Centre for Environment Fisheries & Aquaculture Science

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The role of English seabed sediments in carbon storage, impact of human activities, environmental pressures and potential management options: Evidence review

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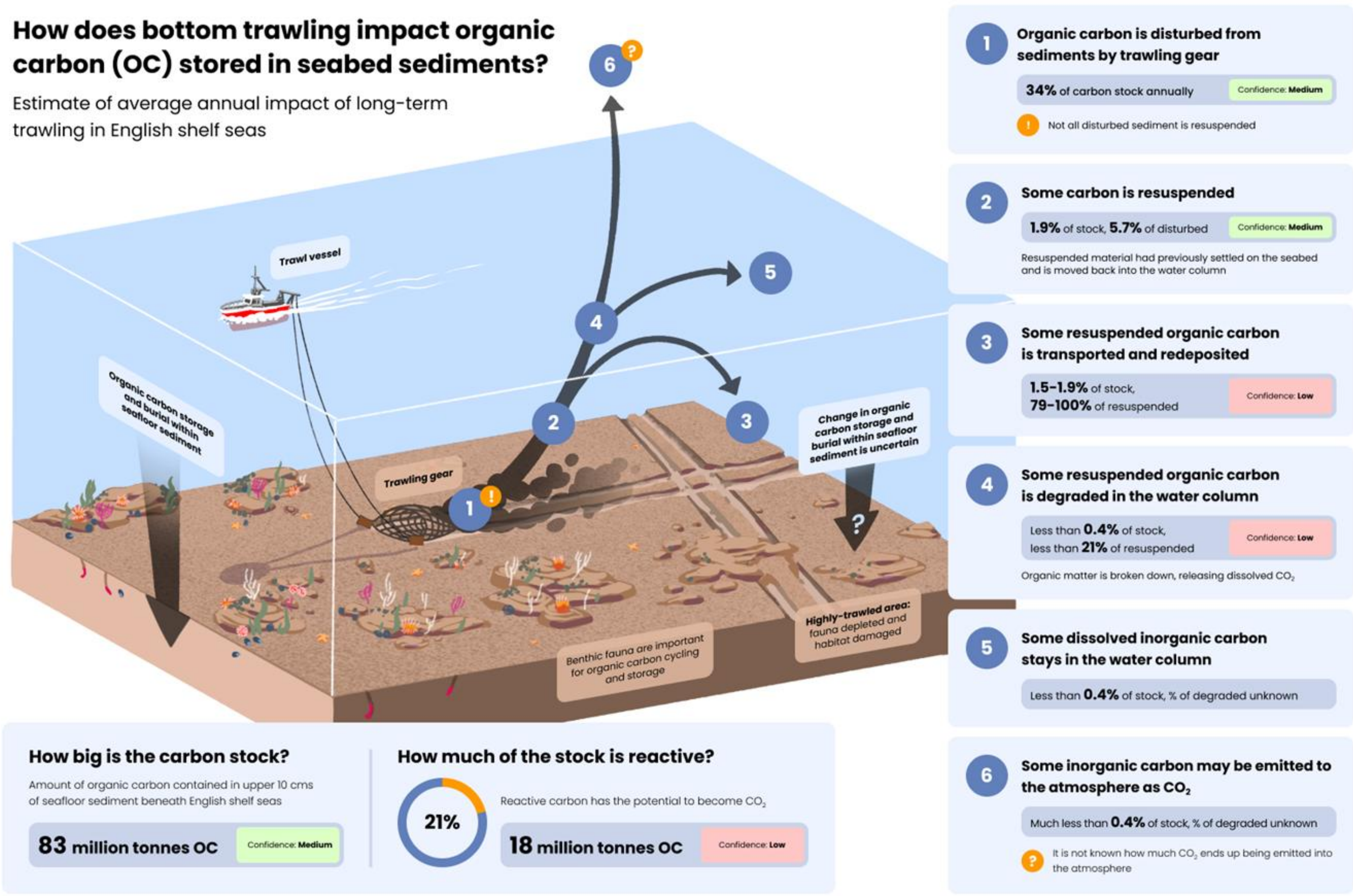

Figure 1. Summary infographic: The key processes in controlling seabed carbon and the effects of bottom trawling, with quantitative estimate of average annual impact of long-term trawling on organic carbon (OC) stored in English shelf seabed sediment and an assessment of the associated confidence in these statements.

Evidence Overview

Policy Background

The protection and restoration of marine habitats which store and sequester carbon (blue carbon) can potentially support UK goals on climate mitigation and adaptation, and also provide multiple other benefits, including supporting biodiversity. That is why UK Government established the cross-Administration UK Blue Carbon Evidence Partnership to progress the evidence base on blue carbon habitats in UK waters, advancing its commitment to protecting and restoring blue carbon habitats, and expanding these concepts to the management of carbon stores in seabed sediment, as a nature-based solution.

Aim of this Briefing

The evidence surrounding organic carbon (hereby referred to as "OC") storage in subtidal seabed sediments and the potential impact from human activities, and climate itself, is growing at pace. This technical briefing assesses the current evidence base, providing confidence levels and options for how this might direct potential next steps. It will inform the direction of Defra's work in the UK and internationally to identify and fill key evidence gaps collaboratively through existing and future programmes. This briefing also identifies a range of measures which could be taken to protect subtidal seabed sediment OC as a nature-based solution to climate change and highlights potential trade-offs.

Key Policy and evidence questions

How much organic carbon is added to and stored in UK subtidal marine sediments?

Subtidal sediments are those which are permanently submerged by water and comprise a range of sediment types from fine-grained mud to coarse-grained sands and gravels. Organic carbon (OC) is input to the seabed from the water column and derived from terrestrial (plant material, detritus) and marine sources (plants, benthos, plankton, fish detritus). OC is incorporated into the seabed and a fraction of this is lost through degradation processes controlled by local biological processes. OC stock at any geographical location, and resulting OC burial rates, are controlled by the balance between input and loss of carbon. The OC reservoir within the sediment, in which carbon is stored long-term (decades to centuries) is described by the density (kg/m^3) and stock (kg/m^2) of OC and the burial rate ($g/m^2/yr$) at which OC is added permanently to the stock.

The UK shelf contains between 240 and 524 Mt (Million tonnes) of organic carbon (880 to 1923 Mt CO_2 equivalent) in the top 10 cm of subtidal sediments. The English component alone contains between 80 and 104 Mt OC (297 to 382 Mt CO_2 equivalent). These OC stock levels in the top 10cm equate to between 1 and 5 times the annual emissions of the UK of 371 Mt CO_2. The largest OC stores are found in muddier, deeper, colder regions of the shelf and coastal areas where sediment builds up at higher rates or where there are increased OC inputs from the marine or land-based sources.

Annually, approximately 424 kt of OC is added to the UK OC stock by burial (~39 kt OC per year in the English North Sea alone) on climate relevant scales (decades to centuries). However, these figures are highly uncertain due to the limited number observations from which they are estimated.

How does human activity impact carbon storage and burial? Which areas are at highest risk?

Human activities, such as trawling or infrastructure development, can disturb sediments and the OC within them but the exact impact and loss or gain of OC depends on a variety of local factors. The disturbance of OC within sediments drives three processes: within-seabed mixing, displacement or resuspension into the overlying water column. Human activities can also change the size structure and functioning of seabed fauna.

If the OC is reactive, all these processes can potentially affect OC degradation, storage or burial. OC remaining within the seabed may be relocated and subsequently stored or degraded. Resuspended OC's vulnerability to degradation (which releases dissolved inorganic carbon as CO_2 to the water column) depends on a both OC reactivity and exposure to increased temperature and oxygen. Un-degraded OC either settles back onto the local seabed or is redistributed by currents.

Between 10 and 35% of the seabed OC stock is classified as reactive (most likely to degrade) when defined by its thermal degradation properties.

Over time and depending on location these combined processes can deplete or enhance the OC stock and the annual OC burial. The stocks at highest risk are those where reactive carbon, preferential environmental conditions for degradation, and pressure from human activities overlap spatially. Disturbing

OC and its consequent degradation may result in an increase in dissolved CO_2 in the water column which has the potential to result in CO_2 emissions into the atmosphere, depending on the interaction with hydrographic and biological processes. Some CO_2 released from seabed organic carbon following disturbance may never reach the atmosphere. We do not have a clear understanding of temporal and spatial CO_2 emission rates linked to differing human activities.

Which human activities drive most change in seabed carbon?

The main human and environmental pressures within the UK shelf of relevance to seabed carbon are demersal trawling, infrastructure development, and climate change.

Demersal trawling can impact OC stores through resuspension and mixing as well as by driving changes in the composition and function of species living in or on the seabed.

Figure 1 illustrates the key processes of OC disturbance, resuspension, transport, degradation and emission associated with long-term trawling of the seabed. Otter trawling has the highest impact on seabed OC in English shelf seas and currently the best evidence suggests that each year demersal trawling overall (otter and beam trawling, >90 % of total activity) disturbs ~28Mt C (~34% of the total OC stock per annum) and of this, 5.7% (~1.6 Mt C, 5.9 Mt CO_2 equivalent) is resuspended into the water column. This source of OC to the water column, equates to the annual CO_2 emissions (4.67 Mt CO_2 equivalent) of ~4.2 million cars (~10% of all UK cars). ***Figure 2*** tracks the magnitude of the OC or dissolved CO_2 involved in each step from disturbance to emission and highlights the rapid decrease in estimates (and associated confidence) from OC stock supply terms to eventual OC resuspension and potential CO_2 emissions.

It has often previously been assumed that all the carbon disturbed by gears is resuspended into the water column. However, in actuality, only a small fraction of that disturbed by gears is resuspended; studies estimate that for a trawl pass, only between 1 and 21% of the disturbed OC is resuspended following otter and beam gears, respectively.

We are currently unsure of the proportion of CO_2 which is emitted into the atmosphere from degradation of reactive resuspended carbon, but accounting for this improved understanding 1) only a small proportion of disturbed seabed OC is resuspended and 2) not all resuspended OC is reactive, is likely to yield lower emission estimates than previously documented. Increasing our understanding of this is a high priority because over 20 % of the UK seabed is trawled and the carbon disturbed, at least once (in some areas up to 15 times) every year, and pressure is particularly high in areas with higher OC stocks.

Most OC disturbance and resuspension occurs in focused, muddy areas with high OC stocks on the Northeast coast, Outer Silver Pit, Celtic Deep and the Irish Sea Mud Belts. These hotspots have been trawled for decades. It is likely that OC reactivity here has been reduced by this long-term pressure because the most reactive OC is gradually lost over repeated disturbances. However, this preliminary conclusion needs confirming with further research, as does the net impact of trawling on OC stock and burial, including the role of benthic fauna and biodiversity changes.

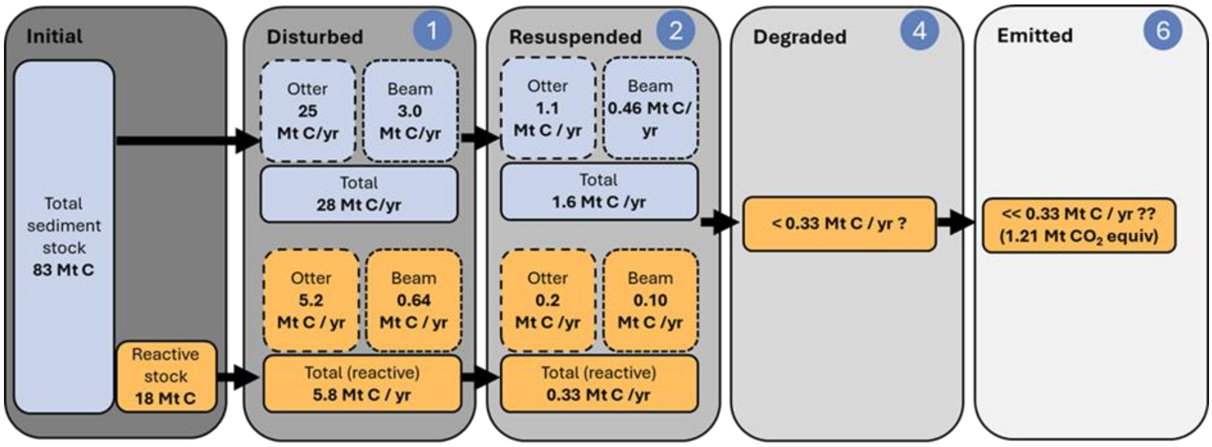

Figure 2. Estimated annual average organic carbon amounts associated with disturbance and resuspension of total and reactive OC stock by long-term trawling activities in English shelf sea waters. White numbers in blue circles match with associated boxes in ***Figure 1***.

Infrastructure such as oil and gas, power and telecoms cabling, pipelines, offshore wind, carbon capture and storage, dredging, disposal, aggregate extraction and other human activities can interact with and affect seabed OC through the disturbance from construction, operation or decommissioning. Although their seabed interactions are focused in smaller areas than trawling, their impacts may be more intense due to their interactions with OC in deeper parts of the seabed (beyond 10 cm). However, at present, these activities are typically found on coarser, shallower areas of the shelf which contain lower stocks of carbon. The exception to this is cable and pipeline elements which also impact coastal carbon stocks as they come ashore.

Climate change itself can act as a pressure on seabed OC stocks and burial by driving changes in OC inputs (i.e., from terrestrial sources and the water column) and directly impacting existing seabed stocks through increased storminess and temperature changes. It is likely that climate forcing (e.g., acute marine heat waves and gradual temperature increases) will both decrease input to and increase OC degradation through biotic and abiotic processes within the seabed, which will affect carbon stocks accumulated over decades. This may be most pronounced in areas where OC degradation is presently slowed due to low temperatures, for example in the northern North Sea and other deep, cold areas of the shelf. However, there are limitations of the existing evidence on the effects of temperature increase on carbon stocks and a lack of predictive models which can estimate the impact climate change will have on seabed OC storage and burial.

How can evidence inform potential measures to manage seabed sediments?

By improving our understanding of how human activities impact seabed OC, we can better define the trade-offs between different management measures, such as the use of the seabed for different human activities and prioritising the use of space. This requires linking both regional and local understanding and considering cross sector relationships and decision-making.

Specific management measures that can be informed include:

1. Spatial placement or restriction of activities - Seabed sediment carbon could be protected by identifying areas where the organic carbon is most reactive and susceptible to causing CO_2 emissions when disturbed, restricting human pressures (e.g., demersal trawling) in these areas. However, scenario testing of area closures has shown that in some circumstances, this may increase the amount of OC disturbed from activities such as trawling due to displacement effects if activities shift towards more highly reactive carbon areas. There is a high uncertainty in the trade-off of prioritising the protection of biodiversity over carbon and vice versa. Understanding carbon reactivity and seabed biological condition in areas surrounding proposed activity locations and across the shelf could be considered to ensure there are no unforeseen climate impacts of planning decisions.

2. Timing of activities – The risk of OC degradation is increased when water temperatures are higher. OC disturbing activities undertaken in shallower seabed areas (~< 30 - 40 m water depth) in spring/summer/autumn months when water temperatures are highest (~ 10 to 18 degrees C) will increase the likelihood of OC degradation and any potential for CO_2 emissions to the atmosphere. Activities which are damaging to seabed carbon could be limited to cooler weather periods. Sea temperatures are rising because of climate change, and this will also increase the risk of OC degradation and any associated emissions.

3. Life-cycle decisions or activity adaptations – For infrastructure sectors, understanding the effect of infrastructure location, construction, operation and decommissioning of sites on OC sinks and emissions across the whole life cycle of the development could be considered. Some activities could be altered to reduce OC degradation risk. For example, demersal trawl gear modifications, which include lighter gear, raised footropes or semi-pelagic trawls, and reduce contact and drag on seabed, and are already underway to protect biodiversity, could also minimise OC impacts.

Priority next steps

To ensure robust evidence is available to inform decision-makers to effectively consider seabed carbon with improved confidence there are some key next steps:

i. Refined mapping of seabed sediment carbon in the UK, including assessments of reactivity and carbon stored below the top 10cm of seabed.
ii. Improved understanding of how seabed sediment carbon changes and degrades in response to contrasting human activities and the impact of environmental factors, such as temperature.
iii. Development of predictive models to assess activity spatial management scenarios and trade-offs, in the context of climate change impacts.

Overview of technical annexes

Annex 1: Evidence review of the existing knowledge across the main topics needed to understand seabed carbon characteristics, change under impact (including to make assessments of the impact of trawling on seabed organic carbon (OC)) and potential management actions.

This includes a summary of what is known, the confidence level (assessed using the Marine Climate Change Impacts Partnership (MCCIP) confidence approach), remaining knowledge gaps and next steps and a summary confidence assessment table.

Annex 2: Information on the MCCIP evidence assessment approach which combines amount and agreement of evidence is also provided. This includes a summary table across all main topics reviewed in *Annex 1* of confidence, knowledge gaps and next steps, as an overview and synthesis of the evidence confidence assessments to highlight rapidly areas to be potentially addressed for policy makers.

