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Contribution of *Spartina maritima* to the reduction of eutrophication in estuarine systems

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The crucial capacity of salt marshes to retain nitrogen, thus reducing eutrophication, greatly depends on the salt marsh maturity, rather than the estuarine system.

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ABSTRACT

Salt marshes are among the most productive ecosystems in the world, performing important ecosystem functions, particularly nutrient recycling. In this study, a comparison is made between Mondego and Tagus estuaries in relation to the role of *Spartina maritima* in nitrogen retention capacity and cycling. Two mono-specific *S. maritima* stands per estuary were studied during 1 yr (biomass, nitrogen (N) pools, litter production, decomposition rates). Results showed that the oldest Tagus salt marsh population presented higher annual belowground biomass and N productions, and a slower decomposition rate for litter, contributing to the higher N accumulation in the sediment, whereas *S. maritima* younger marshes had higher aboveground biomass production. Detritus moved by tides represented a huge amount of aboveground production, probably significant when considering the N balance of these salt marshes. Results reinforce the functions of salt marshes as contributing to a reduction of eutrophication in transitional waters, namely through sedimentation processes.

1. Introduction

Salt marshes are among the most productive ecosystems in the world (e.g. Mc Lusky and Elliott, 2004), and the highly important value of the multiple services provided by wetlands, including salt marshes, has already been estimated (Constanza et al., 1997), highlighting the need to preserve the health of these ecosystems. The productivity of salt marshes is affected by several inter-related parameters, such as the tidal pattern (flooding frequency and duration), soil salinity, temperature, nutrient availability, oxygen levels, sediment type, etc (Ibañez et al., 2000). Moreover, the ecological significance of salt marshes, namely as nursery areas for fish and breeding sites for birds (Mc Lusky and Elliott, 2004), is largely recognized.

As a result of increasing global population and increasing human activities, salt marshes, estuaries and other coastal waters have been subjected to increasing nitrogen (N) loadings with anthropogenic origin, (e.g. Vitousek et al., 1997; see Herbert, 1999). These high increases in N loadings often lead to eutrophication in many estuaries (Valiela and Bowen, 2002; Lillebø et al., 2005), thus representing the principal worldwide agent of change for coastal ecosystems (NRC, 2000). Accordingly, nutrient cycling in coastal ecosystems is a crucial role performed by salt marshes (Nixon, 1980), acting as transformers of nutrients (either functioning as sinks and/or sources) (Ibañez et al., 2000). The reason for its functioning as sinks and/or sources depends on several factors such as the successional age of the tidal marsh, tidal energy, salinity, assimilatory nutrient uptake, N-fixation, oxygen release, nutrient production and losses due to mineralization and nitrification–denitrification, etc (Ibañez et al., 2000; Eyre and Ferguson, 2002; McGlathery et al., 2004). Primary production, organic N burial and denitrification within the sediment constitute processes, which may trap the N in the estuaries (Nedwell et al., 1999). Hence, considering the role of plants in this process, salt marshes have a crucial role in N remediation.

Salt marsh plants possess a well-developed aerenchyma system, which confers on them the ability to transport oxygen to the belowground parts (Maricle and Lee, 2002), where it is used for root respiration and oxidation of the rhizosphere. Therefore, these plants may interfere with benthic nutrient cycles, as well as modifying redox potentials and pH within the sediment, which lastly eventually influences processes such as nutrient adsorption to particles, and several steps of the N cycle (ammonification,

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nitrification, denitrification and N-fixation) (see Pedersen et al., 2004). *Spartina maritima* (Curtis) Fernald is a rhizomatous grass with a continuous but very slow growth, forming extensive monotypic stands, and occupies intertidal mudflats both at the Mondego and Tagus (Portugal) estuaries. Depending on *Spartina* sp. morphology and the stage of vegetation development in the system, they can act as a sink or source of N (e.g. Odum et al., 1995).

As a whole, this study intends to reveal the role of *S. maritima* in N cycling in salt marshes at these two warm-temperate mesotidal estuaries. Thus, the N storage in different and inter-related compartments will be studied: above- and belowground *S. maritima* tissues, detritus export, sediment and litter. Our final goal is to address what the *S. maritima* contribution to the reduction of eutrophication in estuarine and coastal areas is, by removing excess N from these systems.

2. Materials and methods

2.1. Study sites

S. maritima was studied at two warm-temperate mesotidal estuaries (Mondego and Tagus) located on the Atlantic coast of Portugal (40°08′ N, 8°50′ W and 38°49′ N, 08°56′ W, respectively).

The Mondego estuary is about 7 km long and is 2–3 km across at its widest part and drains a hydrological basin of 6670 km^2. It comprises two different arms, northern and southern, separated by an alluvium-formed island (Murraceira island) (Fig. 1a). The northern arm is deeper (4–8 m during high tide) and constitutes the principal navigation channel and the location of Figueira da Foz harbour. The southern arm is shallower (2–4 m during high tide, tidal range 1–3 m), and is characterized by large areas of intertidal flats, which are exposed during low tide, wherein *S. maritima* salt marshes colonise 4% of the lower estuarine areas (Coelho et al., 2004). Two different salt marshes in the south arm were selected: Gala, in the outer part of the estuary (and consequently more influenced by the tidal circulation) and Jusante (Esteiro dos Armazéns), located in the inner part (Fig. 1a).

