

The effect of *Zostera noltii*, *Spartina maritima* and *Scirpus maritimus* on sediment pore-water profiles in a temperate intertidal estuary

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Abstract

The objective of the present work was to study the effect of plants common in temperate latitudes (*Zostera noltii*, *Spartina maritima* and *Scirpus maritimus*) on sediment nutrient profiles, and to compare it to sand- and mud-flats without vegetation. The study focused on the organic matter contents, the concentration of dissolved inorganic nutrients ($\text{PO}_4\text{-P}$, $\text{NH}_3\text{-N}$, $\text{NO}_3\text{-N}$), on the estimation of the total amount of these nutrients during day and night conditions and their potential net-fluxes. It was also hypothesised that in an estuarine system, different plants may have specific effects, and consequently different contributions to the system nutrient dynamics as a whole. Sediment profiles of loss on ignition (LOI) showed an increase of the organic matter contents from sand-flat, to *Zostera*, *Spartina*, mud-flat and *Scirpus*. Statistically, there were significant differences between sediment profiles of phosphate, ammonia and nitrate (Mann-Whitney test, $p < 0.05$), during day and night periods. These results suggest that there is an intense mobility of nutrients in the sediment, showing a day-night variation of nutrient concentrations in the pore-water. In the plants' rhizosphere, the day-night variation of nutrients seemed dependent on plant biomass and penetration of the roots. Additionally, coupling between plant and sediment seems to be a species-specific process. In spring, *Scirpus* salt marsh reaches the maximum density and biomass, and despite the higher organic matter contents in the plant covered sediment, *Scirpus* acts as a sink of nutrients. In contrast, the top 10 cm of the sediment in the *Spartina* salt marsh and in the *Zostera* beds may contribute to the efflux of nutrients during the night period, especially phosphate.

Introduction

Salt marshes and sea-grass beds have been characterised as efficient sinks for nutrients, and buffering the effects of nutrient inputs, (e.g., Anderson et al., 1997; Andersen & Ring, 1999; Flindt et al., 1999). The root-sediment interaction is complex and covers a wide range of biogeochemical processes, (e.g., Caçador et al., 1996; Wigand et al., 1997). Vegetation may also act as sediment traps playing an important role in the settling of suspended matter (Kamp-Nielsen & Flindt, 1993; Caçador et al., 1996, 2000; Andersen & Ring,

1999; Flindt et al., 1999). Several papers have reported chemical changes in the rhizosphere of several plants, including the redox potential (Eh), organic matter contents, metal availability and oxygen and nutrient profiles, (e.g. Kamp-Nielsen & Flindt, 1993; Caçador et al., 1996, 2000; Anderson et al., 1997; Cartaxana & Lloyd, 1999; Flindt et al., 1999; Azzoni et al., 2001). Nonetheless, few papers have addressed comparative studies of different plants in natural estuarine environments (Wigand et al., 1997; Sánchez et al., 1998). It was hypothesised that different plants may have different specific effects, and consequently

different contributions to the system nutrient dynamics as a whole.

The Mondego estuary is located on the Atlantic coast of Portugal (40°08' N, 8°50' W). It is about 7 km long and 2–3 km across at its widest part. Wetland habitats occupy about 18% of the south arm of the Mondego estuary, where the *Scirpus maritimus* L. population occupies the inner mud-flat areas, *Spartina maritima* (Curtis) Fernald occurs in the higher downstream mud-flat and sand-flat areas, and the *Zostera noltii* Hornem beds occupy the downstream mud-flats (Fig. 1). In the 1980s, *Z. noltii* beds occupied a broad expanse along the southern arm reaching the inner most parts of the estuary. Nowadays, this grass-like flowering plant has become restricted to a small patch located downstream, having been replaced elsewhere by green macroalgae (Marques et al., 1997, 2003; Cardoso et al., 2002). These three species also differ in their annual dynamics. New leaves of *Z. noltii* appear in late winter (late February/March) and the eelgrass meadows develop over the intertidal mud-flats in spring/

summer. Leaf cover begins to decline during autumn/winter. *S. maritima* is a rhizomatous grass forming extensive monotypic stands (Sánchez et al., 1997), with a continuous but very slow growth (Adams & Bate, 1995). *S. maritimus* is a stoutly rhizomatous perennial sedge (Karagatzides & Hutchinson, 1991), and usually forms similar dense monospecific stands in shallow brackish marshes (Lieffers & Shay, 1982). In the Mondego estuary this species has a particularly aboveground life cycle with a growing season from January to April/May (Lillebø et al., 2003).