Annex 3: Assessment methodology and results of the OC disturbed or resuspended from otter and beam trawling in English waters.

Annex 4: List of attendees at a workshop held May 2025 which informed the drafting of this report and other contributors.

Annex 1. Evidence Review

A1.1. Carbon in the seabed

Subtidal marine sediments are those which are permanently submerged by seawater, comprising a range of sediment types from fine-grained mud to coarse-grained sands and gravels. Organic carbon (OC) deposited onto the sediment surface from the water column is derived from terrestrial (mostly soil and plant material) and marine sources (phytoplankton, zooplankton and fish). OC is incorporated into the seabed through the action of physical settling processes and biological activity such as bioturbation. A fraction of seabed OC is lost through biologically mediated degradation processes (mainly microbial degradation), mostly near the sediment-seawater interface surface (Arndt *et al*., 2013; Schultz *et al*., 2025).

Organic carbon can be quantified as a carbon density (kg OC m^3) or a stock which integrates to a certain depth (kg OC m^2). The rate (g OC m^2 yr^{-1}) of both OC accumulation on the seabed and carbon burial to a depth at which it is 'permanently' removed to 'long-term' storage further defines the system. This OC storage is therefore generally considered to be relevant to climate change mitigation and adaptation on timescales of at least decades to centuries for policy considerations but potentially longer (Brunner *et al*., 2024). The relative amounts and rates of inputs of OC to the sediment surface and losses following deposition control the OC stock and burial rates at any sediment depth and geographical location (Burdige, 2007; Canfield, 1994).

A1.1.1. Stock

The amount of OC present in the sediments from the surface down to a given depth below the seafloor is calculated from measurements of sediment dry bulk density (DBD - directly measured or derived from mud content, water content or from porosity) and the OC content of sediment. OC stock is therefore not only influenced by the OC content but also the sediment properties (Chatting *et al*., 2025). The interplay between input to the seabed (amount and properties of organic matter: e.g., terrestrial or marine sourced) and storage potential of the seabed system (sediment type, oxygenation, biology) govern the size of the OC stock. For a full discussion of OC stock and burial measurement and quantification methods see the UK Technical Guidance on OC stock and burial (Parker *et al*., in prep A).

The UK EEZ is estimated to contain approximately 240-524 Mt (Million tonnes) of OC (880-1923 Mt CO_2 equivalent) within its top 10 cm (Burrows *et al*., 2024). The component within English shelf sea waters is between 80 and 104 Mt OC (Parker *et al*., 2022). The largest OC stores are generally found in muddier or deeper and colder regions of the shelf or coastal areas with high rates of sedimentation or high terrestrial OC inputs from terrestrial sources (Diesing *et al*., 2021, 2017; Legge *et al*., 2020; Smeaton *et al*., 2021a) though the multiple and potentially competing controls on stocks cannot be expected to scale with accumulation rates (Dahl *et al*., 2025). OC stock in the upper 10 cm derived from both observational and modelling approaches can range from < 0.1 kg OC m^2 for open shelf sands to ~3 kg OC m^2 for high OC input areas near the coast (Legge *et al*., 2020; Parker *et al*., 2022).

Confidence

MEDIUM. There is a good and rapidly developing evidence base of sediment OC content and stock data and good maps of its distribution supported by data across the English waters and UK EEZ region. There is consensus on the key controls on OC stock.

Knowledge gaps

- OC stock observations have historically focused on the upper 10 cm (some much less, e.g., Diesing *et al*., 2017). At these shallow depths, significant microbial degradation of OC matter is still occurring, leading to decreases in sediment OC content with depth, so existing maps of OC stock across English waters may over-estimate stocks at the depths where OC is sequestered on longer timescales. As sedimentation rates can vary spatially, reporting stocks to a consistent time horizon may be an option where this information is available (Bradley *et al*., 2022).
- OC stocks are estimated by multiplying measured OC content with the sediment dry bulk density (DBD), which has not historically been directly co-measured, limiting the accuracy of the calculated OC stocks and hence accuracy of stock maps (Chatting *et al*., 2025).
- Limited sediment OC measurements are available for shallow subtidal areas and inshore coastal areas. The higher terrestrial inputs of OC in these regions may be underestimated by the spatial models used to generate stock maps.
- There is some localised disagreement between available published seabed OC maps, clarification is needed on the pros and cons of different maps and mapping approaches for different applications: which to use when.

Next steps

There is a need for gap filling sampling in some geographic regions and observations of deeper OC content to assess the full stock (to 1 m depth or beyond). Selection of priority sites can be informed by existing stock maps to provide a more spatially representative distribution of data covering the full range of stocks across the seabed with links to different environmental drivers (depth, sediment type, input). Ensuring consistency of sampling methodology, and standardisation of sampling and analysis techniques is critical, including for example, direct measurement of DBD instead of estimation from grain size.

A1.1.2. Burial

Herein, we term OC 'burial' as the rate at which OC is added to the 'long-term' seabed stock (often considered to be storage for more than 1000 years e.g., (Brunner *et al*., 2024)0, but in the UK policy context considered to include timescales of 10's to 100's of years (Parker *et al*., in prep A). For the English shelf seas, we estimate that OC at sediment depths greater than 10 cm is stored long-term since it is buried below the surface-active layer where most organic matter degradation naturally occurs (Parker *et al*., in prep B). OC burial reflects the net balance of OC accumulation rate (OCAR) at the seabed surface (addition) and degradation (loss) from the seafloor as continuous processes with depth in sediments. The OCAR is controlled by the rate of delivery of organic matter to the sediment surface, sediment type, OC composition as well the environmental setting of deposition (oxygen availability, faunal community) (Parker *et al*., in prep B). Some controls on burial rates are the same as those considered for OC stock, and therefore areas of high burial and high carbon stock may be expected to co-occur in deeper, colder, muddier sediment with high organic matter. However, OC type can affect reactivity and therefore the amount of degradation and loss in upper sediments which can alter aspects of the stock and burial relationship. Terrestrial OC inputs are considered to be less likely to be degraded than marine OC (Bianchi *et al*., 2018; Blair and Aller, 2012; Smeaton and Austin, 2022). Other conditions, such as mineral-OC associations also affect reactivity, degradation or burial / transfer efficiency (e.g., Babakhani *et al*., 2025; Bianchi *et al*., 2018; Blair and Aller, 2012; Burdige, 2007).

In the literature, the term 'OCAR', is often used for OC accumulation rate at the seabed surface and burial at various, often ambiguously defined, time or depth horizons. Ideally, it would be reported alongside the relevant depth interval over which OC density and linear sedimentation rate or mass accumulation were measured (Bradley *et al*., 2022; Parker *et al*., in prep A).

OC burial or transfer efficiency has also been proposed to account for continuing degradation with depth (Bradley *et al*., 2022). ***Figure A1.1*** provides a schematic illustration of the processes of accumulation and burial of OC within seabed sediments.

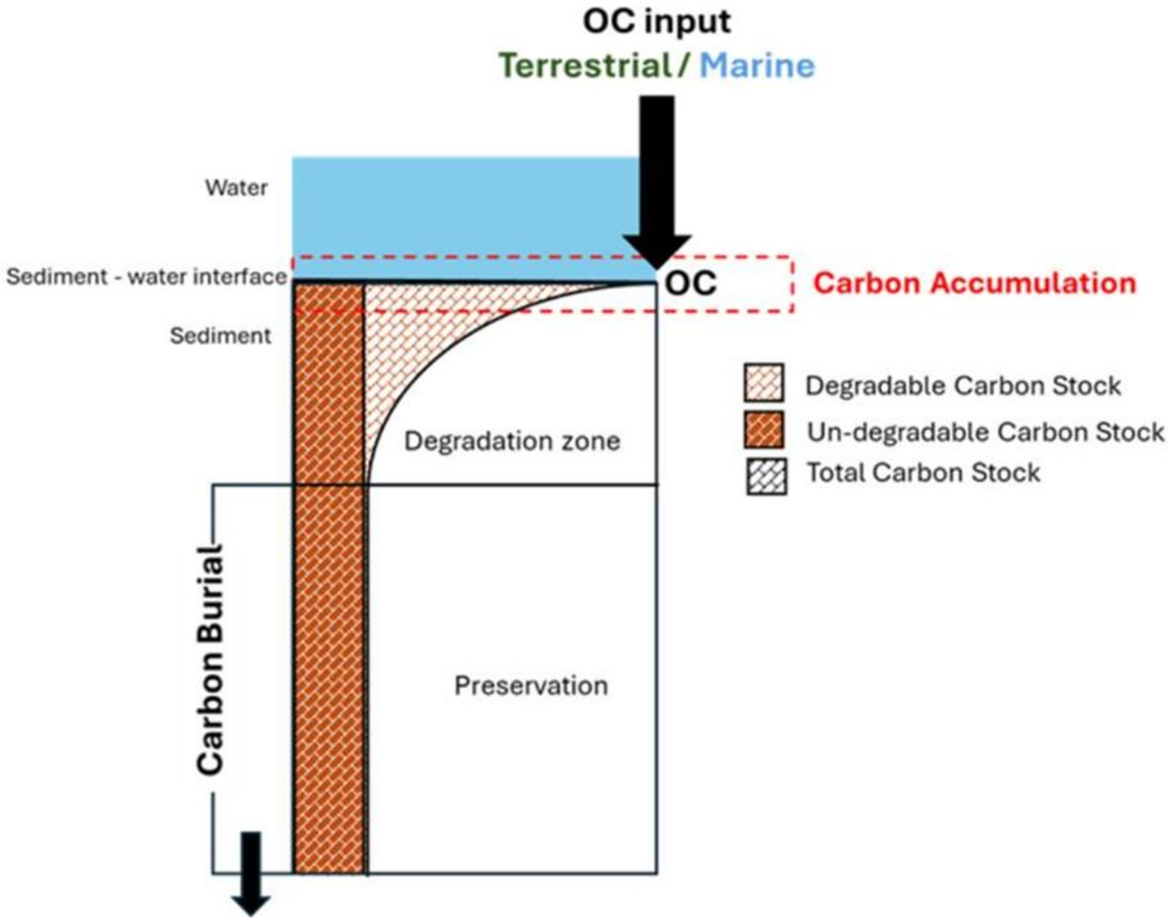

Figure A1.1. Conceptualised plot of organic carbon (OC) within the seabed represented by a constant accumulation rate and lacking biological or physical disturbance (adapted from (Burdige, 2007) with annotations of key elements relating to OC stock and burial rates, reproduced from: (Parker *et al*., in prep A; C Smeaton pers. comm). NB OCAR may be determined at any depth interval.

Only a small fraction of the OC deposited on the shelf seabed is buried long-term (Arndt *et al*., 2013). Annually, approximately 0.424 Mt OC is added to the UK OC stock through burial and accumulation, approximately 10 % of which (0.039 Mt OC) lies within the English North Sea (Burrows *et al*., 2024; Parker *et al*., 2022).

At their lower range, OCAR or burial are not measurable due to very low sedimentation, intense physical mixing of near-surface sediments, and/or erosion, within sands, highly permeable cobbles and coarse substrates. English shelf sea OCAR (at 10 cm depth) range from 10 to 30 g OC m -2 yr -1 in coastal areas of higher deposition and deeper, colder sediments (Legge *et al*., 2020). In deeper depositional regions such as the Farnes, Fulmar, and Celtic Deep, OCAR of up to 25 g C m -2 yr -1 have been observed (Diesing *et al*., 2021; Parker *et al*., in prep B; Powell *et al*., 2002). The fastest seafloor OCAR have been reported from fjordic sediments in Scotland's sea lochs, with rates ranging from 50 to 200 g OC m -2 yr -1 (Burrows *et al*., 2024; Smeaton *et al*., 2021b).

Confidence

LOW. There are relatively few measurements of OCAR or burial for English shelf sediments and the UK shelf region more broadly, and the understanding of mechanisms and controls surrounding OC burial (including conversion of accumulation rates to burial rates at specific sediment depths) and the relationship of both accumulation and burial with OC stock is limited.

Knowledge gaps

- Data availability: insufficient combined measurements of OC stock, properties (reactivity, source) and accumulation/burial rates.
- The relationship(s) between OC stock and burial rates along inshore to offshore gradients to provide understanding of how the presence of terrestrial OC and mineral organic matter associations impact and control OC degradation and storage.
- Measurement and mapping of burial rates in sediments deeper than 10 to 25 cm beneath the seafloor, which are representative of longer-term burial.

Next steps

- Targeted sampling of the shelf seabed conditions which are under-represented in currently available measurements: either geographically or in terms of their environmental conditions.
- Differentiation of seabed areas of active deposition where OC burial is active and stock is growing, from relic sedimentary deposits (e.g., terrestrial peat found buried at depth in marine sediments), since the two types of stock would respond differently to potential seabed carbon management measures (Ward *et al*., 2025).

A1.1.3. Reactivity

OC reactivity describes its susceptibility to degradation and hence its responsiveness to seabed disturbance and potential management measures. Reactivity is controlled by OC source (e.g., terrestrial or marine organic matter), mineral associations, and microbial degradation or alteration in the water column or seabed post deposition. The likelihood that OC will degrade when disturbed is termed 'vulnerability' (Arndt *et al*., 2013; Black *et al*., 2022; Goldstein *et al*., 2020) and is a combination of reactivity and environmental conditions (e.g., temperature and oxygen).

There is variability of OC reactivity within a sediment sample. A portion or 'fraction' of the OC is readily degraded and is considered 'labile', while other portions that tend not to degrade as well are termed 'recalcitrant' or 'refractory' (Baltar *et al*., 2021; Graves *et al*., 2022). Labile OC is usually considered fresh (i.e., young or recently generated), with a simple chemical composition and that facilitates microbial degradation. Labile OC content is often found at shallow sediment depth, having had less time to undergo degradation and alteration after deposition, and may be linked to proximal sources of primary production, such as marine phytoplankton, which are rich in reactive biochemicals such as lipids and proteins. This material is unlikely to make it into long-term storage on climate change relevant scales. Terrestrial OC in the marine environment can also be labile where lateral transport times are short, e.g., in fjords or away from large rivers. Refractory or recalcitrant OC is often considered old (has been actively degraded over long time periods) and now represented by chemical compounds that are energetically expensive for microbes to decompose or are protected (as mineral associated organic matter (MAOM); (Longman *et al*., 2022; Moore *et al*., 2023; Xiao *et al*., 2025), It is also thought to contain an accumulation of biochemicals which are naturally resistant to degradation, some of which may be sourced from terrestrial plants and soils.

The existence of OC fractions with different reactivity is underpinned by biogeochemical observations and is well-represented in numerical models. In some cases, models represent a limited number of 'fractions' with different reactivity, and in other cases, reactivity is represented along a continuous scale (Arndt *et al*., 2013).

There remains partially a disconnect between the theoretical conceptualisation of OC reactivity described above and firm empirical evidence. Measures of reactivity do indeed tend to show a decline with depth. However, measured rates of OC component specific degradation are lacking, and it therefore cannot be quantitatively linked to OC source, geochemical composition, or processes that alter the chemical composition. A large part of the reason for this is that the majority (>70%) of sedimentary OC cannot be characterised in terms of biochemicals, and we lack mechanistic knowledge of some important processes (e.g., chemical transformation, sorption) which act on fresh organic detritus and transform it into sedimentary OC with different types of reactivity (Burdige, 2007).

A range of analytical techniques have been used to identify OC source (marine versus terrestrial) and extent of degradation (Cowie and Hedges, 1994). Traditionally, these have included stable carbon isotopes and lignin phenols to identify OC source, and indices based on amino acids (Dauwe and Middelburg, 1998) or pigments to make relative assessments of reactivity. Different classes of lipids (e.g., fatty acids and alkanes) have been used for both purposes. More recently indices have been added to the 'Toolkit' (Graves *et al*., 2022) based on thermo-gravimetric analysis (TGA; Smeaton and Austin, 2022) and pyrolysis gas chromatography-mass spectrometry (Kleber *et al*., 2021), which have the benefit of studying the whole OC pool at once, not just the sub-set represented by a biochemical class. Each of these techniques does a good job of identifying the comparative reactivity of different samples within a study.

Between 10 and 35% of the carbon stock in the upper sediments of the English shelf is reactive (most likely to degrade) when defined by thermal degradation (TGA) methods from over 1000 measurements taken in offshore environments (Parker *et al*., in prep B; Smeaton and Austin, 2022). This highlights that within the UK shelf, most OC stock (75 to 90 %) is not classified as reactive using the TGA method and therefore potentially resistant to degradation when disturbed. While the density of reactive OC in subtidal sediments is highest in coastal settings where overall OC stocks are highest, deep and cold offshore areas in the North Sea contain the highest proportions of reactive OC (Parker *et al*., in prep B; Smeaton and Austin, 2022). This indicates that degradation of reactive OC following deposition on the seabed is temperature-limited and that these settings have incomplete degradation under unimpacted conditions.

