Dredging and dumping impact coastal fluxes of sediment and organic carbon

Lucas Porz
[redacted]
Helmholtz-Zentrum Hereon https://orcid.org/0000-0002-7761-9587
Jiayue Chen
Helmholtz-Zentrum Hereon
Rümeysa Yilmaz
Helmholtz-Zentrum Hereon https://orcid.org/0000-0001-8486-0937
Jannis Kuhlmann
BUND-Meeresschutzbüro, Bund für Umwelt und Naturschutz Deutschland e.V. (BUND)
Wenyan Zhang
Helmholtz-Zentrum Hereon https://orcid.org/0000-0002-6239-8312
Corinna Schrum
Helmholtz-Zentrum Hereon https://orcid.org/0000-0003-3251-4551

Article

Keywords:

Posted Date: February 20th, 2025

DOI: https://doi.org/10.21203/rs.3.rs-6005877/v1

Additional Declarations: There is **NO** Competing Interest.

Dredging and dumping impact coastal fluxes of sediment and organic carbon

Lucas Porz[1,*], Jiayue Chen[1], Ruemeysa Yilmaz[1], Jannis Kuhlmann[2], Wenyan Zhang[1], Corinna Schrum[1,3]

[1]Institute of Coastal Systems, Helmholtz-Zentrum Hereon, Max-Planck-Strasse 1, 21502 Geesthacht, Germany

[2]BUND-Meeresschutzbüro, Bund für Umwelt und Naturschutz Deutschland e.V. (BUND), Bremen, Germany

[3]Institute of Oceanography, Center for Earth System Research and Sustainability, Universität Hamburg, Bundesstrasse 53, 20146 Hamburg, Germany

*Correspondence to: Lucas Porz [redacted]

Abstract

The disturbance of coastal sediments by human activities constitutes a potentially large disruption to natural sediment and carbon fluxes, but large-scale estimates of these impacts are lacking thus far. Using data analysis and process-based numerical modelling, we estimate the amounts of sediment and organic carbon disturbed, as well as potential CO_2 released from North Sea sediments resulting from (1) dredging in the form of mineral aggregate extraction and (2) dumping of material dredged during waterway maintenance. Despite disturbing less sediment than aggregate extraction, dumping has a greater potential for carbon remineralization due to a higher organic carbon content in estuarine muds compared to subtidal sands and gravels. Overall, we estimate carbon disturbance by both activities to be 1-2 magnitudes higher than by marine construction, but 1-2 magnitudes lower than by bottom-contacting fisheries. Simulations show that most material dumped within the German Bight and Wadden Sea deposits within the coastal basins and intertidal areas after one year, the amount being similar in magnitude to natural sedimentation in that area. These results highlight the potential of human activities to shape long-term coastal morphology, and we argue that they should be considered in regional to global sediment and carbon budgets.

1. Introduction

As the interface between terrestrial and marine environments, coasts and marginal seas play an important role in regional to global sediment and carbon cycles, wherein the seafloor acts both as a zone of transformation and long-term sequestration[1]. Recently, various budget estimates have aimed to quantify coastal particle and solute fluxes on regional or global scales by accounting for natural processes such as river loads, coastal erosion, redistribution by ocean currents, and sedimentation[2–4]. Studies of anthropogenic impacts on these fluxes have largely been limited to effects related to watershed modifications such as river damming, channel deepening, and erosion due to changes in climate and land-use[5–10], as well as associated impacts on ecosystem production and elemental cycles[11,12]. In contrast, activities that cause direct mechanical disturbance and/or relocation of sediment have received little attention. When sediment is disrupted mechanically, organic matter within the suspension plumes can be transported, exposed to oxygenated waters and remineralized more readily than when trapped in the sediment, effectively increasing nutrient turnover rates and thereby reducing the efficacy of Blue Carbon ecosystems as natural nutrient and carbon pumps[13]. Additionally, seafloor disturbances can alter benthic habitats, with adverse impacts on ecosystem functions through changes to both macrobenthic and microbial communities[14–16].

Prevalent human activities with impacts on coastal Blue Carbon ecosystems include the construction of coastal and offshore infrastructure such as wind farms, cables, oil and gas platforms, and harbours[17,18], aggregate mining[19], bottom-contacting fisheries[20], and dredging and dumping[21,22]. It has been suggested that a considerable portion of the global net sediment flux is due to one or several of these activities. For example, the global mass of dredged and dumped material has been estimated to the order of 10 Gt annually[23], rivalling the export of riverine material to the coast in scale[24]. A similar magnitude has been estimated for the amount of sediment resuspended by bottom trawling fisheries on continental shelves[20]. It is thus evident that any holistic analysis of contemporary matter fluxes in the Earth system must account for direct human impacts on sediment disturbance.

In this study, we estimate the amounts of bulk sediment and organic carbon (OC) disturbed or relocated by dredging and dumping in the North Sea, a marginal sea under intense human pressures (Figure 1). We focus on two activities for which large-scale quantifications are lacking thus far: (1) aggregate extraction in the form of sand and gravel mining and (2) dumping of material originating from the dredging of waterways and harbours, or for beach nourishment or construction. Based on publicly available data and numerical simulations, we estimate amounts of disturbed bulk sediment and organic carbon and its potential remineralisation. We analyse the results with an emphasis on the Wadden Sea, Earth's largest tidal flat system that stretches along the Dutch, German, and Danish coasts. Dredging and dumping have been identified as main risks for maintaining the Outstanding Universal Value of the Wadden Sea World Heritage Site[25].

The amount of material extracted from the European seabed has increased drastically, by two orders of magnitude since the 1970's[26]. Aggregate extraction is typically conducted using suction dredgers that pump a sediment-water mixture from the seafloor into hoppers onboard the vessels. The suction heads themselves create resuspension plumes at the seafloor. On the vessels, the excess, sediment-laden water spills back into the ocean as overflow discharge. In addition, the mixture is often screened in the hoppers, that is, the unwanted, fine particulates filtered out. Along with the overflow discharge, this creates highly concentrated surface sediment plumes that can be detected up to several kilometres from the extraction sites[27]. These plumes contain most of the organic matter present in the dredged material, including fragmented benthic invertebrates[28]. Extraction sites are concentrated in the southern North Sea and at the Danish coast.

The majority of dumped material in the North Sea originates from maintenance dredging in navigation channels and harbour basins, with only a small amount of dredged material being disposed of on land[4]. Most dumping is concentrated at the southern North Sea coast near large ports such as those of Antwerp, Rotterdam, and Hamburg. Harbour sludge is typically rich in organic matter[29].

As a result of its relatively shallow depth (average 95 m) and energetic semi-diurnal tidal currents, the North Sea experiences strong benthic-pelagic coupling[30,31]. Therefore, sediment disturbances considerably affect the pelagic ecosystem and element cycles, particularly in the shallower southern North Sea (depths around 15-30 m), where the water column is mixed throughout most of the year, and where many coastal human activities are concentrated.

