Reply to RC1 *(Responses in italics)*

General comments

Porz et al., conducted a modelling study which uses coupled 3D hydrodynamic simulations with a bioturbation model to look at trawling impacts in the North Sea. I think this may be the most holistic and up to date research on this topic that I've seen. Most studies on this topic have just looked at the direct impact of trawling on sediment carbon within a trawl track and some look at how that effect might evolve through time. This study looks at the potential fate of OC once resuspended and shows how trawling can lead to lower OC in some areas and more OC in other areas (something observed in field observations before as well). Furthermore, I was happy to see that in the simulations regarding fisheries closures, trawling effort was redistributed rather than assumed to have decreased. All the praise aside, I think the manuscript still has areas of improvement, most of which I've outlined below. My main concern is that, although, I've seen it mentioned throughout the paper, it was never clear to me exactly how remineralization was addressed by the model. For me, the parts about the removal of OC through resuspension and redistribution to other areas was better explained but I would like to know exactly in the methods, your assumptions on benthic mineralization after trawling as well as once resuspended. It is stated in the discussion that OC is degraded once resuspended but I would like to see further details behind this like how much mineralization decreased/increased (both in the water column and in the sediment) and why.

> *Thank you for the constructive comments that have helped us to clarify and improve our manuscript.*
>
> *We will extend the methods section to include more details on the model description. The degradation rate of each OC pool decreases with sediment depth to reflect the decrease in oxygen availability, and the maximum (oxic) remineralization rate is applied at the uppermost sediment layer (i.e. at the sediment-water interface) as well as to the OC suspended in the water column. We will adapt the methods section 2.1 to explain more clearly how OC degradation is implemented in the model. In addition, we will explain the mechanisms behind trawling resuspension on OC in the model more clearly in the results section 4.1.*

Detailed comments

L11 There are reasons why 3D hydrodynamic models provide much needed insight on this topic but this is not yet clear to the reader. It would be nice to transition from the debate amongst scientists to something like "However, current discussions around the fate of resuspended organic matter are lacking. To help resolve this, we used 3D hydrodynamic… "

> *Good point, this will be added to the abstract.*

L25 is there anything that could be said about what makes these sediments vulnerable? High labile OC/biomass, low natural disturbance etc.?

> *Yes, we defined vulnerability in terms of OC lability in the study, so this will be added to the abstract.*

L30 so does this give reason to advocate for spatial as opposed to effort management?

In the context of carbon and habitat protection, our results may be used to argue in this direction. However, this is only one consideration for fisheries management, which has mostly prioritized prevention of overfishing. In addition, our results do not account for possible changes in catches following spatial effort redistribution. To prevent misunderstandings and considering the other reviewer's caution not to overstate our results, we prefer not to advocate for specific management strategies here.

L49 "seabed destruction" is vague and perhaps too loaded of a term here. Can you be more specific?

Rephrased to "Efforts to maintain or improve benthic ecosystem health (…)".

L70 What I'm missing here are explicit reasons 'why' 3D hydrodynamic models may be useful to this topic. The fate of OC was touched on earlier in the introduction but it would be nice to make it clear to the reader here that while some OC will be mineralized by trawling, some will be resuspended and redeposited (I do see it is touched upon later on). Maybe state things about 'how most models do not take into account resuspension and are thus not able to 'track' the fate of OC particles. This study aims to reconcile this through the use of 3D hydrodynamic model.'

Agreed, this will be added to the introduction.

Introduction in general: It would be helpful to have some information on potential mechanisms affecting OC dynamics. What causes trawl induced CO2 release? What causes CO2 sequestration in sediments. How does trawling potentially increase mineralization (like though O2 exposure from resuspension) or benthic mineralization? What is the role of macrofauna on these processes?

Added: "The premise of those studies is that the remineralization of OC to CO_2 through respiration by benthic biota is inhibited so long as the OC is trapped in sediment layers under low-oxygen conditions, and that mechanical disturbance will increase oxygenation of that OC, thereby causing a net increase in subaqueous CO_2 emissions from the sediment."

Fig 1. Instead of italics, are able to use bold or colored text? That would make the words "pop" out more and make things more obvious to readers.

Font will be changed to bold.

Table 1. In De Borger et al., 2021 we always found reduced total remineralization (the paper is mentioned under studies that show 'increased remineralization'). There are a few instances of increased oxic mineralization (also with relative changes) but never an increase in total mineralization in that study. Morys et al., 2021 also showed lower rather than higher mineralization (lower benthic respiration as a proxy) as well as Bradshaw et al., (2021) which was not included in the table.