The Tagus estuary constitutes one of the largest estuaries on the western coast of Europe. It has a shallow bay covering an area of about 320 km^2 and the river drains an area of 86,000 km^2 (Fig. 1b). Seawater enters the estuary through a deep, narrow inlet channel and tides are semi-diurnal, with average amplitude of 2.4 m ranging from 0.9 m at neap tide to 4.1 at spring tide (Gameiro et al., 2004). This estuary is affected by different pressures, namely navigation (there is a huge amount of naval traffic linked to the Lisbon harbour), urbanism, industry, fisheries, aquaculture and leisure activities. The hydrographic bay of the Tagus estuary has about 2.5 million people. This means that the estuary receives a great amount of domestic/urban residuals. However, agriculture and industrial activities are the major contributors to the decline in water quality, particularly the industrial zone to the south of Lisbon, near the Corroios salt marsh. Food, chemical and metallic industries are the major industrial contributors to the estuarine pollution. This leads to effluent discharges with high organic matter content, oils, sulphates and heavy metals. This study was carried out at the Pancas and Corroios salt marshes. Pancas, located on the eastern bank of the estuary, is a younger and bigger (800 ha) salt marsh with extensive intertidal mudflats, and is part of a Nature Reserve (RNET). Meanwhile, Corroios is located in the southern suburbia of Lisbon, is an older/mature and smaller salt marsh (400 ha) and receives effluent discharges mainly from urban and industrial sources, given the proximity of areas that are urbanized and industrial. This area is characterized by a low hydrodynamic regime. Both marshes are colonized by *S. maritima* (Caçador et al., 2004).

2.2. Sampling strategy

S. maritima samples were collected bi-monthly for a 1-yr period between June 1997 and April 1998 at the Mondego salt marshes, and between June 1998 and April 1999 at the Tagus salt marshes. The sampled stands were uniform in size and in density of stems. At the Mondego salt marshes, five random samples were collected and aboveground material was clipped at ground level for a circle of ∅ 13 cm. Detritus production at the Mondego salt marshes was estimated from Castro (1999). At the Tagus salt marshes, three squares of 0.3×0.3 m^2 were sampled and the detritus accumulated on the square sediment was removed by hand and transported to the laboratory in plastic bags. After this procedure, sediment cores were taken at exactly the same sites, in order to collect the correspondent belowground material. A circular core of ∅ 13 cm and 25 cm depth was used at the Mondego, and ∅ 7 cm at the Tagus *S. maritima* stands. Other rooted sediment samples were also collected to determine the total nitrogen and organic matter content. Subsequently, all the samples were transported to the laboratory to be processed.

Salinity and pH were measured in situ on each sampling date and at each salt marsh, using the following field equipment and respective probes, WTW Cond. 330i/set – Tetracon® 325 probe and WTW pH 330i/set – SenTix® 41 probe.

2.3. S. maritima *processing*

At the laboratory, the material collected both aboveground and belowground was rinsed with demineralised water, the aboveground part separated into stems and leaves and the whole plant dried until it reached a constant weight (48 h) at 60 °C. This procedure was also performed with the detritus collected on the sediment surface.

2.4. Biomass and N production

Biomass production (above- and belowground) was estimated according to the differences between the maximum and minimum biomass recorded during the entire year, as described by De la Cruz and Hackney (1977) for belowground material. N production was estimated in the same way, considering maximum and minimum N pool values. N pool was calculated by multiplying the biomass per the N concentration of *S. maritima*. Turnover rate for above- and belowground biomass and N was also calculated (the ratio between biomass production and the maximum biomass, and the ratio between N production and the maximum N pool, respectively).

2.5. Litterbag field experiment

In order to analyze the decomposition of belowground vegetation, belowground components were collected from several random locations at the Gala and Jusante marshes in June 1997 and at the Pancas and Corroios marshes in February 1999. The samples were rinsed and dried and then, 10×10 cm^2 nylon mesh bags with 450 μm diameter holes containing about 5 g of belowground material were placed in the field. Each bag was individually weighted. In order to reproduce, as closely as possible, their natural habitat, the bags were buried at 10 cm depth in their own environments. Five bags (replicates) at the Mondego estuary and three bags at the Tagus estuary were collected periodically between June and December, and between February and September at the Mondego and Tagus marshes, respectively. The remaining belowground biomass data were fitted to an exponential decay model (first order decay function), $X_t = X_0\,e^{-kt}$, where X_t is final/remaining dry weight in litterbags, X_0 is initial dry weight, t is time in days and k is the decay constant/rate (see Curcó et al., 2002).

2.6. Analytical procedures

Plant material from the Mondego salt marshes was dried to a constant weight at 105 °C and analyzed for total N content (CHN-analyzer, Carlo Erba). The Mondego sediment samples were ground and homogenized, and total N was analyzed according to standard methods described in Limnologisk Metodik (1992). Sediment samples from the Tagus salt marshes were air dried, cleaned of roots with tweezers and passed through a 0.25 mm mesh. For N quantification, sediments and biological material were also ground and homogenized. Total N concentration was quantified in sediment samples, above- and belowground biomass, detritus and litterbag material (these also at the beginning time/day of the experiment) using a CHNS/O analyzer (Fisons Instruments Model EA 1108). Sediment triplicate sub-samples were analyzed for loss of ignition, after 8 h at 450 °C. N annually retained in the sediments of the studied salt marshes was quantified, taking into consideration both the sedimentation rate and the N content in the upper 5 cm of *Spartina* rooted sediment.

2.7. Statistical analyses

Two-way ANOVA (analysis of variance) was performed to test for differences between salt marshes regarding sediment salinity, pH and organic matter. Repeated measures ANOVA were performed in order to detect differences in location (four levels) and date/month (six levels) for all plant part biomass (leaves, stems and belowground).

