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ORIGINAL RESEARCH

Estimating the Pool of Mobile Phosphorus in Offshore Soft Sediments of the Baltic Proper

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Abstract

Background: Eutrophication is a major threat to many coastal ecosystems worldwide. This paper deals with the sediment-water exchange of phosphorus, one of the elements that may stimulate primary production in the aquatic environment. The lack of phosphorus-binding capacity in sediments at low redox-potential is recognized as an important mechanism for eutrophication-related effects in some areas.

Methods: Twelve sediment cores were collected in the Baltic Proper between 61 m and 175 m water depth and a number of phosphorus fractions were analyzed. Integrating the concentrations over the depth profiles, the amounts of mobile phosphorus were estimated in each core.

Results: It was found that sediments below the redox cline in the Baltic Proper contained small amounts of mobile phosphorus. The total amount of mobile phosphorus in the entire Baltic Proper sediments below 65 m water depth was estimated to between 55,000 tonnes and 156,000 tonnes or between less than 10% to around 25% of the phosphate in the system (water plus sediments). This represents the maximum amount of phosphorus that could possibly be released to the water column from these areas. We argue that the most reasonable estimate of the pool of mobile phosphorus in the sediments is the lower number.

Conclusion: The amounts of mobile phosphorus in sediment cores with oxidized surface layers were higher compared with sediment cores with reduced surfaces, indicating that there is a potential phosphorus-binding capacity in sediments below the redox cline if oxic conditions improved. Oxygenation of the Baltic Proper bottom water between 65 m and 100 m could probably remove around 100,000 tonnes of phosphorus from the water column and reduce phosphorus concentrations in the deep water by on average 30 mg/m^3, which would possibly be felt also in the surface water.

Keywords: mobile phosphorus, phosphorus fractionation, sediments, oxygenation, Baltic Proper

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Introduction

Improving the ecological status of the Baltic Sea is largely associated with reducing concentrations of phosphorus and nitrogen in the system.[1,2] Several studies indicate that the reflux of phosphorus from the sediments is similar in magnitude to the terrestrial load. According to the Helsinki Commission,[3] the waterborne inputs of phosphorus to the entire Baltic Sea in 2000 were close to 35,000 tonnes. According to the Baltic Sea Action Plan, the annual phosphorus load should be reduced with around 15,000 tonnes, including 12,500 tonnes to the Baltic Proper.[4] Budget calculations for the Baltic Proper indicate that the sediments annually release between 18,000 and 285,000 tonnes of phosphorus to the water column,[5,6] the latter including resuspension of old clays due to land uplift. Savchuk[7] found that a net flux of around 20,000 tonnes of phosphorus from the sediments of the Baltic Proper was required to sustain measured levels of phosphorus in the water column. According to Conley et al,[8] the variation in the size of the phosphorus pool of the water column is largely explained by the flux of phosphate between the sediments and the bottom water rather than by variations in external load. The size and direction of this flux depends on redox conditions at the sediment surface. Between 1960 and 1990, the area of laminated sediments indicating permanent deep water anoxia increased around 50,000 km^2 in the Baltic Proper.[9] Among measures suggested to address eutrophication, oxygenation of the deep waters to reduce diffusive phosphorus flux from the sediments has been suggested.[10]

Experimental data from the coastal Gulf of Finland showed that the phosphate flux from reduced sediments to water was 4.7 g/m^2/year.[11] A corresponding value for the German Baltic Sea coast was 6.1 g/m^2/year.[12] The annual phosphorus flux from soft sediments at various sites, mainly in the Gotland Basin (approximately 30,000 km^2) of the central Baltic Proper, have been estimated between 0.1 and 3 g/m^2.[13–16] Ahlgren et al[17] found that the phosphorus release from a sediment in the Landsort deep was approximately 0.6 g/m^2/year, and considered that if this value was relevant for the entire area of laminated sediments in the Baltic Proper (about 55,000 km^2 at the time), some 33,000 tonnes of phosphorus would be released from these sediments to the water column annually.

The diffusive flux of phosphate from accumulation bottoms is a reflux of phosphorus originating in settling material, mobilized in the sediments due to degradation of organic material, or anoxic release of phosphorus bound to iron and manganese.[18] Hence, in the long run, the release rate of phosphorus cannot exceed the rate of phosphorus deposition. Ultimately, the maximum release is limited by the amount of potentially mobile phosphorus in the sediments. Estimating the pool of mobile phosphorus in accumulation sediments may hence provide information about potential release of phosphorus to the water column and implications for the ecological status of the Baltic Sea.

Carman and Jonsson[19] attempted to calculate total amounts of phosphorus in Baltic Sea soft sediments and concluded that a major proportion (approximately 95%) of the potentially mobile phosphorus fractions is present in near-shore and archipelago areas. Carman and Cederwall[20] analyzed total phosphorus concentrations in surface sediments (0–1 cm) from different parts of the Baltic Sea and in different bottom types measuring concentrations between 700 µg/g and 2500 µg/g dry weight (median 1300 µg/g). The highest concentrations were found in accumulation areas and the lowest in erosion areas. Emelyanov[21] compiled at least 386 samples of surface sediments (0–5 cm) from different parts of the Baltic Sea with average phosphorus concentrations in different bottom types ranging between 600 µg/g and 1400 µg/g dry weight.

