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Journal of Sea Research

journal homepage: www.elsevier.com/locate/seares

Effects of simulated natural and massive resuspension on benthic oxygen, nutrient and dissolved inorganic carbon fluxes in Loch Creran, Scotland

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ARTICLE INFO

Article history:

Received 12 October 2011

Received in revised form 28 March 2012

Accepted 11 April 2012

Available online 18 May 2012

Keywords:

Resuspension

Oxygen

Nutrients

Dissolved Inorganic Carbon

Loch Creran

Scotland

ABSTRACT

The effect of repeated natural resuspension on benthic oxygen consumption and the effect of natural and massive resuspension on oxygen consumption and fluxes of phosphate, silicate, ammonium and dissolved inorganic carbon (DIC) were studied at two stations (S1 and S2) in a Scottish sea loch. Station S11 had organically enriched sediment and station S1 had lower organic content in the sediment. The fluxes were measured in situ using the Göteborg benthic lander. Natural resuspension, simulating resuspension events due to strong wind, waves or currents, and massive resuspension, simulating resuspension due to e.g. trawling or dredging, were created inside the incubation chambers by regulating the stirring of the incubated overlying water or by retracting and shaking the incubated sediment. Natural resuspension showed clear effects on the oxygen consumption at station S11, where it increased with an average of 12.8 (standard error (s.e.) 0.17) and 7.7 (s.e. 0.12) mmol m⁻² d⁻¹ during the first and second incubations, respectively. At station S1 there was no clear effect of natural resuspension on the oxygen consumption. Massive resuspension increased the oxygen consumption on S1 with an average of 608 (standard deviation (sd) 366) mmol m⁻² d⁻¹ and on S11 with an average of 2396 (sd 2265) mmol m⁻² d⁻¹. The fluxes of ammonium, phosphate and silicate were affected by the massive resuspension in 50, 14 and 33% of the chambers, respectively, on station S11. However, in the majority of the cases there were no effects on the nutrient and DIC fluxes of massive resuspension. The absolute concentrations of DIC, ammonium and silicate did however instantly increase with an average of 419 (sd 297), 48 (sd 27) and 6.9 (sd 3.7) μM, respectively, at S11 upon massive resuspension. The concentrations of phosphate decreased instantly with an average of 0.2 (sd 0.1) μM. On station S1 there were effects only on the ammonium and silicate concentrations, which increased with 0.8 (sd 0.3) and 1.13 (sd 0.36) μM, respectively. The large increase in oxygen consumption due to massive resuspension indicates that activities like e.g. trawling and dredging that take place in areas where water exchange occurs infrequently may lead to oxygen depletion in bottom water, which in turn might affect the ecological balance. Silicate, ammonium and DIC can be released due to massive resuspension and contribute to increased algal blooms in surface waters.

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1. Introduction

The world's oceans act as a natural depository for dissolved and particulate substances transported from the continents (Schultz and Zabel, 2000). A majority of the material is deposited in coastal areas, where it is exposed to different physical, chemical and biological processes. By a combination of degradation, re-cycling and removal the sediment acts as a regulator of the concentrations of many compounds in seawater,

and has an important influence on the chemical composition of the ocean (Kennett, 1982).

When the critical shear stress on the sea floor is exceeded sediment particles are lifted up into the overlying water and resuspension is induced. Resuspension is a common physical process that occurs everywhere in the marine environment, in coastal areas as well as in the deep sea (Gross et al., 1988; Thomsen et al., 1994; Vangriesheim and Khrpounoff, 1990). The shear stress can be a result of bottom currents induced from wind waves or from tides, from barotropic (differences in sea levels), and baroclinic (differences in density) forcing mechanisms. Resuspension can also be induced by biological activity (Graf and Rosenberg, 1997) or by anthropogenic perturbations such as trawling and dredging.

The impact of resuspension on the degradation rate of organic material in the sediment and on the fluxes of different solutes between sediment and overlying water has been studied by a number

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of research teams (Almroth, 2008; Almroth et al., 2009; Blackburn, 1997; Spagnoli and Bergamini, 1997; Ståhlberg et al., 2006; Tengberg et al., 2003; Wainright, 1987, 1990; Wainright and Hopkinson, 1997). Some results indicated that the degradation rate of organic material was affected by resuspension while others found no effects. Also the conclusions regarding the impact of resuspension on the fluxes of solutes varied between the different studies. Most of these studies were performed in laboratories or with models. Only Almroth et al. (2009) and Tengberg et al. (2003) performed their studies in-situ, using the same type of autonomous benthic incubation lander. They found no significant effects of the created natural resuspension on benthic nutrient fluxes or on the degradation rate of organic material. The oxygen consumption was, however, significantly increased as the sediment was resuspended (Almroth, 2008; Almroth et al., 2009).

The aim of this study was to further understand the effects of different strengths of resuspension on benthic fluxes of nutrients, oxygen and dissolved inorganic carbon (DIC). Natural resuspension, induced by e.g. benthic fauna and tidal circulation, and massive resuspension, mimicking e.g. dredging, trawling and large natural events such as turbidity currents and landslides on coastal sediments, were created during in situ chamber incubations using a benthic lander. This study was performed at two sites in a tidally influenced sea loch system located on the west coast of Scotland. One station was organically enriched by a former fish farm and one station was situated further away from influence of human activities serving as a reference station.

2. Material and methods

2.1. Study site

A two-week field study was carried out in Loch Creran, a sea loch (fjord) on the Scottish west coast, north of Oban (Fig. 1) in May 2006. Loch Creran is 12.8 km long and is characterized by four sills that divide the loch into four basins. The first basin has a 7 m deep and 320 m wide sill in the west and has a maximum depth of 27 m. It is exposed to strong tidal currents; hence the sediment in this basin is coarse (Black et al., 2000). The second basin has a maximum depth of 49 m. This basin is characterized by coarse sediments from the second sill to the deepest part of the basin and thereafter by soft, muddy sediments. The sill between the second and third basins is 15 m deep. Basin 3 is relatively shallow, 27 m at the deepest part, and the sediment consists of soft mud. Basins 2 and 3 form the main body of the loch and are referred to as the main basin. The sill that delimits basin 3 from basin 4 is only 3 m deep, and 100 m wide at low water. Basin 4 has a maximum depth of 37 m.

The fresh water supply to the loch is about $286.3 \cdot 10^6 \text{ m}^3 \text{ yr}^{-1}$. There are no severe wave actions in the sheltered loch, but winds and high tidal current contribute to high mixing of the fresh and saline water. The flushing time for the loch is approximately 3 days, when around 60% of the water volume is exchanged with coastal waters. The short flushing time and the high mixing prevent the bottom water from oxygen depletion, as well as serious accumulation or retention of dissolved contaminants (Black et al., 2000).

