Impact of bottom trawling on long-term carbon sequestration in shelf sea sediments

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Key Points:

- Not only the intensity but also the temporal variability of bottom trawling has long-lasting impact on carbon sequestration
- Trawling-induced resuspension and -impaired bioturbation jointly reduce the regional organic carbon sequestration capacity by 21-67%
- Organic carbon stored in the muddy seabed is most sensitive to disturbance by bottom trawling

Abstract

Bottom trawling represents the most widespread anthropogenic physical disturbance to shelf sea sediments. While trawling-induced mortality in benthic fauna has been extensively investigated, its impacts on ecosystem functioning and carbon cycling at regional scales remain unclear. Using the North Sea as an example, we address these issues by synthesizing a high-resolution dataset of bottom trawling impact on sediments, feeding this dataset into a 3-dimensional physical–biogeochemical model to estimate trawling-induced changes in biomass, bioturbation and sedimentary organic carbon, and assessing model results with field samples. Results suggest a trawling-induced net reduction in macrobenthic biomass by 10-27%. Trawling-induced resuspension and reduction of bioturbation jointly and accumulatively reduce the regional sedimentary organic carbon sequestration capacity by 21-67%, equivalent to 0.58-1.84 Mt CO_2 yr^{-1}. Our study emphasizes the need for proper management of trawling on muddy seabeds, if the natural capacity of shelf seas for carbon sequestration should be conserved and restored.

Plain Language Summary

Ocean seabed has been subjected to disturbance by bottom trawling for quite a long time. A bottom trawl consists of a large conic net with a wide mouth and a small enclosed end. The mouth is usually equipped with heavy components to keep the net open and attached on the seabed, effectively crushing every small obstacle in its path. Because of this physical contact, seabed sediments are massively resuspended and mixed, and animals living on or in the sediments are caught, killed or injured. Despite the damage to seabed habitats, quantitative assessment of the impact of trawling on ecosystem and carbon cycling remains poorly constrained. Our study presents an effort towards a better quantitative assessment by constructing a high-resolution, long-term dataset of trawling impacts on sediments, analyzing sediment samples, and performing elaborate modeling. Our results show that bottom trawling not only affects the animals and their function of carbon reworking, but also has a cumulative impact on long-term carbon storage. An almost 20-year reduction of bottom trawling effort has allowed the seabed animals to recover to some extent, but it was insufficient to restore the amount of organic carbon deposited in the sediment, especially in the trawled muddy areas.

1 Introduction

Bottom trawling represents the most widespread anthropogenic physical disturbance to surface sediments and benthic habitats (Halpern et al., 2008; Sala et al., 2021). A recent estimate suggests that ~22 Gt of sediment are resuspended by bottom trawling every year on the world's continental shelves, comparable to the total annual sediment supply through rivers (Oberle et al., 2016). Although bottom trawling has been performed for over a century on heavily fished grounds such as the North Sea, quantifying its impact on benthic biota and biogeochemical cycling has become a focal point of research only in recent decades (Halpern et al., 2008; Hiddink et al., 2017; Amoroso et al., 2018; Sala et al., 2021). In particular, the combination of satellite-based monitoring systems and logbook data have enabled estimates of bottom trawling with high spatial and temporal resolution (Eigaard et al., 2017; Kroodsma et al., 2018; Pitcher et al., 2022).

Bottom trawling significantly restructures the top layers of seafloor sediments and thereby alters benthic faunal communities (Hiddink et al., 2017; Tiano et al., 2022), biogeochemical processes and element fluxes across the sediment-water interface (De Borger et al., 2021). A recent study by Sala et al. (2021) highlighted the impact of bottom trawling on the storage of organic carbon (OC) in seafloor sediments. They suggested that trawling causes remineralization of 0.16–0.4 Gt of sedimentary OC globally every year, resulting in an emission of 0.58–1.47 Gt of CO_2. However, this estimate was subsequently questioned by Epstein et al (2022), who pointed out large uncertainties in several assumptions made by Sala et al. (2021). Epstein et al. (2022) emphasized that there is no consensus in existing literature on whether or to what extent trawling would lead to reduced OC storage. Understanding the fate of OC disturbed by trawling in different environmental settings was identified as a key research gap that would allow incorporating evidence-based considerations of OC sequestration into seabed management.