Post hoc comparisons were performed using the Newman–Keuls test at $\alpha = 0.05$ significance level. Analyses were performed with the STATISTICA 8.0 software package.

3. Results

3.1. Sediment characterization

Some physico-chemical parameters of the salt marsh sediments are described in Fig. 2 and Table 1. Concerning salinity, there are differences between salt marshes and between dates, and there is interaction between location and date (Two-way ANOVA, $F = 2.125$, $p < 0.05$). Corroios was the saltier salt marsh presenting a maximum value of 47. In general, sediment salinity in this salt marsh in June, August and October is statistically different from the other dates and salt marshes (Fig. 2a). The pH was similar

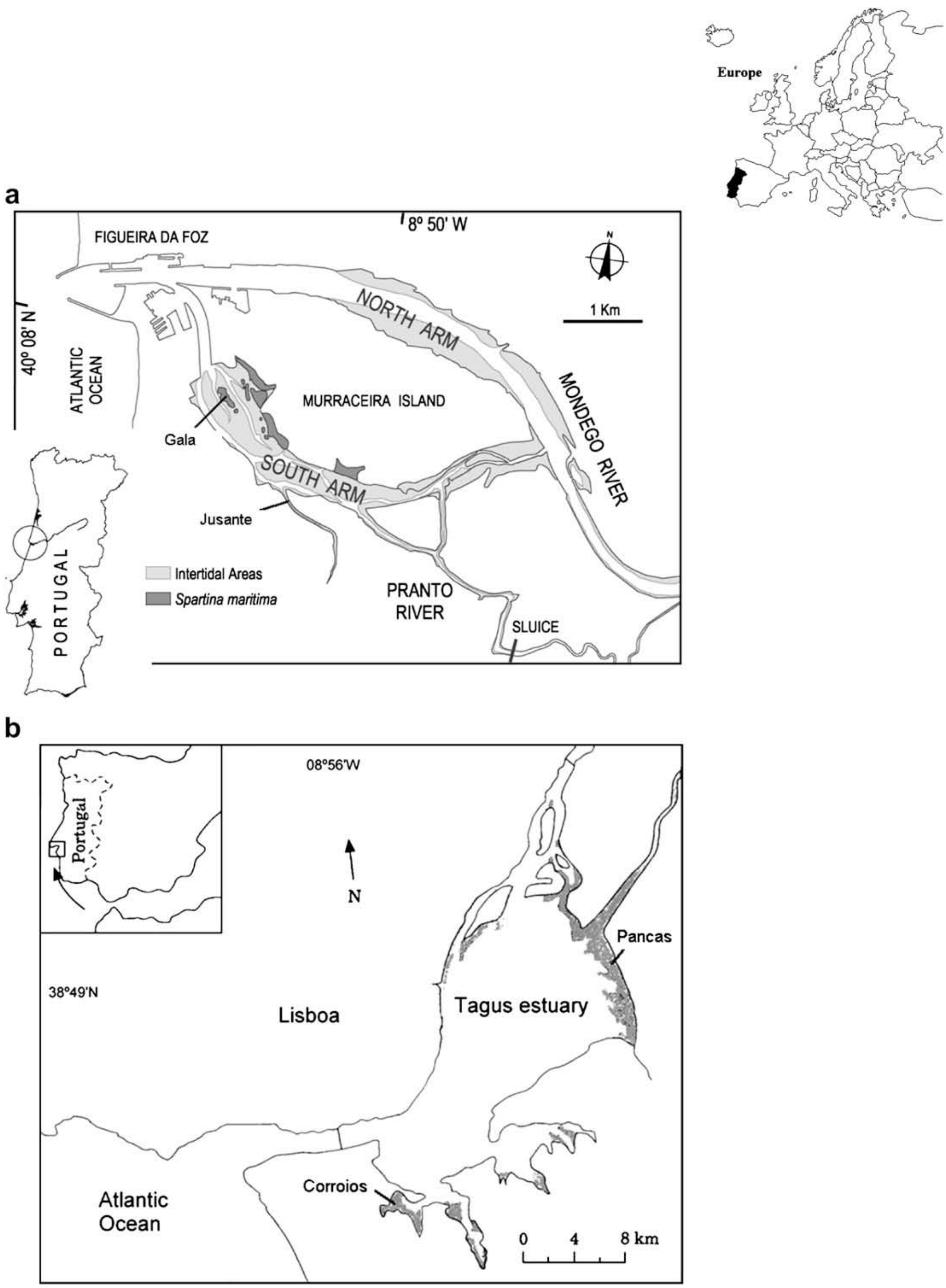

Fig. 1. The location of the studied estuaries, and the indication of the sampling sites at the Mondego (a) and Tagus (b) estuaries.

throughout the year (Two-way ANOVA, $F = 1.59$, $p > 0.05$), ranging between 6 and 7.4, but different between salt marshes (Two-way ANOVA, $F = 91.47$, $p < 0.001$). There is interaction between location and date ($F = 2.23$, $p < 0.05$) and in general, Corroios showed the lowest pH values (statistically different from the other salt marshes), meaning higher plant effect on the rhizosphere (Fig. 2b). Considering organic matter content, Corroios presented significantly higher values than the other salt marshes. There are differences in O.M. between salt marshes ($F = 1429.7$; $p < 0.0001$) and dates ($F = 37.75$; $p < 0.0001$), and there is also interaction between both factors ($F = 21.79$; $p < 0.0001$). Almost all of the months and salt marshes are statistically different from each other (Fig. 2c). The Tagus salt marshes presented a huge percentage of silt and clay, thus retaining mainly fine particles. The Mondego salt marshes presented coarser sediments than those of the Tagus, even if it is fine sand (Table 1).

