

PERSPECTIVE

Rethinking the impacts of bottom trawling on seabed carbon: Biogeochemical mechanisms, vulnerability and long-term climate consequences

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Abstract

1. Bottom trawling is the most widespread anthropogenic disturbance to marine benthic ecosystems, with a growing recognition of its potential to alter sedimentary carbon dynamics and influence ocean–atmosphere CO₂ exchange. Yet, the magnitude and underlying mechanisms of trawling-induced carbon emissions from the seafloor remain poorly understood and subject to ongoing scientific debate.
2. In this perspective, we synthesise current evidence on how physical disturbance caused by demersal fisheries has opposing effects on organic carbon (OC) mineralisation across different compartments with a particular focus on the distinction between short-term remineralisation and long-term carbon burial.
3. We argue that bottom disturbance increases remineralisation in the water column by resuspending reactive OC to oxygenated environments, while decreasing local seabed OC stocks and in situ sediment mineralisation by reducing reactive OC and benthic fauna.
4. We further distinguish between short-term remineralisation of reactive OC and the longer-term impairment of carbon burial in depositional zones. The critical role of benthic fauna, particularly bioturbators, in regulating carbon processing and sequestration remains complex and context-dependent. While highly reactive OC is the most vulnerable to rapid mineralisation, prioritising management solely on the basis of OC reactivity risks overlooking habitats that contribute disproportionately to long-term carbon sequestration. Depositional areas, though sometimes lower in OC lability, can offer greater climate-relevant sequestration value and represent priority habitats for management aimed at protecting long-term carbon burial.
5. *Synthesis and applications:* Given this strong context dependence, effective protection of seabed carbon stocks requires region-specific assessments that identify and prioritise habitats with high burial potential amongst considerations for increased short-term CO₂ release, rather than blanket trawling bans or uniform

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effort reductions. Ultimately, while seabed carbon protection can support climate policy, it must remain secondary to, and never a substitute for, the urgent need to reduce fossil fuel emissions.

KEYWORDS

biogeochemistry, bottom trawling, carbon burial, fisheries management, seabed carbon, spatial management

1 | INTRODUCTION

Marine sediments are one of the largest long-term carbon sinks on Earth, burying an estimated 0.2–0.3 Pg of carbon per year and playing an essential role in climate regulation (Burdige, 2005, 2007). Bottom trawling, which disturbs 14% of the global continental shelf and over 50% of certain regional seas every year (Amoroso et al., 2018), poses a threat to seabed carbon stores by altering biogeochemical degradation pathways, potentially releasing CO₂ back into the active oceanic carbon pool (Porz et al., 2024; Zhang et al., 2024). However, the mechanisms by which bottom trawls release seabed carbon remain debated (Epstein et al., 2022; Hiddink et al., 2023). Although there is broad agreement that trawling results in a net CO₂ release from seabed carbon stocks, studies differ in how in situ sediment mineralisation is affected by trawling. Some studies suggest that trawl activities accelerate organic carbon (OC) degradation within the seabed by exposing buried carbon to oxygen, thus *enhancing* CO₂ release (Atwood et al., 2024; Sala et al., 2021), while others argue that the physical removal of organic matter, benthic fauna and microbes from trawling *reduces* in situ sediment mineralisation (Bradshaw et al., 2021; De Borger et al., 2021; Morys et al., 2021; Tiano et al., 2019, 2022). We propose that trawling exerts opposite effects in different compartments by stimulating mineralisation and CO₂ release in the water column while decreasing mineralisation within the directly impacted sediment.

Furthermore, recent vulnerability assessments have spotlighted areas rich in labile or reactive carbon as highlighting their increased capacity for remineralisation under disturbed conditions (Black et al., 2022; Smeaton & Austin, 2022). Here, lability refers to the intrinsic degradability of OC based on molecular composition, whereas reactivity reflects the context-dependent expression of this degradability under in situ environmental conditions such as oxygen availability and mineral protection (Arndt et al., 2013; LaRowe et al., 2020; Placitu et al., 2025). While we agree that areas with highly reactive OC present a higher immediate risk of CO₂ release from trawling, we question the long-term climate benefit of prioritising protection solely on this basis. Some sediments characterised by high reactivity can exhibit low net burial fluxes, while depositional environments, which can sometimes be characterised by lower OC lability, are more important for long-term carbon sequestration (Rios-Yunes et al., 2023). This raises a critical question for managing seabed carbon: *which combinations of seabed characteristics, such as OC reactivity, depositional settings and burial efficiency, are most*

important to consider to for persistent carbon sequestration over centennial timescales?

Gaining insight on these issues is essential for designing effective management strategies to mitigate fisheries impacts on seabed carbon. Current global-scale carbon loss estimates often extrapolate from simplified assumptions without accounting for key local and regional biogeochemical dynamics. Such generalisations risk inflating emission estimates and could lead to the protection of areas with little long-term climate value, misdirecting resources and delivering negligible benefits. This perspective aims to clarify the mechanistic pathways linking trawling and carbon cycling, assess the relative significance of reactive versus burial-prone carbon pools and highlight how science-based, context-specific management is necessary to ensure seabed carbon policy is effective.