The objective was to study the sediment profiles at *Z. noltii* meadows and on the *S. maritima* and *S. maritimus* salt marshes in comparison with sand and mud-flats without vegetation, concerning: the organic matter contents; the dissolved inorganic nutrients (PO₄-P, NH₃-N, NO₃-N) followed by an estimation of the total amount of these nutrients during day and night conditions; and finally compare the potential net-fluxes. This study took place in May, because spring corresponds to the season where *S. maritimus* and *Z. noltii* reaches maximum

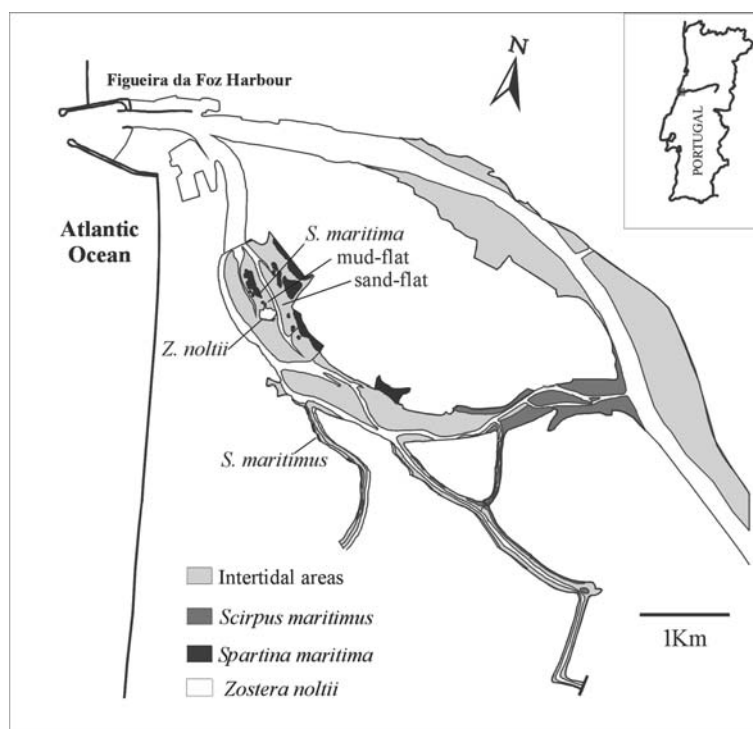


Figure 1. The location of the Mondego estuary and location of the study sites: *Spartina* and *Scirpus* salt marshes, *Zostera* meadows and mud- and sand-flats without vegetation.

aboveground biomass. The mean above and below-ground biomass (Mean \pm STD) in spring is, respectively, 51 ± 29 g Dwt m^{-2} and 25 ± 8 g Dwt m^{-2} for *Zostera*, 1866 ± 679 g Dwt m^{-2} and 2183 ± 1119 g Dwt m^{-2} for *Spartina*, and 435 ± 273 g Dwt m^{-2} and 3374 ± 890 g Dwt m^{-2} for *Scirpus*, in IMAR-Data base and Lillebø et al. (2003).

