport, while areas of deposition (e.g., topographic depressions or low-energy environments) may act as sinks for redeposited material. At the same time, repeated disturbance can reduce the residence time of carbon in sediments, limiting long-term sequestration potential.

Overall, resuspension, transport and redeposition processes introduce significant complexity into the assessment of seabed carbon dynamics. They highlight that the effects of seabed disturbance are not purely local and that both carbon losses and gains may occur across connected sedimentary systems. Consequently, spatial management measures should consider not only areas of high carbon stock but also pathways of sediment transport and zones of deposition when assessing the net impact of seabed-disturbing activities.

3.4.3 Atmospheric exchange of CO₂

The ocean naturally absorbs CO₂ due to physical gas exchange, and this is enhanced by photosynthesis that reduces CO₂ in the water (Lauderdale *et al.* 2016, Lefevre *et al.* 2023, Frazão *et al.* 2025). It is a major sink for anthropogenic CO₂ emissions, capturing about 26% annually (Bange *et al.* 2024, Berzaghi *et al.* 2025), and absorbing the “excess” of atmospheric CO₂ (the quota exceeding the equilibrium). However, some areas, including estuaries (Bange *et al.* 2024), naturally release CO₂, such as where relatively CO₂ rich deep water upwells to the surface. The relative absorption and release of carbon from and to the atmosphere can vary seasonally and in response to sea temperature, as reported off northwest Africa, Baltic Sea, California and Southern Ocean where the sea alternates from being a sink to source of CO₂ seasonally (Lefevre *et al.* 2023, Honkanen *et al.* 2024, Frazão *et al.* 2025, Kerr *et al.* 2025); warmer water leads to outgassing and cooling water to in-gassing (Bange *et al.* 2024).

Wind agitation increases gas exchange with seawater, such that storms may have significant effects and reduced salinity increases gas absorption (Lauderdale *et al.* 2016, Nicholson *et al.* 2022, Bange *et al.* 2024). Considering the magnitude of these primary drivers of CO₂ gas exchange between the atmosphere and the ocean makes it difficult to quantify the effects of subsurface variation in organic carbon deposition and mineralisation due to natural and anthropogenic factors. For example, variation in oxygen and iron sulphide (pyrite) concentrations significantly influences organic carbon mineralisation rates and CO₂ emissions (Kalapurakkal *et al.* 2025). Models based on experiments in the Baltic Sea found that in the absence of seabed trawling the seawater acts as a sink for CO₂, and trawling releases large amounts of CO₂ to the water and atmosphere to the extent that trawling changes an area from being a sink to a source of CO₂ (Kalapurakkal *et al.* 2025).

The potential of the ocean to act as a sink for CO₂ is predicted to decrease under climate change due to warming, increased CO₂ in seawater, decreased buffering capacity and oceanographic conditions (Bange *et al.* 2024, Couespel and Tjiputra 2024); making the need to minimise additional releases from the seabed more important. In addition to the release of carbon from sediments, the depletion of benthic macrofauna may also reduce carbon sequestration in sediments (Mariani *et al.* 2025a). Thus, all studies support the proposition that the protection of muddy seabed from disturbance, such as trawling and dredging, will mitigate against the release of CO₂ from the seabed into the atmosphere.

Whether “blue carbon ecosystems” in Europe, such as macroalgae and seagrass, significantly draw down CO₂ is a separate and debatable issue in part because they occupy limited sea area and in Europe, only Mediterranean *Posidonia* sediments have higher than background organic carbon stores (e.g., Hurd *et al.* 2023, Boyd *et al.* 2024, Lønborg *et al.* 2025). High carbon storage per unit area does not necessarily imply a capacity to offset anthropogenic emissions, there is a need for future research to address blue carbon addition to long-term C stores. (e.g., Hurd *et al.* 2023, Boyd *et al.* 2024, Lønborg *et al.* 2025).

3.5 Discussion of outcomes

A surprising outcome from the comparison of the different estimated maps of the distribution of organic carbon in surface layers of seabed sediments across Europe (Figure 3) was the lack of agreement among the different studies. While all agreed on the range of likely sediment organic carbon density values across European seabeds (0 – 5 kg OC/m²), spatial patterns varied widely where sufficient data exists to allow direct comparisons. One model (Atwood *et al.*, 2020) predicted high OC densities in the southern North Sea, while all the others predicted a particularly low OC density in the same area. Two models predicted high OC densities in the Barents Sea (Diesing, 2021, 2024) while another (Lønborg *et al.*, 2025)(Smeaton *et al.*,

2021) showed little agreement with the output of all other models. Yet all these data products were built on solid data and robust scientific reasoning. While the underlying reasons for this lack of agreement may be varied and cases can be made for some maps being more valid and accurate than others, it is clear that this lack of agreement is a major barrier to spatial management planning for conservation of existing seabed carbon stocks. It also cautions against attempting to quantify the effects of different human activities which may increase or decrease carbon accumulation (Table 13). The approach adopted here has been to include all of this variation among models as an indicator of uncertainty in knowledge, and mismatched in scale and study aims which prevent clear collation of findings.

Rates of sediment organic carbon accumulation have been estimated in map form for limited areas (Norwegian Trough and EEZ (Diesing, 2024; Diesing *et al.*, 2024) but not sufficiently widely to allow a Europe-wide analysis of the impacts of human activities on accumulation rates. Such a Europe-wide map would be a desirable next step and would certainly permit the original goal of this project to be achieved in a quantitative way.

Knowledge of the spatial distribution of seabed disturbing activities, particularly fishing, is better developed than for organic carbon stocks and sequestration rates but only GFW has complete spatial coverage of the region.

Scenarios of the effects of management actions have been built here largely around the control of bottom fishing; the human activity that has most impact on seabed carbon stores (Table 13). Consideration of the reduction in potential disturbance of existing organic carbon stocks that may be achieved by removing that disturbance from management areas does not address anthropogenic effects on sequestration rate directly but does offer a way of comparing the potential outcomes of such management activity. The scenarios presented here are knowingly simplistic, but more nuanced versions can be developed that more realistically take account of, for example, changes in fishing effort by gear and/or target species, and changes in fishers' behaviour in response to regulatory and market forces. Restricting fishing to core fishing grounds may be better achieved by defining such grounds using total effort, rather than a single SAR threshold, and selecting all areas that contribute 90% or 75% of all effort or better landings (Alibert-Deprez *et al.*, 2024).

Data on fishing activity that disturbs seabed sediments was not immediately available for areas beyond the European Atlantic area, and importantly not for the Mediterranean where much bottom trawling occurs (Eigaard *et al.*, 2017). The indirect estimation of disturbance as Swept Area Ratio from Global Fishing Watch (GFW) vessel activity introduced many potential issues, especially in the poor distinction of benthic and pelagic trawls in suggesting seabed disturbance beyond the usual depth limit of fishing. More recent compiled datasets and analyses (Hiddink *et al.*, 2026; van Denderen *et al.*, 2025) do include these missing areas, and have been made using more robust methods than the approximations offered here.

A repeat of the fishery management scenarios outlined here using these new datasets on fishery disturbance would be a worthwhile exercise. However, patterns of seabed disturbance for the Mediterranean shown by Hiddink *et al.* (2026) do appear very similar to that produced by extrapolation from GFW data (Hiddink *et al.* (2026) Figure 1 compared with Figure 32a) The dataset used here show the same areas of intense bottom fishing in the Adriatic, Mediterranean coastal areas of France and Spain, and south of Sicily in the Ionian Sea.

State of the art models of the dynamics of carbon disturbance and fate of disturbed materials have appeared in recent years that fully incorporate the complexities of the fate of disturbed carbon in sediment

and the effects that fishing may have (Porz *et al.*, 2024b; Zhang *et al.*, 2024b). Expanding the spatial extent of these models would produce an immediately more useful set of information for spatial management. At present, effects of transport and subsequent redeposition of disturbed carbon, varying degradability of the carbon itself (Black *et al.*, 2022; Freitas *et al.*, 2021) have not been addressed in scenario development. However, such issues are relatively small considerations compared to the variation and lack of agreement among estimated patterns of sediment carbon in European seas and the lack of data on rates of carbon sequestration.

By far the largest impact on seabed carbon stores is from fishery trawling (Tables 6, 13), because of the area it covers, the amount of seabed surface disturbance, and that it is repeated at time scales that would not allow stores to be replenished or biodiversity to recover (Zhang *et al.* 2024). Dredging for shellfish and aggregates has significant but more spatially limited impacts. Seabed mining would similarly have significant impacts but there are no data on its extent, if any, in European seas. However, a wider range of human activities could have very limited effects, spatially and temporally, on seabed disturbance, and by excluding other seabed disturbing activities they could have long term benefits in seabed stability; namely, wind farms, cables, pipelines, aquaculture, and fixed moorings. Although, propellor wash has a large spatial coverage, much of this will be over deep water and its impacts on the seabed will be limited to shallow harbours and navigation channels.

If fishery trawling occurs within the CSZ and is prohibited, then the targeted fish populations in the CSZ (if any) may recover and spillover into the adjacent areas resulting in decreased fishing around the CSZ. Global scale analysis, using historic no-fishing MPA and GFW data shows that this is the case (McDonald *et al.* 2024), probably due to spillover induced increased catch per unit effort (CPUE) around the MPA (Costello 2024a, 2024b). Phasing out bottom trawling in EU waters would have net societal benefits due to both its impact on biodiversity and greenhouse gas emissions and limited fishery value (Millage *et al.* 2026). More spatially precise data may find that relatively little trawling occurs in the muddiest seabed with most organic carbon (Mariani *et al.* 2025b). Thus, there would not only be cessation of anthropogenic release of organic carbon in the CSZ but also in adjacent areas, although these areas will have reduced organic carbon by definition.

A common outcome across all the sediment carbon models was the positive effects (less sediment carbon disturbed, reduced loss of biodiversity, reduced carbon released to atmosphere) of removing fishing disturbance from non-carbon related management areas (Marine Protected Areas, Offshore Wind Farms).

4. Blue Carbon in a European Legislation Context

Blue carbon is rapidly moving from a research concept to an operational policy priority in Europe. This is because it provides a triple dividend: it supports biodiversity recovery, contributes to climate mitigation and adaptation, and strengthens the resilience of coastal communities while enabling sustainable maritime economies.

4.1 Current policy framework

Across EU policy, blue carbon is increasingly treated as a unifying outcome that must be delivered through integrated marine governance rather than stand-alone projects. The European Green Deal and the EU Biodiversity Strategy to 2030 set the overarching direction for nature recovery and climate neutrality. The Nature Restoration Regulation (EU) 2024/1991 makes this operational through binding, time-bound restoration requirements, including for marine ecosystems. It explicitly recognises that restoring ecosystems contributes to EU climate mitigation and adaptation objectives, and it requires Member States to put restoration measures in place for marine habitats that are not in good condition (notably including habitats such as seagrass beds and sediment bottoms that deliver significant climate-regulation benefits).

In parallel, the Marine Strategy Framework Directive (MSFD, 2008/56/EC) remains the main delivery engine for ecosystem-based management at sea-basin level. It requires Member States to assess status and pressures (Article 8), define Good Environmental Status (Article 9), set targets (Article 10), establish monitoring programmes (Article 11) and implement programmes of measures (Article 13). Blue carbon aligns most directly with Descriptor 1 (Biodiversity) and Descriptor 6 (Sea-floor integrity), with policy-relevant entry points in Commission Decision (EU) 2017/848 for physical loss/disturbance and for maintaining seabed structure and functions.

In practice, carbon sequestration and storage can be treated as an ecosystem service that evidences ‘function’ under D6 (including where threshold values are set regionally for criteria such as D6C3-D6C5), while D1/D6 assessment results can be used to target restoration actions required under Article 5 of the Nature Restoration Regulation. Because blue carbon condition depends on water quality and pressures, it also links to Descriptor 5 (Eutrophication) and, where relevant, to contaminants and other pressures captured in the MSFD descriptor set.

Europe is also reframing blue carbon within a broader ocean governance package under the European Ocean Pact (COM(2025) 281). The Pact explicitly signals support for ‘European blue carbon reserves’ and commits the Commission to present an Ocean Act by 2027. The Ocean Act is expected to provide a single framework to implement the Pact’s objectives, reduce administrative fragmentation, and strengthen sea-basin management and cross-sector coordination. Commission information indicates it will build on a revised Maritime Spatial Planning Directive to improve regional cooperation and ‘sea-basin management’; Parliament tracking also points to the Ocean Act being programmed soon.).

At regional level, the Regional Seas Conventions (OSPAR, HELCOM, Barcelona Convention/UNEP-MAP, Bucharest Convention) provide the legal and institutional platforms for transboundary cooperation that MSFD implementation depends on. These conventions and their strategies/action plans are increasingly integrating climate considerations into biodiversity protection and seabed management, including via regional assessments, common indicators/thresholds, spatial protection measures, eutrophication reduction, and habitat restoration roadmaps. Sea-basin strategies complement this ‘regulatory backbone’ by mobilising political commitment, stakeholder coalitions and project pipelines across borders (e.g., the Atlantic Action Plan, the WestMED Initiative, the Common Maritime Agenda for the Black Sea and the Great North Sea Basin Initiative), which is particularly relevant for scaling restoration, aligning management of

human uses, and coordinating finance for monitoring and implementation.

