



Bottom-Trawling-Enhanced Phosphorus Recycling in the Baltic Sea

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Abstract.

Bottom trawling on continental shelves can lead to extensive sediment resuspension, potentially altering carbon cycling and benthic-pelagic nutrient exchange. We assessed how bottom trawling affects the oxygen exposure time of organic matter (OM) and its transport toward deeper, oxygen-deficient basins in the Baltic Sea. For this, we used a 3-D coupled physical-biogeochemical model with labile and unreactive OM and associated water-column and sedimentary time tracers. Fishing activity was quantified from publicly available datasets and uncertainty in trawling-induced resuspension was addressed using low and high trawling estimates.

Bottom trawling altered the spatial distribution of OM. Labile OM was transported over shorter distances due to its limited lifetime, with bottom trawling increasing its water-column residence time (WCRT) by 3 and 17 % (14 and 76 h) in areas classified as having low and high trawling intensity, respectively. Repeated trawling-induced resuspension had a larger cumulative effect on unreactive OM, increasing its WCRT by 25 and 46 % (16 and 42 d), respectively, over 15 years and substantially affecting its distribution. Bottom trawling had only a minor effect on oxygen deficiency, with maximum increases in hypoxic and euxinic bottom areas of $<7.0 \times 10^3$ and $<3.8 \times 10^3$ km², respectively. Notably, bottom trawling progressively enhanced primary production over 20 years of simulation, reaching increases of up to 12 and 29 % under the low and high trawling estimates, respectively, through increased resuspension and recycling of phosphorus. This benthic-pelagic feedback increases sedimentary OM concentrations and may counteract the commonly proposed effect of enhanced OM mineralization, particularly in systems where primary production strongly depends on phosphate availability.

1 Introduction

The biogeochemical consequences of bottom-trawling have been studied for decades (Mayer et al., 1991). A major focus has been the effect of bottom-trawling on organic carbon (OC) storage. Most widely discussed is the effect of bottom-trawling-induced resuspension, which exposes sedimentary OC to oxic seawater and may thereby enhance its degradation. Recent model estimates of the effect of bottom-trawling on the global sedimentary OC storage range from declines of ~ 0.3 Mt C yr⁻¹ (Khedri et al., 2025) to ~ 10 Mt C yr⁻¹ (Zhang et al., 2024). A meta-analysis of 49 field studies also showed strongly varying results,



whereby 10 % reported an increase, 29 % a decrease, and 61 % no significant change in sedimentary organic carbon stock (Epstein et al., 2022). Thus, despite decades of research, the fate of trawling-disturbed OC remains poorly constrained.

The effect of oxygen exposure on organic matter (OM) degradation depends on OM reactivity. Bulk OM mineralization is primarily driven by the degradation of labile, largely algae-derived detritus, and is controlled by OM reactivity and a range of environmental factors (Middelburg et al., 1993; Arndt et al., 2013). Laboratory experiments show that perturbation and renewed oxygen exposure can enhance OM mineralization, particularly in less reactive sediments (Hulthe et al., 1998; Dauwe et al., 2001; Wu et al., 2026). However, for labile OM, aerobic degradation is often not significantly faster than anaerobic mineralization (e.g., Hansen and Blackburn, 1991; Hulthe et al., 1998).

Long-term OC sequestration depends on the fate of the small, relatively refractory or physically protected fraction that is not rapidly remineralized. Because long-term burial flux is relatively small compared with annual OM supply, and the mechanisms controlling refractory OM breakdown may differ from those governing fresh algal detritus (Burdige, 2007), total sedimentary mineralization rates and long-term OC preservation are not directly linked. Oxygen exposure time (OET) has emerged as a strong predictor of OM preservation (Hartnett et al., 1998; Nierop et al., 2017). Moreover, natural reoxidation events can strongly degrade previously preserved OM (Cowie et al., 1995). However, this degradation is not necessarily directly driven by aerobic respiration of recalcitrant OM. O₂ can also facilitate the initial oxidative breakdown of organic compounds, making them more accessible to subsequent degradation (Burdige, 2007). In addition, oxic bottom waters allow for bioturbation, which can promote OM degradation by redistributing OM and electron acceptors, stimulating microbial activity, and generating redox oscillations that couple aerobic and anaerobic degradation pathways (Aller, 1994; Zonneveld et al., 2010).

Bottom trawling represents a particular sediment disturbance occurring in oxic environments. Experimental trawling has shown increased O₂ drawdown in the water column immediately following sediment resuspension, reflecting the oxidation of resuspended reactive OM and reduced sedimentary compounds (Durrieu de Madron et al., 2005; Kalapurakkal et al., 2025). Meanwhile, benthic remineralization rates have shown inconsistent responses, with approximately equal numbers of studies reporting increased and decreased rates following trawling (Epstein et al., 2022).

Although artificial sediment mixing can transiently increase mineralization rates, only a small fraction of the sedimentary OM may be degraded during such events (Wu et al., 2026). By comparison, OM can reside for decades to centuries in the bioturbated zone and undergo repeated O₂ exposure (Rooze et al., 2024). Trawling-induced changes in benthic macrofauna may therefore also alter bioturbation and OET, potentially counteracting the direct effect of physical sediment disturbance (Hinz et al., 2021; Rooze et al., 2024; Bradshaw et al., 2024).

Additionally, bottom trawling can represent a major physical disturbance to the sediment surface layer, which typically hosts high microbial biomass and rapid metabolic turnover. Mineralization may therefore be affected by changes in benthic trophic state and community structure (Watling et al., 2001; Polymenakou et al., 2005; Packmor et al., 2025). Trawling may also excavate OM from deeper sediment layers and mix it with fresh detritus, potentially enhancing its degradation through priming (Paradis et al., 2019; Zhu et al., 2024).

Regenerated nutrients released during enhanced mineralization may fuel primary production and thereby increase carbon uptake into OM (Dounas et al., 2007). Mineralization in the water column rather than in the sediment may enhance nutrient



transport to the euphotic zone (Tiwari et al., 2025), while bottom-trawling may also reduce benthic removal of nutrients (Pilska et al., 1998; Ferguson et al., 2020). These feedbacks may therefore offset OC loss through enhanced mineralization.

Together, these dynamics complicate the relationship between bottom trawling, OM mineralization, and ecosystem carbon cycling. In particular, the empirical relationship between OET and OM preservation does not provide a direct parameterization of the effect of trawling on mineralization. Oxygen exposure may act directly on OM degradation, but may also correlate with other controls on mineralization, while trawling itself modifies sediment mixing and benthic communities in ways that remain insufficiently constrained.

Here, we use an ecosystem model of the Baltic Sea to focus on physical resuspension and redistribution, while tracking disturbance frequency and OM residence times in the sediment and water column as diagnostics of OM perturbation. At the ecosystem scale, the model allows the consequences of redistributing sedimentary OM and nutrients for coupled benthic-pelagic biogeochemistry to emerge dynamically. Finally, we investigate whether the complex Baltic Sea bathymetry allows for lateral transport of resuspended OM from shallow trawling grounds towards deeper, oxygen-deficient basins, potentially exacerbating oxygen deficiency.

2 Methods

2.1 Study area

The Baltic Sea is a semi-enclosed marginal sea with an average depth of 54 m, but contains several deeper basins (Fig. 1), including the East Gotland Basin (maximum depth ~250 m) and the West Gotland Basin (maximum depth ~460 m). It has restricted water exchange with the North Sea, resulting in a water residence time of >30 years (Carstensen et al., 2014). Saline North Sea water enters the Baltic Sea particularly through minor and major inflow events, whereas numerous rivers provide a large freshwater input. This results in an estuarine-type circulation and a pronounced horizontal salinity gradient. Tides are weak, and water flow is primarily driven by wind forcing and density gradients. The water column is strongly stratified by a permanent halocline, inhibiting vertical ventilation. Dense saline water can remain trapped in deeper basins and become depleted in oxygen. The Bornholm and Gotland basins are characterized by widespread hypoxia, with euxinia occurring particularly in the deeper Gotland basins. Oxygen-rich saline inflows can temporarily ventilate the bottom waters and reduce or even eliminate euxinia, but subsequent strengthening of stratification promotes renewed oxygen depletion (Krapf et al., 2022).

A small part of the hypoxia and euxinia in the Baltic Sea is natural (Carstensen et al., 2014). Foremost due to the agricultural runoff of phosphate, hypoxic and euxinic conditions spread, particularly in the period 1950–1970. Although nutrient inputs began to decline from the 1980s onward, the pronounced reduction in hypoxic area during the 1980s and early 1990s was primarily associated with the 1983–1992 stagnation period without major saline inflows and the resulting weakened stratification, rather than nutrient-load reductions. The major Baltic inflow of 1993 initially ventilated the deep basins, but subsequently restored stronger stratification, contributing to a rapid re-expansion of hypoxia. Since approximately 2000, hypoxic areas have remained persistently large despite continued reductions in external nutrient inputs (Carstensen et al., 2014; Krapf et al., 2022).