2 | MECHANISMS OF SEDIMENT CARBON SEQUESTRATION

In seabed sediments, the long-term carbon sequestration can be referred to as the capacity to prevent carbon from degrading and entering the atmosphere for at least 100 years (ICES, 2024). Only a small fraction of OC deposited on the seafloor ultimately meets this criterion (Middelburg, 2018). Most OC entering benthic systems is rapidly decomposed and respired to inorganic carbon (primarily CO₂) by microbial communities and sediment-dwelling fauna. These organisms play an important role in recycling organic matter and supplying inorganic nutrients to the overlying water.

OC burial follows from the transfer of OC to subsurface and deep sediment layers, where it becomes increasingly isolated from energetically favourable oxidants such as oxygen. Oxygen, the terminal electron acceptor in aerobic respiration, drives rapid degradation of OC. In its absence, microbial degradation continues through suboxic and anaerobic pathways (using oxidants like nitrate, manganese, iron or sulphate), but at a slower rate, as these processes are energetically less efficient. In OC-rich sediments, oxygen depletion can occur within a few millimetres underneath the sediment–water interface, below which a succession of redox reactions that use different oxidants takes place, each less favourable than the previous (Berner, 1980; LaRowe et al., 2020).

This progressive ‘slowing down’ of decomposition is partially governed by the decreasing lability or degradability of OC with depth. More labile compounds such as carbohydrates or nitrogen-rich

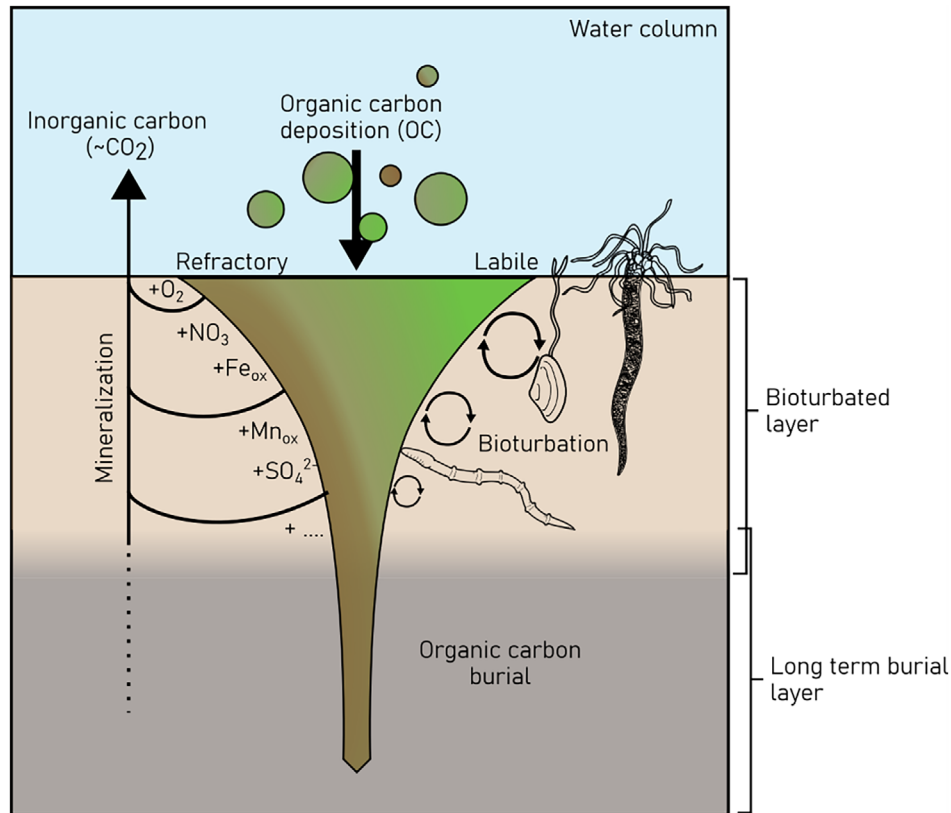


FIGURE 1 Conceptual overview of organic carbon mineralisation and burial within sediments. Deposited OC is progressively degraded through aerobic and anaerobic pathways, with volumetric mineralisation rates generally decreasing with depth as OC becomes less labile and oxidants become less energetically favourable. Bioturbation mixes particles and porewaters within the upper sediment, redistributing OC and oxidants. Long-term carbon sequestration is more reliably indicated by the accumulation of OC below the bioturbation zone (lower section of the figure), where OC becomes isolated from faunal mixing and ventilation and is more likely to be preserved over climate-relevant timescales.

proteins are preferentially consumed by decomposers, whereas more resistant-refractory-compounds (e.g. algeenan and lignin rich detritus) degrade more slowly. Importantly, the terms labile and refractory represent end-members along a spectrum of degradability rather than purely discrete categories.