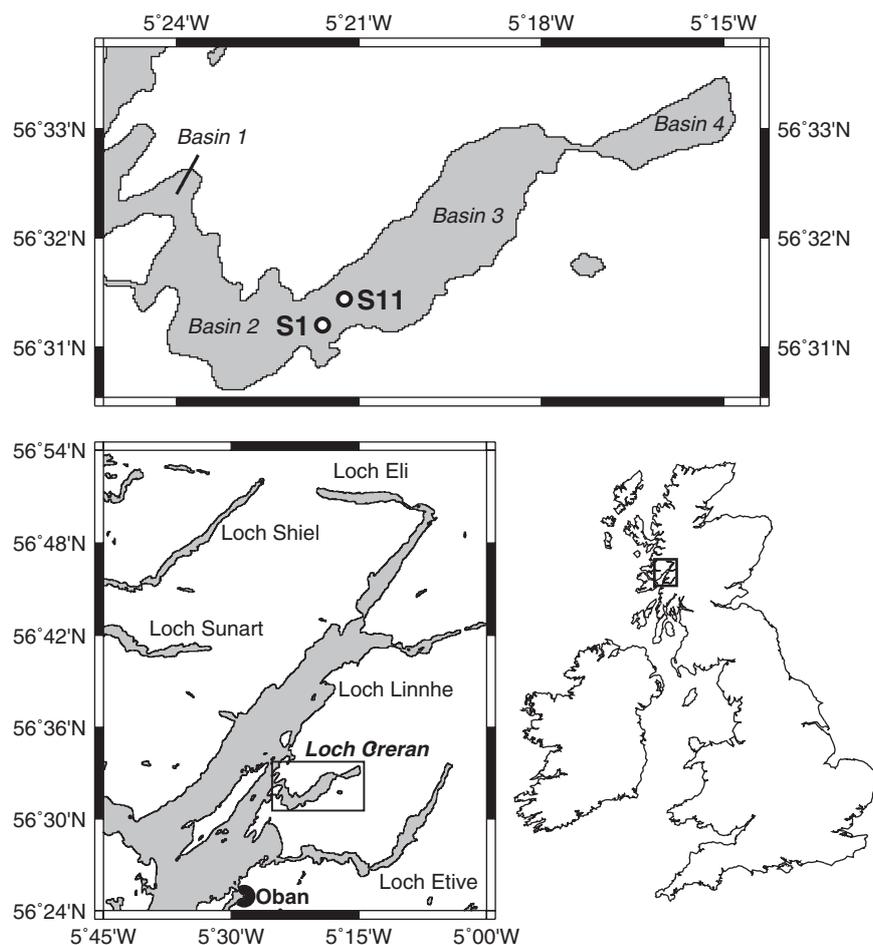


Fig. 1. A map of the study site Loch Creran on the west coast of Scotland. Stations S1 and S11 were studied with chamber incubations using an autonomous benthic lander. Between the two stations a recording doppler current meter (RDCP) was deployed through the whole field work, in order to measure background data of oxygen, turbidity, currents and temperature.

The effect of resuspension on benthic solute fluxes was studied at two stations, S1 and S11 located in the third basin (Fig. 1). Station S11 was located at approximately 26 m depth. Due to a fish farm that was active at this position between approximately 1970 and the end of the 1990s (Black et al., 2000), the sediment was considered organically enriched with an organic carbon concentration of about 7% of sediment dry weight (Lois Calder, pers. com.). Station S1, located at approximately 29 m depth, served as a control station and was considered to be less affected by human activities in general and by organic matter from fish farming activities in particular. At station S1, the organic carbon was about 1.5% of the dry weight. These concentrations of organic carbon were measured in March and October 2006.

2.2. In-situ chamber incubations with the Göteborg benthic lander

The Göteborg lander is normally autonomous for operations down to 6000 m and consists of an outer and an inner frame composed of non-corrosive titanium (Ståhl et al., 2004). Autonomous recovery was not needed during this study and therefore only the inner frame was used, in the same way as was described by Tengberg et al. (2003). The inner frame was equipped with four incubation chamber modules, which each carried ten syringes for water injection and sampling at pre-determined time intervals. Stirring of the overlying water was made by a horizontal Mississippi type paddle wheel placed centrally in the chambers (Tengberg et al., 2004), which can be run at different speeds to create different shear stresses and different levels of resuspension. The lander frame was equipped with floats to regulate its weight and manually lowered to the bottom where the four chambers were gently inserted into the sediment. The incubation started when the chamber lids were closed and ended when the chamber lids automatically were opened and the water in the chambers was exchanged. A known volume (about 60 ml) of a 300 mM bromide solution was injected into each chamber at the start of the incubations. After 30 min the first sample was drawn with the first syringe. Calculating the dilution factor of the bromide gave an estimation of the chamber volume which was used in the flux calculations (Rao and Jahnke, 2004).

During the incubations the sediment was exposed to different levels or strengths of resuspension, which was created by altering the stirring speed of the paddle wheel inside the chamber or by collecting the sediment. The resuspension generated by the change in

stirring speed eroded the sediment from the top and was intended to mimic “natural” resuspension events due to high bottom currents and/or waves. A massive resuspension event, to mimic e.g. trawling or dredging, was created by abruptly capturing the sediment by retracting the chambers and closing the bottom scoops.

All deployments, recoveries and sediment samplings were performed using the research vessels R/V Seol Mara and R/V Calanus. Deployments were carried out during 24 or 48 h. Two deployments took place on station S1 and three deployments on station S11 (Fig. 1, Table 1). During the first part of the incubations the stirring speed was low and no resuspension was created. During all deployments chambers 1 and 2 were used as reference chambers (without resuspension) while “natural” resuspension was created in chambers 3 and 4. During deployments 1 and 3 the stirring speed was increased from low to high level in chambers 3 and 4 in the second half of the incubation, to create natural resuspension. During deployments 2, 4 and 5 natural resuspension was created in chambers 3 and 4 in two steps. After about 1/3 of the incubation time the stirring speed was increased from low to medium level, and after the subsequent about 1/3 of the incubation time the stirring speed was increased further to high level. After the whole incubation the stirring speed was set to low level again and the chamber lids were automatically opened for about 2 h to ventilate the chambers, letting the chamber water return to ambient conditions. Then the lids were closed again and a second incubation, in the same way and on exactly the same spot as the first, was performed. During deployment 2 a third incubation was performed in the same way as incubations 1 and 2, with the exception that at the end of the incubation the sediment in the chambers was captured, and massive resuspension was created. During deployments 4 and 5 the third incubation started with low stirring speed in all four chambers and then the sediment was collected, i.e. massive resuspension was created (Table 1).

Oxygen concentrations and turbidity were measured in each chamber at 1 minute intervals during the entire duration of the deployments using oxygen optodes (Tengberg et al., 2006) and turbidity sensors (Almroth et al., 2009), respectively. Samples for DIC and nutrients were collected with syringes at pre-programmed discrete times from one incubation of each deployment. During deployments 1 and 3, five and four samples were collected before and after, respectively the stirring speed was increased. During deployment 2 three samples were collected during the same time before and after massive resuspension was created. During deployments 4 and 5, five

Table 1
Field summary. Name, period and total length of deployment, water depths and positions of the stations can be found in the three first columns. In total five deployments were performed (deployment number) and at the most were three incubations (incubation number) performed after each other during one deployment. Successfully measured fluxes of oxygen (O₂), dissolved inorganic carbon (DIC) and nutrients (Nu) were performed in different chambers (Chamber number) during the different incubations.

Station name	Deploy. period	Position depth	Deployment number	Incubation number	Control chamber number		Chamber number with natural resuspension		Chamber number with massive resuspension	
					O ₂	DIC, Nu	O ₂	DIC, Nu	O ₂	DIC, Nu
S1	May 2–3, 24 h	56°31.360 N 05° 21.516 W Depth 28.7 m	1	1	–	–	3, 4	3, 4	–	–
S1	May 4–6, 48 h	56°31.356 N 05° 21.572 W Depth 29.2 m	2	1	1, 2	–	3, 4	–	–	–
				2	1, 2	–	3, 4	–	–	–
				3	1, 2	–	3, 4	–	1, 2, 3	1 ^a , 2 ^a , 3 ^a
S11	May 7–8, 29 h	56°31.450 N 05° 21.214 W Depth 26.7 m	3	1	1, 2	1, 2	4	4	–	–
S11	May 9–11, 48 h	56°31.443 N 05°21.207 W Depth 25.4 m	4	1	1, 2	–	3, 4	–	–	–
				2	1, 2	–	3, 4	–	–	–
				3	–	–	–	–	1, 2, 3	1, 2, 3
S11	May 11–13, 42 h	56°31.456 N 05°21.201 W Depth 25.9 m	5	1	1, 2	–	3, 4	–	–	–
				2	1, 2	–	3, 4	–	–	–
				3	–	–	–	–	1, 2, 3, 4	1, 2, 3, 4
Total numbers of.	5	11	16	2	17	3	10	10		

^a Only concentrations were measured before and after massive resuspension, no flux measurements.

and four samples were collected before and after, respectively, the major resuspension was created.

After lander recovery, water samples were filtered through pre-rinsed 0.45 µm pore size cellulose acetate filters into different vials. Samples for dissolved inorganic carbon (DIC) were kept in top filled, gas impermeable glass vials, preserved with zinc chloride and then brought back to Gothenburg for analysis. Incubated sediments were not analyzed, but investigated for larger animals, which were trapped in the chambers and possibly could have influenced the incubations.