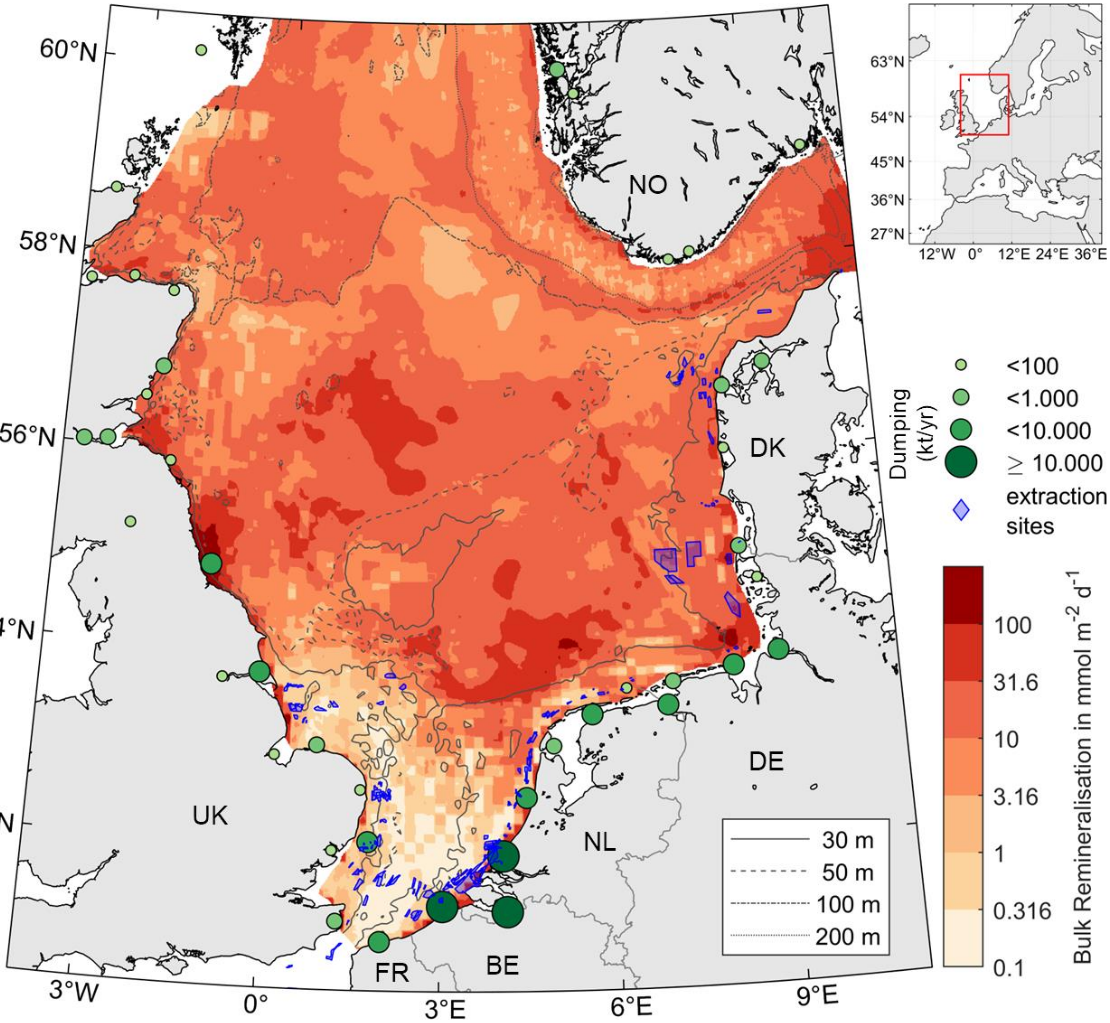


Figure 1. Study area in the North Sea with dredging and dumping locations. Annual bulk dumping activity averaged for 1995-2021 (green circles), and marine aggregate extraction areas (blue polygons). For visual representation, dumping amounts were cumulated on a 1°×1° grid and the dumping site coordinates for each grid cell averaged. Colour scale shows modelled sediment carbon mineralization rates. Projection: Albers Equal-Area Conic.

2. Results

2.1. Aggregate extraction

In total, an order of 100,000 kt of marine aggregates in the form of sand and gravel are extracted each year in the North Sea for use in construction, land reclamation, and beach nourishment, albeit with considerable inter-annual variability (Figure 2). In 2009 and 2010 years, the amount more than doubled compared to the multi-year average.

The sudden increase in extraction starting in 2009 coincides with large coastal engineering efforts with high raw material requirements, such as the construction of the deep sea harbour *JadeWeserPort* in Germany in 2009 and the Dutch sand engine, a large beach nourishment effort completed in 2011[32]. This indicates that individual projects can be responsible for the bulk of the disturbance through aggregate extraction.

The average concentration of sediment OC at the extraction sites is 0.10%. We estimate the recent amount of annually disturbed organic carbon from aggregate extraction in the North Sea to the order of 100 kt. In our model, 87% of this disturbed OC constitutes the refractory fraction, which is unlikely to be remineralized following disturbance, while 10.0% and 3.0% of OC are semi-labile and labile, respectively, and therefore more readily degraded, resulting in a potential OC short-term remineralisation on the order of 50 kt CO_2e/yr for the North Sea. For comparison, the recent fuel emissions of the European dredging fleet was estimated at 600-800 kt CO_2e/yr according to an industry report[33]. Nevertheless, it is important to note that the refractory OC fraction is not fully inert, and may be made more bioavailable when exposed to oxygen, especially when mixed with more labile compounds[34]. Therefore, the longerterm potential of aggregate extraction to cause excess OC remineralization may indeed be somewhat higher, but should not exceed the order of a few hundred kt CO_2e/yr.