None of these ambitions are implementable without credible data. Blue carbon policy is intrinsically MRV-heavy: it requires harmonised mapping of habitats and sediments, baseline carbon stock estimates, pressure and risk layers (e.g., bottom-contact fishing, dredging, anchoring, coastal development), and long-term monitoring to demonstrate permanence and manage the risk of reversals. The Ocean Pact's emphasis on ocean observation and simplification of reporting and data management - together with MSFD reporting cycles and regional assessment processes - creates a pathway to standardise datasets and methods (including through EMODnet, Copernicus Marine services, national monitoring programmes and the EU research/innovation agenda). This is also a precondition for credible certification and finance for blue carbon measures, where robust monitoring, reporting and verification (MRV) and transparent data-sharing are essential to demonstrate real climate and biodiversity outcomes.

This project's findings (the assessment of human impact on seabed carbon) directly support and provide crucial data for core EU and international commitments. The recommendations set out below build on the modelled scenarios that can serve as the scientific basis for future policy measures and enforcement.

4.2 Policy Analysis: Supporting EU and International Commitments

4.2.1 Climate mitigation and adaptation targets

The project findings directly support the EU's legally binding climate goals (as defined in the European Green Deal, under the *Fit for 55* package) by providing essential data for carbon accounting and the deployment of Nature-Based Solutions (NBS). The assessment quantifies the amount of carbon stored and sequestered by healthy seabed ecosystems (e.g. seagrass beds, benthic sediment habitats), establishing a baseline for the marine environment's contribution to EU climate mitigation efforts. It also highlights how destructive human pressures (e.g., bottom trawling, dredging) release stored carbon back into the water column and atmosphere, acting as a "negative emission" or "release". However, under the *Fit for 55* package, including the revision of the Land Use, Land-Use Change and Forestry (LULUCF) Regulation, which is being strengthened to include new carbon removal targets, these findings are particularly pertinent.

In terms of scaling up blue carbon initiatives, the results of this study deliver robust, scientifically sound methodologies to certify marine carbon removal activities under the proposed Carbon Removal Certification Framework (CRCF). The CRCF demands robust monitoring periods and liability mechanisms. Our project's data on the *stability* and *vulnerability* of seabed carbon stocks under different pressures is essential for defining the required permanence period (e.g., is a deep-sea sediment store more stable than a shallow-water marsh?) and calculating the appropriate buffer pool or insurance against carbon reversal.

4.2.2 Achievement of good environmental status of EU seas

The project is intrinsically linked to MSFD Descriptor 6 (Sea-floor Integrity), which focuses on safeguarding the structure and functions of benthic ecosystems. The assessment provides a direct measure of functional damage to the seabed by quantifying the loss of its carbon-sink capacity. Human activities that compromise the seabed's function as a carbon sink also compromise its physical structure and biodiversity. As such the loss of seabed carbon storage potential can serve as a key indicator of adverse effects on the structure and functions of benthic ecosystems (as required by criteria D6C3 and D6C5 of the MSFD). The project has quantified the "extent of the seabed significantly affected by human activities" by focusing on areas where carbon-rich sediments are disturbed, helping define sustainable use of the marine environment.

The project proposes a functional indicator: the *integrity of the seabed as a long-term carbon*

reservoir. Activities that cause significant carbon loss demonstrably compromise the seabed's ecological function, directly failing the GES criteria for Descriptor 6 (Seafloor Integrity).

The project can establish thresholds for acceptable carbon stock disturbance within various marine regions, allowing Member States to set clear, measurable targets for reducing the impact of bottom-disturbing activities (e.g. "no net loss of sedimentary carbon stock in MPAs").

4.2.3 *Biodiversity Strategy and Nature Restoration Regulation (NRR)*

The project's scientific data is central to the spatial planning and binding targets of the EU's nature policies. For instance, this project and data which it provides will be invaluable in assessing progress towards the targets and objectives of the Biodiversity Strategy to protect 30% of EU waters, including 10% strictly, and of the proposed Nature Restoration Regulation (NRR) when it comes to the restoration of carbon-rich marine ecosystems.

Identifying seabed areas with high carbon density helps prioritise them for protection and management under the EU Biodiversity Strategy for 2030. The area of high carbon value often coincide with high biodiversity areas (e.g., seagrass meadows) and should be included in the expanded network of Marine Protected Areas (MPAs).

Furthermore, under the NRR's ambition to guide restoration efforts, this assessment provides the scientific basis and baseline data for the specific, binding restoration targets proposed for marine ecosystems in the NRR, particularly for benthic habitats. Restoration efforts [guided by the results of this study] should maximise the recovery of the natural carbon sequestration function alongside biodiversity, reinforcing the understanding that protecting and restoring biodiversity is a prerequisite for maintaining the ocean's climate regulatory function.

4.2.4 *EU Action Plan to protect and restore marine ecosystems for sustainable and resilient fisheries*

The assessment provides the evidence base for aligning the Common Fisheries Policy (CFP) with environmental objectives. This enables the classification of areas by "carbon risk" (i.e., the potential for carbon release per fishing effort). This directly supports the action plan's goal of increasing synergies, as a climate objective (protecting carbon) becomes a new justification for fisheries management measures. The project provides the evidence needed to justify measures like the gradual phase-out of mobile bottom fishing in all MPAs by 2030, which is a key action in the plan. This shifts the focus from purely stock recovery to a holistic ecosystem approach.

By quantifying the carbon loss associated with destructive fishing gears, the project shows the dual environmental benefit (biodiversity and climate) of limiting these activities. It also highlights that reducing the impact on seabed carbon is not only an environmental goal but also a crucial climate action, thereby increasing synergies between the CFP and the European Green Deal. Healthier, carbon-storing ecosystems also support greater biodiversity, which can lead to more resilient fish stocks in the long term.

4.2.5 *Data, monitoring and MRV as critical enablers*

Blue carbon is only policy-relevant if it can be measured and managed. This requires consistent, interoperable datasets across Member States and neighbouring countries: (i) habitat extent and condition (including seagrass, saltmarsh/coastal wetlands and key sediments); (ii) carbon stock and sequestration-rate estimates with uncertainty bounds; (iii) pressure and risk layers (e.g., bottom-contact fishing effort, dredging footprints, anchoring intensity, coastal infrastructure, nutrient and contaminant inputs); and (iv) long-term monitoring to track restoration outcomes and manage reversal risk.

The MSFD already provides a legal framework for monitoring programmes and reporting cycles, but blue carbon requires additional specificity (e.g., carbon-related functional indicators under Descriptor 6 and stronger links to Descriptor 1 benthic habitat condition). Regional Seas Conventions can support this by developing shared regional baselines, agreeing threshold values and common indicators where MSFD requires regional coordination, and coordinating transboundary assessments and data-sharing.

EU-level data infrastructure is a strategic lever. EMODnet and Copernicus Marine services, together with national monitoring programmes and scientific bodies (e.g., ICES, JRC and research infrastructures funded under Horizon Europe), can be used to standardise mapping, improve comparability and reduce duplication.

The Ocean Pact's focus on ocean observation and its intention to simplify reporting and data management provide a timely opportunity to align blue carbon data streams with wider EU ocean observation initiatives, including for coastal and deep-sea environments, and to create 'decision-grade' datasets that can support enforcement, investment decisions and credible MRV for restoration and protection actions.

4.3 Commitments taken at the international level under the Global Biodiversity Framework

The Global Biodiversity Framework (GBF), specifically Target 8, calls for minimising the impact of climate change and ocean acidification on biodiversity and increasing its resilience through mitigation actions, including Nature-Based Solutions (NBS). Assessing and protecting seabed carbon stocks constitutes an ecosystem-based mitigation action (a type of NBS).

Protecting the ocean's largest carbon sinks minimises the negative climate impacts on biodiversity and increases the resilience of marine ecosystems to climate change. The EU can use the findings from the seabed carbon impact assessment to demonstrate its commitment and leadership in delivering on Target 8, particularly concerning the use of marine ecosystems for climate mitigation, which is a key component of the GBF.

4.3.1 *Sea-basin strategies, macro-regional frameworks and MSP as delivery vehicles*

Beyond binding environmental law, the EU uses sea-basin strategies and macro-regional frameworks to mobilise political commitment, coordinate stakeholders and align funding for cross-border delivery. These frameworks are particularly relevant for blue carbon because the drivers of loss (eutrophication, coastal development, bottom-contact fishing, dredging, and altered hydrology) and the benefits of restoration (fish nursery function, water quality, flood and erosion protection) rarely stop at national boundaries.

In the Mediterranean, the WestMED Initiative provides a platform to connect national administrations, regional organisations and projects around a shared agenda for a sustainable blue economy. It can be used to scale blue carbon through: (i) regional MSP cooperation and common planning principles; (ii) 'project pipelines' for seagrass and coastal wetland protection/restoration; (iii) capacity-building for local authorities on permitting, monitoring and enforcement; and (iv) crowding-in finance (EMFAF, LIFE, Interreg, Horizon Europe, EIB and other blended instruments) for restoration and long-term monitoring.

In the Atlantic, the EU Atlantic Action Plan / Atlantic Strategy similarly provides a cooperation umbrella that can connect seabed carbon protection to fisheries management, marine protected areas, and offshore renewable energy planning. This is relevant where sedimentary carbon stocks on continental shelves overlap with intense bottom-contact fisheries and infrastructure development, and where sea-basin cooperation is needed to harmonise pressure maps, risk screening and mitigation measures.

In the Black Sea, the Common Maritime Agenda (CMA) offers an established regional governance process for sustainable blue economy cooperation. It can help address persistent data and capacity gaps that constrain blue carbon action in the basin by prioritising joint assessments (e.g., seagrass distribution, wetland condition, nutrient load pathways), coordinated restoration pilots, and integration of blue carbon objectives into MSP and coastal zone management.

In the Baltic Sea, the EU Strategy for the Baltic Sea Region (EUSBSR) and HELCOM-VASAB cooperation provide established pathways to integrate blue carbon into MSP, spatial protection measures and eutrophication control. This is directly relevant where carbon preservation depends on improving water clarity and benthic condition, and where cumulative impacts are best addressed through basin-wide measures rather than isolated national actions.

The European Ocean Pact's commitment to an Ocean Act by 2027 is therefore strategically important for blue carbon: it is expected to strengthen sea-basin management and cross-sector coordination, and is widely anticipated to build on a revised Maritime Spatial Planning Directive. If designed well, the Ocean Act can make blue carbon 'implementable' by clarifying governance responsibilities across MSFD-MSP-CFP-Nature Restoration obligations, enabling more coherent programmes of measures and restoration planning at sea-basin level, and reducing reporting and data-management fragmentation while maintaining scientific integrity.

4.3.2 Regional Sea Conventions (RSCs)

These translate global and EU policy into specific cooperative actions for sea basins.

OSPAR has explicitly recognised the importance of the ocean as a natural carbon store. Its North-East Atlantic Environment Strategy (NEAES) 2030 includes the strategic objective of safeguarding the marine environment's role as a natural carbon store. It is working on developing a regional framework for implementing NBS, which includes the protection and restoration of coastal and marine habitats with high carbon sequestration potential (e.g., salt marshes, deep-sea sediments). OSPAR is unique in that it has specific decisions and guidelines governing the geological storage of CO₂ streams beneath the seabed, focusing on ensuring permanence and preventing adverse consequences for the marine environment. Its work is highly relevant to deep-sea blue carbon (stored in sediments) through its measures to manage human activities that can damage the seabed, thus providing a governance layer for protecting the largest oceanic carbon reservoir.

Barcelona Convention (Mediterranean Sea) The Convention for the Protection of the Marine Environment and the Coastal Region of the Mediterranean is governed by UNEP's Mediterranean Action Plan (MAP). The Mediterranean is highly vulnerable to climate change (warming 20% faster than the global average). Blue carbon is framed as a key measure for both climate mitigation and adaptation/resilience. It places a high priority on protecting key Mediterranean blue carbon ecosystems, most notably *Posidonia* seagrass meadows. These meadows are critical biodiversity hotspots and highly effective carbon sinks.

The Convention works to establish a representative, connected, and resilient network of Marine Protected Areas (MPAs). MPAs are key tools for protecting blue carbon sites from degradation caused by coastal development, pollution, and destructive fishing. The Convention and partners (like IUCN Med) are developing a Mediterranean Blue Carbon Strategy to provide a science-based roadmap for the restoration and sustainable management of these ecosystems, aligning with the UN Decade on Ecosystem Restoration.

HELCOM (Baltic Sea) The Baltic Marine Environment Protection Commission (HELCOM) is pioneering the integration of seabed carbon into regional management through its Baltic Sea Action Plan (BSAP). Recognising that the Baltic Sea contains significant sedimentary carbon stocks, HELCOM has prioritised the

protection of "blue carbon" habitats—such as seagrass meadows (*Zostera marina*), macroalgae, and salt marshes—as essential tools for climate mitigation. The project's findings on carbon-stock vulnerability are directly applicable to HELCOM's efforts to define Spatial Protection Measures and to improve the "State of the Baltic Sea" assessments. Furthermore, HELCOM's focus on reducing nutrient loads (eutrophication) is a critical prerequisite for carbon preservation, as clear water and healthy benthic conditions are necessary to maintain the integrity of the sea's natural carbon sinks.