Table 1 is meant to describe the overall effect on sediment OC without distinguishing between benthic and water column remineralization. We will change the first impact in the table to "Depletion of surficial sedimentary OC" to clarify this and include the reference to Bradshaw et al. (2021) in the table.

Methods

L116 as the other models were named, can you please also give the name of some more details for this ecosystem model.

> *Details of the ECOSMO model will be added.*

L158 Metiers provide more detail than gear types as they account for differences within gear types (mesh size, target species etc.). Perhaps rephrase as readers might see the first sentence (not differentiating between gear types) and become critical without understanding what a metier is.

> *Rephrased: "As the GFW data does not distinguish between specific trawled gear types, a gear type is assigned to each vessel at the vessel's average position according to the dominant métier defined by Eigaard et al. (2016; data in ICES, 2019). A métier groups …"*

L246 It's not clear to me that this methodology reflects accurate mixing rates from trawling yet. Is this sentence aiming to state that the mixing coefficients are similar to measured trawled areas? The sentence talks about expected bioturbation which makes me think that the mixing coefficients are just similar to that of high bioturbation by fauna. Skeptical readers may want some more evidence stating how this method of calculating trawl induced mixing reflects real conditions. (Perhaps just rephrasing is necessary).

> *We will split the sentence for clarity. The first part is meant to give the reader an idea of the overall impact expected from trawl mixing by comparing it to a natural process.*
>
> *A validation of this approach is complicated both by the scale problem explained in the first paragraph of the subsection, and because, to our knowledge, trawl mixing has never been quantified based on in-situ measurements. Therefore, we compare our mixing coefficients to those found in a sediment core of a heavily trawled area (Spiegel et al., 2023), where the authors argue that bioturbation cannot account for the strong mixing rate and attribute it to trawling. This explanation will be added to the text.*

L305 Experts will understand the logic for looking only at oxic mineralization as this increases relative to anoxic mineralization after trawling. Many readers may not know that so perhaps add a sentence stating that and why anoxic mineralization is not taken into account.

> *Added: "…, assuming that aerobic microbial respiration is the dominant process for OC remineralization when in contact with oxygenated water."*

Methods general: Perhaps I missed it but what I failed to find was how you explicitly account for changes in mineralization in sediments that were trawled. You may have a relative increase in oxic mineralization but we have found that the total mineralization decreases in sediments after trawling as OM is removed from the system. Deposition of OM from trawling may increase total mineralization as it introduces new OM to a system (though the the opposite can also happen if it smothers benthic fauna). Mineralization in the water column also increases. I see that Table 1 shows the effects considered but it's not clear to me how reduced respiration and increased mineralization are specifically incorporated.

The methods section will be adapted to explain this more clearly. Most of the effects mentioned occur in the model: Macrobenthic respiration scales with biomass, so benthos depletion will reduce that respiration rate. Trawling resuspension temporarily increases water column mineralization due to higher OC content in the water, and can decrease bulk benthic mineralization if the leftover benthic OC is of lower lability. Resuspended labile OC tends to degrade quickly, so even if some of it is redeposited, its effect on benthic rates is not obvious in the model. (See also our response to the previous comment on Table 1). Note that these effects were not explicitly prescribed, but occurred "automatically" as a consequence of the trawling impacts in the process-based model.

Also, I'm not sure where you link the resuspended sediment from trawling to the hydrodynamic model to see where resuspended sediment and OC ends up. It seems like the model takes into account natural resuspension but the link with trawling resuspension is not clear to me.

This link is detailed in 2.3.1. Sediment resuspension: "The daily trawling resuspension rate calculated according to Eq. (3) is added to the natural hydrodynamic resuspension rate at each model time step. (...) The resuspended sediment is distributed evenly over the bottom layer of entire grid cell, where it can be mixed upwards by turbulence and advected horizontally to neighboring grid cells, or redeposited in the absence of currents." We hope that our modifications to the introduction will clarify this approach.

Results

L355 As dead benthos end up in the pool of OC since they're not "removed" from fishing (fishers only remove target fish biomass), how is this accounted for in the results?

Dead macrobenthos is not added to the OC pool in the model, the implicit assumption being that macrobenthos is quickly degraded by microbial activity. The conceptual difficulty with the treatment of dead macrobenthos in the model is that the other POC source (i.e. comparatively small particulate detritus) is assumed to behave similarly to sediment particles and can be treated as such in the model, whereas macrobenthos carcasses would behave very differently (e.g. they would be consumed by scavengers, would not be resuspended as easily nor mixed downward by bioturbators as effectively). This simplification will be added to the methods and its discussion to the section on model limitations.

