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Short-term environmental impact of clam dredging in coastal waters (south of Portugal): chemical disturbance and subsequent recovery of seabed

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Abstract

The physical and chemical changes in sediment and near bottom water caused by clam dredging were examined during July and September 1999, at two locations Vilamoura (VL) and Armona (AR), south coast of Portugal. Sediment cores and near bottom water were collected simultaneously before dredging (control samples) and within short time intervals (min–h) after dredging. After dredging operations, microphytobenthos coming from the path were accumulated in the re-worked sediment (ridge). Chlorophyll *a* in superficial sediment increased from 1.2 $\mu\text{g g}^{-1}$ before dredging to 1.7 $\mu\text{g g}^{-1}$ after dredging and these higher values remained for a few hours. However, the expected increase of chlorophyll *a* in near bottom water due to re-suspension was not observed. After sediment disturbance an instantaneous sorption of phosphorus onto iron oxides occurred in the upper sediment layers (from 2 to 3 $\mu\text{mol g}^{-1}$ before dredging to 4–5 $\mu\text{mol g}^{-1}$ after dredging). A microcosm experiment showed that after sediment disturbance HPO_4^{2-} dissolved in pore water decreased from 40 to 10 μM being simultaneously sorbed onto iron oxides formed in the top layer of sediment. The ammonium, nitrates, organic nitrogen, phosphate and silicate dissolved in pore water decreased immediately after dredging activity and simultaneously

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an increase in near bottom water was sporadically observed. Generally, the re-establishment of seabed was reached within a short time (min–h), at both stations (VL and AR).

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1. Introduction

The use of mobile fishing gears by commercial fishing fleets unquestionably produces a variety of direct and indirect changes on the benthic ecosystem (Newell, Seiderer, & Hitchcock, 1998; Riemann & Hoffmann, 1991). These impacts will depend on many factors such as marine sediment characteristics, type of dredge, fishing operations, depth, tidal strength, currents and period of the year (Churchill, 1989; De Groot, 1984; Prena, Rowell, Schwinghamer, Gilkinson, & Gordon, 1996). Impacts may be expressed by changes in the biology, sedimentology and biogeochemistry of the benthic environment (Mayer, Schick, Findlay, & Rice, 1991). During dredging activity the microphytobenthos is overturned being exported from the drag site to the edges and the remaining was mixed into fishing site (De Jonge & Van Den Bergs, 1987); the nutrients are rapidly released to the water column changing the chemical and biological stability of sediment and biogeochemical processes along vertical profiles of sediment are disrupted (Fanning, Carter, & Betzer, 1982). Redox-dependent sediment phosphate release has been observed in several continental margin environments (Aller, 1980; Ingall & Jahnke, 1994). Retention and release of phosphorus from sediments have been an important matter of research due to the significance of this element in the production and distribution of plankton in lakes, estuaries and coastal systems (Benitez-Nelson, 2000; Froelich, Bender, Luedtke, Heath, & DeVries, 1982; Nixon, 1981). The sediment overturned during dredging releases pore water from deeper sediments to the overlying water, exposing reduced compounds to oxidised regions and transfers freshly deposited organic matter to deeper sediment layers (Aller & Yinst, 1985; Boudreau, 1984).

Dredging activity digs a furrow along a towpath provoking a sediment movement that occurs mainly through slumping of the sides of the furrow. Subsequently, the furrow is filled-in by fine particles transported by tidal currents acting as a sediment-trap (Newell et al., 1998). Simultaneously with the seabed disturbance, sediment clouds of large dimensions are released into the water column and generally settle out within a short-period, as shown by underwater video images (Gaspar, 1996; Mayer et al., 1991). The horizontal dispersal of this material will be accentuated if currents are above the critical threshold for deposition.

To understand the dynamics of marine sediment over continental shelves, many studies have been focused upon sediment re-suspension by the action of winds and turbulent tidal currents (De Jonge & Van Beusekom, 1995) and by the influence of marine animals (Smith & Howell, 1987). Sediment re-suspension mechanism by the action of fishing gear has been overlooked (Churchill, 1989) however, there is a lack of information concerning biogeochemical changes resulting from this activity. The aim of the

present study was to evaluate the biogeochemical changes caused by clam dredging and the subsequent recovery of the seabed at the upper sediment layer. Nutrient changes in pore water and near bottom water and simultaneously the biological and chemical changes in the upper sediment layer were observed within a short time period (min–h).

1.1. Study area and bivalve fishery

The Algarve coast, located at the south of Portugal extends by 100 Km in length. According to Moita (1986) sediments in shallow areas, from coastal line to 25 m depth, range from coarse sand (500 μm) to fine sand (125 μm). Tides are semi-diurnal and the mean amplitude between tides is 2 m, with a maximum of 3.5 and a minimum of 0.5 (Melo, 1989). The drift currents tend to run along the shore, to depths of 30 m or more. The current speed may in extreme condition reach 0.5 m s^{-1} (Moita, 1986).