Potentially mobile phosphorus mostly consists of organic phosphorus forms and phosphorus associated with iron and manganese.[18,22,23] Mobile phosphorus pools in accumulation sediments have been estimated for the Gulf of Finland and the Archipelago Sea[23] and for the coastal sediments of central Sweden.[24] Average depth integrated amounts of mobile phosphorus in Swedish coastal sediments were estimated to 2.5 g/m^2.[24] Conley et al[8] found a significant correlation between the annual change in the anoxic area and the change in the inorganic phosphorus pool in the Baltic Proper with a regression slope of around 2 tonnes of phosphorus per km^2, which would be consistent with a mobile phosphorus amount around 2 g/m^2 released when sediments turn anoxic. A shift in the redox conditions may influence the distribution of the mobile phosphorus between water and sediments while the total amount of phosphorus in the system remains essentially unchanged, as illustrated in Figure 1.

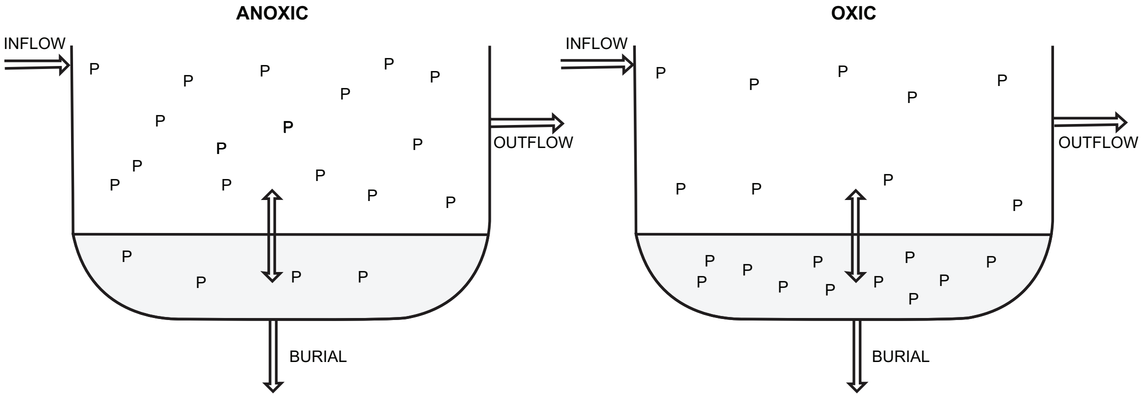

Figure 1. Principal illustration of a system redox change from anoxic sediments containing little mobile phosphorus (left) to oxic sediments containing more mobile phosphorus (right).

In the Baltic Sea, deep soft sediments below 75 m water depth are typically areas of accumulation[9,25] where only diffusive processes operate to release phosphorus and other chemicals, but the actual boundary between accumulation and transportation areas may vary depending on, eg, slopes, topographical sheltering, and water currents. It is sometimes difficult to judge whether a sediment core represents strict accumulation conditions or where resuspension takes place as seldom as once a decade or century. Hence the term "long-term transportation bottoms" has been introduced.[26] Accumulation areas occupy around one third of the bottom area of the Baltic Proper.[9,25,27–29]

In this paper, we analyze 12 sediment cores collected in the Baltic Proper between 61 m and 175 m water depth and calculate the amounts of mobile phosphorus. We assume that our sediment results can be representative of the order-of-magnitude estimate for the entire bottom area of the Baltic Proper. We also compare this amount with the phosphate pool in the water column estimated from monitoring data in the water column to compute the total amount of bioavailable phosphorus in the aquatic ecosystem.

Methods

Sediment sampling, water sampling, and oxygen measurements were performed during a field expedition with R/V Sunbeam in July 2010. Sampling stations are shown in Figure 2.

Water sampling

Water samples at two depth levels in seven stations were collected with a Ruttner sampler and stored cold in plastic bottles. The water salinity, temperature, and oxygen concentration were measured online in the field using a SEBA KLL-Q2 CTD device complemented with an optical oxygen sensor.

Sediment sampling

Twelve sediment cores were collected using a Gemini corer (a twin-barrel Niemistö corer with inner diameter 80 mm[30]). After visual inspection, core samples were sliced in the field in 1 cm thick layers from the surface down to 5 cm sediment depth. In addition, one deeper level was sampled at each site (except in BP6 due limited length of core) to represent burial conditions after sediment diagenesis. All sliced sediment cores were stored in darkness at 4 °C until preparation in the laboratory.

Chemical analyses

Chemical analyses of phosphorus were performed at the Erken Laboratory at Uppsala University. In water samples, standard methods were used for the analyses of dissolved inorganic phosphorus and total phosphorus. Total phosphorus content in the sediments was determined by ashing (520 °C) followed by hot HCl extraction and measurement of dissolved inorganic phosphorus in the extract.[31] Water content was determined after freeze-drying, and organic content after ignition at 550 °C for two hours (loss on ignition) following the Swedish standard method, SS-EN 15169:2007.