The role of inorganic minerals as agents to protect and alter OC, theoretically reducing the labile and increasing the refractory fractions, has been studied over several decades (e.g., in coastal ecosystems: (Fu *et al*., 2024; Keil, 2014; Keil *et al*., 1994; Li *et al*., 2025). Reactive iron (Fe)-OC associations are estimated to protect ~20 ± 15 % of OC in shelf sediments globally (Lalonde *et al*., 2012), but observations are lacking to make comparisons of Fe-OC contributions to OC reactivity as determined by other toolbox techniques in differing places and in disturbed seabed settings.

Clarity on the use of the term 'labile' is key when differentiating between 'labile' as defined from young or fresh carbon (e.g., phyto detritus) vs 'labile' fractions from thermal analytical techniques such as TGA. For this purpose, the focus is on the latter fractions most susceptible to degradation upon disturbance or climate forcing whilst being long-lived enough to have a role on the relevant timescales (decades to centuries).

Confidence

LOW. There is an increasingly tested toolbox of OC analytical techniques and good understanding of OC reactivity and source controls which can describe spatial and temporal differences in OC reactivity as a whole. However, the links and agreement between the techniques and inter-comparisons within case studies is missing as is experimental ground-truthing of chemical descriptors to degradation assessments.

Knowledge gaps

Measured biological degradation rates for sedimentary OC or the different reactive fractions within it. The degradation rates (parametrised as first order decay rates: 'k' values; see e.g., Hiddink *et al*. (2023)) we do have are derived from models and still need to be ground-truthed in some way. We remain unable to cross-reference between different indices and studies, or to link any of them to quantitative biological degradation rates.

Next steps

- Experimental approaches testing the performance and suitability of the methods included in the analytical toolbox in conjunction with modelling and biological degradation studies to ground-truth early microbial degradation in intact sediments and response of sediments to disturbance.
- Linking analytical definitions of reactivity to OC source, composition, mineral association and alteration under disturbance pressures.
- Experimental validation of degradation rates for both undisturbed and disturbed sediment and linking the analytical toolbox parameters to constants or OC parameters used in modelling approaches such as half-life, k or activation energy.

A1.1.4. Integrated organic carbon characteristics

Some important knowledge gaps and next steps integrate across knowledge gaps related to carbon stock, burial and reactivity.

Knowledge gaps

- Linking OC sources to sinks to explore the role of reactivity (and how reactivity is defined) in controlling OC stock and burial.

- Definition of spatial regions of carbon processing to support impact assessment by standardising initial baseline conditions.
- Understanding the role of macrofauna and biodiversity in mediating and controlling OC stock.
- Predictive tools which can address OC stock, burial and reactivity questions in space and time across shelf seas (see Schultz *et al*., 2025).

Next Steps

- Combining 3D transport modelling development with observations of stock, burial and reactivity to link up understanding of the long-term dynamics and controls of OC input and processing in the seabed.
- Delineation (mapping and monitoring) of regions of different potential of OC ecosystem service provision which combine depth, temperature, oxygen, stock, burial and reactivity.
- Exploration of the role of macrofauna and biodiversity in mediating OC stocks using concurrently measured biological and OC measurements from R&D or monitoring.
- Development and intercomparison of both mechanistic and data-driven maps of baseline OC conditions including stock, burial and reactivity descriptions, faunal mediation and terrestrial influences.

A1.2. Trawling gears, distributions and disturbance processes

Towed gears deployed by the fishing community have different components, each of which have different modes and extent of impact which can be described in terms of penetration depths, balance of mixing and resuspension (Hiddink *et al*., 2017; O’Neill *et al*., 2018; O’Neill and Ivanović, 2016; Rijnsdorp *et al*., 2020; van der Reijden *et al*., 2025) There can also be a lot of variation within a component category (Eigaard *et al*., 2017). In general, the physical impacts of differing gear components can be categorized as being:

- Hydrodynamic: mobilisation of sediment and pore-water release via pressure drop and high shear-bed stress in the wake (van der Reijden *et al*., 2025),
- Geotechnical: penetration and mixing, lateral displacement, compaction, which can include decreases in DBD through mixing as sediment is reworked or increases in DBD if fine grained component is lost following disturbance (O’Neill and Ivanović, 2016).
- Impacts on biogeochemical gradients with depth in pore waters and release of pore waters into the overlying water column.

The extent to which these impacts occur at any site depends on the sea state but also sediment properties (e.g., mud and sand content, sediment consolidation or density) as well as the weight, shape and size of the gear component and the speed it is towed (Eigaard *et al*., 2017). The amount and previous storage status (long term versus short term) of OC resuspended into the water column following disturbance by trawling depends on the interplay between these physical processes, how they overturn and mix sub-surface sediment layers and the extent to which these previously isolated and anoxic sediments are exposed to and mobilised into the water column (e.g., Epstein *et al*., 2022; Khedri *et al*., 2025).

Table A1.1 Summarised literature review of the sediment amounts resuspended during trawling by different gear types in various sediment types. The percentage (%) of sediment column that is suspended in the water column is calculated as a proportion of the gear penetration depth. * (assuming a PD = 2.44 cm for otter trawl and PD = 2.72 cm for beam trawl, given in Hiddink *et al*. 2017) ** estimated assuming a sediment density of 1.6 kg l^{-1} (Marija Sciberras pers. comm).

Gear Type	% of suspended sediment layer (mobilized sediment / total gear penetration depth)	Layer of mobilised sediment (mm)	Resuspended mass per unit area (per unit time)	Sediment mud fraction (%)	Data source
SumWing trawl	17	7	10.6 kg m^{-2}	9.3	(Depestele *et al*., 2019)
PulseWing trawl	44	8	13.1 kg m^{-2}	14.7	
Otter trawl (ground gear + doors)	1 *	0.3	0.5 kg m^{-2}	2	(O'Neill and Summerbell, 2011)
	8 *	1.9	3 kg m^{-2}	69	
Beam trawl with tickler chain typical of North (range presents data for 4.5 m and 12 m beam trawl)	10-21*	2.6-5.9	4.2-9.5 kg m^{-2}	NA	(Rijnsdorp *et al*., 2021)
Pulse trawl (PUL-R) (range represents small ≤ 221 kW and large vessels, > 221 kW)	10-11*	2.7 - 2.9	4.3 - 4.6 kgm^{-2}		
Twin otter trawl	3.2	0.08 **	0.14 kg m^{-2}	15	(Mengual *et al*., 2016)
	3.0	0.08 **	0.12 kg m^{-2}	25	
Bottom trawl, with bobbin for ground rope (Rockhopper)	1.6 *	0.40	0.54 kg m^{-2} s^{-1}	47	(Durrieu de Madron *et al*., 2005)
	0.78 *	0.19	0.26 kg m^{-2} s^{-1}	60	
Bottom trawl, without bobbin	1.7 *	0.41	0.54 kg m^{-2} s^{-1}	47	
	0.53 *	0.13	0.18 kg m^{-2} s^{-1}	60	

An understanding of the balance between resuspension (into the water column) and disturbance (within bed) is one of the key factors, alongside reactivity, in determining OC degradation risk and eventual fate over longer periods of time. Both activities are likely to raise the availability of oxygen and hence accelerate the rate of OC degradation. Studies have shown that resuspension may occur for between 0.5 and 41% of disturbed sediments (defined as the full penetration depth of the gear) for differing composite gears (***Table A1.1*** and references therein). The main trawl gears being used in English waters are Otter, beam trawls, dredges (e.g., scallop dredges) and demersal seines (Parker *et al*., in prep B).

To understand the fleet scale effects of trawling gears, both in acute and chronic terms, individual trawler actions need to be integrated across seabed regions and over time. Fleet distributions, activity levels and metrics are readily available for full international fleets in UK waters for the main gear types and target species (e.g., Eigaard *et al*., 2017) as part of the vessel monitoring systems (VMS) on vessels over 12 m. This information is available (ICES, 2021; Matear and Vina-Herbon, 2023) for surface and sub-surface (defined as less than and greater than 2 cm sediment depth) and can be developed into Swept Area Ratios: the cumulative area impacted by fishing gear within a specified area (grid cell) over a year divided by the surface area of the grid cell. While VMS-based data products tend to be aggregated annually, Automatic Identification System (AIS)-based data (e.g., Global Fishing Watch (GFW); Kroodsma *et al*., 2018) is available at daily resolution, resolving the strong seasonality in fishing effort, which may be important to resolve, considering the seasonality inherent to seabed OC supply and degradation (temperature effects, current hydrodynamic conditions). On the other hand, AIS is not mandatory for vessels under 15 m and GFW does not currently distinguish different trawl gears. Hybrid methods using both VMS and GFW data have been implemented to combine the strength of both types of data (Porz *et al*., 2024). Linking vessel information to actual activity (e.g., from logbooks) is important when translating fishing distributions to seabed impacts. This will be important when assessing distribution shifts or displacement, as well as gear switching as a result of management measures.

In order to contextualise trawling disturbances on the seabed and their effect on OC storage, it is important to raise the impact to the fleet/fishery level (Epstein *et al*., 2022; Oberle *et al*., 2016) and compare with the impacts associated with natural disturbance such as storms, waves, tides and currents and other anthropogenic activities (Aldridge *et al*., 2015; Diesing *et al*., 2013; Tiano *et al*., 2024).

Confidence

LOW to **MEDIUM**

MEDIUM. Understanding of sediment mobilization from 'average' trawling gears and the penetration of trawl gears and their components. There are many studies relating component drag to resuspension, but knowledge could be improved by increased inclusion of varying sediment types and trawl speeds. Further, there is much variability due to factors such as component geometry which influences the extent to which the turbulent wake interacts with the seabed (Larsen and O'Neill, 2025).

LOW- MEDIUM. Data on fleet distributions and trawling intensity by gears is available for the larger vessels (>12 m) across the UK region and the distributions are generally in agreement across differing vessel information sources, however understanding of inshore fleets (iVMS) for vessels <12 m is very poor and yet coastal areas of shore fleets also have higher carbon stores.

LOW. Understanding of how sediments are mixed/overturned and thus how seabed OC is relocated within the seabed following trawling is not well studied, confidence is low.

Knowledge gaps

- Understanding, across all sediment types, of:
    - how sub-surface sediment layers are overturned and mixed by differing gear components,
    - the extent to which previously sub-surface sediment layers become exposed to bottom waters and mobilised at the sediment-seawater interface following trawling,
    - the coupling of OC or flocculant OC and suspended particulate matter (SPM) when plumes are created, and how suspended sediment and OC behaviour may couple or uncouple and over what timescales
    - how much OC is released by means of the release of pore water.
- Availability of information on fishing fleet activity: lack of inshore vessel monitoring information (iVMS: Inshore Vessel Monitoring System) analysis (before 2024); differing and refinement of gear-type assumptions and fishing fleet / gear distributions (e.g., for otter trawls – nephrops vs plaice); limitations of temporal resolution for understanding seasonal variability.

Next steps

- Tracking of OC and SPM size in resuspended plumes caused by different gears acting on different substrates

- Tracking of SPM metrics and OC within the seabed under differing trawl actions
- Improved understanding of shift in response of SPM and OC metrics related to trawling intensity and history
- Development of fleet information to cover inshore fleets (iVMS) to provide temporal distributions of pressure.
- Field measurements of particulate sediment, nutrients and OC as well as pore and overlying water post trawl gear passage.
- Better integration and modelling of the varied spatial distribution and gear data sources to understand what the fleet is doing where and when

A1.3. Trawling-carbon interactions and impact

Trawling impacts seabed carbon by three main mechanisms (Kroeger *et al*., 2018; Parker *et al*., 2022):

1. directly through physical mixing,
2. sediment resuspension that may both reduce the carbon flux to the bed and resuspend carbon from within the bed
3. through removal of fauna and changes in functional composition and actions of faunal communities.

There are only 12 observational studies in English waters (Epstein *et al*., 2022; Parker *et al*., 2022) which address the impact of trawling on seabed OC, though this number is growing rapidly. Due to the difference in approaches between these studies (e.g., investigating impact gradients, applying before-after-control impact (BACI); sampling acute versus chronically impacted sites), differing environmental contexts as well as often lack of measurement of key OC parameters (especially stock and burial) there is a lack of consensus on the net effect of trawling activity on sediment OC. It is unclear whether trawling drives an increase or decrease in overall OC stock or burial (Epstein *et al*., 2022).

Internationally focused studies also find an unclear impact of trawling on seabed OC storage (Khedri *et al*., 2025; Tiano *et al*., 2024; De Borger *et al*., 2021b; Epstein *et al*., 2022; Sciberras *et al*., 2016; van de Velde *et al*., 2018) though decreases in OC content and stock in upper sediment layers after trawling has been reported in global metanalyses (Diesing *et al*., 2025; Tiano *et al*., 2024), however, the number of empirical studies remains low.

The evidence and studies on the direct OC relocation and mixing from trawling are limited, and there is often a focus on deeper areas and export of material off the shelf to deeper areas (e.g., Depestele *et al*., 2019; Paradis *et al*., 2019, 2017) as are those focused on OC loss from surface layers during resuspension (Jennings *et al*., 1999).

Some studies have tried to parameterise OC resuspension and emission (e.g., Sala *et al*., 2021) from gear penetration depths, assuming that all the sediment shallower than the penetration depth is resuspended into the water column (though Sala *et al*., 2021 also assume that 87% of resuspended OC resettles onto the seabed). Within the seabed relocation of OC upwards or downwards may alter its degradation risk: OC relocated downwards in the sediment column enters more anoxic / sub-oxic sediment zones where degradation is slower, while OC moved to the surface may enter increasingly oxic environment which might promote degradation. In addition, resuspension may act to disrupt the background balance of erosion/deposition leading to reduced net flux of OC to the seabed.

Mixing of more labile carbon to depth with older OC may potentially promote additional degradation through 'priming' effects (Graves *et al*., 2022; Sanches *et al*., 2021). It is possible that repeated trawl actions may also gradually alter the sediment grain size distribution and reactivity of the OC itself (Lønborg *et al*., 2024) which will complicate the effect of OC relocation or resuspension on degradation processes. The overall outcome of these separate processes is uncertain and likely to be context dependent. The overall effect and balance of OC loss from resuspension and mixing is explored and discussed by Khedri *et al* (2025) where it is argued that introduction of oxygen into the bed may stimulate OC degradation.

Much of the labile or reactive OC, often highlighted for its vulnerability, is also the fraction most likely to degrade rapidly under natural conditions, even in the absence of trawling or other disturbances. While disturbance may accelerate degradation, the ultimate contribution of this fraction to long-term OC sequestration may be limited regardless of fishing pressure. This highlights the need to distinguish between disruptions to short-term biogeochemical cycling from and disruption of true OC sequestration when assessing the impact of demersal fishing.

Biological communities can control OC processing within the seabed through their actions of OC incorporation, both active from the water column and through bioturbation or bioirrigation processes. This can set the biogeochemical oxidation-reduction (redox) conditions for OC degradation by bacteria within sediment depths. The effect of bottom trawling on OC storage and/or degradation thus depends on the local biological community, its function, and sensitivity to trawling pressure. It is well established that repeated trawling changes the structure of benthic communities with large long-lived burrowing species, that have the largest effect on OC cycling, being replaced with small-bodied, opportunistic, motile infauna, and larger, highly vagrant, scavenging species (e.g., Hiddink *et al*., 2017; Sciberras *et al*., 2016), Consequently, intensive bottom trawling can alter the type, mode and action of bioturbation or bioirrigation on seabed OC incorporation and processing (Beauchard *et al*., 2023). Shifts in macrofaunal assemblages may reduce local bioturbation (the reworking of sediment particles) and bioirrigation (the reworking of sediment solutes) by benthic invertebrates. Conversely, trawl-induced faunal regime shifts may lead to increased bioturbation under certain circumstances (Beauchard *et al*., 2023; Tiano *et al*., 2020). The impacts (win-win or trade-offs) of faunal changes both under impact and recovery on long-term carbon storage are poorly studied due to the need for co-incident observations and not yet fully understood (Parker *et al*., 2022; Parker *et al*., B in prep).

Several mechanistic regional and global models exploring the impact of bottom trawling on sedimentary OC stocks have been developed (e.g., De Borger *et al*., 2021b; Porz *et al*., 2024; Sala *et al*., 2021; Zhang *et al*., 2024). An accurate understanding of processes and observational validation are needed to provide confidence in such model predictions. Predicted impacts of trawling on seabed carbon remain highly uncertain and differ by order of magnitude between studies, with differences primarily related to the different underpinning model assumptions of OC degradation rates and of trawling gear impacts on the seabed. While recent modelling studies take bioturbation into account (e.g., De Borger *et al*., 2021b; Porz *et al*., 2024; Zhang *et al*., 2024), the processes are complex and some studies suggest that decreased bioturbation leads to reduced OC degradation rates due to decreased direct biomass respiration and increased sub-oxic respiration pathways which are less efficient in OC degradation, while other studies show that decreased bioturbation may limit the transport of relatively labile OC deeper in the sediment increasing its chance of burial and long-term storage. The balance of these opposing responses is site specific.