The bivalve fishery is a very important activity along the south coast of Portugal. The dredge fleet directs its fishing effort towards four species: *Spisula solida*, *Donax trunculus*, *Ensis siliqua* and *Pharus legumen*. On this part of the Portuguese coast, these species are distributed along a narrow strip of shallow waters (1–15 m depth) on sandy bottoms. In this fishery only mechanical dredges are allowed. Fig. 1 represents a schematic drawing of the clam dredge used along the Portuguese coast.

2. Material and methods

2.1. Field sampling

Taking into consideration the distribution of both commercial bivalve species and fishing effort two stations (VL and AR) were selected (Fig. 2). St. VL (37° 03' 55"N;

Dredge specifications	
Anterior part	
Length of the mouth (cm)	64
Space between rods (cm)	0.8
Number of teeth	10
Space between teeth (cm)	2.2
Tooth length (cm)	15
Tooth angle (degrees)	20°
Net bag	
Length (cm)	250
Mesh size (mm)	25

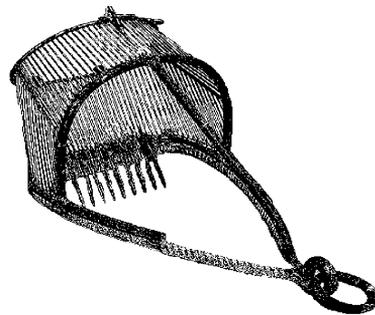


Fig. 1. The mechanical dredge during fishing activity. Legend indicating dredge characteristics.

08° 09' 00" W) is located off Praia da Falésia (*Spisula solida* fishing ground) and st. AR (37° 01' 50" N; 07° 45' 00" W) is located in the adjacent coast of Armona island (*Donax trunculus* fishing ground). In July 1999 at st. VL (10 m depth) a dredging operation was carried out. This trawling operation digs a furrow with 15 cm depth and removes the sediment to the edges (re-worked sediment) reaching 5–10 cm height. Before dredging starts, three PVC sediment cores (5-cm length and 5-cm diameter) and near bottom water (20-cm above sediment surface) were collected by divers (control samples). Immediately after dredging starts, sediment cores and near-bottom water were collected repeatedly (Fig. 3) during short intervals of time: 1, 5, 15, 30, 60, 120, 240 and 420 min. All samples were collected by a team of divers in

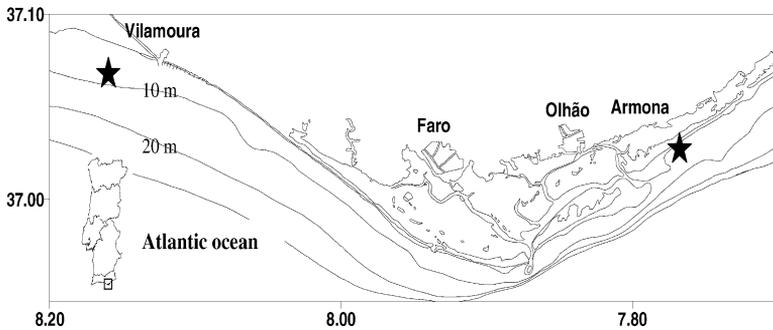


Fig. 2. Map of coastal zone (south of Portugal) with the locations of the studied stations- VL and AR (*).

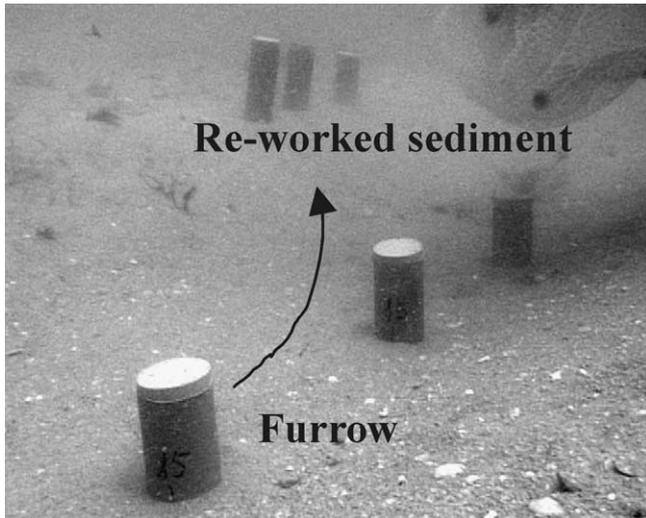


Fig. 3. Collecting sediment cores in the re-worked (ridge) and furrow sediment.