2.3. Study site background information

A profiling current meter (RDCP 600) from Aanderaa Data Instruments (www.aadi.com) was mounted on a separate frame, which was deployed during the whole field study on a location between the two stations S1 and S11 (Fig. 1). The instrument had sensors to record turbidity and optodes to measure oxygen concentrations in the bottom water. It also measured pressure which gave both water level and wave information, salinity, and temperature. The recordings from this instrument were used as background information of the bottom water conditions, i.e. the occurrence of natural resuspension and oxygen concentrations.

2.4. Determination of the effects of resuspension on solute fluxes

To determine if resuspension was successfully created in the different chambers the following criteria were used: 1) the measured turbidity had to increase by at least 100% after the increase in stirring; and 2) the average turbidity had to be at least 5 (±5%) normal turbidity units (NTU). If these criteria were fulfilled the chamber was considered to be a successful resuspension chamber and the results were retained.

The fluxes ($\text{mmol m}^{-2} \text{d}^{-1}$) were calculated using formula (1),

$$F = k * V/A \quad (1)$$

where k is the slope of the linear regression line (change in concentration over time), V is the chamber volume and A is the chamber area. The volume in this study varied in the range of 11–16 l. In the control chambers and in the chambers in which natural resuspension was created all data points, before and after the increase in stirring speed, respectively, were used to calculate the slope. When massive resuspension was created all the data points for nutrients and DIC were used, but for oxygen the data points were used as long as the slope was linear. The uncertainty of each flux, also called the standard error (s.e.) was calculated using formula (2),

$$\text{s.e.} = F * \text{s.e.}_k/k \quad (2)$$

where k is the slope of the linear regression and s.e._k is the standard error of the slope. If the uncertainty of the flux was larger than the flux, it was rejected. However, to prevent low fluxes (often with a greater uncertainty than high fluxes) to be rejected to a larger extent than high fluxes, and in this way introduce a bias, the low fluxes with an uncertainty greater than or equal to the flux were tested by a special method. First the lowest accepted flux (F_{acc}) from the whole data set was identified. Then the low flux had to be lower than the F_{acc} and the uncertainty of the low flux had to be lower than five times the flux. If this was the case, then the low flux was set to zero, otherwise it was rejected (Almroth et al., 2009).

The slopes of the regression lines before and after the time for the increased stirring speed (ISS) were tested (using t -test) and the flux after ISS was retained as an affected flux if the slopes were significantly different ($p \leq 0.05$). The fluxes in the resuspension chambers, where a significant change was found, were compared to the fluxes in the control chambers where no resuspension was induced. If

changes of the fluxes in the resuspension chambers behaved differently compared to changes of the fluxes in the control chambers, we considered effects of resuspension to have occurred (Almroth et al., 2009).

The calculated initial fluxes were set to be the same as the flux before the time of ISS in both control chambers and resuspension chambers. The quantification of the effect of resuspension on the fluxes was obtained by calculating the average change of the fluxes in the resuspension chambers at each deployment. Any change of the fluxes caused by other factors than resuspension in the control chambers during the same deployment was calculated in the same way and at the same time as in the resuspension chambers. The total effect of resuspension was then compensated for these non-resuspension effects. Resuspension might also affect the concentrations in the chambers with a strong response, but with a short duration of less than the time between samples, thus giving the impression of an instant effect. To investigate this possibility, confidence intervals for the linear regressions before and after the time of resuspension were calculated. If the confidence intervals overlapped, no instant changes in concentrations were considered to have occurred (Almroth et al., 2009). During deployment 2 in this study two samples for nutrients and DIC were withdrawn before as well as after massive resuspension was created in the chambers. The data set before the resuspension was then compared with the data set after resuspension using a t -test to find out if the concentrations were affected by the massive resuspension event.

2.5. Analytical methods

Concentrations of DIC (also called total carbonate) were determined with an automated system based on non-dispersive infrared detection of CO_2 using a Li-Cor 6262 detector (Goyet and Snover, 1993; O'Sullivan and Millero, 1998). Prior to detection, all of the dissolved species of the total carbonate system in the sample was converted to CO_2 gas by acidification with phosphoric acid in a "stripping tower". The CO_2 was then stripped from the sample with N_2 -gas and carried to the detector. Certified reference material (CRM, Dickson Laboratories, Scripps Inst. of Oceanography) was used for calibration and correction for system drift after approximately every fifteen samples. The analytical precision was 0.2% RSD (relative standard deviation; $n = 15$) or better.

The nutrients were analyzed at the Scottish Association of Marine Science using a Lachat Quickchem 8000 Flow Inject Autoanalyser. The relative standard deviation for all nutrients with concentrations above 1 µM was 1%. Below 1 µM and above 0.2 µM it rises to around 10% for NH_4^+ and around 5% for $\text{NO}_3^-/\text{NO}_2^-$, PO_4^{3-} , and SiOH_4 . Below 0.2 µM it can be up to 50% for NH_4^+ and 10% for $\text{NO}_3^-/\text{NO}_2^-$, PO_4^{3-} , and SiOH_4 .

Oxygen concentration and turbidity inside the chambers were measured using four oxygen optodes, model 3830, and four turbidity sensors, model 3612A, respectively, from Aanderaa Data Instruments (www.aadi.no). The same types of sensors were also mounted on the RDCP-600 measuring in the bottom water at 15 minute interval during the entire period of the field-work. Oxygen optodes were checked against replicate water samples that were collected at eight occasions and analyzed by Winkler titration in the laboratory. The five optodes were found to be without drift and with an absolute accuracy of better than ±4%. Also previous studies have demonstrated the accuracy, precision and long-term stability of these sensors (Hydes et al., 2009; Körtzinger et al., 2004; Tengberg et al., 2006).

The used turbidity sensors were factory calibrated (accuracy ±2%) in multiple points with standard procedures to output amount of particles in normal turbidity units (NTU). During this field-work no water samples were collected to convert from NTU to site-specific absolute concentrations of particles in mg/l. We do therefore not have detailed information about absolute concentrations of particles

in the water. Earlier studies (Almroth et al., 2009; Tengberg et al., 2003) using the same type of sensors did however give an approximate conversion equation of: Suspended particles (mg/l) = 1.2 * sensor value (NTU) – 0.3. In this study we used the background value measured by the external turbidity sensor (mounted on the RDCP) to confirm that the background value of particles inside the chambers before resuspension was similar to natural levels outside incubation chambers.

3. Results and discussion

3.1. Hydrographical variations

During the entire field-work no major wave motion was detected at the bottom with the RDCP (deployed at 23 m) in spite of intermittently windy conditions. The loch's sheltered location and narrow strait naturally protects it from external forces such as big waves and strong winds. The tidal water level variations reached maximum amplitude of 3 m and showed that the major water circulation mechanism affecting the bottom at which the instruments were deployed in the loch was tidal. Approximately 3.5 m above the bottom the average horizontal current was 7.8 (standard deviation (sd) 4.1) cm/s with a maximum value of 26.6 cm/s. This was not enough to create any major resuspension of bottom sediments, but smaller sediment resuspensions were common and occurred in every tidal cycle. The average turbidity was about 1.4 (sd 0.4) normal turbidity units (NTU), with a maximum value of about 4 NTU.

The bottom water temperature in the loch increased during the field campaign from 8.4 °C to 9.2 °C with an average of 8.6 (sd 0.2) °C most likely due to the unusually warm weather. Salinity, as well as temperature, varied with the tide and ranged between 32.4 and 32.8. The oxygen concentrations in the bottom water was also affected by the tidal circulation and varied with between 230 and 341 $\mu\text{mol l}^{-1}$, average 315 (sd 15) $\mu\text{mol l}^{-1}$. The variations were most likely caused by water circulation, which occasionally brings in bottom water with lower oxygen concentrations. Most of the time the bottom water was supersaturated (average 107%) in oxygen indicating that benthic primary production may occur at these depths.