The blurred picture of the net effect of bottom trawling on OC sequestration in sediments originates from several counteracting mechanisms. On the one hand, trawling-induced resuspension and physical mixing of sediments may enhance remineralization of OC by increasing oxygen exposure time and limit OC sequestration by inhibiting deposition and burial of fine-grained sediments (Hartnett et al., 1998; Zonneveld et al., 2010; Keil, 2017; Freitas et al., 2021; Paradis et al., 2021). On the other hand, intensified lateral transport towards offshore depocenters and increase in primary production from the resuspension of nutrients may offset the loss of OC to varying extents (Dounas et al., 2007; Martín et al., 2008; Paradis et al., 2018). The complexity of OC sequestration is further increased by benthic fauna, which do not only contribute OC but also play a vital role in mediating OC fluxes across the sediment-water interface (Middelburg, 2018; Zhang et al., 2021). The overall effect of trawling on macrobenthos is a depletion of biomass and a change of the community from sessile to mobile and opportunistic species (Kaiser et al., 2006; Sciberras et al., 2018; Tillin et al., 2006). However, for quantitative assessments of how trawling-induced impacts on benthic fauna would affect OC sequestration, the current evidence base is incomplete and often contested (Epstein et al., 2022; LaRowe et al., 2020).

As a heavily fished region, the North Sea has been subject to trawling for more than one century (Thurstan et al., 2010). Bottom trawling is performed in ~90% of the North Sea area (ICES, 2021), with a particularly high intensity in shallow waters (water depth < 300 m) of the Skagerrak, where the swept area ratio (SAR) reaches $\geq 10\ yr^{-1}$ (Figure 1). Bottom trawling intensity shows a positive correlation ($r = 0.18$, $p < 0.001$) with OC contents in near-surface sediments, implying a disproportionately high trawling impact in areas of natural OC burial (Figure 1). Existing estimates of the total stock of OC in the uppermost 10 cm of North Sea sediments range between 96 and 476 Mt (Bockelmann et al., 2018; Wilson et al., 2018; Diesing et al., 2021), with a major part (~75%) being stored in mud depocenters which represent ~20% of the North Sea area (Figure 1). Previous studies have quantified the oceanic and atmospheric OC loads as well as OC accumulation rates (de Haas et al. 1997; Thomas et al., 2005; Diesing et al., 2021), and identified the footprint of trawling on benthic habitats and ecosystem (Eigaard et al., 2017; Rijnsdorp et al., 2018). However, no study has yet addressed the impact of bottom trawling on the temporal and spatial variability of OC storage capacity in the North Sea (Diesing et al., 2021). To achieve this objective, we have synthesized a high-resolution, long-term (71 years) dataset of bottom trawling impacts on sediments, applied 3-dimensional physical-biogeochemical modeling based on the dataset to estimate trawling-induced change of sedimentary OC stock, and evaluated model results with field samples.