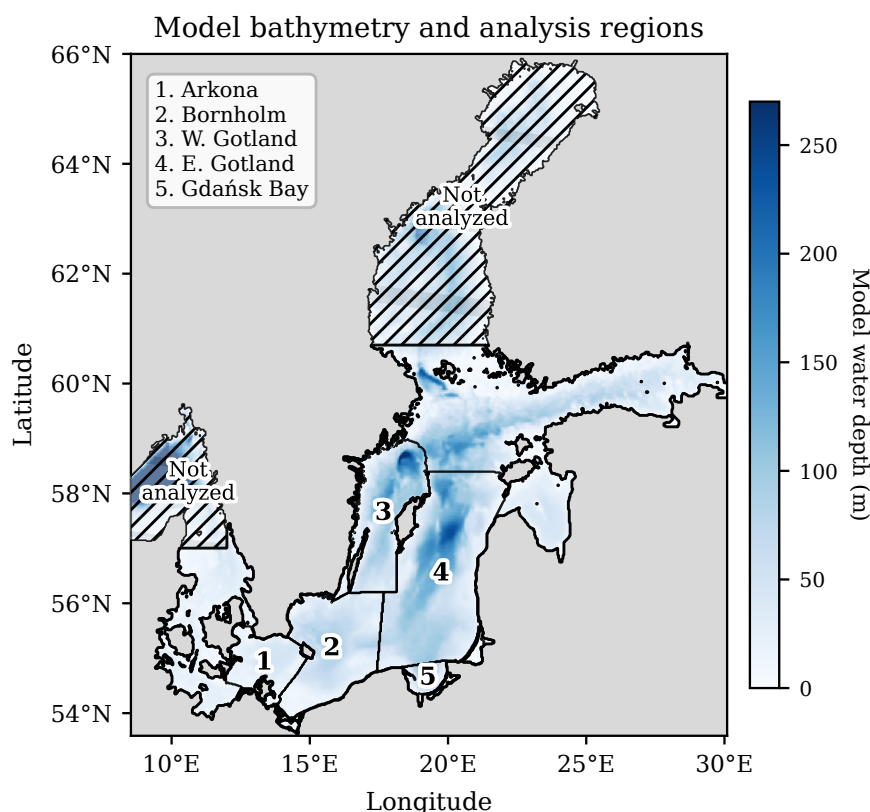


Figure 1. Model bathymetry of the Baltic Sea. Water depth in the Skagerrak (western hatched area) was artificially reduced to improve model stability. Model output from this area and the hatched northern region was excluded from the analysis. The latter is relatively isolated, with little bottom-trawling activity and limited influence on the regions considered here.

Bottom trawling in the Baltic Sea is conducted predominantly using otter trawls. Following the collapse of the eastern and western Baltic cod stocks and the closures of fisheries targeting cod in 2019 and 2021, respectively, flatfish are now the only target species of bottom-trawl fisheries (ICES, 2025, 2026).

95 2.2 Estimating organic matter resuspension

Trawling activity was estimated based on Global Fishing Watch (GFW) data for 2016–2020 (Kroodsmas et al., 2018), which infers fishing activity from Automatic Identification System (AIS) transmissions. AIS broadcasts information on vessel position, speed, and course. GFW uses these data to infer vessel activity and provides daily estimates of fishing effort at a spatial resolution of $0.1^\circ \times 0.1^\circ$, corresponding to approximately 3.4×6.0 nautical miles (n.m.) in the Baltic Sea. We selected only
 100 vessels categorized as trawlers and assumed these to represent bottom trawlers. However, GFW data do not distinguish bottom trawling from other trawling or between specific trawl gear types.



We additionally used International Council for the Exploration of the Sea (ICES) fishing-pressure data for 2016–2020 derived from Vessel Monitoring System (VMS) positions linked to fishing logbooks (ICES, 2022; von Dorrien, 2022). The data are provided on $0.05^\circ \times 0.05^\circ$ c-squares ($\sim 1.7 \times 3.0$ n.m.) and include parameters directly related to bottom-contact fishing, such as the swept-area ratio (SAR), defined as the area swept by fishing gear relative to the total seabed area. AIS coverage is biased toward larger vessels, as AIS is mandatory for European Union (EU) fishing vessels >15 m. Similarly, VMS data generally exclude fishing vessels <12 m, which were not subject to mandatory VMS reporting. Consequently, vessel-tracking data may incompletely represent bottom-trawling activity and its physical impact on the seabed, particularly in regions dominated by small vessels (Marsaglia et al., 2025; Schönke et al., 2026).

We have applied two approaches to estimate trawling-induced resuspension. The first approach used only AIS-derived resuspension rates (R_{AIS}) calculated following Porz et al. (2024). This method estimates SAR from vessel size and engine power using the empirical relationships in Eigaard et al. (2016), and subsequently estimates resuspension rates based on SAR, sediment mud content, and the hydrodynamic drag of the gear components using the empirical relationship of O'Neill and Ivanović (2016). Mud content was obtained from the substrate map of Leipe et al. (2017), supplemented with European Marine Observation and Data Network (EMODnet) data (EMODnet Geology, 2022) where necessary. Resuspension rates were set to zero in regions where ICES fishing-pressure data indicated no bottom-trawling activity to avoid unrealistically high bottom trawling effort in regions dominated by midwater trawling.

The second approach scaled AIS-derived resuspension rates by the VMS-derived SAR:

$$R_i = R_{\text{AIS},i} \frac{S_{\text{ICES},i}}{S_{\text{AIS},i}} \quad (1)$$

where R_i and $R_{\text{AIS},i}$ are the ICES-constrained and AIS-derived resuspension rates in grid cell i , respectively, and $S_{\text{ICES},i}$ and $S_{\text{AIS},i}$ are the corresponding annual-mean SAR estimates. This retains the daily temporal variability of the AIS-derived forcing and excludes trawling from areas without recorded ICES fishing activity.

Data from 2016–2020 were averaged by calendar day, resulting in a single year of forcing with daily resolution. This forcing was repeated for all simulation years. The trawling forcing therefore represents the recent bottom-trawling activity rather than historical trawling during the simulated period (1978–1997). Both the intensity and spatial distribution of bottom trawling may have differed during the simulated period (ICES, 2024). However, this study does not aim to reconstruct historical changes in bottom-trawling activity, for which comparable spatially resolved vessel-tracking data are unavailable, but to assess the sensitivity of the Baltic Sea ecosystem to bottom trawling under observation-based forcing.

Sediment resuspension rates were multiplied by surficial organic carbon concentrations to obtain maximum OC resuspension rates. Surficial OC concentrations were interpolated by kriging using data from Leipe et al. (2011) and Bunke (2018).

The two approaches produced substantially different annual-mean OC resuspension forcings (Fig. 2), with overall higher resuspension rates in the first than in the second approach. Given the uncertainty associated with both vessel-tracking datasets and our aim of assessing ecosystem sensitivity to bottom trawling, we retained both forcings in the simulations and hereafter refer to them as the high and low trawling estimates, respectively. The simulation without bottom trawling is hereafter referred to as the baseline simulation.

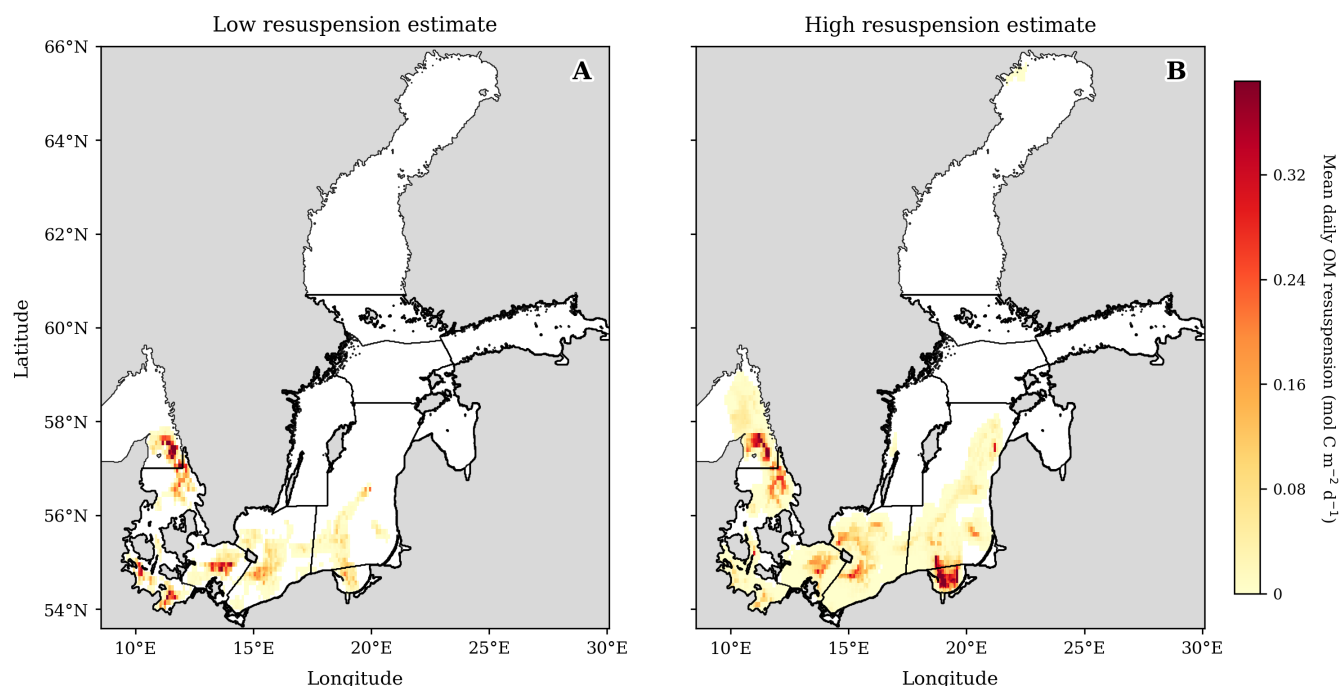


Figure 2. Mean maximum potential daily organic matter resuspension rate due to bottom trawling for the low (A) and high (B) resuspension estimates (Sect. 2.2). The actual forcing varies daily over a one-year cycle that is repeated throughout the simulations.