Bucharest Convention (Black Sea) The Convention on the Protection of the Black Sea Against Pollution aims to protect and preserve the Black Sea ecosystem, which faces unique challenges related to limited water exchange and significant riverine nutrient input (eutrophication). Blue carbon is integrated through the Convention's focus on biodiversity conservation and combating eutrophication. Protection and restoration efforts target coastal wetlands and marine habitats (like submarine *Posidonia*-like meadows, though the actual species is different) to improve the overall ecological quality of the sea. However, since excessive nutrient load (eutrophication) severely impacts coastal vegetation (a key blue carbon component), the Convention's protocols on land-based sources of pollution (LBS) are indirectly vital for protecting blue carbon health. Reducing pollution helps maintain the vitality of coastal vegetation that stores carbon. Compared to OSPAR and Barcelona, the Bucharest Convention area often faces greater challenges in developing specific, large-scale blue carbon projects due to fewer data and capacity constraints, but the foundation is being built through regional projects that link ecosystem protection to climate resilience.

4.3.3 European Parliament (EP)

The European Parliament provides political oversight and advocacy for stronger protection. The Parliament has called for a global moratorium on deep-sea mining, explicitly justifying the stance by stating the risk of disrupting the deep-sea, which is the world's largest carbon sink, and causing the irreversible release of stored carbon. The Parliament has taken a strong, unified stance against deep-sea mining, with seabed carbon being a core environmental concern in its resolutions. In response to decisions by countries to open areas for deep-sea mining, the EP has passed resolutions calling for a global moratorium on the industry. These resolutions explicitly state that deep-sea mining activities pose a risk of disrupting the world's largest carbon sink—the deep sea—and could cause the irreversible release of stored carbon, which would exacerbate the climate crisis. The EP is thus using the threat to the carbon sink as a key justification for a moratorium.

4.3.4 The EU Ocean Pact and upcoming "Ocean Act"

This is the newest, overarching strategic initiative that brings everything above under one roof, signalling the future direction of EU marine policy. The EU Ocean Pact is the European Commission's strategic framework, developed in response to the climate and biodiversity crises, aiming to unify all existing ocean policies. It emphasizes the ocean's role as a climate regulator and the world's largest carbon sink. The Pact is set to culminate in a proposed "Ocean Act" by 2027. This Act is expected to be a major piece of legislation that will:

- Streamline and reinforce the Maritime Spatial Planning Directive to ensure better regional cooperation and faster implementation of Green Deal targets.
- Integrate and streamline the targets from various pieces of legislation (MSFD, Birds & Habitats Directives, CFP) to ensure coordinated delivery of 30% marine protected areas and ecosystem restoration.

The Pact explicitly encourages the establishment of well-managed marine protected areas and "blue carbon reserves" to safeguard the ocean's natural carbon removal potential.

5. Recommendations and Technical Options

Blue carbon should be addressed in the next phase of EU ocean governance as a strategic issue at the intersection of biodiversity protection, climate mitigation, coastal resilience and sustainable use of marine space. Carbon-rich coastal and benthic ecosystems support essential ecological functions while also contributing to **carbon sequestration and storage**, yet their role remains only **partially embedded** in operational EU policy and management tools. The current policy landscape already provides a strong basis for action: the European Green Deal, the EU Biodiversity Strategy to 2030, the Nature Restoration Regulation, the Marine Strategy Framework Directive, the Marine Action Plan, the Kunming-Montreal Global Biodiversity Framework and the Regional Seas Conventions all point toward the need to protect, restore and better manage blue carbon ecosystems and carbon-rich seabed. The **European Ocean Pact** also signals a stronger EU role, including support for blue carbon reserves and a forthcoming **revision of the MSFD** intended to accelerate delivery and simplify reporting and data management.

The policy challenge is therefore no longer whether blue carbon matters, but **how to integrate** it in a practical and legally coherent way across the Union's marine governance architecture. Two implications follow. First, blue carbon should be treated as both a **biodiversity and a climate-regulation issue**, not as a separate niche domain. Second, implementation will depend on **stronger links** between ecological assessment, spatial planning, pressure management, restoration policy and sea-basin cooperation. In operational terms, the most immediate entry points remain the MSFD, especially biodiversity and seafloor integrity, the Nature Restoration Regulation, and the sea-basin frameworks through which Member States already cooperate. The case for action is reinforced by the growing evidence that **bottom-disturbing activities**, especially mobile fishing gears, can compromise long-term carbon storage, while **restoration and protection measures** can deliver both biodiversity and climate benefits if they are supported by better data, monitoring and enforcement.

REC1: Exclude fisheries bottom contact gears in blue-carbon-relevant areas through a targeted and adaptive approach.

Measures that exclude fishing gear that disturb the seabed should be prioritised in areas where there is clear evidence of spatial overlap between mobile bottom-contacting gears and carbon-rich or carbon-vulnerable seabed habitats, in line with the ecosystem-based approach required under the Marine Strategy Framework Directive (MSFD) and the objectives of the EU Biodiversity Strategy for 2030. Given that bottom-contacting fishing gears represent a dominant pressure on seabed integrity across European seas, reducing this pressure constitutes a key entry point for achieving Good Environmental Status (Descriptor 6) and supporting climate mitigation objectives.

Such measures should be implemented in a spatially targeted manner, informed by best available scientific evidence on carbon stocks, habitat sensitivity, and recovery potential, and integrated within Maritime Spatial Planning (MSP) processes. A uniform or precautionary blanket approach could be avoided in favour of risk-based prioritisation, consistent with proportionality principles under EU law.

Where fisheries exclusions are introduced, they should be accompanied by adaptive management provisions under the Common Fisheries Policy (CFP), including monitoring, evaluation, and review mechanisms, as well as, where appropriate, complementary effort-management or capacity-adjustment measures. This is necessary to account for uncertainty in fleet behavioural responses to spatial restrictions. Alternative fishing methods, such as traps and hook and line fishing, may avoid seabed disturbance. Fishing effort may be reduced, redistributed, or partially displaced depending on economic, regulatory, and ecological conditions, and these responses may influence the net environmental outcome.

Scenario analyses indicate that bottom fisheries exclusion in Marine Protected Areas (MPAs) and other spatial designations can contribute to reducing seabed carbon disturbance and support the objectives of the Nature Restoration Regulation and climate mitigation policies. However, outcomes are sensitive to assumptions regarding the redistribution of fishing effort. In particular, environmental benefits may be diminished where effort is reallocated to areas of comparable or higher carbon sensitivity, while alternative responses, such as reductions in overall effort or increased catch efficiency, may enhance net benefits. Accordingly, fisheries exclusion measures should be designed and evaluated within an adaptive, evidence-based framework that explicitly considers these uncertainties.

The MSFD is currently under revision, with the Ocean Act planned to be reviewed around the same time. This provides a unique opportunity to integrate explicit seabed protection policy objectives such as the exclusion of bottom fisheries in Marine Protected Areas under both the Ocean Act and the revised MSFD.

REC2: Develop carbon-sensitive zones as a complementary management category alongside MPAs.

The EU should promote the identification of **carbon-sensitive zones** where sedimentary carbon density, long-term storage potential, or vulnerability to disturbance justify dedicated management attention. These zones should complement, **not replace**, existing marine protected areas. Their purpose would be to ensure that climate-regulating functions are explicitly considered in zoning, management and permitting decisions, including in areas not currently protected for biodiversity reasons alone. Because current estimates of sediment organic carbon vary significantly across models and sea basins, this instrument should initially be introduced through a precautionary and adaptive framework, prioritising areas where **evidence is strongest** and updating boundaries as knowledge improves. The scientific material makes clear that estimates of **seabed carbon stocks still vary** widely across Europe, and that confidence is uneven between basins, with notably weaker evidence in parts of the Mediterranean and Black Sea. Carbon-sensitive zoning should therefore be tied to a rolling evidence review rather than fixed once and for all.

REC3: Make environmental impact assessment and strategic environmental assessment explicitly blue-carbon relevant.

Environmental assessment frameworks should be amended or interpreted so that likely impacts on carbon-rich coastal and benthic ecosystems are treated as a material factor in project authorisation and **plan preparation**. This should apply to offshore and coastal activities with potential seabed or habitat disturbance, including dredging, aggregates extraction, coastal construction, port development, seabed infrastructure and other bottom-disturbing uses. Where relevant, assessments should examine expected carbon-stock disturbance, potential loss of sequestration function, restoration feasibility, cumulative impacts and interaction with other pressures. The case for this is strong because blue carbon is already closely **linked to MSFD** biodiversity and seafloor integrity objectives, while the **scientific evidence** on disturbance shows that carbon loss risk is shaped by habitat type, disturbance intensity, degradation processes and the fate of resuspended material. A **more explicit blue-carbon dimension** in EIA and SEA would therefore improve both prevention and consistency across policy tools.

REC4: Establish obligated carbon monitoring and reporting within the EU marine governance framework.

A formal monitoring and reporting obligation is needed if blue carbon is to move from concept to implementation. Member States should be required to progressively **integrate blue carbon** into marine observation, ecological assessment and reporting systems, with common minimum standards and a shared technical framework. This should include the spatial extent and condition of relevant habitats, sedimentary carbon stocks where feasible, pressure indicators, and time-series data sufficient to detect deterioration or recovery. It should also support interoperable geospatial products and shared basin-scale datasets. The policy rationale is straightforward: without **a credible monitoring base**, Member States cannot set

baselines, determine trends, evaluate measures or justify restoration and protection priorities. The scientific evidence also shows that the largest current constraints are **fragmented data**, uneven spatial coverage, uncertain carbon-stock maps, and the need for better models of degradation, remineralisation, transport and atmospheric exchange.

REC5: Align blue carbon action more closely with the Nature Restoration Regulation and MSFD implementation.

Blue carbon should be **embedded** within the operational relationship between **restoration policy** and marine **environmental status assessment**. In practical terms, this means restoration measures under the National Plans for the Nature Restoration Regulation should be informed by the same ecological and pressure evidence used under the MSFD, while MSFD assessments should better reflect the climate-regulation function of relevant habitats and sediments. This would **reduce policy fragmentation** and help ensure that biodiversity recovery and climate mitigation are pursued through the same management logic. It would also support more coherent national implementation by **avoiding parallel reporting systems** that do not speak to each other. The existing policy framework already points toward this direction, especially through the recognition that restoring ecosystems contributes to climate mitigation and adaptation, and through the MSFD's focus on benthic condition and pressure management.

REC6: Strengthen the role of Regional Seas Conventions and sea-basin cooperation in blue carbon implementation.

Blue carbon should be operationalised at **sea-basin scale** wherever possible. The **Regional Seas Conventions** are the most appropriate platforms for developing threshold values, common methods, regional targets and **transboundary cooperation** on blue carbon, especially where habitats, fishing pressure and sediment processes transnational boundaries. The future EU framework should therefore encourage basin-specific target-setting, data harmonisation and cooperative development of blue carbon priorities through OSPAR, the Barcelona Convention, HELCOM and the Bucharest Convention, while also taking account of the particular **knowledge and capacity gaps** in some sea basins. This approach would be consistent with the broader evolution of EU ocean governance toward **stronger regional cooperation** and would help avoid fragmented national approaches to essentially transboundary ecological functions.

REC7: Address the main knowledge gaps as an implementation priority, not as a parallel research agenda.

Task 2 and 3 of the project identified a number of knowledge gaps that should be treated as policy-relevant implementation issues. These include limited understanding of the scale of carbon sequestration improvement that management may deliver, unresolved questions on the relative contribution of terrestrial and marine carbon pathways, **insufficient knowledge** of how carbon disturbance translates into atmospheric outcomes, and uncertainty over how measures affect different sea basins. These gaps do not justify delay, but they do justify phased implementation, **stronger monitoring obligations** and more cautious claims regarding carbon benefits. In practice, the EU should prioritise improved seabed carbon mapping, better assessment of carbon accumulation and vulnerability, stronger evidence on disturbance and recovery processes, and better integration of ecological and activity data across sea basins -the recently announced **OceanEye** can become a key element.

REC8: Integrate socio-economic transition measures into blue carbon policy from the outset.

Any serious **blue carbon strategy** will have distributive consequences, especially for fisheries and other **users of marine space**. Measures such as fisheries exclusion zones and carbon-sensitive zoning will be more robust if they are accompanied by transition pathways, including support for less disturbing gears and practices, predictable planning, stakeholder engagement and, where justified, targeted mitigation of socio-economic impacts. The scientific evidence does not support a simplistic assumption that exclusion alone will

produce optimal outcomes. It instead suggests that **unmanaged displacement can worsen disturbance**, which means policy design must explicitly consider behavioural and economic responses. This also supports a broader coexistence logic: **blue carbon protection should be integrated into marine planning** in a way that reduces avoidable conflict and promotes workable combinations of environmental protection and sustainable use where possible.

