COMMENT

Limited capacity to retain phosphorus in the Baltic proper offshore sediments

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Comment to: Stigebrandt, A. 2018: On the response of the Baltic proper to changes of the total phosphorus supply. *Ambio* 47: 31–44. <https://doi.org/10.1007/s13280-017-0933-7>.

Based on calculations using a phosphorus (P) budget model, Stigebrandt (2018) concludes that the P-concentration in the water column of the Baltic proper (BP) could be reduced by about 70% within 10–15 years if the deep bottoms were oxygenated. The calculations assume an annual influx from the sediment to the water column of almost 100 000 tonnes, which could be switched off if the sediments were oxidised. However, the P storage capacity is strictly limited to the uppermost oxidised layers of the sediment cores. Below the sediment redox cline, the total P-concentration levels out around $1000 \text{ mg kg}^{-1} \text{ dw}$ regardless of the oxygen conditions in the upper sediment layer (Rydin et al. 2011; Malmaeus et al. 2012; Puttonen et al. 2015). The maximum capacity of BP sediments to retain P from recent settling matter would be around 100 000 tonnes *in total*, assuming oxygenation of $50\,000 \text{ km}^2$ currently anoxic bottoms; see further Malmaeus and Karlsson (2012).

Apart from the redox potential, the ability of the sediments to absorb phosphorus from the water column depends on the availability of iron and manganese in the sediment and bottom waters. Measurements of the P store in deep sediments of the BP indicate that there is a potential phosphorus binding capacity of around 2 g m^{-2} if oxygen conditions improved (Malmaeus and Karlsson 2012). This is consistent with Conley et al. (2002) who found a significant correlation between the annual change in the anoxic area and the change in the inorganic phosphorus pool in the BP with a regression slope of around 2 g m^{-2} , a figure which is also cited by Stigebrandt (2018).

Comparing sediment cores from the generally well-oxidised Bothnian Sea (BS) with corresponding data from reduced sediments from the BP indicates about ten times more mobile P (more specifically iron bound P, “Fe–P”) stored in the upper sediments of the BS (Malmaeus and Karlsson 2016). Figure 1 shows the P-content in a typical sediment core from accumulation areas in the deeper parts of the open BS and the BP, respectively. Below the oxidised layer, there is essentially no mobile P present and the P burial is restricted to immobile P forms including apatite-P and refractory organic P forms (Rydin et al. 2011). A shift in the redox conditions may change the equilibrium content of P between water and sediments while the total amount of phosphorus in the system remains essentially unchanged (Fig. 2). We have previously described the BP and the BS as examples of two different P regimes where oxygenation of the BP might trigger a regime shift (Malmaeus and Karlsson 2016).

An example of a system that recently has recovered from hypoxia is the Stockholm inner archipelago. The sediment surface on accumulation areas has switched from being reduced by the end of the 1990s to a fairly thick oxidised layer in 2008 (Karlsson et al. 2010) containing significant amounts of mobile P (Rydin et al. 2011). However, after an initial drop in TP-concentrations in the surface water between 1995 and 2000, the TP-concentration has levelled out around $1.3 \mu\text{mol TP l}^{-1}$ during the following decade, indicating, despite being well-oxidised, a limited capacity for the sediments to further accumulate P from settling matter.

To conclude, the P mass balance of the BP proposed by Stigebrandt (2018) is inadequate. By assuming a sustained flux of P from anoxic sediments which is not supported by sediment data, it lacks a functional parameterisation of fundamental processes. Thereby, the possible positive

Fig. 1 Depth profiles of total P, iron bound P (Fe-P), aluminium bound P (Al-P), calcium bound P (Ca-P) and organic P (Org-P) in **a** core from BP, **b** core from BS. Reprinted from Malmaeus and Karlsson (2016), with permission from Föreningen Vatten

effect of oxygenation of BP deep sediments on P-concentration in the upper water layer is exaggerated. Moreover, a mass balance model predicting future conditions of the Baltic Sea should also take into account the erosion and resuspension of particulate P, including the effects of land uplift on the deposition of nutrients (Jonsson et al. 1990; Karlsson et al. 2014). A more reasonable expectation of improved oxygen conditions would be to reach the conditions of the early 1990s, when the P-content in the water column was approximately 100 000 tonnes less than today, equivalent to a 30% decrease of the P-concentration. The winter concentration of dissolved inorganic phosphorus (DIP) in surface water of BP would then reassemble the prevailing conditions in the BS with a DIP-concentration around $0.35 \mu\text{mol l}^{-1}$ compared to current level around $0.5 \mu\text{mol l}^{-1}$.

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Fig. 2 Principal illustration of a system redox change from anoxic sediments containing little mobile phosphorus (left) to oxic sediments containing more mobile phosphorus (right). From Malmaeus and Karlsson (2012)

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