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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.

Keywords

Sediment resuspension, benthic flux, Baltic Sea, Gulf of Finland, oxygen, nutrients

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 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).

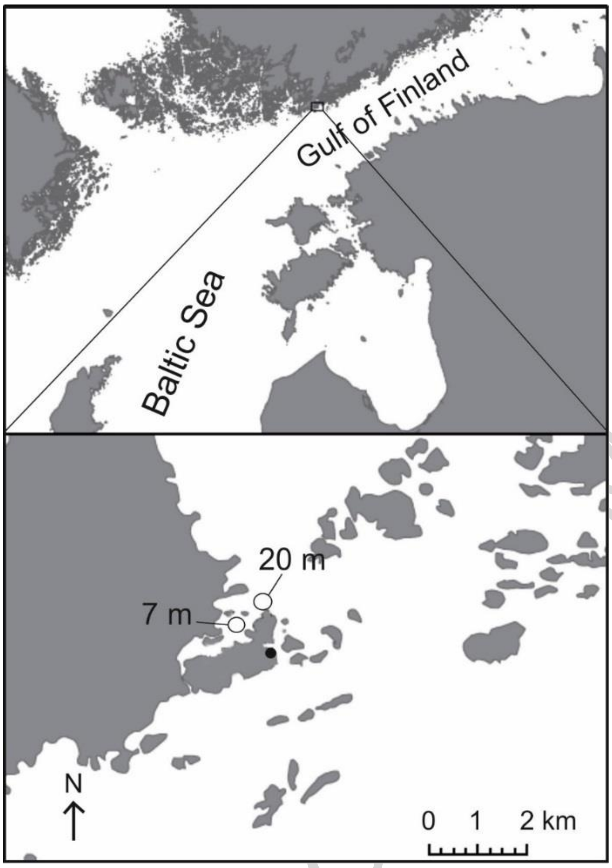

Fig. 1. Map of the study area. The study sites are marked with open circles and Tvärminne Zoological Station with a closed black circle (contains data from the National Land Survey of Finland Topographic Database 01/2017).

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 one minute 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 was adjusted to create slow stirring for the pre-incubation periods and control phases of the experiments or to induce resuspension with two different intensities. Both landers were lowered to the sea floor with a rope vertically and very slowly to avoid the disturbance of surface sediment. The buoyancy of the landers were adjusted to reach the wanted penetration depth and thus the volume of the chambers. The chambers lids were kept open during the lowering to flush away the water from shallower depths.

Three experiments (2 at the 20 m station, 1 at the 7 m station) were conducted in May and four experiments (2 at both stations) in August in 2014. In each experiment, the big and small landers were both deployed. The incubation of each chamber of the big lander consisted of different periods as follows: the first 2 h pre-incubation period (slow stirring, 60 rpm) + 12 h control phase (slow stirring, 60 rpm) + the second 2 h pre-incubation period + 12 h resuspension phase (low R-level: 160 rpm, high R-level: 230 rpm). Thereby, the same sediment was used for control measurements and resuspension experiments. In May at the 7 m station, only high R-level was induced. In August at 20 m station, same stirring speed of 230 rpm was used for both R-levels, but the chamber volume was adjusted to be larger (13%) for the low R-level. For the small lander, the incubation of both chambers consisted of a 3 h pre-incubation period (slow stirring) and 12 h control phase (slow stirring). The pre-incubation periods allowed ambient bottom water conditions (e.g. oxygen concentration) to be established in the chambers. The control phase corresponded to the incubation period of low hydrodynamic conditions and the fluxes measured are called hereafter as initial fluxes. The chambers were covered with black plastic to avoid the interference of primary producers (assimilation of nutrients, oxygen production) on the measured fluxes.

The water samples for the benthic nutrient flux calculations were withdrawn with pre-determined time intervals as follows: Big Lander; at the beginning of the incubation and every 3.9 h (control phase) or 2.8 h (resuspension phase), Small lander; at the beginning of the incubation and every 1.4 h. The sampled water was replaced by bottom water that entered passively from outside through a coil in the lid of the chamber. After the recovery of the landers, the water samples were immediately filtered through prewashed cellulose acetate membrane filters of 0.45 µm pore size (VWR International, USA).

At the end of the incubations, the sediment in the chambers of the big lander was captured and investigated for larger animals which may affect the nutrient fluxes (e.g. Bonaglia et al., 2013; Ekeroth et al., 2016a).

A recording current meter (Seaguard RCM, Aanderaa Data Instruments, Norway, ADI) mounted with the same type of conductivity, oxygen and turbidity sensors as in each incubation chamber was deployed on top of the small lander to collect the data on these parameters in the ambient bottom water during the incubations.

2.3 Calculation and validation of benthic fluxes

The fluxes of benthic solutes (mmol m^{-2} d^{-1}) were calculated based on the concentration change of each solute over time in each incubation chamber by fitting a least square regression model to these data and multiplying the obtained slope of the regression (if $p < 0.05$) by the volume, and dividing by the bottom area of the chamber. The concentration data was corrected for the inflow of ambient bottom water into the chambers when withdrawing samples.

To avoid the rejection of low fluxes to a larger extent than high fluxes (low fluxes often have greater relative uncertainty than high fluxes), the low fluxes with uncertainties greater than or equal to the flux were examined with the method presented in Almroth et al. (2009). First, the lowest accepted flux (Facc i.e. lowest significant flux according to the regression model) from the whole data set of each solute was identified. If the low flux was lower than Facc and the uncertainty of the low flux (unc_{flux} = flux × standard error of the slope / slope) lower than five times the flux, the low flux was set to zero, otherwise it was rejected (only 3 DIP fluxes in Aug and 1 in May were set to zero at the 20 m station).

2.4 Surface sediment and pore water sampling and analyses

Sediment cores for surface sediment (top-most 0.5 cm) and pore water samples were taken with a HTH corer (Renberg and Hansson, 2008) on 28 April and 29 July in 2014. The pore water samples from the surface sediment (three replicates, 0-1 cm) were collected with Rhizon filters (Rhizon CSS, 0.2 µm pore size, polyethersulfon membrane, 5 cm porous, glass fiber strengthener, Rhizosphere Research Products, Netherlands)(Seeberg-Elverfeldt, et al., 2005). Duplicate surface sediment samples (top-most 0.5 cm) were analyzed for water content (%) by drying at 105 °C overnight and for organic content (dried samples) by loss on ignition (LOI) at 550 °C for 2 h.

2.5 Chemical and statistical analyses

The concentrations of DIP, NO_x (nitrate+nitrite; Koroleff, 1983), DSi (Mullin and Riley, 1955) and NH_4 (manual indophenol-blue method; Solorzano, 1969) for the pore water and incubation samples were determined spectrofotometrically from duplicate samples (Thermo Scientific Aquakem 250). The pore water samples were diluted (1:10) and analyzed immediately after sampling. The concentrations of dissolved iron (DFe) were determined from diluted (1:10) and fixed (nitric acid, 0.15 ml HNO3 65–69%, to 30 ml of sample) pore water samples with inductively coupled plasma optical emission spectrometry (ICP-OES).

