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Different reasons for low pore water phosphate concentrations observed at a shallow brackish site in a German Baltic Sea lagoon

Abstract

In the sediment pore water of a brackish shallow water site (0.5 m water depth) with abundant macrophyte stock located in the Darss-Zingst-Bodden-Chain (DZBC), concentrations of soluble reactive phosphate (SRP; PO_4^{3-}) are remarkably low (0-3 µM) throughout the year. The corresponding calculated fluxes into the overlying water are negligible. During dark sediment core incubations in the laboratory lasting 5-6 hours, fluxes of SRP were not detectable, but certainly <200 µmol P m^{-2} d^{-1}, in agreement with scarce literature data. These observations indicate that during periods without substantial erosion, this sediment probably does not support any significant efflux of SRP to the overlying water.

Here we present our views as to why the concentrations are as low, discussing the potential sinks and sources for PO_4^{3-} based on a preliminary set of data and literature. By comparison with a deeper site (2 m water depth) consisting of a different sediment type with fewer organisms (benthic fauna and macrophytes), we conclude that the biological structures probably generate additional capacity for adsorption of SRP. Adsorption is likely more important for causing low PO_4^{3-} concentration in the pore water than burrow ventilation (bioirrigation). We hypothesize that under these circumstances benthic macrophytes cover their P-demand by uptake through the roots, whereas pelagic phototrophs do not receive much SRP from the sediment.

Keywords: Soluble reactive phosphate, sediment, sink, source, adsorption, burrow, root

1 Introduction

Sediments of aquatic ecosystems in general, and the Darss-Zingst-Bodden-Chain (DZBC) as well, are considered sites of accumulation for phosphorus (SUNDBY et al. 1992). Phosphorous is continuously washed into the Bodden chain ecosystem from surrounding agricultural and riverine sources in particulate and dissolved form and accumulates in the sediment in different chemical compounds and states. The dominant mobile form is soluble reactive phosphate (SRP), the PO_4^{3-}-ion that is available for primary production and therefore accounts for eutrophication processes.

The sediment is also viewed as a constant source of PO_4^{3-} released to the overlying water fueling primary productive processes therein.

With respect to phosphorous cycling many fresh and brackish water systems have been conceived as P-limited (STERNER 2008, LEWIS & WURTSBAUGH 2008) and their eutrophication state also is ascribed to a continuous or recurring phosphorous fertilization from within the system, particularly from the sediments (PITKÄNEN et al. 2001). Similarly, the sediments in estuaries and even in the DZBC are until now viewed as a source of phosphorous (BLÜMEL et al. 2003). Even sediment excavation for remediation purposes has been discussed as a possible action against its continuously elevated state of eutrophication (QUANDT & KNAACK 2005).

In the context of the ongoing project BACOSA (Baltic Coastal System Analysis and Status Evaluation), we examine the potential export of SRP from the sediment as a nutrient for benthic and pelagic primary production and its possible role in the recent reappearance of massive macrophyte canopies at a shallow water site (0.5 m water depth). At this routinely sampled location in a brackish lagoon near Dabitz, Northeastern Germany (54,3670° N; 12,8060° E), pore water concentrations of PO_4^{3-} constantly are remarkably low and do not seem to indicate that this sediment is a direct source of PO_4^{3-} to the overlying water. This is different at close-by located sediments from 2 m water depth. It is a recurring observation that shallow fresh water and marine sediments contribute less to benthic SRP-fluxes to the overlying water and contain lower concentrations of SRP than depositional sediments from greater water depths (KLEEBERG et al. 2013, BONAGLIA et al. 2014). While BACOSA has not finished its program, findings thus far will be compared and discussed in terms of potential sinks and sources for dissolved PO_4^{3-} in the sediment and transport mechanisms to the overlying water. We will consider the order of magnitudes of available data and identify the present state of knowledge for this shallow sediment.

2 Theory

The supply of organic matter to shallow coastal sediments is smaller compared to deeper sites because lateral transport processes transfer particulate matter to depositional sites like troughs and basins (KLEEBERG et al. 2013). Temporal deposition of particulate matter in shallow locations generally impacted by wave action and erosion, and in situ production of organic matter by phototrophs is possible, but overall morphology of the system defines erosion areas and accumulation areas. Phosphorus, associated with the organic matter (OM), may remain in the organic pool as part of total phosphorous (TP) and accumulate in the basins. Decay of OM and diagenesis liberates PO_4^{3-} into the pore water. Therefore, PO_4^{3-} is expected to be more abundant where accumulation of OM is high.