Phosphorus forms were separated into NH_4Cl-rP, BD-P, NaOH-rP, NaOH-nrP, HCl-rP, and residual phosphorus following a sequential extraction scheme.[32] These fractions are defined by the extraction method, but ideally each fraction corresponds

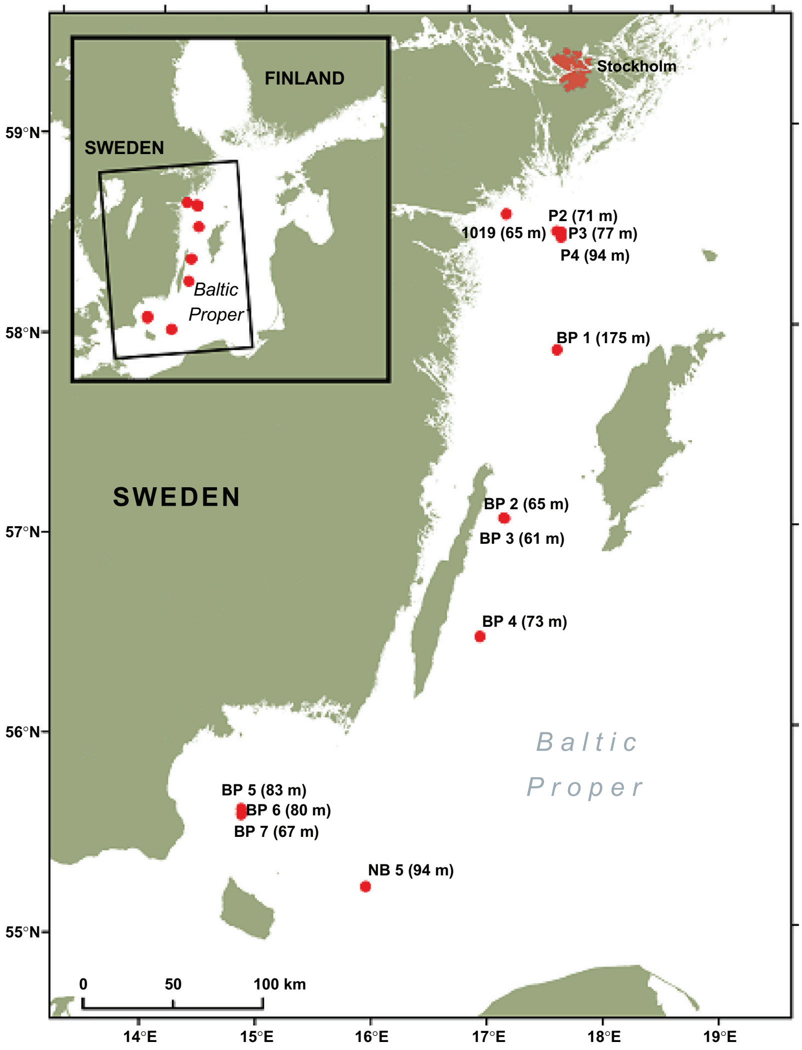

Figure 2. Positions of sediment sampling stations.

to a specific phosphorus-containing substance in the sediment. Generally, NH_4Cl-rP is regarded as loosely bound phosphorus, BD-P as phosphorus associated with iron hydroxides, NaOH-rP as phosphorus bound to aluminum, NaOH-nrP as organic phosphorus forms, and HCl-rP as calcium-bound phosphorus compounds. Residual phosphorus is given by subtracting extracted and identified phosphorus from total phosphorus. Phosphorus fractionations were started within a week after sampling. In the following, we will refer to BD-P as iron bound phosphorus and NaOH-nrP as organic phosphorus.

Chemical analyses of iron and manganese were performed by ALS Scandinavia AB. The sediments to be analysed for metal content were dissolved in nitric acid (7 M) and water (volume ratio 1:1) in a microwave oven. The water samples to be analysed for metal concentrations were acidified using nitric acid (14 M) and water (volume ratio 1:100). Analyses were performed according to modified EPA-standards 200.7 (ICP-AES) and 200.8 (ICP-SFMS).

Quantifying the pool of mobile phosphorus

To compute the amount of mobile phosphorus per area unit from sediment core data, the phosphorus concentration in deep sediment where sediment diagenesis has ceased, ie, the burial concentration, was subtracted from the higher concentrations in more shallow layers. As an alternative, 1000 µg/g dry weight was used as a standardized burial concentration, since this is the typical burial concentration in sediments from other parts of the Baltic Sea.[17,18,23,24]

Concentrations were multiplied with dry matter content (adjusting for sediment water content) to get the amount of mobile phosphorus in each layer. The surpluses in each sediment layer were taken as mobile phosphorus and integrated over the depth profile to obtain the amount of mobile phosphorus per square meter accumulation bottom area. This procedure was followed for total phosphorus as well as for the different phosphorus fractions. Three different estimates of the pool of mobile phosphorus in each core were made, ie, the amount of mobile total phosphorus using the burial concentration in each core as a measure of immobile phosphorus subtracted from the total amount ("Mobile TP"), the amount of mobile total phosphorus using 1000 µg/g dry weight as a measure of immobile phosphorus ("Mobile TP_{1000}") and the sum of iron bound phosphorus, organic phosphorus, and residual phosphorus ("Sum of mobile P-fractions").

Results

Results from water sampling are shown in Table 1. CTD profiles are shown in Appendix 1. Anoxic conditions prevailed below approximately 70 m in the stations northwest from Gotland (1019, P2, P3, P4, and BP1), below 65 m east of Öland (BP2, BP3, and BP4) and again below 70 m in the southwestern stations (BP5, BP6, BP7, and NB5). The highest total phosphorus and dissolved inorganic phosphorus concentrations generally occurred in water samples close to the sediment surface.