The differences in the benthic oxygen and nutrient fluxes between different study sites (7 m vs 20 m) and dates (May vs August) as well as between the control and resuspension phases were analyzed with two-sample Student's t-test (SAS, 2008). The nutrient flux data were pooled for each solute in each station for May and August experiments to increase the number of observations and thereby the statistical power of the used test. The differences in the initial nutrient concentrations between the control and resuspension phases as well as the differences in the pore water nutrient concentrations between May and August were also analyzed with two-sample Student's t-test. Before analyses, the normality of the datasets were verified with the Shapiro-Wilk test (SAS, 2008).

3. Results

3.1 Turbidity and oxygen concentrations in the ambient bottom water and in incubation chambers

During the experiments in May, the ambient bottom water temperature (range 6.5–7.3 °C), salinity (5.9 psu, practical salinity units) and turbidity (range 2–6 NTU) were fairly constant at the 20 m station. At the 7 m station, the temperature was notably higher and more variable (8.5–12 °C). The temperature variations seemed to occur with changes in salinity and turbidity indicating movements of water masses in the area. For instance, the lowest temperature record (8 °C) coincided with the highest record of turbidity (35 NTU) and salinity (5.9 psu). The oxygen concentration was high at both stations (range 350–390 µM) during the experiments (Table 1).

In August, the difference in temperature between the stations was higher than in May showing more constant values for the 20 m station (range 5.5–7.5 °C) than for the 7 m station (range 11.5–15.4 °C). Again, a larger temperature range at the 7 m station was an indication of movements of water masses with different temperatures. There were, however, no concomitant peaks in turbidity (range 2–6 NTU). In August, salinity was notably higher in the near-bottom water at the 20 m station (above 6.1 psu) than at the 7 m station (below 5.7 psu). The bottom water at both stations had similar salinity in May. The oxygen concentrations varied between 190–250 µM at the studied stations, being markedly lower in August than in May (Table 1).

Table 1. Bottom water temperature, turbidity, oxygen concentration and salinity outside the chambers (Seaguard sensor measurements 2 m above the bottom) during the incubations

May	depth (m)	T (°C)	Turbidity (NTU)	O_2 (µM)	salinity (psu)
26-27	7	8.5-12.0	5-35	350-390	5.7-5.9
24-25	20	7.1-7.2	2-6	355-370	5.9
22-23	20	6.5-7.3	2-6	370-380	5.9
Aug	depth (m)	(°C)	(NTU)	(µM)	
17-18	7	11.5-14.3	2-5	190-215	5.6-5.7
19-20	7	12.5-15.4	2-5	205-245	5.5-5.7
15-16	20	5.5-6.5	2-6	220-250	6.3-6.5
13-14	20	5.5-7.5	2-6	220-240	6.1-6.4

The intensity of the resuspension treatments induced during the experiments was evaluated with the aid of turbidity recordings. The turbidity values as well as the oxygen concentration measured in the incubation chambers were compared to ambient bottom water conditions to verify the representativeness of the incubation conditions. The pre-incubation periods, i.e. ventilation of the chambers with the lids open, always allowed the near-bottom conditions to be established before the control and resuspension phase incubations (Table 1 and 2).

In May, the turbidity in the incubation chambers varied from 2 to 5 NTU during the control phase of the experiments at the 20 m station, thereby corresponding well with the values of the ambient bottom water (Table 1 and 2). The low resuspension treatment caused a small increase (range 8–11 NTU) and the strong treatment a notably higher increase (range 40–115 NTU) in turbidity. The oxygen concentrations in the chambers at the start of the incubations for the control and resuspension phases (range 309–350 µM) were a bit lower than in the ambient bottom water (range 355–380 µM), which was measured 2 meters above the bottom (Table 1 and 2). However, it is worth noticing that the oxygen concentrations in the chambers were high and that the resuspension treatment started from the same level as the control phase incubations (Fig. 2), showing that the ventilation of incubation chambers conducted by the second pre-incubation period reproduced the ambient bottom water conditions well.

Only one experiment was conducted at the 7 m station in May, and the aim was to induce strong resuspension during the treatment. However, only a moderate turbidity increase was created, since the turbidity values ranged from 7 to 25 NTU in the control phase and from 5 to 45 NTU in the resuspension phase (Table 1 and 2). The oxygen concentrations resembled those at the 20 m station, being high and similar to the ambient bottom water conditions at the beginning of the incubations.

In August, the turbidity values in the incubation chambers during the control phase (range 2–8 NTU) were similar to those in the ambient bottom water in all the experiments (Table 1 and 2). At the 20 m station, despite the difference in the chamber volumes, both resuspension treatments caused similar turbidity increases (low R-level, range 50–120 NTU; high R-level, range 60–115 NTU) which were markedly higher than for the control phase. At the 7 m station, the resuspension treatments resulted in different turbidity levels, the range for low stirring being from 7 to 11 NTU and for high stirring from 22 to 55 NTU (Table 2).

The oxygen concentrations in the chambers at the start of the incubations were lower in August than in May, but always similar to ambient bottom water conditions (Table 1 and 2). During the incubations (control and resuspension phases of all experiments considered), the oxygen concentration linearly decreased by up to 42% down to a concentration of 115 µM in August (Table 2, Fig. 2). In May, the corresponding highest decrease was 40% and the lowest concentration in the chamber at the end of the incubation 195 µM, still representing well oxidized conditions (Table 2).

Table 2. Turbidity (range of all chambers) and oxygen concentrations (mean of different chambers at the start and in the end of the incubation) during the control (C) and resuspension (R) phases of the experiments.