3.2. Above- and belowground biomass, and N pool

S. maritima biomass is statistically different between salt marshes (repeated measures ANOVA, $F = 165.6$; $p < 0.0001$) and between sampling dates ($F = 188.1$; $p < 0.0001$). Moreover, there is

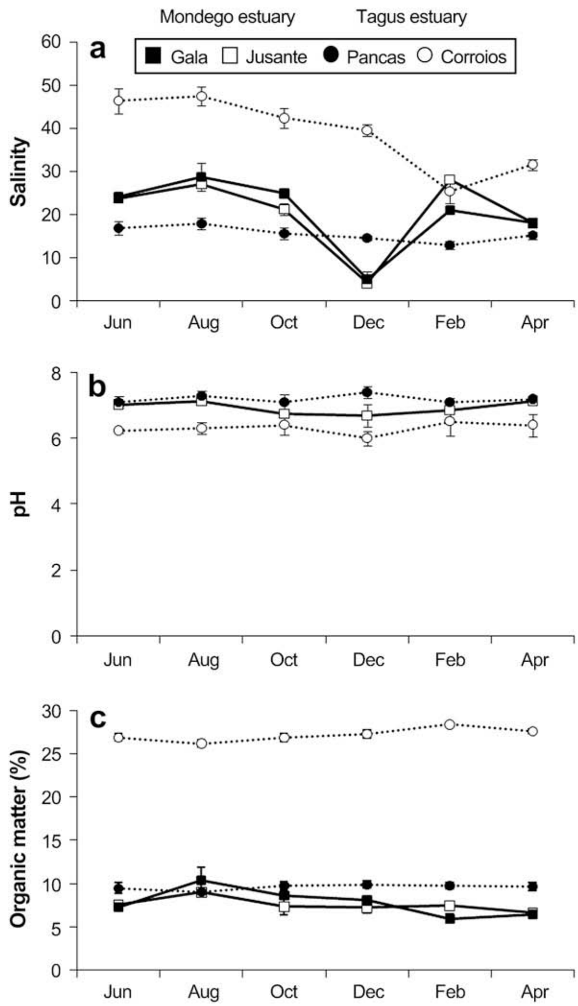

Fig. 2. *Spartina* rooted sediment characteristics (average ± SD; $n = 3$) in the salt marshes of the Mondego and Tagus estuaries; (a) salinity, (b) pH and (c) organic matter content.

a significant interaction between both factors (salt marsh and date) ($F = 202.8$; $p < 0.0001$). Regarding leaf biomass, Gala presents statistically higher values than almost all the salt marshes and sampling dates, except in December and also in August (Gala and Jusante are not different in some months) (Table 2). The stem biomass presents significant differences between Gala and the other salt marshes (except for Jusante in April). In October and December, the Jusante stem biomass is statistically different from the other salt marshes on different sampling dates. There are no differences in stem biomass among the other salt marshes and dates. Corroios presented the highest belowground biomass values, with all sampling dates being statistically different from almost all

Table 1
Sediment granulometry for Mondego and Tagus salt marshes

Estuary	Granulometry	
Mondego	Gala	Silt and clay: 6% Fine sand: 56% (63–125 μm); 38% (>125 μm)
	Jusante	Silt and clay: 15% Fine sand: 54% (63–125 μm); 31% (>125 μm)
Tagus	Pancas	Silt: 60%
	Corroios	Clay: 38% [a]

[a] Caçador et al. (2004).

Table 2
Spartina maritima leaves, stems and belowground biomass in Mondego and Tagus salt marshes for a 1-yr period (average ± SD; $n = 5$ (Mondego); $n = 3$ (Tagus) (gDW m^{-2}))

		Mondego		Tagus	
		Gala	Jusante	Pancas	Corroios
Leaves	Jun	1132 ± 519	243 ± 47	146 ± 9	112 ± 2
	Aug	539 ± 173	365 ± 62	248 ± 37	137 ± 13
	Oct	683 ± 174	376 ± 97	248 ± 36	103 ± 2
	Dec	270 ± 32	158 ± 41	185 ± 25	105 ± 4
	Feb	642 ± 194	139 ± 31	84 ± 7	109 ± 6
	Apr	553 ± 102	276 ± 65	94 ± 9	76 ± 4
Stems	Jun	2064 ± 1372	1084 ± 130	118 ± 9	112 ± 4
	Aug	2329 ± 893	1201 ± 506	237 ± 21	152 ± 15
	Oct	3527 ± 430	1939 ± 527	238 ± 17	93 ± 1
	Dec	2131 ± 501	1401 ± 276	163 ± 8	107 ± 6
	Feb	2958 ± 938	924 ± 181	83 ± 10	110 ± 16
	Apr	1556 ± 453	957 ± 58	96 ± 9	117 ± 11
Belowground	Jun	1404 ± 591	3250 ± 633	826 ± 79	7189 ± 124
	Aug	1332 ± 642	3596 ± 1077	1173 ± 184	4671 ± 77
	Oct	1320 ± 172	3608 ± 723	1194 ± 225	3699 ± 283
	Dec	850 ± 217	2871 ± 581	804 ± 115	4506 ± 273
	Feb	1745 ± 219	2800 ± 891	527 ± 24	4851 ± 150
	Apr	966 ± 271	2737 ± 425	670 ± 54	5452 ± 167

the other sampling dates of Gala, Jusante and Pancas. Gala and Pancas (all months) present statistically similar belowground biomass in relation to each other, but different from that of Jusante and Corroios. The Jusante belowground biomass was different from the other salt marshes (Table 2).