Reactivity, however, is not solely determined by molecular composition, but is a feature which emerges from the interaction between OC properties and environmental context, including oxygen exposure, microbial accessibility, burial below the bioturbation zone and physical protection within the sediment matrix (Arndt et al., 2013; LaRowe et al., 2020; Placitu et al., 2025). As a result, OC that is intrinsically labile may exhibit low reactivity if degradation is constrained under certain conditions, while relatively less labile material may become reactive if environmental barriers to degradability are removed. Anthropogenic disturbances such as bottom trawling can alter the fraction of the OC pool that becomes environmentally accessible for mineralisation by exposing previously protected material to oxygen, with implications for whether this carbon is remineralised or would otherwise have contributed to long-term burial.

Bioturbation, the combined term for the mixing and ventilation processes carried out by benthic animals such as crustaceans, polychaetes and echinoderms, disturbs the vertical zonation of

mineralisation processes, which makes the absolute depth of OC in the sediment an imperfect proxy for its potential for long-term sequestration (Canfield, 1994; Kristensen et al., 2012). Bioturbating organisms redistribute organic material within the sediment through feeding, burrowing or defecation activities (Middelburg, 2018). Additionally, some bioturbators exchange porewater with the overlying water column for respiration or feeding activities (Kristensen et al., 2012; Middelburg, 2018). This activity can introduce oxidants such as oxygen into deeper sediment layers and can increase microbial and faunal access to organic matter (Canfield, 1994; Middelburg, 2018). These redox oscillations, either by moving older OC upwards, or dissolved oxidants downward, may promote mineralisation (Aller, 1994; Hulthe et al., 1998; Moodley et al., 2005). Conversely, faunal-driven non-local transport can relocate OC to deeper sediment layers (Aller, 1982; Kristensen et al., 2012; Tiano et al., 2022) and may potentially increase the burial efficiency by moving OC deeper towards the bottom of the bioturbated mixed layer (Figure 1).

As these faunal activities co-regulate the ultimate fate of OC, a more informative indicator of carbon sequestration is the accumulation of OC below the bioturbated mixed layer (Figure 1), where residence times increase and exposure to oxidants and fauna is reduced

(Boudreau, 1998; Hartnett et al., 1998; Middelburg, 2018; Scholz et al., 2021). This OC, once isolated from more frequent re-oxidation and bioturbation, is more likely to remain preserved over climate-relevant timescales (Arndt et al., 2013; Hartnett et al., 1998).

3 | PHYSICAL DISTURBANCE PATHWAYS FROM BOTTOM DISTURBANCE

Bottom trawling exerts three primary types of physical disturbances on seabed sediments: sediment *erosion (and associated resuspension)*, *mechanical mixing* and *redemption*. Each process distinctly alters carbon cycling, depending on the sediment context, hydrodynamic regime and the nature of the disturbed carbon pool (Figure 2).

3.1 | Erosion and resuspension: Local reduction and water column acceleration

The most immediate effect of trawling is the erosion of the sediment surface layer, which is typically enriched in reactive OC and inhabited by active microbial and benthic faunal communities. The magnitude of this erosion is governed by hydraulic drag of gear components interacting with the seafloor, which is a function of gear type, towing speed and sediment properties (O'Neill & Summerbell, 2016; Ghorai et al., 2025). Erosion has been found to account for roughly 20%–25% of the total gear penetration depth from beam trawlers (Depestele et al., 2019). Penetration depth has been approximated for multiple gear types though it is known to deepen when towed at slower speeds and with heavier gear components (Ghorai et al., 2025; Hiddink et al., 2017). This disturbance exposes deeper, more refractory substrates and facilitates the release of reduced compounds such as ammonium and sulphides which oxidise rapidly

upon contact with oxygenated bottom waters and phosphate (Riemann & Hoffmann, 1991; Tiano et al., 2021). In some settings, gear penetration may extend below the bioturbated mixed layer, physically re-exposing OC that would otherwise be considered effectively buried and isolated from rapid degradation, increasing its susceptibility to remineralisation (Bradshaw et al., 2021; Bunke et al., 2019).

The resuspension of organic particles into the water column leads to increased mineralisation due to higher oxygen availability, stimulating CO₂ and nutrient release (Riemann & Hoffmann, 1991; Tiano et al., 2019, 2021; Figure 2). Research into the degradation of resuspended OC in the water column reveals a clear but spatially heterogeneous potential for oxygen-fuelled degradation in the water column in resuspension experiments (Bartl et al., 2025; Lønborg et al., 2024).