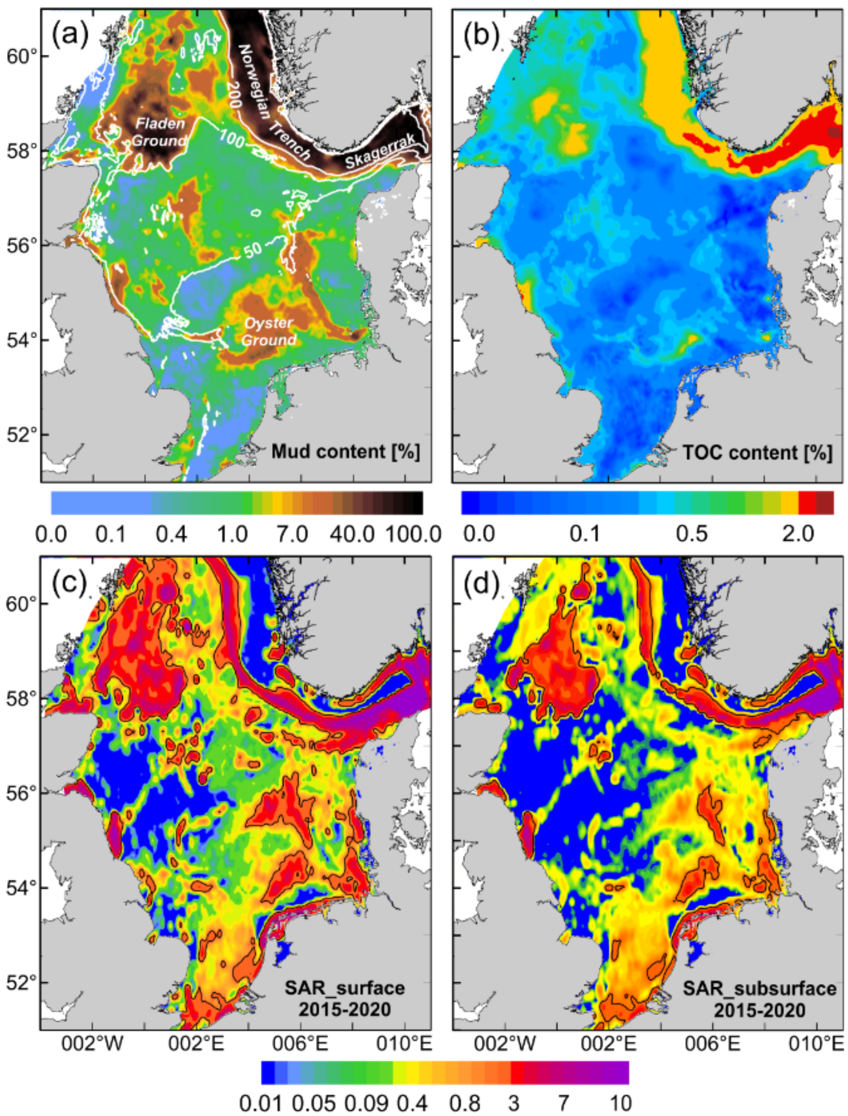

Figure 1. Top: (a) Mean mud content (%) in the upper 10 cm sediment, with marked large-scale mud depocenters. (b) Mean Total Organic Carbon (TOC) content (%) in surface 10 cm sediment interpolated from existing field data. Source of (a) & (b): Bockelmann et al. (2018). Bottom: Synthesized annual total bottom trawling intensity in terms of swept area ratio (SAR, yr^{-1}) averaged over the period of 2015-2020 in (c) surface sediments (0-2 cm) and (d) sub-surface sediments (2-10 cm). The contour line of SAR=1 is indicated in (c) and (d). All plots are in logarithmic scale.

2 Materials and Methods

2.1 Synthesis of Bottom Trawling Data 1950-2020

Annually aggregated spatial data on bottom trawling in the North Sea including gear-type information for 2009-2017 (ICES, 2019) were combined with daily fishing effort data for 2012-2020 (Kroodsma et al., 2018) in order to generate a daily time-series of fishing effort on a

0.1°×0.1° grid. Based on the penetration depths of different gear components in different sediment types, the daily SAR fields in three depth intervals in seafloor sediment (0-2 cm, 2-5 cm, and 5-10 cm) were generated (Text S1).

A historical reconstruction of bottom trawling effort (Couce et al., 2020) was used to hindcast trawling back until 1985. The availability of bottom trawling data before 1985 is, however, limited. Two methods were employed to fill the data gap for the period 1950-1984. Method 1 is based on the relationship between trawling effort and total annual landings. The time series 1985-2020 of bottom trawling effort shows a high correlation (r = 0.86) with the annual landing data of demersal and benthic fish (ICES, 2021; Figure S1). Based on this correlation, we extrapolated the time series of bottom trawling data back to 1950 through a linear regression between the trawling and landing data. Method 2 is based on the relationship between the total trawling effort and the UK portion in the North Sea. Among all North Sea countries, trawling data from the UK have the longest temporal coverage dating back to the 1910s (Engelhard, 2016). The trawling effort of UK vessels shows an almost linear (r = 0.98) relationship with the total effort in the North Sea in 2003-2020. Based on this relationship, the total trawling effort for 1950-1984 was assumed to also scale linearly with the UK trawling effort. Results from the two reconstructions show distinct variations (Figure S1). Method 1 yields a high fishing effort in the 1970s and 1980s that is comparable to that of the 1990s and a lower level in the 1950s and 1960s, comparable to the 2010s, whilst Method 2 produces almost the opposite pattern. Both reconstructed datasets were used in simulation to constrain the uncertainty in the estimation. The spatial and seasonal distribution of trawling effort in the time span 1950-2015 is assumed to follow the same pattern as in 2016-2020 based on the fact that the distribution of fishing effort among countries, seasons and gear types is fairly stable (Couce et al., 2020, Figure S2&S3).

2.2 Numerical Modeling

We applied a 3-dimensional physical-biogeochemical model to simulate the impact of bottom trawling on macrobenthos and OC cycling in surface sediments (Figure 2). The model consists of three major components, with HAMSOM (HAMburg Shelf Ocean Model, Schrum, 1997) for hydrodynamics, ECOSMO (ECOSystem Model, Daewel & Schrum, 2013) for biogeochemistry and TOCMAIM (TOC-MAcrobenthos Interaction Model, Zhang & Wirtz, 2017) for macrobenthos. OC is divided into three pools depending on the degradability, namely labile (i.e., of high nutritional quality for macrobenthos), semi-labile (i.e., of intermediate nutritional quality), and refractory (i.e., of low nutritional quality). With a Neumann boundary condition of OC fluxes at the sediment-water interface calculated by the pelagic model component, sedimentary OC content is solved by a mass balance equation including the impacts of deposition/erosion, oxygen-dependent first-order degradation, macrobenthic uptake and bioturbation. Temporal change of macrobenthic biomass is calculated based on food availability in the form of OC, temperature, oxygen, and mortality caused by predation and bottom trawling. Bioturbation scales with macrobenthic biomass and is inversely related with local OC resource. The impact of bottom trawling on OC sequestration in sediments is implemented through enhanced OC resuspension and enhanced mortality of macrobenthos. The latter subsequently affects macrobenthic uptake of OC and bioturbation intensity, which feed back to the vertical mixing efficiency, and thereby to OC sequestration. Based on field assessments of trawling-induced mortality of benthic fauna (Bergman & Van Santbrink, 2000; Hiddink et al., 2017), three trawling impact scenarios, namely Trawling_10th pct, Trawling_50th pct and Trawling_90th pct representing low (10th percentile, corresponding to depletion rate of 0.11 for SAR=1), medium