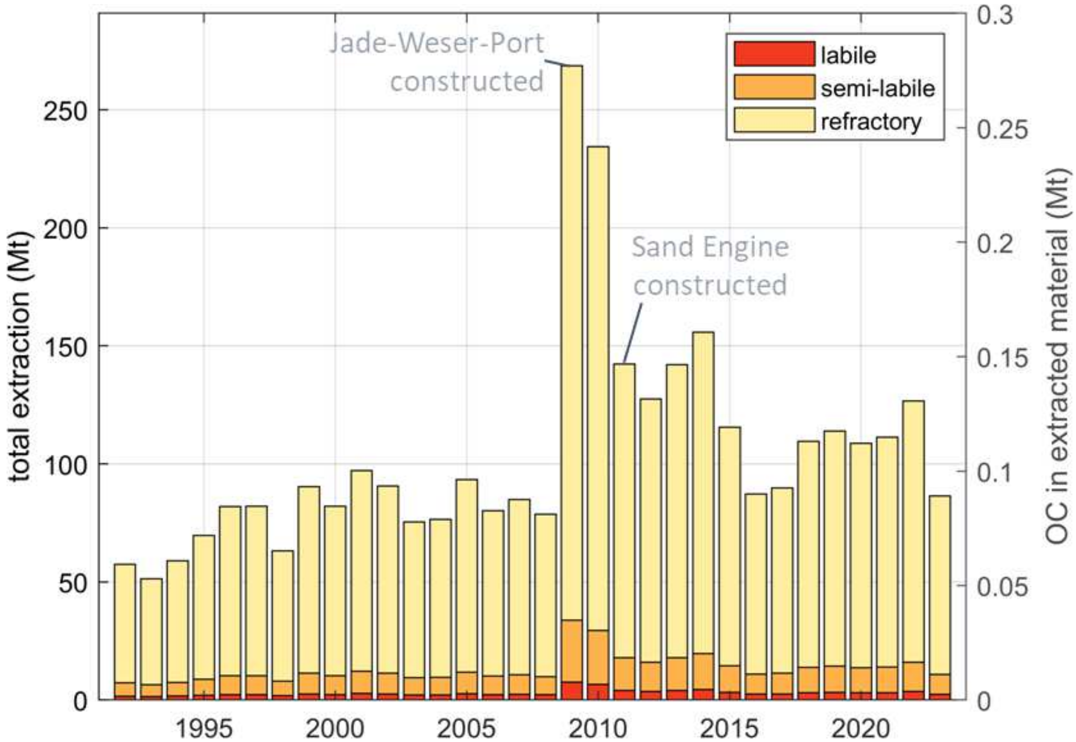


Figure 2. Time series of aggregate extraction in the North Sea. Total extracted amounts over time (left axis) with estimates of the disturbed sedimentary OC of different labilities according to the numerical model (right axis).

2.2. Material dumping

Recent dumping of dredged material in the North Sea is reported at 50,000-100,000 kt/yr. Despite interannual variance, the data show no clear trend during the past decades, with the apparent onset of increase after 2008 attributable to the inclusion of data from the UK in that year. Our estimate for the amount of organic carbon contained in dumped material is in the range of 500-5,000 kt/yr, reflecting the uncertainty in the OC content of dumped material (Figure 3b).

In our dumping simulations, a large portion of the dumped material remains close to the coast in both simulations with slowly sinking and more rapidly sinking tracers (Figure 4). However, the slowly sinking tracers distribute more toward the northeast along the direction of the residual circulation, while the rapidly sinking tracers stay closer to the dumping locations. This is especially apparent in the shallow English Channel, where the slowly sinking material is nearly completely winnowed by strong currents, while the quickly sinking particles remain in place even after one year. At the end of the simulation year 2012, 99.6% (92.3%) of the slowly (rapidly) sinking dumped OC is deposited on the seabed, while the remainder of 0.4% (7.7%) is in suspension in the water column. Of the material dumped within the German Bight and the Wadden Sea area, 59.4% (68.6%) remain within the Wadden Sea World Heritage area, and 25.3% (38.8%) deposits within the 24 German Wadden Sea basins[35]. Notably, 22.0% (34.0%) deposits at depths of <1.5 m, which corresponds to the mean low water level in the Wadden Sea and is roughly equivalent to its intertidal zone.

The amount of bulk sediment deposited in the Wadden Sea in the model after one year is on the order of 8,000 kt, which is the same magnitude as total mud deposition in the Wadden Sea[4]. This suggests that dumping can be as important for the internal distribution of mud in the Wadden Sea as natural sedimentation processes.

Estimating the potential remineralisation and corresponding climate impact of dumped material is complicated by technical and conceptual challenges. Firstly, a large proportion of the dumping sites are located within estuaries (Figure 3a), where it is quickly transported back into the estuaries by tidal pumping as part of the residual estuarine circulation within a short period of time, and after which it may be dredged and dumped again. Our simulations mirror this phenomenon, where a large part of dumped material deposits in the intertidal zone. This means that the same material can be redeposited several times throughout the year and would thus be double billed in the total quantities shown in Figure 3b, even if the sediment budget of the overall system remained unchanged. Nevertheless, the simulations give an indication of the overall transport patterns of dumped OC.

Secondly, the lability, i.e. the mineralisation rate of the OC in the dumped material, is largely unknown. Although it has been shown that large estuaries and harbour basins such as those of the Elbe act as efficient bioreactors and thus OC exported from the estuary is largely inert and slowly microbially degraded[36], dredged material may still be at the beginning of the mineralisation process and can therefore contain labile OC[37]. Nevertheless, our results allow an estimate of the upper limit of remineralisation of around 1,000 kt CO_2e/yr, assuming that no more than 10% of the dumped OC is remineralized following dredging and dumping, which is about the maximum amount of oxic remineralisation found in a 21-day incubation experiments using mud from the port of Hamburg[37]. The fact that such a large amount of dumped material accumulates in the intertidal area may be significant since it has been shown that aerially exposed harbour sludge emits CO_2 at a rate ~4 times faster than when permanently inundated[38].

