CARBON STORAGE IN TAGUS SALT MARSH SEDIMENTS

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Abstract. Seasonal variation of above ground and belowground biomass of *Spartina maritima* and *Halimione portulacoides*, decomposition rates of belowground detritus in litterbags, and carbon partitioning in plant components and sediments were determined in two Tagus estuary marshes with different environmental conditions. Total biomass was higher in the saltier marsh from 7,190 to 6,593 g m^{-2} dw and belowground component contributed to more than 90%. Litterbag experiment showed that 30 to 50% of carbon is decomposed within a month (decomposition rate from 0.024 to 0.060 d^{-1}). Slower decomposition in subsequent periods agrees with accumulation of carbon concentration in sediment. Atmospheric carbon annually transferred to the plant belowground biomass is stored more efficiently in sediments of Corroios than Pancas.

Keywords: carbon, *Halimione portulacoides*, litterbags, salt marsh, *Spartina maritima*, Tagus estuary

1. Introduction

The nature and extent of the routes followed by primary production in marine communities have important implications in carbon consumption and preservation in marine ecosystems and global carbon budget (Cebrian, 2002). Salt marshes typically exhibit high rates of productivity (Mitsch and Gosselink, 2000) and are excellent carbon sinks as they take CO_2 from the atmosphere and store it in living plant tissue (Williams, 1999). The importance of these aspects is recognised with the creation and restoration of wetlands degraded or destroyed (Craft *et al*., 1999).

Much has been written about whether salt marshes export materials to the adjacent seawaters (*cf.* Weinstein and Kreeger, 2000). The outwelling hypothesis, which states that organic matter exported from coastal marshes fuels food chains in adjacent waters (Teal, 1962; Nixon, 1980, Odum *et al*., 1995), has stimulated research on net aerial primary production (Bouchard and Lefeuvre, 2000). The export varies geographically, inter-annually, with local differences related to tidal movement, the primary medium of transfer of aerial organic matter (Gross *et al*., 1990; Morris and Haskin, 1990; Bouchard and Lefeuvre, 2000). Most studies were concentrated on the aboveground standing crop; the contribution of belowground

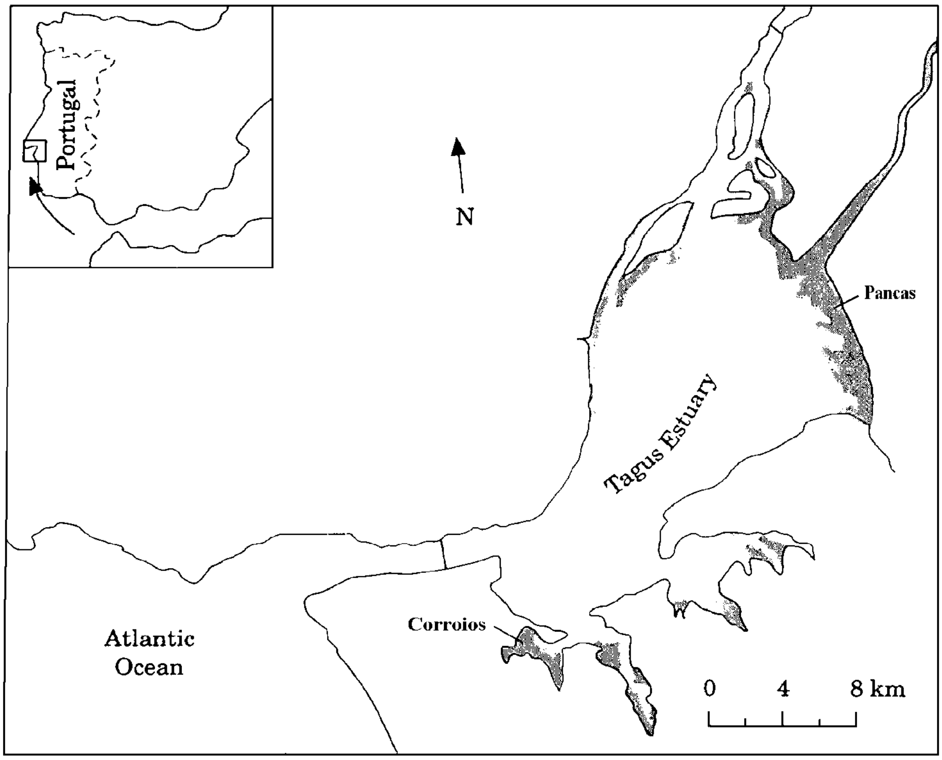

Figure 1. Location of the Tagus estuary and sampling tidal marshes.