The pore water distribution of a dissolved substance reflects a set of reactions and (transport) processes, referred to as sinks and sources, which affect its local concentration. In the case of $PO_4^{3-,}$ the sources include production during mineralization of organic material at all depths in the sediment as well as liberation due to the reductive dissolution of adsorption sites by bacteria or sulfide, namely mineral iron surfaces, in reduced sediment layers (ANSCHUTZ et al. 2007, SLOMP & VAN CAPPELLEN 2009, SLOMP 2011). Dissolution of adsorption sites occasionally leads to the formation of a sub-surface concentration maximum in PO_4^{3-}, with higher PO_4^{3-}-concentrations in the sediment than in the overlying water (similarly in pore water NH_4^+-

concentrations) while in contrast adsorption in oxidized sediment layers acts as sink for SRP.

This simplified picture, the existing paradigm stating the importance of the link between P and Fe through redox sensitive oxides, is being challenged for fresh water systems. In their review HUPFER & LEWANDOWSKI (2008) point out that alternative adsorption sites ($Al(OH)_3$, unreducible iron oxides and other than redox-dependent dissolution mechanisms (Ca - P bonds) make P release from these sediments more complex than previously thought. Compared to fresh water, in brackish systems hydrogen sulfide exists in varying concentrations as a competitive reactant for iron.

In general terms PO_4^{3-} sinks in these sediments are represented by adsorption onto particulate matter, losses based on diffusion along concentration gradients, ventilation of invertebrate burrows and uptake by rooted plants. The concentration difference between pore water and overlying water drives a diffusive flux of solutes directed vertically towards the sediment - water interface. In permeable sediments this flux may be considerably enhanced by advection of pore water when currents or waves impact the sediment below the threshold of particle resuspension (HUETTEL et al. 2003, FORSTER et al. 1996). Ventilation of burrows renders burrow water concentrations more similar to the overlying water than to adjacent pore waters. Thus bioirrigation, the exchange of solutes between sediment pore water and overlying water due to burrow ventilation, acts to transport PO_4^{3-} away from the sediment through radial diffusion towards the burrow walls (DALE et al. 2011, ALLER 2014). Bioirrigation may also establish oxidized burrow walls that act as a barrier adsorbing some of the PO_4^{3-} onto amorphous iron hydroxides (ALLER 2014). Bioirrigation activity thus is a sink within the sediments; however, it may supply pelagic primary producers with small pulses of SRP.

Similarly, it may be assumed that a diffusive flux exists directed towards the roots of submersed plants that reduce adjacent pore water concentrations by active uptake of PO_4^{3-} (MOELLER et al. 1988; ANGELSTEIN & SCHUBERT 2008). Here, too, excretion of molecular oxygen along roots leads to oxidation of sediment and metal crust establishment thus ultimately interfering with phosphate transport to the root (SUNDBY et al. 1998, LASKOV et al. 2006, JOVANOVIC et al. 2015). Uptake of SRP by roots represents a sink for the entire system at least for the growth season, since all PO_4^{3-} is fixed in macrophyte plant tissue. Finally, uptake, accumulation and release by benthic bacteria may affect dynamics and overall concentrations (DALE et al. 2013).

In the discussions below we assume steady state for all given sources and sinks (BERNER 1980) since we have so far no indications for short-term variations in pore water PO_4^{3-} concentrations at this shallow location. Spatial heterogeneity seems to exceed temporal variations by in large, but throughout the year the concentrations remain continuously low at the shallow Dabitz site.