(50th percentile / depletion rate of 0.2) and high (90th percentile / depletion rate of 0.3) impact levels in mortality, respectively, were simulated and compared to a non-trawling scenario (No-trawling). Model details are provided in Text S2.

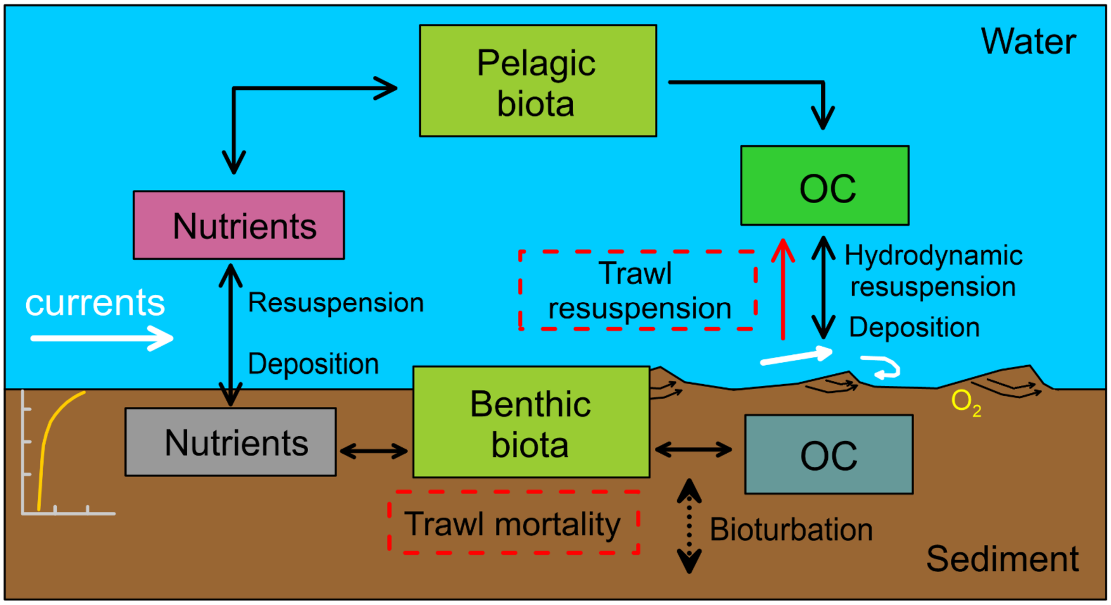

Figure 2. Schematic illustrating the benthic-pelagic coupling and impact of bottom trawling implemented in the HAMSOM-ECOSMO-TOCMAIM coupled numerical model.

2.3 Sediment Sampling and Analysis

Our simulation results have been confirmed by field data of OC and macrobenthic biomass (in ash free dry weight hereafter) in seafloor surface sediments of the southern North Sea (Zhang et al., 2019). In this study, the model domain was extended to the entire North Sea and additional field data from the northern part (Table S3) were compiled to assess the model performance (Figure 3). In particular, recently-collected sediment samples in both trawled and untrawled areas were analyzed. Processing procedures are the same as described in Zhang et al. (2019) and explained further in Text S3. The measured OC data and estimated bioturbation rates at these field stations were compared to the simulation results (Figure S5).

3 Results and Discussion

3.1 Impact of trawling on macrobenthos and bioturbation

The long-term hindcast simulation encompasses the period 1950 - 2016. The simulation period for model spinup until approaching a relatively stable level for macrobenthic biomass is about 25 years (Zhang et al., 2019). We focus on analysis of results starting from 1985, after which the time series of trawling are identical for both methods of reconstruction (section 2.1). The simulation results show similar variation patterns for 1985-2016 using both methods (Figure 3). Comparison with field data suggests a generally satisfactory model performance in capturing spatial distribution of macrobenthic biomass (Figure 3a, b), TOC content and bioturbation rates (Figure S5). In all scenarios, simulation results confirm a peak of spatial mean biomass in the area between 53° and 54°N, and a decrease toward the north in the shelf (water depth < 300 m) as reported by ICES (2007). The mean biomass rises again at ~57.5° owing to increased production along the shelf edge and shallow parts (water depth < 300 m) of the Skagerrak, with reported field measurements between 5 to 30 g m^{-2} by Rosenberg et al. (1996) and Ståhl et al. (2004), and model results between 3 and 26 g m^{-2}. Another peak in mean biomass occurs in the area between 58° and 59°N, where two large-scale mud depocenters (the Fladen Ground and the Norwegian Trench) are located (Figure 1a). Reported field data of macrobenthic biomass give 11 g m^{-2} (spatial mean) in the Fladen Ground (de Wilde & Kok, 1986) and between 2-5 g m^{-2} in the deep trench (Rosenberg et al., 1996). Our simulation results show consistency with field data in the Fladen Ground, whilst the values in the deep trench seem to be overestimated (Figure 4a).