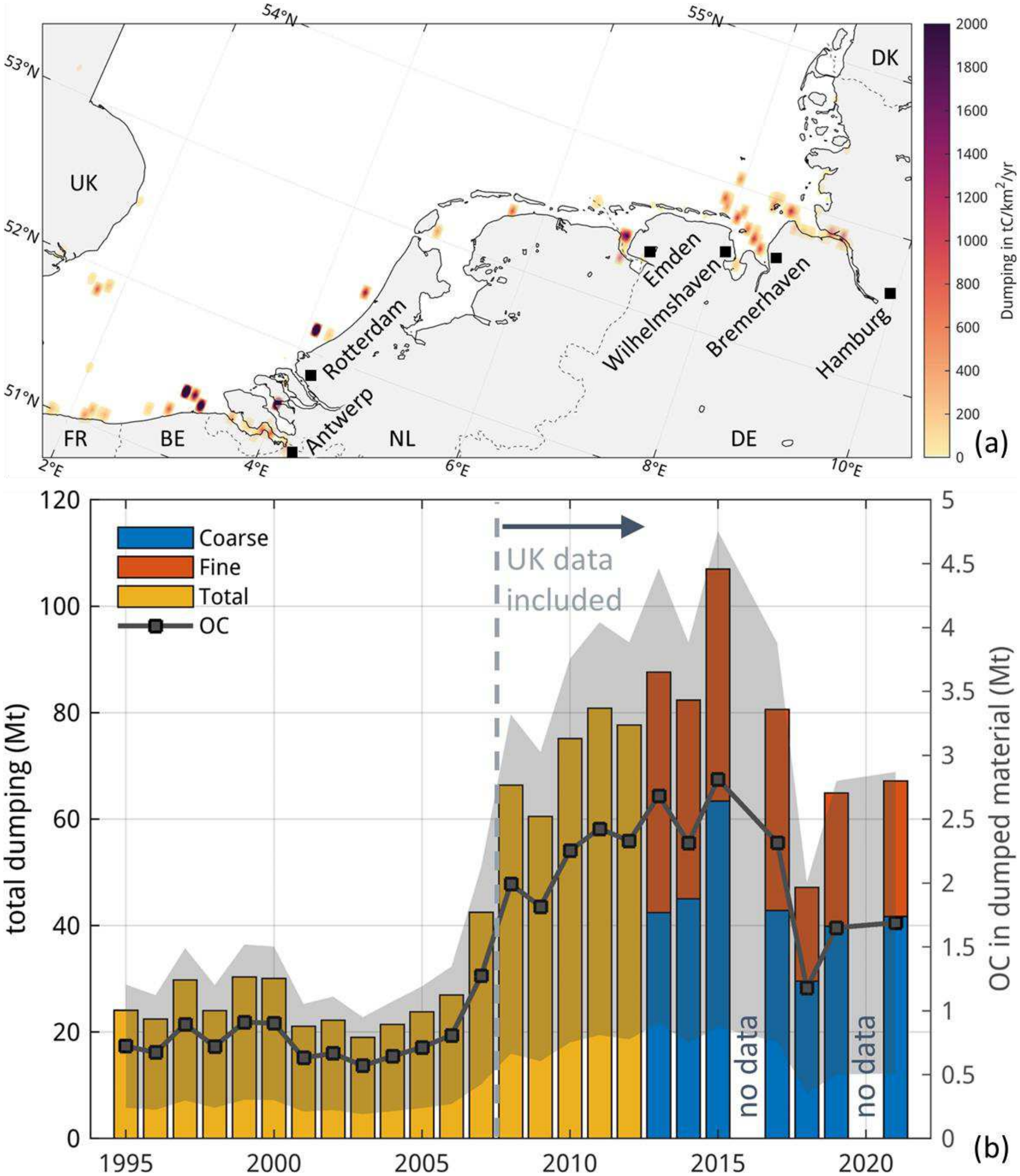
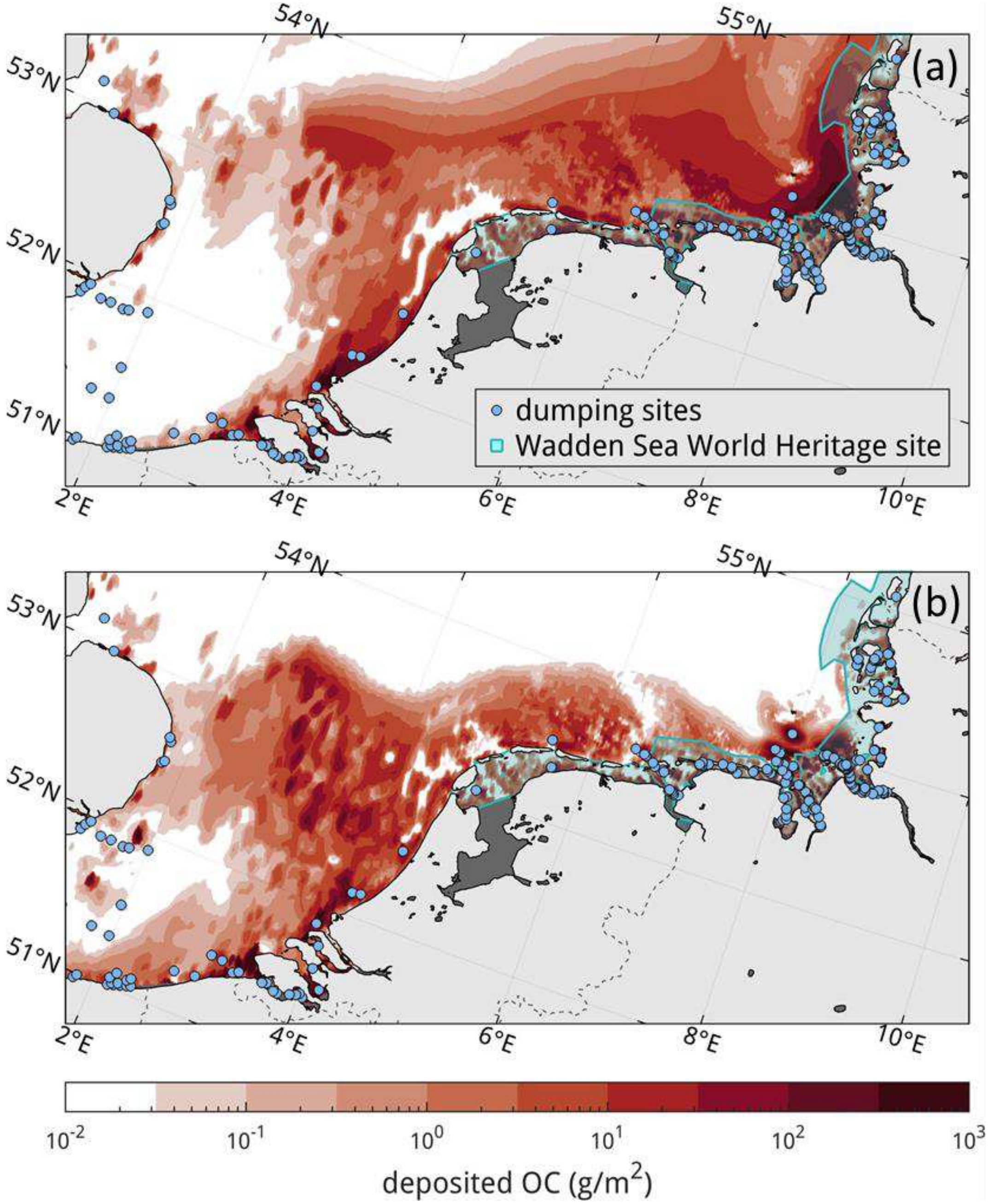


Figure 3. Distribution and amount of material dumping in the North Sea. (a) Southeastern North Sea coast with estimated dumped OC densities cumulated on a 3'×3'- grid and the locations of large ports (projection: oblique Mercator), (b) Dumped bulk amounts in the entire North Sea over time (left axis) and estimate of dumped organic carbon (right axis) with ranges indicated in grey shading based on OC contents in dumped material of 2-8% (average: 5%) and 0-2% (average: 1%) in the fine and coarse fractions, respectively.



165 Figure 4. Dumping simulation results. Spatial distribution of dumped sediment OC in the southeastern North Sea area after one year of continuous dumping with particle sinking velocities of (a) 0.05 mm/s and (b) 1 mm/s are shown. Note the logarithmic colour mapping. Dumping locations are marked as blue circles and Wadden Sea World Heritage site in blue shading. Areas in dark grey are not included in the model domain. Projection: oblique Mercator.

2.3. Comparison to other impacts

Table 1 lists the estimated impacts on sediment and OC in comparison to other sediment-disturbing activities for which estimates have been compiled. For the North Sea, the largest total net impact on OC turnover is from bottom-contacting fisheries, estimated to the order of 1,000 kt CO_2e/yr[39,40]. However, this impact has decreased during the last decade with an overall decrease of fishing effort in the area due to declining fish stocks and fishing quotas.