the same location within the first 2 m of the trawling track. Each sampling time comprises six sediment cores: three from the centre of the ridge (re-worked sediment) and three from the furrow. Cores were filled up with sediment and closed with rubber stoppers in order to avoid sediment oxidation. With this sampling procedure sediment cores surface remained undisturbed. Subsequently cores were rapidly sliced onboard into horizontal layers (0–2 cm) within a few minutes to minimise changes resulted from exposure of sediment surfaces to the atmosphere. The 2-cm top sediment layers from three cores composed each sample. All sampling material was pre-cleaned with HCl in order to avoid contamination. Previous experiments show that dissolved Fe was not affected significantly (Caetano, Madureira, Vale, Bebianno, & Gonçalves, 1995; Madureira, Vale, & Gonçalves, 1997). Samples were stored in leakproof polycarbonate vials, completely filled and kept in a refrigerated chamber. In September 1999, another dredging operation was carried out at st. AR (3 m depth) with the same dredge and using the sampling methodology described above. Sediment cores and near bottom water were collected before dredging (control samples) and immediately after dredging within a short time scale (1, 5, 20, 60, 120, 240 and 420 min). In addition, to characterise the grain size fractions a sediment core (25-cm length and 5-cm diameter) was collected before dredging activity at both stations (VL and AR) to determine CaCO_3 , organic matter as loss of ignition (LOI), total organic carbon (TOC) content and porosity.

2.2. Laboratory analysis

2.2.1. Pore water and near bottom water

In the laboratory the samples were centrifuged for 30 min at 3000 r.p.m. and 4 °C to separate pore water from the solid phase. The resulting pore water was filtered through 0.45 µm Millipore filters and stored at 4 °C until the analysis. Each integrated sample of pore water was composed by water extracted from three cores (0–2 cm layer). Samples of near bottom water were filtered through 0.45 µm Millipore filters and stored during a week at 4 °C until the analysis. The ammonium (NH_4^+), nitrate (NO_3^-), phosphate (HPO_4^{2-}) and silicate (Si(OH)_4) were determined using a “SKALAR” autoanalyser. The detection limit used in the present method was 0.2 µM for ammonium and silicate and 0.05 µM for nitrate and phosphate. Total organic nitrogen (TON) was determined by potassium peroxodisulphate oxidation in autoclave (1.5 bar; 120 °C) as described in Grasshoff (1983) and total nitrogen determined by colorimetric method using the autoanalyser.

2.2.2. Solid fraction

Part of the upper sediment layers (0–2 cm) from each core were dried to 80 °C until a constant weight and ground to a fine powder, other part of these samples was conserved wet under N_2 atmosphere. The total organic carbon and nitrogen were determined in the powder samples. The amorphous iron oxides (FeOOH) and the phosphate sorbed onto iron oxides (P-FeOOH) were determined in the wet samples. Total carbon and nitrogen and inorganic carbon and nitrogen (loss on ignition) in the solid phase was determined using a CNH analyser “NC 2500 CE instruments”

with acetanilide as reference material (Byers, Mills, & Stewart, 1978). Iron and phosphorus were removed from the sediment (wet fraction) by ascorbate extraction following the procedure described in Anschutz, Zhong, Sundby, Mucci, & Gobeil, (1998). Total dissolved iron was measured by atomic absorption spectroscopy (AAS) using direct aspiration into an air-acetylene flame of a Perkin Elmer AA100. The precision error of these analyses was $\pm 5\%$ and phosphate was determined colorimetrically as the molybdenum complex (Grasshoff, 1983), using a spectrophotometer Hitachi 150-12. The organic matter content in each layer was determined by “loss on ignition”. The chlorophyll *a* was extracted with acetone (90%) from the upper sediment layers and determined by spectrophotometry according to Lorenzen (1967). For the granulometric characterization the sediment cores were sliced in three superficial layers (0–2; 2–4 and 4–6 cm) and two deeper layers (10–12 and 19–21 cm).

2.3. *Microcosm experiment*

In order to better understand the field results a microcosm experiment was undertaken to study phosphorus sorption. Sandy sediment was collected at station AR by divers in plastic bags hermetically closed in situ. Near bottom water was also collected at the same station. In the laboratory sediment (1000 g) was carefully placed inside three transparent plexiglass chambers ($15 \times 15 \times 15 \text{ cm}^3$) with small taps at each face. The collected seawater was added carefully to the chambers (1.5 l per each) to minimise re-suspension. Sediment showed similar porosity (0.4 ± 0.02) and organic matter ($0.7 \pm 0.09\%$) with the field studied samples. In each microcosm the seawater was aerated constantly in order to maintain oxygen saturation and the system remained undisturbed for 24 h to re-establish the normal pore water chemistry. After this period the sediment was strongly stirred using a Politron (PT 3000) equipped with a rod-helix, which causes a total sediment re-suspension. Samples of near bottom water, pore water and the upper sediment layer were collected from each chamber in the following time scale: before stirring, immediately after stirring and 10, 30, 60, 180, 330, 1340 and 1780 min after stirring. Near bottom water was collected with a syringe, superficial sediment was collected with a small plastic tube (2-cm length and 1-cm diameter) to avoid disturbing the superficial sediment and pore water was collected through the taps 1-cm below sediment surface. Phosphate (HPO_4^{2-}) was determined in near bottom water and pore water. Phosphorus sorbed onto iron oxides (P-FeOOH) and iron oxides (FeOOH) were determined in the upper sediment layer (0–1 cm).

2.4. *Statistical analysis*

The existence of significant differences between data was tested using the non-parametric Wilcoxon's test for two matched samples (Scherrer, 1984).