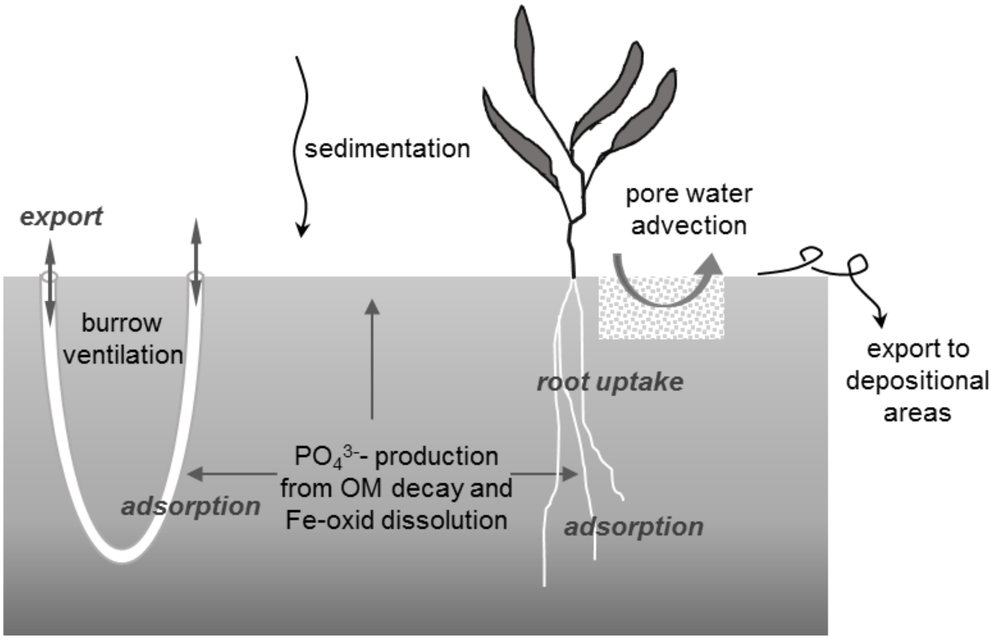

Fig. 1: Schematic showing major transport processes, sources and sinks (italic, grey) regulating pore water PO_4^{3-} -concentrations. Straight arrows depict diffusive fluxes. OM: organic matter.

3 Observations

During BACOSA field work in 2014 the Dabitz shallow (0.5 m) and deep site (2 m) were sampled for sediment parameters in March, May, July, September and November. Sediment characteristics differ at both sites (Table 1). Water content (weight loss upon drying), median grain size and grain fraction <63 µm (both dry sieving), permeability (content head permeameter) and content of organic matter (loss on ignition) differ as expected according to topography. Based on the higher organic content, the bacterial mineralization of organic matter liberating PO_4^{3-} should be higher at 2 m water depth.

Measured permeability at the shallow site is at the limit of 1-3 x 10^{-2} m^2 above which advection of pore water can be induced by currents above the sediment (HÜTTEL et al. 1998). This is somewhat astonishing in view of the relatively large median grain size. However, FORSTER et al. (2003) showed that skewed grain size distributions can render measurable permeability much smaller that theoretically expected. There is a skewed grain size distributions here (data not shown) with many small grains possibly clogging pores. At the deep site there was no measurement possible within an acceptable time interval, indicating that $k < 10^{-14}$ m^2. Thus, we exclude advective pore water effects in the following interpretation of our observations at both sites.

The two stations are similar in total phosphorous inventory calculated as the inventory in the upper 0-10 cm per m^2 (colorimetric determination after acid *persulfate* digestion).

There is a pronounced difference in macrophyte coverage, which is high at the shallow site and negligible at 2 m depth. BLINDOW & MEYER (this issue) present data from 2001–2007 which represent the current situation well with around 70 % versus ~2 % coverage. The abundance of burrowing macrofauna also differs markedly. Sieving on eight occasions (500 µm mesh; BITSCHOFSKY et al. this volume) we found high numbers of 3000 Ind. m^{-2} on average of the polychaete *Hediste diversicolor* at the shallow site. Though data are not available, observations while sampling at the deeper site indicated much fewer animals, presumably chironomid larvae or small worms.

Tab. 1: Site characteristics at 0.5 and 2 m water depth. Means and standard deviations (s.d.) for water content (n=5), median grain diameter (n=5), fraction <63 µm in the sediment (n=5), k: permeability (n=3), LOI: Loss on ignition (n=5), TP-i: Total Phosphorous inventory (0-10 cm sediment depth, n=3), plant cover (% area) and benthic infauna abundance (n=3). Measurements are from March, May, July, September, and November 2014. [1] very low (not measurable in acceptable time interval); [2] plant cover taken from BLINDOW & MEYER (this issue); [3] Minimum abundance of *H. diversicolor* at 0.5 m site, mean± % s.d.; [4] no numbers available, but only worms observed while sediment samples.