components to nutrient and energy budgets of the adjacent coastal ecosystems often has been neglected (Groenendiijk and Vink-Lieavaart, 1987). Belowground production in salt marshes may exceed aboveground production (Kostka *et al.*, 2002). Due to this high belowground allocation, decomposition of roots contributes greatly to carbon turnover in salt marsh sediments (Scheffer and Aerts, 2000). The oxidation of organic matter depends on the chemical composition of halophytes (Hemminga and Buth, 1991), the delivery of atmospheric oxygen at the rhizosphere and the complex root-sediment interactions (Caçador *et al.*, 1996). Tidal inundation affecting the sediment environmental conditions also influences the decomposition rate (Foote and Reynolds, 1997).

The aim of this study was to estimate the aboveground and belowground production of *Spartina maritima* and *Halimione portulacoides* in two marshes of the Tagus estuary, detritus production, and the decomposition rate of belowground biomass using the litterbag method. On the basis of production data and carbon concentrations in plant components, sediment cores and decomposing litter, we examined the carbon accumulation rate in vegetated sediments of the two salt marshes.

2. Site Description

The Tagus estuary is one of the largest estuaries on the Atlantic coast of Europe, covering about 320 km^2. The southern and eastern parts contain extensive intertidal mud flats harbouring salt marsh plant communities dominated by *Spartina maritima* (Poales: Poaceae), *Halimione portulacoides* (Caryophyllales: Chenopodiaceae) and *Arthrocnemum fruticosum* (Caryophyllales: Chenopodiaceae). A typical zonation is visible, with homogeneous stands of the pioneer species *S. maritima* colonising the bare muds of low marshes and natural depressions, *H. portulacoides* occupying the banks of creeks, and *A. fruticosum* being found largely in the upper parts of the salt marshes. The study was carried out in two marshes: Pancas and Corroios (Figure 1). The marshes were chosen due to their contrasting characteristics: Pancas is a young salt marsh with extensive mudflats (800 ha) located in the Tagus Nature Reserve; Corroios is older, smaller (400 ha) and located in the proximity of urbanised and industrial areas. Due to the highly branched system of channels and the high tidal ranges (max. 4 m), the sites where the study took place experienced two tidal flushing twice each day.

3. Materials and Methods

3.1. Sampling

Two pure stands of *S. maritima* and *H. portulacoides* were surveyed between June 1998 and April 1999 in Pancas and Corroios. Aboveground biomass was determined every two months by clipping the vegetation at ground level in three squares of 0.3 × 0.3 m. At each period, detritus deposited on the sediment of the same plots was removed by hand and transported to the laboratory in plastic bags. After cutting the aboveground material and removing the detritus, two sediment cores were taken at each study site using a 7 cm diameter, 100 cm long tube. In one core, belowground biomass of each plant was sorted out from the sediment cores to a depth of 25 cm depth where most of roots are present. The second core was sliced at intervals of 0–5, 5–15, 15–25, 25–35, 35–45 and 45–55 cm and total carbon was determined. Three sediment cores were collected from non-vegetated areas of the sites and sliced at the same intervals.

3.2. *In-situ* Measurements

Sediment temperature was measured at low tide at 15 cm depth using a digital thermometer. Approximately at the same depth, redox potential (Eh) and pH were measured *in situ* using a Crison pH/mV meter with a platinum electrode. Pore water of rooted sediments was removed by suction with a syringe equipped with a tube that was introduced at 15 cm depth in the sediment. Salinity was measured in pore waters using a refractometer.