3. Results

3.1. Sediment: biological and chemical changes in seabed

3.1.1. Sediment characteristics

The sediment characteristics from station VL were different from those found at the station AR (Table 1). Sediment at st. VL contains more percentage of fine particles (silt + clay) than the sediment from st. AR. The percentage of CaCO₃ and organic matter was also higher at st. VL. The smaller particles found in superficial sediment of this station may indicate that these surfaces are less disturbed by natural processes than sediments more exposed to winds and tidal currents in shallow water. These finding may be reinforced by the organic matter content that was nearly two times higher than that found in st. AR. The organic nitrogen content in studied sediment layers was below the limit of detection (<0.001%).

3.1.2. Chlorophyll *a*

Chlorophyll *a* recorded in the ridge (re-worked sediment) of the station VL increased slightly after dredging (Fig. 4). This increase from $1.2 \pm 0.22 \mu\text{g g}^{-1}$ (before dredging) to $1.7 \pm 0.30 \mu\text{g g}^{-1}$ (after dredging) may be related to the sedimentation of re-suspended sediments. The concentrations obtained concomitantly in the deeper layer, that became exposed during the tow (furrow), were significantly lower than those found in the re-worked sediment (Wilcoxon's test $p \leq 0.01$). Results point to the recovery of seabed seven hours after dredging. At st. AR the chlorophyll *a* in the

Table 1

Percentage of grain-size distribution, carbonate content (CaCO₃), porosity (ϕ), organic matter content by loss on ignition (LOI) and total organic carbon (TOC) of sediments collected at different depths at stations VL and AR

Grain size (%)		CaCO ₃ (%)	Porosity	LOI (%)	TOC (%)						
Sand		Silt + clay									
Layers (cm)	> 2 mm	1 mm	500 μm	250 μm	125 μm	63 μm	< 63 μm				
<i>Station VL</i>											
0–2	0	6	27	57	5	1	4	11	0.301	0.874	0.21
2–4	1	9	29	52	5	0	4	13	0.268	0.969	0.52
4–6	–	–	–	–	–	–	–	–	0.302	0.781	0.43
10–12	2	8	31	53	4	1	1	8	–	–	–
19–21	4	9	30	49	5	1	2	10	–	–	–
<i>Station AR</i>											
0–2	0	1	13	60	25	0	1	6	0.329	0.662	0.34
2–4	0	1	15	60	24	0	0	5	0.290	0.600	0.09
4–6	–	–	–	–	–	–	–	–	0.316	0.592	0.06
10–12	0	3	23	47	27	0	0	6	–	–	–
19–21	0	1	18	52	28	0	1	6	–	–	–

furrow was also significantly lower than that found in the ridge (Wilcoxon's test $p \leq 0.01$) remaining approximately constant ($\approx 0.8 \mu\text{g g}^{-1}$) over the studied period (Fig. 4). The expected increase of chlorophyll *a* in near bottom water during sediment re-suspension was not observed at both stations oscillating within a narrow range during the period of observation (from 0.5 to $1 \mu\text{g l}^{-1}$).

3.1.3. Ascorbate-extractable iron (FeOOH) vs ascorbate-extractable phosphorus (P-FeOOH)

After dredging activity the concentration of phosphorus removed from the sediment samples by ascorbate extraction ($4\text{--}5 \mu\text{mol g}^{-1}$) exceeded the concentration of iron oxides formed in these sediments ($1.5\text{--}2 \mu\text{mol g}^{-1}$). The molar ratio P:Fe was calculated over the studied period (7 h) in the ridge (re-worked sediment) and furrow at st. VL (Fig. 5). The instantaneous increase of P:Fe ratio obtained when sediment was disturbed points to the adsorption of phosphorus onto iron oxides that have been formed. The same process was observed at st. AR, however, the higher values of P:Fe ratio remained for a longer period (Fig. 5).

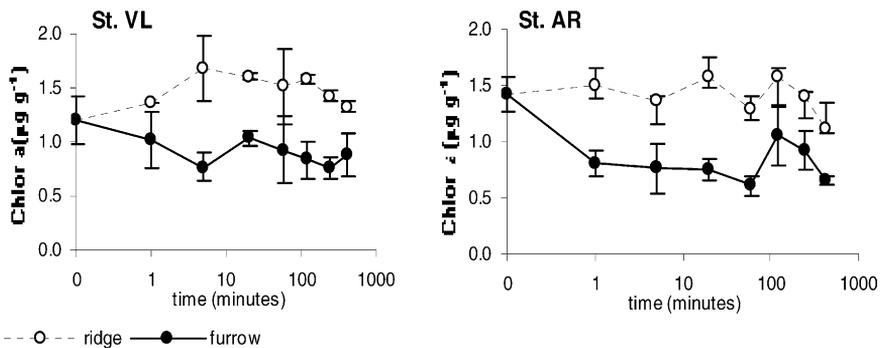


Fig. 4. Variations of the mean concentrations of chlorophyll *a* ($\mu\text{g g}^{-1}$) obtained in the ridge (\circ) and furrow (\bullet) sediment before dredging (0 min); immediately after dredging (1 min) and 5, 15, 20, 30, 60, 120, 240 and 420 min after dredging (logarithmical time scale), at stations VL and AR.