Material and methods

Five different study areas were established in the southern arm of the Mondego estuary on the 18th of May 2000: a bare sediment mud-flat; a sand-flat area; the *Zostera* beds; the *Spartina* salt marsh; and the *Scirpus* salt marsh. In order to characterise each area, triplicate sediment cores (10 cm depth) were analysed (1 cm slices) for percentage of water contents (Wwt–Dwt, 105 °C for 24 h), and loss on ignition (LOI) (Dwt–AFDW, 550 °C for 6 h). Sediment nutrient profiles were studied by placing vertically dialysis chambers in the muddy and sandy bare sediments and in the plants' rhizospheres; for a more detailed description of the technique see Kamp-Nielsen & Flindt (1993). In our case, the water samples were collected with a syringe (2.5 ml, corresponding to each chamber volume), and simultaneously the chamber was filled up with distilled water. To evaluate the effect of plants, samples were taken after 12 h exposure under dark conditions (night period) and 12 h under light conditions (day).

All water samples were analysed for dissolved inorganic phosphate, ammonia and nitrate in a rapid flow autoanalyser (RFA 300 Alpkem) according to Alpkem methodologies (1990). A non-parametric Mann-Whitney test was applied to determine the significance of differences (95% confidence level) between the sediment nutrient profiles (Zar, 1996).

Estimates of the amount of nutrients in the sediment at each depth were performed considering the LOI, the nutrient concentration in the interstitial water, the sediment sample specific mass and the water volume fraction. The total amount was obtained by integration of the amounts through depth.

Possible night efflux rates were calculated taking into account the difference between the night and day total amount plus the estuarine

area occupied by each species population (*Zostera* = 8850 m^2 , *Spartina* = 104720 m^2 and *Scirpus* = 105863 m^2).

Results

The profiles of percentage of LOI in the sediment indicate an increase of organic matter from sand-flat, to *Zostera*, *Spartina* and to mud-flat (Fig. 2). *Scirpus* marshes, located in the most inner estuarine areas, with lower hydrodynamics and higher sedimentation of fine sediments, showed a higher percentage of LOI.

Phosphate and ammonia concentrations in sediment pore-water increased with depth, especially in *Zostera* (Fig. 3a and b) and in the mud-flat (Fig. 4a and b) profiles, and during the night. On the other hand, nitrate concentrations were

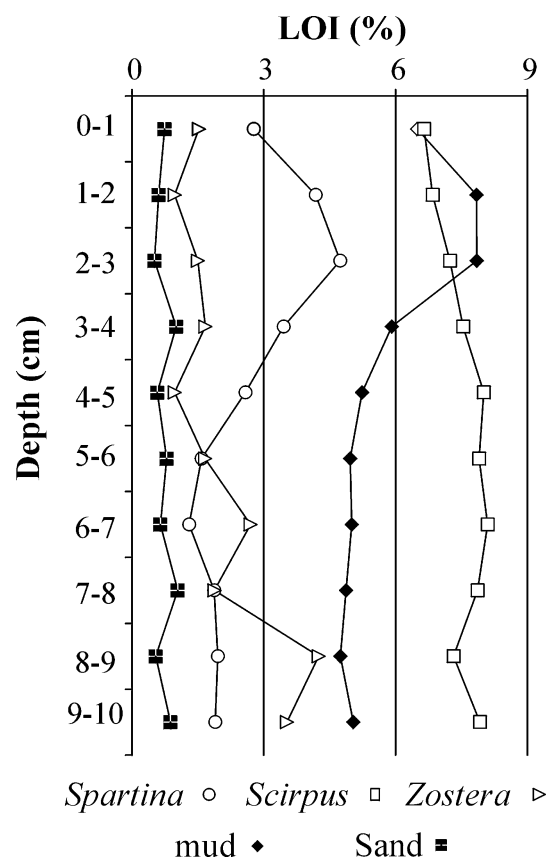


Figure 2. The profile of sediment LOI in *Spartina*, *Scirpus* and *Zostera* rhizosphere, and in mud- and sand-flats without vegetation.