Both estimates show substantial trawling activity in the northwestern part of the model domain (the Skagerrak). We excluded this area from our analysis because its dynamics are strongly influenced by the model boundary conditions, and its bathymetry was made shallower for numerical reasons (Fig. 1). We also excluded the Gulf of Bothnia because of its very limited trawling activity and limited exchange of resuspended matter with the regions considered here (Fig. 1).

140 2.3 Model setup

The Ecological ReGional Ocean Model (ERGOM)-Modular Ocean Model version 5 (MOM5) model adapted for the Baltic Sea was used to simulate coupled circulation and biogeochemistry at 1 n.m. horizontal resolution, as described in detail by Neumann et al. (2022). In brief, the ecosystem model simulates carbon, nitrogen, sulfur, and phosphorus dynamics, including several phytoplankton classes and bulk zooplankton. The sediment is represented by a single fluff layer containing state variables for
 145 detritus and phosphate adsorbed to iron(III) oxyhydroxides (Fe-P). Burial is parameterized using threshold concentrations for both detritus and Fe-P, with excess material removed from the model. Hydrodynamic shear stress and biogenic resuspension can mobilize detritus and Fe-P from the fluff layer into the bottom water. Water-column detritus and Fe-P have fixed sinking velocities of 4.5 and 1.0 m d^{-1} , respectively.



Mineralization rates are temperature-dependent. Under oxic conditions, the half-lives of sedimentary and water-column
150 detritus range from 289 to 50 d and from 327 to 73 d, respectively, between 5 and 15 °C. Thus, non-buried detritus is relatively labile. Under euxinic conditions, mineralization rates are reduced by 80 %. The model is calibrated against water-column parameters rather than sedimentary observations, reflecting its design to capture bulk nutrient and O₂ dynamics on relatively short timescales rather than long-term carbon sequestration.

For the purpose of this study, we have made several modifications to the model. First, bottom-trawling was added as a driver
155 for resuspension of detritus, using the rate expression

$$R_{X,i} = R_{N,i} \frac{D_{X,i}}{D_{N,i}} \quad (2)$$

where $R_{N,i}$ is the maximum resuspension rate (Eq. (1)) converted from C to N units using the Redfield ratio, the model
currency for detritus; D_X is the sedimentary inventory of detritus class X ; and D_N is the sum of all sedimentary detritus
classes. Several detritus classes are used to account for non-Redfieldian stoichiometry (Neumann et al., 2022), although the
160 one with Redfieldian stoichiometry (D_{rf}) constitutes by far the largest fraction. Bottom-trawling-induced resuspension of Fe-P
was parameterized as

$$R_{FeP,i} = R_{N,i} \frac{FeP_i}{D_{rf,i}} \quad (3)$$

whereby FeP denotes the Fe-P sedimentary contents. This results in approximately equal fractions of Fe-P and Redfieldian
detritus being resuspended.

165 A state variable was added for unreactive OM to both the water column and sediment. Unreactive OM does not undergo any biogeochemical transformations and is transported in the same way as labile detritus, but differs in its burial parameterization. Sedimentary unreactive OM was removed by first-order burial with a constant rate coefficient of $1.8 \times 10^{-4} \text{ d}^{-1}$, which corresponds to a burial timescale of approximately 15 years, estimated from an assumed scraping depth of 15 mm and a typical burial velocity of 1 mm yr^{-1} . For bottom-trawling-induced resuspension, its concentration substituted D_X in Eq. (2), while the
170 denominator remained unchanged and thus depended only on the labile detritus inventory.

A fully conservative variant of unreactive OM, not removed by burial, was also included. Its transport patterns were nearly indistinguishable from those of the buried variant, indicating that burial had little influence on its simulated redistribution. Therefore, in the text, we refer to both state variables as unreactive OM. We show results for conservative OM, except for the variance in residence time described below, which was only tracked for the buried variant and only concerns the results shown
175 in Fig. 4.

For Redfieldian labile and unreactive OM, additional moment tracers were used to track the mean and variance of residence time in both the water column and sediment. The governing equation for the n th raw moment follows Delhez and Deleersnijder (2002) and Rooze et al. (2023):

$$\frac{\partial C \mu_n}{\partial t} + v \cdot \nabla C \mu_n = n C \mu_{n-1} + \nabla \cdot (K \cdot \nabla C \mu_n) + \frac{\partial \mu_n C}{\partial t} \Big|_{R_i} \quad (4)$$

180 where the raw moments are defined as $\mu_n = \langle \tau^n \rangle$, with τ denoting residence time. The first term on the right-hand side accounts for aging. The final term represents biogeochemical reactions and exchange processes. For consumption reactions



that are independent of residence time, as well as exchange between the water column and sediment,

$$\left. \frac{\partial \mu_n C}{\partial t} \right|_{R_i} = \mu_n R_i \quad (5)$$

whereas production of new material, such as through primary production, is described by

$$185 \quad \left. \frac{\partial \mu_n C}{\partial t} \right|_{R_i} = 0 \quad (6)$$

Throughout the remainder of the manuscript, we convert the raw to the standard centralized variance or standard deviation (σ).

All simulations were initialized from the model state on 1 January 1978 of the existing ERGOM-MOM5 simulation described by Neumann et al. (2022). The added unreactive OM tracers were initialized with spatially uniform concentrations. Because their resuspension fluxes are proportional to their respective tracer inventories, their initial concentration values do not affect their final spatial distribution. Small, numerically non-zero water-column concentrations were used for initialization, and all associated residence time moments were set to zero.

2.4 Model diagnostics and post-processing

Resuspension frequencies for the different drivers were calculated during post-processing from spatially integrated quantities. For each OM pool p , the standing stock was calculated as

$$195 \quad S_p(t) = \sum_i A_i C_{p,i}(t) \quad (7)$$

where $S_p(t)$ is the spatially integrated standing stock of labile or unreactive OM, A_i is the bottom area of grid cell i , and $C_{p,i}$ is the areal stock of the respective OM pool. The spatially integrated resuspension $R_{p,m}$ was calculated as

$$R_{p,m}(t) = \sum_i A_i F_{p,m,i}(t) \quad (8)$$

whereby F is the modeled resuspension flux and subscript m denotes the resuspension mechanism (hydrodynamic resuspension, bioresuspension, or bottom trawling). The integrated stocks and resuspension rates were averaged over 1988–1997, and the resuspension frequency was calculated as

$$f_{p,m} = \frac{\overline{R_{p,m}}}{\overline{S_p}} \quad (9)$$

where f is the resuspension frequency.

Primary production rates were only saved in the low-trawling estimate simulation. Therein, annual changes in phytoplankton biomass relative to the baseline closely tracked those in primary production ($r = 0.996$), differing on average by 0.3 %. Therefore, relative changes in primary production in both simulations were estimated from relative changes in total phytoplankton biomass.



3 Results

The simulated frequency of OM resuspension caused by bottom trawling varied among regions, trawling estimates (Fig. 2),
210 and OM reactivity. In particular, Gdańsk Bay showed a strong difference in resuspension frequency between the low and
high trawling estimates (Fig. 3). Both estimates resulted in low average trawling-induced resuspension frequencies in the W.
Gotland and E. Gotland basins (Fig. 3). Labile OM was generally resuspended more frequently than unreactive OM across the
different regions (Fig. 3). Hydrodynamic resuspension was relatively more important for labile than unreactive OM, whereas
trawling-induced resuspension was relatively more important for unreactive than labile OM (Fig. 3). Bioresuspension was a
215 minor driver of resuspension for labile OM, but exceeded hydrodynamic resuspension of unreactive OM in several regions; the
latter was very low in all regions except the Arkona Basin (Fig. 3).