Depth (m)	**Water Content** (% FW)	**MD** (µm)	**Fraction <63 µm** (%)	**k x10^{-12}** (m^2)	**LOI** (%DW)	**TP-i** (mmol m^{-2})	**Plant cover [2]** (%)	**Infauna [3]** (Ind m^{-2})
0.5	23±2	300±4	2.5±1.7	1.3±0.1	0.8±0.1	569±32	70	3058±62%
2.0	75±4	80±0.2	34±1.7	<0.01[1]	9.3±1.9	599±36	2	few [4]

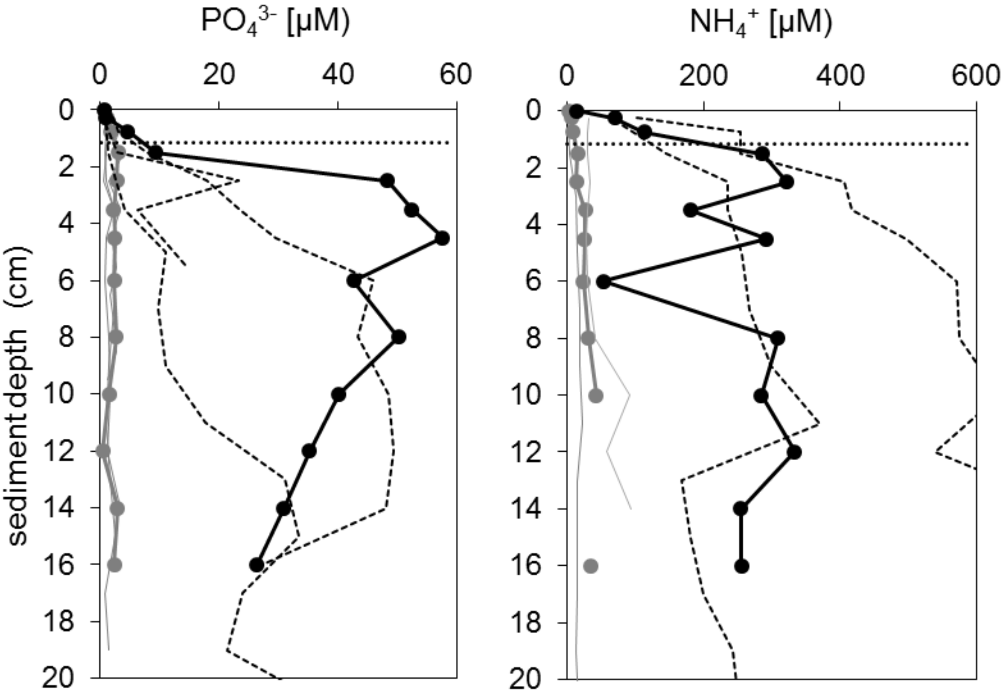

Fig. 2: Pore water phosphate (left) and ammonium concentrations (right) from July 2014 indicated by solid lines and symbols in gray for the shallow site (0.5 m) and black for the deep site (2 m). Pore water distributions from March, May and September of the respective solute are depicted without symbols and dashed lines. For both solutes concentrations differ markedly between the shallow (gray) and deep site (black). Uppermost points indicate concentrations in the overlying water (<1 µM PO_4^{3-} and ~14 µM NH_4^+). Horizontal dotted lines indicate the depth of the oxidized surface sediment.

Typical pore water profiles from the shallow and deep site show the difference in PO_4^{3-} concentration that is the issue of this article. Low concentrations with a small gradient at the sediment surface at 0.5 m (Fig. 2) contrast concentrations up to 50 µM

PO_4^{3-} at 2 m. Variations indicated by 2-3 additional profiles in figure 2, sampled between March and September, may show seasonal or spatial heterogeneity. They support the general pattern of high versus low pore water concentrations. Ammonia concentrations for comparison in the right panel show that NH_4^+-concentrations are also depleted at the shallow site.

In order to quantify bacterial PO_4^{3-} production we retrieved sediment from 5-10 cm sediment depth of both sites, excluding roots and burrows as much as visibly possible. The sediment was mixed and incubated for up to 25 days in replicate vials under anoxic conditions (vials filled without headspace and incubated buried in anoxic mud). Analyzing samples sequentially, we observed linear increases of PO_4^{3-}-concentrations in the pore water. Since SRP concentrations basically remain at the same concentration levels down to 20 cm depth (Fig. 2), we assume this depth as the productive sediment layer for the following discussion. We calculated areal rates of 167 at the shallow site and 50 µmol PO_4^{3-} m^{-2} d^{-1} at the deep site along with ammonia production rates from the same experiments (table 2). Thus at both sites generation of PO_4^{3-} is observed.