According to the biomass patterns, N pool was higher in the aboveground part of *S. maritima* at Gala, while at Pancas, Corroios and Jusante it was the belowground part that presented the highest N pool (Fig. 3).

3.3. Biomass and N productions

Gala and Corroios presented the highest total (above + belowground) biomass production (3728 and 3610 gDW m^{-2} yr^{-1}) of *S. maritima*, followed by Jusante (2059 gDW m^{-2} yr^{-1}) (Fig. 4a). The lowest *S. maritima* biomass production occurred at Pancas (986 gDW m^{-2} yr^{-1}). The relative proportion of aboveground/belowground biomass production varied greatly when considering all the salt marshes studied (Fig. 4a).

Considering N production, it can clearly be observed that there is a tendency on the part of the Mondego and the Tagus locations and, more specifically, on the part of the Gala and Jusante locations to the Pancas and Corroios locations, to improve the percentage of belowground N production of *S. maritima*, rather than aboveground vegetation (Fig. 4b).

According to the highest total biomass production of *S. maritima* at Gala and Corroios, these sites presented the highest N pools in the plant (Fig. 4b). Pancas presented both the lowest biomass and N production and Jusante showed an intermediate total biomass production, but an N production equal to Corroios. Thus, the same amount of N produces lower *Spartina* biomass at Jusante, when compared to Corroios, demonstrating lower N use efficiency.

At Gala, the turnover rate for above- and belowground biomass is similar (0.50 and 0.51, respectively) (Fig. 5). Considering aboveground biomass, Pancas presented the highest turnover and Corroios the lowest (0.66 and 0.33, respectively). The turnover rate for belowground biomass was similar between Gala, Pancas and Corroios (about 0.50) and lower at Jusante (0.22) (Fig. 5). The turnover rate for N was lower at Gala in the belowground material and at Corroios in the aboveground part of *S. maritima*. As a whole, Pancas presented the highest turnover rates and Corroios the lowest ones

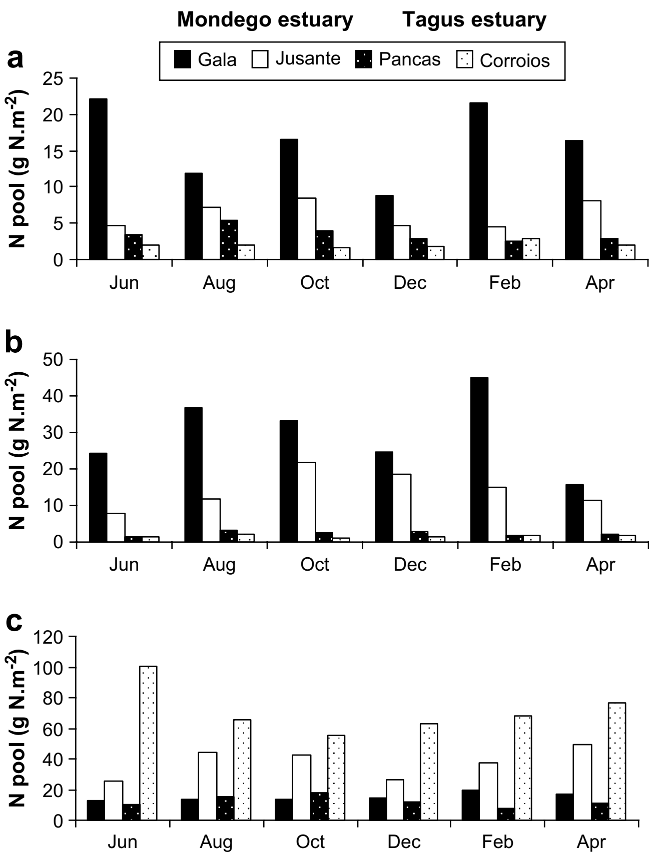

Fig. 3. Nitrogen pool ($gN\,m^{-2}$) (Biomass × N concentration) of *Spartina maritima* leaves (a), stems (b) and belowground biomass (c) in the salt marshes of the Mondego and Tagus estuaries for a 1-yr period.

(Fig. 5), meaning that younger salt marshes presented higher turnover rates.

3.4. Detritus production: biomass and nitrogen pool

Less than 6% of the *Spartina* biomass production was retained as detritus, and all the rest (more than 94%) did not remain there, being exported from the salt marsh (Fig. 5). The Mondego salt marshes presented low biomass retention as detritus, with slightly higher values of detritus retention occurring in the Tagus salt marshes. In view of aboveground *S. maritima* N production, the highest detritus N pool retained in the estuary occurred in the Tagus salt marshes (Pancas and Corroios). At Gala and Jusante, less than 2% of the total N aboveground production stays in the salt marsh as detritus; all the rest is exported from the salt marsh to adjacent areas (Fig. 5). Although Tagus retains slightly more N as detritus than Mondego, this is a slight difference in the N pool, with all salt marsh systems exporting an extremely large amount of N annually produced by *S. maritima*.