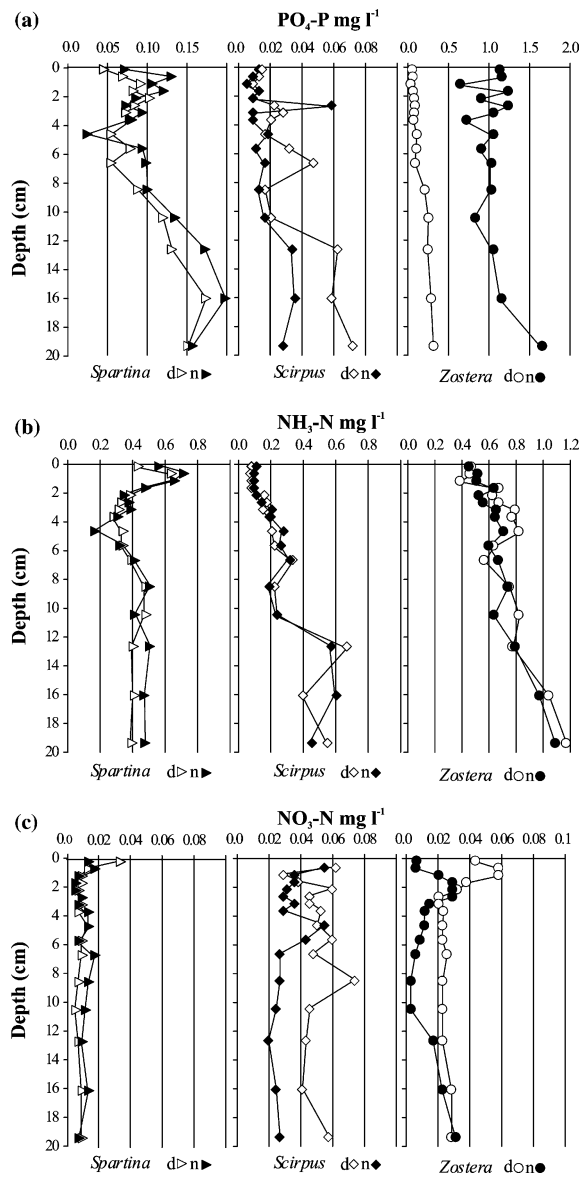


Figure 3. Nutrient concentrations in sediment pore-water profiles in *Spartina*, *Scirpus* and *Zostera* rhizosphere, during day and night: (a) Phosphate; (b) Ammonia; (c) Nitrate.

higher during the day and tended to decrease with depth, except for *Scirpus* rhizosphere where it was quite constant (Fig. 3c), and in the sand-flat were it only slightly increased (Fig. 4c).

The non-parametric Mann-Whitney tests showed that day-night profiles were significantly different in the mud and sand-flats without