Currently the best evidence suggests that in English waters, each year demersal trawling overall (otter and beam trawling, >90 % of total activity) disturbs ~28Mt C (~34% of the total OC stock per annum) and of this, 5.7% (~1.6 Mt C, 5.9 Mt CO_2 equivalent) is resuspended into the water column. This source of OC to the water column, equates to the annual CO_2 emissions (4.67 Mt CO_2 equivalent) of ~4.2 million cars (~10% of all UK cars)[1].

Otter trawls lead to the most significant disturbance of both sediments and OC (25 Mt OC yr-1 disturbed, 1.1 Mt OC yr-1 resuspended) followed by beam trawls (3.0 Mt OC yr-1 disturbed, 0.46 Mt OC yr-1 resuspended). See Annex 2 of this report for methods and maps based also on (Black *et al*., 2022; Epstein and Roberts, 2022) as developed as part of this community activity.

The otter trawling fleet focuses on muddier substrates which generally have high OC stock, all areas where OC disturbance is greatest have been trawled for a number of decades (including north-east Farnes, Outer Silver Pit, Celtic Deep, Irish Sea Mud Belt). In these areas it is possible that the OC stock reactivity may have decreased over time with repeated disturbance and re-exposure to oxic conditions removing the most reactive components of the organic carbon pool (Lønborg *et al*., 2024).

Confidence

LOW to **MEDIUM.**

LOW: Confidence in the net effect of trawling on seabed OC is low. It has been measured by only very few studies and there is little agreement across regions with different OC characteristics. Key processes including OC relocation following disturbance, priming and seabed faunal community changes are poorly understood as are interactions between these processes.

MEDIUM: Confidence in the magnitude of impacts is medium. Mechanistic and process modelling studies have some consensus but are few in number and need future development to address feedback with observational validation where possible.

MEDIUM: Confidence in spatial mapping approaches to estimate regional scale OC-fleet interaction and resulting resuspension is medium. These show some consensus and improvement of consideration of key factors, but uncertainty estimates are often missing.

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[1] Considering the average car drives 7,100 miles per year in the UK, the average car releases and estimated 1,470,120 grams (1.5 kg) of CO_2 into the atmosphere each year (DoT - https://www.nimblefins.co.uk/average-co2-emissions-car-uk#nogo); Assuming 41.9 million vehicles in 2025 https://www.gov.uk/government/statistics/vehicle-licensing-statistics-january-to-march-2025/vehicle-licensing-statistics-january-to-march-2025

Knowledge gaps

- Fundamental observational and process modelling work is needed to understand the key direct and indirect impacts of trawling on net OC stock and burial. Key questions include:
    - How does fleet – OC interaction and change vary across shelf settings / regions?
    - What is impact of repeated trawling?
    - How are macrofauna and OC dynamics coupled under pressure scenarios and potential OC release from the seabed across differing timescales?
    - What is the net effect of trawling impacts which act in opposite directions on OC stock, including within bed priming, resuspension loss, biological functional / trait change, reduced bioturbation alongside increased physical mixing by gear components?

Next steps

- Combined analysis of recent observational data across trawling gradients, available from various national and international programmes. Ensuring that data are compatible between various related projects and programmes and that knowledge is shared and developed collaboratively to maximise outputs and impact across programmes. This is a key objective in the UK BCEP Evidence Needs Statement.
- Targeted additional sampling and data collation of co-incident OC and benthic fauna data, across the full range of spatial areas representing different OC characteristics to explore of the net effect of changes in biodiversity and structure, OC relocation and mixing on long-term OC storage
- Improvement of both process-based, and data-driven spatial predictive tools to reach consensus between approaches and estimates of the impact of trawling on OC storage across all spatial scales from local to regional.
    - Spatial mapping of sediment OC reactivity and/or degradation rates and associated vulnerability following disturbance by integrating spatial distribution of pressures (building on e.g., (Diesing *et al*., 2025; Epstein *et al*., 2025).
    - Future development of process-based models (building on e.g., (De Borger *et al*., 2021b; Porz *et al*., 2024; Zhang *et al*., 2024) to resolve feedback loops, including physical-biogeochemical-human coupled models.

- Relevant work in the UK includes two NERC projects (Impacts of bottom trawling on seabed carbons storage (SeaStore), 2025-2028[2], Managing shelf sea carbon cycles and greenhouse gas release from physical disturbance of the seafloor (C-floor), 2024-2028[3,4], as well as on-going UK Govt funded R&D and international activities such as CONVEX seascape survey (Convex Seascape Survey | Ocean & Climate Research) under ICES FISH CARBON (WKFISHCARBON2) and ICES Fisheries, Benthic Impact and Trade-offs (WGFBIT) Working Groups and the OSPAR Benthic Habitats Expert Group (OBHEG) https://www.ospar.org/work-areas/bdc which is currently discussing a new benthic indicator for marine assessment and also provide advice to the Intersessional Correspondence Groups under Biodiversity Committee (BDC).

A1.4. Degradation risk and fate

The vulnerability of OC (likelihood to degrade when disturbed) upon resuspension is controlled by a combination of its reactivity, potential mineral association, and environmental conditions (e.g., temperature, oxygen availability) of the bottom waters (Arndt *et al*., 2013; Burdige, 2007; Canfield, 1994; Middelburg, 2018). It is likely that resuspension will increase OC degradation of reactive OC as it is moved into an environment where conditions favour aerobic respiration. OC degradation rates are controlled initially by trawl plume conditions and the ambient water environmental conditions as well as the transport duration (hours, days to weeks) (Lønborg *et al*., 2024; Pusceddu *et al*., 2005). These conditions vary seasonally as well as spatially across English shelf seas.

A1.4.1. Resuspension degradation risk

Temperature and oxygen are major controlling factors in OC degradation rates in the UK shelf sea sediments, with higher degradation rates at raised temperatures (Jessen *et al*., 2017; Lønborg *et al*., 2018). OC resuspension into colder and deeper regions which seasonally stratify (e.g., the northern North Sea) and elsewhere in winter months when temperatures will have a lower degradation risk. Detailed information on spatial and seasonal bottom water temperature conditions for the UK shelf including long-term baselines are available (e.g., Cornes *et al*., 2025) but have not yet been integrated into

[2] https://gtr.ukri.org/projects?ref=NE%2FZ503770%2F1. PI: Jan Hiddink
[3] https://gtr.ukri.org/projects?ref=NE%2FZ503782%2F1 PI: Martin Solan
[4] https://gtr.ukri.org/projects?ref=NE%2FZ503885%2F1, PI: James Strong

seabed OC risk mapping in the UK. Oxygen at low levels (hypoxia or anoxia) may limit OC degradation but although there is seasonal draw down of oxygen due to production cycles, these conditions rarely occur within the UK shelf due to strong tidal mixing (Greenwood *et al*., 2010; Große *et al*., 2016; Queste *et al*., 2016).

Several past studies have explored risk assessments of OC from trawling such as Black *et al*. (2022) who combined carbon stock and reactivity, trawling pressure and exposure time to identify areas on higher OC vulnerability. Epstein *et al*. (2025) calculated a unitless measure of relative OC risk to describe the scale for potential degradation of OC at a specific location within a study area. This approach combined spatially resolved estimates of seabed OC disturbance from mobile bottom fishing with factors known to influence carbon remineralisation: sediment mud content, bottom water temperature and oxygen concentration. Their relative OC degradation risk metric incorporated an exponential dependence of temperature on degradation rates based on links to bacterial metabolic rates, and a Michaelis-Menton-type relationship for oxygen which describes a rapid decline in degradation rate of particulate organic carbon (POC) at low oxygen concentrations and little impact of oxygen at high concentrations. A similar approach has been taken by Parker *et al*. (in prep B) for the North Sea combining OC stock and reactivity, trawling pressure (OC disturbance and resuspension estimates) as well as average bottom temperature ranges to determine comparative risk areas for OC degradation upon disturbance.

Confidence

MEDIUM. There is high-level of agreement and many past studies on temperature and oxygen levels controlling OC biogeochemical degradation both in the seabed and in the water column. However, this is largely for labile phytodetrital material rather than seabed resuspended material.

Knowledge gaps

Although temperature and oxygen are known to control OC degradation, the limits between maxima and minima and the OC-temperature / OC-oxygen degradation relationships are not defined for shelf systems. There are no systematic studies which define specific limits or thresholds for temperature and oxygen shelf conditions and OC degradation rates or risk, which are expected to be dependent on both the OC characteristics and any mineral association.

Next steps

- Experimental testing of degradation of OC under resuspension across seabed source and water column environmental conditions.
- Integration of seabed OC reactivity descriptions, water column environmental conditions and OC degradation relationships will allow the identification and mapping of areas of higher or lower risk for OC released into the water column.

A1.5. Emission controls and timescales of exchange with the atmosphere

Some of the particulate organic and inorganic carbon in the seabed that is disturbed by trawling and released into the water column will be transformed into dissolved inorganic carbon (DIC). There are multiple processes which can affect the fate and eventual exchange of this DIC with the atmosphere.

Dissolved nutrients will also be released directly from the bed during gear impacts (Breimann *et al*., 2021) but also as part of the water column OC degradation (as per OC composition of N, P, Si etc). The balance and amounts of these nutrients can contribute to OC production via primary production or other food-web processes depending on the water column conditions (nutrient, oxygen, light, temperature). Some observational studies (though none in UK shelf) have indicated enhanced primary production following trawling resuspension, potentially leading to re-assimilation of carbon and dampening of outgassing (Pilskalin *et al*., 1998; Dounas *et al*., 2007; Siddiqui *et al*., 2024). Tiwari *et al*. (2025) also modelled the impact of trawling-released particulate organic matter on primary production in the North Sea and reported a similar effect. Despite these studies the fate of trawling released organic and inorganic nutrients and impact on OC production and degradation and eventual DIC outgassing is poorly understood.

DIC influences seawater CO_2 concentration, which in surface waters will alter the exchange of CO_2 with the atmosphere (Humphreys *et al*., 2018). This is the final step that could lead to CO_2 emission derived from any human disturbance of the seabed and is key in linking direct management of human activities affecting seabed carbon stores / sinks to climate change mitigation. Any DIC sourced from trawling impact can be conceptualised as a perturbation to the spatially and temporally variable ‘background’ marine carbon cycle, but the potential impact on air-sea CO_2 exchange is difficult to differentiate.

Northwest European shelf seas are a net sink of atmospheric CO_2 (Legge *et al*., 2020), with increasing atmospheric CO_2 driving increasing DIC and contributing to ocean acidification (Findlay *et al*., 2025; Humphreys *et al*., 2020). There is significant seasonal and spatial variability in the flux of CO_2 between shelf sea surface waters and the overlying atmosphere (Hartman *et al*., 2019; Humphreys *et al*., 2019; Kitidis *et al*., 2019; Rippeth *et al*., 2014). DIC is made up of dissolved CO_2, bicarbonate, and carbonate ions, in a chemical equilibrium that is impacted by numerous biogeochemical processes, physical factors, and anthropogenic pressures (Humphreys *et al*., 2019). The exchange of CO_2 between the ocean surface and atmosphere is primarily controlled by:

1) The physical limit on the rate of air-sea gas transfer, which is directly influenced by wind and waves.

2) The magnitude and direction of the difference between the CO_2 partial pressure in seawater and in the atmosphere. Seawater will absorb CO_2 from the atmosphere if the partial pressure of CO_2 in the seawater is lower than the partial pressure in the atmosphere above it, and seawater will release CO_2 to the atmosphere if the partial pressure difference is reversed. Changes throughout the year as well as the rise in atmospheric CO_2 levels influence the partial pressure difference. Seawater CO_2 partial pressure is controlled by water temperature, salinity and biological activity, which all determine seasonal variations in the amount available to exchange with the atmosphere. Photosynthesis removes DIC/CO_2 and respiration produces DIC/CO_2. Warmer and saltier water can hold less dissolved CO_2, which changes the partial pressure of CO_2.

Larger-scale processes also modify the physics and chemistry of surface waters. Shelf currents transport water masses, including waters with different temperature, salinity and DIC concentration (Kossack *et al*., 2024; Sims *et al*., 2022). Wind and waves mix the surface waters (Lincoln *et al*., 2016), which helps distribute CO_2 vertically, preventing concentration at the surface (Kitidis *et al*., 2019). Surface waters can become stratified, meaning the formation of a near-surface layer that is distinct from deeper waters. Across 70% of the northwest European continental shelf this occurs seasonally, during summer, as a consequence of thermal stratification in the deeper areas with weaker tides (Rippeth *et al*, 2005). It can also occur periodically closer to the shore due to freshwater inputs (Verspecht *et al*.,2009). When deep layers are isolated from the atmosphere by seasonal stratification, and so air-sea exchange of CO_2 will be delayed or not be directly altered by the impacts of trawling.

There have been no observational studies that demonstrate a direct impact from trawling on surface water DIC and sea-air CO_2 exchange. However, recent work has begun to constrain potential emissions numbers and investigate the complexity of the potential impacts of seabed disturbance on the ocean carbon cycle and highlight their indirect impacts on emissions (Attwood *et al*., 2024). Van de Velde (2025) modelled the impact of trawling and dredging on the marine carbonate system on a global scale, simulating the removal of alkalinity and associated reduction in the capacity of the ocean to store CO_2 as 'indirect' trawling related emissions.

Confidence

LOW No studies have directly linked trawling (or other seabed disturbances) to enhanced surface DIC and perturbed sea-air CO_2 exchange emissions. Recent work illustrates the impacts on the wider marine carbon system and highlights the complexity of relevant ocean processes.

Knowledge gaps

Fate and role of dissolved organic and inorganic nutrients release by trawling and OC degradation in controlling DIC residence times and emission. Understanding of DIC release generated from particulate organic carbon (POC) disturbed by trawling, water column residence times of POC /DIC / CO_2 in contrasting mixed and seasonally stratified regions, and shelf-wide sea-air exchange rates.

Next steps

- Development of risk maps of POC disturbance and degradation to DIC coupled to physical process emission potential.
- Improve understanding of the impact of physical mixing on surface expression and resultant sea-air CO_2 emissions across UK shelf from key physical principals through modelling.

A1.6. Other infrastructure and activity interactions

Seabed infrastructure including oil and gas, power or telecoms cabling, pipelines, offshore wind, and Carbon Capture and Storage (CCS) and other human activities such as dredging and disposal and aggregate extraction can interact with and affect seabed OC through resuspension, mixing, scour and/or deposition. These processes can occur throughout the life cycle (construction, operation and decommissioning) of the activity or infrastructure (Heinatz and Scheffold, 2023; Lonsdale *et al*., 2020; Watson *et al*., 2024; Woodward-Rowe *et al*., 2025).

Aggregate extraction is typically focused in areas of coarse substrates with low organic carbon, whereas maintenance/navigational dredging occurs mostly in inshore and estuarine regions where organic material may routinely accumulate (Parker *et al*., in prep B.). Disposal of dredged material sees the re-location of higher OC sediments, resulting in increases of OC in some areas (Parker *et al*., 2017). Porz *et al*., 2026 show that despite disturbing less sediment than aggregate extraction in the North Sea, disposal causes greater OC disturbance and both activities to be higher than by marine construction, but lower than by bottom-contacting fisheries.

Infrastructure consisting of hard substrates (Offshore wind, oil and gas) above the seabed can promote OC accumulation in nearby sediments through bio-deposition from attached epifaunal communities (Ivanov *et al*., 2021; Krone *et al*., 2013; Maar *et al*., 2009). This can enhance OC degradation and content nearby infrastructure in the top 10 cm of sediment. Additionally, the presence of infrastructure often excludes bottom trawling (e.g., De Borger *et al*., 2021a), reducing local sediment disturbance but potentially displacing trawling pressure elsewhere.

Although spatially limited, infrastructure impacts may be more intense due to deeper seabed-OC interactions. However, they are typically constructed at present in coarser, shallower areas of the shelf which contain lower carbon stocks. The exception to this is cable or pipeline interactions with coastal carbon stocks as they come ashore where the trenching / burial activities can disturb higher carbon levels in these areas (Clare *et al*., 2023). These activities are much more spatially restricted than trawling or climate change pressure.

Confidence:

LOW. There is a very limited evidence base relating to infrastructure sector activities and seabed OC, with little agreement on net OC affects over life cycles and on climate relevant scales. However, the mechanisms associated with these activities and their effect on the seabed are relatively well understood and impacts on carbon can therefore potentially be conceptualised.

Knowledge gaps

- Understanding of the spatial overlap of vulnerable carbon and localised pressure from infrastructure related activities. Available seabed OC stock maps (e.g., Diesing *et al*., 2021, 2017; Smeaton *et al*., 2021a) are limited to shallow sediments depths (less than 10 cm below the seafloor), and do not incorporate information on OC reactivity, and many activities will impact OC buried deeper beneath the seabed. There is also

limited data to show the spatial extent, mode of action or frequency of some of these activities.
- There is little, to no empirical evidence of how these activities can affect OC sequestration and storage.
- Expectations for future increases or decreases in the extent and modes of these activities as a result of policy priorities or ambitions, for example: the increasing use of marine offshore renewables.
- The net effect of OC connectivity between structures and expansion or redistribution of activity sectors and interactions between sectors.