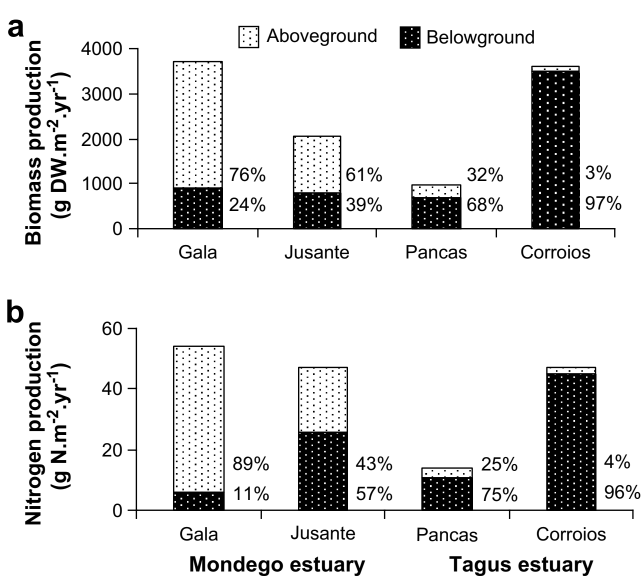

Fig. 4. Biomass (a) and nitrogen (b) production for aboveground and belowground parts of *Spartina maritima* at the salt marshes of the Mondego and Tagus estuaries.

3.5. Decay rate – Litterbag field experiment

S. maritima decomposition rate (velocity at which belowground material decomposes) varied among the salt marshes (Table 3). Gala and Pancas presented the highest decay rate after 6 months and Corroios presented the lowest decay rate (Fig. 6). Considering the previous results and extrapolating them to the belowground N production at all salt marshes, it can be observed that, for example after 6 months, Gala and Pancas constitute the sites with more N mineralized and Corroios the salt marsh where 65% of the belowground N production still remains in the form of litter (Fig. 5).

3.6. N retention in the salt marsh sediments

The Mondego salt marshes (Gala and Jusante) present similar values of N annually stored in the sediment, and Pancas (Tagus) presents slightly lower values. The N retained in the sediments of the Corroios salt marsh is 2- to 3-fold higher, when compared to the other salt marshes (Table 4). From the total N quantified, in the Pancas salt marsh sediment, a very small amount (0.3%) corresponds to inorganic N (ammonium, nitrate and nitrite) and more than 99% of the total N corresponds to organic N (Cartaxana and Lloyd, 1999). According to the same study, the sediment inorganic N is mainly in ammonium form, with a maximum ratio ammonium/nitrate in August (196). The median ratio was 18, and a minimum ratio of 3 occurred in February, while nitrite corresponds to only 1% of the sum $NO_3^- + NO_2^-$. At the Gala salt marsh, one may infer from Lillebø et al. (2006) that the sediment inorganic N is also mainly in ammonium form since the concentration of ammonium at the sediment pore water profiles (20 cm depth) were one order of magnitude higher than the nitrate concentrations (the range was, respectively, 0.2–0.7 mg NH_4-N L^{-1} and 0.01–0.03 mg NO_3-N L^{-1}). N stored in the salt marsh sediments comes from *S. maritima* belowground production and also external sources. By subtracting the N produced by *S. maritima* belowground material from the N annually retained in the sediment, the amount of N that comes from an external source and is retained in the sediment is obtained. Thus, at Jusante and Corroios, the greater percentage of N content in the sediment comes from the *S. maritima* belowground system (Fig. 5). Conversely, at Gala and Pancas only about a 1/4 and 1/3 of total N retained in the sediment results from *S. maritima* production, with the majority of the N coming from external sources (Fig. 5).

4. Discussion

The high belowground/aboveground biomass ratio observed in Corroios for *S. maritima* has already been described as a result of stressing environmental conditions for *Phragmites australis* in the Po Delta, Italy (Scarton et al., 1998 (1999)); and also for the seagrass *Zostera capensis* at Mozambique (De Boer, 2000). It is already known that environmental stress leads plants to attempt adaptation by investing in the belowground biomass (Groenendijk and Vink-Lieavaart, 1987) and that these plants under unfavourable soil