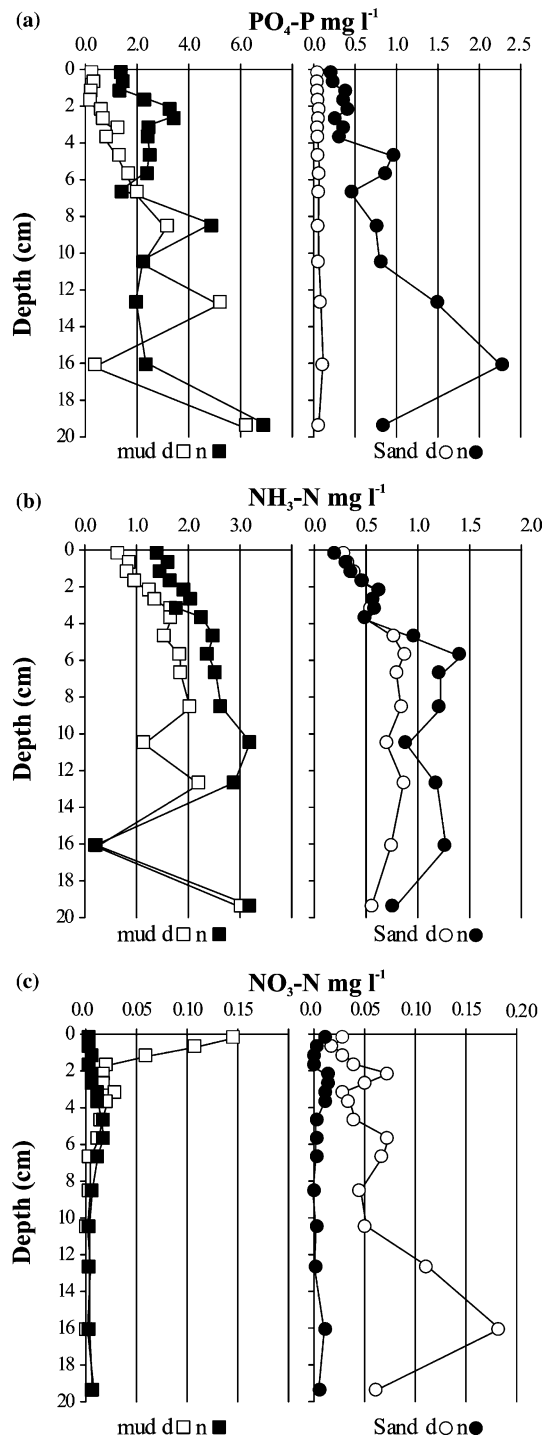


Figure 4. Nutrient concentrations in sediment pore-water profiles mud- and sand-flats without vegetation, during day and night: (a) Phosphate; (b) Ammonia; (c) Nitrate.

vegetation (Table 1A). In the vegetated flats, day-night profiles were statistically different for PO₄-P and NO₃-N in *Z. noltii* rhizosphere and

for NO₃-N in *S. maritimus* rhizosphere. In the *Spartina* rhizosphere there were no statistically significant differences between day and night

Table 1. Results from the non-parametric Mann-Whitney expressing the significance of differences (95% confidence level) in sediment PO₄-P, NH₃-N and NO₃-N profiles

		Mud-flat	Sand-flat	<i>Spartina maritima</i>	<i>Scirpus maritimus</i>	<i>Zostera noltii</i>
A: Between day and night concentrations						
PO ₄ -P	Mud-flat	0.0079	–	–	–	–
	Sand-flat	–	0.0000	–	–	–
	<i>Spartina maritima</i>	–	–	n.s.	–	–
	<i>Scirpus maritimus</i>	–	–	–	n.s.	–
	<i>Zostera noltii</i>	–	–	–	–	0.0000
NH ₃ -N	Mud-flat	0.0136	–	–	–	–
	Sand-flat	–	n.s.	–	–	–
	<i>Spartina maritima</i>	–	–	n.s.	–	–
	<i>Scirpus maritimus</i>	–	–	–	n.s.	–
	<i>Zostera noltii</i>	–	–	–	–	n.s.
NO ₃ -N	Mud-flat	n.s.	–	–	–	–
	Sand-flat	–	0.0000	–	–	–
	<i>Spartina maritima</i>	–	–	n.s.	–	–
	<i>Scirpus maritimus</i>	–	–	–	0.0017	–
	<i>Zostera noltii</i>	–	–	–	–	0.0033
B: Between concentrations during day						
PO ₄ -P	Sand-flat	0.0000	–	–	–	–
	<i>Spartina maritima</i>	0.0000	0.0003	–	–	–
	<i>Scirpus maritimus</i>	0.0000	0.0034	0.0000	–	–
	<i>Zostera noltii</i>	0.0000	0.0001	n.s.	0.0000	–
NH ₃ -N	Sand-flat	0.0002	–	–	–	–
	<i>Spartina maritima</i>	0.0000	0.0109	–	–	–
	<i>Scirpus maritimus</i>	0.0000	0.0001	0.0007	–	–
	<i>Zostera noltii</i>	0.0006	n.s.	0.0002	0.0000	–
NO ₃ -N	Sand-flat	0.0022	–	–	–	–
	<i>Spartina maritima</i>	n.s.	0.0000	–	–	–
	<i>Scirpus maritimus</i>	0.0014	n.s.	0.0000	–	–
	<i>Zostera noltii</i>	0.0129	0.0033	0.0000	0.0002	–
C: Between concentrations during night						
PO ₄ -P	Sand-flat	0.0000	–	–	–	–
	<i>Spartina maritima</i>	0.0000	0.0000	–	–	–
	<i>Scirpus maritimus</i>	0.0000	0.0000	0.0000	–	–
	<i>Zostera noltii</i>	0.0000	0.0021	0.0000	0.0000	–
NH ₃ -N	Sand-flat	0.0000	–	–	–	–
	<i>Spartina maritima</i>	0.0000	0.0167	–	–	–
	<i>Scirpus maritimus</i>	0.0000	0.0001	0.0016	–	–
	<i>Zostera noltii</i>	0.0000	n.s.	0.0004	0.0000	–
NO ₃ -N	Sand-flat	n.s.	–	–	–	–
	<i>Spartina maritima</i>	0.0205	0.0065	–	–	–
	<i>Scirpus maritimus</i>	0.0000	0.0000	0.0000	–	–
	<i>Zostera noltii</i>	0.0134	0.0038	n.s.	0.0003	–