L356: The loss of 14% of benthos in the North Sea can be taken out of context here. Maybe state that this is the difference between trawling and no trawling scenarios.

Replaced "loss" by "difference".

Use of 'REF' (reference simulation): I see why you have chosen REF/reference as it represents the status quo of trawling in the North Sea. Nevertheless, I was often confused as a reader since most of the time I see this term (reference) used, it is synonymous to 'control' conditions which are typically undisturbed such as in experimental studies. I would consider using a different term like 'SQ' for 'status quo' simulation or 'baseline' simulation (BASE) to not confuse readers in a similar manner.

We agree that the use of the term "reference" can be confusing here. We will use "baseline" (BASE) instead of "reference" (REF).

L368: Trawling pressure is highest in the summer therefore their effect is also high. OC influx is also highest in the spring and summer so does that mitigate some of the trawling effect.

Fresh OC influx from planktonic detritus during the simulation period, which accounts for less than 0.5% of OC stock in the surface 10 cm sediment, is not considered in the model, as explained in sections 2.1 and 4.5. We do acknowledge that this is a shortcoming of our model. Nevertheless, we argue that this should not have a major impact on our results; Seasonal OC deposition occurs initially as a highly porous and soft fluff layer which is unlikely to provide significant mechanical resistance to bottom trawling gear or buffer resuspension and penetration, so it seems appropriate to ignore the fresh deposit and apply the full trawling resuspension rates and gear penetration to the partially consolidated sediment bed. This argument will be added to section 4.5.

Discussion

L427: I imagine this may be quite difficult to incorporate to the models but how would you answer the question about how trawling leads increases in certain types of macrobenthos like benthic scavengers and more r selected species? In Tiano et al., 2020, we speculate that trawling may have led to more large infauna (sediment mixers/bioirrigators) occuring in the Frisian Front as they tend to survive trawling effects by living deeper in the sediment. Potential discussion here, though our example may be a special case.

We do not explicitly distinguish between different species traits or functional groups in the model and therefore used an averaged depletion rate of 20%. Nevertheless, the median biomass depth Z_0 can be used as a simple indicator for the benthic community structure. A small value of Z_0 indicates that macrobenthos are concentrated near the sediment-water interface, while an increase of Z_0 suggests that macrobenthos tend to live deeper. We do see a deepening of Z_0 after trawling, which is supported by the results in Tiano et al. (2020). A Figure E1b will be added to show this and it will be included in results and discussion. Scavengers will also be mentioned in section 4.5.

L430: So can you say that the results suggest a greater direct effect on benthos rather than OC?

It is true that redeposition does not mitigate net benthos depletion in the same way as net OC depletion in the model. However, it is difficult to compare measures of sediment OC and macrobenthos biomass objectively, so we'd prefer to leave this interpretation to the reader.

L456: As OC influx is lower in the winter, are fisheries closures less effective during these times? I was wondering that since MPA's in the low OC Dogger Bank show little effect, perhaps it's the same during the time of year when OC may be lower.

It is difficult to answer this based on our results since fishing effort is also lowest in winter, and because we do not consider additional OC sedimentation from planktonic detritus in summer. We prefer not to speculate here but will include this point in section 4.5 of the discussion.

L521-528: I would specify this explanation of the depositional pattern in the models also somewhere in the methods. It is relevant here in the discussion as it explains certain model limitations but I wanted to ask questions on this topic much earlier in the manuscript so an explanation on how the model handles annual OC deposition early in the methods would be nice.

This explanation will be moved to the methods section 2.1.

L587: I'm confused now. I thought all 'reference' simulations were the status quo trawled simulations? Please check this and make consistent throughout the paper.

Correct, this was an oversight. In an earlier stage of the study, we had labelled the "no-trawling" scenario as the "reference". This also caused the sign of the changes plotted in Fig. 6a and Fig. E1 to be reversed, which will be corrected. We will use "baseline" (BASE) instead of "reference" (REF) and check all instances to make it consistent throughout.

L608: Perhaps you can also (re)state here how much of the North Sea is closed for the different scenarios.

We agree with this suggestion but prefer to state the resulting redistribution of trawling effort as a more meaningful measure of the impacts on fishing fleets: "Around 30% of recent trawling effort was located inside of each closure area, with the exception of planned Offshore Windfarms, which overlap with only 5% of trawling effort. (…) closing 23% of the North Sea's area to trawling reduced the net impacts of trawling …"

L610: I agree with you guys. This is a really good study, great job!

Thank you!