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Interactive comment on "Efficient removal of phosphorus and nitrogen in sediments of the eutrophic Stockholm Archipelago, Baltic Sea" *by* Niels A. G. M. van Helmond et al.

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The manuscript addresses the critical process of sediment P burial for the development of eutrophication. It also covers nitrogen turnover on which I am not an expert. My review will therefore focus on the P.

Reply: We thank the reviewer for taking the time to critically assess this work. We reply to all points raised below.

The burial of P in accumulation bottom areas in four sites is presented with high-quality data, both regarding the accumulation rate of matter and the P content and P-forms in

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these layers. I find the manuscript well written in terms of language and easy accessible. I do, however get the impression that the main scope with the P investigation partly was something more than the burial as it is presented; a “sink-switch” process to e.g vivianite-formation, as evident from the many references included covering that possible process.

Reply: In our study, we assess the processes controlling the removal of phosphorus (P) and nitrogen (N) in the eutrophic Stockholm Archipelago, as indicated in both the abstract and introduction. Since P is predominantly removed by burial we have looked into its different sedimentary forms. Given that sink-switching to vivianite occurs in sediments of other areas in the Baltic Sea (e.g. Egger et al., 2015), it was indeed one of our aims to study whether this is the case in the Stockholm Archipelago. Our data suggest a vivianite-type mineral might be present at depth at Strömmen. We agree with the reviewer that vivianite formation received too much attention in the original manuscript and we will remove some of this text, including many of the references.

Main concerns

The outcome of the study regarding the P burial ends up rather basic by summing up total-P concentrations in deeper sediment layer with the sediment accumulation rate at the specific site. With all the supporting data presented, perhaps could new insights be developed? I suggest a more in-depth analysis of the P burial both in a spatial (quantitative) scale, as well as in a qualitative (formation of refractory P that forms during diagenesis and resists it) perspective. I offer my reflections on the subject as a platform to develop the discussion:

Reply: We respond point-by-point to these comments and the other suggestions of the reviewer below.

Does the lack of concentration changes in most P forms with sediment depth (Fig. 6) actually reflect mainly inert P forms settling out on the sediment surface, resistant to sediment diagenesis? Even the ”authigenic P” (Ca-P) seems thus to have been formed

elsewhere than in the present sediment profile, since it already in the top sediment layers is present at a concentration it will remain throughout the sediment profile. The "sink-switch" process seems to be virtually absent (except perhaps for the Strömmen station).

Reply: We will add a few lines to the discussion (section 4.1.2) to emphasize this: "The constant concentrations of most P forms in the sediment below the clearly "enriched" surface sediments, suggest there generally is little to no sink-switching of sediment P forms in the Stockholm Archipelago. The curved shape of the porewater HPO42- profiles indicate, however, that there is still some release of P to the porewater at depth and we attribute this to slow degradation of organic matter. Both the detrital and authigenic (Ca-P) fractions are likely buried in the form in which they reached the sediment-water interface."

Indeed, some share of the organic P settling out on the sediment surface is mineralized, as evident from the decline in org-P concentration in the top ca 5 cm. This is well presented in Fig 9 where the "background" concentration is indicated. Perhaps the "top-layer" (indicated as red labelled "surface sediment sink") actually represents the P active in turn-over, as suggested in Rydin 2011. All the P indicated as background concentration would then largely be inert P forms, not relevant for the eutrophication process. A key question would then be to what extent autochthonous organic P (e.g. plankton) contributes to the supply of organic sediment P resistant enough to get permanently buried. Is the only main sink-switch of importance in this region the transformation of dissolved P in the water column to organic P (plankton), to a larger or lesser extent permanently buried in the sediment?

Reply: We agree that the red-labeled "top-layer" in Fig. 9 likely represents the P active in turn-over. We will change the term "surface sediment P sink" to "surface sediment P pool" (both in Fig. 9, which will become Fig. 10 in the revised manuscript, and throughout the text), to clarify that this part of the P is not permanently buried and is the P active in turn-over. In addition to this adaption we will add a sentence to acknowl-

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edge that this P pool represents the P active, as previously suggested by Rydin et al. (2011) – discussion, section 4.1.1: "For our study sites in the Stockholm Archipelago we calculated that this surface sediment P pool, i.e. the P active in turn-over as earlier already suggested by Rydin et al. (2011),. . ."

The "background-P", may indeed largely represent inert forms of P, with the exception of the Strömmen station, as already indicated by the reviewer in his previous comment. Sedimentary C/N ratios for the studied sites are, however, close to the Redfield-ratio, indicating that most of the organic matter has a "marine" i.e. planktonic origin, suggesting that most of the organic P is of autochthonous origin. We will clarify this in the revised discussion, section 4.1.1: "Besides Fe-oxides, a major part of the surface sediment P pool consists of P in organic matter (Fig. 6), which, based on the C/N values close to the Redfield-ratio (Fig. 5), is predominantly of marine origin. Part of the organic matter (and the P associated with it) is lost with depth (Fig. 6), because the most labile organic matter is degraded in the upper centimeters of the sediment, releasing the P associated with it to the pore water."