Conversely, within the sediment itself, mineralisation rates often decline following erosion, specifically when redeposition is limited. This is attributed to the removal of the most degradable OC fractions and the loss of key biological degradation agents, microbial communities and sediment fauna such as bioturbators (Pusceddu et al., 2014; Tiano et al., 2019; Watling et al., 2001). Although some studies have observed higher sediment mineralisation rates in trawled sediments (Bradshaw et al., 2024; Paradis et al., 2019; van de Velde et al., 2018), these increases are often associated with OC deposition either from anthropogenic-induced redeposition of resuspended material or from natural depositional processes. Where such depositional (or redepositional) effects are absent and erosion dominates, erosion-driven removal of labile OC and benthic fauna generally reduces total sediment oxygen consumption (Bradshaw et al., 2021; Morys et al., 2021; Tiano et al., 2019, 2022). This reduction in biological oxygen demand has been linked with deeper oxygen penetration into surface sediments following trawling disturbance (Bradshaw et al., 2021; De Borger et al., 2021; Tiano et al., 2019).

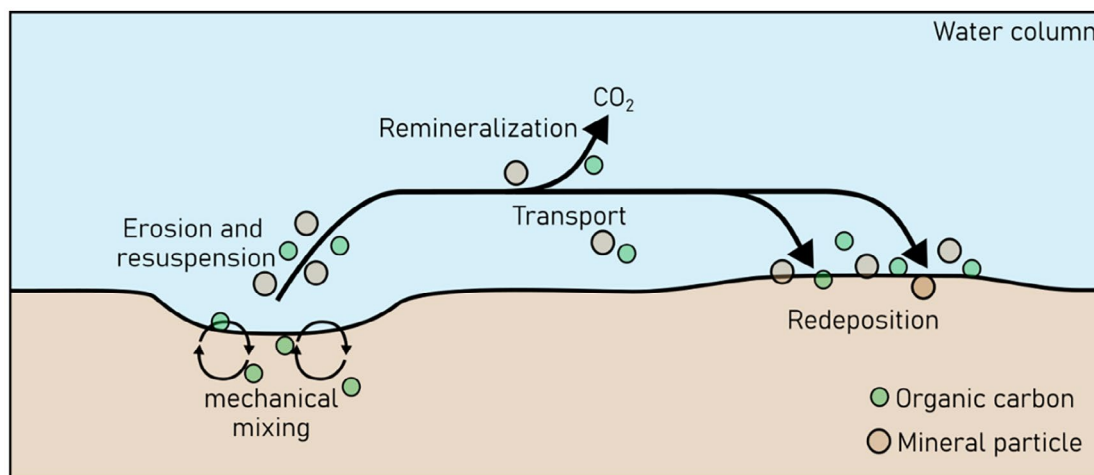


FIGURE 2 Overview of physical disturbances to organic carbon (OC) and seafloor sediment caused by bottom trawl fisheries. A single disturbance event induces erosion and resuspension of surface sediments and mechanical mixing within the seabed, and lateral transport of OC and mineral particles. Resuspended OC is exposed to oxygenated conditions in the water column, where remineralisation may be enhanced. Mobilised OC is subsequently redeposited, with spatial outcomes depending on hydrodynamics, seabed morphology and the extent of degradation during transport.

Thus, while mineralisation in the water column accelerates, mineralisation within the sediment compartment is typically reduced, until fresh organic inputs and biological recolonisation occurs.

3.2 | Mechanical mixing: Transient oxygenation and ambiguous outcomes

Trawling also induces vertical mixing beneath the erosion layer, redistributing OC in various stages of decomposition, oxygen and altering redox gradients that regulate microbial processes such as denitrification (Depestele et al., 2019; Ferguson et al., 2020; Figure 2). However, it is a common misconception that this temporary enhancement in sediment oxygenation leads to sustained increases in carbon mineralisation. Field and mesocosm experiments show that the oxygen spike is ephemeral, often returning to new steady-state conditions within hours (Fivash et al., 2020; Scholz et al., 2021; Tiano et al., 2021). Longer-term increases in oxygen availability within the sediment are linked to a reduction in sediment respiration after erosion (removal of the upper sediment layers) rather than through mechanical mixing of the sediment (De Borger et al., 2021; Tiano et al., 2019, 2021). Although trawling-induced mixing could enhance burial by redistributing organic matter below the active bioturbation zone (Zhang et al., 2024), this mechanism likely only partially compensates for faunal loss, and there is no direct evidence that it increases long-term burial.

There is limited evidence showing that mechanical mixing alone (not accounting for erosion-driven sediment resuspension) leads to persistent increases in CO₂ production from the directly impacted seabed. Apparent increases in mineralisation observed in some studies may be confounded by concurrent deposition of fresh organic matter (natural or otherwise) rather than the act of mechanical mixing itself (Paradis et al., 2019; van de Velde et al., 2018). The concept of priming, where small additions of labile carbon stimulate microbial degradation of otherwise stable carbon pools, has been suggested as a potential mechanism in bottom trawl impacts (van de Velde et al., 2018). However, experimental evidence suggests that such responses are not universal and may occur only under specific environmental or sedimentary conditions (Tiano et al., 2021).