The long-term time series of modelled total biomass for the entire North Sea in each scenario show a generally stable level between 1985 and 2016 characterized mainly by seasonal fluctuations associated with food supply (Figure 3c, d). The measured values from two large-scale ICES surveys (April-May in 1986 and May-June in 2000) are approximately the same (3.06 Mt, Duineveld et al., 1991; ICES, 2007) and lie between the results of the scenarios Trawling_10th pct and Trawling_50th pct, about 20% lower than in the No-trawling scenario. Seasonal fluctuations are normally between $0.15 - 0.6$ Mt, accounting for 5-15% of the total biomass. Besides seasonal fluctuations, inter-annual variations (≤ 0.3 Mt yr^{-1}) and longer-term variations are also seen. The former is mainly related to hydro-climatic fluctuations (reflected by the North Atlantic Oscillation winter index, see Zhang et al. (2019)) impacting the primary production (Figure 3f), whilst the latter appears to be associated with variations in the trawling effort, e.g. an increasing trend of biomass since 2008 due to reduced trawling (Figure 3c,d).

For the period 1985 - 2008, the trawling-induced reduction of biomass ranges between 14-17% in the low-impact scenario (Trawling_10th pct) and between 23-27% in the high-impact scenario (Trawling_90th pct) compared to the No-trawling scenario when using the reconstructed trawling data from Method 1. Biomass reduction is lower when using the reconstructed data from Method 2, with 10-14% in the low-impact scenario and 21-24% in the high-impact scenario, respectively. In all trawling scenarios, an apparent increase of biomass is seen starting in 2008 (Figure 3c,d). The biomass reduction amounts to 11% (Trawling_10th pct) and 17% (Trawling_90th pct) in 2015-2016 using reconstructed data from Method 1. Similar values are seen in the results using reconstructed data from Method 2. This trend is caused by a decline of bottom-trawling starting in 2001, with the total annual effort dropping from ~3×10^6 hours in 2001 to ~1.6×10^6 hours in 2008 and remaining relatively stable afterwards (Figure 3c,d). It is worth noting that although the total accumulative trawling effort is ~10% higher in the reconstructed time series (1950-1984) from Method 2 than that from Method 1 (Figure S1), simulation results indicate higher biomass during 1985 - 2008 using Method 2 (as described above). This is due to lower trawling effort in the reconstructed time series from Method 2 for 1968 - 1984, which allows a recovery of biomass that is similar to the pattern in 2008-2016. The difference between the two results becomes smaller with time but still exists until 2016, suggesting a long-lasting impact of historical trawling on macrobenthos.

The reduction in biomass obtained from our simulations is consistent with the estimates by Rijnsdorp et al. (2020), who combined information about trawling pressure, gear characteristics, habitat characteristics and sensitivity of benthic community to assess impact of bottom trawling for the period 2010–2012. Their results suggest a 13% reduction of total biomass in the North Sea by trawling, with highest reduction (26%) in fine-grained sediments (mud) and lowest reduction (9%) in coarse sediments. Similar patterns are also seen in our simulation results, with biomass reduction of up to 30% in frequently trawled (annual SAR > 5) mud depocenters (e.g. the Fladen Ground and the Skagerrak) and up to 15% in trawled sandy seabeds (Figure 4a, b). Meanwhile, some un-trawled and less trawled areas are featured by a slight increase of biomass (< 5 %) due to deposition of resuspended OC from adjacent trawled areas.