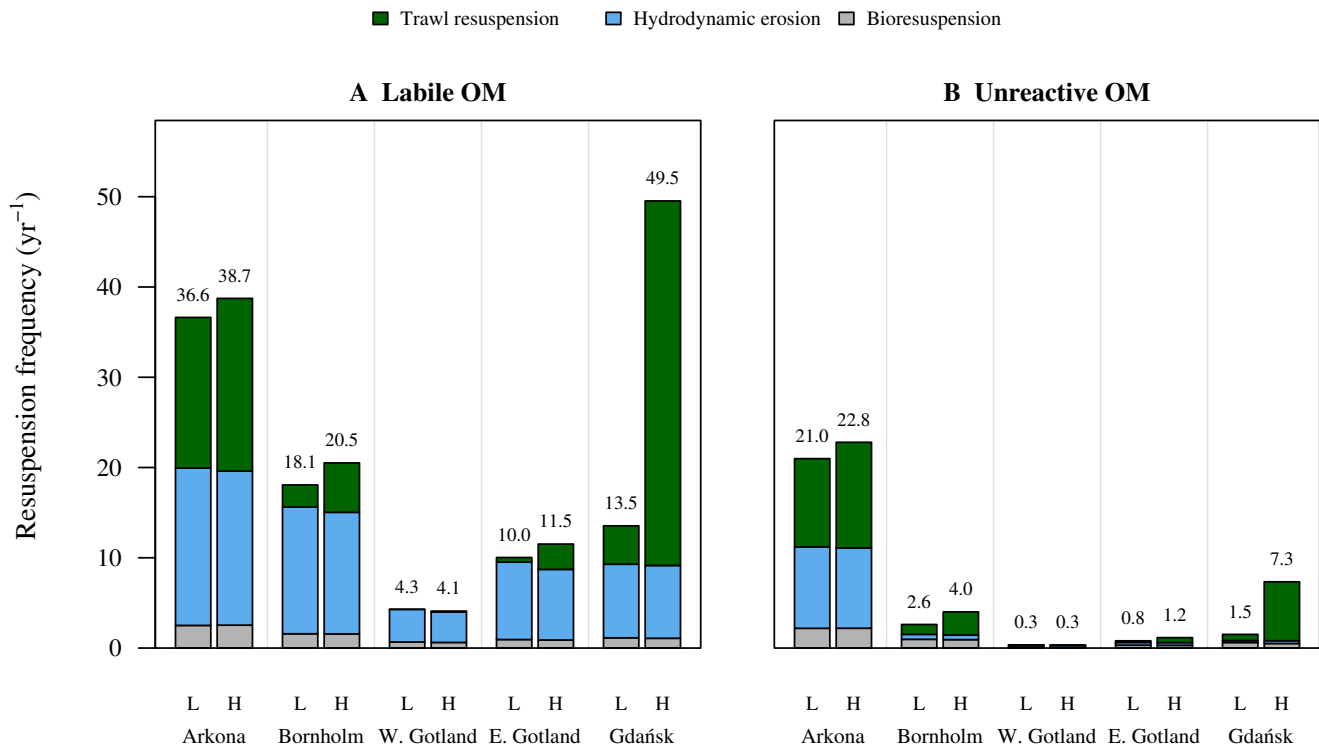


Figure 3. Resuspension frequencies of labile (A) and unreactive (B) organic matter (OM) driven by bottom trawling, hydrodynamic erosion, and bioresuspension over 1988–1997, calculated as described in Sect. 2.4. Letters L and H below the bars denote results from the low and high trawling estimate simulations, respectively, with each pair representing one region.

Whereas the preceding regional comparison considered differences between the low- and high-trawling estimate simulations, Table 1 examines spatial differences within the high-estimate simulation. Here, the model domain is divided into untrawled, low-trawling, and high-trawling areas based on trawling-induced resuspension intensity. These results confirm the contrasting



220 importance of the different resuspension mechanisms for labile and unreactive OM and show that the increase in water-column residence time (WCRT) followed the trawling-intensity gradient, with a markedly stronger response for unreactive than for labile OM (Table 1).

Table 1. Organic matter and phosphorus responses across spatial trawling-intensity classes in the high-resuspension estimate simulation, averaged over 1988–1997. Classes are defined by annual mean trawling-induced sediment resuspension as untrawled ($0 \text{ kg m}^{-2} \text{ yr}^{-1}$), low ($>0\text{--}1 \text{ kg m}^{-2} \text{ yr}^{-1}$), and high ($>1 \text{ kg m}^{-2} \text{ yr}^{-1}$).

	Units	Untrawled zones	Low-trawling zones	High-trawling zones
Area and trawling intensity				
Area	km^2	2.1×10^5	6.7×10^4	5.4×10^4
Area of study domain	%	63.1	20.6	16.3
Mean trawling sediment resuspension	$\text{kg m}^{-2} \text{ yr}^{-1}$	0.0	0.2	8.9
Labile organic matter				
Stock in trawling simulation	mol C km^{-2}	1.7×10^5	1.2×10^5	1.8×10^5
Stock change vs. baseline	%	+15.4	+20.0	+0.8
Water residence-time change vs. baseline	%	+0.6	+3.0	+16.7
Trawling resuspension frequency	yr^{-1}	0.0	1.0	20.7
Hydrodynamic resuspension frequency	yr^{-1}	12.9	17.3	4.6
Bioresuspension frequency	yr^{-1}	1.6	1.9	1.2
Unreactive organic matter				
Stock change vs. baseline	%	+0.7	+31.9	−10.8
Water residence-time change vs. baseline	%	+1.4	+25.3	+45.5
Trawling resuspension frequency	yr^{-1}	0.0	0.2	2.6
Hydrodynamic resuspension frequency	yr^{-1}	0.5	0.9	0.5
Bioresuspension frequency	yr^{-1}	0.4	0.5	0.7
Iron-bound phosphate				
Stock in trawling simulation	mol P km^{-2}	1.6×10^4	7.9×10^4	1.3×10^5
Stock change vs. baseline	%	+57.5	+96.9	−41.4



The effect of bottom trawling on WCRT varied among basins and between trawling estimates. Results for the relatively heavily trawled Arkona Basin using the low trawling estimate are shown in Fig. 4. The WCRT of labile OM showed no clear long-term trend and was increased by 13 % on average by trawling (Fig. 4). The WCRT of unreactive OM increased throughout the simulation, with trawling increasing WCRT by 27–53 %. The local standard deviations of WCRT of both labile and unreactive OM were of the same order of magnitude as their means (Fig. 4), indicating broad, right-skewed local residence-time distributions. Hence, a relatively small fraction of OM with long water-column residence times disproportionately increased the mean WCRT. Within the Arkona Basin (Fig. 4), labile OM spent 3.4 and 2.9 times longer in the fluff layer than in the water column in the baseline and trawling simulations, respectively. For unreactive OM, the corresponding ratios were 14.4 and 9.6 in the final simulation year. The sedimentary residence-time distribution of labile OM was strongly right-skewed, whereas that of unreactive OM was less skewed (Fig. 4).

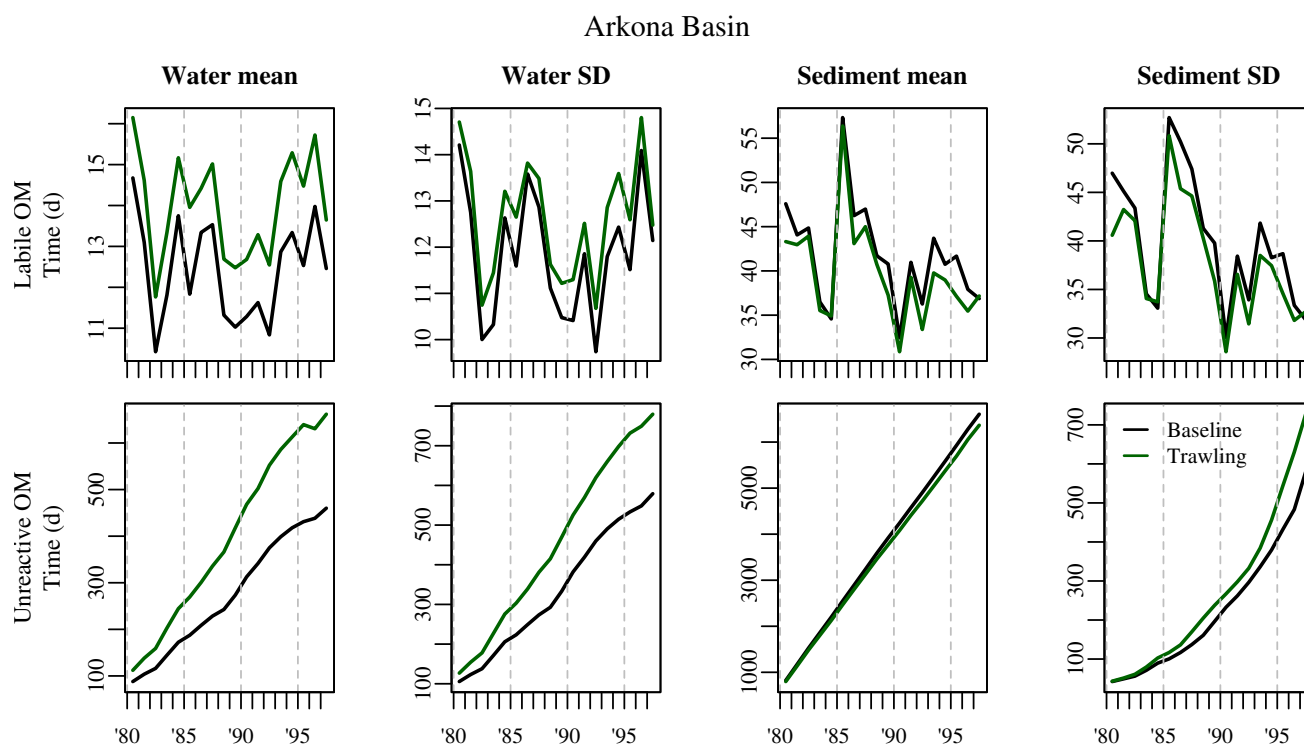


Figure 4. Mean residence times of labile and unreactive organic matter (OM) in the water column and fluff layer in the Arkona Basin for the baseline and low trawling estimate simulations. Standard deviations (SD) represent the spread in residence times within local OM populations.