Exp/date			Big Lander, C-phase		Big Lander, R-phase		Small Lander, C-phase	
	level	depth	Turbidity	start-end	Turbidity	start-end	Turbidity	start-end
May	of R	(m)	(NTU)	O_2 (µM)	(NTU)	O_2 (µM)	(NTU)	O_2 (µM)
26-27	high	7	7-25	345-287	5-45	359-309	4-15	324-195
24-25	low	20	2-5	350-289	8-11	349-289	2-5	329-227
22-23	high	20	2-5	337-273	40-115	347-248	2-5	309-205
Aug			(NTU)	(µM)	(NTU)	(µM)	(NTU)	(µM)
17-18	low	7	2-4	200-172	7-11	198-162	2-4	191-138
19-20	high	7	2-4	235-188	22-55	212-164	2-5	197-115
13-14	low	20	3-8	202-168	50-120	203-159	2-4	183-136
15-16	high	20	2-5	188-150	60-115	200-156	2-5	206-150

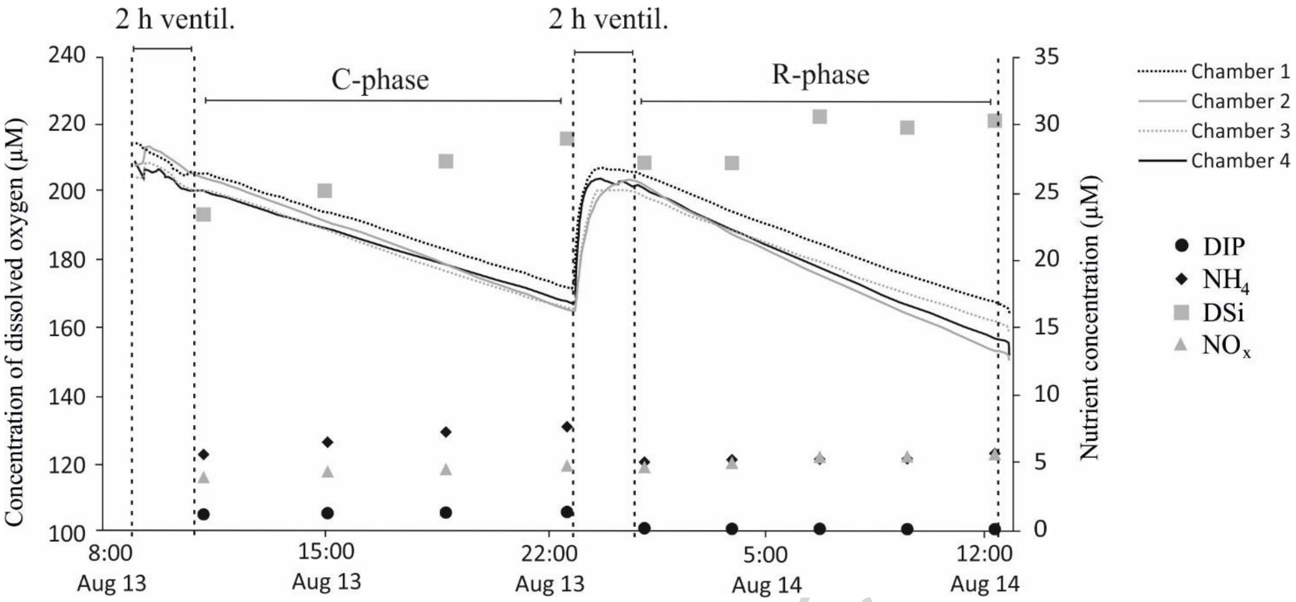

Fig 2. Typical trend of dissolved oxygen concentrations during the experiment in the incubation chambers of the big Benthic Lander (e.g. Aug 13–14). Sampling time points and typical development of DIP, NH_4, NO_x and DSi concentrations of one chamber. The pre-incubation periods (2 h ventilation), control phase (C-phase) and resuspension phase (R-phase) marked with dotted lines.

The initial bottom water concentrations of all studied nutrients were lower in May compared to in August ($p<0.001$, t-test) (Table 3). Apart from the NH_4 that showed 15% lower concentration and NO_x that showed 9% higher concentration in the beginning of the resuspension phase at the 20 m station in August, there were no significant differences in the nutrient concentrations between the initial conditions in the control and resuspension phases ($p<0.001$, t-test). This indicates that the pre-incubation period allowed ambient bottom water conditions to be established before resuspension treatment in all the experiments.

Table 3. Initial mean ± standard deviation (SD) bottom water concentrations (µM) of the studied solutes in the incubation chambers for the shallow and deep stations in May and Aug (NA = conc. below detection limit).

Exp/date	Big and Small Lander, C-phase				Big Lander, R-phase			
May	DIP	NH_4	NO_x	DSi	DIP	NH_4	NO_x	DSi
7 m	0.10±0.03	0.44±0.23	NA	8.89±1.21	0.13±0.01	0.29±0.02	NA	9.19±0.53
20 m	0.32±0.03	0.61±0.27	NA	8.47±1.37	0.34±0.04	0.36±0.21	NA	8.58±1.49
Aug								
7 m	0.69±0.17	3.84±1.63	2.32±0.66	16.2±1.78	0.69±0.09	3.78±0.56	2.43±0.51	16.1±1.15
20 m	1.25±0.15	5.72±0.55	4.44±0.50	27.9±3.03	1.17±0.05	4.87±0.22	4.84±0.18	28.8±2.52

3.2 Surface sediment characteristics and pore water solute concentrations

The water content (±SD) of the surface sediment (top-most 0.5 cm) was 90±0.5% and the organic content of dry matter (±SD) 10.1±1.00% for the 7 m station at the end of April. The respective values at the end of July were 91±0.7% and 11.2±0.10%, i.e. no seasonal differences were observed (t-test, $p > 0.05$, n=4). In spring at the 20 m station, the water and organic content of the surface sediment were 96±1.5% and 13±0.85%, respectively, whereas in summer significantly lower values were observed, 93±1.4% 10.9±0.19 (t-test, $p<0.05$, n=4). On both sampling dates, the water content was lower at the 7 m station compared to 20 m station (t-test, $p<0.05$, n=4).

At the 7 m station, the dissolved nutrient and iron concentrations in the sediment pore water (top-most 1 cm) were, apart from NO_x, lower in May than in August (Table 4). In contrast at the 20 m station, no statistically significant seasonal differences were observed for any solute (Table 4). However, the DIP concentration seemed to be higher and DFe/DIP lower in August.

Table 4. Pore water concentrations of DIP, NH_4, NO_x, DSi and DFe, and the DFe to DIP ratio in the top-most 1 cm before the lander experiments at the studied stations in spring and summer of 2014.

7 m station	May	August	difference May vs Aug
Solute	conc. (µM) ± SD	conc. (µM) ± SD	**t-test: t_{df}, p**
DIP	4.66±1.73	46.2±14.3	**t_3=4.96, p=0.035**
NH_4	15.4±0.95	62.6±19.8	**t_3=4.26, p=0.050**
NO_x	2.54±1.17	2.35±0.67	t_3=0.21, p=0.862
DSi	47.5±0.16	123±24.1	**t_3=5.43, p=0.032**
DFe	94.0±3.80	193±34.5	**t_3=4.94, p=0.036**
DFe/DIP	19.5±6.2	4.4±1.2	**t_3=4.16, p=0.047**
20 m station			
Solute	conc. (µM) ± SD	conc. (µM) ± SD	
DIP	8.47±5.02	28.4±17.6	t_4=1.88, p=0.183
NH_4	38.7±8.46	32.4±10.5	t_4=0.80, p=0.469
NO_x	2.60±0.91	3.00±0.35	t_4=0.71, p=0.536
DSi	76.4±14.1	95.0±39.1	t_4=0.78, p=0.504
DFe	98.5±25.8	143±89.5	t_4=0.83, p=0.482
DFe/DIP	14.9±9.0	5.1±0.1	t_4=1.91, p=0.129

3.3 Oxygen fluxes and effect of resuspension

The initial benthic oxygen uptake (i.e. the flux during the C-phase) was around 23.5 mmol m^{-2} d^{-1} at the 20 m station and 28.1 mmol m^{-2} d^{-1} at the shallow station in May (Fig. 3). In August, clearly lower mean uptake rates were measured at both stations; 12.0-13.0 mmol m^{-2} d^{-1} at the 20 m station, 11.0-15.9 mmol m^{-2} d^{-1} at the 7 m station ($p < 0.05$) (Fig. 3).