At a regional scale, the impact of bottom trawling on macrobenthos is not merely a reduction of biomass, which is within 30% in existing estimations (Hiddink et al., 2017; Rijnsdorp et al., 2020) including this study. Biomass reduction together with trawling-induced changes of benthic community structure may lead to altered dynamics in benthic carbon cycling (Paradis et al., 2021; Sciberras et al., 2018). Bioturbation as a key mechanism for transporting OC from surface sediments to deeper horizons is significantly impaired, and is only partly counterbalanced by trawling-induced physical mixing in the upper most few centimeters (De Borger et al., 2021). Our simulation results (Figure 4c, d) suggest a substantial trawling-induced reduction of bioturbation rates in the North Sea, with largest reduction (up to 50%) in frequently trawled (annual SAR > 5) muddy seafloor, and moderate reduction (10-20%) in frequently trawled (annual SAR > 3) sandy seafloor. Meanwhile, the edges of frequently trawled areas feature a slight increase of bioturbation due to enhanced OC deposition, though these parts are still subject to trawling but with a much lower intensity (annual SAR < 0.1, Figure 1c, d). It is worth noting that the areas displaying the largest biomass reduction are also hotspots of bioturbation in the No-trawling scenario (Figure 4c). In energetic coastal seas such as the North Sea, where natural sedimentation rates are generally low (< 1 mm yr^{-1}, Diesing et al., 2021), bioturbation plays a key role in transporting OC from the oxic sediment surface to deeper anoxic horizons, thereby facilitating long-term OC sequestration (Zhang et al., 2019). The reduction of bioturbation in these key functional hotspots of OC sequestration would inevitably have a long-term impact. Though ecosystem changes in the North Sea have been attributed mainly to variations in climate and nutrients (Clark & Frid, 2001), our results point toward trawling as another possible main driver of changes in benthic ecosystem.

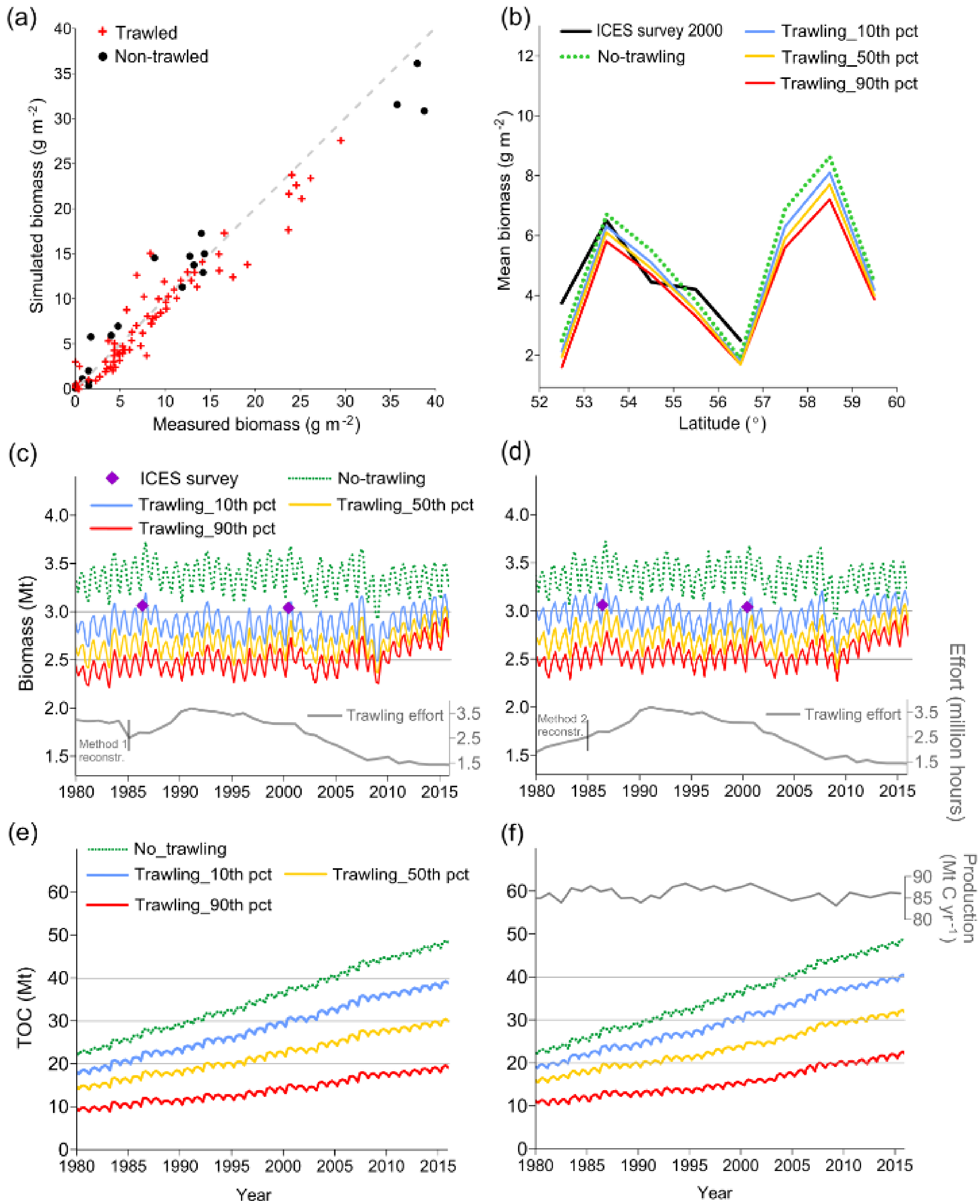

Figure 3. (a) Scatter plot showing a general consistency between simulated macrobenthic biomass (scenario: Trawling_50th pct from Method 1) and station data. Annual SAR is used to distinguish trawled (SAR >= 1) and non-trawled (SAR < 1) stations. (b) Distribution of mean macrobenthic biomass for each degree of latitude in the year 2000. Model scenarios are based on