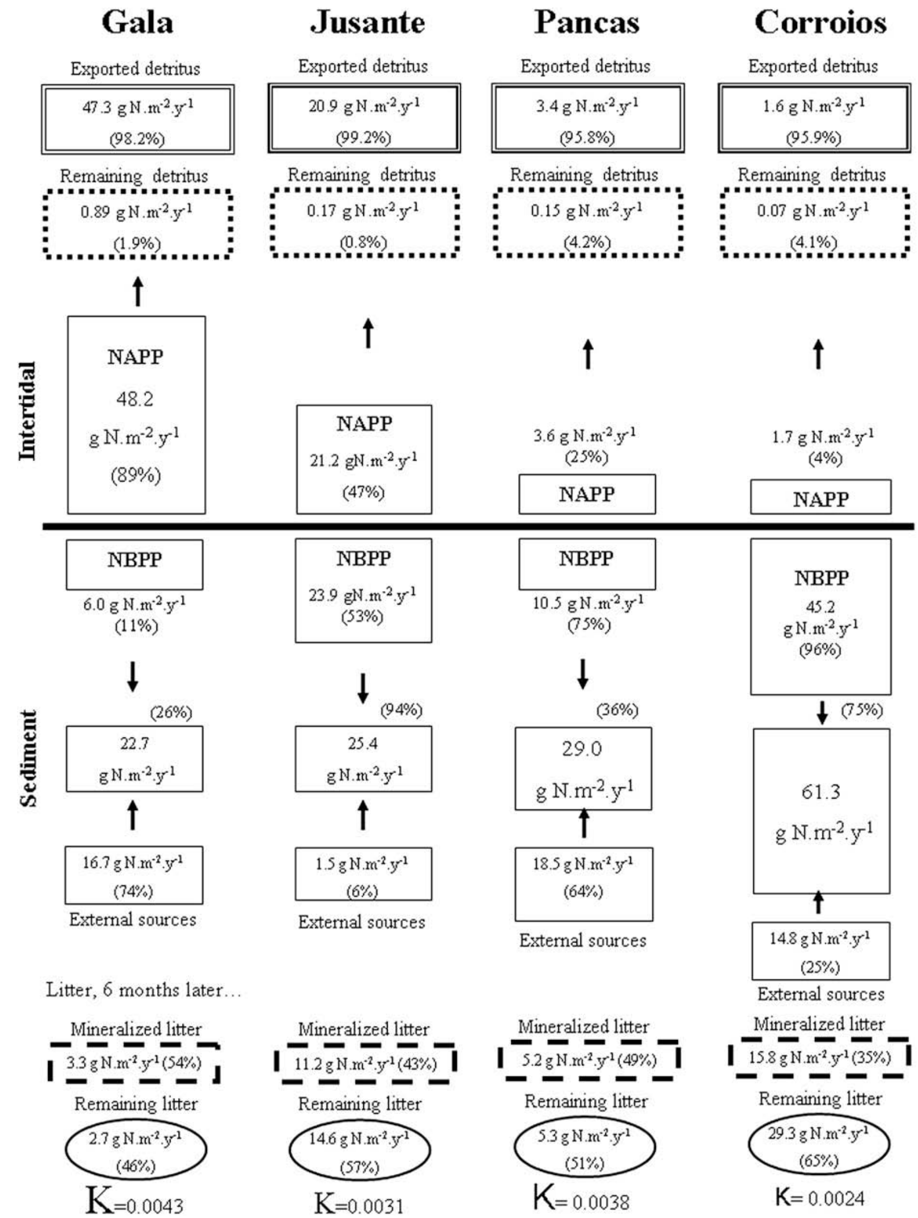

Fig. 5. Schematic representation of *Spartina maritima* biomass and N productions, turnover rates, detritus moved by tides, decomposition of belowground material after certain period and nitrogen retention in the sediment of the salt marshes of the Mondego estuary. NAPP means "Net Aboveground Primary Production" and NBPP, "Net Belowground Primary Production".

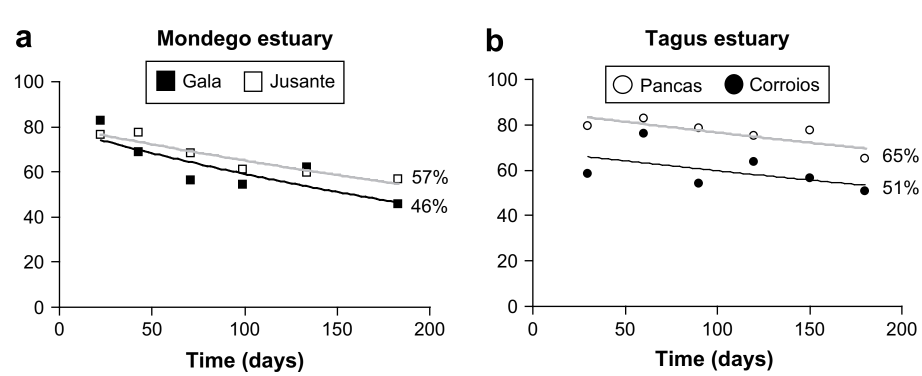

Fig. 6. Remaining belowground material of *Spartina maritima* (dry weight – % (X_t)) over 180 days of decomposition in the litterbags.

Table 3
Decomposition rates (k) for *Spartina maritima* belowground biomass at Mondego and Tagus salt marshes during a 180 days period, according to the equation $X_t = X_0\ e^{-kt}$

Mondego				Tagus			
Gala		Jusante		Pancas		Corroios	
t (d)	k	t (d)	k	t (d)	k	t (d)	k
22	0.0087	22	0.0123	31	0.0179	31	0.0076
43	0.0087	43	0.0059	59	0.0045	59	0.0032
71	0.0081	71	0.0053	87	0.0068	87	0.0027
99	0.0061	99	0.0049	118	0.0038	118	0.0024
134	0.0036	134	0.0038	150	0.0038	150	0.0017
183	0.0043	183	0.0031	180	0.0038	180	0.0024

X_t is remaining dry weight in the litterbags (%) (see Fig. 6), X_0 is initial dry weight and t is time in days.

conditions need a greater root surface (see Caçador et al., 1999). Thus, the increasing of the below/aboveground ratio from Gala, Jusante to Pancas and Corroios, may, in this way, indicate an increase in physiological stress of *S. maritima*. Several factors, namely soil salinity, tidal inundation, nutrient availability, sediment type and drainage, may affect the primary production of salt marsh plants (Ibañez et al., 1999, 2000). Thus, physical and chemical characteristics of the rooted sediments are important in determining plant productivity. Several authors have pointed out salinity as a determinant factor in the productivity of salt marsh plants, with lower salinity values favouring the productivity of marsh plants (Ibañez et al., 1999, 2000; Curcó et al., 2002; see Edwards and Mills, 2005).