3.3 | Redeposition: Redistribution of carbon with differing impacts

The final stage of physical disturbance is the redeposition of resuspended sediment and organic matter, whose fate depends on complex interactions between hydrodynamics, sediment grain size and seabed morphology (Figure 2). Redeposition can result in both enhanced or reduced mineralisation. In some contexts, the settling of fresh, labile OC may fuel microbial activity and enhance CO₂ release (Paradis et al., 2019; van de Velde et al., 2018). In others, the burial of organic material under low-oxygen conditions or the smothering of benthic fauna (Mestdagh et al., 2018) may slow down

mineralisation and can potentially inhibit decomposition, promoting OC storage. In addition, redeposition of fine-grained material can form a surface 'capping' layer that reduces sediment permeability and oxygen diffusion, thereby decreasing oxygen penetration depth and altering benthic solute exchange (Vopel et al., 2008).

Trawling can relocate organic material from erosion-dominated areas to adjacent depositional environments such as within bathymetric depressions (de Haas et al., 1997; Luisetti et al., 2019; Porz et al., 2024; Figure 2). While this redistribution may increase OC concentrations in new locations, the prior resuspension exposes buried material to oxygen and microbial activity in the water column, potentially offsetting any gains in sequestration. The net effect of trawling on carbon storage thus depends not only on the magnitude and direction of resuspension and redeposition, but also on whether the redistributed carbon is ultimately mineralised or buried beyond the reach of further degradation. These processes take place alongside natural sediment dynamics, making it essential to distinguish between anthropogenic and baseline mineralisation rates when evaluating long-term climate impacts.

Importantly, the effects described above span different temporal scales and also lines of evidence. Acute responses to trawling are primarily documented through short-term observations and experiments (in situ and laboratory; Tiano et al., 2024; Paradis et al., 2022), whereas evidence for longer-term changes in carbon burial and sequestration has been inferred from modelling studies (Porz et al., 2024; Zhang et al., 2024), though the explicit quantification of climate-relevant burial disruptions on centennial (>100 year) timescales has yet to be directly quantified (ICES, 2024).

4 | BIOGEOCHEMICAL AND ECOLOGICAL INTERACTIONS AFTER DISTURBANCE

Although biogeochemical characteristics of sediments may recover following physical disturbances once more organic matter reaccumulates, longer-lasting impacts from trawling can arise through disruptions to benthic ecological communities (De Borger et al., 2021; Hale et al., 2017; ICES, 2025; Sciberras et al., 2016; Zhang et al., 2024). Recent modelling studies emphasise the potential importance of fauna-driven processes in shaping the fate of sediment carbon after bottom trawling (Porz et al., 2024; Zhang et al., 2024). In these particular models, variation in the presence or absence of certain benthic fauna account for the largest differences in projected carbon outcomes. An important assumption in these simulations is that trawling reduces or removes key bioturbators, decreasing or inhibiting the net downward transport of carbon into deeper sediment layers where sequestration is likely. However, this assumption does not apply universally.

Regional differences in benthic community responses to trawling present challenges in predicting the effects of trawling on benthic ecosystem functioning. For example, the North Sea region known as the Frisian Front has undergone a well-documented regime shift which is hypothesised to have been driven, at least partially, by