Key messages

The scientific evidence emerging from previous Tasks, supports three main messages for policy discussion.

First, pressure reduction on the seabed is necessary, but **spatial restrictions** will only be effective if they are **evidence-based**. The scenario analysis shows that exclusion from MPAs, offshore wind areas, carbon protection zones and core fishing grounds can reduce estimated carbon disturbance, sometimes substantially. Blue carbon policy should therefore focus on managed pressure reduction.

Second, data limitations remain a major constraint on precision, particularly outside the better-studied North Sea. Current carbon-stock maps diverge significantly, some regions are poorly covered, and activity datasets remain uneven, especially in the Mediterranean and Black Sea. **A stronger EU blue carbon framework** should therefore be built around progressive improvement in data, common methods, basin-scale harmonisation and adaptive management.

Third, blue carbon policy must be precautionary, operational and realistic. The scientific material supports stronger action, but it also shows that **much more information is needed** before decisions with major social and economic consequences can be taken at scale without safeguards. The most defensible path for the EU is therefore to combine immediate action on protection, restoration, monitoring and pressure reduction with a staged improvement in evidence, monitoring, modelling and implementation tools. That approach would be consistent with both the current policy direction at EU level and the actual state of knowledge.

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7. Supplementary Information

Figure S 4. Model uncertainty in predicted percentage organic carbon on seabed sediments

Calculated as the standard deviation of bootstrapped estimates of mean percentage. From Figure 3 Modelled organic carbon content of seabed sediments. (top) Estimated percentage of organic carbon. (bottom) Carbon density in kg/m² from (Lønborg, et al., 2025). (top). Areas of higher uncertainty are shown as deeper red shades.

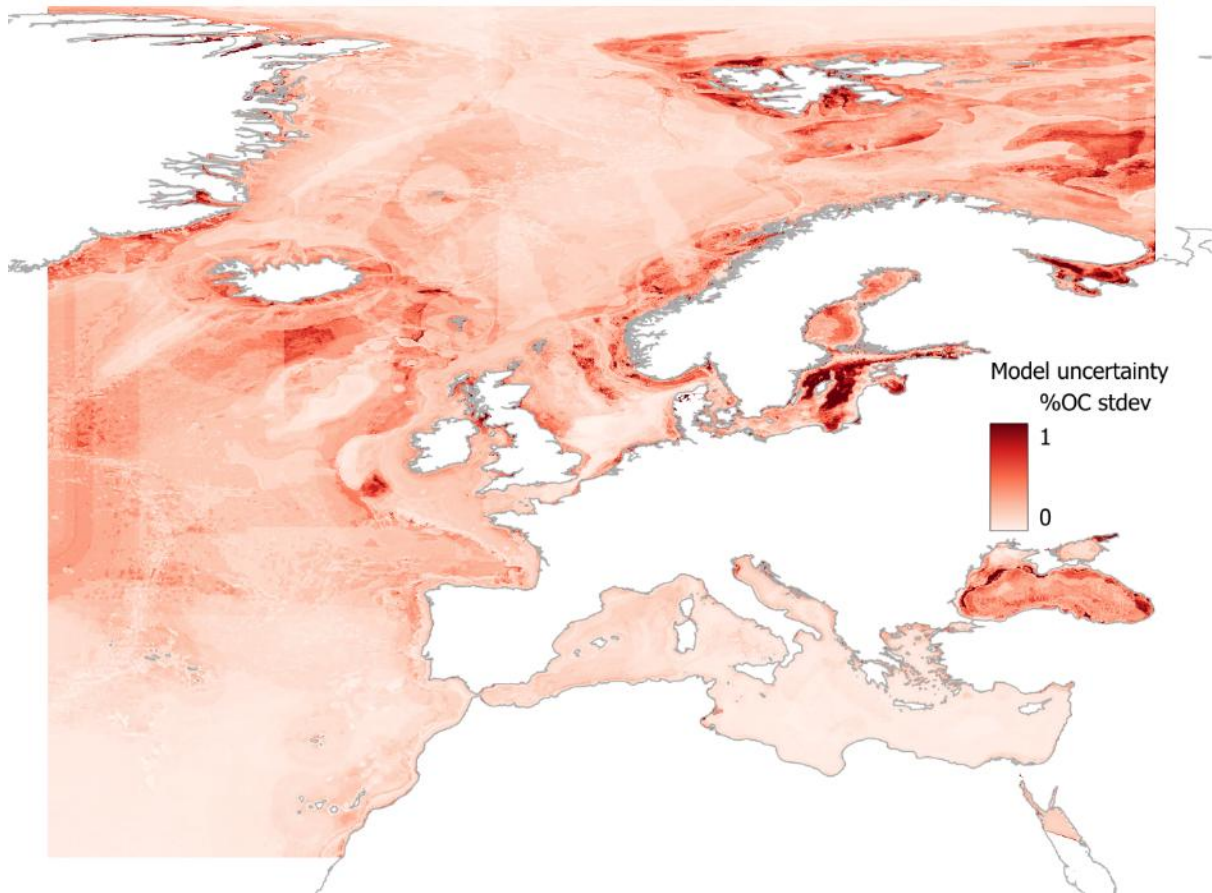


Figure S 5. Model uncertainty in predicted density of organic carbon in seabed sediments

Calculated as the standard deviation of bootstrapped estimates of mean density. Areas of higher uncertainty are shown as deeper purple shades.

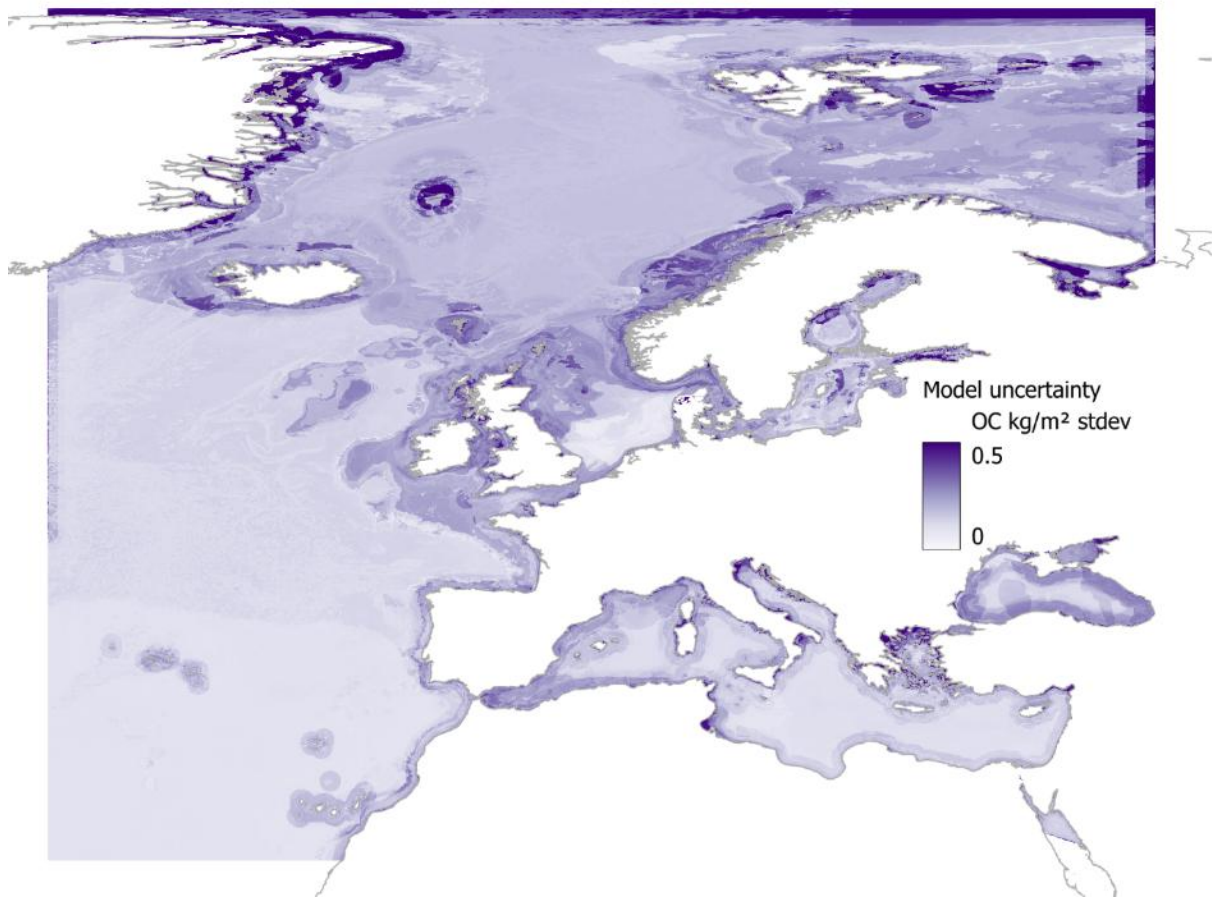


Figure S 6. Locations with (left) percentage organic carbon overlaid on %OC uncertainty and (right) locations of sediment organic density data in the Euro-Carbon dataset

The much smaller number of organic carbon density locations indicates lower confidence in this predicted measurement.

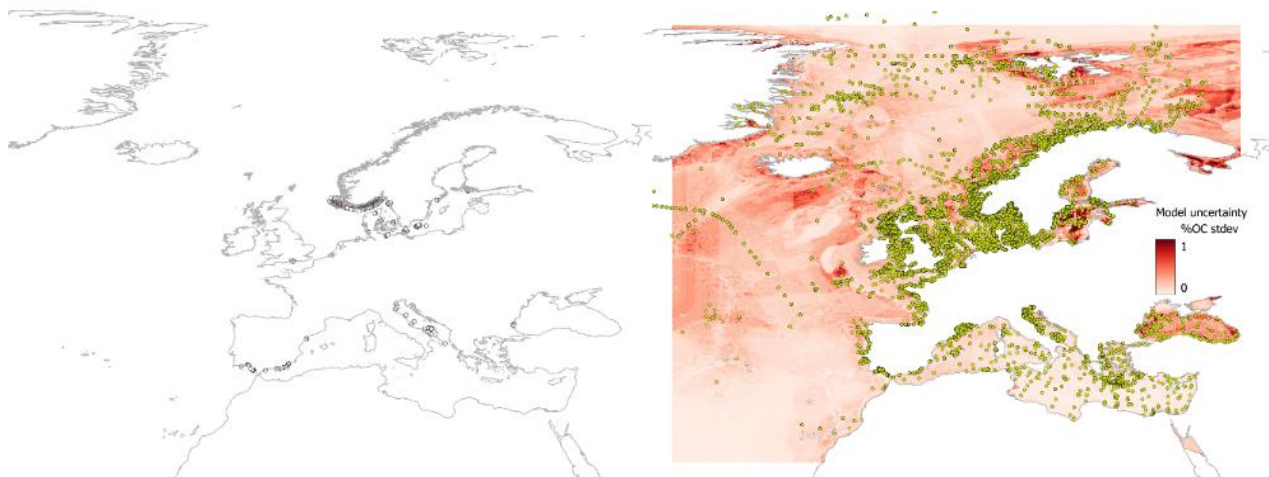


Figure S 7. Comparison of predicted organic carbon density of seabed sediments in the North Sea and nearby regions

From (Diesing, 2021; Diesing *et al.*, 2017a, 2024; Lønborg, Graversen, Addamo, Assis, *et al.*, 2025; Smeaton, Hunt, *et al.*, 2021).