Depth profiles of total phosphorus and the two mobile fractions (iron bound and organic phosphorus) in the 12 sediment cores are shown in Figure 3. Chemical data characterizing surface sediments are given in Table 2. Based on water and organic content and visual inspection of, eg, occurrence of laminations in the surface sediment[33] it appears that sediments collected below 70 m water depth were generally accumulation or long-term transportation areas. In addition, station 1019 at 65 m water depth was apparently located in an accumulation area which could be explained by topographic sheltering. The deep sediment sample in BP6 was lost before analysis, so one data point is missing. Oxygen measurements combined with visual inspection of sediment cores indicated that all sediments except 1019, BP2, and BP3 were anoxic.

Mobile amounts of total phosphorus calculated with three different methods are shown in Table 3. Tentative estimates of the total amount of mobile phosphorus in the entire Baltic Proper (excluding Gulfs of Riga and Finland and the Danish Straits) based on extrapolations of numbers in Table 3 are given in Table 4. For these calculations, hypsographic information from SMHI (Sweden's Meteorological and Hydrological Institute)[34] was used and the area at each 1 meter depth interval was multiplied with measured mobile phosphorus concentration. Mobile phosphorus was represented by measurements at different depths and linear interpolation between sampling depths. Below 175 m

Table 1. Results from water sampling.

Station	Water depth (m)	Sampling depth (m)	Salinity (psu)	Oxygen (g/m³)	TP (mg/m³)	DIP (mg/m³)	Fe (mg/m³)	Mn (mg/m³)
1019 (WG)	65	5	5.7	10.4	19	5	6.4	2.4
		60	7.8	4.5	109	98	13	31
P4 (WG)	94	5	5.8	10.2	25	7	2.5	1.1
		90	7.5	0.01	52	47	16	147
BP1 (WG)	175	5	6	10.2	18	5	15	1.1
		100	9.8	0.01	60	60	22	90
BP4 (WG)	73	5	6.3	10.4	20	5	1	0.9
		65	9	0.02	170	158	22	171
BP5 (HB)	83	5	6.5	10.1	20	5	1	0.8
		80	15.5	0.01	257	245	300	1330
NB5 (BOB)	94	5	6.5	10.4	23	6	1	1.1
		90	15.9	0.02	78	70	48	449
BP2 (WG)	65	5	6.2	10.4	18	6	1	0.9
		60	4.9	3.5	174	161	39	168

Abbreviations: WG, Western Gotland Basin; HB, Hanö Bay; BOB, Bornholm Basin; TP, total phosphorus; DIP, dissolved inorganic phosphorus.

depth the concentration measured at BP1 was used. Estimated total amounts of mobile phosphorus ranged between 55,000 and 156,000 tonnes.

Combining hypsographic data with data on dissolved inorganic phosphorus and total phosphorus in the water column from the Shark database available via the Swedish Meteorological and Hydrological Institute July 2010 (20 depth levels, eight stations) allowed a very rough estimate of the phosphorus amount present in the water column. Using this method, we estimated the amount of dissolved inorganic phosphorus to 491,000 tonnes and the amount of total phosphorus to 659,000 tonnes in the entire water column of the Baltic Proper at the time of our sediment sampling. The dissolved inorganic phosphorus amount calculated for the water column is in the upper range of values estimated by Conley et al[8] between 1970 and 2000. Savchuk[7] estimated the total phosphorus amount in the Baltic Proper to 418,000 tonnes in a budget for the period 1991–1999.

