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Benthic fluxes of oxygen and inorganic nutrients in the archipelago of Gulf of Finland, Baltic Sea – Effects of sediment resuspension measured in situ

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ABSTRACT

Benthic fluxes of oxygen and dissolved inorganic nutrients; phosphate (DIP), ammonium (NH_4), nitrate + nitrite (NO_x), and silicate (DSi); and the effects of resuspension on these were studied in situ with the Göteborg benthic landers in the Gulf of Finland archipelago, Baltic Sea. The benthic fluxes were examined at two shallow stations at depths of 7 m and 20 m in May and August 2014. Resuspension altered benthic fluxes of oxygen and nutrients in most of the experiments in August, but not in May, which was mainly due to weaker resuspension treatments in spring. Additionally, the benthic nutrient regeneration rates were higher and redox conditions lower in August when the water was warmer. In August, resuspension increased the benthic oxygen uptake by 33–35%, which was, in addition to stronger resuspension treatment, attributed to higher amounts of dissolved reduced substances in the sediment pore water in comparison to conditions in May. Adsorption onto newly formed iron oxyhydroxides could explain the uptake of DIP by the sediment at the 20 m station and the lowering of the DSi efflux by 31% at the 7 m station during resuspension in August. In addition, resuspension promoted nitrification, as indicated by increased NO_x fluxes at both stations (by 30% and 27% at the 7 m and 20 m station, respectively) and a lowered NH_4 flux (by 48%) at the 7 m station. Predicted increases in the magnitude and frequency of resuspension will thus markedly affect the transport of phosphorus and silicon and the cycling of nitrogen in the shallow areas of the Gulf of Finland.

1. Introduction

Sediment resuspension caused by physical forces, such as waves and currents, is a common phenomenon in marine shallow coastal areas (e.g. Blomqvist and Larsson, 1994; Valeur et al., 1995) and may be an important factor that affects mineralization and recycling of nutrients and productivity of overlying waters (e.g. Fanning et al., 1982; Sloth et al., 1996; Thomsen et al., 2002; Ståhlberg et al., 2006; Porter et al., 2010; Capet et al., 2016). Resuspension in the shallow coastal areas of the Baltic Sea can induce mixing of sedimentary particles and nutrients into the water column (Floderus and Pihl, 1990; Blomqvist and Larsson, 1994; Danielsson et al., 2007). Inorganic nutrients such as ammonium (NH_4) and phosphate (DIP) can, depending on the physico-chemical conditions of the ambient bottom water, be taken up by or released from resuspended particles due to sorption/desorption processes (Morin and Morse, 1999; Pant and Reddy, 2001; Almroth-Rosell et al., 2012). Nutrients dissolved in the sediment pore water can also be mixed into the overlying water body (e.g. Christiansen et al., 1997; Spagnoli and Bergamini, 1997). Additionally, the oxygen consumption of the surface sediment and overlying water may be affected, with further consequences to nutrient cycling (Wainright and Hopkinson, 1997; Almroth et al., 2009; Moriarty et al., 2017). For instance, if resuspension stimulates hypoxia and anoxia, the benthic fluxes of DIP and dissolved silicate ($Si(OH)_4$, hereafter called DSi), are likely to increase (e.g. Sundby et al., 1986; Danielsson et al., 2008; Danielsson, 2014; Ekeroth et al., 2016b; Tallberg et al., 2017). On the other hand, when redox-sensitive dissolved substances, such as ferrous iron, are mixed into bottom water that is rich in oxygen, soluble iron will be oxidized and scavenge DIP (e.g. Sundby et al., 1992). DSi may also be efficiently adsorbed by both iron (Fe) and aluminum (Al) oxides under oxygenated conditions (Anderson and Benjamin, 1985; Tallberg et al., 2008; Tuominen et al., 1998) and resuspension of Fe- and Al-oxides may affect the net benthic fluxes of both DIP and DSi by changing the concentration gradients. Since an oxygen deficit may also affect the

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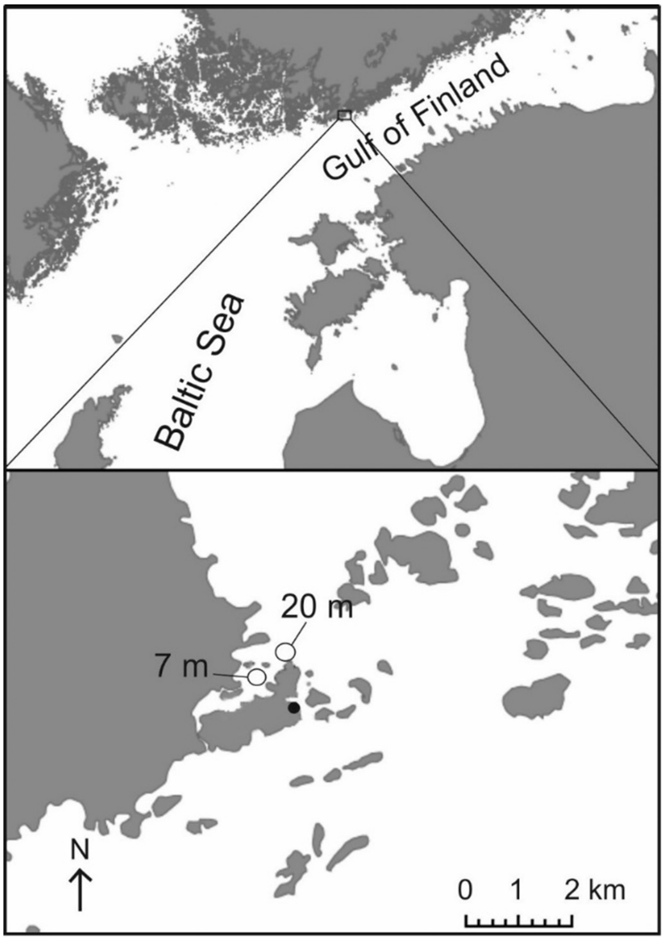

Fig. 1. Map of the study area. The study sites are marked with open circles and Tvärminne Zoological Station with a closed black circle (contains data from the National Land Survey of Finland Topographic Database 01/2017).

reaction and transformation pathways of nitrogen and thereby alter the benthic fluxes of different nitrogen forms (Hannig et al., 2007; De Brabandere et al., 2015; Holmroos et al., 2016), resuspension-altered oxygen consumption may also influence nitrogen fluxes. This may in turn have implications for the mainly nitrogen-limited primary production of the Baltic Sea (Tamminen and Andersen, 2007).