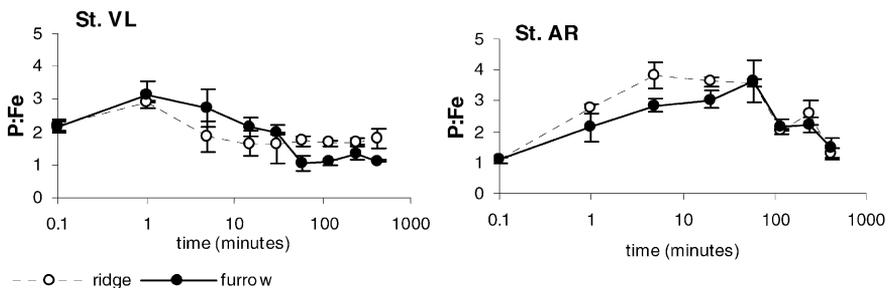


Fig. 5. Variation of the mean P:Fe ratio obtained in the ridge (\circ) and furrow (\bullet) sediment before dredging (0 min); immediately after dredging (1 min) and 5, 15, 20, 30, 60, 120, 240 and 420 min after dredging (logarithmical time scale), at stations VL and AR.

To confirm these field findings sediment perturbation was simulated in the laboratory with the water temperature ranging from 22 to 25 °C and oxygen saturation from 80 to 90%. The molar ratio P:Fe was calculated from the mean concentrations of P-FeOOH and FeOOH obtained in the upper sediment layer. Fig. 6a shows a sharp increase of P:Fe ratio immediately after stirring the sediment decreasing to the initial values after one day of experiment. This increase of P:Fe occurs simultaneously with the decrease of HPO_4^{2-} in pore water (Fig. 6b). The plot of P sorbed onto iron oxides vs HPO_4^{2-} in pore water is an inverse linear relationship ($P_{\text{sorbed}} = -0.22 \text{HPO}_4^{2-} + 8.8$; $r^2 = 0.5$; $n = 10$; $p \leq 0.05$) meaning that the most part of phosphate dissolved in pore water is sorbed onto iron oxides since no significant changes were found in near bottom water.

3.2. Pore water and near bottom water

The concentrations of ammonium, nitrate, total organic nitrogen, phosphate and silicate obtained in pore water of the ridge and furrow sediment (0–2 cm) over the studied period at stations VL and AR are represented in Table 2.

3.2.1. Nitrogen compounds

Ammonium in pore water (st. VL) decreased markedly during the first 5 min after dredging (from 311 to 124 μM) and concentrations obtained in the ridge and furrow

Table 2

Concentrations of ammonium, nitrate, total organic nitrogen, phosphate and silicate (μM) obtained in pore water of the ridge and furrow sediment (0–2-cm), during the studied period at stations VL and AR

Time Scale (min)	NH_4^+ (μM)		NO_3^+ (μM)		TON (μM)		HPO_4^{2-} (μM)		$\text{Si}(\text{OH})_4$ (μM)	
	Ridge	Furrow	Ridge	Furrow	Ridge	Furrow	Ridge	Furrow	Ridge	Furrow
<i>Station VL</i>										
Control (0)	311		11.70		750		4.50		5.90	
1	136	174	5.20	7.00	199	354	1.30	3.80	0.50	10.40
5	124	159	4.80	6.40	205	196	1.80	2.40	0.60	8.00
15	271	159	6.40	8.40	328	122	3.80	2.70	4.10	8.60
30	220	160	7.40	6.40	105	95	3.20	3.00	1.60	5.10
60	175	151	4.40	4.20	226	75	2.60	1.30	7.70	7.70
120	230	156	6.60	5.10	345	83	2.80	2.20	6.50	7.20
240	198	200	6.90	7.20	388	89	3.20	2.50	6.80	6.90
420	290	233	9.30	6.10	363	94	3.70	2.70	5.80	7.90
<i>Station AR</i>										
Control (0)	81		4.30		585		21.10		8.61	
1	115	140	1.90	1.60	439	677	19.00	7.70	7.60	10.70
5	63	104	1.50	1.70	283	571	17.20	15.30	2.60	8.40
20	84	126	0.30	1.60	719	324	19.90	9.20	4.80	9.90
60	71	66	1.80	0.80	750	620	14.00	8.80	10.50	7.80
120	60	57	0.80	0.80	950	459	14.20	10.60	8.70	8.50
240	115	73	2.10	2.60	634	665	17.20	7.50	11.80	14.30
420	56	60	0.70	2.80	511	740	12.20	8.10	9.10	6.60