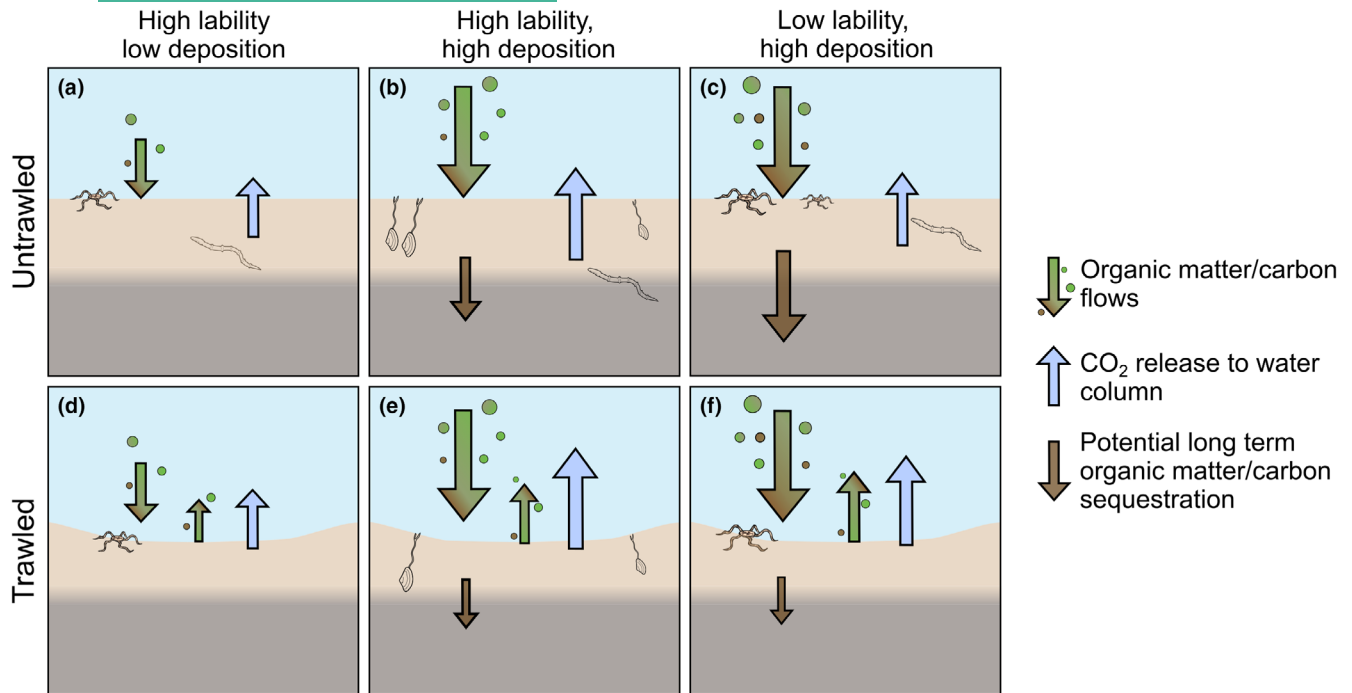


FIGURE 3 Conceptual examples of marine habitats illustrating potential combinations of organic matter (OM) lability, deposition rate and trawling disturbance. (a, d) In low depositional environments, regardless of OM lability, local burial can be expected to be very limited, resulting in minimal long-term carbon sequestration (e.g. permeable sands or other non-depositional sites). (b, e) High-deposition, high-lability sites (e.g. productive coastal waters receiving predominantly algal derived OM) often exhibit high remineralisation. Here, OM burial rates may vary, but the majority of deposited material is remineralised. Trawling resuspends deposited OM increasing the proportion of CO_2 produced in the water column and potentially reduces the fraction of OM that is ultimately buried. (c, f) These effects are amplified in low-lability, high-deposition settings, where burial efficiency would otherwise be high, such as within low-energy bathymetric depressions or fjord sediments receiving comparatively higher proportions of intrinsically less degradable OM (e.g. terrestrial compounds) or OM that is physically protected by mineral associations. In such environments, OM may remain near the sediment surface for extended periods where bioturbation is limited (owing to low OM quality and often anoxic conditions), increasing vulnerability to trawling-induced resuspension and reducing burial efficiency. All panels are intended to illustrate processes within various environmental contexts rather than universal conditions.

bottom trawl disturbances (Amaro, 2005; Tiano et al., 2020; van Nes et al., 2007). The benthic community there is now dominated by large deep-dwelling bioturbators which are able to evade direct contact with towed fishing gear. Contrary to expectations, trawling in this area has potentially led to increased bioturbation activity which may be enhancing the faunal-mediated transport of OC to sequestration level depths (Beauchard et al., 2023; Tiano et al., 2020). This challenges the notion that trawling leads to consistent declines in benthic ecosystem functioning. This variability complicates predictions about how benthic disturbance will alter sediment carbon cycling across regions. While some ecosystems may exhibit declines in biological mixing and enhanced carbon preservation post-trawling, others may undergo compensatory shifts in community structure that sustain or even enhance certain biogeochemical functions.

This suggests that the ecological pathways linking trawling, benthic fauna and carbon cycling can be highly context-dependent. Models such as those by Zhang et al. (2024) offer valuable large-scale insights, but local assessments are necessary to refine assumptions and improve predictions for how trawling truly impacts benthic carbon. In particular, greater emphasis should be placed on understanding the conditions under which trawling may lead to functional

replacement rather than functional loss in benthic communities, and how such changes in biological community structure affect sediment carbon dynamics over decadal timescales, which are currently poorly understood.

5 | AREAS OF UNCERTAINTY

Several fishing-mediated disturbance pathways affecting OC dynamics were synthesised by Epstein et al. (2022), which highlighted processes in which demersal trawling has been linked to altering seabed carbon storage through resuspension, oxygen exposure and changes to benthic communities. Building on this, we extend the framework by providing the detailed mechanisms in which specific physical disturbance pathways interact with sedimentary context to affect mineralisation and burial processes. This allows us to clarify which environmental characteristics are most relevant for managers seeking to protect sedimentary carbon over climate-relevant timescales.

Despite advances in our understanding of how bottom trawling affects biogeochemistry, key mechanisms remain poorly understood.

When bottom trawling disturbs sediments, a complex suite of biogeochemical processes takes place including the redistribution of OC, microbial communities, minerals and alkalinity between the sediment and the overlying water column. The fate of these components remains uncertain, particularly over the broad spatio-temporal scales relevant to long-term carbon cycling.