Method 1-reconstructed trawling data. (c) Time series of simulated total macrobenthic biomass in the North Sea using Method 1-reconstructed data (gray line with y-axis on the right), with two large-scale ICES survey results marked (ICES, 2007). (d) Similar to (c) but using Method 2-reconstructed data. (e) Time series of estimated net change of total organic carbon (TOC) stock in the North Sea sediments in four model scenarios using Method 1-reconstructed data. The reference is the initial TOC stock (Figure 1b) specified for the simulation. (f) Similar to (e) but using Method 2-reconstructed data. Time series of simulated net annual primary production is indicated by the grey line with y-axis on the right in (f).

3.2 Impact of trawling on OC sequestration

Organic carbon preserved in surface sediments is susceptible to the impact of trawling. In particular, the labile fraction is largely depleted in frequently trawled sites (De Borger et al., 2021; Paradis et al., 2021). Our simulation results show that the natural sequestration capacity of OC in North Sea sediments, reflected by a net change of the OC stock, amounts to 0.2-1.2 Mt yr^{-1} with a long-term mean of 0.75 Mt yr^{-1} in the No-trawling scenario (Figure 3e, f). Seasonal fluctuations associated with deposition of planktonic detritus range between 1 and 3 Mt. The ratio of the annual net increase to the seasonal deposition suggests that 10-25% of deposited OC would be preserved without trawling. This natural sequestration capacity is increasingly impaired with an increasing trawling-induced mortality in macrobenthos (Figure 3e, f). In the low-impact scenarios (Trawling_10th pct), the annual net changes in the OC stock range between -0.05 and 1.25 Mt yr^{-1} with a long-term mean accumulation of 0.6 Mt yr^{-1}, corresponding to a 20% reduction of the natural sequestration capacity. This reduction reaches 67% (using Method 1-reconstructed data) and 60% (using Method 2-reconstructed data) in the high-impact scenarios (Trawling_90th pct). Similar to the spatial patterns in the change of biomass and bioturbation, frequently trawled muddy areas show the largest reduction of OC (10-20%) compared to the No-trawling scenario, while frequently trawled sandy areas feature a 5-10% reduction of OC (Figure 4e, f). Meanwhile, untrawled and less trawled areas (annual SAR < 0.1) are characterized by a slight increase of sedimentary OC (≤10%), but this increase can offset the net decrease only to a small extent (Figure 3e, f).

Our simulated OC accumulation rates in the North Sea are lower but still at the same order of magnitude as previous estimates, e.g. 1.1 Mt yr^{-1} by de Haas et al., (1997) and 1.43 ± 2.07 Mt yr^{-1} by Diesing et al. (2021), and confirm the Norwegian Trough and Skagerrak as the major OC depocenters. Trawling impacts were not explicitly distinguished in previous estimates, which were based on interpretation of sediment samples. The disentangling of trawling impacts in our simulations allows an assessment of modified OC sequestration capacity in the depocenters. A comparison between the long-term varying trends of macrobenthic biomass and the sedimentary OC stock (Figure 3) shows that in contrast to the (albeit slow) recovery of biomass due to reduction of trawling in the past decade, the divergence in the OC stock between the trawling and No-trawling scenarios becomes increasingly larger. This indicates that although an almost 20-year reduction of bottom trawling could allow the stock of macrobenthic biomass to recover to some extent, it is insufficient to restore the OC sequestration rates, especially in the trawled muddy areas. Indeed, the muddy areas still show a reduced capacity for OC sequestration due to a persistently high trawling pressure there.

It is noteworthy that the North Sea still acts as a net carbon sink, albeit with strongly reduced capacity by trawling, as simulated in the high-impact scenario. For that scenario, the spatially averaged reduction of OC storage capacity over the entire North Sea amounts to 0.87 t C $km^{-2}yr^{-1}$, equivalent to 3.19 t CO_2 $km^{-2}yr^{-1}$. This is much lower than the global estimate of Sala et al. (2021), who presented an average steady-state remineralization in trawled areas of 32 t C $km^{-2}yr^{-1}$ or 118 t CO_2 $km^{-2}yr^{-1}$. The difference between these estimates is likely explained by the simplified model of trawling impacts in Sala et al. (2021), which did not include natural remineralization and benthic ecosystem functioning. To further constrain the uncertainty in the estimate, other relevant processes in OC cycling and sequestration (e.g. gear-induced mixing and nutrient resuspension, bedform migration) need to be incorporated. Nevertheless, our study points out a central role of benthic ecosystem functioning in long-term carbon sequestration in shelf seas.