profiles considering the three nutrients analysed (Table 1A).

The nutrient profiles in the mud- and sand-flat without vegetation were statistically different from each other and from all other studied areas during day (Table 1B) and night situations (Table 1C). There were statistically significant differences concerning the concentrations of the three nutrients analysed between *Spartina* and *Scirpus* rhizosphere profiles and between *Spartina* and *Zostera* rhizosphere profiles, under day and night situations. *Scirpus* and *Zostera* rhizosphere were also statistically different for $\text{PO}_4\text{-P}$, $\text{NH}_3\text{-N}$ and $\text{NO}_3\text{-N}$ during the day (Table 1B) and night (Table 1C).

The total amount of phosphate in the first 10 cm of sediment was lower in the sand-flat, increasing in *Scirpus*, *Spartina* and in *Zostera* rhizosphere, and was much higher in the mud-flat without vegetation (Fig. 5a). The total amount of ammonia was lower in *Scirpus* rhizosphere, increasing in the sand-flat, *Zostera* rhizosphere, mud-flat and was highest in *Spartina* rhizosphere (Fig. 5b). Nitrate total amount was higher in *Scirpus* rhizosphere, decreasing in *Spartina* and *Zostera* rhizosphere, in sand-flat, and was much lower in the mud-flat without vegetation (Fig. 5c).

Zostera roots penetrate approximately 5 cm while *Scirpus* and *Spartina* may have active roots down to 20 cm in depth. The potential nutrient efflux from plants' rhizospheres during the night shows that at this time of the year *Scirpus* salt marsh acts as a sink of nutrients, *Spartina* salt marsh may contribute to the efflux of nutrients during the night period, especially phosphate, and *Zostera* beds may have a comparatively strong contribution to phosphate efflux during the night (Fig. 6).

Discussion

The day-night amount of nutrients exchanged in the sediment pore-water without vegetation and the day-night sediment-water exchanges in plants' rhizospheres seem quite different. However, LOI can express the potential availability of nutrients in the sediment, explaining the low phosphorus and nitrogen concentration in the sand-flat profiles compared with the high concentration in the