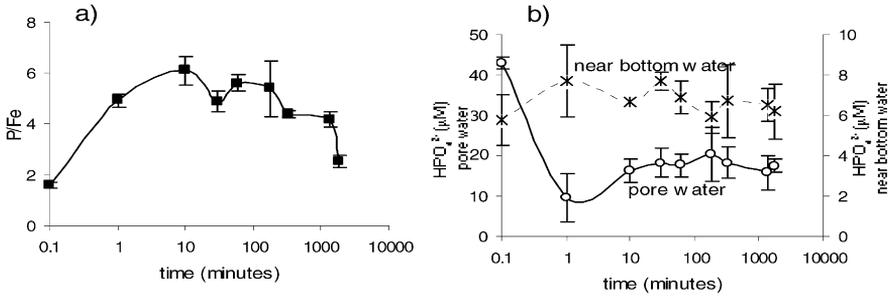


Fig. 6. Microcosm experiment: (a) Variation of the mean P:Fe ratio in the upper sediment layer (■) before stirring (0 min); immediately after stirring (1 min) and 10, 30, 180, 330, 1340 and 1780 min after stirring (logarithmical time scale). (b) Variation of the mean concentrations of phosphate (μM) in pore water (○) and simultaneously in near bottom water (★) before stirring (0 min); immediately after stirring (1 min) and 10, 30, 180, 330, 1340 and 1780 min after stirring (logarithmical time scale).

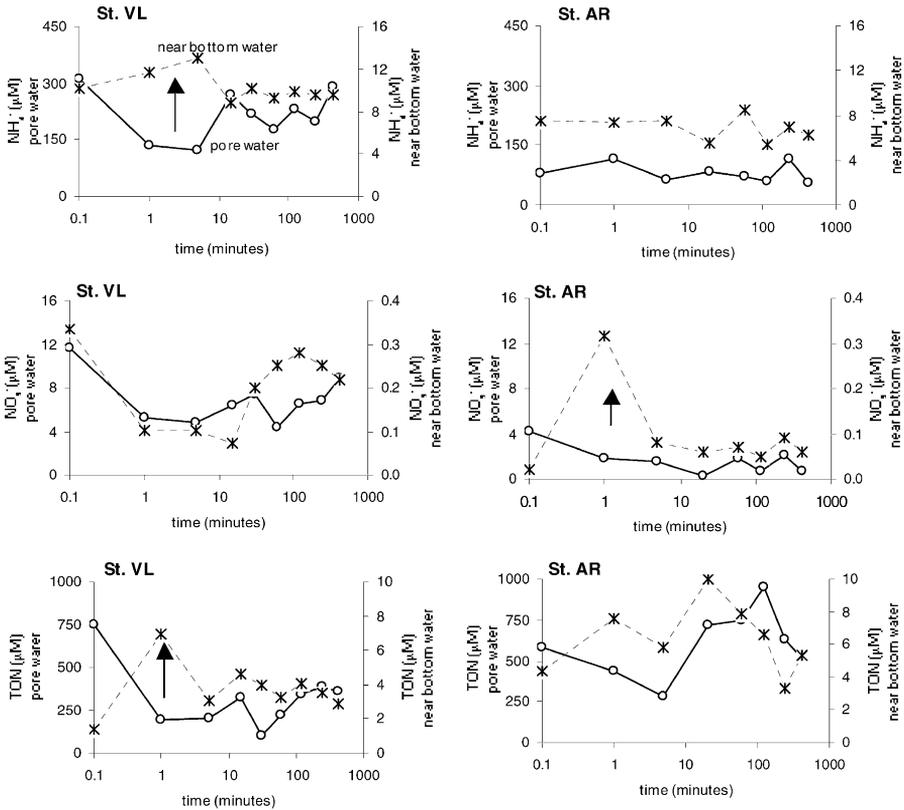


Fig. 7. Variation of ammonium, nitrate and total organic nitrogen (μM) dissolved in the pore water of the re-worked sediment (○) and concomitantly in near bottom water (★), before dredging (0 min); immediately after dredging (1 min) and 5, 15, 20, 30, 60, 120, 240 and 420 min after dredging (logarithmical time scale), at stations VL and AR.

sediment were very similar (Table 2). The increase of NH_4^+ in near bottom water from 8 to 13 μM observed within the first minutes after dredging may reflect transport across the sediment-water interface (Fig. 7). Levels of ammonium were re-established 7 h after dredging. At station AR the ammonium in pore water was 2-fold lower than that obtained at station VL and the concentrations found in the ridge and furrow sediment were similar through out the studied period (Table 2).

Nitrate in pore water decreased after dredging at both stations (Fig. 7) and, the concentrations obtained in the ridge and furrow sediment were not significantly different if we compare two matched samples (Wilcoxon test). The concentrations of nitrate in re-worked sediment (st.VL) tend to be re-established 7 h after fishing activity. The increase of nitrates in near bottom water observed at station AR immediately after dredging (from 0.02 to 0.32 μM) may be due to the instantaneous transport across the sediment-water interface during disturbance (Fig. 7).