Next steps

- Extension of OC and reactivity maps to depth relevant for infrastructure – OC interaction and change assessments.
- Fundamental observations of activity - OC change across differing life-cycle stages.
- Development and testing of predictive tools capable of investigation of coupled seabed and water column OC changes on climate relevant timescales, including scaling and connectivity effects

A1.7. Climate forcing and seabed OC adaption

Climate change and associated forcing, such as storms, can act as a pressure on seabed OC stock and burial by driving changes in OC input and OC seabed processing or natural disturbance. Climate forcing can affect carbon cycling in the water column by influencing POC input from terrestrial inputs through river catchments as well as water column organic matter production and oxygen and temperature changes impacting OC degradation between source and sink.

OC degradation following deposition in sediments is also influenced by changes in temperature, oxygen, and biota, all of which are affected by climate change. OC already buried in the sediment can be impacted by in situ temperature changes. These processes and their alteration under climate forcing will all vary spatially across the shelf as determined by hydrography, sediment type and depth, and temporally with season (Kroeger *et al*., 2018; Legge *et al*., 2020; MCCIP, 2020). These changes may occur gradually due to baseline shifts on ecosystem conditions or as a result of episodic marine heat waves (Berthou *et al*., 2024; Hobday *et al*., 2018; Jacobs *et al*., 2024) which have potentially more acute conditions at the seabed (Wilson *et al*., 2025).

Shallow coastal and shelf waters are subjected to frequent and locally severe events of sediment resuspension, due to wave action, storms and near-bottom water currents. The predicted increase in the magnitude of storms (Bricheno *et al*., 2025) could lead to expansion of areas where seabed carbon stores are exposed to larger natural disturbance pressures, including resuspension.

Considering the net/cumulative effect of climate change forcing, it is likely that climate forcing will decrease OC input to the bed and increase degradation rates within the bed (van der Molen *et al*., 2013). It may also allow degradation of OC stocks accumulated over decades or longer timescales, including relic pools. This will be most pronounced potentially in areas where OC processing at present is temperature limited, for example, the northern North Sea and other deep, cold areas of the shelf. Recent studies (Queirós *et al*., 2023) have also developed climate change predictions for seabed carbon, although these are at low confidence due to lack of skill for models in prediction present and future carbon stocks and burial in space.

Other, region-specific modelling studies have suggested decreases in OC seabed stock of ~ 6-10% per degree increase in seabed temperature (Parker *et al*., 2022) as a result of the rates of biological processes, such as carbon remineralisation, increasing with temperature. This assumed temperature response is reasonable for labile carbon, but it is not known if the same relationship with temperature is valid for the more refractory sequestered OC where it is more difficult to test the temperature response. If the assumed response holds, benthic OC stock can be expected to decrease in response to climate temperature increases.

Overall, temperature is expected to be a dominant control on seabed OC stock and decreases in stock occur on the same timescale as the OC degradation half-life (~reactivity), so temperature response can be very slow for more refractory or stable OC. Observable decreases in stock may lag temperature changes by decades, depending on the spectrum of OC degradation rates in a given carbon stock i.e., the ratios of differing OC stabilities within a stock.

Although oxygen conditions at sufficiently low levels to inhibit OC degradation (hypoxia or anoxia) conditions rarely occur at present, this is predicted to worsen with climate change (i.e. warmer temperatures (and therefore lower deep water O_2 when stratification forms), with extended periods of stratification. The response of regions with differing hydrography – for example, well mixed (e.g., southern North Sea, eastern Irish Sea) and seasonally stratified (e.g., northern North Sea and Celtic Sea) will be very different (Rippeth *et al*., 2024). The net impact of this process on OC degradation both within the water column (relevant input to disturbance) and also within the bed is unclear.

Reactivity is a key factor determining sequestration/burial rates, with labile OC being consumed before it can be buried benthic the most biogeochemically active zone. Increasing seabed temperature is expected to decrease OC burial and therefore the amounts stored because a higher proportion of the input OC is predicted to be degraded in near-surface sediments.

The dominance of climate factors (storm magnitude increases, temperature increase, changes in OC input, carbon lability and faunal mixing) will vary with seabed setting (and link to water column OC input changes), but the clear influence of temperature and natural disturbance (both present day and under climate forcing) will be key for any future predictions of seabed OC parameters.

Confidence

LOW. Only a few studies have focused on climate forcing of OC stocks and burial directly, rather than water column or biogeochemical processes which may control them. There are few observations on long-term shifts in sediment OC baselines and gaps in knowledge of the complex controlling mechanisms and feedback which will drive adaptation.

Knowledge gaps

- The process-based models which have been used to investigate climate impacts on seabed OC are not good at reproducing observed time integrated OC stocks and burial which limits their use in providing a full understanding of the system now and into the future.
- The effect of key climate drivers (temperature, oxygen, input, turnover, faunal shifts), both for gradual baseline shifts and marine heat waves, on OC with different characteristics is not well understood.

Next steps

- Development of risk maps for seabed OC stocks with temperature or OC input changes (short-term) based on experiments to parameterise the response of OC to climate forcing.
- Coupled spatial water column and seabed models to investigate OC input to and within seabed cycling changes are needed on climate relevant scales (decades to centuries, gradual changes and marine heat waves).

A1.8. Management measures to support shelf seabed organic carbon storage and climate change mitigation potential

A1.8.1. Spatial placement or restriction of activities

Management measures or restrictions on seabed use could be imposed in areas of high OC vulnerability. Seabed sediment carbon could be protected by identifying areas where the organic carbon is most reactive and susceptible to become emissions when disturbed and restricting human pressures (e.g., demersal trawling) in these areas. Protection may afford both emission avoidance (stock is not degraded) or emission savings (when stock and burial may recover over long timescales). The management outcomes for both of these potential benefits depends on if the OC stock is reactive and can recover (is an active depositional or relic feature).

The current UK MPA network was designated to protect biodiversity features but may offer modest co-benefits for sediment OC storage through protection from activities which disturb the seabed and promote OC degradation. The MPA network cover 40% of English Waters. In the English shelf seabed most sedimentary OC (67 to 81%) resides outside the network, some in areas subject to significant chronic trawling pressure (Parker *et al*., 2022).

Scenario testing of spatial closures of the seabed to certain activities has shown that in some cases, localised protection may actually increase the overall seabed OC-demersal trawling interaction. This is because areas designated for specific features or high biodiversity do not necessarily overlap with areas of high carbon (Parker *et al*., 2022) and there are potential displacement effects of activities (i.e. activity is increased outside the managed area as a result of management) towards more highly reactive OC areas (Parker *et al*., in prep B; Parker *et al*., 2022; Le Quesne *et al*., 2021).

The trade-offs between the recovery of biodiversity and sediment OC stock post-disturbance (e.g., after spatial closure to trawling) are uncertain, and the expected net change in OC storage and accumulation following seabed protection is largely unknown (Parker *et al*., in prep B; Parker *et al*., 2022). There is also high uncertainty in the trade-off of prioritising the protection of biodiversity over OC and vice versa, both under impact and recovery conditions in the long-term.

Knowledge of the location of reactive OC stocks in relation to spatial protection measures and existing impactful activities is needed. This information could provide the regional scale screening of areas (and carbon) that might be at risk from seabed disturbance (from trawling activity and / or other human disturbance or infrastructure activities) and worth protecting through introduction of new management measures. Understanding OC reactivity and seabed biological condition in areas surrounding proposed activity locations and across the shelf could help reduce unforeseen climate impacts of planning decisions. It can also support marine spatial planning initiatives of various human activities across English Waters and UK EEZ.

Confidence

MEDIUM. Areas of OC stock under pressure from human activities and their relationship to existing management networks have been identified, but additional spatially resolved knowledge of the reactivity of OC is required to enable development of risk maps across English waters and to support the development of management measures.

LOW. The confidence in outcomes for OC spatial management actions is limited as there are very few examples of protection measures (often for biodiversity purposes) which have tracked OC storage changes across scales.

Knowledge gaps

- Spatially resolved knowledge of seabed OC condition, most significantly reactivity, in relation to existing management measures.
- Linking pressure (disturbance) from human activity to specific impacts on seabed OC storage and burial, and how impacts are likely to change in scenarios of protection from pressure (recovery) or increasing pressure. This includes recovery timescales of OC stock and burial following disturbance reduction.
- Displacement of pressure or activity changes (e.g., gear switching) because of potential management measures in certain areas (to include socio-economic effects influencing OC outcomes).
- The trade-offs between recovery of biology and biodiversity, and OC storage and accumulation for different protection scenarios.
- Knowledge on the cumulative impacts to OC storage and accumulation from multiple marine pressures and sector-sector interactions.
- Insufficient long-term monitoring of OC responses to management measures - especially in the UK context that MPAs were not designed around carbon objectives and therefore very little data has been collected on this specifically.

Next steps

- Research on shelf seabed OC pressure and recovery changes post protection to inform understanding of effective management measures to safeguard shelf OC storage.
- Spatial exploration of OC status in comparison to historic seabed disturbance from human activities to establish risk and potential of specific sites for recovery.
- Tracking of coupled biological and OC stock recovery during and following management of activities which disturb the seabed.
- Identification of potential priority areas to protect if emission avoidance was prioritised. For example, such areas would have high seabed OC stocks, be relatively unimpacted by disturbance from human activities to date and / or have high OC burial rates which will allow for rapid recovery of OC stock after disturbance is ceased. Emission savings priority areas would have high carbon stocks and were currently heavily impacted by disturbance from human activities. These priority areas may be within or adjacent to the current English MPA network or found in other areas entirely.

A1.8.2. Timing of activities

The risk of OC degradation is greatest in waters that have higher temperatures and are well oxygenated. Seabed disturbance activities undertaken in shallower, well mixed shelf areas (~ < 30-40m water depth) which have higher water temperatures in spring, summer and autumn months (~ 10 to 18 degrees C) may lead to an increased likelihood of seabed OC degradation following disturbance and resuspension, and possibly subsequent emission of CO_2 to the atmosphere (Lønborg *et al*., 2024; Tiwari *et al*., 2025). Restriction of activities which disturb reactive sediment OC stocks to cooler months of the year could decrease the risk of OC degradation. However, in winter months the breakdown of seasonal stratification increases the connectivity between the seabed and the air-sea interface in some areas of the English shelf. The interaction of OC degradation risk, water column feedback and subsequent emission risk due to water column conditions, both in space and time (season), is a key consideration of the timing of management measures.

Sea temperatures are rising because of climate change, and this will also increase the risk of OC degradation and any associated emissions if hydrographic conditions allow. Changes in stratification timing, intensity and oxygen levels will also need to be considered.

Note that seasonal restrictions would not be intended to allow OC stocks to 'recover' in the same way as seasonal/periodic closures to fishing for spawning or biodiversity protection, they would aim to limit disturbance to times when OC degradation risk is least.

Confidence

HIGH (but specifics for risk or impact assessment – **LOW**). Both English shelf sea bottom water temperatures and the impact of temperature on OC degradation are well understood which would allow timing and locations of higher degradation risk to be identified. The specific thresholds of environmental conditions to OC degradation within the water column are not yet accurately parametrised.

Knowledge gaps

There are few studies which include the delineation of temperature to OC degradation response relationships across a range of relevant temperatures and OC reactivities to inform definition of risk boundaries (thresholds or tipping points) for bottom water temperatures to identify specific high-risk areas in time and space.

Next steps

- Experimental studies to describe OC degradation curves with temperature (perhaps oxygen).
- Spatial designation of areas with different risk levels in terms of current and expected future bottom water temperatures/oxygen levels, hydrography and OC stock reactivity.

A1.8.3. Activity placement and lifecycle decisions

The location and physical nature of some activities could be altered to reduce OC degradation risk.

For infrastructure sectors consideration of the sediment OC interactions over the whole life cycle (pre-placement, construction, operation and decommissioning) is needed to minimise degradation and potential emission risk and maximise storage. Some human activity or infrastructure placement or modes of action could be altered to reduce OC degradation risk for example, avoiding placement of infrastructure on highly reactive or vulnerable OC stores, assessing methods for cable laying can be altered to minimise OC disturbance and resuspension (e.g., ploughing vs jetting). Similarly, different decommissioning methods (e.g., leaving in place or removing structures) could maximise the net sediment OC sink and reduce OC degradation risk. These considerations of placement methodologies are also important for sediment dredge and disposal or beneficial use material placements.

For demersal trawling gear modifications which both reduce biodiversity impact (Szostek *et al*., 2022) and could reduce OC disturbance, including (see e.g., ICES, 2023; Lucchetti *et al*., 2023):

- Lighter gear (e.g., replacing steel trawl doors with hydrodynamic or composite ones) can reduce drag and gear seabed penetration.
- Raised footropes or semi-pelagic trawls can reduce contact with the seabed, cutting both habitat disturbance and the resuspension of carbon-rich sediments.
- Reduced contact and drag on seabed (e.g., skids on bottom of scallop dredges; (Easton *et al*., 2025) reduce fuel consumption as a primary objective but also reduce the impacted area of sediment mixing and resuspension (e.g., Suuronen *et al*., 2012).

Alternative towing techniques or shorter tow durations can similarly limit both ecological and potentially minimise carbon impacts.

Confidence

MEDIUM confidence in how contrasting human activities and infrastructure physical actions interact with the seabed as well as choice of location/site that could minimise shelf sediment OC disturbance and degradation risk or increase OC seabed storage. Less evidence on long-term net impacts of life cycle placement and modes of action decisions.

LOW confidence in net OC impact assessments across scales from gear modifications sector- sector displacement outcomes (as a result of management measures or infrastructure development).

Knowledge gaps

There is very little information on the benefits resulting from trawling gear modification or infrastructure / activity approaches (construction, decommissioning) to minimise OC impacts.

Lack of understanding of differing human sector-sector interactions e.g., response of other sectors to infrastructure placement (offshore wind) acting as an exclusion area to activities

Next steps

Observational and modelling work to examine differing life cycle/activity scenarios and options to minimise carbon disturbance or risk. This includes carbon benefits of trawling gear modification and sector - sector interactions (gear switching or displacement) from infrastructure placements or life-cycle decisions (e.g., leave in place vs remove).

A1.9. References

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Annex 2. Confidence assessment

Confidence for each topic of evidence reviewed has been assigned following the Marine Climate Change Impacts Partnership (MCCIP) Report card approach, as outlined in MCCIP report card (2020) and discussed in Frost *et al*. (2017) (***Figure A2.1***).

The confidence ratings of low, medium or high are based upon the amount of evidence available and the level of scientific consensus or agreement. A 'high' rating indicates a large evidence base from differing sources (literature, studies, modelling and experiments), with a high level of consensus. An overall rating of 'low' is achieved when either the amount of evidence and / or the level agreement or consensus is low.

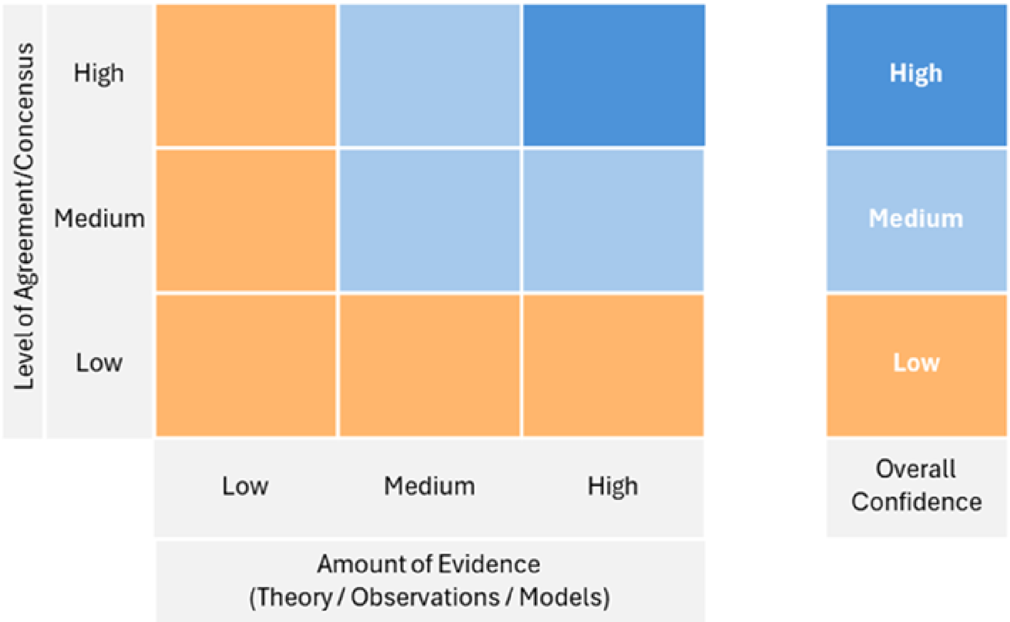

Figure A2.1 Visualisation of the matrix used to perform confidence assessments for each evidence topic, following MCCIP approach (e.g., Frost *et al*., 2017; MCCIP, 2020). Reproduced from Parker *et al*., in prep (in prep 2026).