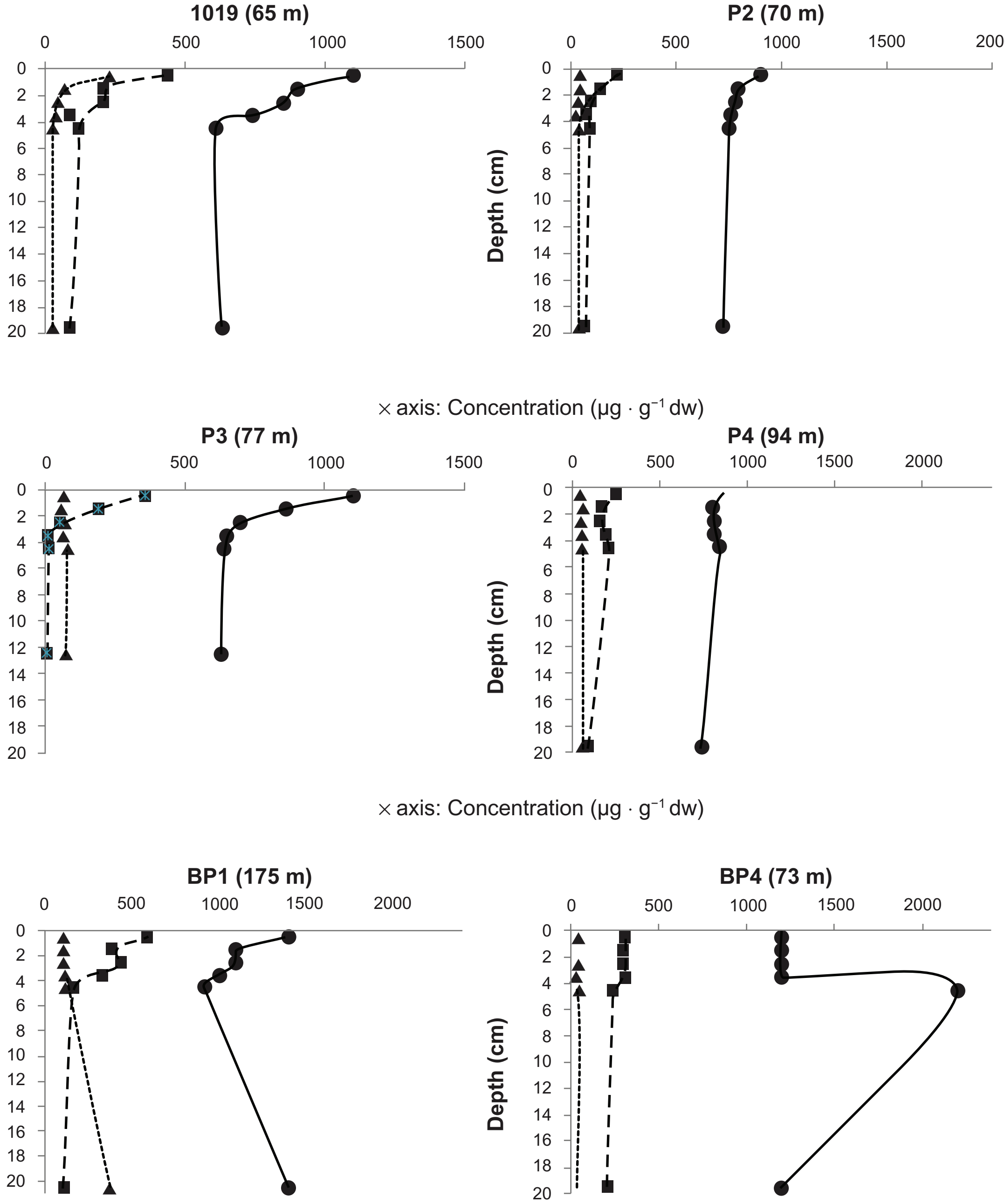

Figure 3. (*Continued*)

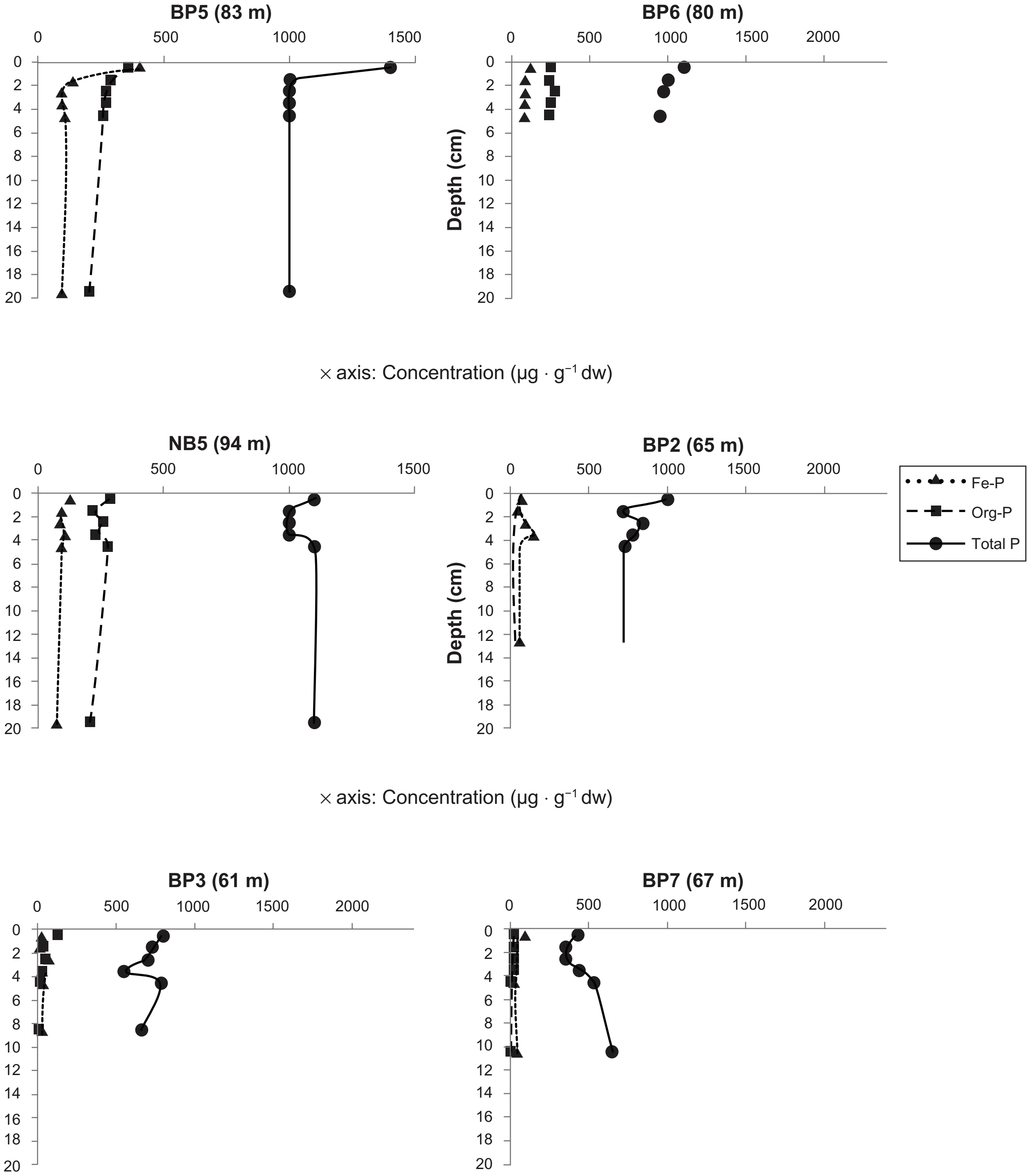

Figure 3. Depth profiles (cm) of iron bound phosphorus (Fe-P), organic phosphorus (Org-P) and Total phosphorus measured in µg/g dry weight. All profiles represent accumulation areas except BP2, BP3 and BP7 which represent transport areas.