Pore water profiles indicate that there is a flux across the sediment-water interface. These fluxes are quantified based on the observed concentration gradients from the upper 2 cm including the overlying water concentration. PO_4^{3-}-fluxes thus calculated using Fick's First Law of Diffusion and temperature and tortuosity corrected diffusion coefficients (BOUDREAU 1997) are presented in table 2. The corresponding NH_4^+-fluxes and N:P ratios are also presented.

An alternative method to obtain interfacial fluxes is the interpretation of the data using the model software PROFILE (BERG et al. 1998). This method takes into consideration the whole data set, not only those values close to the interface, and thus seems more reliable when profiles are not smooth. We used the same diffusion coefficients as in the gradient based calculation. These calculations provide another different measure of fluxes, however, based on the same data.

Tab. 2: Data on production rates and fluxes of PO_4^{3-} and NH_4^+ at both sites. Volumetric production rates were integrated to 20 cm sediment depth; fluxes are additionally given as percentage of the integrated production in parentheses; * the model PROFILE (BERG et al. 1985) was used to interpret pore water SRP profile and extract fluxes at the sediment-water interface.

Depth (m)	**Integrated production (µmol m^{-2} d^{-1})**		**Gradient based molecular fluxes (µmol m^{-2} d^{-1})**		**Model* based molecular fluxes (µmol m^{-2} d^{-1})**	
	PO_4^{3-}	**NH_4^+**	**PO_4^{3-}**	**NH_4^+**	**PO_4^{3-}**	**NH_4^+**
0.5	167	6386	1.1 (0.6)	15 (0.2)	0.6 (0.4)	n. c.
2.0	50	1540	18 (36)	1625 (90)	67 (134)	n. c.

Model PO_4^{3-} distributions were fitted to the July data from figure 2 for both sites (Fig. 3) and fluxes calculated (Tab. 2). At the shallow site the modelled flux is very small and closely resembles the gradient based flux (Tab. 2). The modelled flux at the deep site (67 µmol P m^{-2} d^{-1}) is much larger than the corresponding gradient based value. This is also reflected by the steeper gradient of the modelled dashed line in figure 3, which takes into account the production of SRP reflected by the subsurface maximum at 5 cm depth.

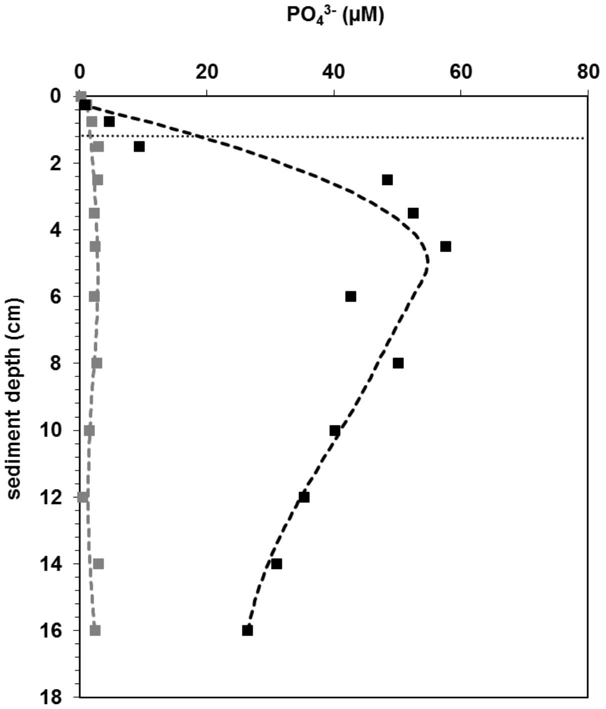

Fig. 3: Modelled PO_4^{3-}-concentrations (dashed lines) fit to main profiles (July; squares) from figure 2. Shallow site: grey; deep site: black. Horizontal dotted line indicates the depth of the oxidized surface sediment. This model interpretation using the software "*PROFILE*" yields a flux of 0.6 µmol PO_4^{3-} m^{-2} d^{-1} for shallow and 67 µmol PO_4^{3-} m^{-2} d^{-1} for the deep site.