Table A2.1 provides an indicative overview and synthesis of the confidence assessments from sections above to highlight rapidly areas to be potentially addressed for policy makers. The confidence assessments are expanded upon in the detailed text in the sections above to cover both elements of the confidence assessment relating to amount of evidence and level of agreement/consensus.

Table A2.1 Summarised confidence, knowledge gaps and next steps across topics. Overview and synthesis of the evidence confidence assessments to highlight rapidly areas to be potentially addressed for policy makers.

Topic	Confidence	Knowledge gaps and uncertainties	Next steps
Seabed Organic Carbon characteristics (section 1.1)	**Stock** (M)	• Stocks below 10 cm • Co-measured sediment carbon content and dry bulk density • Carbon stock measurements in shallow subtidal areas with high terrestrial carbon inputs	• Gap filling of subtidal organic carbon content sampling at priority locations and below 10 cm depth. • Ensuring consistency of sampling methodology, and standardisation of sampling and analysis techniques.
	Burial (L)	• The relationship(s) between OC stock and burial rates along inshore to offshore gradients. • Measurement of burial rates in sediments deeper than 10 to 25 cm beneath the seafloor	• Targeted sampling of the shelf seabed conditions which are under-represented in available measurements: either geographically or in terms of their environmental conditions. • Differentiation of seabed areas of active deposition & burial from relic sedimentary deposits
	Reactivity (L)	• Measured biological degradation rates for sedimentary OC and the different analytically defined reactive fractions • Defining OC reactivity when considering climate change mitigation relevant timescales	• Experimental approaches testing the performance and suitability of the methods included in the analytical toolbox in conjunction with modelling and biological degradation studies • Linking definitions of reactivity to carbon source, composition, mineral association • Experimental validation of degradation rates for both undisturbed and disturbed sediment and linking the analytical toolbox parameters to constants or OC parameters used in modelling approaches such as half-life, k or activation energy.
	Integrated carbon characteristics	• Data availability: insufficient combined measurements of OC stock, properties (reactivity, source) and accumulation/burial rates. • Best choice of carbon map and mapping methods for a given application • Linking OC source and reactivity to OC stock and burial • The role and trade-offs in biodiversity and macrofauna in mediating and controlling OC parameters • Understanding of spatial carbon processing regions from data and mechanistic modelling	• Combined observational and modelling approaches to improve understanding of OC controls in the seabed • Exploration of concurrently measured biological and OC data • Development and intercomparison of modelling and data derived maps of carbon processing regions (stock, burial and reactivity)
Change under impact (sections 1.2 to 1.7)	**Trawling gears, distributions and disturbance** (L-M)	• Understanding, across all sediment types differing gear components and actions (mixing, mobilisation, pore-water effects) • Coupling of OC and suspended particulate matter (SPM) when plumes are created and over what timescales • Lack of inshore vessel monitoring information; within gear type assumptions by fleets; limitations of temporal resolution for understanding seasonal variability.	• Tracking of OC, SPM and pore-water metrics both within the seabed and in plumes from differing gears, seabed impact history and intensity • Development of fleet information to cover iVMS, within gear variability and provide temporal distributions of pressure (within year).

Topic	Confidence	Knowledge gaps and uncertainties	Next steps
	Trawling-carbon interactions and impact (L-M)	• Fundamental observational and process modelling work is needed to understand the key direct and indirect impacts of trawling on net OC stock and burial across differing shelf regions. Key topics include acute vs chronic impacts; macrofaunal and biodiversity changes (impact and recovery); net effect of opposing processes.	• Combined analysis of recent observational data across trawling gradients, available from various national and international programmes - methodological comparability is a key objective • Collection of co-incident carbon and faunal impact / recovery data • Assessments impact of OC relocation and mixing on long-term OC storage • Improvement of both process-based, and data-driven spatial predictive tools to develop consensus between approaches on the impact of trawling on OC storage across all spatial scales from local to regional.
	Resuspension degradation risk (M)	• There are no systematic studies which define specific limits or thresholds for temperature and oxygen shelf conditions and seabed OC degradation rates or risk	• Experimental testing of degradation of OC under resuspension across seabed source and water column environmental conditions (temperature and oxygen). • Identification and mapping of areas of higher or lower degradation risk for OC released into the water column.
	Transport and re-deposition (M)	• Coupled understanding of OC transport and degradation including rates of both processes in differing environmental conditions or locations • Understanding of particle-OC distributions within plumes and associated settling information.	• Sensitivity modelling of OC release and fate for different source locations across the English shelf seas for all seasonal conditions. • Collection of new data on plume properties and settling velocities and integration of these data into models.
	Emission (L)	• Combined understanding of generation of DIC from particulate organic carbon (POC) disturbed by trawling, residence times of POC /DIC / CO_2 in the water column (including biological interaction), and shelf-wide sea-air exchange rates their including seasonality.	• Development of risk maps of POC disturbance and degradation to DIC coupled to physical and biological controls on emission potential. • Impact of physical mixing on surface expression and resultant sea-air CO_2 emissions across UK shelf from key physical principals through modelling.
	Other Infrastructure & activities (L)	• Understanding of the interaction level and distribution of carbon and pressure from infrastructure related activities. • Little to no empirical evidence of how infrastructure activities can affect carbon sequestration and storage across life cycles. • Expectations for future increases or decreases in the extent and modes of these activities • The net effect of carbon connectivity between structures and expansion or redistribution of activity sectors and interactions between sectors.	• Extension of carbon and reactivity maps to depth relevant for infrastructure – OC interaction and change assessments; Data to show the spatial extent, mode of action or frequency of activities. • Fundamental observations of activity - OC change across differing life-cycle stages. • Development and testing of predictive tools capable of investigation of coupled seabed and water column carbon changes on climate relevant timescales, including scaling and connectivity effects
	Climate (L)	• Poor model skill for present carbon stock and burial distributions and future adaptation. • The effect of key climate drivers (temperature, oxygen, storms, input, turnover, faunal shifts) on organic carbon with different characteristics is not well understood.	• Development of risk maps for seabed OC stocks with climate temperature, storms or OC input changes (short-term) based on experiments to parameterise the response of OC to climate forcing • Coupled spatial water column and seabed models to investigate OC input to and within seabed cycling changes are needed on climate relevant scales (decades to centuries).

Topic	Confidence	Knowledge gaps and uncertainties	Next steps
Potential Management Actions (section 1.8)	**Spatial management & protection** (L/M)	• Spatially resolved knowledge of seabed OC condition, most significantly reactivity, in relation to existing or future management measures • Knowledge on how carbon impacts are likely to change in scenarios of protection from pressure (recovery) or increasing pressure. • Displacement of pressure or activity changes (e.g., gear switching) because of potential management measure in certain areas • The trade-offs between recovery of biology and biodiversity and OC for different protection scenarios	• Research on shelf seabed OC pressure and recovery changes post protection • Spatial exploration of OC status in comparison to historic seabed disturbance from human activities to establish current risk and potential of specific sites for recovery. • Tracking of coupled biological and OC stock recovery during and following management of activities which disturb the seabed. • Identification of priority of areas to protect for differing carbon reasons.
	Timing of activities (H/L)	• Definition of risk boundaries (thresholds or tipping points) for bottom water temperatures or oxygen levels to identify specific high-risk areas for OC degradation in time and space.	• Experimental studies to describe OC degradation curves with temperature (perhaps oxygen). • Spatial designation of areas with different risk levels in terms of current and expected future bottom water temperatures/oxygen levels and OC stock reactivity.
	Activity placement and life cycle decisions (M/L)	• There is very little information on the benefits resulting from trawling gear modification or infrastructure / activity approaches (construction, decommissioning) to minimise OC impacts. • Lack of understanding of differing human sector-sector interactions e.g., response of other sectors to infrastructure placement	• Observational and modelling work to examine differing life cycle/activity scenarios and options to minimise carbon disturbance or risk. Including trawling gear modification carbon effects and sector - sector interactions (gear switching or displacement) from infrastructure placements or life-cycle decisions (e.g., leave in place vs remove).

Annex 3. Revised estimate of sediment organic carbon disturbance and resuspension due to trawling in English waters and UK EEZ

A3.1. Introduction

This quantitative estimate of the impact of trawling activity on UK subtidal sedimentary organic carbon stock builds upon and advances previous global and regional scale estimates (e.g., Epstein *et al*., 2021; Sala *et al*., 2021, Millage *et al*. (submitted) and Cefas reports (Pressures report; Parker *et al*., B in prep) through 2 main routes

1. Incorporating UK-specific spatially resolved estimates of subtidal sediment organic carbon reactivity,
2. Accounting for gear-specific penetration and hydraulic properties in estimates of the volume of sediment disturbed and the proportion of disturbed sediment which is resuspended.

We aim to:

- constrain the potential impact of bottom trawling fleets on seabed organic carbon within English and UK shelf areas using best available information from published literature and recent results from Defra-funded research and development programmes, both spatially (as maps) and as overall total values (summary statistics), to provide improved estimates of potential CO_2 release to the atmosphere due to bottom trawling.
- explore spatial patterns of seabed organic carbon trawling pressure (both disturbance and resuspension) to support potential future decisions on management.

A3.2. Methods

A3.2.1. Fishing pressure

Benthic fishing pressure was quantified based on the ICES dataset (ICES, 2021) compiled to support OSPAR assessment of benthic impacts of fishing activity (Matear, *et al*., 2023). ICES summarised fishing data as cumulative pressure for all gears and for specific gear groups including otter trawlers and beam trawlers which are the predominant bottom impacting gear in the UK EEZ (Parker *et al*., in prep). We used the estimates of the surface (top 2 cm) swept-area and swept-area ratio at 0.05° by 0.05° c-square resolution (approximately 15 km² at 60°N latitude), and calculate the mean swept area ratio for each c-square overall years (2009-2020) assuming that null values in the annual data represented the absence of fishing activity in that year.

The swept-area ratio represents the cumulative area impacted by fishing gear within a specified area (grid cell or c-square) over a year divided by the surface area of the grid cell. The area of abrasion due to fishing (swept area) for the dataset is based on broad assumptions about the gear type (e.g., gear widths; see Eigaard *et al*., 2016).

The dataset was generated using monitored vessel activity from vessel monitoring systems (VMS) and logbook data and for the period 2009 to 2020. Data are included from Belgium, Denmark, Estonia, France, Germany, Ireland, Latvia, Lithuania, the Netherlands, Poland, Spain, Sweden and the UK. There was no suitable data from Iceland, Norway and Portugal, and no data submitted from the Faroe Islands, Greenland, and Russia, and therefore data does not contain fishing statistics from all the European countries that could potentially be fishing in UK waters. Furthermore, the data does not include smaller vessels (<12 m). Overall uncertainty is expected to be highest in coastal areas (ICES, 2021).

A3.2.2. Carbon Stock

There are several modelled maps of OC stocks within the subtidal seabed sediments of the UK EEZ in the peer reviewed literature available (e.g., Atwood *et al*., 2020 at the global scale, and Diesing *et al*. 2017, Smeaton *et al*. 2021, and Diesing *et al*. 2021 at the more regional scale). In this analysis, the OC stock map produced by Diesing *et al*., (2017) is used. While this map does not incorporate information from more recent sampling and analysis, it was chosen is the most appropriate for this work. The map is based on predictive mapping (random forest) of seabed carbon using about 850 measurements of particulate organic carbon measured by Cefas on sediment samples collected between 1996 and 2015 (Mason *et al*., 2017) with measurements taken to be representative of the top 10 cm of sediments, but more than 80% of samples were from only 0-2 cm sediment depth and less than 10% of samples extended to 10 cm below the seabed. The seabed organic carbon map extent is limited by that of its sediment grain size predictor layer (Stephens and Diesing,

2015) and does not cover the northern and northeastern parts of the UK EEZ. Diesing *et al*. (2017) mapped percentage organic carbon (POC) in seabed sediments, and we followed their procedure of converting that output to carbon density (kg m-3) by estimating dry bulk density (DBD) from the % mud map of Stephens and Diesing (2015).

While Smeaton *et al*. (2021) derived an alternative map of subtidal seabed OC by deriving a relationship between measured organic carbon content (in about 600 samples) and sediment grain size to predict OC in about 35,000 measurements of grain size, which were then spatially extended by kriging to map the full UK EEZ, there is limited agreement between the two maps and the Diesing *et al*. (2017) map is in better agreement with more recent samples and unpublished mapping work (Clare *et al*., 2025). A third seabed sediment map within the UK EEZ was published by Diesing *et al*. (2021), but it covers only the North Sea and is based mostly on Norwegian trench data and may be less accurate for UK waters.

For our analysis, the OC stock for the top 10 cm, originally mapped on a 500 m^2 grid, was maintained in the native CRS, and the fishing pressure data (at c-square resolution of 0.05°) was resampled to the same resolution and CRS. Where the OC map does not fully cover English waters (missing southwest extreme, amounting to 3.8 %) nor the UK EEZ (missing additionally northern and northwestern Scottish waters, amounting to 46 %), we have not estimated OC densities beyond the map extent with values presented representing UK and English shelf seas.

A3.2.3. Carbon lability

The proportion of labile OC (most likely to be degraded under disturbance) within seafloor sediments was mapped based on lability data for 829 sediment samples of the top 10 cm of sediment (***Figure A1.1***) from Smeaton and Austin (2022) (excluding fjord samples) and unpublished Cefas samples (Parker *et al*., in prep.) measured in the same laboratory. The percentage of labile OC was estimated by thermogravimetric analysis (TGA) which quantifies the amount of OC lost during heating; labile OC was defined as that lost at temperatures between 200 and 400 °C (Graves *et al*., 2022; Smeaton and Austin, 2022. It is noted that TGA documents the levels and categories of organic matter but here we have assumed it to be a good approximation for OC.

Following the approach of Black *et al*. (2022), average labilities were derived for sediment type groups (classifications) of samples, and these were applied across the study area to roughly estimate lability maps. While Black *et al*.

(2022) derived and applied average lability percentages for a simplified 5 Folk classification scheme based on n=375 samples, we explored the use of both a 6-group EUNIS level-3 habitat type classification (JNCC, 2025; habitats A5.1-4 and 'other') and a 9-classification UKSeaMap sediment substrate classification (JNCC, 2025) based on more than twice as many lability measurements. For EUNIS level 3 habitats other than the 4 dominant types of sublittoral sediment, which were under-represented in the lability data set, the overall average lability was applied. Both EUNIS and sediment type classification were explored to include a range of substrate granularity levels and the potential impact of water depth (accounted for in EUNIS habitats).

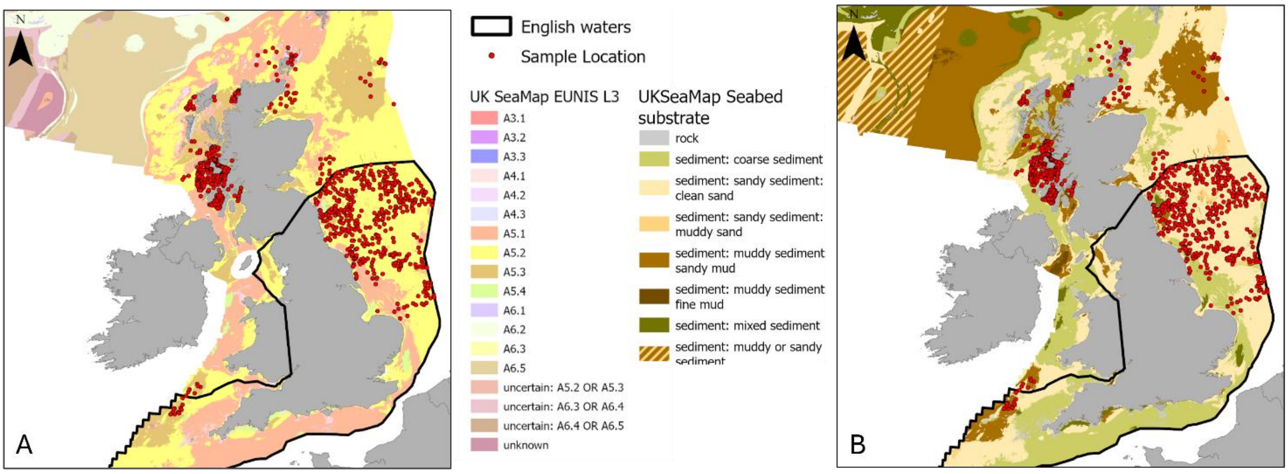

Figure A 3.1 Lability sample locations (red dots) overlaid on EUNIS level 3 habitats (A) and seabed substrate classification (B). Sediment maps from JNCC, 2025.