3.2. Natural and massive resuspension

The lander was deployed five times, providing in total 40 chamber measurements of benthic fluxes of oxygen, nutrients and DIC with or without created resuspension (Table 1). During three deployments (2, 4 and 5) repeated natural resuspension experiments were performed by ventilating (opening) the chambers between multiple incubations. Thus, the effect of resuspension could be measured several times on exactly the same site. In 14 chambers, during 7 incubations, the stirring speed was increased in two steps, in order to create resuspension of different strengths. Natural resuspension, according to our criteria, was created in 7 of the chambers at the first step of increased stirring speed and in total in 11 chambers after the second step. The stirring speed was kept at a low level throughout the incubations in 14 chambers, which were used as control chambers. During deployments 1 and 3 there was no repeated resuspension experiment and the stirring speeds increased from low to high in one step in two and one of the chambers, respectively. There was no control chamber during deployment 1, and during deployment 3 there were two control chambers.

The turbidity in the resuspension chambers where natural resuspension was successfully created was on average 6.5 NTU (sd 3.9) and 8.9 NTU (sd 4.0 NTU) after the first and second increases in stirring speed, respectively. These turbidity values in the chambers during resuspension events were well above the natural turbidity measured (average 1.4 NTU and maximum 4 NTU) outside the chambers during the whole field study. The average background level of suspended particles was 1–2 NTU both inside the control chambers and before

increasing the stirring speed in the other chambers. Using the conversion formulas presented in Almroth et al. (2009), see Section 2.5, the depth of the sediment that was resuspended (D_{rsed}) in the chambers ranged from 0.26 to 2.6 μm (formula 3)

$$D_{\text{rsed}} = \text{Turb} \cdot H / \rho_{\text{sed}} \quad (3)$$

where Turb is the average turbidity in NTU recalculated to turbidity in mg/l, H is the height (dm) of the incubated water in the chambers and ρ_{sed} is the wet sediment density of 1.2 kg l^{-1} (Almroth et al., 2009)

Massive resuspension events were created during three incubations, in which fluxes were successfully measured in ten of the chambers (Table 1). The turbidity during these resuspension events reached the maximum value of the sensors and were thus well above 120 mg/l. These resuspension events were created as the sediments in each chamber were automatically captured by a spring-activated mechanism without any dampening, and thus well shaken, simulating dredging or trawling.

3.3. The effect of resuspension on benthic solute fluxes

3.3.1. Oxygen consumption

3.3.1.1. Natural resuspension. The initial oxygen consumption at the fish farm station (S11) and the reference station (S1) ranged from 22.9 to 68.9 $\text{mmol m}^{-2} \text{d}^{-1}$ and from 24.8 to 40.9 $\text{mmol m}^{-2} \text{d}^{-1}$, respectively (Fig. 2). Both the highest and lowest average oxygen consumptions were found at the fish farm site S11 indicating that the spatial variability between repeated deployments within one station appeared to be as large as in-between the two sites. The variability of oxygen uptake rates most likely reflected a combination of patchiness of organic matter and fauna distributions in the sediment at the two stations, especially at station S11.

The oxygen consumption in general seemed to decrease with time during the incubations giving the concentration versus time plots an exponential (or “banana like”) shape (Fig. 8). This banana shape may be a result of decreased oxygen concentrations in the water of the chambers and thus increased transport resistance through the diffusive boundary layer (DBL) (Hall et al., 1989). This phenomenon was seen during all deployments and incubations. Thus, to be able to investigate the effect of resuspension on benthic solute fluxes, especially oxygen, it is very important to compare the behavior of fluxes in resuspension chambers with fluxes in reference chambers.

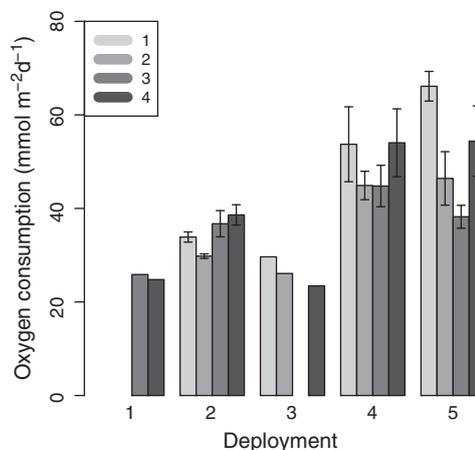


Fig. 2. The average initial oxygen consumption in the chambers from the two stations S1 (deployments 1 and 2) and S11 (deployments 3–5). The error bar shows the standard deviation from the repeated incubations during each deployment. No error bars mean that there were no repeated incubations, hence there is only one data for each chamber.

At station S11, deployments 4 and 5, there were clear effects on the oxygen consumption as the stirring speed was increased the first time (1st ISS), from low to medium level (Fig. 3). As the stirring speed increased, resuspension of different levels was created in the chambers, and the oxygen consumption increased compared to the reference chambers. The effect on the oxygen consumption was seen during all the repeated incubations in the 4th and 5th deployments (Fig. 3a). However, the effect of resuspension was larger during the first incubation when the oxygen consumption increased with 6.2–18 mmol m⁻² d⁻¹, compared to the second incubation when it increased with 5.8–10 mmol m⁻² d⁻¹. This corresponds to an increase in oxygen consumption with 12–36%, which is in accordance with the results from a study in the Gulf of Finland where the oxygen consumption increased with on average 59% due to resuspension (Almroth et al., 2009). As the stirring speed was further increased (2nd ISS), from medium to high level, no further increase in the oxygen consumption was observed even though the resuspension (as measured by turbidity) increased in all resuspension chambers. In fact, during the first incubations the change in oxygen consumption decreased during the 2nd ISS, compared to the initial fluxes (Fig. 3b). During the second incubation there was no clear pattern (Fig. 3b) of the change in oxygen consumption.

The increase in consumption at deployments 4 and 5 at the 1st ISS and the lack of further increased consumption during the 2nd ISS seemed to occur regardless of the strength of the created resuspension. A plot (Fig. 4) of the oxygen consumption versus the turbidity in the chambers showed that there was no relation between the two variables. The criteria for successfully having created resuspension in a chamber (described in Section 2.4) might thus not be necessary to use, at least not for calculating oxygen fluxes. This is in accordance with previous

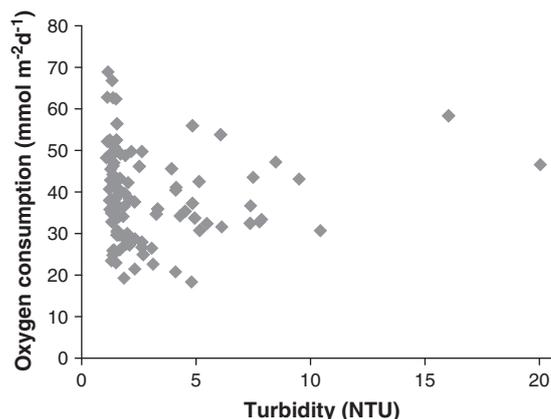


Fig. 4. The oxygen consumption (mmol m⁻² d⁻¹) versus turbidity (NTU) in chambers at stations S1 and S11. There is no clear relation between the two variables.

studies by Jørgensen and Des Marais (1990) who showed an inverse relation between DBL thickness and oxygen consumption rates in sediments with high oxygen consumption. The oxygen influx increased with increasing water flow velocity, which compressed the DBL and in turn increased the diffusive flux of oxygen into the sediment. The decrease in oxygen consumption, after the second increase in stirring speed, during the first incubation, might be because the DBL thickness was already compressed and the maximum oxygen transport to the sediment was thus achieved already in the first step. A large part of the reduced substances was oxygenated already during the first increase in stirring speed, i.e. the oxygen demand was lower in the resuspension chamber as the stirring speed was increased the second time.