The difference in mean OM depth between the trawling and baseline simulations is shown in Fig. 5 for the low and high trawling estimates. Mean depths were calculated over all grid cells experiencing at least some trawling activity (Fig. 2). As these cells differ substantially in bathymetry, hydrodynamics, and trawling intensity, the domain-wide mean is primarily used to



compare temporal trends and differences between labile and unreactive OM rather than its absolute magnitude. Labile detritus showed a strong annual pattern, with the trawling and baseline simulations generally converging in spring and diverging during the remainder of the year. Under the high trawling estimate, this seasonal redistribution was superimposed on a long-term increase in mean depth, becoming particularly pronounced after the late 1980s and reaching its largest difference in 1993. This long-term deepening was much weaker under the low trawling estimate, for which the difference in mean depth remained close to zero for much of the simulation and became negative toward its end. Unreactive OM was redistributed to greater mean depth during the first years of the simulation under both trawling estimates (Fig. 5), with substantially greater redistribution under the high estimate. Under the high trawling estimate, the difference from the baseline subsequently remained relatively constant, whereas under the low estimate it gradually declined from the late 1980s onward and converged with the baseline toward the end of the simulation.

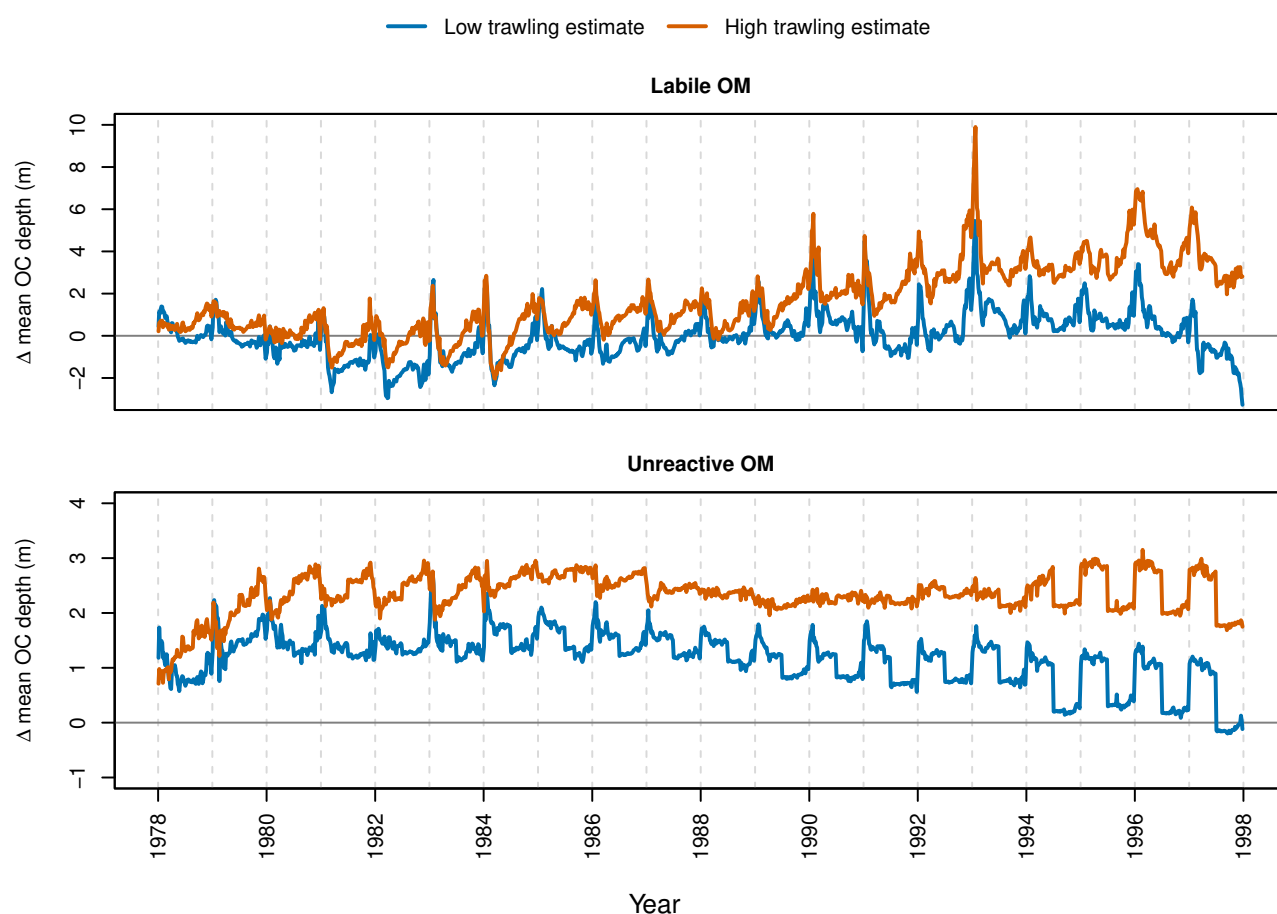


Figure 5. Changes in mean depth of labile (top) and unreactive (bottom) organic matter (OM) in the low and high trawling estimate simulations relative to the baseline simulation. Mean sedimentary OM depth was calculated as the OM-inventory-weighted mean water depth across trawled grid cells. Positive values indicate a greater mean OM depth in the trawling simulation than in the baseline simulation.



In heavily trawled areas, such as Gdańsk Bay, labile OM was depleted along the shallow coast and redeposited in the deeper central bay (Fig. 6AC). Despite this local depletion, bottom trawling led to higher labile OM concentrations on average compared with the baseline simulation. The redistribution was considerably stronger for unreactive OM (compare Fig. 6AC and BD), particularly in Gdańsk Bay and along the Eastern Gotland Basin coast extending northeastward from Gdańsk Bay, as well as in the northern Bornholm Basin. Unreactive OM was predominantly redeposited in nearby deeper areas (Fig. 6BD).