3.3. Determination of biomass and detritus

The collected aboveground plant material was transported to the laboratory, rinsed with demineralised water, separated into stems and leaves, and dried to constant weight at 80 °C. Belowground material in the upper 25 cm was separated from the sediment using a 212 μm-mesh sieve and demineralised water. The remaining plant material was dried at 80 °C for 48 hr and weighed (Gross *et al.*, 1991). The detritus collected on the sediment surface was treated in similar way.

3.4. Litterbag field experiment

Belowground biomass of *S. maritima* and *H. portulacoides* was collected from several locations at the Pancas and Corroios marshes in February 1999. The samples were rinsed and then dried. Approximately 5 g of root material were placed in 24, 10×10 cm nylon mesh bags with 450-μm diameter holes. The bags were buried at 10 cm depth in their respective environments in order to mimic as closely as possible their natural habitat. A set of three bags was collected monthly for each plant species between February and September. In the laboratory, the plant material was removed from the litterbags, rinsed with distilled water, dried at 80 °C for 48 hr, weighed and analysed for total carbon. Before burying litterbags, subsamples of each species were saved to determine initial carbon concentrations. Decay rates (k) were determined through this first-order decay function, $X_t = X_o e^{-kt}$ (Bouchart and Lefeuvre, 2000).

3.5. Determinations of grain size and total carbon

Sediment samples were air-dried and cleaned of roots with tweezers, passed through a 0.25 mm mesh. After destroying organic matter by loss on ignition at 550 °C and carbonates by HCl dissolution, particle size was determined according to Stoke's law, in a 1000 mL measuring cylinder beaker with distilled water (Gee and Bauder, 1986). For carbon measurements, sediments and biological material were ground and homogenised. Total carbon (C) concentration was determined on all materials using a CHNS/O analyser (Fisons Instruments Model EA 1108).

3.6. Statistical analysis

The obtained data were statistically analyzed using one-way analysis of variance following Sokal and Rohlf (1981).