Line 391: Only "near shore construction and dredging (line 391) is presented as alternative sources for the P accumulated than land-derived. Another explanation for the high burial rate could be that the sediment to a large extent consists of old sediment (old clays) that already have undergone sediment P diagenesis processes one or even several times during the Baltic Sea life span, exposed to resuspension due to land up-lift (ca 0,5 cm/yr), and a secondary (or a third) settling out on accumulation bottom areas (Karlsson et al 2019 and references therein). But also P from the catchment (e.g. Lake Mälaren) of course contributes to this pool of P.

Reply: We agree with the reviewer that there are other alternative sources of sediment and associated P that may influence sediment and P accumulation rates. We will adapt our discussion (section 4.1.2) to clarify this: "Further research of P burial rates at additional locations in the Stockholm Archipelago, including the impact of anthropogenic activities on sedimentation rates (e.g. near-shore construction and dredging) and of

redeposition of sediments that have already undergone one or multiple diagenetic cycles (after resuspension due to, for example, land uplift; Jonsson et al., 1990; Bryhn and Håkanson, 2011) is required before these results can be extrapolated to the scale of the entire system."

A back of the envelope calculation regarding the Lake Mälaren impact on the P burial in the region might look something like this: The Stockholm county archipelago covers a water area of 3100 km2. Assuming that only 25% of this area represents accumulation bottom conditions; 780 km2, and an average burial rate of 3 g/m2 yr, it ends up to 2340 ton P/yr. This is a high flux compared to external inputs, and corresponds to as much as ca 15% of the total P input to the Baltic proper. Thus, a high share of the P found in accumulation bottom sediment seems to be recycled.

Reply: It would indeed be interesting to analyze P burial on a spatial and quantitative scale, as suggested by the reviewer. Our study, however, is specifically aiming to assess the processes controlling the removal of P and N. Our dataset is therefore not suited for (detailed) spatial and quantitative analysis of P burial. Large outstanding questions that need to be answered before reliable budget calculations can be made, are for example: What part of the Stockholm Archipelago represents accumulation areas? How much P (and in what forms) is buried in euxinic areas? We will clarify this in the revised discussion (4.1.2): "Furthermore, it remains unclear what parts of the Stockholm Archipelago represent areas of net sediment accumulation (Karlsson et al., 2019; Asmala et al., 2019) and how much P (and in what form) is buried in euxinic parts of the Stockholm Archipelago. Hence, our results cannot be directly used to resolve the apparent discrepancy between the model results of Almroth-Rosell et al. (2016) and Walve et al. (2018)."

To summarize my thoughts: the archipelago sediment seems effective in permanently trapping already inert, particulate P. But less efficient in transforming the "surface sediment sink" (Fig 9) into P forms that will be permanently buried.

Reply: The reviewer's observation that the P in the "surface sediment sink" is not efficiently permanently buried is correct. Organic P is not inert, however. With the previously suggested adaptions this should now be clarified.

The Discussion can be expanded with comparisons to other studies regarding accumulation of matter and phosphorus in the region; see Karlsson et al 2019 for suggestions on references for a more developed Discussion. Both the "surface sediment sink" (Figure 9), and the sediment accumulation rate, in Baggensfjärden and Erstaviken, are close to those found in a recent study in the adjacent Björnöfjärden (Rydin & Kumblad, 2019).

Reply: We will expand the discussion based on the reviewer's comments and suggestions, also including the studies the reviewer refers to in the discussion sections 4.1.1 and 4.1.2.

Specific comments:

Figure 10 is of limited value since it (only) shows that the P concentration at depth is rather constant, and the burial rate is largely dependent on sediment accumulation rate (at the investigated sites).

Reply: Figure 10 is not key to our study. We will therefore remove the sentence in the discussion introducing Fig. 10 (lines 389-390 of the original manuscript): "...hence our study sites plot above the linear relationship between rates of sediment accumulation rate and P burial (Fig. 10; Table 5) in the coastal zone of the Baltic Sea (Asmala et al., 2017)." To keep the figure available for interested readers we will move it to the supplementary material, where it will become Supplementary Figure 5.

The references need a check. Are all the references present needed? Line 802: Rydin et al 2011 reference is missing.

Reply: We thank the reviewer for pointing out this mistake. We will recheck our references and correct them where necessary.

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Line 900: It would be useful to present sediment accumulation rates as g DW/m2 yr besides cm/yr to compensate for the compacting of the surface sediment.

Reply: We will add the sediment accumulation rates in g DW m-2 yr-1 to Table 5 as suggested by the reviewer.

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