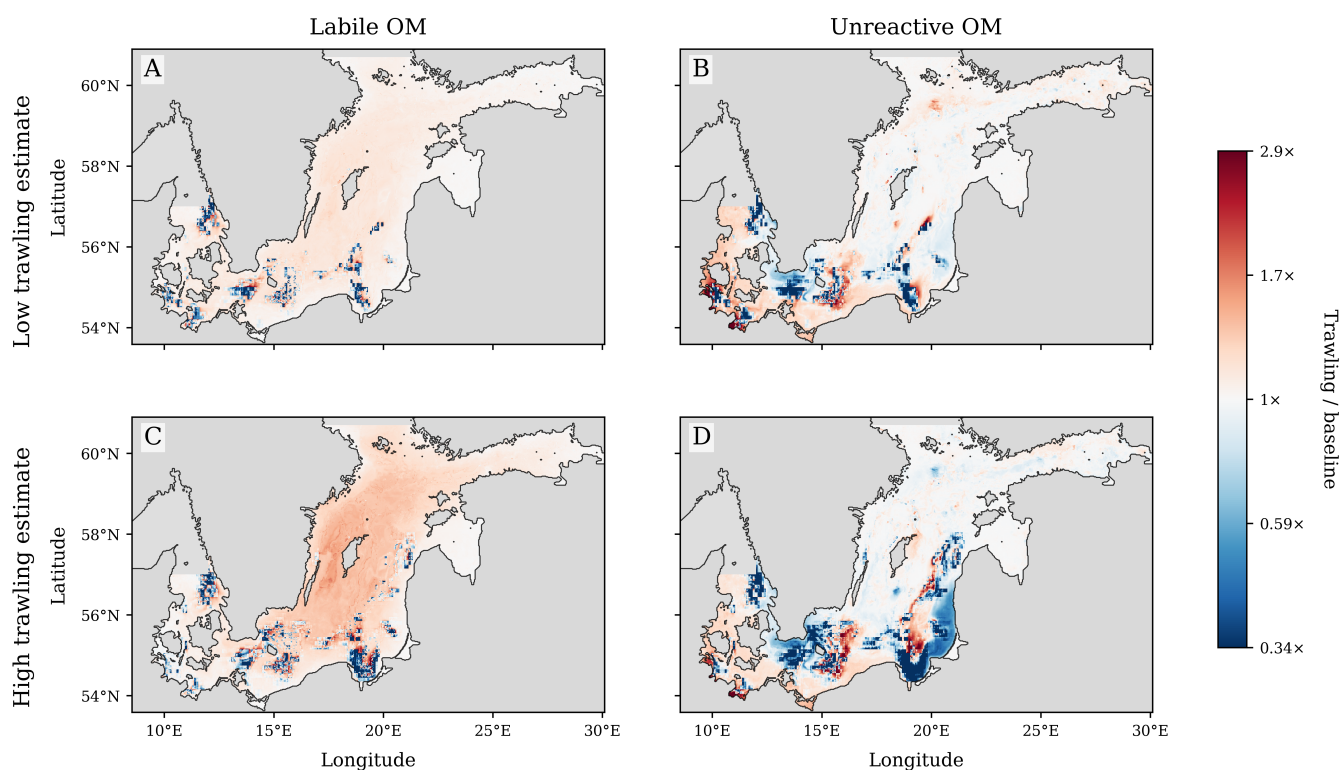


Figure 6. Changes in fluff-layer organic matter (OM) stocks relative to the baseline simulation at the end of the simulated period. The left and right columns show labile and unreactive OM, respectively, and the upper and lower rows show results from the low and high trawling estimate simulations, respectively. Values show the ratio of OM stocks in the trawling to the baseline simulation (see color bar).

Bottom trawling increased remineralization and phytoplankton biomass relative to the baseline simulation, with substantially larger increases under the high than the low trawling estimate (Fig. 7AC). The increase in remineralization occurred predominantly in the sediment and became more pronounced toward the end of the simulation under both trawling estimates (Fig. 7A). The main P pools were elevated relative to the baseline between 1980 and 1986, indicating a higher P inventory in the trawling simulations (Fig. 7B). From 1986 to 1995, sedimentary Fe-P was lower than in the baseline simulation under both trawling estimates; under the high estimate, this decrease coincided with a pronounced increase in dissolved P. From 1995 onward, sedimentary Fe-P approached the baseline under the low estimate, but increased above the baseline under the high estimate. Water-column Fe-P remained higher than in the baseline throughout the simulation under both trawling estimates.



The change in sedimentary Fe-P followed the trawling-intensity gradient, decreasing in highly trawled areas but increasing in areas with low or no trawling impact (Table 1). Primary production increased relative to the baseline simulation over the simulated period, reaching up to 12 % and 29 % under the low- and high-trawling estimates, respectively (Fig. 7C). Hypoxic and euxinic bottom area decreased over time in all simulations (Fig. 7D). This evolution was nearly identical in the baseline and low-trawling estimate simulations, whereas the decrease was slightly retarded in the high-trawling estimate simulation.

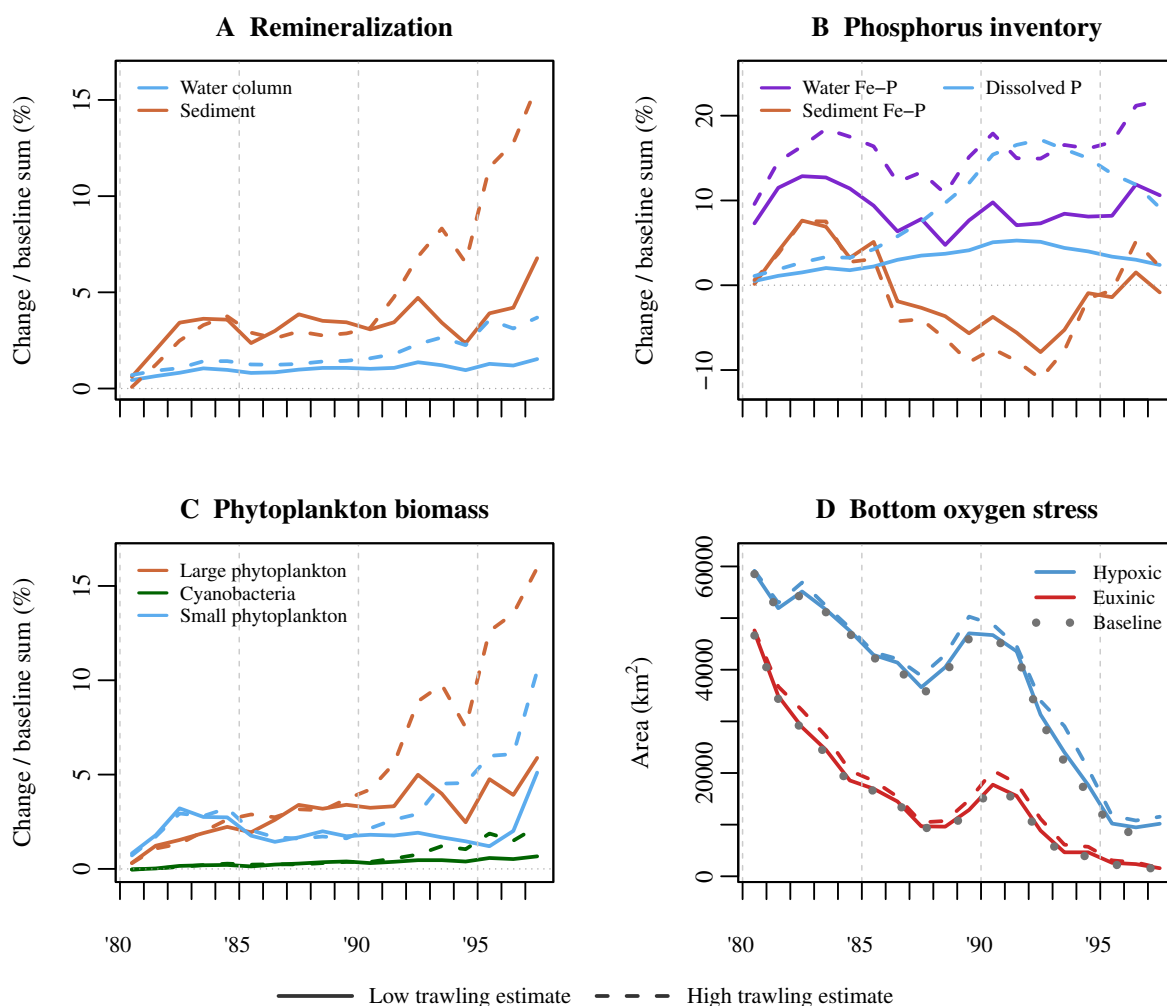


Figure 7. Time series of integrated remineralization rates (A), phosphorus inventory (B), phytoplankton biomass (C), and bottom-water areas experiencing oxygen stress (D). Solid and dashed lines show results from the low and high trawling estimate simulations, respectively (see lower legend); dotted lines in panel D show the baseline simulation. For panels A–C, annual mean differences between the trawling and baseline simulations for each component are expressed as a percentage of the sum of the corresponding components in the baseline simulation. In panel B, P denotes phosphate, and Fe-P denotes iron-bound phosphate.



4 Discussion

265 The simulation results provide insight into the sensitivity of the Baltic Sea to bottom-trawling. Below, we will discuss the ramifications of the increased OM-OET (Sect. 4.1), the redistribution of OM (Sect. 4.2), and the simulated biogeochemical feedback that led to increased sedimentary OM concentrations (Sect. 4.3).

4.1 Implications of bottom-trawling-induced resuspension for organic matter fate

As the model applies a similar description of detritus remineralization in the fluff layer and water column, resuspension has a
270 negligible direct effect on the mineralization rate per unit of organic carbon. Here, we therefore assess the potential effects of enhanced OM-OET a posteriori.

4.1.1 Implications from the model results

Bottom trawling emerged as a significant driver of labile-detritus resuspension in the heavily trawled Gdańsk Bay and Arkona Basin (Fig. 3A). Nonetheless, natural hydrodynamics contributed substantially to resuspension in all basins, including heavily
275 trawled areas (Fig. 3A), indicating that benthic communities and sedimentary OM in these environments are naturally exposed to recurrent resuspension. In contrast, unreactive OM was less frequently resuspended by hydrodynamics, with bottom trawling generally becoming the dominant resuspension mechanism (Fig. 3B). Hence, bottom trawling may particularly affect the fate of more refractory OM, for instance through changes in trophic state or priming.

The increase in the labile OM-OET appeared modest even in heavily trawled areas (Fig. 4; Table 1). The short half-life of
280 labile OM limits the number of times that it can be resuspended. In contrast, unreactive OM can be resuspended many times, whereby the effect of bottom-trawling keeps adding up to the WCRT (Fig. 4; Table 1). Consequently, if water-column exposure enhances OM degradation, the cumulative effect of bottom trawling could be greater for refractory than for labile OM, because labile OM is generally mineralized before undergoing repeated resuspension, whereas refractory OM can experience multiple trawling-induced resuspension events. However, the large local standard deviations, which exceed the mean WCRTs (Fig. 4),
285 indicate a strongly skewed response: a relatively small fraction of unreactive OM is resuspended repeatedly, whereas a large fraction is rarely or never resuspended, likely reflecting the large spatial variation in trawling intensity. Explicitly coupling enhanced degradation to water-column exposure would therefore produce a nonlinear response, as repeated exposure primarily depletes the frequently resuspended OM while leaving the remainder largely unaffected.