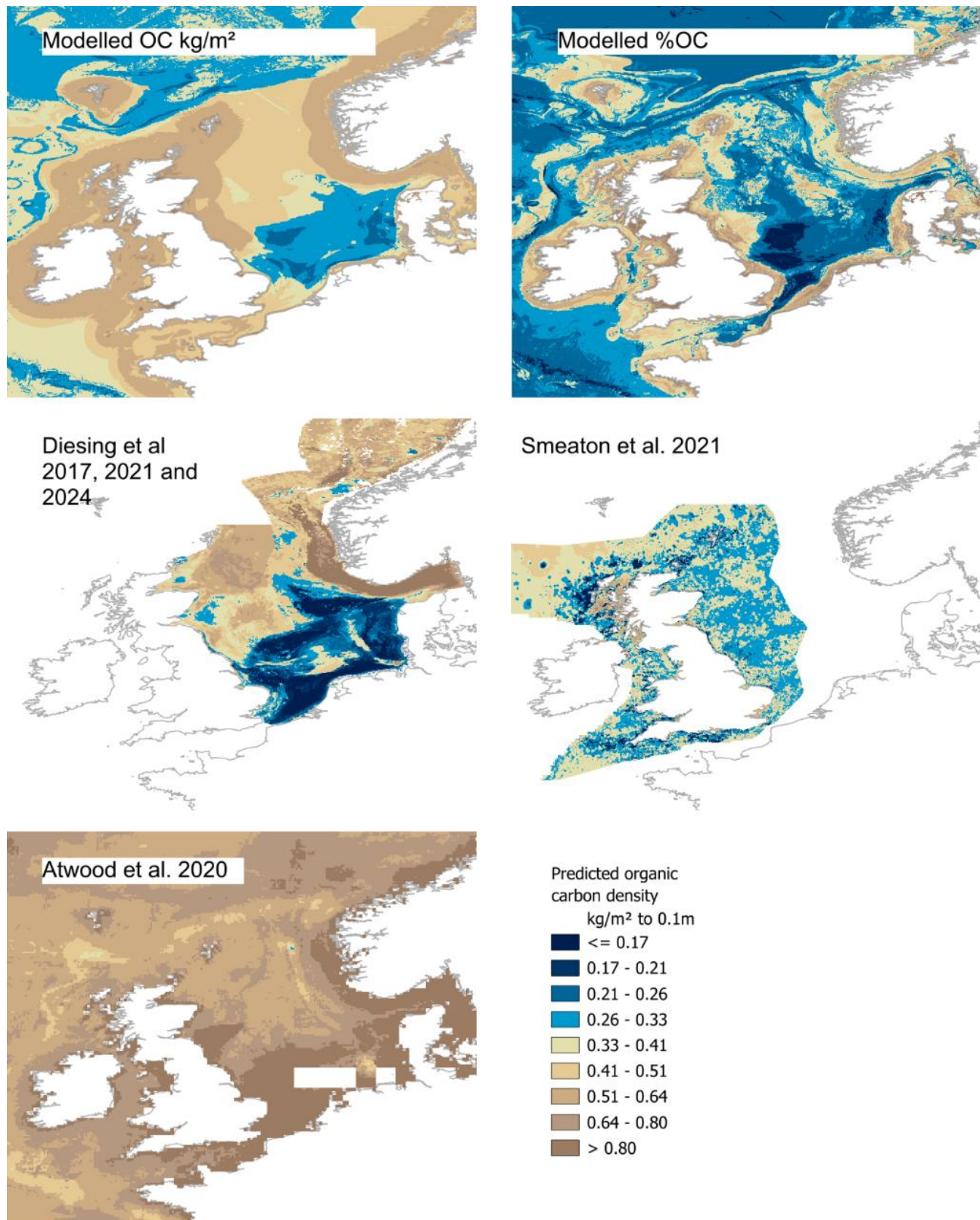


Table S 1. Literature sources for organic carbon data across MSFD subregions

Publication	Sub-region	Region Name	Freq	Year	Author
10.1029/1999PA000419	MIC	Mediterranean Sea	18	2000	Martinez-Ruiz
10.1016/j.ecolind.2012.12.020	MIC	Mediterranean Sea	12	2013	Karakassis
10.1016/j.marenvres.2009.12.007	MIC	Mediterranean Sea	11	2010	Papageorgiou
10.3354/meps295091	MIC	Mediterranean Sea	8	2005	Hyland
10.1016/j.ecss.2007.05.024	MIC	Mediterranean Sea	3	2007	Apostolaki
10.1007/s10533-017-0323-z	MIC	Mediterranean Sea	1	2017	Silburn
10.1029/2020GL091279	MWE	Mediterranean Sea	100	2021	Paradis
10.1016/j.gca.2017.12.024	MWE	Mediterranean Sea	68	2018	Zhuang
10.1016/j.pocean.2013.07.014	MWE	Mediterranean Sea	49	2013	Salvad��
10.1016/j.marpolbul.2007.10.015	MWE	Mediterranean Sea	40	2008	Magni
10.4081/aiol.2023.11124	MWE	Mediterranean Sea	36	2023	Magni
10.1016/j.gca.2013.05.001	MWE	Mediterranean Sea	35	2013	Cathalot
10.1016/j.csr.2007.10.010	MWE	Mediterranean Sea	28	2008	Lansard
10.1016/j.pocean.2013.07.023	MWE	Mediterranean Sea	25	2013	Pedrosa-P��mies
10.1080/02757540310001629161	MWE	Mediterranean Sea	25	2004	Magni
10.1016/j.ecoleng.2014.09.017	MWE	Mediterranean Sea	24	2014	Zaaboub
10.1016/j.marpolbul.2017.07.033	MWE	Mediterranean Sea	21	2017	Trifuoggi
10.1016/j.pocean.2005.02.016	MWE	Mediterranean Sea	21	2005	Gr��mare
10.1016/j.csr.2019.05.009	MWE	Mediterranean Sea	20	2019	Pruski
10.1016/j.marpolbul.2007.12.004	MWE	Mediterranean Sea	18	2008	Magni
10.1029/2019JG005233	MWE	Mediterranean Sea	18	2019	Belshe
10.1007/s10750-005-4367-z	MWE	Mediterranean Sea	16	2005	Magni
10.1016/j.ecss.2017.03.004	MWE	Mediterranean Sea	15	2017	Quir��s-Collazos
10.1016/j.csr.2020.104076	MWE	Mediterranean Sea	12	2020	Kumar
10.1016/j.ecss.2008.11.025	MWE	Mediterranean Sea	10	2009	Lansard
10.1016/j.marpolbul.2007.01.007	MWE	Mediterranean Sea	8	2007	Como
10.1016/j.marchem.2003.09.007	MWE	Mediterranean Sea	4	2004	Forja
10.1007/s10533-017-0323-z	MWE	Mediterranean Sea	3	2017	Silburn
10.1016/j.ecss.2007.05.024	MWE	Mediterranean Sea	3	2007	Apostolaki
10.1016/j.csr.2011.03.007	MWE	Mediterranean Sea	2	2011	Pastor
10.1016/j.orggeochem.2006.07.025	MWE	Mediterranean Sea	1	2006	Capel
10.1016/j.orggeochem.2008.11.001	MWE	Mediterranean Sea	1	2009	S��nchez-Garc��a
10.1016/j.marpolbul.2017.07.026	MAD	Mediterranean Sea	211	2017	Lopes-Rocha
10.1002/9781119543626.ch8	MAD	Mediterranean Sea	165	2020	Testa
10.1016/j.ecss.2013.06.001	MAD	Mediterranean Sea	92	2013	Rampazzo
10.1016/j.ecss.2009.07.031	MAD	Mediterranean Sea	56	2009	Giani
10.1016/j.scitotenv.2010.10.050	MAD	Mediterranean Sea	23	2011	Kim
10.1016/j.scitotenv.2016.04.086	MAD	Mediterranean Sea	22	2016	Combi
10.1016/j.ecss.2019.106305	MAD	Mediterranean Sea	20	2019	Alvisi
10.1093/jpe/rtaa052	MAD	Mediterranean Sea	20	2020	Vitti
10.1016/j.ecss.2019.106547	MAD	Mediterranean Sea	14	2020	Fazi
10.1016/j.csr.2015.12.005	MAD	Mediterranean Sea	8	2016	Franzo
10.1016/j.ecss.2013.03.022	MAD	Mediterranean Sea	8	2013	Vianello

Publication	Sub-region	Region Name	Freq	Year	Author
10.1016/j.ecss.2005.03.005	MAD	Mediterranean Sea	5	2005	Sangiorgi
10.1007/s10533-017-0323-z	MAD	Mediterranean Sea	1	2017	Silburn
10.3354/aei00031	MAL	Mediterranean Sea	230	2011	Apostolaki
10.3354/meps295091	MAL	Mediterranean Sea	132	2005	Hyland
10.1016/j.ecolind.2012.12.020	MAL	Mediterranean Sea	55	2013	Karakassis
10.1016/j.marenvres.2009.12.007	MAL	Mediterranean Sea	45	2010	Papageorgiou
10.1016/j.margeo.2010.10.007	MAL	Mediterranean Sea	22	2010	Versteegh
10.1016/j.csr.2005.08.018	MAL	Mediterranean Sea	18	2005	Polymenakou
10.1016/j.csr.2005.08.021	MAL	Mediterranean Sea	3	2005	Polymenakou
10.1016/j.ecss.2007.05.024	MAL	Mediterranean Sea	3	2007	Apostolaki
10.1016/j.gca.2017.01.042	BLK	Black Sea	121	2017	Kraal
10.1016/j.gca.2010.08.006	BLK	Black Sea	69	2010	Ertefai
10.1371/journal.pone.0167493	BLK	Black Sea	65	2016	Dahl
10.1016/j.chemgeo.2018.10.024	BLK	Black Sea	46	2019	Lenstra
10.1016/j.marpolbul.2022.114020	BLK	Black Sea	31	2022	Ä-zÄyker
10.1007/s00367-003-0148-8	BLK	Black Sea	30	2003	Blinova
10.1006/ecss.2000.0670	BLK	Black Sea	23	2002	Galimov
10.1016/j.gca.2016.05.025	BLK	Black Sea	12	2016	Kusch
10.1016/j.marpolbul.2022.113959	BLK	Black Sea	11	2022	Ä-zÄyker
10.1016/j.gca.2021.04.037	BLK	Black Sea	3	2021	Zhu
10.1016/j.gca.2020.01.031	BLK	Black Sea	1	2020	Lenstra
10.1007/s10533-017-0323-z	MAL	Mediterranean Sea	1	2017	Silburn
10.1016/j.scitotenv.2023.163957	ABI	North East Atlantic Ocean	202	2023	Mazarrasa
10.1371/journal.pone.0167493	ABI	North East Atlantic Ocean	121	2016	Dahl
10.3354/cr01010	ABI	North East Atlantic Ocean	119	2011	Abrantes
10.1007/s10021-021-00660-6	ABI	North East Atlantic Ocean	103	2022	Martins
10.1038/srep41225	ABI	North East Atlantic Ocean	90	2017	Sousa
10.1007/s10021-022-00801-5	ABI	North East Atlantic Ocean	81	2023	De Los Santos
10.1016/j.ecss.2010.10.038	ABI	North East Atlantic Ocean	71	2011	GarcÄa-Gil
10.1038/s41598-018-37031-6	ABI	North East Atlantic Ocean	24	2019	Santos
10.1016/j.csr.2020.104076	ABI	North East Atlantic Ocean	20	2020	Kumar
10.1016/j.orggeochem.2008.11.001	ABI	North East Atlantic Ocean	18	2009	SÄnchez-GarcÄa
10.1016/j.rsma.2019.101009	ABI	North East Atlantic Ocean	18	2020	SaÄ±Ä©
10.1016/j.csr.2021.104419	ABI	North East Atlantic Ocean	16	2021	Dubosq
10.1016/j.marchem.2003.09.007	ABI	North East Atlantic Ocean	13	2004	Forja
10.5894/rgci452	ABI	North East Atlantic Ocean	10	2014	Camacho
10.1016/j.pocean.2005.02.016	ABI	North East Atlantic Ocean	9	2005	GrÄ©mare
10.1016/j.csr.2021.104616	ABI	North East Atlantic Ocean	7	2022	Fontanier
10.1016/j.pocean.2008.07.004	ABI	North East Atlantic Ocean	7	2008	Koho
10.1016/j.ecss.2011.05.029	ABI	North East Atlantic Ocean	6	2011	De La Rosa
10.1016/j.orggeochem.2006.07.025	ABI	North East Atlantic Ocean	5	2006	Capel
10.3354/meps203181	ABI	North East Atlantic Ocean	4	2000	Boschker
10.1007/s00227-012-2110-7	ABI	North East Atlantic Ocean	3	2013	Magni
10.1016/j.csr.2007.10.004	ABI	North East Atlantic Ocean	2	2008	Ortega
10.1016/j.rsma.2021.101834	ACS	North East Atlantic Ocean	4	2021	Grey

Publication	Sub-region	Region Name	Freq	Year	Author
10.1016/j.ecss.2019.05.014	ACS	North East Atlantic Ocean	1	2019	Jordan
10.1002/lno.12299	ANS	North East Atlantic Ocean	582	2023	Leiva et al.
10.3389/fmars.2023.1141448	ANS	North East Atlantic Ocean	338	2023	Spiegel
10.5194/bg-18-2139-2021	ANS	North East Atlantic Ocean	256	2021	Diesing
10.1029/2019JG005430	ANS	North East Atlantic Ocean	159	2020	Dahl
10.1029/2023JG007978	ANS	North East Atlantic Ocean	114	2024	Watts
10.1371/journal.pone.0167493	ANS	North East Atlantic Ocean	82	2016	Dahl
10.1016/j.scitotenv.2023.163957	ANS	North East Atlantic Ocean	44	2023	Mazarrasa
10.1038/s41598-020-70403-5	ANS	North East Atlantic Ocean	44	2020	Dahl
10.1038/s41598-024-74760-3	ANS	North East Atlantic Ocean	43	2024	Gagnon
10.1371/journal.pclm.0000099	ANS	North East Atlantic Ocean	43	2023	Dahl
10.3389/fmars.2021.811533	ANS	North East Atlantic Ocean	42	2022	Asplund
10.1002/ece3.5962	ANS	North East Atlantic Ocean	40	2020	Mueller
10.1007/s00227-011-1819-z	ANS	North East Atlantic Ocean	37	2012	Gullström
10.1016/j.envres.2015.05.018	ANS	North East Atlantic Ocean	33	2015	Sähring
10.5194/bg-16-3835-2019	ANS	North East Atlantic Ocean	29	2019	Charrieau
10.1016/j.scitotenv.2014.12.063	ANS	North East Atlantic Ocean	17	2015	Zhao
10.1016/j.csr.2015.06.009	ANS	North East Atlantic Ocean	15	2015	Oehler
10.1016/j.csr.2016.03.020	ANS	North East Atlantic Ocean	14	2016	Kaiser
10.1007/s11368-016-1500-8	ANS	North East Atlantic Ocean	11	2017	Hansen
10.1007/s00227-012-2110-7	ANS	North East Atlantic Ocean	10	2013	Magni
10.1016/j.ecss.2017.02.002	ANS	North East Atlantic Ocean	9	2017	Le Guitton
10.1007/s10533-008-9191-x	ANS	North East Atlantic Ocean	8	2008	Rauch
10.3389/fmicb.2015.01290	ANS	North East Atlantic Ocean	6	2015	Oni
10.1093/femsec/fiz131	ANS	North East Atlantic Ocean	5	2019	Aepfler
10.1016/j.csr.2020.104327	ANS	North East Atlantic Ocean	4	2021	De Borger
10.1002/lno.11009	ANS	North East Atlantic Ocean	3	2018	Dahl
10.1016/j.gca.2008.03.016	ANS	North East Atlantic Ocean	3	2008	Knab
10.1016/j.csr.2018.05.005	ANS	North East Atlantic Ocean	2	2019	Rosales Villa
10.1016/j.ecss.2008.02.018	ANS	North East Atlantic Ocean	2	2008	Engelsen
10.5194/bg-15-6979-2018	ANS	North East Atlantic Ocean	1	2018	Lenstra

Table S 1. Sediment carbon stocks per MSFD subregion and EUNIS habitat type

Showing only habitats with >10 Mt of carbon stores in the top 0.1m of sediment per subregion. Total area of each habitat is shown as 1000s of km². Average predicted carbon density is shown as kg/m². Carbon stocks are expressed in Mt as the product of average carbon density and total area of each habitat.