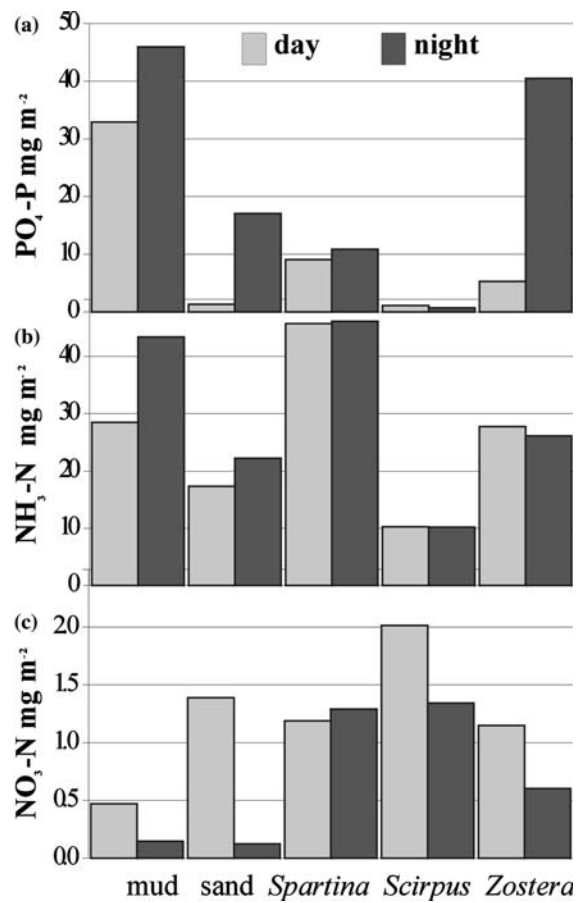


Figure 5. Total amount of nutrients in *Spartina*, *Scirpus* and *Zostera* rhizosphere, and in mud- and sand-flats without vegetation, during day and night: (a) Phosphate; (b) Ammonia; (c) Nitrate.

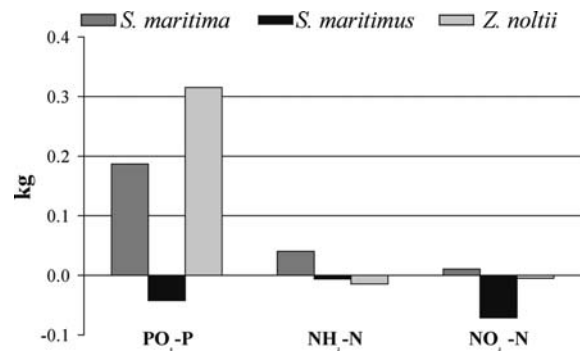


Figure 6. The potential night efflux of phosphate, ammonia and nitrate from *Spartina*, *Scirpus* and *Zostera* rhizospheres.

mud-flat (Falcão & Vale, 1998), as particle-water equilibrium and reactions between these two phases can influence the nutrient availability for plant uptake. On the other hand, in the plant rhizosphere, nutrients may diffuse towards the roots and the uptake of water by plants creates advective transport of water and salt in the direction of the roots. Additionally, the sediment phosphate adsorption capacity and the form of dissolved inorganic nitrogen will be dependent upon the oxic state of the sediment, (e.g., Flindt, 1994; Cowan et al., 1996). In the areas without vegetation, the significant differences between day and night profiles, with higher phosphate and ammonia concentrations during the night coupled with the extremely low nitrate concentration, may reflect oxygen depletion due to respiration, which during the day may be compensated by autotrophic oxygen production from associated microalgae. In addition, the integrated low amount of nitrate and the high ammonia pool most likely also reflect the oxygen limitation of the nitrification process (Kamp-Nielsen & Flindt, 1993; Flindt, 1994; Flindt et al., 1999). In the colonised sediments day-night variation of nutrient concentrations in sediment pore-water seemed to be very much dependent on plant root biomass and penetration in depth. In spring, the average biomass of *Zostera* roots in the top 5 cm of sediment is 25 ± 8 g Dwt m^2 , while salt marsh plants have active roots down to 20 cm in depth and the average roots biomass is respectively 2183 ± 1119 g Dwt m^2 for *Spartina* and 3374 ± 890 g Dwt m^2 for *Scirpus*. These results suggest that in spring these species may enhance the nutrient uptake for growth purposes and promote a more oxidized rhizosphere, which explains the lower phosphate and ammonia concentrations in the interstitial water during day and night situations, when compared with bare muddy sediments. Nutrient profiles in *Zostera* beds should be compared to sandy-muddy bare sediment.