Most prominent among on-going marine infrastructure construction is the deployment of vast offshore windfarms in coastal waters globally. The initial disruption during the placement of pile foundations and cables is followed by an equilibration phase during which the ecosystem adjusts to the newly formed artificial reef, and by a decommissioning phase, during which additional sediment disturbance may occur. For commissioned and planned offshore wind farms in the southern North Sea, OC disturbance was estimated at 400 kt and remineralization at 400 ktCO_2 during wind turbine construction and decommissioning[17]. For a typical twenty-year life cycle of wind turbines, this is equivalent to 20 ktC/yr and 20 ktCO_2/yr, respectively, somewhat less than our estimated impact for aggregate extraction and substantially less than bottom-contacting fisheries and dumping. In addition, positive artificial reef effects outweigh the initial loss during pile construction, resulting in a net positive impact of offshore wind on OC sequestration on the order of 50 ktC/yr in additional uptake[17]. A similar magnitude has been estimated for OC disturbance due to installation of subsea communication cables[18].

A comparison to human impacts on riverine fluxes is not straight-forward, since contrasting effects on riverine export to the coast have been determined, with increased solute fluxes due to changing climate and land use and decreased particulate fluxes due to retention by damming. In addition, riverine nutrient loads may play a more important role for the coastal carbon cycle than direct carbon exports by enhancing primary production and thereby increasing biological carbon fixation[12]. Nevertheless, considering the total OC export from rivers in the entire North Sea of around 1,000 ktC/yr[41] along with global estimates for effect of damming (13% decrease[42]) and of European climate and land use change (20% increase[7]) brings the human impact on direct riverine export of OC to the order of 100 ktC/yr, which is smaller than disturbances by both bottom-contacting fisheries and dumping, and similar to the disturbance by aggregate extraction.

Table 1. Coastal ocean sediment and organic carbon disturbances in comparison. Estimated magnitudes of direct human impacts on bulk sediment disturbance, sediment organic carbon disturbance and potential sediment carbon remineralization in the North Sea are listed with recent (decadal) and projected trends denoted as stagnant (→), increasing (↑), or decreasing (↓).

Impact	Sediment disturbance (kt/yr)	Organic carbon disturbance (ktC/yr)	Organic carbon remineralization (ktCO_2e/yr)	Recent trend	Projected trend	Sources
Bottom-contacting fisheries	10^6	10^4	10^3	↓	n.a.	[39,40]
Dumping	10^4	10^2–10^3	10^2–10^3	→	↑	This study
Aggregate extraction	10^5	10^2	10^1–10^2	→	↑	This study
Offshore wind farm construction/ decommissioning*	n.a.	10^1	10^1	↑	↑	[17]
Subsea telecommunication cable installation**	n.a.	10^2	10^1	↑	↑	[18]

*Southern North Sea only, assuming ~25% of disturbed carbon is remineralized[17]

**assuming 2 orders of magnitude lower impact than trawling[18]

3. Discussion

We show that dredging and dumping can impact the morphodynamics of coastal zones of the North Sea at the same magnitude as natural processes of erosion and sedimentation. Based on these results, we argue that in heavily managed systems, no sediment or carbon budget can be complete without consideration of the direct human impacts. The same likely applies to many densely populated coastal regions globally. Examples of other seafloor impacts that have been observed, but for which large-scale quantifications of corresponding sediment and carbon fluxes are yet to be quantified, include anchor dragging, mooring and ore mining[43,44].

In terms of carbon disturbance and associated potential climate impact, the most substantial impacts in the North Sea are assessed, in descending order of magnitude, as follows: bottom-contacting fisheries, material dumping, aggregate extraction, and marine construction. However, this sequence is subject to change in the coming decades, as certain activities such as wind farm construction increase at a rapid pace, while others, such as fishing, have shown decreasing trends. Additionally, sea level rise is expected to enhance the sediment deficit in coastal regions such as the Wadden Sea, which will require additional dredging and sand nourishment to prevent the drowning of coastal landscapes[45]. Likewise, dumping of harbour mud is projected to increase with increasing ship sizes, requiring deeper and wider navigation channels[46].

While this study gives first estimates of the magnitudes, further studies gauging impacts of sediment-disturbing activities on the overall carbon cycle should include resolving indirect effects, such as changes to ecosystem production and benthic-pelagic coupling. For example, metabolic processes may generate not only dissolved inorganic carbon, but also alkalinity, which under some circumstances can strengthen the coasts role as a carbon sinks[47].

4. Methods

4.1. Aggregate extraction data

Data on 217 existing extraction areas[48] and extraction mass and/or volume[26,48,49] from 1992-2023 was analysed. Only extraction areas with a status classified as "Active" were considered, and a large shell extraction area spanning a large stretch of the Dutch coast was excluded from analysis.

In cases where extraction amounts were given in volume, they were converted to mass using the averaged porosity of all extraction sites of 0.36 and a grain density of 2,650 kg/m³. Porosity was derived by interpolation of more than 2,000 sediment samples collected in the region[50]. The amount of OC impacted was calculated for three OC classes of different labilities based on results of a numerical model (see Sect. 4.3). As an exact colocation of extracted amounts to extraction sites was not possible for all data points, we assumed that the extracted amount was evenly distributed across all extraction sites. For the same reason, it was not always possible to distinguish between extracted amounts inside and outside of the North Sea for the UK, Denmark, Germany, France, and Norway. Therefore, the total amounts may be overestimated since they also contain extraction from the English Channel and the Baltic, Irish and Celtic Seas. However, since the largest extraction sites are located within the North Sea, and the largest amounts by far are extracted from the Dutch coast, we do not expect this to affect the magnitude of our estimate.

4.2. Dumping data

Dumping data[51] compiled by the OSPAR commission were analysed for information on dumping locations and quantities, containing data for 1995-2021, except for the years 2016 and 2020, as well as information on material composition (such as grain size) starting 2013. Beach nourishment has been included in monitoring efforts starting from 2013. No data for the UK is contained before 2008, and activities in Denmark and Norway appear from 2013.

Individual activities for which no deposit amounts were specified were ignored in further processing. Deposited amounts were located using deposit site codes for the years 2014, 2015, 2017-2019, and 2021 and filtered for the North Sea area. For the latter three years, no deposit site codes are included for activities in Denmark, and for 2018, no deposit site codes are included for some activities in Belgium, preventing a location of those activities. Though grain size was not specified for those activities, nearly all of them were classified as land reclamation, beach nourishment or construction, indicating that this dumped material comprised coarse-grained sediment. In total, 11.2, 3.2 and 1.6 Mt of dumping are omitted in the years 2018, 2019 and 2021, respectively, amounting to a few percent of the multi-year average.

Because of the heterogenous nature of dumping data documentation, dumped material was categorized into three types based on sediment descriptions in the data: "coarse" for sand and coarser material (22.0% of activities), "fine" for silt and finer material (12.8% of activities), and "mixed" for mixtures of coarse and fine material (13.4% of activities). Sediments with no sediment type information (51.7% of all activities) were categorized as "mixed" (see Table S2 for details).

An OC content of 2-8% and 0-1% was assumed in the fine and coarse fraction, respectively, based on the composition of harbour muds sampled at the port of Hamburg[29].