Total organic nitrogen decreased sharply from 750 to 200 μM at station VL within the first minutes after dredging (Fig. 7) and the concentrations observed in the ridge and furrow sediment were significantly different (Wilcoxon test, $p \leq 0.05$). The increase of organic nitrogen in near bottom water from 1.4 to 6.9 μM immediately after dredging may result from bottom release during sediment disturbance. A decrease of organic nitrogen in pore water (from 585 to 283 μM) was also found in the re-worked sediment within the first five minutes after dredging at station AR.

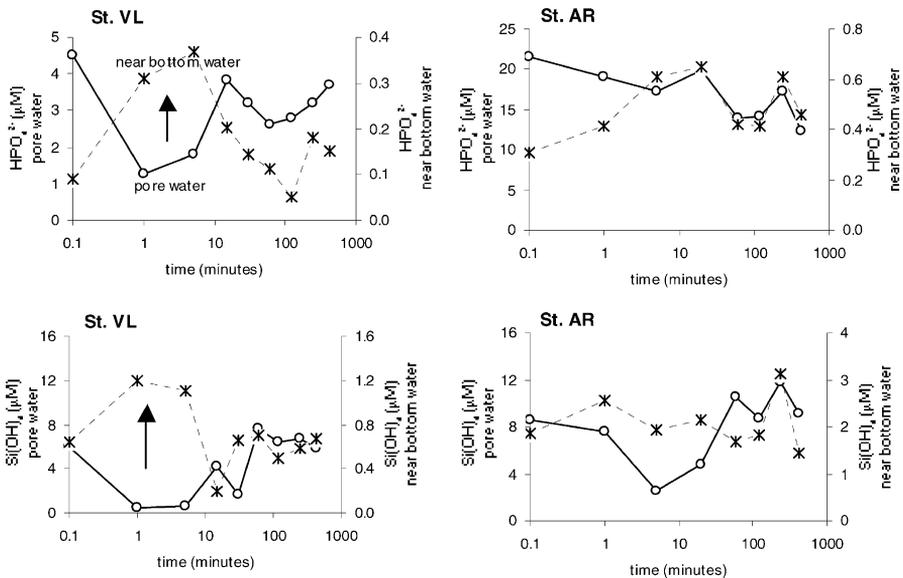


Fig. 8. Variation of phosphate and silicate (μM) dissolved in the pore water of the re-worked sediment (○) and concomitantly in near bottom water (★), before dredging (0 min.); immediately after dredging (1 min) and 5, 15, 20, 30, 60, 120, 240 and 420 min after dredging (logarithmical time scale), at stations VL and AR.

3.2.2. Phosphate

Phosphate dissolved in pore water of re-worked sediment (st. VL) decreased within the first minutes after dredging from 4.5 to 1.5 μM (Fig. 8). This decrease in pore water corresponded to a slight increase in near bottom water from 0.09 to 0.37 μM immediately after dredging suggesting that a small fraction of phosphate dissolved in pore water may be exported to the water column. At station AR phosphate decreased slightly in pore water of re-worked sediment however, the expected increase in near bottom water was not observed (Fig. 8).

3.2.3. Silicate

Silicate decreased sharply in the pore water of re-worked sediment (st. VL) within the first five minutes after dredging (from 6 to 0.6 μM) as illustrate Fig. 8. In the furrow (Table 2), the silicates were significantly higher than those obtained in the re-worked sediment (Wilcoxon test, $p \leq 0.05$). The increase of silicates in near bottom water immediately after dredging (from 0.6 to 1.2 μM) is probably due to the release during sediment disturbance. At station AR the silicates also showed a sharp decrease in pore water of re-worked sediment within the first minutes after dredging. One h after dredging, concentrations were re-established to the initial levels in the seabed of both stations.

4. Discussion

During dredging a furrow is formed exposing the underlying sand with a spoil ridge on either side of the depression. In the present study the chemical and biological characteristics observed in the furrow often contrast with the ones obtained in ridge (re-worked sediment). The microphytobenthos of superficial sediment is removed by the teeth of the dredge along the path, being exported from the fishing site (De Jonge & Van Den Bergs, 1987) and being accumulated along the ridge. This may explain the contrast of chlorophyll *a* concentrations found in the re-worked sediment and in the exposed furrow (Fig. 4), where microphytobenthos production is lower in deeper sediment layers (Boon, Duineveld, Berghuis, & Van der Wele, 1998). It is known that episodic events promoting intense sediment re-suspension and mixing can recover deeply buried cells to re-inoculate the sediment surface (Brotas & Serôdio, 1995). However, in the present work, the fast accumulation of microphytobenthos exported from the drag site to the edges (re-worked sediment) precedes the recovery of buried microphytobenthos cells.