4.1.2 Comparison to previous studies

290 Recent studies have substantially reduced earlier estimates of trawling-induced OM mineralization by accounting for realistic sedimentary OM reactivity and disturbance timescales (Hiddink et al., 2023; Khedri et al., 2025). Even within this more conservative framework, however, the magnitude of the assumed effect of oxygen exposure on OM reactivity remains uncertain. Khedri et al. (2025) assumed that enhanced oxygen exposure increased the first-order mineralization constant by a factor of 1–5, uniformly sampled with a mean factor of 3, based on differences between oxic and anoxic OM reactivities compiled



295 by Katsev and Crowe (2015), which integrate various environmental controls and therefore cannot be interpreted directly as aerobic enhancement of OM mineralization. With respect to our study area, mineralization rates in the deep Gotland Basin showed no detectable decrease during transitions from oxic to anoxic water-column conditions (Schneider and Otto, 2019), while high OC mineralization rates have been measured in anoxic Baltic Sea sediments (Placitu et al., 2025).

Our results also highlight the importance of the reference state used to estimate additional OET. For labile OM in particular, an entirely undisturbed sediment neglects the substantial resuspension already caused by natural hydrodynamics (Fig. 3A). Hydrodynamic resuspension was less frequent for unreactive OM (Fig. 3B). However, along the trawling intensity gradient (Table 1), trawling-induced increases in WCRT remained modest, averaging less than 50 % even in high-impact areas. For unreactive OM, the relative WCRT increases correspond to absolute increases of 0.8, 16, and 42 days in the no-, low-, and high-impact areas, respectively, after approximately 15 years of trawling (Table 1). Much larger increases, on the order of
 305 hundreds of days, occurred locally in the intensively trawled Arkona Basin (Fig. 4).

To evaluate the relevance of these increases for carbon storage, they should be compared with OET accumulated naturally within sediments. Meile and Van Cappellen (2005) estimated an OET of approximately 200 days for organic carbon in an idealized shallow (20 m) sediment when accounting for bioturbative particle mixing, burial, and mineralization, despite an oxygen penetration depth of only 1 mm. This estimate also excludes bioirrigation, whereby benthic fauna transport oxygenated
 310 bottom water through burrows and other sediment structures, increasing O₂ penetration and OM-OET (Forster and Graf, 1995; Volkenborn et al., 2012). Thus, although trawling can strongly increase OET locally, its contribution appears modest over larger spatial scales in the Baltic Sea relative to natural drivers. In more heavily trawled areas, the modeled increase can nevertheless approach estimates of natural sedimentary OET that exclude bioirrigation, while the additional contribution of bioirrigation to OM-OET remains difficult to quantify.

315 The importance of bioturbation is also consistent with field observations showing that its effects on sediment mixing can be indistinguishable from those of bottom trawling (Forster et al., 2024; Rooze et al., 2024). Enhanced OET alone may therefore not provide a sufficient mechanistic explanation for reduced sedimentary OC following bottom trawling; observed OC depletion may partly reflect relocation of resuspended material rather than enhanced mineralization, as discussed in Sect. 4.2. However, Zhang et al. (2024) observed a shift in the relationship between OC and mud content in heavily trawled areas, suggesting that
 320 enhanced mineralization also plays a role.

4.2 Redistribution of organic matter caused by bottom-trawling

The results show distinct patterns for the redistribution of labile versus unreactive OM. For labile OM, there is a strong seasonal cycle, which is particularly clear in the average depth time series (Fig. 5). Bottom-trawling resuspended fresh detrital material produced during warmer seasons. Trawling-induced transport can either increase or decrease the average depth of labile OM, depending on the year (Fig. 5). This variability may reflect wind-driven circulation associated with upwelling and downwelling. During coastal upwelling, surface Ekman transport is offshore and is compensated by shoreward transport at depth (e.g., Masini et al., 2025). Trawling-induced resuspension can therefore result in either shoreward or offshore sediment transport, depending on prevailing circulation (Mengual et al., 2019).



During colder months, primary productivity is negligible. Given that the temperature-dependent half-life of labile sedimentary detritus is between 50 and 289 days under oxic conditions in the model, most will be respired before the next spring bloom occurs. Assuming primary production is similarly distributed in the trawling and baseline simulations, the spring and summer blooms lead to the same distribution of fresh sedimentary detritus in both simulations. Thus, the labile sedimentary detritus depth redistribution is reset in this sense each year (Fig. 5). The areas with stronger depletion and accumulation of labile OM are relatively near each other, which indicates transport over limited distances (Fig. 6AC). The relatively short transport distances are qualitatively consistent with Almroth-Rosell et al. (2011), who showed that natural resuspension of sedimentary OM with a mineralization half-life of ~ 4 yr primarily facilitated redistribution within individual sub-basins. Despite the annual resetting, our model also showed a long-term increase in the average depth and total amount of labile OM, particularly in the high-trawling simulation. This longer-term trend is discussed further in Sect. 4.3.

In contrast to labile OM, unreactive OM was located, on average, persistently at greater depth in the trawling simulations than in the baseline and showed only a weak annual cycle (Fig. 5). Unreactive OM can undergo many repeated resuspension cycles and hence be transported over greater distances. Accordingly, substantial transport also occurred between basins, such as export from Gdańsk Bay towards the Eastern Gotland Basin (Fig. 6BD). However, unreactive OM did not increase substantially in the deep basins, indicating that enhanced transport towards greater water depths does not necessarily result in increased deep-basin deposition. As OM reactivity decreases, its redistribution increasingly resembles that of fine sediment, allowing comparison with previous Baltic Sea sediment-transport simulations. Porz et al. (2023), for example, found that bottom trawling enhanced inter-basin sediment transport in the southwestern Baltic Sea, with finer, more slowly settling particles being transported over greater distances.

Trawling-induced erosion of the fluff layer exposes underlying sediment, whereas our model does not vertically resolve the sediment. Because the OM concentration of newly exposed sediment may be higher, lower, or similar to that of the eroded surface layer, modeled changes in fluff-layer OM concentrations (Fig. 6) should not be interpreted as corresponding changes in surficial sediment OM concentrations.

4.3 Biogeochemical feedbacks to bottom-trawling

4.3.1 Modeled biogeochemical feedback dynamics

Bottom-trawling increased labile detritus concentration in the Baltic Sea, particularly in the high trawling estimate simulation (Fig. 6C). This contrasts with the commonly assumed decline in OC stocks resulting from trawling (see introduction). However, labile detritus accounts for only a small fraction of the sedimentary OC stock, and ERGOM was not designed to capture long-term carbon preservation. Before this study, it only included labile OC; moreover, burial is parameterized independently of actual sedimentation, and modeled OC burial rates have not been calibrated against field data. Nonetheless, the enhanced primary production caused by bottom trawling increases OC input to the sediment. Whether this ultimately enhances long-term OC burial depends on how strongly primary production and burial are coupled, which cannot be assessed with the present model formulation.



The substantially stronger biogeochemical response in the high- than in the low-trawling estimate simulation (Figs. 6, 7) appears to originate to a large degree from differences in the prescribed trawling intensity in Gdańsk Bay (compare Figs. 2 and 6). Gdańsk Bay receives the Vistula, a large river draining into the Baltic Sea, resulting in high nutrient inputs and relatively OM-rich sediments and thereby making trawling-induced resuspension particularly consequential. Resuspended material from Gdańsk Bay and subsequently regenerated nutrients can furthermore be transported away from Gdańsk Bay (Fig. 6), extending the effect beyond the directly trawled area.

The enhanced primary production is mainly driven by trawling-induced resuspension of sedimentary Fe-P. Accordingly, sedimentary Fe-P decreases while water-column phosphate increases, particularly between 1985 and 1995 (Fig. 7B). Importantly, trawling also increases the total P inventory, indicating that the higher water-column phosphate does not merely reflect redistribution of P from the sediment to the water column. The spatial pattern provides insight into this reduced burial, as trawling redistributed Fe-P from areas with relatively high stocks to those with lower stocks (Table 1), thereby reducing the amount of Fe-P exceeding the fixed burial threshold in ERGOM. Since Fe-P does not react in the water column in ERGOM, the binding capacity is retained during resuspension. Hence, repeated resuspension of Fe-P reduces P burial and thereby retains more P within the active benthic-pelagic cycle, which is the main mechanism by which bottom trawling enhances primary production in the model.

The importance of P recycling for primary production in ERGOM was previously demonstrated by Börgel et al. (2023), who showed that faster sedimentary mineralization enhanced the upward P flux and thereby primary production. Their simplified 0-D box model captured the essence of how repeated recycling of P before burial can amplify primary production without an increase in external nutrient loading. Here, bottom trawling produces a related feedback by repeatedly resuspending sedimentary P and delaying its burial, thereby prolonging its residence in the active benthic-pelagic P system.