EUNIS code	Description	Subregion	Reg	Region	Area km ² x 1000	C kg/m ²	% OC	Mt OC
A6	Deep-sea bed	Bay of Biscay and the Iberian Coast	ATL	North East Atlantic Ocean	420	0.22	0.13	93
A6.5	Deep-sea mud				194	0.32	0.19	62
A5.37	Deep circalittoral mud				33	0.65	0.29	21
A5.27	Deep circalittoral sand				36	0.52	0.23	19
NA	NA				47	0.32	0.12	15
A5.25 or A5.26	Circalittoral fine sand or Circalittoral muddy sand				15	0.67	0.72	10
A6.5	Deep-sea mud	Celtic Seas	ATL	North East Atlantic Ocean	171	0.30	0.16	51
A6	Deep-sea bed		ATL		158	0.26	0.12	42
A5.27	Deep circalittoral sand		ATL		59	0.65	0.27	38
A5.15	Deep circalittoral coarse sediment		ATL		50	0.75	0.34	38
NA	NA		ATL		31	0.75	0.58	23
A5.37	Deep circalittoral mud		ATL		27	0.54	0.23	15
A6	Deep-sea bed	Macaronesia	ATL	North East Atlantic Ocean	2096	0.16	0.07	334
A6.5	Deep-sea mud		ATL		1569	0.14	0.08	223
A6.5	Deep-sea mud	Greater North Sea, incl. the Kattegat and the English Channel	ATL	North East Atlantic Ocean	58	0.77	0.33	44
A5.27	Deep circalittoral sand	Greater North Sea, incl. the Kattegat and the English Channel	ATL		107	0.30	0.24	33
A5.37	Deep circalittoral mud	Greater North Sea, incl. the Kattegat and the English Channel	ATL		65	0.41	0.32	27
A5.25 or A5.26	Circalittoral fine sand or	Greater North Sea, incl. the	ATL		47	0.30	0.56	14

EUNIS code	Description	Subregion	Reg	Region	Area km ² x 1000	C kg/m ²	% OC	Mt OC
	Circalittoral muddy sand	Kattegat and the English Channel						
A5.15	Deep circalittoral coarse sediment	Greater North Sea, incl. the Kattegat and the English Channel	ATL		25	0.53	0.26	13
A5.44	Circalittoral mixed sediments	Baltic Sea	BAL	Baltic Sea	97	0.48	0.49	47
A5.26 or A5.35 or A5.36	Circalittoral muddy sand or Circalittoral sandy mud or Circalittoral fine mud	Baltic Sea	BAL		49	0.55	0.54	27
A5.27 or A5.37	Deep circalittoral sand or Deep circalittoral mud	Baltic Sea	BAL		41	0.49	0.80	20
A5.25	Circalittoral fine sand	Baltic Sea	BAL		28	0.49	0.43	14
A5.45	Deep circalittoral mixed sediments	Baltic Sea	BAL		26	0.46	0.57	12
A5.36	Circalittoral fine mud	Baltic Sea	BAL		19	0.63	0.79	12
A5.23	Infralittoral fine sands	Baltic Sea	BAL		23	0.51	1.49	12
A5.23	Infralittoral fine sand	Baltic Sea	BAL		23	0.51	1.49	12
A5.43	Infralittoral mixed sediments	Baltic Sea	BAL		21	0.50	1.75	11
Na	NA	Black Sea	BLK	Black Sea	421	0.54	0.30	226
A6	Deep-sea bed	Greater North Atlantic	ATL	North East Atlantic Ocean	3947	0.23	0.12	894
NA	NA	Greater North Atlantic	ATL		2008	0.29	0.21	575
A6.5	Deep-sea mud	Greater North Atlantic	ATL		1487	0.28	0.25	422
A5.27	Deep circalittoral sand	Greater North Atlantic	ATL		294	0.58	0.37	169
A5.15	Deep circalittoral coarse sediment	Greater North Atlantic	ATL		197	0.64	0.44	126
Na	NA	Greater North Atlantic	ATL		200	0.61	1.02	122
A5.37	Deep circalittoral mud	Greater North Atlantic	ATL		257	0.45	0.52	116
A6.2	Deep-sea mixed substrata	Greater North Atlantic	ATL		127	0.29	0.19	36

EUNIS code	Description	Subregion	Reg	Region	Area km ² x 1000	C kg/m ²	% OC	Mt OC
A5.25 or A5.26	Circalittoral fine sand or Circalittoral muddy sand	Greater North Atlantic	ATL		47	0.74	0.76	35
NA	NA	Greater North Atlantic	ATL		91	0.35	0.22	32
A5.14	Circalittoral coarse sediment	Greater North Atlantic	ATL		54	0.54	0.59	30
A5.35	Circalittoral sandy mud	Greater North Atlantic	ATL		20	0.96	1.03	19
A5.45	Deep circalittoral mixed sediments	Greater North Atlantic	ATL		40	0.38	0.59	16
A4.33	Faunal communities on deep low energy circalittoral rock	Greater North Atlantic	ATL		33	0.46	0.73	15
A6.11	Deep-sea rock	Greater North Atlantic	ATL		34	0.37	0.31	13
A5.46	Mediterranean biocoenosis of coastal detritic bottoms	Adriatic Sea	MED	Mediterranean Sea	21	0.82	0.62	17
A5.39	Mediterranean biocoenosis of coastal terrigenous muds		MED		21	0.63	0.49	13
A5.47	Mediterranean communities of shelf-edge detritic bottoms		MED		22	0.50	0.29	11
A6.51	Mediterranean communities of bathyal muds	Aegean-Levantine Sea	MED		342	0.30	0.06	101
A6.511	Facies of sandy muds with <i>Thenea muricata</i>	Aegean-Levantine Sea	MED		232	0.31	0.07	71
A5.39	Mediterranean biocoenosis of coastal terrigenous muds		MED		21	0.93	0.70	20
A5.46	Mediterranean biocoenosis of coastal detritic bottoms		MED		26	0.65	0.51	17
A5.38	Mediterranean biocoenosis of muddy detritic bottoms		MED		20	0.71	0.49	14

EUNIS code	Description	Subregion	Reg	Region	Area km ² x 1000	C kg/m ²	% OC	Mt OC
A5.47	Mediterranean communities of shelf-edge detritic bottoms		MED		20	0.68	0.35	14
A5.23	Infralittoral fine sands		MED		14	0.76	0.72	11
A5.23	Infralittoral fine sand		MED		14	0.76	0.72	11
A6.51	Mediterranean communities of bathyal muds	Ionian Sea and the Central Mediterranean Sea	MED	Mediterranean Sea	376	0.25	0.05	95
A6.511	Facies of sandy muds with <i>Thenaea muricata</i>		MED		190	0.26	0.07	49
A5.46	Mediterranean biocoenosis of coastal detritic bottoms		MED		57	0.32	0.20	18
A5.23	Infralittoral fine sands		MED		32	0.48	0.48	15
A5.23	Infralittoral fine sand		MED		32	0.48	0.48	15
A5.47	Mediterranean communities of shelf-edge detritic bottoms		MED		33	0.31	0.15	10
A6.51	Mediterranean communities of bathyal muds	Western Mediterranean Sea	MED	Mediterranean Sea	266	0.38	0.10	102
A6.52	Communities of abyssal muds		MED		268	0.36	0.06	97
A6.511	Facies of sandy muds with <i>Thenaea muricata</i>		MED		153	0.38	0.10	58
A5.46	Mediterranean biocoenosis of coastal detritic bottoms		MED		38	0.66	0.42	25
A5.47	Mediterranean communities of shelf-edge detritic bottoms		MED		37	0.45	0.29	17
A5.39	Mediterranean biocoenosis of coastal terrigenous muds		MED		20	0.63	0.38	13

Table S 2. Occurrence of EUNIS habitat codes across MSFD Benthic Broad Habitats (Vasquez *et al.*, 2023) in EUSeamap2023.

Nrecs refers to the number of habitat polygons present for each combination of EUNIS codes and MSFD habitats.

EUNIScomBD	MSFD_BBHT	nrecs
A6.11: Deep-sea rock	Lower bathyal rock and biogenic reef	4370
A6.11: Deep-sea rock	Abyssal	1375
A6.11: Deep-sea rock	Upper bathyal rock and biogenic reef	49791
A6.3 Deep-sea sand or A6.4 Deep-sea muddy sand	Upper bathyal sediment	10500
A6.3 Deep-sea sand or A6.4 Deep-sea muddy sand	Lower bathyal sediment	3615
A6.3 Deep-sea sand or A6.4 Deep-sea muddy sand	Abyssal	1217
A6: Deep-sea bed	Upper bathyal sediment	15133
A6: Deep-sea bed	Abyssal	43467
A6: Deep-sea bed	Lower bathyal sediment	172
A6.2: Deep-sea mixed substrata	Upper bathyal sediment	7178
A6.2: Deep-sea mixed substrata	Lower bathyal sediment	4045
A6.2: Deep-sea mixed substrata	Abyssal	1115
A6.5: Deep-sea mud	Abyssal	20119
A6.5: Deep-sea mud	Lower bathyal sediment	18452
Na	Na	964300
A5.33 or A5.34: Infralittoral sandy mud or Infralittoral fine mud	Infralittoral mud	1170
A5.35 or A5.36: Circalittoral sandy mud or Circalittoral fine mud	Circalittoral mud	739
A5.37: Deep circalittoral mud	Offshore circalittoral mud	61727
A5.27: Deep circalittoral sand	Offshore circalittoral sand	155459
A5.25 or A5.26: Circalittoral fine sand or Circalittoral muddy sand	Circalittoral sand	56537
A5.23 or A5.24: Infralittoral fine sand or Infralittoral muddy sand	Infralittoral sand	53570
A5.15: Deep circalittoral coarse sediment	Offshore circalittoral coarse sediment	143035
A5.13: Infralittoral coarse sediment	Infralittoral coarse sediment	81097
A5.14: Circalittoral coarse sediment	Circalittoral coarse sediment	71553
A4.12 or A4.27 or A4.33: Sponge communities on deep circalittoral rock or Faunal communities on deep moderate energy circalittoral rock or Faunal communities on deep low energy circalittoral rock	Offshore circalittoral rock and biogenic reef	61579
A3: Infralittoral rock and other hard substrata	Infralittoral rock and biogenic reef	162929
A4: Circalittoral rock and other hard substrata	Circalittoral rock and biogenic reef	51252
A5.33: Infralittoral sandy mud	Infralittoral mud	25082
A5.35: Circalittoral sandy mud	Circalittoral mud	21952
A6.5: Deep-sea mud	Upper bathyal sediment	70851
A5.45: Deep circalittoral mixed sediments	Offshore circalittoral mixed sediment	11476