At the shallow site, neither the gradient based nor the modelled PO_4^{3-}-fluxes compare well with the integrated P-production. They account for less <1%, as the NH_4^+-flux which amounts to 1.2% of the NH_4^+-production. A very small fraction of the microbially produced PO_4^{3-} (and NH_4^+) seems to escape the sediment through diffusion along concentration gradients towards the sediment water interface. This is in agreement with the low pore water concentrations generally found for both solutes at 0.5 m depth and points to similar processes affecting both solutes at this site.

At the deep site both PO_4^{3-}- and NH_4^+-fluxes constitute a higher percentage of the respective production in the sediment. Given uncertainties in production rates measurements and the differences between gradient based approaches versus model based calculations outlined above, the efflux of PO_4^{3-} at the 2 m site closely fits the integrated production rate. This is true, too, for the NH_4^+-flux. Ammonium adsorption to sediment particles is a reversible salinity dependent process and not redox sensitive (MACKIN & ALLER 1984).Therefore production should actually equal export, if no other sinks are present in the sediment.

We tried to measure fluxes across the sediment-water interface at several occasions by monitoring start and end concentrations in the water overlying the sediment. We did this only for the shallow site both in laboratory core and in situ chamber incubations. Concentration changes were too low within the given incubation time (5-6 hours) and enclosed overlying water volume to reliably detect a flux of SRP. However, we can confine the flux to <200 µmol PO_4^{3-} m^{-2} d^{-1}, which is the magnitude of the P-fluxes that reported so far in this area of the DZBC by BADER & SCHLUNGBAUM 1982. These authors report between 60 and 157 PO_4^{3-} µmol m^{-2} d^{-1} while including anoxic conditions during the experiment that would theoretically have fostered dissolution of iron minerals and thus enhanced the PO_4^{3-}efflux. While we do not know the magnitude of the benthic PO_4^{3-}-flux, it is likely that this flux is minute at the shallow site because the shape of the pore water profiles does not support any significant flux. Consequently, there must be one or more other mechanisms acting as sink(s) for PO_4^{3-} in this sediment.

4 Discussion

We consistently observed low SRP in the pore water at the shallow site despite a TP inventory, which is similar to that at the deep site. Material eroded at shallow sites by wave action is subsequently washed to topographic deeps where phosphorous accumulates (KLEEBERG et al. 2013). The high organic matter content at the deep site is an indication of this happening in the Bodden. However, similar TP inventories at both the shallow and deep site seem somewhat contradict the notion of higher P-accumulation in the deeps. Certainly more data are needed to further clarify this here. Our data suggest, though, that high pore water SRP concentrations here are not simply related to a high TP-content in the sediment.

During erosion of particles some pore water is necessarily entrained as well. KLEEBERG et al. (2013) report significant entrainment of SRP along with particulate matter from a shallow lake sediment during erosion events. While this certainly also occurs at our shallow Bodden station, we currently do not have sufficient information to account for the effect of this process.

Other factors responsible for the observed low SRP at the shallow station are the adsorption of phosphate or export/uptake of phosphate from interstitial waters.

4.1 Bioirrigation and uptake

Burrows constructed by benthic animals influence this sediment to about 17 cm depth. Along with roots, that also protrude to a similar depth, they form a complex three-dimensional structure that affects pore water concentrations, but that is not well represented in vertical pore water concentration profiles. Horizontal slicing homogenizes concentrations within each sediment slice. Pore water extraction by Rhizone also averages local solute differences by withdrawing water from an ellipsoid volume (SEEBERG-ELVERFELDT et al. 2005). In either case, one average concentration per depth interval is obtained. This does not capture horizontal gradients well that may exist along roots and burrows. Therefore, limited understanding of how spatial heterogeneity affects spatial distribution of solutes and fluxes hampers our ability to interpret these pore water profiles.

Ventilation of burrows by benthic animals, bioirrigation, can substantially enhance the export of solutes from sediments to the overlying water (KRISTENSEN et al. 2010, ROSKOSCH et al. 2010). If conditions are such that the pore water surrounding the burrows contains higher concentrations of PO_4^{3-} than the water flushed trough the burrows by ventilation, PO_4^{3-} will diffuse into the burrow and repeatedly be flushed from there into the overlying water (DAVEY et al. 1990). Bioirrigation does enhance solute exchange and SRP export from the sediment in some circumstances as observed for *H. diversicolor* and *Marenzelleria* spp. through direct measurement by KRISTENSEN (2010) and RENZ & FORSTER (2014).