For the baseline simulation, there is a strong decrease in hypoxic and euxinic bottom area over the entire simulated period (Fig. 7D). The representation of historical oxygen dynamics in the MOM5-ERGOM model has been evaluated previously (Krapf et al., 2022; Neumann et al., 2022). Bottom-trawling only appears to slightly further slow down this recovery in the high trawling estimate simulation (Fig. 7D), despite significant changes in primary production (Fig. 7C). In the low trawling estimate simulation, the effect on hypoxic/euxinic bottom area is negligible. This suggests that changes in primary production caused by bottom trawling are small relative to the processes governing the decadal evolution of oxygen deficiency in the eutrophied Baltic Sea.

4.3.2 Comparison with previous studies and model limitations

Dounas et al. (2007) prescribed trawling-induced nutrient effluxes in a 3-D ecosystem model based on experimental measurements and predicted that the resulting nutrient regeneration enhanced annual net primary production (NPP) by 15 %. Hence, they already demonstrated how trawling-induced benthic nutrient release can affect pelagic productivity. In their oligotrophic Cretan Sea system, this response was primarily associated with enhanced nitrogen availability, whereas in our eutrophic Baltic Sea simulations it was driven by phosphorus recycling. Our simulations additionally identify repeated resuspension of sedimentary P and reduced burial as a mechanism sustaining this coupling over longer timescales.



Tiwari et al. (2025) likewise found that bottom-trawling can enhance basin-wide NPP by 0–8 % in a coupled North Sea ecosystem model, depending on the parameterization of trawling-induced resuspension. The potential increase in NPP was attributed to enhanced remineralization of resuspended particulate organic matter and subsequent transport of regenerated nutrients, particularly nitrate, into the euphotic zone. In our simulations, however, enhanced water-column remineralization of labile OM appears less important because benthic and pelagic labile detritus have similar reactivities and trawling in our analyzed domain is largely confined to shallow areas (Figs. 1, 2). Differences in nutrient limitation may further contribute to differences in the magnitude and mechanisms of the NPP response: nitrogen availability is an important control on North Sea NPP, whereas P recycling can strongly affect Baltic Sea production. In addition, Tiwari et al. (2025) did not include trawling-induced resuspension of Fe-P, whereas in our model, resuspension of Fe-P reduces P burial and prolongs P recycling, contributing to the stronger NPP response in our simulations.

The effect of bottom-trawling on nutrients has also been estimated with the 1-D, depth-resolved European Regional Seas Ecosystem Model (ERSEM) (Allen and Clarke, 2007). The model cannot represent physical sediment resuspension, but it includes a food web model that interacts with sediment biogeochemistry across several depth layers. Modeling by Allen and Clarke (2007) suggests that, particularly, mortality of filter feeders leads to sediment oxidation, increasing phosphate adsorption, which decreases phosphate efflux, opposite to our results. Another ERSEM study (van der Molen et al., 2013) also predicted decreased phosphate efflux due to trawling. Notably, this response to faunal mortality is not universal among models; other trawling models have represented macrofaunal mortality as a reduction in bioturbation, which would tend to reduce rather than enhance oxygen transport into the sediment (De Borger et al., 2021; Zhang et al., 2024). These contrasting responses reflect differences in process representation, particularly faunal controls on sediment oxygenation in ERSEM versus Fe-P resuspension in ERGOM.

Many studies have measured the response of phosphate efflux to trawling or natural resuspension. Mechanistically, one would expect at least an increase just after a resuspension event, as porewater gets flushed. Several studies support this (e.g., Durrieu de Madron et al., 2005); yet, some studies observed no significant change (e.g., Warnken et al., 2003; Almroth et al., 2009). The iron-bound phosphate pool far exceeds the dissolved sedimentary phosphate inventory and can be resuspended as particulate material. This mechanism agrees with observations by Laima et al. (2001), who linked resuspended particulate P to phosphate-bearing Fe oxides in the SW Baltic Sea.

Iron cycling is not explicitly resolved in ERGOM. Resuspended Fe-P remains particulate in the model and eventually re-settles, without altering the prescribed sedimentary phosphate-binding capacity. In reality, disturbance of the Fe-rich surface layer may transiently reduce phosphate sorption capacity, which may subsequently recover as surface sediment conditions readjust (Morys et al., 2021). Furthermore, resuspended Fe phases, including reduced Fe minerals such as pyrite, may undergo redox transformations during transport and can be reoxidized and redeposited as reactive Fe(III) phases under oxic conditions, potentially increasing phosphate sorption capacity.

The modeled reduction in P burial must be interpreted cautiously. Burial in ERGOM is parameterized independently of actual sediment accumulation and calibrated to water-column rather than sedimentary P profiles. Our 20-year simulations do not explicitly resolve the processes controlling long-term P burial, which depends on sediment accumulation, sedimentary



redox zonation, and the partitioning among P phases (Slomp et al., 2013; Kuliński et al., 2022). Rather, burial in this study represents removal of P from the active benthic-pelagic cycle. While ERGOM captures the dependence of sedimentary P retention on redox conditions, the effect of large-scale redistribution of Fe-P caused by resuspension on retention is less well constrained. Experiments nevertheless indicate that trawling can temporarily enhance phosphate efflux and shorten sedimentary P storage and recycling times (Morys et al., 2021; Laima et al., 2001). Thus, enhanced P cycling within the benthic-pelagic system is a plausible consequence of repeated trawling-induced resuspension.

5 Conclusion

In this study, we applied different estimates of bottom-trawling-induced resuspension in the Baltic Sea, reflecting large uncertainties in the underlying fishing-activity data. Bottom trawling can become a major driver of OM resuspension in heavily trawled basins, while the fate of resuspended OM strongly depends on its reactivity. Increased WCRTs were most pronounced for unreactive material that can undergo repeated resuspension cycles. Labile OM was redistributed over relatively short distances, whereas unreactive OM underwent greater cumulative transport. However, even these persistent fractions did not accumulate substantially in the deepest basins within the simulated period. Thus, our results do not support substantial transport of trawling-resuspended OM from shallow fishing grounds into deep oxygen-deficient basins as a mechanism exacerbating hypoxia.

Bottom trawling increased the WCRT of OM, particularly for unreactive OM in heavily trawled areas, although resuspension also transported OM away from trawling hotspots. Within the simulated period, the additional WCRT remained smaller than that associated with initial sinking and hydrodynamic resuspension, while its magnitude relative to sedimentary OET resulting from bioturbation and bio-irrigation remains uncertain.

Particularly interesting is the modeled increase in primary production caused by bottom trawling, which is linked to decreased sedimentary P sequestration in the model. Although experimental studies have shown that bottom-trawling may enhance benthic P efflux, uncertainty remains regarding its overall impact on P sequestration, which may also depend on trawling-induced changes in bioturbation and bio-irrigation and their effects on sedimentary redox conditions and, consequently, the availability of P-binding iron oxides.

Given the limited additional WCRT resulting from bottom trawling relative to other drivers enhancing OET and the increased detritus settlement resulting from enhanced primary production in the model, our results caution against assuming a simple causal chain from bottom trawling-induced oxygen exposure to enhanced OM mineralization and reduced carbon storage as a generally applicable response to bottom trawling. By capturing coupled benthic-pelagic feedbacks, ecosystem models provide a framework for assessing these interacting effects at the regional scale. Further development of depth-resolved sedimentary processes and benthic heterogeneity within such models could allow contrasting sedimentary and ecological environments to respond differently to bottom trawling and provide a more comprehensive assessment of its effects on marine carbon cycling.



Code and data availability. The ERGOM model code, processed data, and scripts required to reproduce the figures are available in version 1.0 of the repository accompanying this manuscript (Rooze et al., 2026), at <https://git.iow.de/rooze/bottom-trawling-ergom-baltic/releases/tag/v1.0>.

465 Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used ChatGPT (OpenAI) to improve language and readability. The authors take full responsibility for the content of the publication.

Author contributions. J.R. performed the modeling, extended ERGOM to include time tracers, and wrote the first draft. L.P. estimated sediment resuspension rates in the Baltic Sea. D.O. and C.v.D. contributed to providing and analyzing fishing data. T.N. contributed to
470 ERGOM model development. H.R. implemented trawling-induced resuspension and led the modeling component of the project. All authors discussed the results, reviewed the manuscript, and contributed to writing and editing. All authors approved the manuscript for submission.

Competing interests. The authors declare that they have no conflict of interest.

Acknowledgments

This research was funded by the German Federal Ministry of Education and Research (BMBF) grants 03F0848A and
475 03F0937A (MGF Baltic Sea projects). L.P. is supported by the collaborative project KomSO (grant 3523NK370A-E) coordinated by the German Federal Agency for Nature Conservation (BfN), and by the Helmholtz research programme POF IV “The Changing Earth – Sustaining our Future” within “Topic 4: Coastal zones at a time of global change”. We thank the MGF Ostsee consortium and Leibniz Institute for Baltic Sea Research Warnemünde (IOW) for valuable discussions and collaboration.



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