A3.2.4. Disturbance and resuspension

Table A3.1 Summary of depths of literature data used for the depth of sediments below the seabed which are disturbed (in cm) and resuspended (in mm).

Gear type	Depth of disturbed sediments (cm)*	Depth of resuspended sediments (mm)	Percentage of disturbed which is resuspended	Average resuspended depth (mm)
Otter Trawl	2.44 ± 1.14	0.3 - 1.9 **	1 – 8 %	1.1
Beam Trawl	2.72 ± 1.24	2.6 – 5.8 ***	10 – 21 %	4.2

* Penetration depths from Hiddink *et al*. (2017), as mean ± standard deviation.
** Otter trawl depth of resuspension from O'Neil & Summerbell, (2011).
*** Beam trawl depth of resuspension from Rijnsdorp *et al.* (2021).

Depths (beneath the seafloor) of disturbance and resuspension are shown in ***Table A3.1***. These were applied to the trawling SAR maps to (spatially) define the volume of sediment disturbed and that information combined with the seabed OC density map to calculate the mass of both total and labile OC disturbed and resuspended (***Figure A3.2*** illustrates the workflow). Note that otter trawls are wider than beam trawls (Eigaard *et al*., 2016) and thus disturb a greater volume of sediment per trawl pass despite their slightly shallower depth of penetration – gear width is accounted for in SAR.

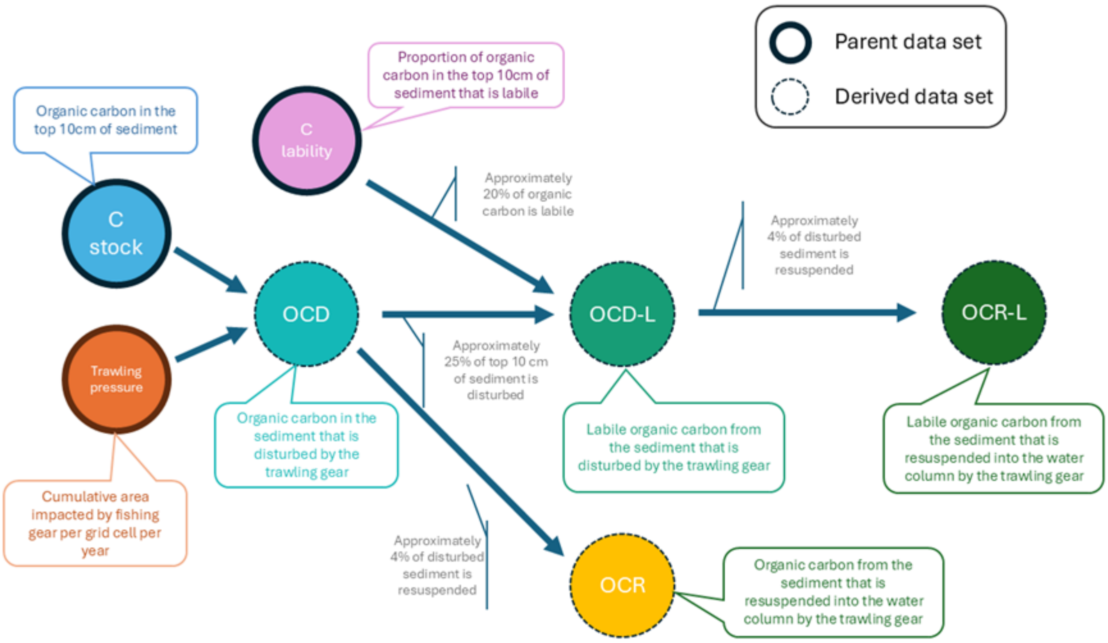

Figure A1.2 Workflow to obtain an estimate of the resuspended labile organic carbon (OC) due to fishing pressure in the UK shelf waters.

A3.3. Results:

A3.3.1. Fishing pressure

Overall annual average fishing pressure (cumulative annual impact on surface sediments, representative of the period 2009-2020 and limited by the omissions of some vessel from some countries and of some sizes from the ICES, 2021 dataset) are summarised for both the UK EEZ and English waters in ***Figure A3.3***. Otter trawling is widespread across the whole UK EEZ, while the majority of beam trawling (94 %) occurs in English waters (compared to only 32 % of the total UK EEZ otter trawling activity). For English waters, the cumulative annual beam trawling was 19 % of the cumulative impact of otter trawling.

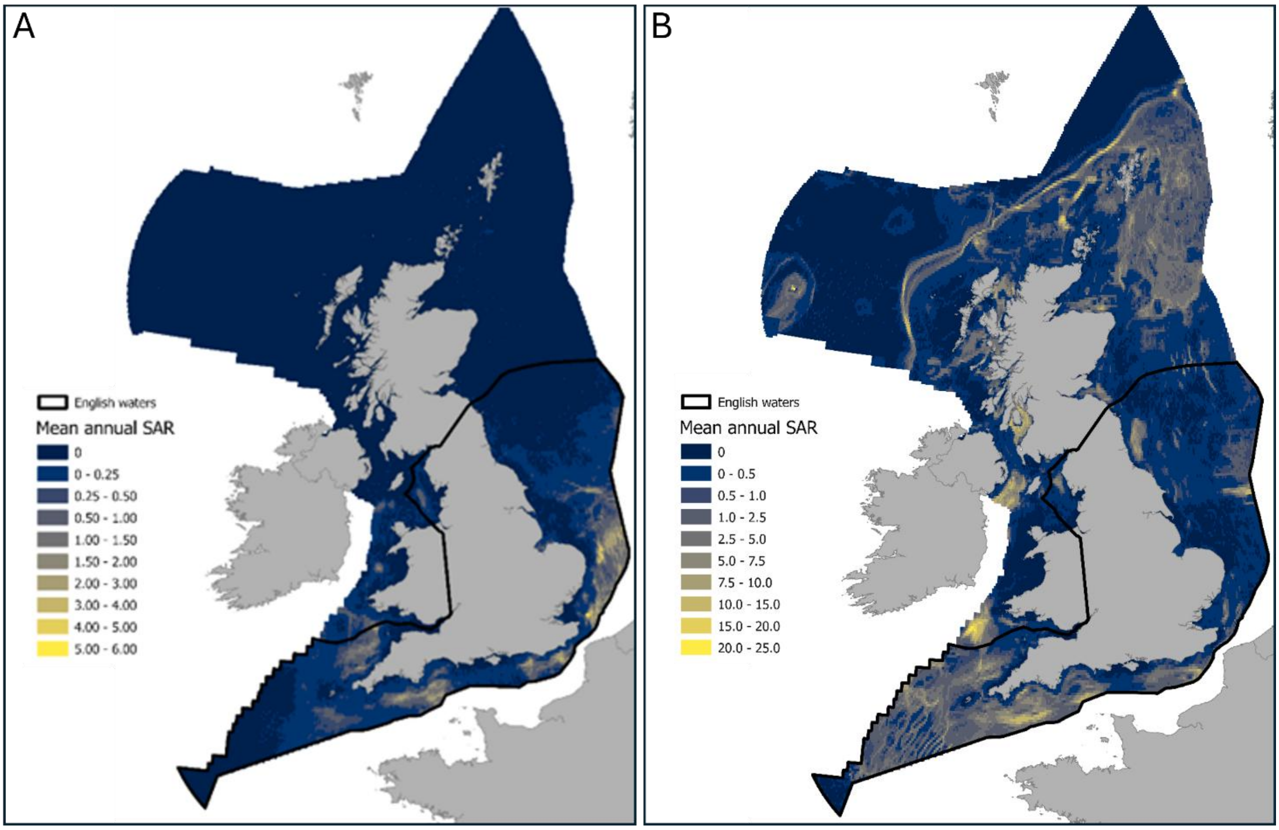

Figure A3.3 Fishing pressure due to (A) beam and (B) otter trawling in the UK EEZ, as surface swept area ratio per c-square (0.5 x 0.5-degree resolution) as overall average for 2009-2020, calculated from ICES, 2021.

Highest otter SAR include the marine area off the Northwest coast of Scotland, and areas in the western English Channel and the southern Celtic Sea. Smaller localised areas of high activity are also seen west of the Isle of Man and in the waters around the Isle of Arran in the Firth of Clyde, Silver Pit and Farnes areas in the North Sea. To the north of Scotland there appears to be an otter trawling 'route', appearing as a line feature on the map, running from south-west to north-east which requires further analysis. The area's most heavily impacted by beam trawling are the southern North Sea, the English Channel, and the southern Celtic Sea.

A3.1.1. Carbon stock

The mass of OC in the top 10 cm of seafloor sediments per km^2 in each grid square derived, calculated from Diesing *et al*. (2017) is shown ***Figure A3.4***. High OC stocks are present around the coastal areas and in particular the north-east coast of England and Scotland, the south-west coast, and the east coast of Scotland. Sandier areas of the North Sea typically show lower carbon stock levels. The total mass of OC stock across the continental shelf of the UK EEZ was calculated as 164.9 Mt which compares favourably with an estimate of

240 Mt by Burrows *et al* 2024 for the UK EEZ. The English component of this stock was estimated at 83.5 Mt which represents around 51% of the total UK EEZ stock.

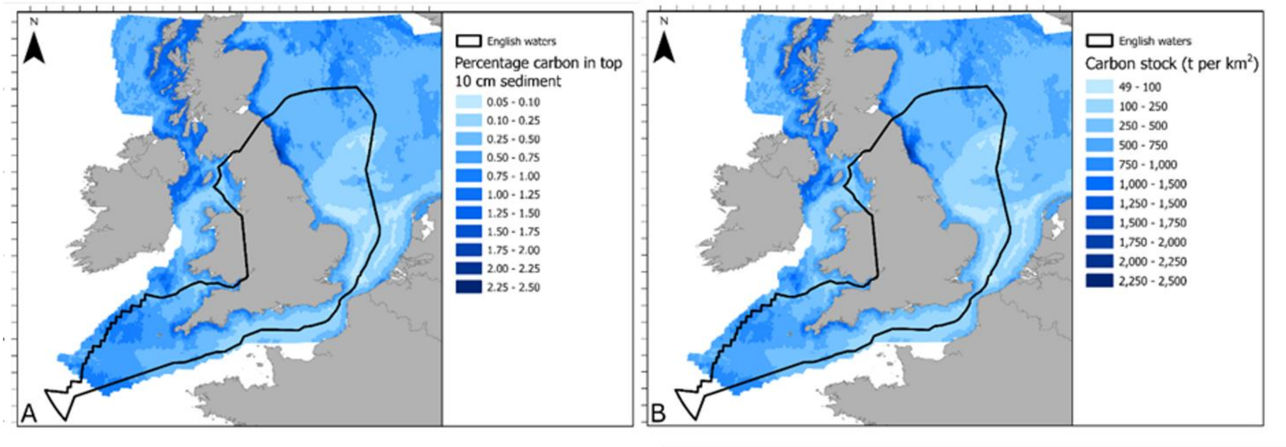

Figure A3.4 **A** Predicted sediment percentage organic carbon (OC) and **B** stock (t/km^2) in the top 10 centimetres based on predictive mapping (Diesing *et al*., 2017), converted to the spatial resolution as the pressure data.

A3.1.2. Carbon lability

Sample data are summarised by the 4 EUNIS (level 3) habitat classifications considered in and 9 sediment classifications in ***Table A3.2*** and ***Figure A3.5***. Overall, an average of about 20 % (7-40 %) of OC is classified as 'thermally labile' by TGA. For parts of the study area consisting of habitats other than the 4 main relevant EUNIS classifications, the average of the 4 groups was applied (20.6 % labile). The estimated spatial distribution of OC lability and labile organic carbon are shown in ***Figure A3.6***. Average sediment OC lability proportions for similar classifications are comparable to those obtained in the Folk Classification approach of Black *et al*., (2022) and for the coastal and offshore UK EEZ sediment data summarised in Smeaton and Austin, 2022. However, the assumed predictive power of sediment type and EUNIS habitat classifications for organic carbon lability has not been robustly assessed at this stage, and the distribution of lability values measured is not distinct between all classifications used. There is minimal variance in OC lability shown across sediment or EUNIS endpoints (mud – sand) which is not as would be expected from the observational evidence base which shows higher lability / reactivity in deeper colder areas. For example, ranging from TGA labile/reactive fraction of 30-35 % in Fulmar region (deep, cold, muddy sand) of the North Sea to 10-15 % on Dogger Bank (shallow, mobile sand).

The apparent OC lability assessments for rock is an artefact of the combination of point and map information. The sediment-classification-derived map appears to show more granularity than the habitat-classification-derived map, likely because it includes more categories and avoids the use of an overall-mean for unclassified areas (the ‘other’ habitat category). The total stock of labile OC in the study area is not significantly different between mapping approaches.

Table A3.2 Sediment organic carbon lability (as measured by thermogravimetric analysis, TGA) data summarised by seafloor habitat and sediment type classifications. Note that in this analysis areas deemed to be rock seafloor substrate coincided with samples with OC possibly reflecting issues with the seafloor substrate mapping. Note that the apparent OC lability assessments for rock is an artefact of the combination of point and map information.

Classification	No. Samples	Labile proportion of total organic carbon (%)				
		Avg	Min	Max	St. Dev	St. Err
Habitats: EUNIS level 3						
A5.1: Sublittoral coarse sediment	138	20.7	12.1	39.9	5.0	0.4
A5.2: Sublittoral sand	499	22.4	7.3	43.4	6.5	0.3
A5.3: Sublittoral mud	163	20.2	9.8	43.3	6.3	0.5
A5.4: Sublittoral mixed sediments	17	19.2	13.3	28.7	4.1	1.0
Seafloor substrate						
Rock	11	21.3	15.7	28.7	4.7	1.4
Coarse Sediment	138	20.7	12.1	39.9	5.0	0.4
Mixed Sediment	17	19.2	13.3	28.7	4.1	1.0
(Muddy) Muddy Sand	49	18.6	10.5	24.8	3.0	0.4
Fine Mud	8	18.9	12.9	25.6	4.3	1.5
Sandy Mud	6	17.8	13.8	24.1	4.5	1.9
Sandy Mud / Muddy Sand	101	21.2	9.8	43.3	7.4	0.7
(Sandy) Muddy Sand	16	20.3	12.4	30.5	4.7	1.2
Clean Sand	483	22.4	7.3	43.4	6.5	0.3

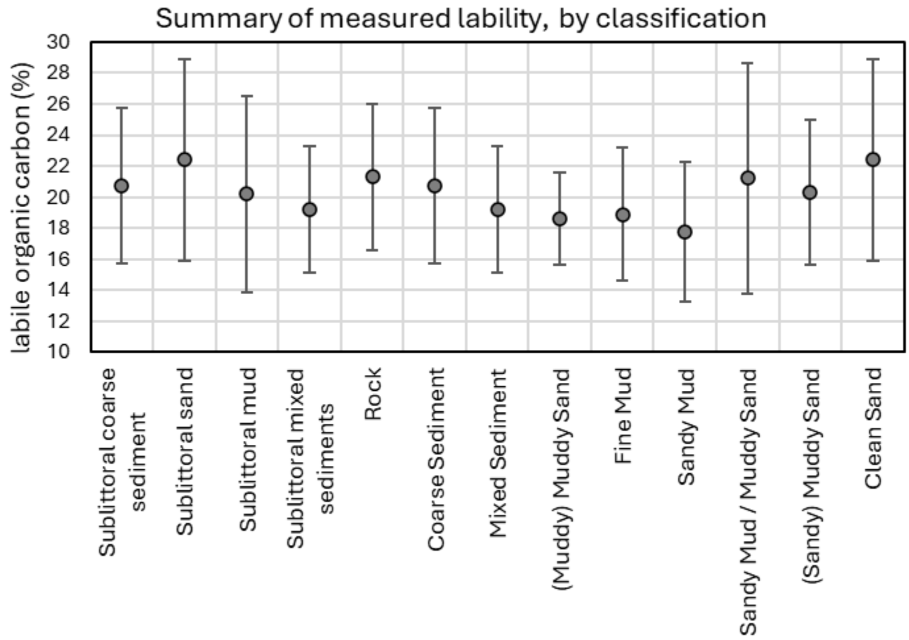

Figure A3.5. Percentage of organic carbon, which is labile, classified by EUNIS habitats (first 4 categories) and seabed substrate. Error bars show standard deviation of measurements taken in that habitat or substate, and filled circles are the mean (average). Note that the apparent OC lability assessments for rock is an artefact of the combination of point and map information.