Considering what has been mentioned above, the high sediment salinities and the fact that Corroios is an older salt marsh may explain the productivity of *S. maritima* at this site. Moreover, Corroios is the site under the greatest stress in this study, given the pollution and the urban and industrial discharges from the very nearest and densely populated city of Lisbon. Thus, *S. maritima* seems to reduce the aboveground production due to these stressful conditions and strongly invest in the belowground material. Edwards and Mills (2005) showed that the belowground production of *Spartina alterniflora* increased with the increasing age of the created salt marshes in Louisiana, accompanied by a tendency to decrease the aboveground biomass production. Accordingly, Pancas is a younger salt marsh, which may explain the higher percentage of aboveground biomass than Corroios and consequently the higher belowground production at Corroios. Gala and Jusante are younger salt marshes, given their characteristics of much open water and relatively simple tidal outlets in the sea, compared with Corroios, which presents channels relatively more complex (Valiela et al., 2000). In young salt marshes, concerning physical and chemical characteristics, the competition for nutrients is low, which in turn reduces the amount of belowground material vital for the plant (Caçador et al., 1999); this explains the higher aboveground biomass production in the youngest salt marshes.

Table 4
N annually retained in the salt marsh sediments of the Mondego and Tagus salt marshes, concerning sedimentation rate and N content in the upper 5 cm of *Spartina* rooted sediment

	Mondego		Tagus	
	Gala	Jusante	Pancas	Corroios
Sedimentation rate (cm yr^{-1})	0.7[a]	0.7[a]	1.0[b]	1.0[b]
Sediment N (mgN gDW) (average ± SD; $N = 12$)	3.24 ± 0.74	3.63 ± 1.02	2.93 ± 0.23	6.13 ± 0.25
N retained (gN m^{-2} yr^{-1})	22.7	25.4	29.3	61.3

[a] Extrapolated from Castro (2005).
[b] In: Caçador et al. (2007).

According to some authors, mature salt marshes (such as Corroios) export more material than the youngest ones (Valiela et al., 2000). However, in this study, the amount/percentage of the detritus that is exported is very similar among (young and mature) salt marshes.

Considering the total aboveground production, the export of N by detritus transport is probably significant for the N balance of the salt marsh. Thus, the mineralization of *Spartina* sp. derived organic matter and, consequently, the N cycling takes place almost entirely outside the salt marsh system, namely in the estuary or in the coastal areas, which is the opposite to that which has been described for other salt marshes (Hemminga et al., 1996; Bouchard and Lefeuvre, 2000). Nevertheless, the high detritus exportation is not surprising in the Mondego and Tagus salt marshes since the tidal inundation occurs twice a day, contributing to the washing out of detritus.

The decomposition rate of *S. maritima* varied among the salt marshes, with Corroios (the oldest salt marsh) presenting the slowest decay rate. This slower decomposition process in Corroios indicates a tendency for higher accumulation of *S. maritima* derived organic matter in the sediments of this salt marsh, thus a higher N retention in these sediments. Villar et al. (2001) also reported the net accumulation of macrophyte detritus due to high macrophyte production and low decomposition rates. Differences in decomposition rate have frequently been explained by differences in the chemical composition of the litter (N, P and C content) and tidal action along the elevation gradient of the salt marsh (see De Boer, 2000; see Bouchard and Lefeuvre, 2000; see Villar et al., 2001). The chemical composition of the litter is not considered in this work but may be an important aspect to consider in future works. Considering the fact that Corroios is an older salt marsh, it may be hypothesized that this salt marsh may be on a higher elevation than the others. Thus, the tidal flushing may be lower, which may reduce the decomposition kinetics at this site, since this aspect seems important in maintaining litter moisture (see Bouchard and Lefeuvre, 2000) and consequently in accelerating decomposition. According to some authors (see De Boer, 2000) the higher organic matter content in the sediment and the higher clay content (which increases the water retention capacity) favour decomposition. However, at Corroios, there is high organic matter content (27%) and high clay content but the decomposition rate was slow. One possible explanation may be the variation of influence of all these parameters (e.g. chemical composition of the litter, tidal inundation, litter moisture, etc) during the year.

N stored in the studied salt marsh sediments results from *Spartina* belowground production and also from external sources (namely sedimentation processes). At Jusante and Corroios, the main percentage of N retained in the sediment comes from the belowground production of *S. maritima*. This makes sense since these salt marshes present lower decomposition rates and higher belowground N production, contributing to this higher N retention/accumulation in the sediment. According to some authors (Rozema et al., 2000), the increased N content in salt marsh sediment with the increasing age of the salt marsh indicates that the salt marsh acts as a sink for N, which can be stated with regard to Corroios.

5. Conclusions

Salt marshes have a crucial role on eutrophication reduction by taking up dissolved inorganic nitrogen for growth purposes, by enhancing N cycling through denitrification, and N retention through sedimentation processes. Plants uptake and transform the inorganic N into organic N, which is then accumulated in the sediment. In this work, the contribution of sedimentation and the sink function of the salt marshes were analyzed. Overall, this study reveals some differences among all the salt marshes studied, with the oldest salt marsh (Corroios) presenting the most uncharacteristic features, namely a greater capacity to sequestrate N in comparison to the younger marshes.

To sum up, *S. maritima* salt marshes may trap N, removing its excess and, therefore, helping to reduce eutrophication in the estuarine ecosystem. Nevertheless, this ability to remove N varies among salt marshes and estuaries, depending on their biotic and abiotic characteristics, particularly when considering young and mature/old salt marshes.

Considering this study, we can hypothesise that more favourable environmental conditions for the increase of *S. maritima* biomass (e.g. an increase in the salt marsh area and optimum environmental parameters such as salinity and tidal inundation) would contribute to a greater allocation/incorporation of N in the plant and, therefore, to the reduction of reactive N in the estuarine system. This would, consequently, contribute to the reduction of the eutrophication status of the estuaries.

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