In May, no effect of resuspension on oxygen fluxes was detected. In August, resuspension increased the benthic oxygen uptake in three out of four experiments (Fig. 3). At the 20 m station, both resuspension intensities increased the oxygen uptake up to mean fluxes of 16.1 (by 35%) and 17.3 mmol m^{-2} d^{-1} (by 33%) for high and low resuspension intensity, respectively. However, no difference in the effect between the intensities was detected (t-test: t_6= 0.80, p=0.44).

At the 7 m station, no difference between different intensities was tested because the resuspension treatment increased the oxygen uptake (by 35%) statistically significantly in only one of the experiments (up to a mean flux of 14.8 mmol m^{-2} d^{-1}) in August. However, the other experiment also indicated higher oxygen uptake due to resuspension but this effect was not statistically significant (Fig. 3).

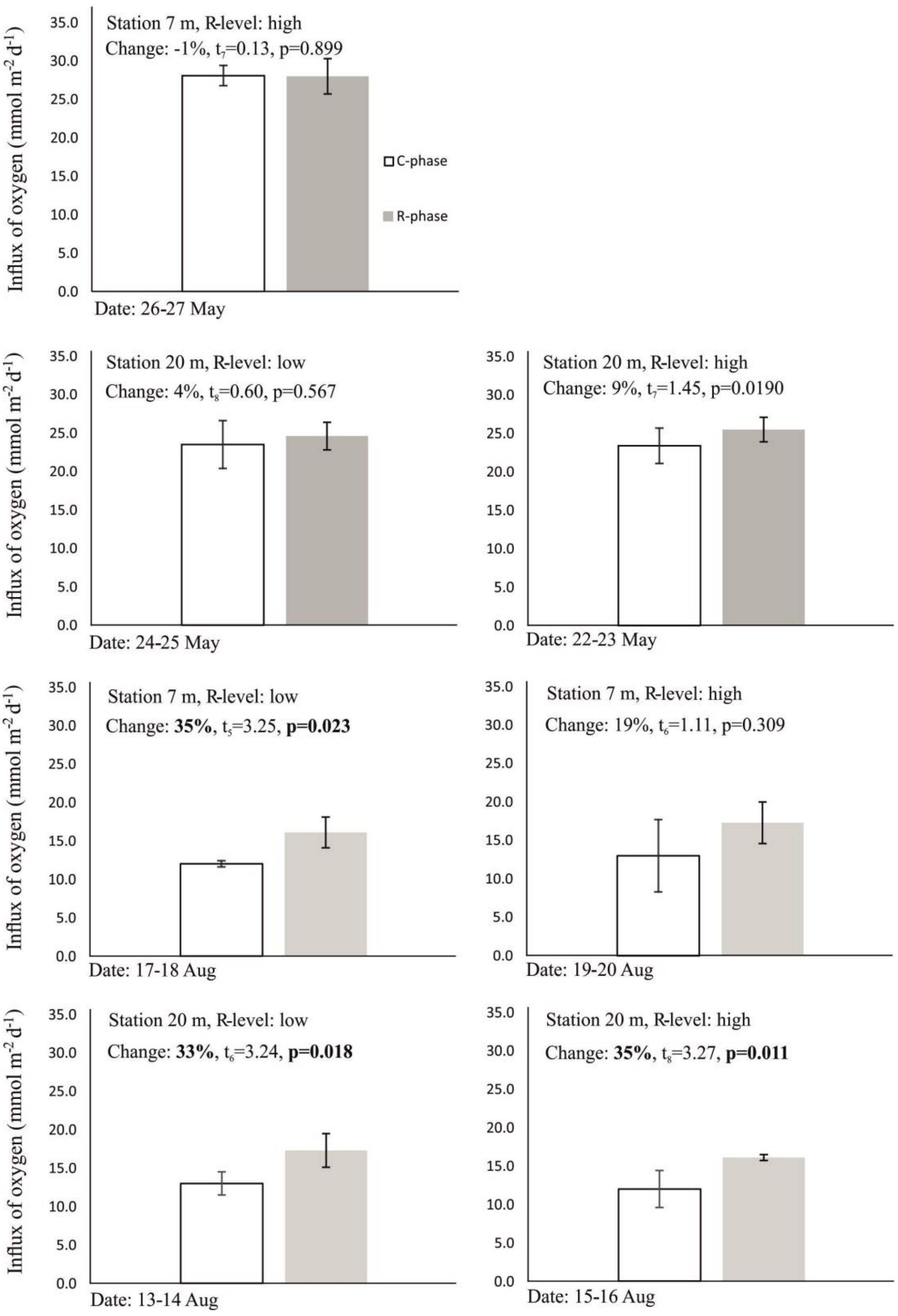

Fig 3. The initial O$_2$-influxes (C-phase) (i.e. benthic oxygen uptake) and the influxes during resuspension (R-phase) in May and August at two studied stations. The statistical results (t-test: t$_{df}$, p-value) for the effect of resuspension on measured fluxes (significant differences in percentages and p-values in bold font) are also shown.

3.4 Benthic fluxes of inorganic nutrients and effects of resuspension

To increase the statistical power for detecting the effect of resuspension treatment on the benthic nutrient fluxes the data of both treatment intensities for each nutrient were pooled for the 7 m and 20 m stations for May and August (Table 5). This was justified by the fact that resuspension seemed to consistently decrease the fluxes of DIP, NH_4 and DSi and increase the fluxes of NO_x, although the effect was generally not statistically significant in each single experiment. Additionally, it was possible to test the difference between the treatment intensities only for DIP at the 20 m station and for NO_x at the 7 m station in August, however, no statistical differences were observed (DIP: t_3=2.77, p=0.070, NO_x: t_5=1.17, p=0.295).