The sediment overturned by dredge probably allows oxygen penetration into the upper sediment layers. When an oxidised surface layer is present, substantial amounts of phosphate can be retained in the sediment through adsorption to iron oxides (Anschutz et al., 1998; Krom & Berner, 1981; Slomp, Malschaert, & Van Raaphorst, 1998; Sundby, Gobeil, Siverberg, & Mucci, 1992). Van Raaphorst et al., (1988) confirmed this general pattern in their modelling analysis demonstrating that sorption in the oxygenated surface layers of the sediments could temporarily trap the phosphate produced through mineralization. The adsorption processes generally

results in a buffering of pore water HPO_4^{2-} concentrations to low values in the oxidized sediment zone (Froelich, 1988; Sundby et al., 1992) thus, the diffusive transport of HPO_4^{2-} to the overlying water is limited. On the other hand, the benthic infauna activity contributes to the oxygen penetration into burrows, decreasing the solubility of previously dissolved forms of phosphorus (Clavero, Niell, & Fernandez, 1991). The effective retention of phosphate in the upper sediment layers through sorption onto iron oxides recorded immediately after dredging operations, indicate that these sediments have a high and instantaneous capacity to adsorb phosphorus when clouds of particles are formed, hindering the release of phosphate to the water column. The microcosm experiment reinforce these findings since after sediment stirring the sorption of phosphorus onto iron oxides in the top-layer of sediment occurs simultaneously with the decrease of HPO_4^{2-} in pore water and with an insignificant increase in near bottom water.

During dredging activity, when the pore water of superficial sediment is renewed, nutrients are released into the water column (Fanning et al., 1982) since the sediment is a sink for nutrients (Henriksen, Rasmussen, & Jensen, 1983; Sundby et al., 1992; Forja, Blasco, & Gómez-Parra, 1994). According to the results found in the present study sediments function as a source of nutrients during the fishing disturbance. Ammonium, nitrates, organic nitrogen, phosphates and silicates decreased in the pore water of re-worked sediment (ridge) immediately after dredging, suggesting its export to the water column. The sporadic observation of an increase in those nutrients in near bottom water immediately after dredging, in spite of the intense dilutions and currents in the water column, reinforce that nutrients are exported from bottom to water column. Studies performed by Falcão and Vale (1998) and Caetano et al. (1995) showed that advective transport of ammonium from sediment to the water column occurs in a faster time scale than nitrification processes. In the present study an important decrease of organic nitrogen in pore water was recorded during the dredging activity (from 750 to 200 μM) suggesting large availability of this organic form for mineralization in the water column and consequently availability of nitrogen for phytoplankton uptake and growth. Other studies on ecological impacts of dredging showed that in dredged areas the concentration of silicates is much higher than in undredged areas (Riemann & Hoffmann, 1991). These authors demonstrated that during fishing operations the water column receives organic and inorganic nutrients that may cause significant changes in the nutrient levels. Therefore, phytoplankton primary production may increase in response to dredging activity, if it is controlled by nutrients. On the other hand, phosphorus is temporarily retained in sediments in response to perturbation of the seabed by fishing operations, however, this retention is only maintained during the period of iron oxides conservation. In the case of iron-rich sediment surface formation it was proposed that these layers act as a regulator of the phosphate flux out of the sediment (Sundby et al., 1992; Anschutz et al., 1998). The extension of the phosphorus pulse effect (retention-release) is a function of fishing effort and of the geochemical characteristic of sediments.

The amount of nitrogen and phosphorus exported to the water column associated with the dredging was estimated on the basis of ammonium and phosphate gradients in pore water during the first 5 min of trawling since pore water is renewed during

sediment disturbance. Studies performed by Falcão and Vale (1995) showed that physical disturbance of sediment increases dissolved ammonium by a factor of 1.9, thus we may consider that physical processes caused by trawling also desorbs ammonium easily bounded to sediment particles. On the other hand, the present experiment shows a negligible release of dissolved phosphate during sediment disturbance. Based on the number of boats (23) operating in each study area, the time of trawling (6 h), number of dredges per boat (2) and towed area per min ($32 \text{ m}^2 \text{ min}^{-1}$) we estimate that $530\,000 \text{ m}^2$ of sediment is re-worked per day. Using the data from Table 2, assuming that water content in sediment remains close to 20% and that the nutrient concentrations in pore waters are relatively constant in the sediment overturned (10 cm depth) we could estimate the amount of NH_4^+ and HPO_4^{2-} exported to water column. For station VL the nitrogen and phosphorus output associating with the dredging was 67 kg of N- NH_4^+ and 0.9 kg of P- HPO_4^{2-} per day. At station AR a lower amount of nitrogen (13 kg of N- NH_4^+ and 1.3 kg of P- HPO_4^{2-}) was exported to the water column per day. These estimates suggest that dredging causes distinct chemical impact at the studied sites over short-term periods. In fact, N:P ratio (77) in station VL exceeded largely the Redfield ratio indicating a large availability of nitrogen. On the contrary, the ratio found in station AR (10) was closer to the Redfield ratio pointing to a slight nitrogen limitation during physical disturbance. The difference in the estimated outputs suggests that clam dredging in deeper stations, where sedimentary organic matter content is higher, will cause more impact in the internal loadings of nitrogen and phosphorus unbalancing the N:P ratio. Shallow areas like station AR with higher exposure to winds, waves and tidal currents, tend rapidly to restore the sediment characteristics as demonstrated by Krost, Bernhard, Werner, and Hukriede, (1990).

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