The larger increase in oxygen consumption during the first incubation, at both stirring speeds, compared to the second incubation, might be due to at least two reasons. First, there were more reduced solutes available to oxidize during the first incubation and the 1st ISS, thus the oxygen demand was larger then. Second, no new organic matter, or reduced solutes, was probably transported into the chambers during ventilation between incubations. Instead some of the resuspended particles (inorganic as well as organic) were probably ventilated out from the chambers at the end of the first incubation. Observations of the turbidity showed that the level of resuspension slightly decreased between incubations, probably due to the out-ventilation of smaller particles as well as re-arrangement of the sediment particles on the sediment surface.

The lowest oxygen consumption was found at station S11, during deployment 3 (Fig. 2). During this deployment oxygen consumption

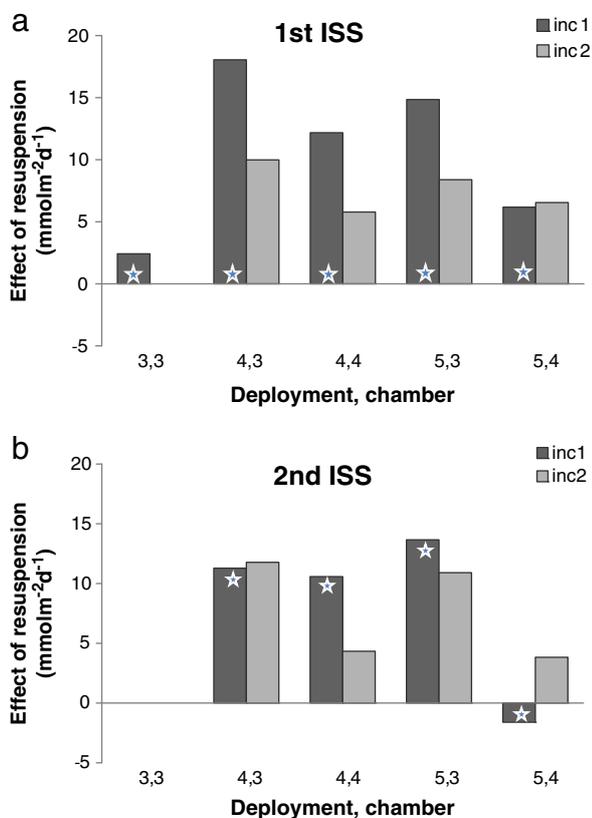


Fig. 3. The effect of resuspension on the oxygen consumption as the stirring speed was increased from low to medium level (left) and from medium to high level (right) at station S11. The dark gray bars represent the effect of resuspension during the first incubation and the light gray bars represent the effects during the second incubation (repeated incubation). Significant resuspension was created in the chambers marked with stars.

Table 2

The average^a effects of natural resuspension on oxygen consumption in mmol m⁻² d⁻¹ and in %, and the standard error (s.e.) of the effects as a result of the first step of increased stirring speed (ISS) are shown for the different incubations during deployments 3, 4 and 5. The average start values of the oxygen concentrations (μM) in the chambers are given as the bottom water (BW) concentrations.

Deployment	Incubation	BW [O ₂] μM	Effect of resuspension (mmol m ⁻² d ⁻¹) (%)	s.e. (mmol m ⁻² d ⁻¹)
1	1	326	–	–
2	1	322	–	–
3	1	307	2.4	10.3
4	1	299	15.1	30.2
4	2	–	7.9	17.2
5	1	313	10.5	23.2
5	2	–	7.5	17.3

^a In deployment 3 there was only one resuspension chamber.

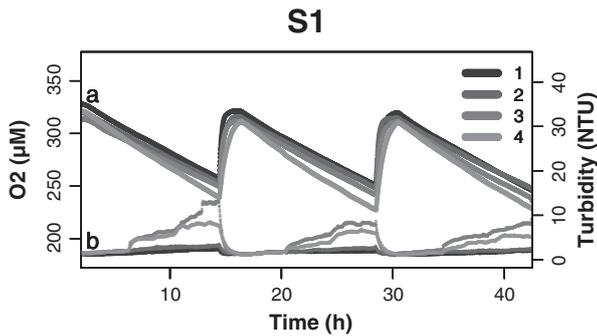


Fig. 5. Example of repeated incubations at station S1, during deployment 2. Repeated incubations were also performed during deployments 4 and 5 at station S11. Oxygen concentration (starts at letter a) was measured with optodes, and turbidity (starts at letter b) with sensors every minute, inside chamber 1–4 (legend). Samples for nutrients and DIC were collected during the last incubation before and after massive resuspension was created. After each incubation the chamber lids were opened to ventilate the chambers, and oxygen as well as turbidity went back to initial concentrations, before the lids were closed and the next incubation started.

was only successfully measured in one of the two resuspension chambers, which showed an increase in oxygen consumption as natural resuspension was created (Fig. 3 and Table 2). No repeated incubations were made at this deployment.

Three repeated incubations were successfully performed at station S1 during deployment 2 (Fig. 5). Resuspension above 5 NTU was created in three of six resuspension chambers and in the remaining three resuspension chambers the average turbidity was above 3.3 NTU. The effects of resuspension on the oxygen consumption were much lower at S1 compared to station S11 and the pattern was somewhat irregular. The consumption seemed to alternatively increase or decrease (Fig. 6). The highest observed effect ($2.7 \text{ mmol m}^{-2} \text{ d}^{-1}$) corresponded to 6.6% of the initial consumption. The changes in oxygen consumption during the second increase in stirring speed were in the same range as during the first increase in stirring speed, and the largest change in consumption ($3.5 \text{ mmol m}^{-2} \text{ d}^{-1}$) corresponded to 9.8% of the initial oxygen consumption. The unclear pattern and the low range of change during the first increase in stirring speed indicated that there were no significant effects of resuspension on the oxygen consumption at station S1. During the second increase in stirring speed the oxygen consumption decreased more in the resuspension chambers compared to the control chambers, which is the same behavior as during the first incubations at station S11.

3.3.1.2. Massive resuspension. The effect on oxygen consumption due to massive resuspension was dramatic (Fig. 7) in all cases. When sediment was collected a strong mixing of sediment and water occurred

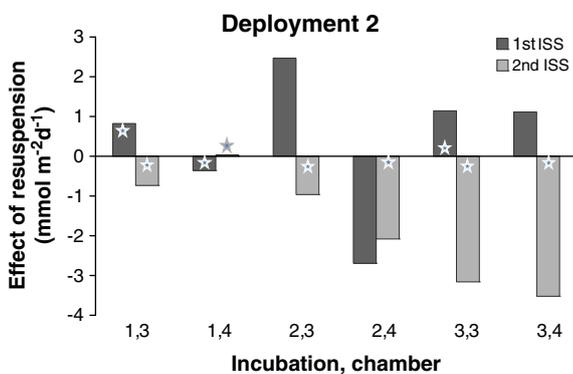


Fig. 6. The effects of resuspension during deployment 2 at the non-fish farm-affected station (S1). Resuspension (turbidity > 5 NTU) was created in the chambers with the stars.

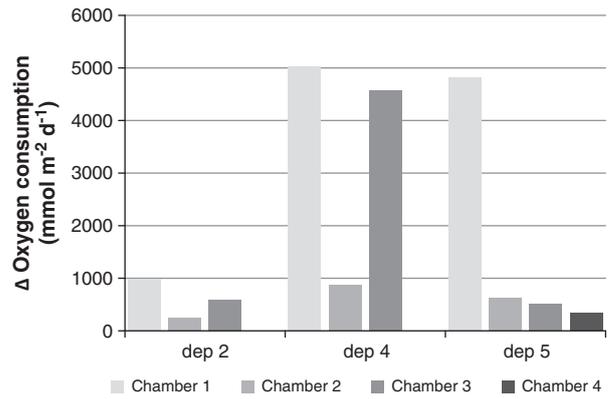


Fig. 7. The change in oxygen consumption ($\text{mmol m}^{-2} \text{ d}^{-1}$) due to massive resuspension is shown for each chamber.

and reduced substances were exposed to the oxygenated bottom water (and vice versa), resulting in an enormous increase in oxygen consumption, i.e. a rapid decrease in oxygen concentration in the incubation chambers as a result (Fig. 8). The lowest increase in consumption was $252 \text{ (s.e. 37.8) mmol m}^{-2} \text{ d}^{-1}$ corresponding to an increase of 1013% at station S1. The highest increase in consumption was $5025 \text{ (se 602) mmol m}^{-2} \text{ d}^{-1}$ corresponding to an increase of 16,948% at station S11. This indicates that major resuspension, caused by e.g. dredging or trawling, of organically rich sediments like the ones studied here, will immediately lead to a very high consumption of oxygen, which can have important, at least temporarily, chemical and biological effects on the local environment.