3.4.1 Spatial and temporal differences of initial benthic fluxes of DIP, NH_4, NO_x and DSi

In May, only one experiment was conducted at the 7 m station and significant initial fluxes (according to regression analysis conducted for each solute in each single chamber) were obtained only for NH_4 (0.37 mmol m^{-2} d^{-1}) and DSi (2.85 mmol m^{-2} d^{-1}) (C-phase, Table 5). Due to the low number of measurements, the statistical power to detect spatial differences between fluxes at the 7 m and 20 m station was very low, and no such differences were observed. The benthic fluxes at the 20 m station in May were as follows: DIP 0.04 mmol m^{-2} d^{-1}, NH_4 0.36 mmol m^{-2} d^{-1}, NO_x 0.23 mmol m^{-2} d^{-1}, DSi 2.58 mmol m^{-2} d^{-1} (C-phase, Table 5). In August, the fluxes of all measured solutes were higher at the 7 m than at the 20 m station (t-test, p <0.05). At the 7 m station, the initial mean fluxes for DIP, NH_4, NO_x and DSi were 0.15 mmol m^{-2} d^{-1}, 1.12 mmol m^{-2} d^{-1}, 0.49 mmol m^{-2} d^{-1}, and 3.47 mmol m^{-2} d^{-1}, respectively, whereas at the 20 m station, the corresponding fluxes were <0.01 mmol m^{-2} d^{-1}, 0.55 mmol m^{-2} d^{-1}, 0.36 mmol m^{-2} d^{-1}, and 2.47 mmol m^{-2} d^{-1} (C-phase, Table 5). The initial fluxes of DSi measured with the small lander (range of mean fluxes in May and Aug 1.9–3.3 mmol m^{-2} d^{-1}) were originally presented in Tallberg et al. (2017) and used here as a control phase fluxes.

As for spatial differences, the temporal differences of the benthic nutrient fluxes at the 7 m station were either not significant or not tested due to too few or no significant fluxes in May. At the 20 m station, NO_x was the only solute showing a significant difference in initial fluxes between studied months being approximately 1.5-fold in August compared to in May (t_{14}=4.04, p=0.001) (Table 5).

3.4.2 Effects of resuspension on nutrient fluxes

In May, no significant effects of resuspension were observed. In August at the 20 m station, the flux of DIP that initially was close to zero changed to an influx (mean flux -0.13 mmol m^{-2} d^{-1}) due to resuspension (Table 5). At the same station, the efflux of NO_x increased by 27% (to a mean flux of

0.46 mmol m^{-2} d^{-1}) in the resuspension treatment. The flux of NH_4 and DSi were not statistically significantly affected, although for NH_4 there seemed to be a marked decrease. Contrary to this, the resuspension treatment caused significant changes in the benthic effluxes of NH_4 and DSi at the 7 m station, decreasing the mean flux of NH_4 and DSi by 48% and 31%, respectively. Additionally, the efflux of NO_x was increased by 30% (to a mean flux of 0.64 mmol m^{-2} d^{-1}) (Table 5).

Table 5. The initial nutrient fluxes (C-phase) and the fluxes during resuspension (R-phase) at the two studied stations during *in situ* incubations with the Göteborg Benthic Landers (data pooled from two experiments for both stations, apart from the 7 m station in May where only one experiment was conducted). The statistical results (t-test) for the effect of resuspension on measured fluxes of DIP, NH_4, NO_x and DSi (significant effects of resuspension in percentages and p-values in bold font) are also shown.

May						
7 m station	Mean flux (mmol m^{-2} d^{-1})				t-test	change
Solute	C-phase	±SD	R-phase	±SD	t_{df}, p-value	in %
DIP	*		*			
NH_4	0.37	0.24	*			
NO_x	*		*			
DSi	2.85	0.57	2.53	0.76	t_5=0.63, p=0.555	-11
20 m station						change
Solute	C-phase	±SD	R-phase	±SD	t_{df}, p-value	in %
DIP	0.04	0.04	0.06	0.01	t_5=0.69, p=0.519	43
NH_4	0.36	0.13	0.35	0.08	t_{10}=0.15, p=0.884	-3
NO_x	0.23	0.05	0.23	0.04	t_{10}=0.31, p=0.760	-4
DSi	2.58	0.42	2.21	0.34	t_{13}=1.56, p=0.142	-14
August						
7 m station	Mean flux (mmol m^{-2} d^{-1})					change
Solute	C-phase	±SD	R-phase	±SD	t_{df}, p-value	in %
DIP	0.15	0.10	0.08	0.03	t_{10}=0.15, p=0.155	-49
NH_4	1.12	0.61	0.58	0.29	t_{15}=2.16, p=**0.047**	**-48**
NO_x	0.49	0.11	0.12	0.09	t_{17}=2.79, p=**0.013**	**30**
DSi	3.47	1.04	2.41	0.67	t_{17}=2.40, p=**0.028**	**-31**
20 m station						change
Solute	C-phase	±SD	R-phase	±SD	p-value	in %
DIP	<0.01	0.04	-0.13	0.08	t_{14}=4.09, p=**0.001**	**-7745**
NH_4	0.55	0.30	0.36	0.16	t_{16}=1.49, p=0.156	-34
NO_x	0.36	0.07	0.46	0.09	t_{15}=2.53, p=**0.023**	**27**
DSi	2.47	0.54	2.36	0.55	t_{10}=0.32, p=0.755	-4

* no significant fluxes detected

4. Discussion

4.1 *In situ* incubation conditions and successfulness of resuspension treatments

The oxygen concentrations, turbidity and salinity in the incubation chambers in the beginning of the experiments were representative of the conditions in the ambient bottom water. In addition, the nutrient concentrations in the beginning of the control and resuspension phase were at a similar level, indicating that the pre-incubation period always allowed ambient bottom water conditions to be established before resuspension treatments. The experiment conditions could thus be considered to represent *in situ* conditions.

A higher number of significant benthic fluxes for the studied nutrients were observed in August than in May, when the bottom water nutrient concentrations were low and close to the detection limits. This was most likely due to colder water and lower bacterial activity (Rose, 1967; Bergström et al., 2010), which resulted in lower regeneration of nutrients in the sediment in May. In general, the activity of heterotrophic bacteria in the studied area has been observed to be higher during the warm summer months (Vetterli et al., 2015). The lower supply of sedimentary nutrients was also seen in the pore water concentrations, especially at the 7 m station where the concentrations were, apart from NO_x, significantly lower in May than in August. During the experiments, the temperature difference between May and August was only minor or negligible at the studied stations. In August, however, the temperature was approximately 8-10 °C higher during the preceding weeks and decreased just prior to the experiments due to an upwelling event. Additionally, the major input of organic material (i.e. the settling of the diatom bloom) generally occurs in spring (Heiskanen et al., 1998), and thus the surface sediment most likely contained fresher material in May compared to in August at both stations, although the statistically significant difference was observed only for the 20 m station.