EUNIScomBD	MSFD_BBHT	nrecs
A5.44: Circalittoral mixed sediments	Circalittoral mixed sediment	29763
A5.43: Infralittoral mixed sediments	Infralittoral mixed sediment	43794
A3.1: Atlantic and Mediterranean high energy infralittoral rock	Infralittoral rock and biogenic reef	33998
A3.2: Atlantic and Mediterranean moderate energy infralittoral rock	Infralittoral rock and biogenic reef	36574
A4.2: Atlantic and Mediterranean moderate energy circalittoral rock	Circalittoral rock and biogenic reef	40882
A4.1: Atlantic and Mediterranean high energy circalittoral rock	Circalittoral rock and biogenic reef	40716
A3.3: Atlantic and Mediterranean low energy infralittoral rock	Infralittoral rock and biogenic reef	83774
A4.27: Faunal communities on deep moderate energy circalittoral rock	Offshore circalittoral rock and biogenic reef	31636
A4.33: Faunal communities on deep low energy circalittoral rock	Offshore circalittoral rock and biogenic reef	105653
A4.12: Sponge communities on deep circalittoral rock	Offshore circalittoral rock and biogenic reef	13644
A4.3: Atlantic and Mediterranean low energy circalittoral rock	Circalittoral rock and biogenic reef	72778
A6: Deep-sea bed	Lower bathyal sediment or Lower bathyal rock and biogenic reef	12519
A6: Deep-sea bed	Upper bathyal sediment or Upper bathyal rock and biogenic reef	46667
A5.36: Circalittoral fine mud	Circalittoral mud	9841
A5.34: Infralittoral fine mud	Infralittoral mud	19268
A6.611: Deep-sea Lophelia pertusa reefs	Upper bathyal rock and biogenic reef	654
A5.23: Infralittoral fine sands	Infralittoral sand	135742
A4.26 or A4.32: Mediterranean coralligenous communities moderately exposed to hydrodynamic action or Mediterranean coralligenous communities sheltered from hydrodynamic action	Circalittoral rock and biogenic reef	10371
A5.46: Mediterranean biocoenosis of coastal detritic bottoms	Circalittoral sand	22293
A5.47: Mediterranean communities of shelf-edge detritic bottoms	Offshore circalittoral sand	8596
A6.3: Deep-sea sand	Upper bathyal sediment	1124
A6.3: Deep-sea sand	Lower bathyal sediment	216
A5.47: Mediterranean communities of shelf-edge detritic bottoms	Offshore circalittoral coarse sediment	1985
A5.46: Mediterranean biocoenosis of coastal detritic bottoms	Circalittoral coarse sediment	10584
A5.46: Mediterranean biocoenosis of coastal detritic bottoms	Circalittoral mixed sediment	1200
A5.47: Mediterranean communities of shelf-edge detritic bottoms	Offshore circalittoral mixed sediment	596
A5.13: Infralittoral coarse sediment	Infralittoral mixed sediment	1037

EUNIScombD	MSFD_BBHT	nrecs
A6.11: Deep-sea bedrock	Upper bathyal rock and biogenic reef	1082
A6.11: Deep-sea bedrock	Lower bathyal rock and biogenic reef	583
A6.51: Mediterranean communities of bathyal muds	Lower bathyal sediment	568
A5.39: Mediterranean biocoenosis of coastal terrigenous muds	Offshore circalittoral mud	2149
A5.39: Mediterranean biocoenosis of coastal terrigenous muds	Circalittoral mud	2583
A6.51: Mediterranean communities of bathyal muds	Upper bathyal sediment	1271
A5.47: Mediterranean communities of shelf-edge detritic bottoms	Offshore circalittoral mud	5446
A6.511: Facies of sandy muds with <i>Thenea muricata</i>	Upper bathyal sediment	1948
A5.38: Mediterranean biocoenosis of muddy detritic bottoms	Circalittoral mud	5272
A6.511: Facies of sandy muds with <i>Thenea muricata</i>	Lower bathyal sediment	1468
A6.4: Deep-sea muddy sand	Lower bathyal sediment	646
A6.4: Deep-sea muddy sand	Upper bathyal sediment	1783
A5.535: [<i>Posidonia</i>] beds	Infralittoral rock and biogenic reef	31919
A5.5353: Facies of dead "mattes" of [<i>Posidonia oceanica</i>]	Infralittoral rock and biogenic reef	7487
A4.26D: Coralligenous platforms	Circalittoral rock and biogenic reef	281
A6.6: Deep-sea bioherms	Upper bathyal rock and biogenic reef	13
A6.6: Deep-sea bioherms	Lower bathyal rock and biogenic reef	4
A6.61: Communities of deep-sea corals	Lower bathyal rock and biogenic reef	42
A6.4: Deep-sea muddy sand	Abyssal	7
A6.52: Communities of abyssal muds	Abyssal	167
A5.6: Sublittoral biogenic reefs	Offshore circalittoral rock and biogenic reef	2462
A5.61: Sublittoral polychaete worm reefs on sediment	Circalittoral rock and biogenic reef	486
A5.435: Oyster beds on shallow sublittoral muddy mixed sediment	Infralittoral rock and biogenic reef	73
A5: Sublittoral sediment	Na	21024
A5.625: [<i>Mytilus edulis</i>] beds on sublittoral sediment	Infralittoral rock and biogenic reef	1004
A5.611: [<i>Sabellaria spinulosa</i>] on stable circalittoral mixed sediment	Circalittoral rock and biogenic reef	505
A5.625: [<i>Mytilus edulis</i>] beds on sublittoral sediment	Circalittoral rock and biogenic reef	460
A5.612: <i>Sabellaria alveolata</i> on variable salinity sublittoral mixed sediment	Infralittoral rock and biogenic reef	169
A5.61: Sublittoral polychaete worm reefs on sediment	Infralittoral rock and biogenic reef	552
A5.62: Sublittoral mussel beds on sediment	Circalittoral rock and biogenic reef	195
A5.6: Sublittoral biogenic reefs	Infralittoral rock and biogenic reef	223
A5.6: Sublittoral biogenic reefs	Circalittoral rock and biogenic reef	120

EUNIScombD	MSFD_BBHT	nrecs
A5.23 or A5.33 or A5.34: Infralittoral fine sands or Infralittoral sandy mud or Infralittoral fine mud	Na	346
A5.39 or A5.47: Mediterranean biocoenosis of coastal terrigenous muds or Mediterranean communities of shelf-edge detritic bottoms	Na	510
A6.51 or A6.511 or A6.4: Mediterranean communities of bathyal muds or Facies of sandy muds with <i>Thenea muricata</i> or Deep-sea muddy sand	Na	244
A5.39 or A5.46 or A5.38: Mediterranean biocoenosis of coastal terrigenous muds or Mediterranean biocoenosis of coastal detritic bottoms or Mediterranean biocoenosis of muddy detritic bottoms	Na	224
A6: Deep-sea bed	Na	3
A6.11: Deep-sea bedrock	Abyssal	12
A6.3: Deep-sea sand	Abyssal	9
Na	Infralittoral sand	2158
Na	Infralittoral mud	1465
A5.25: Circalittoral fine sand	Circalittoral sand	6639
A5.35: Circalittoral sandy mud	Circalittoral mud or Offshore circalittoral mud	125
A5.26: Circalittoral muddy sand	Circalittoral sand	1700
A5.5352: Ecomorphosis of "'barrier-reef'" [<i>Posidonia oceanica</i>] meadows	Infralittoral rock and biogenic reef	6
A5.14: Circalittoral coarse sediment	Circalittoral mixed sediment	7
A5.529: Facies with [<i>Ficopomatus enigmaticus</i>]	Infralittoral rock and biogenic reef	3
Na	Infralittoral mixed sediment	968
Na	Infralittoral rock and biogenic reef	565
Na	Infralittoral mud or Infralittoral sand	94
Na	Upper bathyal sediment or Lower bathyal sediment	800
Na	Abyssal	22
Na	Circalittoral sand	244
Na	Offshore circalittoral sand	322
Na	Circalittoral coarse sediment	271
Na	Infralittoral coarse sediment	1556
Na	Offshore circalittoral coarse sediment	28
Na	Circalittoral mixed sediment	461
Na	Offshore circalittoral mixed sediment	106
Na	Circalittoral rock and biogenic reef	234
Na	Circalittoral mud	591
Na	Offshore circalittoral mud	802
A5.39 or A5.46 or A5.38: Mediterranean biocoenosis of coastal terrigenous muds or Mediterranean	Circalittoral mud or Circalittoral sand	4

EUNIScombD	MSFD_BBHT	nrecs
biocoenosis of coastal detritic bottoms or Mediterranean biocoenosis of muddy detritic bottoms		
A5.23 or A5.33 or A5.34: Infralittoral fine sands or Infralittoral sandy mud or Infralittoral fine mud	Infralittoral mud or Infralittoral sand	328
A5.39 or A5.47: Mediterranean biocoenosis of coastal terrigenous muds or Mediterranean communities of shelf-edge detritic bottoms	Offshore circalittoral mud or Offshore circalittoral sand	3
A6.51: Mediterranean communities of bathyal muds	Upper bathyal sediment or Lower bathyal sediment	16
A6.511: Facies of sandy muds with <i>Thenea muricata</i>	Upper bathyal sediment or Lower bathyal sediment	4
A6.4: Deep-sea muddy sand	Upper bathyal sediment or Lower bathyal sediment	1
A5.62: Sublittoral mussel beds on sediment	Infralittoral rock and biogenic reef	3282
A5.631: Circalittoral <i>Lophelia pertusa</i> reefs	Offshore circalittoral rock and biogenic reef	90
A5.613: [<i>Serpula vermicularis</i>] reefs on very sheltered circalittoral muddy sand	Infralittoral rock and biogenic reef	52
A5.613: [<i>Serpula vermicularis</i>] reefs on very sheltered circalittoral muddy sand	Circalittoral rock and biogenic reef	1
A5.434: [<i>Limaria hians</i>] beds in tide-swept sublittoral muddy mixed sediment	Infralittoral rock and biogenic reef	241
A5.24 or A5.33 or A5.34: Infralittoral muddy sand or Infralittoral sandy mud or Infralittoral fine mud	Infralittoral mud or Infralittoral sand	12234
A5.23: Infralittoral fine sand	Infralittoral sand	7470
A4.4: Baltic exposed circalittoral rock	Circalittoral rock and biogenic reef	2035
A3.5: Baltic moderately exposed infralittoral rock	Infralittoral rock and biogenic reef	6196
A3.6: Baltic sheltered infralittoral rock	Infralittoral rock and biogenic reef	8085
A4.5: Baltic moderately exposed circalittoral rock	Circalittoral rock and biogenic reef	7783
A5.24: Infralittoral muddy sand	Infralittoral sand	1983
A5.27 or A5.37: Deep circalittoral sand or Deep circalittoral mud	Offshore circalittoral mud or Offshore circalittoral sand	215
A5.26 or A5.35 or A5.36: Circalittoral muddy sand or Circalittoral sandy mud or Circalittoral fine mud	Circalittoral mud or Circalittoral sand	6978
A3.4: Baltic exposed infralittoral rock	Infralittoral rock and biogenic reef	1317
Na	Offshore circalittoral rock and biogenic reef	292
A4.6: Baltic sheltered Circalittoral rock	Circalittoral rock and biogenic reef	7610

Table S 4. Scenario outcomes for European seabed disturbance scenarios

Except for percentages and SAR values, values shown are summed values of Mt C across model domains (non-NA grid cells). Total sediment organic carbon disturbed may be obtained by multiplying density values by grid cell areas. 'Total before effect' is the sum of density values before exclusion, 'total effect' after exclusion. 'total SAR before effect' and 'total SAR effect' are the summed SAR values before and after respectively. 'OC saved' is the difference between summed density values before and after exclusion.

Scenario	Total before effect	Total effect	Total SAR before effect	Total SAR effect	SAR type	Exclusion	OC density type	OC saved
1	347	305	35533	31308	ICES	MPAs	Wilson <i>et al.</i> 2018	42.8
1	239	208	26219	22926	OSPAR	MPAs	Wilson <i>et al.</i> 2018	31.3
1	270	212	24572	19767	GFW	MPAs	Wilson <i>et al.</i> 2018	58.0
1	546	461	46981	41752	ICES	MPAs	Atwood <i>et al.</i> 2020	85.2
1	383	316	30790	26648	OSPAR	MPAs	Atwood <i>et al.</i> 2020	67.0
1	1927	1699	103779	92939	GFW	MPAs	Atwood <i>et al.</i> 2020	227.8
1	126	113	17166	14880	ICES	MPAs	Diesing <i>et al.</i> , 2021/24	13.4
1	97	85	12738	10748	OSPAR	MPAs	Diesing <i>et al.</i> , 2021/24	12.5
1	137	117	19662	16313	GFW	MPAs	Diesing <i>et al.</i> , 2021/24	20.0
1	90	72	15656	12820	ICES	MPAs	Smeaton <i>et al.</i> 2021	18.1
1	65	53	11642	9642	OSPAR	MPAs	Smeaton <i>et al.</i> 2021	12.3
1	68	52	10249	7913	GFW	MPAs	Smeaton <i>et al.</i> 2021	16.0
1	85	71	12390	10204	ICES	MPAs	Bockelmann <i>et al.</i> 2018	14.0
1	80	66	11037	9138	OSPAR	MPAs	Bockelmann <i>et al.</i> 2018	14.3
1	105	84	12387	9210	GFW	MPAs	Bockelmann <i>et al.</i> 2018	21.3
1	411	359	47582	42265	ICES	MPAs	MPA Europe 2025	51.8
1	283	243	31304	27095	OSPAR	MPAs	MPA Europe 2025	40.1
1	1451	1306	108770	97316	GFW	MPAs	MPA Europe 2025	144.9
2	347	335	35533	34179	ICES	OWFs	Wilson <i>et al.</i> 2018	12.7
2	239	231	26219	25196	OSPAR	OWFs	Wilson <i>et al.</i> 2018	8.5
2	270	262	24572	23607	GFW	OWFs	Wilson <i>et al.</i> 2018	8.5
2	546	520	46981	45404	ICES	OWFs	Atwood <i>et al.</i> 2020	25.7
2	383	363	30790	29627	OSPAR	OWFs	Atwood <i>et al.</i> 2020	19.4
2	1927	1898	103779	102211	GFW	OWFs	Atwood <i>et al.</i> 2020	28.4
2	126	121	17166	16181	ICES	OWFs	Diesing <i>et al.</i> , 2021/24	5.3
2	97	92	12738	11835	OSPAR	OWFs	Diesing <i>et al.</i> , 2021/24	5.1
2	137	132	19662	18774	GFW	OWFs	Diesing <i>et al.</i> , 2021/24	5.4
2	90	88	15656	15261	ICES	OWFs	Smeaton <i>et al.</i> 2021	2.4
2	65	63	11642	11306	OSPAR	OWFs	Smeaton <i>et al.</i> 2021	2.0
2	68	66	10249	9887	GFW	OWFs	Smeaton <i>et al.</i> 2021	2.3