Discussion

Apart from the redox potential, the ability of the sediments to absorb phosphorus from the water column also depends on the availability of iron and manganese in the sediment and bottom waters. A low iron:phosphorus ratio may limit the potential phosphate co-precipitation with iron oxyhydroxide.[35] There were no correlation between iron and phosphorus or between manganese and phosphorus in the surface sediments in this study ($r^2 < 0.2$), both if total

Table 2. Characteristics of surface sediment (0–1 cm) samples.

Station	Water depth (m)	Water content (%)	LOI (%)	Fe mg/g dw	Mn mg/g dw	TP mg/g dw	Comment
1019 (WG)	65	87.9	12.5	32.2	0.38	1100	Oxic surface
P2 (WG)	70	81.5	10.6	40.1	0.45	900	1 cm recent material on top of light gray postglacial clay
P3 (WG)	77	87.3	14.8	35.5	0.41	1100	2 cm recent material on top of light gray postglacial clay
P4 (WG)	94	86.6	11.8	40.0	0.61	860	2 cm recent material on top of medium to dark clay
BP1 (WG)	175	95.8	32.0	26.2	0.37	1400	2 cm recent material on top of laminated sediment. Annual layers around 2 mm thick down to 15 cm
BP4 (WG)	73	86.5	13.8	23.2	0.27	1200	1 cm recent material on top of silt
BP5 (HB)	83	88.5	15.4	31.8	0.51	1400	*Beggiatoa* colonies on sediment surface, laminated dark gray
BP6 (HB)	80	83.7	13.0	29.9	0.50	1100	*Beggiatoa* colonies on sediment surface. Dark gray
NB5 (BOB)	94	88.4	16.8	31.5	2.2	1100	*Beggiatoa* colonies on sediment surface. 1 cm recent material on top of dark gray clay
BP2 (WG)	65	48.1	2.6			1000	1 cm recent material on top of gray homogenous clay
BP3 (WG)	61	57.5	2.5	6.8	0.082	800	1 cm recent material on top of silt
BP7 (HB)	67	36.1	2.3	11.6	0.14	430	Silty light brownish gray clay

Abbreviations: WG, Western Gotland Basin; HB, Hanö Bay; BOB, Bornholm Basin; LOI, loss on ignition; dw, dry weight.

phosphorus or iron bound phosphorus were used in the statistic. Karlsson et al[36] indicates that iron levels above 48 mg/g dry weight would be needed to allow iron bound phosphorus formation in sediments. Such high iron levels were not found in any surface sediment in this study. Iron concentrations in the water samples were generally lower than dissolved inorganic phosphorus concentrations, similar to results from a study in the north-western Baltic Proper,[35] while some water samples contained relatively high values of manganese concentrations. Correlations between dissolved inorganic phosphorus, iron, and manganese in the water column were significant ($n = 14$; $r^2 > 0.77$). Similar statistics were obtained for the deep water samples ($n = 7$) but correlations were insignificant if only surface water samples were included, indicating that the correlation depends on common interactions with the sediments.

This study was based on a limited number of data from sediments in a restricted part of the Baltic Sea. This allows us only to make tentative extrapolations regarding the total amount of mobile phosphorus in the system. Still such order of magnitude estimates contain valuable information about the functioning of the system and the relative importance of the sediments in the phosphorus budget. This information complements earlier estimates of phosphorus pools and fluxes based on other methods. The limited amount of data is especially evident in transportation sediments which were only represented by three cores (BP2, BP3, and BP7). Accumulation or possibly long-term transportation sediments were represented by nine cores distributed at depths between 65 m and 175 m in the Western Gotland Basin, Hanö Bay, and Bornholm Basin. In total, the area below 65 m amounts to 89,400 km^2 or 43% of the bottom area of the Baltic Proper.

The applied method for calculating the amount of potentially mobile phosphorus in the sediment has previously been used in more shallow depths in coastal areas.[18,24] The method may overestimate the mobile amount since it assumes that all the material in the sediment cores emanates from a prevailing (constant) sedimentological regime. In this study, many cores only contained 1 or 2 cm of recent material on top of silt or glacial/postglacial clays. Based on burial

Table 3. Mobile phosphorus present in collected sediments calculated as mobile TP (using TP concentration at stabilization depth to determine immobile phosphorus concentration), mobile TP_{1000} (assuming 1000 µg/g dry weight as immobile phosphorus concentration) and as the sum of the mobile P-fractions.