4.3. Numerical models

We use a suite of process-based numerical models to (1) simulate the amounts and labilities of organic carbon in the seabed to gauge the impacts of aggregate extraction and (2) simulate the distribution of dumped material.

The first is the Total Organic Carbon Macrobenthos Interaction Model (TOCMAIM)[52], which accounts for OC lability through three sediment classes with different degradation rate constants. This model applies the phyto-detritus fields of the NPZD-type ecosystem model ECOSMO [53] to assign fresh input of OC at the seafloor, where it is consumed and mixed vertically by bioturbating macrobenthos and degraded through microbial respiration. The model is run for 63 years, at which point a quasi-equilibrium between the OC lability classes has established. There is a strong seasonal signal of fresh (highly labile) OC at the seafloor surface following the phytoplankton blooms, most of which is remineralized by the end of the year. Therefore, we use the end-of year fields of the year 2013 and average the OC lability contents over the upper 30 cm, corresponding to the typical depth of furrows observed following trailer head suction dredging[54,55] .

The second model is a 3D coupled hydrodynamics and sediment transport model based on the SCHISM modelling system[56]. The validated setup covers the entire Northwest European shelf[57], and the spatial resolution of the unstructured model grid was increased in the Wadden Sea and the German Bight in order to adequately represent the flow dynamics there[58]. The resolution in the German Bight ranges from 0.7

km to 5 km and is around 1 km in the Wadden Sea area with local refinements at complex features such as flow-confining channels.

For a representative picture of recent activities, dumping was assumed to be continuous and the dumping volumes since 2014 were averaged over time. Based on the estimated dumped OC amounts and assuming an average OC content of 5% in the dumped material, dumping was implemented as an additional constant source of water and sediment at the sea surface at each model grid cell nearest to each dumping location. For each location, dumped water volumes (in m^3/s) were assigned as

$$V_{\mathrm{dump}} = \frac{M_{\mathrm{dump,OC}}}{C}, \tag{1}$$

where $M_{\mathrm{dump,OC}}$ (in kg/s) is the average OC dumping rate according to our estimate (see Sect. 4.2), and C (in kg/m^3) is the corresponding sediment concentration of the mixture, calculated to a constant value of

$$C = \frac{\rho_W \cdot \rho_S}{\rho_W + \rho_S \cdot WC} = 296\,\frac{\mathrm{kg}}{\mathrm{m}^3}, \tag{2}$$

where $WC = 300\%$ is the water content of bulk sediment (expressed as weight water per weight dry bulk sediment) based on measurements in estuarine muds[37], $\rho_W = 1{,}000\ \mathrm{kg/m^3}$ is the water density and $\rho_S = 2650\ \mathrm{kg/m^3}$ is the average sediment grain density.

Some dumping points are located within estuaries that are outside of the model domain, accounting for about 20% of the total dumped amount, and these dumping sites are not considered in the model.

The dynamic behaviour of dumped material is not well known. In the model, OC is treated as a mass-conservative, sinking tracer with a constant sinking speed of 0.05 mm/s (see Table S2 for details).

However, in natural suspensions, particles with high organic matter content form larger aggregates at high concentrations with significantly higher sinking velocities[59]. Therefore, a sensitivity experiment was carried out with a sinking rate increased by a factor of twenty to account for the possible influence of aggregation. We simulate one full year of dumping using hydrographic conditions of 2012.

References

1. Dunne, J. P., Sarmiento, J. L. & Gnanadesikan, A. A synthesis of global particle export from the surface ocean and cycling through the ocean interior and on the seafloor. *Global Biogeochem. Cycles* **21**; https://dx.doi.org/10.1029/2006GB002907 (2007).
2. Tegler, L. A. *et al.* Distribution and Drivers of Organic Carbon Sedimentation Along the Continental Margins. *AGU Advances* **5,** e2023AV001000; https://dx.doi.org/10.1029/2023AV001000 (2024).
3. Legge, O. *et al.* Carbon on the Northwest European Shelf: Contemporary Budget and Future Influences. *Frontiers in Marine Science* **7**; https://dx.doi.org/10.3389/fmars.2020.00143 (2020).
4. Colina Alonso, A. *et al.* A mud budget of the Wadden Sea and its implications for sediment management. *Communications Earth & Environment* **5,** 153; https://dx.doi.org/10.1038/s43247-024-01315-9 (2024).
5. Syvitski, J. P. M., Vörösmarty, C. J., Kettner, A. J. & Green, P. Impact of Humans on the Flux of Terrestrial Sediment to the Global Coastal Ocean. *Science* **308,** 376–380; https://dx.doi.org/10.1126/science.1109454 (2005).
6. Bianchi, T. S. *et al.* Anthropogenic impacts on mud and organic carbon cycling. *Nature Geoscience* **17,** 287–297; https://dx.doi.org/10.1038/s41561-024-01405-5 (2024).
7. Zhang, H. *et al.* Global changes alter the amount and composition of land carbon deliveries to European rivers and seas. *Communications Earth & Environment* **3,** 245; https://dx.doi.org/10.1038/s43247-022-00575-7 (2022).
8. Regnier, P. *et al.* Anthropogenic perturbation of the carbon fluxes from land to ocean. *Nature Geoscience* **6,** 597–607; https://dx.doi.org/10.1038/ngeo1830 (2013).
9. Grasso, F., Bismuth, E. & Verney, R. Unraveling the impacts of meteorological and anthropogenic changes on sediment fluxes along an estuary-sea continuum. *Scientific reports* **11,** 20230; https://dx.doi.org/10.1038/s41598-021-99502-7 (2021).
10. Mazarrasa, I., Garcia-Orellana, J., Puente, A. & Juanes, J. A. Coastal engineering infrastructure impacts Blue Carbon habitats distribution and ecosystem functions. *Scientific reports* **12,** 19352; https://dx.doi.org/10.1038/s41598-022-23216-7 (2022).

11. Bauer, J. E. *et al.* The changing carbon cycle of the coastal ocean. *Nature* **504,** 61–70; https://dx.doi.org/10.1038/nature12857 (2013).

12. Mathis, M. *et al.* Enhanced CO2 uptake of the coastal ocean is dominated by biological carbon fixation. *Nature Climate Change* **14,** 373–379; https://dx.doi.org/10.1038/s41558-024-01956-w (2024).

13. Keil, R. Anthropogenic Forcing of Carbonate and Organic Carbon Preservation in Marine Sediments. *Annu. Rev. Mar. Sci.* **9,** 151–172; https://dx.doi.org/10.1146/annurev-marine-010816-060724 (2017).

14. Kenny, A. J. *et al.* Assessing cumulative human activities, pressures, and impacts on North Sea benthic habitats using a biological traits approach. *ICES J Mar Sci* **75,** 1080–1092; https://dx.doi.org/10.1093/icesjms/fsx205 (2018).

15. Todd, V. L. G. *et al.* A review of impacts of marine dredging activities on marine mammals. *ICES J Mar Sci* **72,** 328–340; https://dx.doi.org/10.1093/icesjms/fsu187 (2015).