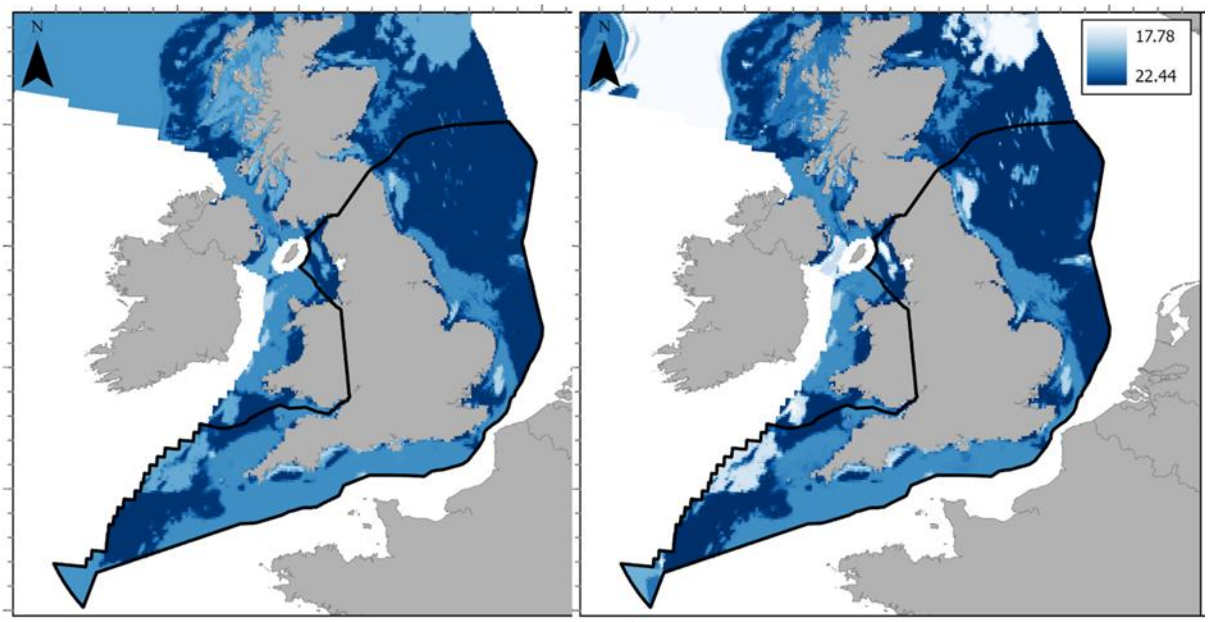

Figure A3.6 Estimated carbon lability (as percentage of total sediment organic carbon) based on classification of available lability samples by habitat (**A**), and sediment type (**B**). The boundaries of English waters are shown by the dark black outline.

A3.1.3. Carbon disturbed and resuspended

The amount of sediment OC (both total and labile fraction) estimated to be disturbed and resuspended from UK and English shelf sediment by otter and beam trawling annually is visualised in ***Figure A3.7*** and ***Figure A3.8*** summarised in ***Table A3.3*** and ***Figure A3.9*** and ***Figure A3.10***. Given the similarity between results between lability quantification approaches, only the results from the habitat-classification-based estimate are shown.

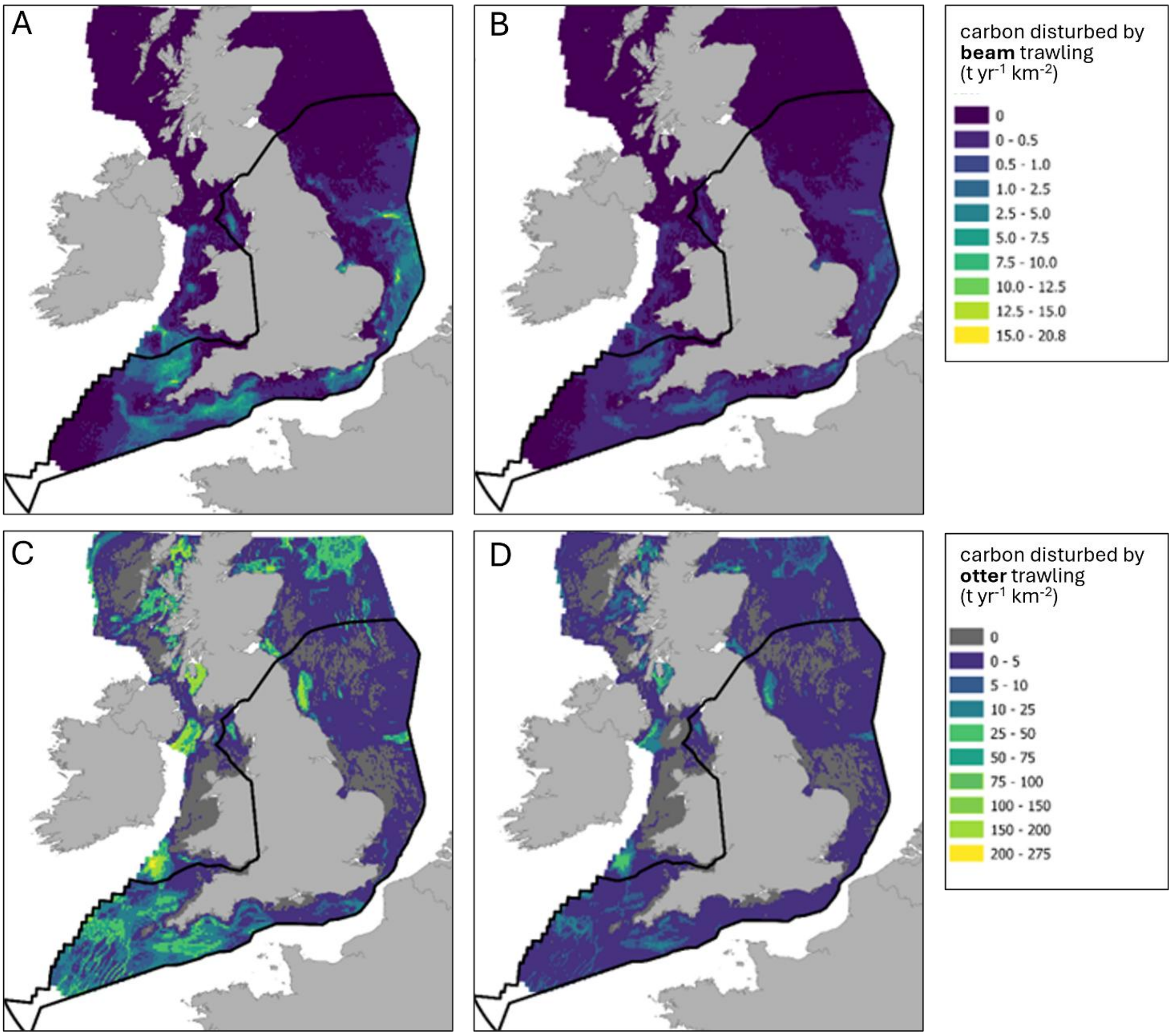

Figure A3.7 Estimated amount of sediment organic carbon *disturbed* by beam (**A** & **B**) and otter (**C** & **D**) trawling both as *total* carbon (**A** & **C**) and *labile* carbon (**B** & **D**).

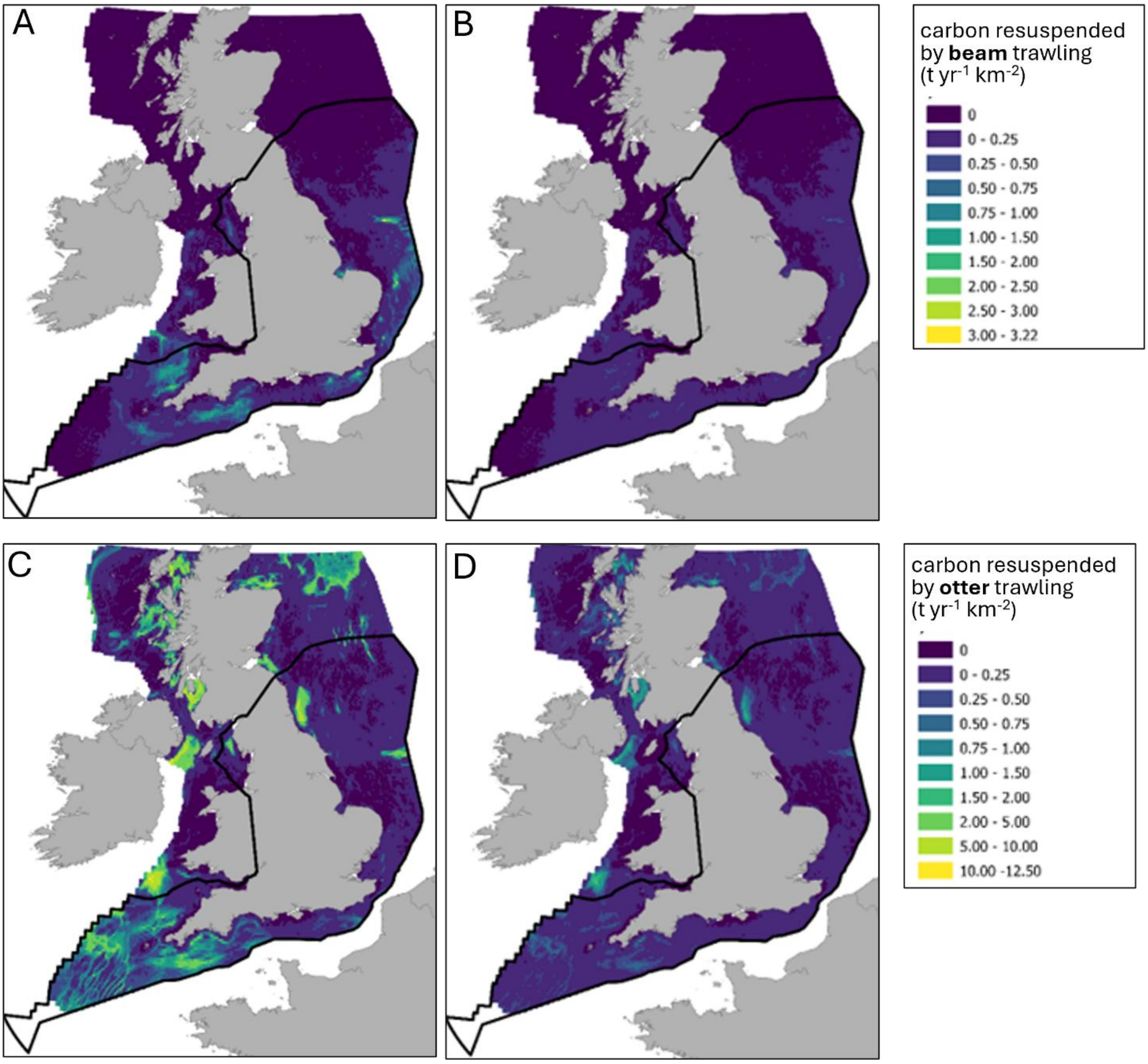

***Figure A3.8*.** Estimated amount of sediment organic carbon *resuspended* by beam (**A** & **B**) and otter (**C** & **D**) trawling both as *total* carbon (**A** & **C**) and *labile* carbon (**B** & **D**).

Table A3.3 Estimates for the mass of seabed organic carbon disturbed by trawling, annually over the shelf seas of the UK EEZ and English waters within the domain of the sediment organic carbon map of Diesing *et al*., (2017).

		Mass of Organic Carbon (MT)			
		Disturbed		Resuspended	
		Total	Labile	Total	Labile
Otter	UK	55.90	11.29	2.52	0.51
	Eng	25.33	5.19	1.14	0.23
Beam	UK	3.21	0.69	0.50	0.11
	Eng	2.97	0.64	0.46	0.10
Total	UK	59.12	11.98	3.02	0.62
	Eng	28.31	5.82	1.60	0.33

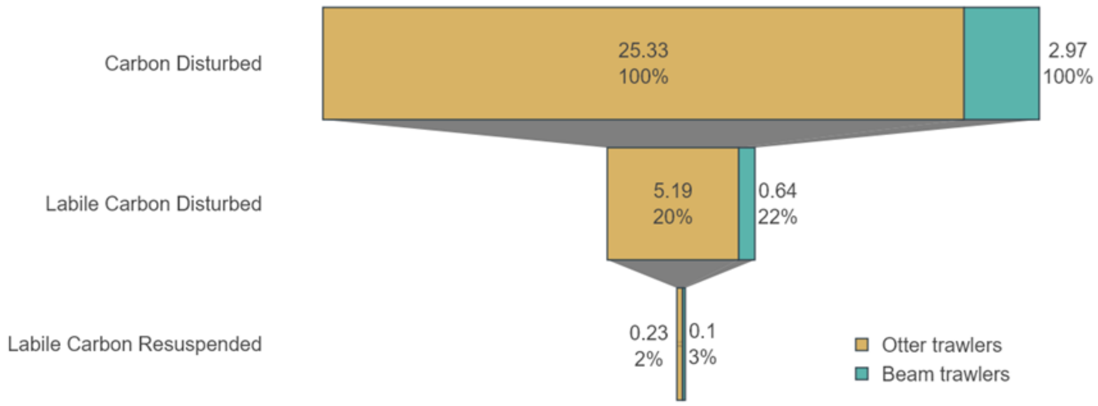

Figure A3.9 Visualisation of estimated mass of organic carbon disturbed and resuspended by otter and beam trawling, annually in the UK EEZ extent.

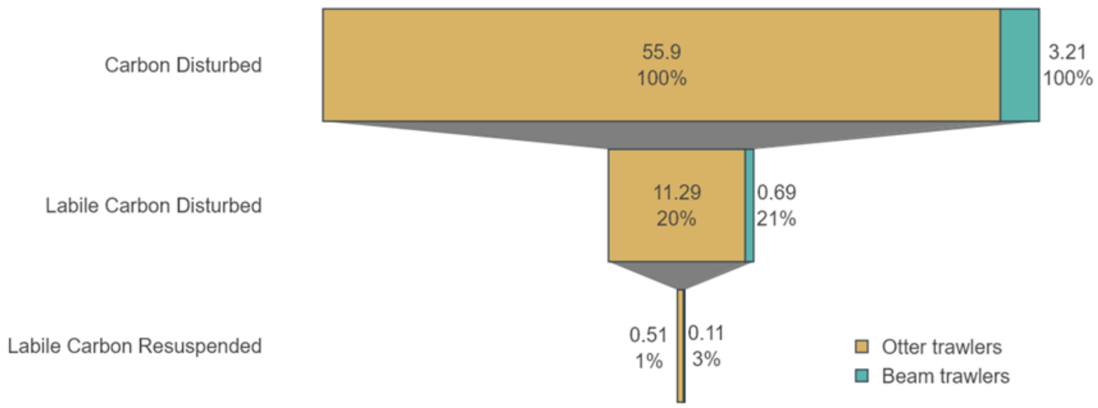

Figure A3.10 Visualisation of estimated mass of organic carbon disturbed and resuspended by otter and beam trawling, annually in English waters.

A3.4. Conclusion and next steps

By estimating the amount of labile OC resuspended annually due to bottom trawling in UK shelf seas, we constrain the maximum potential carbon released to < 330 and 620 kt C yr^{-1} (1.21 to 2.28 Mt CO_2 equivalents) for English waters and UK EEZ respectively.

Our results illustrate the order-of-magnitude effect of differentiating carbon disturbance (to the full trawling gear penetration depth) from resuspension. These numbers provide a potential maximum source term for carbon net remineralisation / loss or CO_2 emission. However, due to the high uncertainty in processes controlling carbon degradation within the water column or resulting CO_2 emission here (see section 1.4 and 1.5 in Annex 1) we have not developed these estimates further. It is, however, likely that much of the resuspended 'labile/reactive' carbon is not oxidised before it resettles onto the seabed and that much of the oxidised carbon cannot be directly linked to changes in the ocean's exchange of CO_2 with the atmosphere. Our assumption that recalcitrant or refractory OC will not be degraded needs testing further.

Our estimate relies on a number of assumptions and approximates which could be addressed by future work to improve confidence of the magnitude and variability of these estimates and the impact of trawling on organic carbon stored in sediments in UK shelf seas. These include:

- Inclusion of inshore fishing fleet (<12 m vessel length) and full international vessel data in the mapping of fishing pressure (SAR) and more complex accounting for variability of gear morphologies including sediment-type dependant penetration depths and gear component – drag assumptions.
- Improved seabed organic carbon mapping to the entire UK EEZ, exploring different predictive mapping approaches and incorporating additional seabed carbon sample data and/or new predictor variables.
- Improved mapping of organic carbon lability, including: (i) applying predictive mapping analogous to that used for seabed carbon stock mapping and (ii) Exploring alternative or additional analytical approaches to defining and quantifying the proportion of labile organic carbon beyond TGA
- Development of this workflow to refine elements above and provide comparison of differing methods where these estimates are being assessed (Sala *et al*., 2021; Atwood *et al*., 2024; Epstein *et al*., 2024; Khedri *et al*., 2025). This would be towards providing a consistent methodology and framework for assessment of carbon changes and adaptation upon human disturbance and across not only trawling but also other human activity and infrastructure effects.

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This evidence briefing was prepared as a UK national community effort to ensure consensus around the evidence base, confidence level, uncertainties and gaps and next steps. International experts from key areas also contributed to discussions and as co-authors.

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