A major knowledge gap lies in understanding the long-term balance between accelerated mineralisation and the disruption of natural OC burial caused by seafloor disturbance (Figure 3). Trawling can rapidly remineralise OC upon resuspension into an oxygen-rich water column. However, the most vulnerable OC to trawl disturbance tends to be the most highly labile and reactive OC, which are forms that are likely to degrade relatively quickly even in the absence of disturbance (Tiano et al., 2024). In such cases, trawling may simply accelerate what is already a short-term cycle, creating uncertainty about the true long-term climate impact caused by bottom disturbance (Figure 3). A potentially greater concern lies in the capacity of demersal fisheries to disrupt carbon burial in depositional zones, where OC is more likely to be sequestered over centennial timescales and does not always exhibit highly reactive properties.

Another key area of uncertainty concerns the effects of trawling on the spatial distribution of OC. Most studies report reduced benthic OC stocks within directly impacted trawl tracks. However, some studies have observed higher OC concentrations in areas with relatively intense trawling activity, which typically lead to higher mineralisation rates (Epstein et al., 2022; Tiano et al., 2024; Zhang et al., 2024). These patterns may represent an artefact of fishing effort being concentrated in naturally productive, carbon-rich habitats, rather than a causal effect of disturbance on carbon accumulation. Nevertheless, it is likely that trawling removes OC in directly impacted areas while promoting secondary OC redeposition in adjacent or more sheltered environments, where resuspended particles eventually settle (e.g. de Haas et al., 1997; Luisetti et al., 2019). While some attempts have been made to quantify this redistribution (Porz et al., 2024), accurately predicting the fate of trawl-mobilised carbon remains challenging due to complex interactions between hydrodynamics, sediment composition and carbon reactivity. Closing these knowledge gaps will require integrating empirical and modelling approaches. Examples may include targeted field observations that track the redistribution and transformation of trawl-mobilised OC in directly impacted and deposition zones, alongside tailored sediment transport models.

While this paper focuses on OC dynamics, recent work has highlighted that bottom disturbance may also affect inorganic carbon (IC) cycling through mineral-driven processes. van de Velde et al. (2025) demonstrates how seabed disturbances can accelerate pyrite oxidation, reducing ocean alkalinity and leading to a source of CO₂ release which has been overlooked in previous research. In addition to sediment carbon pools themselves, such disturbances may also alter benthic-pelagic coupling, nutrient availability and biological productivity with implications for the efficiency of the biological carbon pump and air-sea CO₂ exchange (Siddiqui et al., 2024; Tiwari

et al., 2025). Such findings showcase gaps in our current understanding of the complex biogeochemical processes triggered by seabed disturbances spanning OC and IC cycles and ecosystem effects.

6 | DISCUSSION AND CONCLUSIONS

This paper identifies multiple pathways by which bottom trawling alters sedimentary carbon dynamics, emphasising how physical disturbance changes both mineralisation rates and burial processes through mechanisms such as erosion, mechanical mixing and redeposition. Available research suggests that when degradable OC is present in sediments, bottom trawling causes increased remineralisation in the water column through resuspension, while simultaneously decreasing in situ sediment mineralisation through the removal of fauna (micro and macro) and reactive organic matter in the impact site. The potential disruption of long-term burial by the erosion of surface layers and benthic faunal functions remains a crucial yet underexplored research challenge. These processes vary widely across sediment types, hydrodynamic regimes and ecological contexts, supporting the need to treat seabed carbon dynamics as spatially and functionally heterogeneous (Porz et al., 2024). These challenges echo recent syntheses that highlight both the benefits and limitations of using OC stocks and vulnerability proxies to inform spatial management under uncertainty (Diesing et al., 2025; Epstein, Fuller, Gullage, & Baum, 2025; Epstein, Fuller, Johannessen, et al., 2025).

From a climate policy perspective, these nuances matter. Not all highly labile and reactive fractions of carbon are likely to be equally relevant for long-term climate mitigation. Much of the labile OC at the sediment surface is likely to remineralise rapidly even without trawling meaning that protecting such areas may reduce short-term CO₂ emissions but contribute little to enhancing long-term sequestration. By contrast, depositional zones can exhibit lower apparent OC reactivity at times but higher burial potential (Diesing et al., 2021; Rios-Yunes et al., 2023) and may yield more climate benefits if protection is prioritised in these areas in addition to other aspects such as risk of accessibility to demersal fishing (Diesing et al., 2025). This creates a management challenge as efforts aimed at reducing near-term remineralisation by protecting areas rich in reactive OC (and associated CO₂ release) may not coincide with protecting burial hotspots where long-term carbon storage is the strongest. In some settings these objectives may align (e.g. depositional areas receiving substantial reactive OC inputs), whereas in others they may diverge, requiring context-specific management approaches. From a climate-mitigation perspective, we argue that protecting environments with high burial efficiency may yield more durable benefits, even when the associated OC is not highly reactive. This approach expands upon reactivity focused frameworks (e.g. Smeaton & Austin, 2022) by integrating broader sedimentary and biogeochemical controls on long-term carbon storage.