16. Bonthond, G. *et al.* Benthic microbial biogeographic trends in the North Sea are shaped by an interplay of environmental drivers and bottom trawling effort. *ISME Commun* **3,** 132; https://dx.doi.org/10.1038/s43705-023-00336-3 (2023).

17. Heinatz, K. & Scheffold, M. I. E. A first estimate of the effect of offshore wind farms on sedimentary organic carbon stocks in the Southern North Sea. *Front. Mar. Sci.* **9**; https://dx.doi.org/10.3389/fmars.2022.1068967 (2023).

18. Clare, M. A., Lichtschlag, A., Paradis, S. & Barlow, N. L. M. Assessing the impact of the global subsea telecommunications network on sedimentary organic carbon stocks. *Nature Communications* **14,** 2080; https://dx.doi.org/10.1038/s41467-023-37854-6 (2023).

19. Goedefroo, N. *et al.* Understanding the impact of sand extraction on benthic ecosystem functioning: a combination of functional indices and biological trait analysis. *Frontiers in Marine Science* **10**; https://dx.doi.org/10.3389/fmars.2023.1268999 (2023).

20. Oberle, F. K. J., Storlazzi, C. D. & Hanebuth, T. J. What a drag: Quantifying the global impact of chronic bottom trawling on continental shelf sediment. *J. Mar. Sys.* **159,** 109–119; https://dx.doi.org/10.1016/j.jmarsys.2015.12.007 (2016).

21. Palanques, A., Guillén, J., Puig, P. & Durán, R. Effects of long-lasting massive dumping of dredged material on bottom sediment and water turbidity during port expansion works. *Ocean & Coastal Management* **223,** 106113; https://dx.doi.org/10.1016/j.ocecoaman.2022.106113 (2022).

22. van de Velde, S. J., van Lancker, V., Hidalgo-Martinez, S., Berelson, W. M. & Meysman, F. J. R. Anthropogenic disturbance keeps the coastal seafloor biogeochemistry in a transient state. *Scientific reports* **8,** 5582; https://dx.doi.org/10.1038/s41598-018-23925-y (2018).

23. Cooper, A. H., Brown, T. J., Price, S. J., Ford, J. R. & Waters, C. N. Humans are the most significant global geomorphological driving force of the 21st century. *The Anthropocene Review* **5,** 222–229; https://dx.doi.org/10.1177/2053019618800234 (2018).

24. Syvitski, J. P. & Kettner, A. Sediment flux and the Anthropocene. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* **369,** 957–975; https://dx.doi.org/10.1098/rsta.2010.0329 (2011).

25. Common Wadden Sea Secretariat (CWSS). Report on the State of Conservation of the World Heritage property "The Wadden Sea (N1314)", https://www.waddensea-worldheritage.org/2024-report-state-conservation-world-heritage-property-wadden-sea-n1314 (2024).

26. ICES. Working Group on the Effects of Extraction of Marine Sediments on the Marine Ecosystem (WGEXT). ICES Scientific Reports (2019).

27. Spearman, J. A review of the physical impacts of sediment dispersion from aggregate dredging. *Marine Pollution Bulletin* **94,** 260–277; https://dx.doi.org/10.1016/j.marpolbul.2015.01.025 (2015).

28. Newell, R., Hitchcock, D. & Seiderer, L. Organic Enrichment Associated with Outwash from Marine Aggregates Dredging: A Probable Explanation for Surface Sheens and Enhanced Benthic Production in the Vicinity of Dredging Operations. *Marine Pollution Bulletin* **38,** 809–818; https://dx.doi.org/10.1016/S0025-326X(99)00045-4 (1999).

29. Zander, F., Groengroeft, A., Eschenbach, A., Heimovaara, T. J. & Gebert, J. Organic matter pools in sediments of the tidal Elbe river. *Limnologica* **96,** 125997; https://dx.doi.org/10.1016/j.limno.2022.125997 (2022).

30. Jago, C. F. & Jones, S. E. Observation and modelling of the dynamics of benthic fluff resuspended from a sandy bed in the southern North Sea. *Cont. Shelf Res.* **18,** 1255–1282; https://dx.doi.org/10.1016/S0278-4343(98)00043-0 (1998).

31. Couceiro, F. *et al.* Impact of resuspension of cohesive sediments at the Oyster Grounds (North Sea) on nutrient exchange across the sediment–water interface. *Biogeochemistry* **113,** 37–52; https://dx.doi.org/10.1007/s10533-012-9710-7 (2013).

32. Stive, M. J. *et al.* A New Alternative to Saving Our Beaches from Sea-Level Rise: The Sand Engine. *Journal of Coastal Research* **29,** 1001–1008; https://dx.doi.org/10.2112/JCOASTRES-D-13-00070.1 (2013).

33. European Dredging Association (EuDA). Annual Report 2023, https://european-dredging.eu/pdf/EuDA_23.pdf (2023).

34. Sanches, L. F., Guenet, B., Marino, N. d. A. C. & de Assis Esteves, F. Exploring the Drivers Controlling the Priming Effect and Its Magnitude in Aquatic Systems. *J Geophys Res Biogeosci* **126,** e2020JG006201; https://dx.doi.org/10.1029/2020JG006201 (2021).

35. Benninghoff, M. & Winter, C. Recent morphologic evolution of the German Wadden Sea. *Scientific reports* **9,** 9293; https://dx.doi.org/10.1038/s41598-019-45683-1 (2019).

36. Gebert, J. & Zander, F. Aerobic and anaerobic mineralisation of sediment organic matter in the tidal River Elbe. *Journal of Soils and Sediments* **24,** 2874–2886; https://dx.doi.org/10.1007/s11368-024-03799-6 (2024).

37. Zander, F., Heimovaara, T. & Gebert, J. Spatial variability of organic matter degradability in tidal Elbe sediments. *Journal of Soils and Sediments* **20,** 2573–2587; https://dx.doi.org/10.1007/s11368-020-02569-4 (2020).

38. Paranaíba, J. R. *et al.* CO2, CH4, and N2O emissions from dredged material exposed to drying and zeolite addition under field and laboratory conditions. *Environmental Pollution* **337,** 122627; https://dx.doi.org/10.1016/j.envpol.2023.122627 (2023).

39. Porz, L. *et al.* Quantification and mitigation of bottom-trawling impacts on sedimentary organic carbon stocks in the North Sea. *Biogeosciences* **21,** 2547–2570; https://dx.doi.org/10.5194/bg-21-2547-2024 (2024).

40. Zhang, W. *et al.* Long-term carbon storage in shelf sea sediments reduced by intensive bottom trawling. *Nature Geoscience*; https://dx.doi.org/10.1038/s41561-024-01581-4 (2024).

41. Thomas, H. *et al.* The carbon budget of the North Sea. *Biogeosciences* **2,** 87–96; https://dx.doi.org/10.5194/bg-2-87-2005 (2005).

42. Maavara, T., Lauerwald, R., Regnier, P. & van Cappellen, P. Global perturbation of organic carbon cycling by river damming. *Nature Communications* **8,** 15347; https://dx.doi.org/10.1038/ncomms15347 (2017).