	Water depth m	Mobile TP g/m^2	Mobile TP_{1000} g/m^2	Sum of mobile P-fractions g/m^2
BP3 (WG)$^{\text{ox}}$	61	2.70	0	5.28
1019 (WG)$^{\text{ox}}$	65	2.15	0.13	2.57
BP2 (WG)$^{\text{ox}}$	65	2.25	0	4.41
BP7 (HB)	67	0	0	1.51
P2 (WG)	70	0.47	0	0.88
BP4 (WG)	73	2.94	4.96	3.71
P3 (WG)	77	1.27	0.14	1.61
BP6 (HB)	80	0.48	0.18	0.51
BP5 (HB)	83	0.49	0.49	1.22
P4 (WG)	94	0.89	0	1.53
NB5 (BOB)	94	0.16	0.32	0.31
BP1 (WG)	175	0.10	0.35	1.33
Minimum		0	0	0.31
Mean		1.16	0.55	2.07
Maximum		2.94	4.96	5.28
Standard deviation		1.07	1.40	1.59

Note: $^{\text{ox}}$Visual inspection combined with water column oxygen profiles indicated that these cores were oxic.
Abbreviation: TP, total phosphorus.

concentrations of total phosphorus, layers below 5 cm or so do not appear to consist of recent material in several cores even if this was not revealed by the visual inspection. It should be kept in mind though that the sediment growth in offshore Baltic sediments is low, typically ranging from 1 to 2 mm/year,[9] compared with coastal sediments typically growing 1–2 cm/year.[37]

A reasonable guess is that total phosphorus concentrations below 1000 µg/g dry weight represent material not recently deposited (silt or glacial/postglacial clays) containing insignificant amounts of mobile phosphorus. Supporting this presumption is the minor concentrations of iron bound and organic phosphorus found in these layers. Following this presupposition the amount of potentially mobile phosphorus in the sediments is best represented by the lower estimates in Table 4. This estimate is particularly affected by the anomalous phosphorus concentration measured at 4–5 cm sediment depth in BP4 (Fig. 3). If the outlier values in BP4 were replaced with interpolated values between P2 and P3, the mobile phosphorus amount calculated with this method is reduced to 30,400 tonnes in the Baltic Proper. The other methods used for calculating the total amount of mobile phosphorus in the sediments are less sensitive to the BP4 anomaly. The numbers representing the total amount of mobile phosphorus in the offshore Baltic Sea may be compared with sediments along the Swedish east coast between Öregrund and Oxelösund estimated to between 1000 and 4000 tonnes,[24] representing considerably higher concentrations of phosphorus in surface sediments.

Table 4. Estimated amounts of mobile phosphorus in the Baltic Proper sediments using different methods to compute mobile phosphorus (compare with Table 3).

Depth interval	Area km^2	Mobile TP tonnes	Mobile TP_{1000} tonnes	Sum of mobile P-fractions tonnes
60–69 m	14,600	28,900	359	53,700
70–95 m	38,800	35,400	33,500	54,600
96–175 m	39,900	14,800	19,800	42,700
176–411 m	4050	412	1400	5390
Total	97,300	79,500	55,100	156,300

Abbreviation: TP, total phosphorus.

Based on our highest estimate, mobile phosphorus in the sediments below 60 m in the Baltic Proper (156,300 tonnes) account for around 25% of the dissolved inorganic phosphorus and around 20% of the total phosphorus in the system (water column plus sediments). Jonsson et al[9] measured total phosphorus concentrations in eight surface sediments (0–5 cm) below 88 m depth in different parts of the Baltic Proper in 1986–1989 and found total phosphorus concentrations between 700 µg/g and 1200 µg/g dry weight indicating similarly small amounts of mobile phosphorus during a period of large dissolved inorganic phosphorus amounts in the water column.[8]

Assuming a typical potential of the sediments to retain mobile phosphorus to be 2 tonnes per km^2 (consistent with the regression by Conley et al,[8] and consistent with our data and coastal data presented by Malmaeus et al,[24] the sediments below 65 m depth that presently contain little phosphorus could theoretically absorb 180,000 tonnes of phosphorus from the water column in the Baltic Proper if oxygenated. The corresponding number for the sediments between 65 m and 100 m water depth would be around 100,000 tonnes, and the area equivalent to the expansion of laminated sediments between 1960 and 1990 according to Jonsson et al.[9] Reducing the amount of phosphorus in the bottom waters by 100,000 tonnes corresponds to a decrease in phosphorus concentration around 30 mg/m^3 in the deep water (below 65 m), and the effect would possibly be felt also in the surface water although less dramatic. It is worth reflecting on the fact that the adjacent Bothnian Sea, where almost all sediment surfaces are oxic,[38] typically has total phosphorus concentrations in surface water around 10 mg/m^3 lower than the Baltic Proper,[6] keeping in mind that also the external P loading is lower to this basin.[3]

It appears that nearly all mobile phosphorus is present in the top 3–4 cm of the sediments indicating a turnover time around 15–40 years given a sediment growth of 1–2 mm/year.[9] This in turn implies an average annual release from the estimated sediment pool of mobile phosphorus to the water column around 0.1 g/m^2, which is the same order of magnitude as reported by Hille et al,[15] but lower than the calculations presented by Emeis et al,[14] Ahlgren et al,[17] and Mort el al.[16] One reason for the discrepancy could be that the studies by us and Hille et al[15] integrate a number of sampling stations from soft bottoms of various depths, whereas the other studies were concentrated to deep holes (>100 m water depth). Presumably larger release rates can also be associated with short-term redox conditions that may be present during some pore water studies but not representative for long-term conditions studied in sediment cores representing time integration over decades.

Given the recognition of the eutrophication problems in the Baltic Sea and the ambitious action plans to address them, such as the Baltic Sea Action Plan aiming to reduce annual external phosphorus inputs by some 15,000 tonnes, it remains of paramount importance to improve the knowledge about the pools and dynamics of mobile phosphorus in sediments. We suggest that further efforts to measure amounts of mobile phosphorus in sediments in different areas of the Baltic Sea should be made promptly and in concert with the development of future action plans.