At our shallow site high abundances of *Hediste diversicolor*, a polychaete living alternatively as filter-feeder or deposit feeder, but also capable of predation, suggest a strong influence on pore water concentrations. In contrast to the situation outlined above, concentrations observed in the pore water are low, gradients of both PO_4^{3-} and NH_4^{3-} between pore water and burrow water must be small and fluxes accordingly, too. In cases when there is a substantial average concentration of a solute, burrow ventilation is able to reduce the adjacent pore water concentrations remarkably. ZIEBIS et al. (1996) found a concentration reduction from ~100 to ~10 µM NH_4^{3-} due to the ventilation of crustacean burrows in the Mediterranean Sea.

Whether the pore water in our case is deprived of phosphate and ammonia because of ventilated burrows remains unclear. Ventilation certainly has the potential to cause the low pore water concentrations here, however, once the concentrations are low in the pore water the resulting small concentration differences suggests a limited effect of these burrows on PO_4^{3-} and NH_4^{3-} export. This remains to be seen in future incubation experiments that include burrow ventilation activity.

Macrophytes can acquire SRP alternatively via shoots or roots and may change the proportion of these routes according to the concentrations of PO_4^{3-} available to them in the surrounding sediment or water at any time (KUFEL & KUFEL 2002, ANGELSTEIN & SCHUBERT 2008).

If uptake through roots is a sink to pore water concentrations they should reduce pore water concentrations visibly. With the high coverage of submersed macrophytes, roots are obviously another candidate for a sink at the shallow site. We do not know, yet, to which extent P from the sediment is allocated to plant biomass here and what the demand for PO_4^{3-} of macrophytes is at Dabitz.

The capacity of sulfide oxidizing bacteria to affect PO_4^{3-} dynamics specifically in oscillating redox conditions (Dale et al. 2013) as well as the formation of phosphate-containing minerals along root mineral crust that could remove P from short-term diagenetic cycling (SUNDBY et al. 1992) are further issues that we cannot exclude.

4.2 Role of adsorption

PO_4^{3-} is known to adsorb to mineral surfaces with iron and manganese oxides that are mainly present in superficial sediments of both saline and fresh water systems (PANT & REDDY 2001; HUPFER & LEWANDOWSKI 2008). Additionally $Al(OH)_3$ and iron oxides that are not reduced quickly in response to redox changes also contribute to adsorption capacity of sediments (HUPFER & LEWANDOWSKI 2008).

Measurements of oxygen (O_2-microelectrode, ex-situ; REVSBECH & JORGENSEN 1983) and redox potential (Eh; Pt-electrode, Schott) were performed at the shallow site only and are used to illustrate the oxidation state at the sediment-water interface. Although there are no data available for the deep site, oxygen penetration there will likely be similar.

Oxygen only penetrates the upper 1.5 mm of the sediment at 0.5 m depth. The oxidized sediment layer, as defined by redox potentials (Eh) >100 mV, is between 1 and 1.5 cm thick. Below this depth, the sediment is reduced and anoxic (Fig. 4). The thickness of oxidized sediment (Eh) in relation to sediment containing dissolved O_2 is 10:1 in figure 4, similar to findings by FORSTER & GRAF (1992). This is typical for non-permeable sediments in productive shallow water sites.

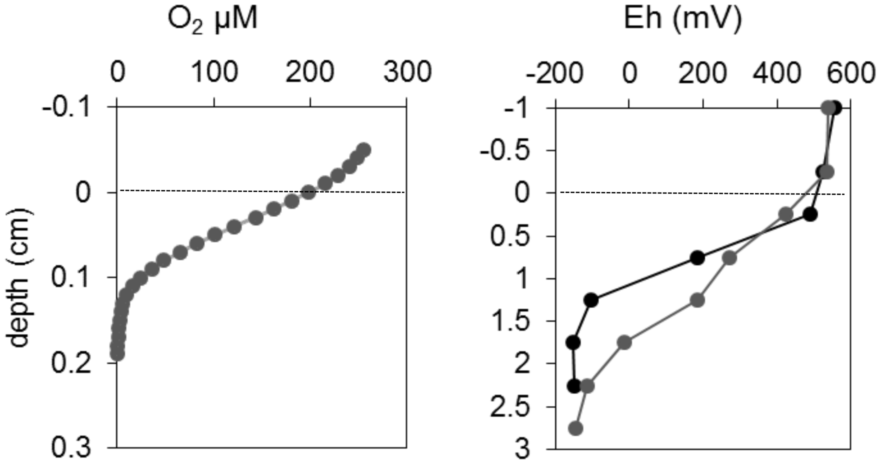

Fig. 4: Oxygen distribution measured with a microelectrode ex-situ (left) and redox potential distribution (Eh, right) at the sediment-water interface. Oxygen values are averages (n=7), Eh-profiles show two individual measurements.