3.3.2. Dissolved inorganic carbon and nutrients

Samples for nutrients and dissolved inorganic carbon (DIC) were withdrawn in the last incubation during all deployments. Both initial fluxes (Fig. 9), i.e. fluxes before the time when the stirring speed was increased, and fluxes after resuspension were calculated in both control and resuspension chambers. The stirring speed was increased in order to create natural resuspension in the resuspension chambers during deployments 1 and 3. During deployment 1, at station S1, the created resuspension was low, the turbidity only increased on average from 1.36 (sd 0.0) NTU to 3.6 (sd 0.7) NTU. No data were

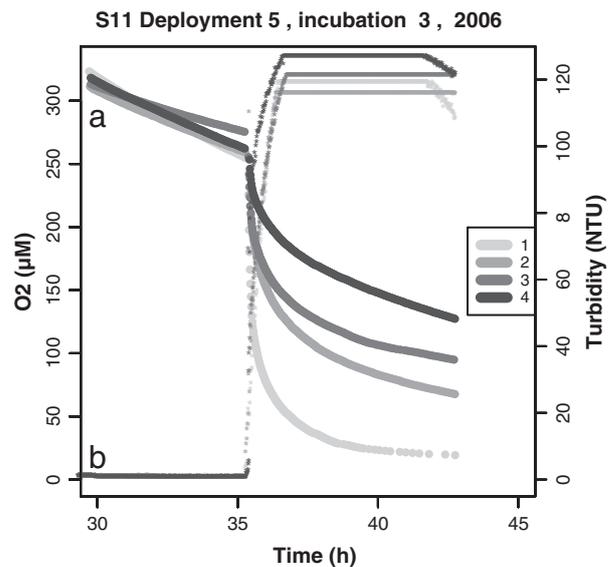


Fig. 8. The oxygen concentrations (start at letter a) decreased dramatically as massive resuspension was created, showed by the increased turbidity (starts at letter b), in the chambers (legend).

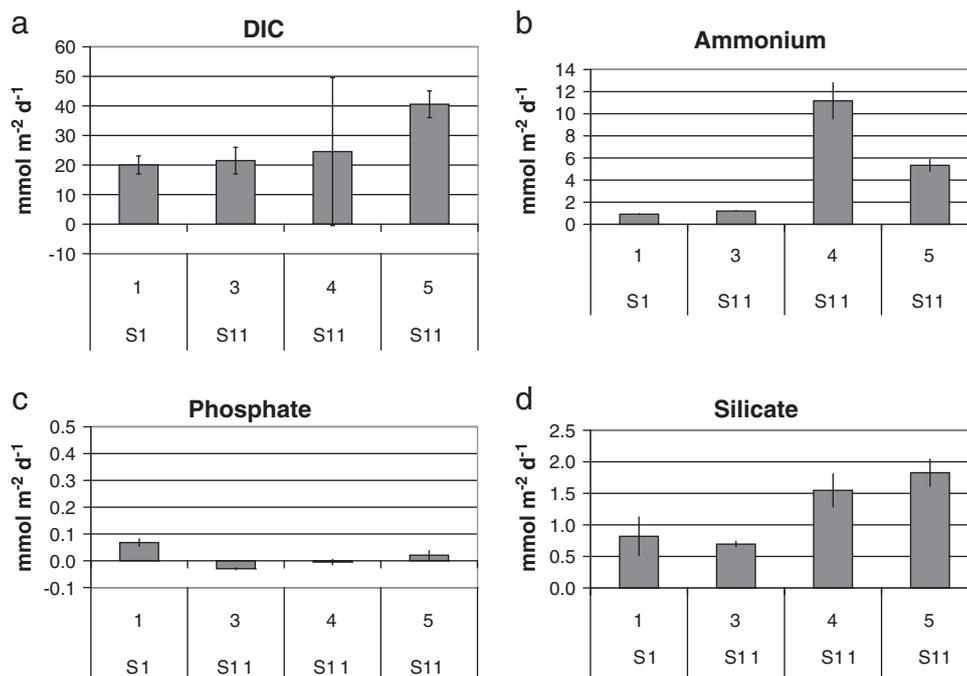


Fig. 9. The average initial fluxes ($\text{mmol m}^{-2} \text{d}^{-1}$) of DIC (a), ammonium (b), phosphate (c) and silicate (d) during the different deployments (1,3,4,5) at the two stations S1 and S11. The error bars show the standard error of the average fluxes.

received from the control chambers. Also at station S11, deployment 3, the created resuspension was on the lower limit; the turbidity increased from 1.3 to 4.8 NTU in only one chamber. Even though the created resuspension was low, there was an increased stirring speed in three of the in total five chambers, which should decrease the DBL thickness (Jørgensen and Des Marais, 1990). However, no statistically significant changes in the fluxes or concentrations of DIC or nutrients were observed due to natural resuspension or increased stirring speed in this study. Thus, more field studies need to be performed to be able to make conclusions in a statistically significant way about the effects of natural resuspension on benthic fluxes of nutrients and DIC in sea lochs.

During deployments 4 and 5 at station S11, massive resuspension was successfully created in seven of the eight chambers, causing rapid mixing of oxygenated overlying water, sediment and pore water. Due to technical reasons no control chambers could be used when massive resuspension was created, which makes the study of its effect somewhat uncertain. However, the observed changes during deployments where massive resuspension was created were not observed during deployments where there were control chambers or natural resuspension. Therefore, it can be suggested that the observed changes are due to massive resuspension. The magnitude might not be exactly measurable due to lack of control chambers, but the errors should be of minor magnitude. The average initial DIC fluxes at stations S1 and S11 was 20 (s.e. 3.1) and 30 (s.e. 14) $\text{mmol m}^{-2} \text{d}^{-1}$, respectively (Fig. 9a), which were not affected by the massive resuspension in any of the chambers (Table 5). However, the initial concentrations of DIC (Table 3) increased instantly (Fig. 10 left and

Fig. 11a) in all chambers (Table 6) with an average of 419 μM (sd 297), which corresponded to 20.4%. The instant increase in concentration of DIC observed at station S11 was not observed during deployment 2 at station S1, where no effects of resuspension on concentrations were observed.

At station S1 the average initial flux of ammonium was low, 0.9 (s.e. 0.03) $\text{mmol m}^{-2} \text{d}^{-1}$, as well as at station S11 during deployment 3, where it was 1.2 (s.e. 0.03) $\text{mmol m}^{-2} \text{d}^{-1}$ (Fig. 9b). At S11 during deployments 4 and 5 the initial flux was higher due to the organically enriched sediment (Fig. 9b) and an effect on the ammonium fluxes (Table 4) was observed in two out of four chambers (Table 5) with significant fluxes due to created massive resuspension. The low initial ammonium flux measured during deployment 3 is in accordance with the lower oxygen consumption during this deployment, which indicates that there was a patchiness of the organic material at station S11. During deployments 2, 4 and 5 the ammonium concentrations (Table 3) instantly increased (Fig. 11b) in all chambers (Table 6). During deployment 2 the concentrations increased with an average of 0.8 (sd 0.3) μM corresponding to an increase as large as 18% (sd 10%). At station S11 the massive resuspension caused a dramatic increase of the ammonium concentrations (Fig. 11b) ranging from 9.9 to 81 (on average 48 (sd 27)) μM corresponding to an increase of 106–956% (on average 482%). The increase of ammonium concentration due to massive resuspension events was probably caused by mixing of sediment and pore water containing larger concentration of ammonium. The larger increase at S11 was most likely due to higher pore water concentrations of ammonium in the top 25 mm of the sediment; on average (from two sediment profiles) 157 (sd 47) μM compared to the average concentration at S1 which was 82 (sd 6.7) μM . Ammonium shows also an adsorption–desorption behavior to particle surfaces (e.g. Landén and Hall, 1998). As sediment particles with high concentrations of ammonium in the surrounding pore water were resuspended into the overlying water the concentration in the surrounding water became lower and ammonium might be desorbed from the particles. Thus, this mechanism could have contributed to the increased ammonium concentrations upon resuspension.