Conclusion

Sediments below the redox cline in the Baltic Proper contained small amounts of mobile phosphorus. However, there were some anomalies in the data indicating that there may be some variation. Assuming that the low levels measured in most of the sediments below the redox cline were representative for the sediments in the study area the total amount of mobile phosphorus in the entire Baltic Proper sediments below 65 m water depth was estimated to 55,000 tonnes or less than 10% of the dissolved inorganic phosphorus in the system (water plus sediments). Using a different approach, the highest estimate of total amount of mobile phosphorus in the sediments below 65 m water depth in the area was 156,000 tonnes, or around 25% of the total amount of dissolved inorganic phosphorus in the system. We argue that the lower number is the most reasonable estimate of the pool of mobile phosphorus in the sediments. The amounts of mobile phosphorus in sediment cores with oxidized surface layers were higher compared with sediment cores with reduced surfaces, indicating that there is a potential P-binding capacity in sediments below the redox cline if they were oxygenated. Oxygenation of the Baltic Proper bottom water between 65 m and 100 m could probably remove around 100,000 tonnes of phosphorus from the water column and reduce phosphorus concentrations in the deep water by on average 30 mg/m^3, which would possibly be felt also in the surface water.

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Disclosures

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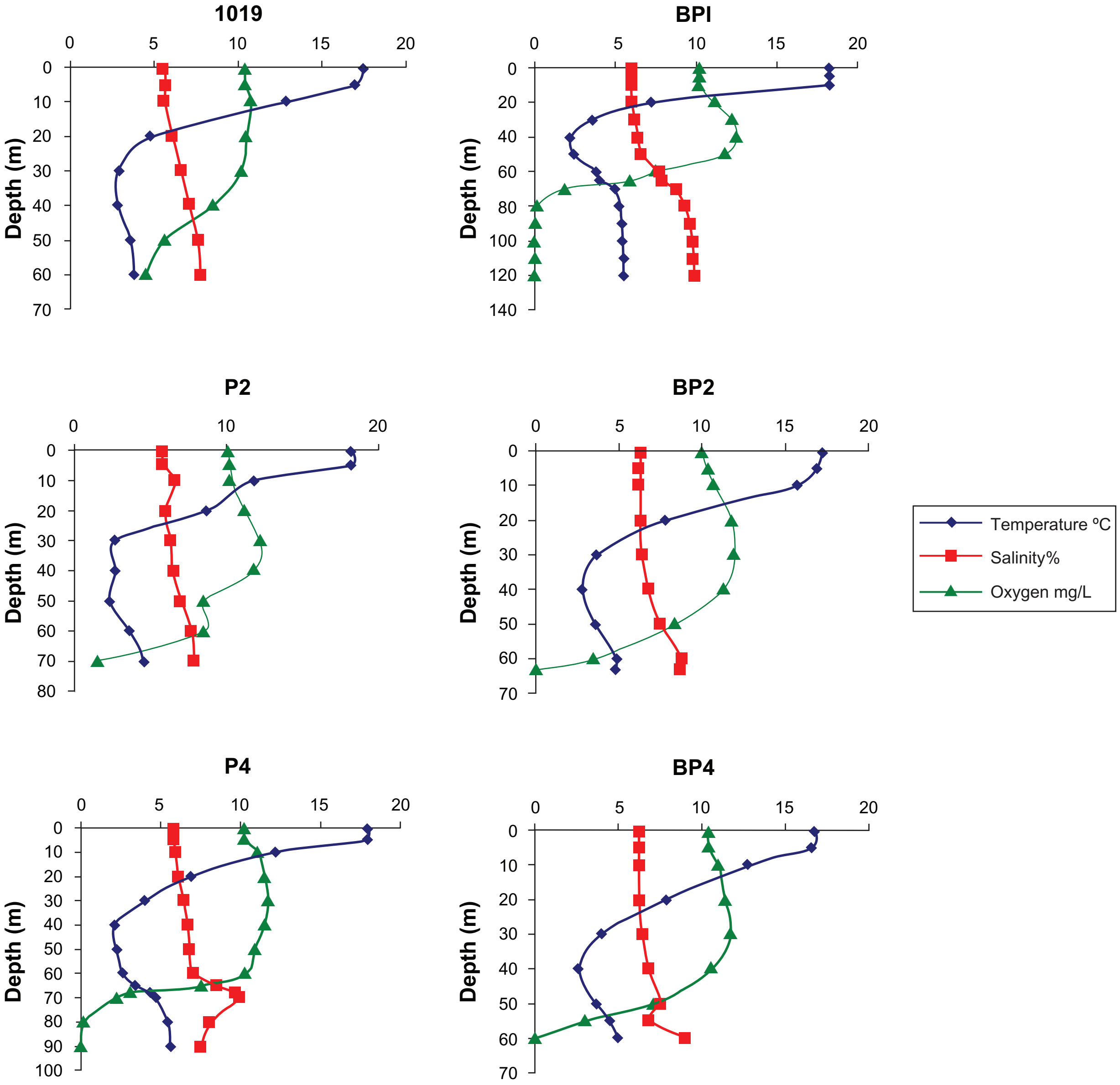
Appendix



Appendix 1. Depth profiles of temperature, salinity, and oxygen in water.