In addition to the above mentioned factors, the lack of resuspension-induced effects on nutrient and oxygen fluxes in May may have been due to the weakness of the induced resuspension treatments (verified by the lower turbidity values in the incubation chambers). Especially at the 7 m station, the increase in turbidity was very low despite the fast stirring speed used. Partly, this may have been due to larger chamber volumes, i.e. a longer distance between the paddle wheel and the sediment surface (average chamber height 24 cm in May vs 18 cm in August). Additionally, a viscid biofilm on the sediment surface was visually observed during the critical shear stress determinations in May (Niemistö unpublished), probably caused by periphytic algae.

4.2 Initial and resuspension altered benthic fluxes of oxygen and nutrients

4.2.1 Oxygen

The initial benthic uptake of oxygen (i.e. the flux during C-phase) measured in May in the present study were markedly higher compared to the *in situ* influxes obtained outside the archipelago in the deeper areas of the GoF from erosion and transport bottoms (Almroth et al., 2009). The benthic oxygen penetration depth and consumption rate is known to be dependent on the oxygen supply (Rasmunsen and Jørgensen, 1992; Glud et al., 2003; Beutel et al., 2007). During the experiments in May, the oxygen concentration in the ambient bottom water was high (340-350 µM vs. 251-285 µM in Almroth et al., 2009), enabling high benthic influxes. The lower oxygen supply in August, shown by the lower oxygen concentration in the bottom water (190-250 µM), is a plausible explanation for the markedly lower initial benthic influxes recorded at the time. During the experiments, neither station showed any marked difference in water temperature between May and August, and temperature could thus not explain the seasonal differences in benthic oxygen consumption. At the 20 m station, however, the organic content of the surface sediment was higher in May, and may thus have contributed to the higher uptake of oxygen, which mainly was due to greater oxygen supply.

The resuspension treatment increased the benthic oxygen uptake only in August (in 3 out of 4 experiments). This was due to a stronger resuspension treatment in August than in May, indicated by the higher turbidity values, as well as due to lower oxygen concentration in the ambient bottom water, i.e. lower penetration depth to sediment, in August. The resuspension-induced increase in benthic oxygen consumption has been concluded to be a result of mixing and oxidation of reduced dissolved inorganic sedimentary substances in the bottom water (e.g. Anderson et al., 1986; Almroth et al., 2009). Additionally, the thickness of the diffusive boundary layer decreases due to increased water mixing and results in a higher penetration of oxygen and oxidizing of reduced compounds deeper in the sediment pore water (Jørgensen and Revsbech, 1985; Almroth et al., 2009). In August, the lower oxygen concentration in the bottom water most likely resulted in a thinner oxidized layer at the surface sediment than in May, which together with strong resuspension treatment resulted in increased oxygen consumption. These conditions were manifested as higher pore water concentrations of dissolved phosphate and iron in the surface sediment in August compared to in May. In addition to the direct oxidation of reduced substances, the benthic oxygen consumption may also have been enhanced due to resuspension-increased mineralization (Ståhlberg et al., 2006; Moriarty et al., 2017).

Almroth et al. (2009) discussed that as resuspension increases benthic oxygen consumption, it may enhance the spreading of hypoxic and anoxic areas, which in turn may lead to increased effluxes of redox dependent substances. In the shallow areas examined in the present study, the resuspension-induced increase in benthic oxygen consumption will most likely be compensated for by the continuous presence of oxygen rich bottom waters. However, the observed resuspension-induced oxygenation of the surface sediment should result in enhanced bacterial degradation of organic matter, since aerobic degradation is more effective compared to anaerobic degradation (e.g. Hulthe et al., 1998). The increase in the frequency and intensity of resuspension has been shown to increase the benthic and near-bottom oxygen consumption and mineralization (Wainright and Hopkinson, 1997; Ståhlberg et al., 2006). Therefore, along with the foreseen intensification of winds and sediment resuspension events in the future (Danielson et al. 2007; Neumann, 2010), the regeneration and effluxes of benthic nutrients of the studied areas may be enhanced.

4.2.2 Phosphate, DIP

The initial mean fluxes of DIP were very low or undetectable, especially in May. Such low fluxes are common for well oxygenated bottoms (Sundby et al., 1986; Almroth et al., 2009; Viktorsson et al., 2012) and generally reflect conditions in which the dissolved iron to phosphate ratio in the pore water is high (Gunnars and Blomqvist, 1997). The DFe:DIP (molar) ratio showed high values in the studied areas, ranging from 14.9 to 19.5 in May and from 4.4 to 5.1 in August, indicating strong P binding capacity of the surface sediment under the prevailing oxic conditions (Gunnars and Blomqvist, 1997).

Phosphate and iron dissolved in the pore water can be transported to oxygenated near-bottom water due to resuspension and result in decreased effluxes or increased influxes of phosphate due to co-precipitation with newly formed iron oxyhydroxides (Spagnoli and Bergamini, 1997; Almroth et al., 2009; Almroth-Rosell et al., 2012), formation of which can occur in time scales of seconds (Wang and Cappellen, 1996). This was likely the case at the 20 m station in August, when the mean initial DIP flux close to zero changed to an influx during the resuspension phase. The low DIP efflux at the 7 m station also decreased but not significantly. In May, the lower pore water concentrations of DIP and DFe due to the more oxidized conditions in combination with the weaker resuspension treatment were the most likely factors behind the non-significant effects of the resuspension treatments.

Although the DIP fluxes were low in the studied area, the observed scavenging of near-bottom and sedimentary phosphate to iron oxides may be important on a larger scale, due to resuspension-induced transport of material which is known to be important in the Baltic Sea (e.g. Jönsson et al., 2005; Danielsson et al., 2007; Almroth-Rosell et al., 2011). The newly formed iron oxides rich in P may be redistributed to areas with lower redox conditions and P may be released due to reductive dissolution (e.g. Mortimer, 1942; Sundby et al., 1986; Almroth et al., 2009). Therefore, the predicted intensification of the transport of coastal nutrients due to enhanced resuspension together with expanding hypoxia (Carstensen et al., 2014) may have consequences of unexpected magnitude for the internal loading of phosphorus and eutrophication development of the Baltic Sea.

4.2.3 Dissolved silicate, DSi

The initial effluxes of DSi measured from the 7 m bottoms in the present study were at the same level as the fluxes obtained from *in situ* benthic lander measurements during well oxidized conditions in the deeper areas of the GoF, but clearly lower than the fluxes measured there during low oxygen concentrations (Almroth et al., 2009). Therefore, our results provide additional evidence that effluxes of DSi are low in the GoF under well oxidized conditions. Our findings are also in concordance with studies conducted e.g. in the Baltic proper (Danielsson, 2014; Ekeroth et al., 2016a) and in the archipelago of Stockholm, northwestern Baltic proper (Ekeroth et al., 2016b).