In the shallow coastal areas of the Gulf of Finland (hereafter GoF, Fig.1), which is one of the most eutrophied basins of the Baltic Sea (e.g. Andersen et al., 2015), particulate matter settling onto the sediment is usually dominated by planktonic sources during the vernal bloom period, whereas resuspended sediments may be the major source of settled material during the rest of the year (Heiskanen and Leppänen, 1995; Heiskanen et al., 1998). Consequently, the effect of resuspension on benthic solute fluxes and nutrient recycling in the GoF is potentially high. The temporal occurrence as well as the magnitude and direction of the resuspension-altered fluxes are, however, crucial for the importance of this phenomenon. In the GoF, the main periods of new primary production are the spring bloom that consists of diatoms and dinoflagellates and the late summer bloom that consists of nitrogen-fixing cyanobacteria (Vahtera et al., 2007). As described above, the resuspension events that occur close to or during these phytoplankton bloom periods may either provide more or limit the amount of available nutrients for primary production. Therefore, resuspension events may have strong local importance especially in the shallow and sensitive archipelago of the GoF. Additionally, resuspension redistributes particles and nutrients to other areas (Jonsson et al., 1990; Jönsson et al., 2005; Danielsson et al., 2007; Almroth-Rosell et al., 2011). In the future, the transport of nutrients will most likely be enhanced, since more frequent and harsher resuspension events are foreseen to occur due to climate change (Danielsson et al., 2007). Enhanced transport of coastal nutrients to deeper areas together with spreading areas of hypoxia/anoxia (Carstensen et al., 2014) may have severe consequences for the internal load and eutrophication development of the Baltic Sea.

It is always challenging to maintain in situ conditions (e.g. temperature, pressure, light, intact sediment-water interface) when recovering sediment cores for benthic solute flux studies (e.g. Koschinsky et al., 2001). Devices that provide the possibility to conduct such studies in situ enable us to address many of these challenges. Benthic fluxes of nutrients and oxygen have previously been measured in situ in the shallow archipelago areas of the GoF (Villnäs et al., 2013). Additionally, studies on the effects of resuspension on benthic solute fluxes in pelagic areas of the GoF have been conducted in situ (Almroth et al., 2009). However, in situ studies on the effects of resuspension have not been conducted in the sensitive archipelago, where spatial and temporal differences, e.g. grain size, water content and organic content of surface sediment, may be high. In these areas, resuspension may have high local importance for nutrient cycling and productivity as well as affect the transport of nutrients and particles to deeper areas. This study was carried out in situ with the Göteborg benthic landers (e.g. Ståhl et al., 2004; Tengberg et al., 2003) in the shallow outer archipelago of the northern shore of the GoF. Our aim was to clarify the effects of resuspension on benthic inorganic nutrient and oxygen fluxes during two different seasons.

2. Material and methods

2.1. Study area

The experiments were conducted at two coastal stations located in the Storfjärden basin, north-western Gulf of Finland, Baltic Sea (Fig. 1). The shallow station (59°51.115, 23°14.459, depth 7 m) represents an transportation bottom where the sediment is a mainly mud with some fine-grained sand. The sediment at the deeper station (59°51.218, 23°15.009, depth 20 m) consists mainly of loose soft mud representing thus an accumulation bottom (Kauppi et al., 2018) (Fig. 1). These stations in the outer archipelago of GoF are fairly sheltered from strong wind-induced surface waves. However, the area is connected to the deeper waters of the GoF via a narrow straight and therefore it is prone to occasional upwelling that may cause strong currents and mixing of nutrients from deeper water layers to the surface water (Haapala, 1994). The current speeds recorded during strong wind forcing and upwelling events can exceed the critical current velocities that initiate sediment resuspension in the studied locations (Niemistö unpublished).

2.2. In situ measurements of benthic fluxes with the Göteborg benthic landers

The small Göteborg benthic lander and the inner frame of the big Göteborg benthic lander (Almroth-Rosell et al., 2012; Ekeroth et al., 2016b; Ståhl et al., 2004; Tengberg et al., 2003; Viktorsson et al., 2012) were used for benthic solute flux measurements in situ. The small lander has two and the big lander four open-bottomed 400 cm^2 incubation chambers. Each quadratic chamber was equipped with a turbidity sensor (model 3612A), an oxygen optode (models 3830 and 3835) and a conductivity and temperature sensor (model 3919A) (Aanderaa Data Instruments, Norway, ADI). These parameters were measured at 1 min intervals during the experiments. The chamber modules were also equipped with ten syringes that were used for water injection and sampling at pre-determined time intervals. The injection of a known volume of deionized water caused a decrease in salinity from which the water volume of the chamber during incubation could be calculated. In each chamber, stirring of the overlying water was induced by a horizontal Mississippi type paddle wheel placed centrally in the chambers (Tengberg et al., 2004). The speed of the paddle wheel