Although there is broad consensus that trawling mobilises seabed carbon and directly releases CO₂, substantial scientific

uncertainties remain. These include the long-term fate of disturbed carbon, the relative importance of disturbance-induced vs. natural remineralisation and the role of benthic fauna in mediating recovery and sequestration, all of which have been explored across empirical, modelling and management-focused studies with varying conclusions (Diesing et al., 2025; Epstein, Fuller, Johannessen, et al., 2025; Zhang et al., 2024). Furthermore, global-scale estimates of trawling-induced CO₂ emissions remain highly uncertain and sensitive to underlying assumptions and have been criticised for oversimplifying processes leading to potentially overinflated emission figures (Hiddink et al., 2023; Khedri et al., 2025; Sala et al., 2021). In light of these uncertainties, we currently caution against the premature adoption of carbon credit schemes linked to reductions in trawling. Beyond uncertainties related to OC remineralisation, additional processes may further complicate carbon accounting; recent modelling suggests that trawling may disrupt inorganic carbon cycling through alkalinity loss, reducing the ocean's ability to buffer CO₂ (van de Velde et al., 2025). As such, market-based approaches should only be considered once the scientific basis for quantifying long-term carbon benefits has been robustly established.

The consequences of benthic disturbance for carbon cycling can vary considerably across sedimentary and ecological contexts. In coarse-grained, sandy environments, such as much of the southern North Sea, sediments are typically dynamic, carbon-poor and characterised by low long-term burial potential (de Haas et al., 1997; Diesing et al., 2021). In these settings, trawl-induced erosion and resuspension can enhance water column mineralisation (Tiano et al., 2021, 2022), though effects on climate-relevant carbon burial remain uncertain and are potentially limited. In contrast, fine-grained muddy sediments, typically associated with low-energy, depositional environments, hold higher OC densities and tend to be relatively more important for long-term carbon burial (Diesing et al., 2021). These habitats often support diverse and functionally important benthic communities, while experiencing deeper gear penetration and slower recovery of benthic fauna after disturbance (Hiddink et al., 2017; Sciberras et al., 2018). Trawl-induced disruptions of benthos-mediated biogeochemical functions can lead to longer-lasting effects than mechanical disturbance alone (De Borger et al., 2021; Tiano et al., 2022).

Disturbance history also factors into observed biogeochemical responses as repeatedly trawled sediments can show weaker effects compared to previously undisturbed or lightly disturbed areas (De Borger et al., 2021). The relative importance of erosion, mixing and redeposition varies spatially in that erosion and mixing often dominate within trawl tracks (Morys et al., 2021; Tiano et al., 2019), whereas redeposition can be substantial in adjacent depositional settings (Porz et al., 2024), particularly in bathymetric depressions and submarine canyons, where resuspended material may accumulate (Arjona-Camas et al., 2021; Paradis et al., 2019, 2022).

Given the diverse sediment types, biological communities and carbon sequestration potential across marine regions, tailored, habitat-specific management approaches are likely to be more

effective than blanket trawling bans or uniform effort reductions if the goal is to reduce the effect of bottom disturbance on long-term carbon dynamics. Area-based strategies that consider carbon storage potential alongside ecological and fisheries considerations are more likely to deliver co-benefits for long-term ecosystem functioning, the livelihoods of the communities that depend on them and climate mitigation (Tiano et al., 2024). This includes prioritising regions that function as important carbon sinks, such as muddy, low-energy depositional environments, rather than focusing solely on areas characterised by high short-term mineralisation or degradation potential.

Finally, while protecting seabed carbon can play a supporting role in climate mitigation, it must be kept in perspective given its uncertainties. The priority for climate action must remain the drastic reduction of fossil fuel emissions from known sources. Seabed carbon protection should complement, not substitute for, the reduction of primary fossil fuel emissions (ICES, 2024). Moving forward, research is urgently needed to close knowledge gaps on the long-term fate of buried carbon, baseline rates of natural remineralisation and the functional roles benthic communities play in carbon cycling and their capacity to recover these functions following disturbance. These insights are essential for designing effective science-based management strategies in a changing ocean environment.

AUTHOR CONTRIBUTIONS

Justin C. Tiano – Conceptualisation, Writing – original draft, Writing – review and editing.

Emil De Borger – Writing – original draft, Writing – review and editing, Visualisation.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

This study did not generate or analyse new datasets. All information supporting the conclusions of this article is available within the published literature cited in the manuscript.

ETHICS STATEMENT

This study did not involve animal experimentation, human participants or field sampling and therefore did not require ethical approval.

STATEMENT ON INCLUSION

This study is a perspectives piece based on a synthesis of existing literature and expert knowledge and did not involve primary data collection. The authorship team is based in the Netherlands and Belgium, and both authors have conducted research on this topic within European waters. Efforts were made to include and cite relevant literature from scientists working in the regions discussed to ensure appropriate interpretation of the concepts and context.

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