Macrophytes can influence the nitrogen cycling directly by taking up dissolved inorganic nitrogen for growth purposes. Additionally, ammonification may be enhanced by re-mineralisation of particulate organic matter (Kemp et al., 1984), by dissolved organic nitrogen released from the plant roots (Smith et al., 1988) and from breakdown of senescent plant material (Kenworthy & Thayer, 1984). The nitrification process is generally limited

by low oxygen and ammonia concentrations (Henriksen & Kemp, 1988).

The sediment pore-water profiles also showed that plant coverage influences differently the nutrient profiles. Results show that *Z. noltii*, *S. maritima* and *S. maritimus* have a specific interaction with the sediment, as has been suggested for other species (Wigand et al., 1997). Significant differences between various plant rhizosphere nutrient profiles may result from the depth of root penetration, plant biomass and plant physiology.

Zostera noltii is able to take-up nutrients from the water column through the leaves and from the interstitial water via the rhizomes (Short, 1987). However, it has been shown that rooted submersed macrophytes are able to take up almost all phosphorus needed from the interstitial water (Flindt et al., 1999). The penetration of *Zostera* roots into the sediment aerates the upper layers, and allows oxygen to penetrate into the top few centimetres (Short, 1987). The low phosphate concentrations during the day, especially in the top 5 cm of the sediment, may express the increased P-adsorption due to the release of oxygen, and the consumption for growth purposes. However, during the night, and considering the top 10 cm of the sediment, *Z. noltii* beds may make a comparatively strong contribution to the phosphate efflux, due to the prevalence of heterotrophic processes and the fact that the rooting zone only covers 50% of the sediment column. In *Zostera* beds, nitrogen is usually the limiting element and is most easily absorbed as ammonium (Short, 1987). Relatively high nitrification rates in *Zostera* beds have been attributed to the release of oxygen from roots (Barko et al., 1991; Flindt, 1994). Additionally, stimulated denitrification has been explained by enhanced nitrification and leakage of easily degradable dissolved organic carbon (Flindt, 1994).

Both salt marsh species have the ability to transport oxygen to the belowground parts, down to 20 cm depth into otherwise impermeable sediments, where it is used for root respiration and oxidation of the rhizosphere (Adams & Bate, 1995; Cleavinger et al., 1995). This process may lead to the precipitation of iron oxides around the roots (Vale et al., 1990), and ultimately increase the phosphate adsorption capacity of the sediment

(Berner & Berner, 1996). Moreover, rhizosphere oxidation can provide aerobic micro-sites with available nitrate, and mitigate the likely predominance of ammonium over much of the marshes (Adam, 1990; Kamp-Nielsen & Flindt, 1993). The oxygen diffusion to the sediment is driven by photosynthetic oxygen production (Azzoni et al., 2001), and the fact that the *Scirpus* population is reaching maximum density and biomass, may enhance both biotic and abiotic reoxidation of reduced compounds. Additionally, the likely increase in oxidised surface area of *Scirpus* compared to *Spartina* suggests a higher nitrification rate in the root rhizosphere and subsequently denitrification. Further on, denitrification may be stimulated by high quality dissolved organic carbon released by the roots (Kamp-Nielsen & Flindt, 1993; Flindt et al., 1999). On the other hand, *Scirpus* is a C3 photosynthetic mechanism type (Boschker et al., 1999), while *Spartina* is an alternative (C4) type (Carter, 1988), or just a C4 type (Benito & Onaindia, 1991). It has been suggested that plants with a C4 photosynthetic pathway have, at least theoretically, a number of competitive advantages over C3 species (Adam, 1990), namely a higher potential productivity, higher water-use efficiency and also a more efficient use of available nitrogen (Adam, 1990). Furthermore, *Spartina* has continuous growth, and considering the top 10 cm were the rooting zone covers 100% of the sediment, this salt marsh area may contribute to the efflux of phosphate during the night period.

Our results show that nutrients are intensely exchanged inside the colonised sediments, and suggest that coupling between plant and sediment is a species-specific process, allowing a more comprehensive and environmentally correct understanding of estuarine systems functioning.

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