Table 3
Initial average bottom water concentration (μM) of dissolved inorganic carbon, ammonium, phosphate and silicate in the incubation chambers at stations S1 and S11. The standard deviations of the concentrations are given as \pm values.

Station	[DIC]	$[\text{NH}_4^+]$	$[\text{PO}_4^{3-}]$	$[\text{Si}(\text{OH})_4]$
S1	1995 \pm 4.0	1.5 \pm 0.1	0.27 \pm 0.01	2.24 \pm 0.11
S11	1836 \pm 13.0	4.4 \pm 2.3	0.31 \pm 0.06	1.44 \pm 0.40

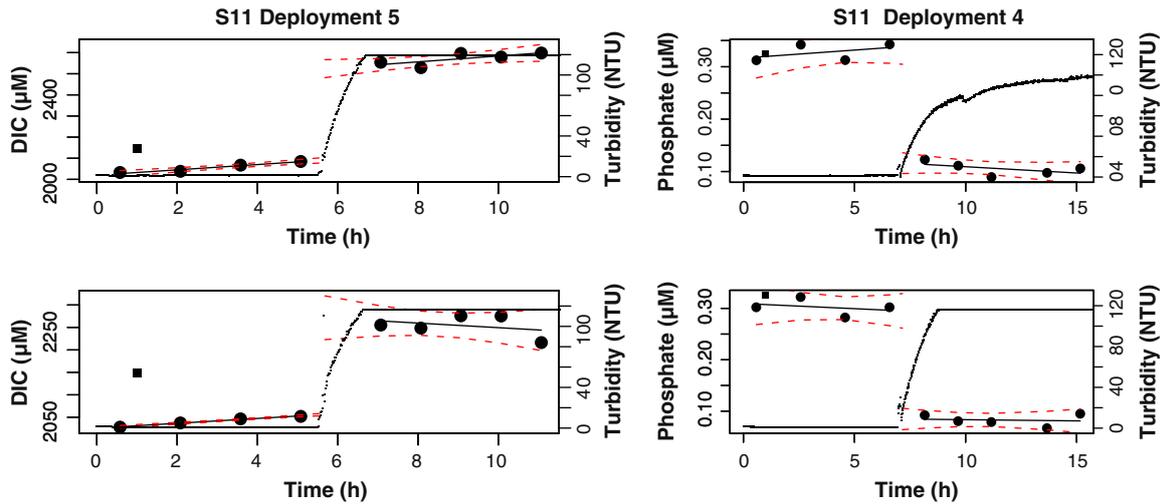


Fig. 10. Example of the DIC (left) and phosphate (right) concentrations with time (filled circles) during the third incubation in deployments five and four, respectively. A massive resuspension was created after about half the incubation time and the turbidity (small dots) quickly increased. The concentrations of DIC increased and the concentrations of phosphate decreased instantaneously, but the fluxes (calculated by linear regression) remained at the same level. The dotted lines show the confidence interval for each flux.

At station S11 the initial phosphate concentrations (Table 3) instantly decreased in all chambers (Table 6a) with an average of 0.20 (sd 0.11) μM as massive resuspension was created (Fig. 11c), which corresponded to a decrease of 62%. At station S1 no statistically significant change (*t*-test) in concentrations was found due to the massive resuspension. The average initial fluxes (Fig. 9c) at stations S1 and S11 were about zero $\text{mmol m}^{-2} \text{d}^{-1}$ (0.07 (s.e. 0.01) and <0.001 (s.e. 0.01 $\text{mmol m}^{-2} \text{d}^{-1}$), respectively). Due to very low fluxes the uncertainties of the fluxes were in many cases low, but still as large or larger as the flux itself. A change in flux (Fig. 10 right) was only

observed in one of the seven chambers (Table 5). In this chamber a relatively high efflux became negative, but with a larger uncertainty of the flux as the resuspension occurred (Table 4). The large change in flux was so clear that this single result had a relatively high importance when counting the number of affected fluxes (Tables 5, 6). The instant decrease in phosphate concentrations can most likely be explained by phosphate being adsorbed to newly formed iron oxides. As pore water and sediment were mixed with overlying water, oxygen dramatically decreased when re-oxidizing reduced substances, e.g. when reduced iron was oxidized to iron oxides. This may also

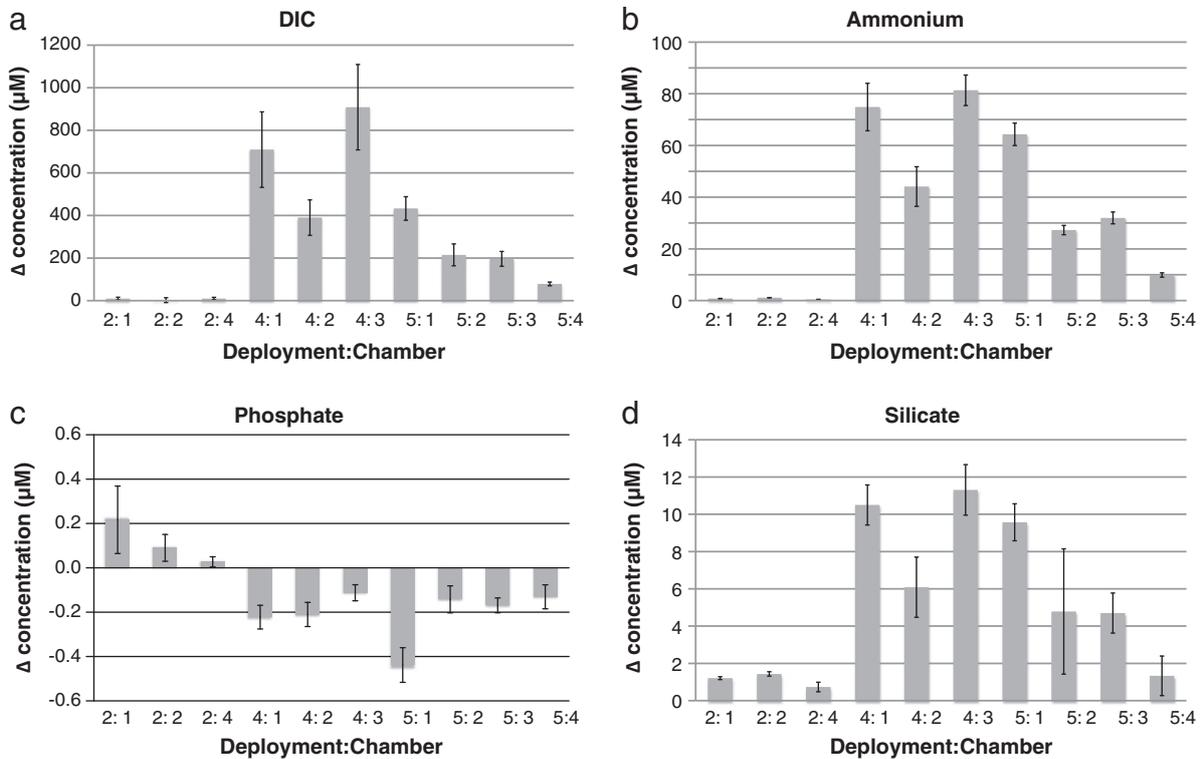


Fig. 11. The change in concentration (μM) of DIC (a), ammonium (b), phosphate (c) and silicate (d) due to the created massive resuspension in the chambers. The error bars for deployment 2 shows the standard deviation of the change in concentrations. For deployments 4 and 5 the error bars show the sum of the confidence intervals.