Spatial differences in the initial DSi effluxes between the studied stations were observed only in August, when the 7 m station showed on average 40% higher effluxes compared to the 20 m station. Although the differences in the abundance and composition of the benthic fauna can be strongly connected to DSi effluxes (Rutgers van der Loeff et. al., 1984; Bonaglia et. al., 2013), the higher effluxes at the 7 m station could not be explained by higher faunal activity, as the number of individuals of the two most abundant species sieved from the incubated sediments was higher at the 20 m station. The mean densities (±SD) of *Macoma Baltica* and *Marezelleria* spp. for the 20 m and 7 m station were 253±25 vs 83±24 ind. m^{-2} (t_{13}=13.53, p<0.001) and 388±187 vs 50±32 ind. m^{-2} (t_{12}=4.34, p=0.001), respectively. The absolute densities were, further, low compared to e.g. densities of *Marenzelleria* spp. that have been shown to increase the effluxes of DSi (2000 ind m^{-2}, e.g. Bonaglia et al., 2013; Ekeroth et al., 2016a). Thus, the higher DSi fluxes recorded at the 7 m station were perhaps simply due to the higher water temperature during and prior to the experiments (5 to 10 °C higher than at the 20 m station), since the dissolution of biogenic silica is positively dependent on temperature (e.g. Lewin, 1961). The finding that the highest pore water concentrations of DSi were measured at the 7 m station in August corroborated this conclusion. Additionally, the fact that the highest fluxes were recorded in August agrees with previous studies stating that benthic DSi effluxes tend to peak late in summer due to the slow initial dissolution of the Si frustules deposited right after the diatom spring bloom (Tallberg et al., 2013). It is also possible that spatial variability of sediment silica content (i.e. diatom frustules) and uncertainty induced into the flux estimates by the regression application (8% of the mean flux for the 7 m and 14% for the 20 m station) may have contributed to the difference (in absolute numbers quite small) between the fluxes at the two stations.

Almroth et al. (2009) presented both negligible, negative and positive effects of resuspension on the benthic fluxes of DSi during their studies on the pelagic bottoms of the GoF. In the present study, apart from a very small number of fluxes that remained unaffected during the resuspension phase, the resuspension treatment seemed to consistently decrease the effluxes of DSi. However, due to high variation between the fluxes measured in the different incubation chambers, a statistically significant decrease in the mean flux was observed only for the 7 m station in August.

The benthic DSi flux rate in coastal marine sediments generally depends on dissolution of biogenic silica (BSi) (Rutgers van der Loeff et al., 1984; Testa et al., 2013), but other factors (presented below, e.g. resuspension) may also affect the rate. According to Almroth et al. (2009), resuspension should increase benthic DSi effluxes via enhanced BSi dissolution, since resuspension should decrease the dissolved silicate concentration in the ambient water and indirectly stimulate dissolution rates due to the inverse relationship between dissolution rate and dissolved silicate concentration (Ragueneau et al., 2001). In the present study, resuspension appeared to decrease the DSi fluxes, however. The 12 h incubation was most likely too short for any enhanced dissolution of BSi due to resuspension to be discerned; rate constants for the dissolution of BSi have been estimated to range between 3×10^{-6} and 1×10^{-4} h^{-1} (compiled by Khalil et al., 2007), i.e. a time-scale of days to weeks. This indicates that what actually occurred was adsorption of DSi onto resuspended sediment particles, a process which occurs at time-scales of minutes (Gehlen & Van Raaphorst, 2002). Sorption of DSi appears as the rapid first response to drastic changes in silicate concentrations that can occur due to resuspension: apparently, this phenomenon is not constrained only by the concentration of Si in the surrounding media but also by particle surface characteristics (e.g. MacKenzie et al., 1967; Gehlen & Van Raaphorst, 2002). The fact that the concentration of DSi in the near-bottom water in our study was < 30 µM, e.g. markedly lower than that of the pore waters (120 µM), does thus not preclude adsorption of Si by the resuspended particles but rather agrees with earlier findings for North Sea sediments (Gehlen & Van Raaphorst, 2002). Given the high concentrations of DFe in the pore water of the studied area, we suggest that redox-dependent reactions, i.e. formation of new Fe-oxyhydroxides, and the subsequent adsorption of DSi were responsible for the resuspension-induced decrease in the DSi flux. Resuspension resulted in newly formed iron oxides (see discussion on DIP above), some of which are known to be effective adsorbents for DSi (Sigg and Stumm, 1981; Anderson and Benjamin, 1985).

Danielsson (2014) stated that there are signs of Si limitation in some areas of Baltic Sea, which seem to be affecting both the quantity and quality of the diatoms in the spring blooms (Olli et al., 2008). In such areas, sediments are an important internal source of Si (Danielsson, 2014). According to our results, resuspension can decrease the benthic efflux of DSi in the studied coastal area and, as for DIP, contribute to the transport of this element from one area to another. If more silicate is transported from shallow to deep areas in the future, the Si cycle of the Baltic Sea can be affected. In theory, the higher amounts of Si transported to hypoxic and anoxic areas would be expected to result in higher total benthic effluxes of DSi, assuming that Si release is indeed dependent on redox conditions as proposed by e.g. Danielsson (2014) and Lehtimäki et al. (2016). However, the transport of DSi (or other elements) from the deeper waters, especially from the profundal water masses below the permanent halocline back to shallow waters, require major Baltic inflows or strong upwelling events. In the short term, the intensification of resuspension events (frequency and strength) in shallow coastal areas can rather be expected to reduce water column DSi availability for diatoms, which may affect the structure and composition of the phytoplankton assemblage of the Baltic Sea. The process is further complicated by the fact that the DSi sorption process is reversible, and longer resuspension events (>12 h) may rather lead to increased desorption of DSi from resuspended particles (Gehlen & Van Raaphorst, 2002).

4.2.4 Nitrogen, NH_4 and NO_x

The initial benthic NH_4 fluxes presented here are comparable with other benthic lander measurements, e.g. from a Scottish fjord (Almroth-Rosell et al., 2012) or Kanholmsfjärden in the Stockholm archipelago, Baltic Sea (Ekeroth et al., 2016b), conducted in well oxygenated conditions. NH_4 fluxes of a similar level were also measured by Almroth et al. (2009) in a few of their lander incubations for the pelagic area of GoF with low near-bottom oxygen concentrations. However, they mainly recorded markedly higher fluxes, which have commonly been observed also for other areas of the Baltic Sea with hypoxic or anoxic near-bottoms conditions (e.g. Ekeroth et al., 2016b). The low and positive benthic NO_x fluxes of the present study were of a similar level as the NO_x fluxes recorded in a boxcosm experiment conducted during oxygenated conditions with sediments collected from the western Baltic proper (Ekeroth et al., 2016a). On the other hand, negative benthic NO_x fluxes during well-oxygenated conditions have also been recorded *in situ* in the Swedish archipelago (Ekeroth et al., 2016b).

