Response to referee comments to *Egusphere-2026-959*; anonymous referee #1

This is an interesting manuscript on legacy organic matter and ammonium in Baltic Sea sediments, and on benthic ammonium fluxes. The authors high-light and quantify (via modelling) the very long time the Baltic Sea needs to recover from decades of enhanced eutrophication and oxygen deficiency – even if external nutrient loads are drastically reduced. This quantification is welcome and highly needed.

Response: We thank the reviewer for their time and their positive evaluation of the importance of our study.

Considering the very long time the Baltic Sea needs to recover (as mentioned above), it would be an improvement of the manuscript if the authors could include a section giving their view on the suitability of sea-based methods (often also called ecological engineering) to improve the environmental status of the Baltic Sea or at least the coastal part of the Baltic Sea. Would, according to the authors, for example oxygenation (in one way or the other) faster lead to improvements than only reduction of external nutrient loads? Are there any other sea-based methods that the others favour or recommend? Considering that the authors' model results suggest so very strong persistence of the legacy OM and ammonium, one would expect that the authors add this section and respond to the questions I have raised. I am sure that most future readers of this manuscript have the same questions.

Response: We appreciate the reviewer's comment. Based on the results of our study, we recommend to continue curbing the current nutrient load to the coastal Baltic Sea and furthermore, to account for internal ammonium loading when setting nutrient load targets. Both recommendations aim to decrease the amount of organic matter loading to coastal sediments to enable the system to naturally go back to its pre-industrial state. The fact that such ecosystem restoration can take centuries to be achieved is an important outcome of our study, as it (i) highlights the long-lasting ecological consequences of past human actions and (ii) serves as a reminder and warning to ecosystems in the beginning stages of eutrophication to take swift action to abate further eutrophication. In this context, discussing ecological- or geo-engineering approaches to fix the ammonium legacy in Baltic Sea coastal sediments is beyond the scope of this manuscript.

I am not much involved in modelling any longer, so it essential that at least one of the other reviewers is a modeler and thoroughly scrutinizes the modelling part of the manuscript. I have not done that.

Response: During the revision of our manuscript, we identified an error in our model-code, specifically in using downcore porosity to rectify solid-to-porewater reaction rates and sedimentation rates of sediment solids and porewater. After fixing the error, we carefully re-calibrated and re-run the model. The main conclusions remain similar and the major changes expected in the revised text will be the magnitude of pools and efflux, while other interpretations and conclusions still stand as they are. We are truly sorry for this mistake and apologize for these late changes. The details of the corrected model will be described in the supplementary material during the revision, and all figures will be updated.

General: The model includes different levels of organic loading, but I did not notice whether you discussed variable C/N ratios of the deposited organic matter. Would doing that improve the model predictions?

Response: The model uses a multi-G approach, i.e. the organic carbon (OC) pool was divided into three pools: 50% of TOC is the reactive pool (OC1) with a C/N ratio of 6.6 representing the marine derived fresh carbon, 16% of TOC is the less reactive pool (OC2) with a C/N ratio of 25 representing the terrestrial-derived carbon, and the remaining 34% of TOC is the non-reactive pool (OC3) that gets buried directly without degradation, i.e. no contribution to ammonium. As different combinations of OC1, OC2 and OC3 proportions can change the amount of released ammonium, the magnitude of calculated ammonium stock and efflux may face uncertainties if we re-calibrated the model using geochemical profiles from other coastal areas. However, the timeframe needed for the ecosystem recovery would remain similar at a fixed sedimentation rate.

<u>Comments by line number</u>

Line (L) 20: "… *accumulated via OM burial and mineralization*…"; Please instead write "…accumulated via OM **deposition** and mineralization…". The term burial is often used to reflect the ultimate removal of a substance from further (re)cycling.

Response: We will revise the sentence according to the reviewer's suggestion.

L 40 and elsewhere: "...*phosphate (PO_4^{3-})*.."; PO_4^{3-} is not the main species of dissolved inorganic P in seawater. Please instead use Dissolved Inorganic Phosphorous (DIP) – here and everywhere in the manuscript.

Response: We will revise the sentence according to the reviewer's suggestion.

L 45-46: …*PO_4^{3-} due to its crucial role in the repeated occurrences of massive cyanobacteria blooms and metal recycling*…; Do you mean the role of metal recycling in the dynamics (retention and release) of PO_4^{3-}(or DIP)? If so, this is not what you wrote.

Response: We will edit the sentence as following: "…DIP due to its crucial role in the repeated occurrences of massive cyanobacteria blooms and close coupling to metal recycling..."

Figure 1: There are more published papers on NH4 effluxes under varying bottom water oxygen conditions in the Baltic Sea than those cited in Figure 1. Since this manuscript focuses on the Baltic Sea, I suggest that the authors are more comprehensive in this regard and cite more of these papers.