Scenario	Total before effect	Total effect	Total SAR before effect	Total SAR effect	SAR type	Exclusion	OC density type	OC saved
2	85	80	12390	11401	ICES	OWFs	Bockelmann <i>et al.</i> 2018	5.1
2	80	74	11037	10125	OSPAR	OWFs	Bockelmann <i>et al.</i> 2018	5.7
2	105	98	12387	11484	GFW	OWFs	Bockelmann <i>et al.</i> 2018	6.7
2	411	397	47582	45982	ICES	OWFs	MPA Europe 2025	14.4
2	283	274	31304	30111	OSPAR	OWFs	MPA Europe 2025	9.3
2	1451	1436	108770	107167	GFW	OWFs	MPA Europe 2025	15.5
3	347	155	35533	17442	ICES	CFGs	Wilson <i>et al.</i> 2018	192.4
3	239	142	26219	15846	OSPAR	CFGs	Wilson <i>et al.</i> 2018	97.4
3	270	92	24572	9230	GFW	CFGs	Wilson <i>et al.</i> 2018	178.3
3	546	288	46981	26478	ICES	CFGs	Atwood <i>et al.</i> 2020	257.7
3	383	212	30790	18115	OSPAR	CFGs	Atwood <i>et al.</i> 2020	171.0
3	1927	345	103779	30306	GFW	CFGs	Atwood <i>et al.</i> 2020	1581.9
3	126	91	17166	12527	ICES	CFGs	Diesing <i>et al.</i> , 2021/24	34.5
3	97	63	12738	8767	OSPAR	CFGs	Diesing <i>et al.</i> , 2021/24	34.1
3	137	62	19662	9092	GFW	CFGs	Diesing <i>et al.</i> , 2021/24	75.3
3	90	47	15656	8442	ICES	CFGs	Smeaton <i>et al.</i> 2021	43.4
3	65	42	11642	7605	OSPAR	CFGs	Smeaton <i>et al.</i> 2021	23.7
3	68	23	10249	3924	GFW	CFGs	Smeaton <i>et al.</i> 2021	44.9
3	85	54	12390	8381	ICES	CFGs	Bockelmann <i>et al.</i> 2018	31.1
3	80	45	11037	7296	OSPAR	CFGs	Bockelmann <i>et al.</i> 2018	35.0
3	105	26	12387	4353	GFW	CFGs	Bockelmann <i>et al.</i> 2018	79.2
3	411	191	47582	27002	ICES	CFGs	MPA Europe 2025	220.1
3	283	150	31304	18584	OSPAR	CFGs	MPA Europe 2025	133.1
3	1451	199	108770	30894	GFW	CFGs	MPA Europe 2025	1252.4
4	347	194	35533	25616	ICES	CPZs	Wilson <i>et al.</i> 2018	153.4
4	239	147	26219	20282	OSPAR	CPZs	Wilson <i>et al.</i> 2018	91.8
4	270	142	24572	17399	GFW	CPZs	Wilson <i>et al.</i> 2018	128.1
4	546	441	46981	43132	ICES	CPZs	Atwood <i>et al.</i> 2020	104.7
4	383	305	30790	27919	OSPAR	CPZs	Atwood <i>et al.</i> 2020	78.4
4	1927	1173	103779	81103	GFW	CPZs	Atwood <i>et al.</i> 2020	753.7
4	126	49	17166	9830	ICES	CPZs	Diesing <i>et al.</i> , 2021/24	76.7
4	97	38	12738	7318	OSPAR	CPZs	Diesing <i>et al.</i> , 2021/24	58.8
4	137	59	19662	12273	GFW	CPZs	Diesing <i>et al.</i> , 2021/24	78.4

Scenario	Total before effect	Total effect	Total SAR before effect	Total SAR effect	SAR type	Exclusion	OC density type	OC saved
4	90	51	15656	9804	ICES	CPZs	Smeaton <i>et al.</i> 2021	39.3
4	65	38	11642	7477	OSPAR	CPZs	Smeaton <i>et al.</i> 2021	27.2
4	68	37	10249	6308	GFW	CPZs	Smeaton <i>et al.</i> 2021	30.7
4	85	23	12390	7941	ICES	CPZs	Bockelmann <i>et al.</i> 2018	61.9
4	80	21	11037	6936	OSPAR	CPZs	Bockelmann <i>et al.</i> 2018	59.2
4	105	22	12387	7784	GFW	CPZs	Bockelmann <i>et al.</i> 2018	83.6
4	411	279	47582	39413	ICES	CPZs	MPA Europe 2025	132.5
4	283	203	31304	26277	OSPAR	CPZs	MPA Europe 2025	80.1
4	1451	733	108770	83611	GFW	CPZs	MPA Europe 2025	718.3

Table S 5. As For Table S 4 but scenario outcomes for North Sea seabed

Total effect	Total SAR before effect	Total SAR effect	SAR type	Impact	OC density type	OCS saved
99	12900	10863	ICES	MPAs	Wilson <i>et al.</i> 2018	18.5
83	10919	9320	OSPAR	MPAs	Wilson <i>et al.</i> 2018	14.9
97	11915	9092	GFW	MPAs	Wilson <i>et al.</i> 2018	33.0
149	14295	11848	ICES	MPAs	Atwood <i>et al.</i> 2020	49.8
133	12689	10615	OSPAR	MPAs	Atwood <i>et al.</i> 2020	41.9
185	14138	10853	GFW	MPAs	Atwood <i>et al.</i> 2020	79.6
76	12610	10355	ICES	MPAs	Diesing <i>et al.</i> 2021/24	13.2
69	11146	9193	OSPAR	MPAs	Diesing <i>et al.</i> 2021/24	12.2
79	12864	9582	GFW	MPAs	Diesing <i>et al.</i> 2021/24	19.8
29	7156	5822	ICES	MPAs	Smeaton <i>et al.</i> 2021	7.8
25	6031	5026	OSPAR	MPAs	Smeaton <i>et al.</i> 2021	5.7
23	4974	3713	GFW	MPAs	Smeaton <i>et al.</i> 2021	8.0
71	12390	10204	ICES	MPAs	Bockelmann <i>et al.</i> 2018	14.0
66	11036	9138	OSPAR	MPAs	Bockelmann <i>et al.</i> 2018	14.3
84	12386	9210	GFW	MPAs	Bockelmann <i>et al.</i> 2018	21.3
95	14816	12292	ICES	MPAs	MPA Europe 2025	21.8
85	13055	10922	OSPAR	MPAs	MPA Europe 2025	19.2

Total effect	Total SAR before effect	Total SAR effect	SAR type	Impact	OC density type	OCS saved
105	14784	11346	GFW	MPAs	MPA Europe 2025	34.6
110	12900	11960	ICES	OWFs	Wilson <i>et al.</i> 2018	7.5
91	10919	10083	OSPAR	OWFs	Wilson <i>et al.</i> 2018	6.6
124	11915	11104	GFW	OWFs	Wilson <i>et al.</i> 2018	6.8
182	14295	13284	ICES	OWFs	Atwood <i>et al.</i> 2020	16.9
160	12689	11763	OSPAR	OWFs	Atwood <i>et al.</i> 2020	15.3
247	14138	13170	GFW	OWFs	Atwood <i>et al.</i> 2020	17.3
84	12610	11625	ICES	OWFs	Diesing <i>et al.</i> , 2021/24	5.3
76	11146	10243	OSPAR	OWFs	Diesing <i>et al.</i> , 2021/24	5.1
93	12864	11976	GFW	OWFs	Diesing <i>et al.</i> , 2021/24	5.4
35	7156	6832	ICES	OWFs	Smeaton <i>et al.</i> 2021	2.0
29	6031	5753	OSPAR	OWFs	Smeaton <i>et al.</i> 2021	1.6
29	4974	4658	GFW	OWFs	Smeaton <i>et al.</i> 2021	2.0
80	12390	11400	ICES	OWFs	Bockelmann <i>et al.</i> 2018	5.1
74	11036	10124	OSPAR	OWFs	Bockelmann <i>et al.</i> 2018	5.7
98	12386	11484	GFW	OWFs	Bockelmann <i>et al.</i> 2018	6.7
111	14816	13781	ICES	OWFs	MPA Europe 2025	6.0
98	13055	12099	OSPAR	OWFs	MPA Europe 2025	5.8
133	14784	13787	GFW	OWFs	MPA Europe 2025	6.9
80	12900	8903	ICES	CFGs	Wilson <i>et al.</i> 2018	37.3
71	10919	7841	OSPAR	CFGs	Wilson <i>et al.</i> 2018	27.3
43	11915	4669	GFW	CFGs	Wilson <i>et al.</i> 2018	87.6
131	14295	9255	ICES	CFGs	Atwood <i>et al.</i> 2020	67.8
110	12689	7997	OSPAR	CFGs	Atwood <i>et al.</i> 2020	65.5
66	14138	4717	GFW	CFGs	Atwood <i>et al.</i> 2020	198.3
58	12610	8542	ICES	CFGs	Diesing <i>et al.</i> , 2021/24	31.2
50	11146	7420	OSPAR	CFGs	Diesing <i>et al.</i> , 2021/24	31.0
30	12864	4487	GFW	CFGs	Diesing <i>et al.</i> , 2021/24	68.4
24	7156	4685	ICES	CFGs	Smeaton <i>et al.</i> 2021	12.9
21	6031	4160	OSPAR	CFGs	Smeaton <i>et al.</i> 2021	9.3
12	4974	2090	GFW	CFGs	Smeaton <i>et al.</i> 2021	19.1
54	12390	8381	ICES	CFGs	Bockelmann <i>et al.</i> 2018	31.1
45	11036	7296	OSPAR	CFGs	Bockelmann <i>et al.</i> 2018	35.0
26	12386	4353	GFW	CFGs	Bockelmann <i>et al.</i> 2018	79.2
74	14816	9705	ICES	CFGs	MPA Europe 2025	42.7
63	13055	8342	OSPAR	CFGs	MPA Europe 2025	40.9
37	14784	4974	GFW	CFGs	MPA Europe 2025	102.8

Total effect	Total SAR before effect	Total SAR effect	SAR type	Impact	OC density type	OCS saved
65	12900	9588	ICES	CPZs	Wilson <i>et al.</i> 2018	52.0
56	10919	8270	OSPAR	CPZs	Wilson <i>et al.</i> 2018	41.6
58	11915	7815	GFW	CPZs	Wilson <i>et al.</i> 2018	72.4
134	14295	11975	ICES	CPZs	Atwood <i>et al.</i> 2020	64.6
116	12689	10528	OSPAR	CPZs	Atwood <i>et al.</i> 2020	59.0
128	14138	9637	GFW	CPZs	Atwood <i>et al.</i> 2020	136.1
43	12610	8142	ICES	CPZs	Diesing <i>et al.</i> , 2021/24	46.8
37	11146	7009	OSPAR	CPZs	Diesing <i>et al.</i> , 2021/24	43.9
46	12864	8684	GFW	CPZs	Diesing <i>et al.</i> , 2021/24	52.6
25	7156	5014	ICES	CPZs	Smeaton <i>et al.</i> 2021	12.5
20	6031	4188	OSPAR	CPZs	Smeaton <i>et al.</i> 2021	10.5
19	4974	3345	GFW	CPZs	Smeaton <i>et al.</i> 2021	11.9
23	12390	7941	ICES	CPZs	Bockelmann <i>et al.</i> 2018	61.9
21	11036	6936	OSPAR	CPZs	Bockelmann <i>et al.</i> 2018	59.2
22	12386	7784	GFW	CPZs	Bockelmann <i>et al.</i> 2018	83.6
85	14816	12558	ICES	CPZs	MPA Europe 2025	32.2
77	13055	11147	OSPAR	CPZs	MPA Europe 2025	27.2
106	14784	12728	GFW	CPZs	MPA Europe 2025	34.1

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