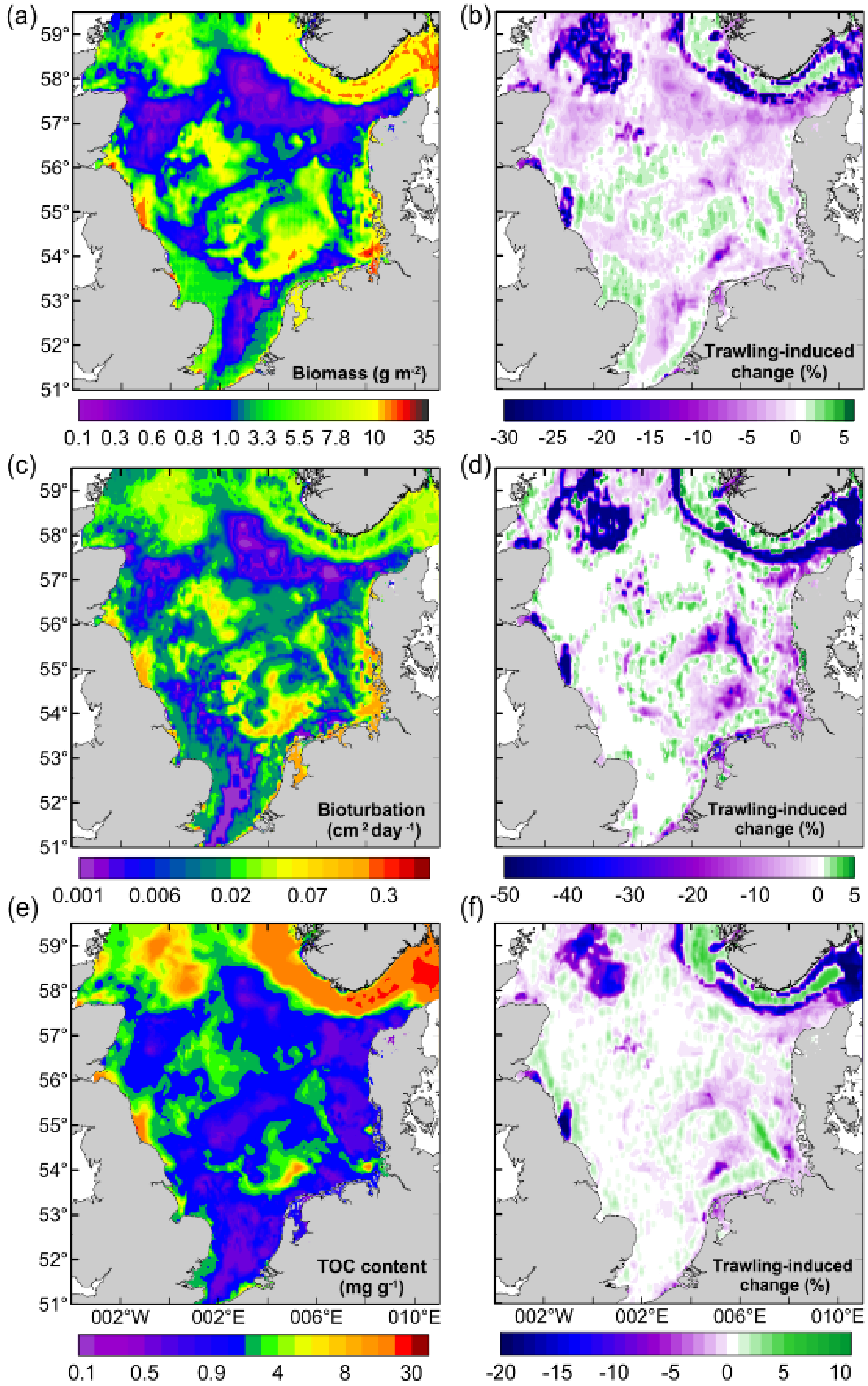

Figure 4. Simulation results of the No-trawling scenario in August 2015 and trawling-induced accumulative relative changes (scenario: Trawling_50th pct) in August 2015. (a) and (b) are for macrobenthic biomass. (c) and (d) are for mean bioturbation rates in the upper-most 10 cm sediments. (e) and (f) are for mean TOC content in the upper-most 10 cm sediment. Positive and negative values in (b), (d) and (f) indicate increase and reduction, respectively.

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Open Research

Datasets for this research are available at zenodo https://doi.org/10.5281/zenodo.7560324. The source code of TOCMAIM with a coupling interface to 3-D physical-biogeochemical models are stored in Mendeley Data with open access at http://dx.doi.org/10.17632/2vvny3xd85.2

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