Animal tubes and rooted plants transport O_2 influencing this sediment. The same complex three-dimensional structure that potentially reduces PO_4^{3-} by bioirrigation and root uptake (see above) likely produces an oxygen distribution along many biological interfaces far below the sediment-water interface at the shallow site.

Bioirrigation oxidizes sediments by pumping O_2 into the burrows, subsequently forming an oxidized halo around each burrow. To our knowledge, it remains to be shown in detail under which circumstances adsorption of PO_4^{3-} to the oxidized sediment layer surrounding the burrow walls interferes with radial diffusion and subsequent export of PO_4^{3-} from the sediment by ventilation. At the oxidized surface layer at the sediment-water interface (Fig. 4) adsorption of SRP is not enough to reduce concentrations to zero, as visible in figure 2, where profiles support a flux out of the sediment despite the oxidized “barrier”. Thus, one could assume that PO_4^{3-} might in principle escape through the oxidized, adsorptive barrier that a halo represents. As discussed above, with small concentration gradients in our case this flux should be minute.

The O_2-diffusion from burrows constructed by the polychaete *Hediste diversicolor* is generally found to be about 1 mm deep into the adjacent sediment (FENCHEL 1996), however, with pronounced diurnal and activity dependant fluctuations on the scale of hours (FORSTER & GRAF 1992). At Dabitz, burrows of this species measuring 2.5 – 3.0 mm in diameter extend to between 13 and 17 cm sediment depth (U. LEHMANN 2015; data not shown). Each burrow provides roughly 15 cm^2 of surface for the additional transport of oxygen into otherwise anoxic sediments (U. Lehmann 2015, data not shown). At an abundance of several thousand Ind. m^{-2} (BITSCHOFSKY et al., this volume) this macrozoobenthos species alone is likely to oxidize a considerable volume of sediment.

Rooted plants excrete oxygen and oxidize sediment layers adjacent to the outer cuticula in defense against toxicity of metal ions. For *Ruppia maritima* and *Potamogeton crispus information on the extent of sediment oxygenation by roots is available in the literature (*LASKOV et al. 2006, JOVANOVIC et al. 2015). Species from the same genus, *P. pectinatus* and *Ruppia spp., as well as Chara spp.* dominate at the shallow Dabitz site. Jovanovic et al. (2015) report the oxic volume surrounding roots of young isolated individuals of *R. maritima* to be 5.4 mm³ per plant. They also provide relations to root biomass. Laskov et al. (2006) calculated the radial oxygen loss, ROL, in *P. crispus* as 3 – 4 µmol O_2 h^{-1} per plant. With a parameter relating rhizome biomass to oxygen input it would be possible to estimate the extent of root related oxygen input. Laskov et al. (2006) also found that *P. crispus* reduced ROL at night by only 30% of the daytime value, whereas other species display stronger diurnal change with no oxygen at night (Hemminga 1998).

It may be assumed with certainty that at about 70% coverage of plants and given abundant burrowing polychaetes, burrow walls and root surfaces increase the volume of oxidized sediment substantially at the shallow site, generating a three-dimensional network of geochemically active interfaces.

4.3 Conclusions

Despite the erosional character of the shallow site, the inventory of TP is as high as at the deep site. How this relates to SRP-production in the sediment at the shallow site, pore water concentrations and efflux of SRP to the overlying water, cannot be resolved and is an issue for future investigations.

We conclude that at this shallow erosional site in the lagoon, bioirrigation and uptake by roots constitute sinks for SRP, which potentially cause the observed low pore water concentration. Bioirrigation probably does not export much SRP due to small radial concentration gradients. The uptake by roots likely constitute a more prominent sink, since low SRP concentrations in the water necessitate uptake through the roots. We suspect that the interfaces between biological structures and sediment also constitute an additional quantitatively important mechanism for adsorption of SRP in addition to the oxidized sediment surface. This sink for PO_4^{3-} would be particularly effective because of its delicate and deep reaching spatial distribution. A mass balance including the role of burrows and roots is necessary before we will know their quantitative importance during periods without substantial erosion.

Thanks

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