Response: We searched for published benthic ammonium flux data under varying bottom water oxygen conditions using web-of-knowledge and the search criteria "benthic ammonium flux" and "Baltic Sea". Subsequently, we selected the coastal studies manually by going through the results, so as not to miss studies that are coastal but might use another wording, e.g. fjord or estuary. Only studies from the coastal Baltic Sea including Kattegat (coastal zone defined as 1 nautical mile from land, following the European Water Framework Directive) that were derived from actual flux incubations, using sediment cores or benthic chambers, and provided ammonium flux results under varying oxygen conditions were included. While there is a large pool of studies conducted in the open waters of the Baltic Sea, studies conducted in the coastal zone are much fewer and only include the ones we show in Figure 1. We repeated our literature search on 13th April 2026 to include potential new papers that were published in the last months but did not find any new studies that match above criteria. If the reviewer has specific papers in mind that we missed, we are happy to include them in our compilation.

L 77-78: "*This is not only a larger pool of bioavailable N than the pelagic pool of dissolved inorganic nitrogen (DIN) in the coastal Baltic Sea…";* Please explain how you define the **coastal** Baltic Sea, preferably the first time you mention the coastal Baltic Sea.

Response: We defined the coastal area of the Baltic Sea according to the definition of "coast" given by the European Water Framework Directive, i.e. 1 nautical mile from land (the direct wording of the implementation strategy is *"'Coastal water' means surface water on the landward side of a line, every point of which is at a distance of one nautical mile on the seaward side from the nearest point of the baseline from which the breadth of territorial waters is measured, extending where appropriate up to the outer limit of transitional waters"*; European Communities: Common implementation strategy for the water framework directive (2000/60/EC), guidance document no 5, transitional and coastal waters – typology, reference conditions and classification systems, working group 2.4 – COAST, Office for official publications of the European Communities, ISBN 92-894-5125-4, 2003). We will add the information on coastal boundaries to the text.

L 111: "…*and thus available*…"; Should be: …and **is** thus available…

Response: We will edit the sentence according to the reviewer's suggestion.

L 124-125: "*Only a small part of water column NO3- is assumed to diffuse back into the sediments, as coastal water turbulence is stronger than diffusion."* I do not think that this is correct. The nitrate formed during nitrification in the oxygenated bottom water may very well be taken up by the reduced sediment surface and consumed by either denitrification or DNRA – regardless of turbulence. Please rewrite or at least explain yourself in greater detail.

Response: We agree with the reviewer that nitrate can diffuse back into the sediment. However, being subject to a dynamic coastal system (including vertical water mixing by wind, waves, upwelling and densitydifferences), it can also be displaced to other water layers and subsequently be taken up in primary production. Thus, it cannot be assumed that all nitrate that was formed from benthic ammonium release will stay in the bottom water and diffuse back into the sediment. We will reformulate the sentence for more clarity.

L 125-127: "*In the absence of hydrogen sulfide (H2S), this NO3- can be reduced to N2, while in the presence of H2S dissimilatory nitrate reduction to ammonium (DNRA) dominates, further enriching the NH4+ pool";* Please be more specific and correct: Denitrification **can** proceed with H2S as electron donor. Also, please provide references stating that DNRA dominates (over denitrification) in the presence of H2S.

Response: In the Baltic Sea coastal zone, benthic denitrification is pre-dominantly carried out by heterotrophic bacteria and is thus bound to organic carbon as electron donor. Hence, it does not proceed when hydrogen sulfide becomes available. We will clarify this in the text. Further, we will add a reference for the fact that DNRA often dominates over denitrification in the presence of hydrogen sulfide.

L 281-287: In sediments with high organic loading, can an abundance of sulphide explain low rates of nitrification, and hence high ammonium effluxes, even under normoxic bottom water conditions?

Response: The model includes relevant sulfide processes, and sulfide can be either consumed by reduced iron or oxidized by oxygen. The latter can lead to low rates of nitrification, but the degree of this impact is largely dependent on the availability of oxygen and iron oxide. Please note that all of these processes are tightly linked to the amount of organic matter available for degradation, and the model outputs we see here are the integrated net effects of all of these processes on ammonium efflux.

L 335-336: "*For instance, a higher salinity is often found in open coastal systems*;…" Is it? If so, why? And higher than where? I do not understand what you mean. A clarification is absolutely necessary.

Response: With "open coastal systems" we meant coastal systems with free water exchange, which are mainly at an oceanic coast and thus high saline, as opposed to a semi-enclosed systems with limited water exchange such as the Baltic coastal zone. We will edit this statement for better clarity.