Table 4

Nutrient fluxes ($\text{mmol m}^{-2} \text{d}^{-1}$) before (BR) and after resuspension (AR) in chambers which were affected by massive resuspension. The uncertainty of the fluxes is described by the standard error (s.e.).

Substance	Station	Deployment	Chamber	Flux BR	s.e. BR	Flux AR	s.e. AR
NH_4^+	S11	4	1	11.2	3.3	-3.86	1.6
NH_4^+	S11	5	1	10.0	2.0	0.46	1.6
PO_4^{3-}	S11	5	1	0.19	0.05	-0.014	0.02
$\text{Si}(\text{OH})_4$	S11	4	1	2.3	0.4	0.3	0.2
$\text{Si}(\text{OH})_4$	S11	5	1	2.0	0.4	0.2	0.4

explain why an efflux of phosphate can change direction and become an influx. On a longer time scale the phosphate might have been released again if all the oxygen and other oxidants, like the iron oxides, have been consumed because of stimulated oxygen consumption due to resuspension.

The initial silicate concentrations (Table 3) increased instantly as massive resuspension was created at both stations (Fig. 11d) in all resuspension chambers (Table 6). At S1 the concentrations increased with an average of 1.13 (sd 0.36) μM , which corresponds to an increase of 32.8%, due to massive resuspension. At station S11 the increase in concentration was even larger (Fig. 11d), by an average of 6.9 (sd 3.7) μM , which corresponds to a 200% increase. The initial silicate fluxes (Fig. 9d) varied between 0.35 (s.e. 0.01) and 2.32 (s.e. 0.41) $\text{mmol m}^{-2} \text{d}^{-1}$ with both the highest and lowest fluxes at station S11. The average flux was 1.3 (s.e. 0.17) $\text{mmol m}^{-2} \text{d}^{-1}$. The fluxes remained unaffected of the resuspension events in four chambers (Table 5), but in two chambers (one in each of deployments 4 and 5) the fluxes decreased and went from being effluxes to become influxes (Table 4). The uncertainty of the flux after resuspension during deployment 5 was too high, but as there was no doubt that there was a statistically significant decrease of the flux it was included as a result. A decrease of silicate fluxes due to resuspension has also been observed in an earlier study in the Gulf of Finland, Baltic Sea (Almroth et al., 2009), but we have no obvious explanation for this behavior. Williams et al. (1985) discussed different ways for which silicate concentrations can decrease in sea water, e.g. complexation with manganese and sulfate or adsorption of silicate on clay minerals. On the other hand, Siever and Woodford (1973) suggested that dissolved silicate has to be present in concentrations higher than 1 ppm less than a crossover point of 12 ppm (125 μM) to be adsorbed to clay minerals like e.g. kaolinite. Thus, this explanation is not likely valid since the silicate concentrations are below this crossover point.

4. Concluding remarks

Natural resuspension clearly led to higher benthic oxygen consumption at station S11, which had organically enriched sediment due to organic matter deposition from a former fish farm. The effects on the oxygen consumption were higher during the first (of a series of multiple incubations) incubation in all resuspension chambers, where it increased with an average of 12.8 (s.e. 0.17) $\text{mmol m}^{-2} \text{d}^{-1}$, compared to the second incubation, where it increased with an average of 7.7 (s.e. 0.12) $\text{mmol m}^{-2} \text{d}^{-1}$. Also resuspension seemed to be more easily created during the first incubation compared to the second. At

Table 5

The frequency of the effect of massive resuspension on benthic fluxes of nutrients and DIC at station S11 are shown by the relation (C) between the number of chambers, with approved fluxes, in which massive resuspension was created (A) and the number of chambers in which there was an effect on the fluxes due to resuspension (B).

		DIC	NH_4^+	PO_4	Si
A	Nr of chambers	6	4	7	6
B	Effect on fluxes	0	2	1	2
C	Frequency (%)	0	50	14	33

Table 6

The frequency of the effect of massive resuspension on the concentrations of nutrients and DIC at station S11(a) and at S1(b) is shown by the relation (F) between the number of chambers where the concentrations are compared (D) and the number of chambers in which an instant change in concentration was observed (E).

a		DIC	NH_4^+	PO_4	Si	b		DIC	NH_4^+	PO_4	Si
D	Nr of chambers	7	7	7	6	3	3	3	3	3	3
E	Effect on conc.	7	7	7	6	0	3	0	3	0	3
F	Frequency (%)	100	100	100	100	0	100	0	100	0	100

the station S1, which was not affected by the fish farm and had lower sedimentary organic content than S11, the effects on the oxygen consumption were not clear. There were not enough data to be able to significantly evaluate the effect of natural resuspension on the fluxes of DIC and nutrients.

The oxygen consumption increased in 100% of the cases due to the created massive resuspension. The fluxes increased on S1 with on average 608 (sd 366) $\text{mmol m}^{-2} \text{d}^{-1}$ and on S11 with on average 2396 (sd 2265) $\text{mmol m}^{-2} \text{d}^{-1}$, corresponding to 2038% and 7366%, respectively. The fluxes of ammonium, phosphate and silicate were affected by the massive resuspension in 50, 14 and 33% of the chambers, respectively, on station S11. All the affected fluxes were effluxes that decreased and some of them became influxes. The decreased effluxes of ammonium could be due to that some of the ammoniums were oxidized to nitrate by stimulated nitrification. Unfortunately there were no nitrate data in this study. The decrease in phosphate efflux in one of the chambers might be a result of adsorption to iron oxides in this chamber. However, in the majority of the cases there were no effects of massive resuspension on the nutrient and DIC fluxes. On the other hand, the concentrations of DIC, ammonium and silicate instantly increased with an average of 419 (sd 297), 48 (sd 27) and 6.9 (sd 3.7) μM , respectively at S11 upon massive resuspension, which corresponded to percentage increases of 20.4, 482 and 200%, respectively. The concentrations of phosphate decreased instantly with an average of 0.2 (sd 0.1) μM , corresponding to 62%, probably due to adsorption onto newly formed iron oxides. On station S1 there were effects of massive resuspension only on the ammonium and silicate concentrations, which increased with 0.8 (sd 0.3) and 1.13 (sd 0.36) μM , respectively. The increase occurred when the sediment and the pore water, with high concentrations of these substances, were mixed with the overlying water. Ammonium was probably also desorbed from resuspended sediment particles, onto which ammonium was adsorbed in the sediment. Unfortunately it was not possible to use any control chambers when creating massive resuspension, i.e. massive resuspensions were created in all four chambers during the deployments. In spite of this, the above described changes in concentrations and fluxes are reliable in the sense that they occur, but minor errors in magnitude, which would have been corrected if there were control chambers, might exist.

The results from this study suggest that bottom areas with low-normal organic carbon content, which regularly are exposed to natural resuspension, do not show any clear trend in oxygen consumption due to resuspension events. However, at bottom areas which are organically enriched, e.g. due to fish farming, the oxygen consumption is significantly increased also at low resuspension levels. This response to resuspension at organically enriched bottoms can lead to oxygen depletion in areas where resuspension frequently occurs and the water exchange is limited.

Massive resuspension led to a dramatic increase of oxygen consumption at both the reference station and the organically enriched station. This indicates that activities such as trawling and dredging that take place in areas where water exchange occurs infrequently may lead to oxygen depletion in bottom water. Silicate, ammonium and DIC can be released due to massive resuspension and contribute to increased algal blooms in surface waters. On shorter time-scales, as in this study, the phosphate concentration is decreased as it can

adsorb to newly formed iron oxides, as long as oxygen is still present. On longer time-scales massive resuspension events may lead to a total depletion of oxidants, which probably would lead to a release also of phosphate from the sediment. This case would further contribute to eutrophication of the coastal water.

Acknowledgments

We thank the captain and crew of R/V Seol Mara and R/V Calanus, chief scientist C. Rabouille, M. Kononets who made the map of the study site, and the Scottish Association for Marine Science for organizing the field-work and hospitality. Financial support for this study was provided by the EU-STREP program (project COBO with Contract no. 505564).

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