43. Watson, S. J. *et al.* The footprint of ship anchoring on the seafloor. *Scientific reports* **12,** 7500; https://dx.doi.org/10.1038/s41598-022-11627-5 (2022).

44. Feldens, P., Schwarzer, K., Sakuna-Schwartz, D. & Khokiattiwong, S. Geomorphological Evolution of the Andaman Sea Offshore Phang Nga Province (Thailand) during the Holocene: An Example for a Sediment Starving Shelf. *Coasts* **2,** 1–16; https://dx.doi.org/10.3390/coasts2010001 (2022).

45. Hofstede, J. L. A. & Stock, M. Climate change adaptation in the Schleswig-Holstein sector of the Wadden Sea: an integrated state governmental strategy. *Journal of Coastal Conservation* **22,** 199–207; https://dx.doi.org/10.1007/s11852-016-0433-0 (2018).

46. Cronin, M., Judd, A., Blake, S. & Lonsdale, J. Assessment of Data on the Management of Wastes or Other Matter (Dredged Material) 2008 - 2020. In *The 2023 Quality Status Report for the North-East Atlantic* (London, 2023).

47. Norbisrath, M. *et al.* Metabolic alkalinity release from large port facilities (Hamburg, Germany) and impact on coastal carbon storage. *Biogeosciences* **19,** 5151–5165; https://dx.doi.org/10.5194/bg-19-5151-2022 (2022).

48. AZTI. EMODnet Human Activities, Aggregate Extraction (rev. of 2023-09-15). Available at https://ows.emodnet-humanactivities.eu/geonetwork/srv/api/records/fde45abd-7bf3-4f05-869c-d1ce77f4ac63?language=all-4f05-869c-d1ce77f4ac63 (2014).

49. Walker, R. *et al.* Effects of extraction of marine sediments on the marine environment 2005-2011. ICES Cooperative Research Reports (CRR), https://ices-library.figshare.com/articles/report/Effects_of_extraction_of_marine_sediments_on_the_marine_environment_2005-2011/18624086 (2016).

50. Bockelmann, F.-D., Puls, W., Kleeberg, U., Müller, D. & Emeis, K.-C. Mapping mud content and median grain-size of North Sea sediments – A geostatistical approach. *Mar. Geol.* **397,** 60–71; https://dx.doi.org/10.1016/j.margeo.2017.11.003 (2018).

51. OSPAR Commission (OSPAR). Dumping and Placement of Wastes or Other Matter at Sea. Data Source: OSPAR Data and Information Management System. Available at https://odims.ospar.org/en/submissions/ospar_dumping_at_sea_2021_01/ (2021).

52. Zhang, W. *et al.* The Budget of Macrobenthic Reworked Organic Carbon: A Modeling Case Study of the North Sea. *J. Geophys. Res. Biogeosci.* **124,** 1446–1471; https://dx.doi.org/10.1029/2019JG005109 (2019).

53. Daewel, U. & Schrum, C. Simulating long-term dynamics of the coupled North Sea and Baltic Sea ecosystem with ECOSMO II: Model description and validation. *J. Mar. Sys.* **119-120,** 30–49; https://dx.doi.org/10.1016/j.jmarsys.2013.03.008 (2013).

54. Birchenough, S. N., Boyd, S. E., Vanstaen, K., Coggan, R. A. & Limpenny, D. S. Mapping an aggregate extraction site off the Eastern English Channel: A methodology in support of monitoring and management. *Estuarine, Coastal and Shelf Science* **87,** 420–430; https://dx.doi.org/10.1016/j.ecss.2010.01.005 (2010).

55. Kenny, A. J. & Rees, H. L. The effects of marine gravel extraction on the macrobenthos: Results 2 years post-dredging. *Marine Pollution Bulletin* **32,** 615–622; https://dx.doi.org/10.1016/0025-326X(96)00024-0 (1996).

56. Zhang, Y. J., Ye, F., Stanev, E. V. & Grashorn, S. Seamless cross-scale modeling with SCHISM. *Ocean Model.* **102,** 64–81; https://dx.doi.org/10.1016/j.ocemod.2016.05.002 (2016).

57. Kossack, J., Mathis, M., Daewel, U., Zhang, Y. J. & Schrum, C. Barotropic and baroclinic tides increase primary production on the Northwest European Shelf. *Front. Mar. Sci.* **10**; https://dx.doi.org/10.3389/fmars.2023.1206062 (2023).

58. Chen, J. *et al.* Physical mechanisms of sediment trapping and deposition on a spatially confined mud depocenter in a high-energy shelf sea. *ESS Open Archive*; https://dx.doi.org/10.22541/essoar.173924131.11557916/v1 (2025).

59. Winterwerp, J. C. On the flocculation and settling velocity of estuarine mud. *Cont. Shelf Res.* **22,** 1339–1360; https://dx.doi.org/10.1016/S0278-4343(02)00010-9 (2002).

60. Zhang, W. Modelled benthic oxygen flux for the German Bight, v2. Available at https://doi.org/10.17632/2vvny3xd85.2 (2021).

61. Zhang, W. Field and Model Data for Bottom Trawling Impacts in the North Sea. Available at https://doi.org/10.5281/zenodo.8297751 (2023).

Acknowledgments

This study is a contribution to the project APOC funded by the German Federal Ministry of Education and Research (BMBF) within the MARE:N program (grant 03F0874C) and to the collaborative project KomSO (grant 3523NK370A-E) funded by the German Federal Agency for Nature Conservation (BfN). It is also supported by the Helmholtz research program POF IV "The Changing Earth – Sustaining our Future" within "Topic 4: Coastal zones at a time of global change". This work used resources of the German Climate Computing Centre (DKRZ) granted by its Scientific Steering Committee (WLA) under project ID bg1244. We thank Ulrike Hanz and Enpei Li for fruitful discussions.

Materials & Correspondence

Correspondence to: Lucas Porz (lucas.porz@hereon.de)

Author Contribution

LP and WZ conceptualized the study. WZ and CS acquired funding for the projects leading to the study. LP and JC designed the numerical model experiments and processed the outputs. LP, RY and JK analysed the data. LP drafted the manuscript in consultation with all co-authors.

Competing interests

The authors declare that they have no competing interests.

Code availability

The SCHISM model including the sediment module is available at https://github.com/schism-dev. The TOCMAIM model is available at ref. [60].

Data availability

Aggregate extraction polygons available at ref. [48], extracted amounts from refs. [48], [49],[26], with data of the latter extracted from the WGEXT dashboard at https://rconnect.cefas.co.uk/content/a8a6ece2-deb9-477c-b74b-b2f31652c213/ (last accessed 23.01.2025). Dumping sites and amounts from ref. [51]. Modelled OC pools of different labilities are available at ref. [61]. Wadden Sea World Heritage site boundaries available from http://marineregions.org/mrgid/26877 (last accessed 23.01.2025).

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- Dumpdredgencommsuppl.pdf