The presence of oxygen and the supply of NH_4 are fundamental for nitrification (NH_4^+ oxidized to NO_x-N) (e.g. Thamdrup and Dalsgaard, 2008). Therefore, the fact that the near-bottom oxygen concentrations were markedly higher but the benthic NO_x flux undetectable (shallow station) or lower (deep station) in May compared to in August could be explained with the lower NH_4 supply in spring. Indeed, the NH_4 concentrations in the near-bottom water of both stations and in the pore water of the 7 m station were significantly lower in May. Since the organic content of the surface sediment showed no marked differences between the studied periods, the higher water temperature was considered the major driver for more intensive ammonification and nitrification in August. At the time of the experiments, the temperature difference between May and August was only minor or negligible. However, as mentioned above, temperature had decreased ca 10 °C just prior to the experiments due to an upwelling event. This was also clearly indicated by the increased salinity (from 5.8 to 6.3) measured at the 20 m station before the first experiment. Jäntti et al. (2011) concluded that since the sudden increase in salinity can increase the benthic efflux of NH_4 due to ion pairing of saltwater anions and the blocking of ion-exchange sites by seawater cations (Gardner et al., 1991; Seitzinger et al., 1991), it may stimulate nitrification. In the present study, the rather small change in salinity, 0.5 psu, was unlikely reason for the stimulation of nitrification. However, considering the high water temperature prior to the August experiments, our findings are in line with the study of

Jäntti et al. (2011), in which the highest nitrification rates in the Storfjärden area were measured during warm summer months, and the high NH_4 availability resulting from enhanced mineralization was suggested to be the driving factor. The DNRA (dissilimilatory nitrate reduction to ammonium, requires NO_3^-) that dominates the nitrate reduction under hypoxic conditions (Jäntti and Hietanen, 2012), could be excluded as a major process causing the higher concentrations of NH_4 in August, since the observed conditions of high bottom water oxygen concentrations rather stimulate the nitrogen removal processes denitrification (heterotrophic reduction of NO_x to gaseous N_2) and anammox (anaerobic ammonium oxidation, requires NH_4^+ and NO_2^-) in sediment (e.g. Beutel, 2006; Neubacher et al., 2013). Additionally, DNRA has been estimated to be of minor importance in the studied area (Jäntti et al., 2011).

Spagnoli and Bergamini (1997) stated that resuspension can increase the benthic NH_4 flux by enhancing degradation of organic material. On the other hand, Almroth et al. (2009) observed that resuspension decreased benthic NH_4 fluxes, and that such an effect was measured only under low oxygen concentrations (<15 µM). At the 7 m station of the present study, a decrease in the NH_4 flux was measured during the resuspension treatment under well-oxidized conditions in August. In theory, NH_4^+ ions could be adsorbed onto resuspended particle surfaces, which would decrease the NH_4 flux. This was not likely, however, since the desorption of ions should be expected when the sedimentary particles are mixed from the high ambient NH_4^+concentration of the pore water into lower NH_4^+ concentration of the bottom close water (Almroth-Rosell et al., 2012). Nevertheless, the decrease of NH_4 flux observed in the present study coincided with an increase of the NO_x flux, suggesting an enhanced nitrification due to resuspension-induced increase in benthic O_2 supply. Such stimulation of nitrification due to resuspension has been previously observed e.g. by Spagnoli and Bergamini (1997) and Moriarty et al., (2017). Similarly, Almroth-Rosell et al. (2012) suggested that the decrease of the benthic NH_4 flux during resuspension in a Scottish fjord was due to enhanced nitrification. Since the NO_x flux also increased due to resuspension at the 20 m station in the present study in August, we conclude that during warm summer months when the supply of NH_4 is enhanced due to more intensive ammonification, sediment resuspension promotes nitrification in the studied area. In the future, the intensified resuspension in the archipelago areas resulting in enhanced nitrification may strongly affect the nitrogen dynamics of the GoF, since the higher supply of NO_x may strongly promote denitrification (De Brabandere et al., 2015; Holmroos et al., 2016) and thus removal of nitrogen given that the supply of NH_4 would not limit nitrification. This development would enhance the existence of N-limitation in the Gulf due to increased N purification by coastal sediments. On the other hand, enhanced resuspension is likely to increase the transport of organic material to deeper areas (e.g. Danielsson et al., 2007; Almroth-Rosell et al., 2011; Capet et al., 2016). If higher amounts of organic nitrogen are transported to hypoxic and anoxic areas, in which DNRA can be the dominant pathway for nitrogen cycling, this nutrient will recycle in the ecosystem and not be removed (Jäntti and Hietanen, 2012).

Conclusions

This study reports on benthic fluxes of oxygen and inorganic nutrients and the effects of resuspension on these fluxes measured *in situ* in the shallow and sensitive archipelago of the Gulf of Finland. In May, during colder water conditions and higher oxygen supply, the benthic influx of oxygen was higher than in August. Higher water temperature and benthic regeneration of nutrients on the course of the growing season enabled a higher number of significant initial fluxes to be observed in August than in May. Resuspension altered the benthic fluxes of oxygen and nutrients in most of the experiments in August, but not in May. This was attributed to higher amount of regenerated benthic nutrients, lower redox conditions and stronger resuspension treatments in August.

In August, resuspension induced an increase of the benthic uptake of oxygen by 33–35% in three out of four experiments due to mixing of dissolved reduced substances into the near-bottom water. The benthic fluxes of nutrients were also altered due to resuspension in August, with the DIP flux turning from zero to negative (20 m station) and the DSi as well as NH_4 flux showing a decrease (7 m station) by 31% and 48%, respectively. The NO_x flux markedly increased at both stations; at the 7 m station by 30% and at the 20 m station by 27%.

The effect of resuspension on DIP and DSi fluxes was concluded to be due to adsorption onto newly formed iron oxyhydroxides, suggesting that locally, resuspension may trap these nutrients, albeit not necessarily permanently for DSi. However, the adsorption of these solutes onto newly formed light particles also enables their redistribution to deeper areas with lower redox conditions. Thus, together with spreading of hypoxia, resuspension may have consequences for recycling dynamics of these redox dependent nutrients on a larger spatial scale. The coinciding decrease of the NH_4 flux and increase of the NO_x flux was considered as an indication of resuspension-promoted nitrification, which may have a strong impact on the N-limited primary production of the GoF with the predicted intensification of resuspension events in the future.

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Highlights

- Sediment resuspension alters the benthic fluxes of oxygen and inorganic nutrients
- Resuspension decreases fluxes of redox depended nutrients and promotes nitrification
- Transport and cycling of nutrients in the Gulf of Finland will intensify in future