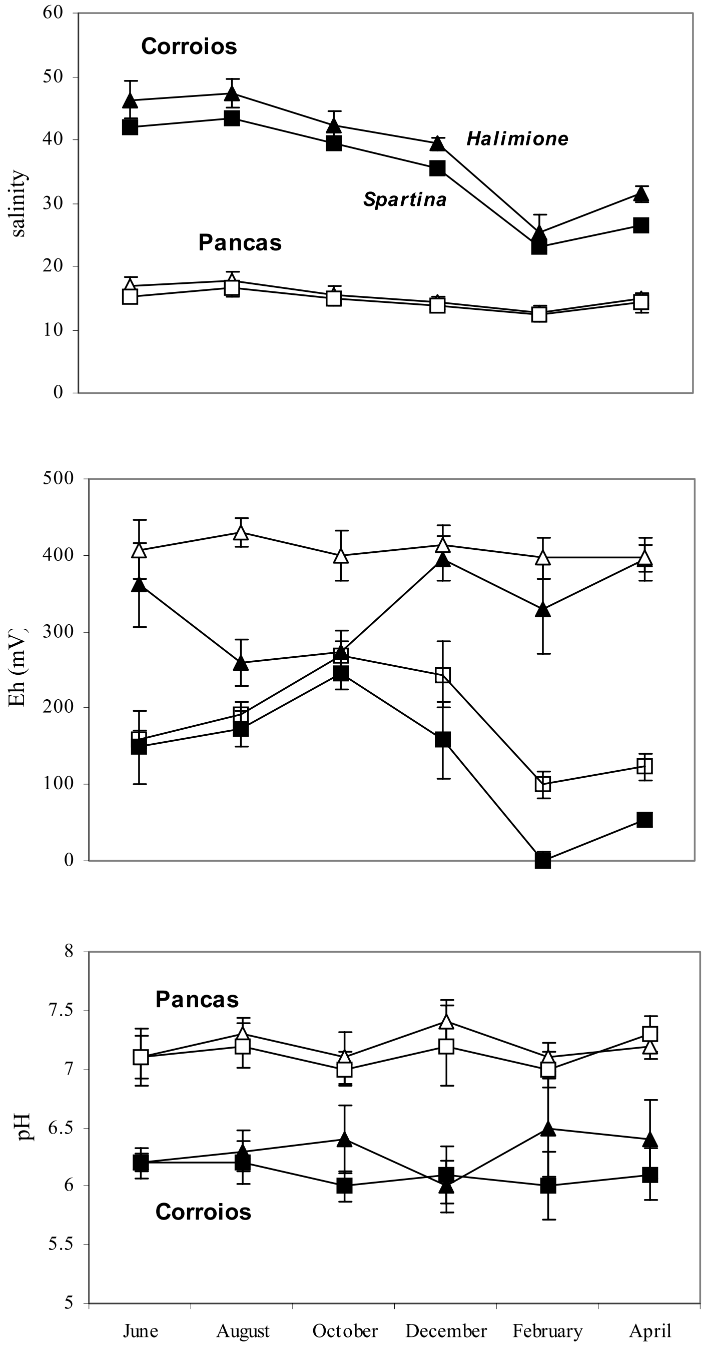

Figure 2. Seasonal variation of salinity, redox potential and pH in rooted sediments of *Spartina maritima* and *Halimione portulacoides* in Pancas and Corroios salt marshes (means ± standard deviations).

4. Results and Discussion

4.1. Physical and chemical characteristics of rooted sediments

Sediments of both salt marshes were comprised mainly of fine particles, about 60% silt and 38% clay. Sediment temperature was similar in the two marshes and varied seasonally between 15 and 26 °C. Rooted sediments were saltier in Corroios (salinity between 23 and 47 ppt) than in Pancas (13 to 19 ppt) reflecting the salinity gradient along the estuary (Figure 2). The salinity remained relatively constant in Pancas and decreased substantially in Corroios, as freshwater moved seaward in winter. The redox potential was higher in sediments colonised by *H. portulacoides* (max. 430 mV) than by *S. maritima* (max. 270 mV) in the two marshes, and decreased in winter (0–100 mV) when temperature was lower and the plants became less active (Caçador *et al*., 2000). pH in rooted sediments was lower at Corroios (6.0–6.5) than at Pancas (7.0–7.4) and did not differ considerably between the two plant communities or seasonally.

4.2. Aboveground and belowground biomass

Belowground biomass exceeded aboveground biomass at both sites (Figure 3). The highest values were in Corroios with 7,190 g m^{-2} of *S. maritima* roots and 6,593 g m^{-2} of *H. portulacoides* roots contributing 96 and 90% of the total biomass, on average respectively. Belowground biomass in Pancas accounted, on average, for 73% (*S. maritima*) and 54% (*H. portulacoides*) of the total biomass. Among the aboveground components, stems of *H. portulacoides* in Pancas had the highest biomass (510 to 1,920 g m^{-2}) and leaves of *S. maritima* in Corroios lowest biomass (75 to 135 g m^{-2}). Considering all the data, plant biomass of the two marshes differed significantly ($p < 0.05$). Whereas leaf and stem biomass of *S. maritima* and *H. portulacoides* in Corroios were relatively constant throughout the year, seasonal variations were observed in Pancas, with maximum values in August (*S. maritima*) and October (*H. portulacoides*), and a minimum in February. Belowground biomass of the two species varied seasonally: values at Corroios increased from February to June and at Pancas between February and October. Presumably the prolonged growth in Pancas reflects lower salinity conditions (cf. Mendelssohn and Morris, 2000).

4.3. Carbon in leaves, stems, and belowground biomass

Leaf C concentrations ranged between 280 and 440 mg g^{-1} throughout the year. These values are in accordance with the ranges of C concentration reported in plants from other tidal marshes (Groenendijk and Vink-Lievaart, 1987, Zawislanski *et al*., 2001). For each tissue type, C concentrations did not differ between species or with season ($p > 0.05$).

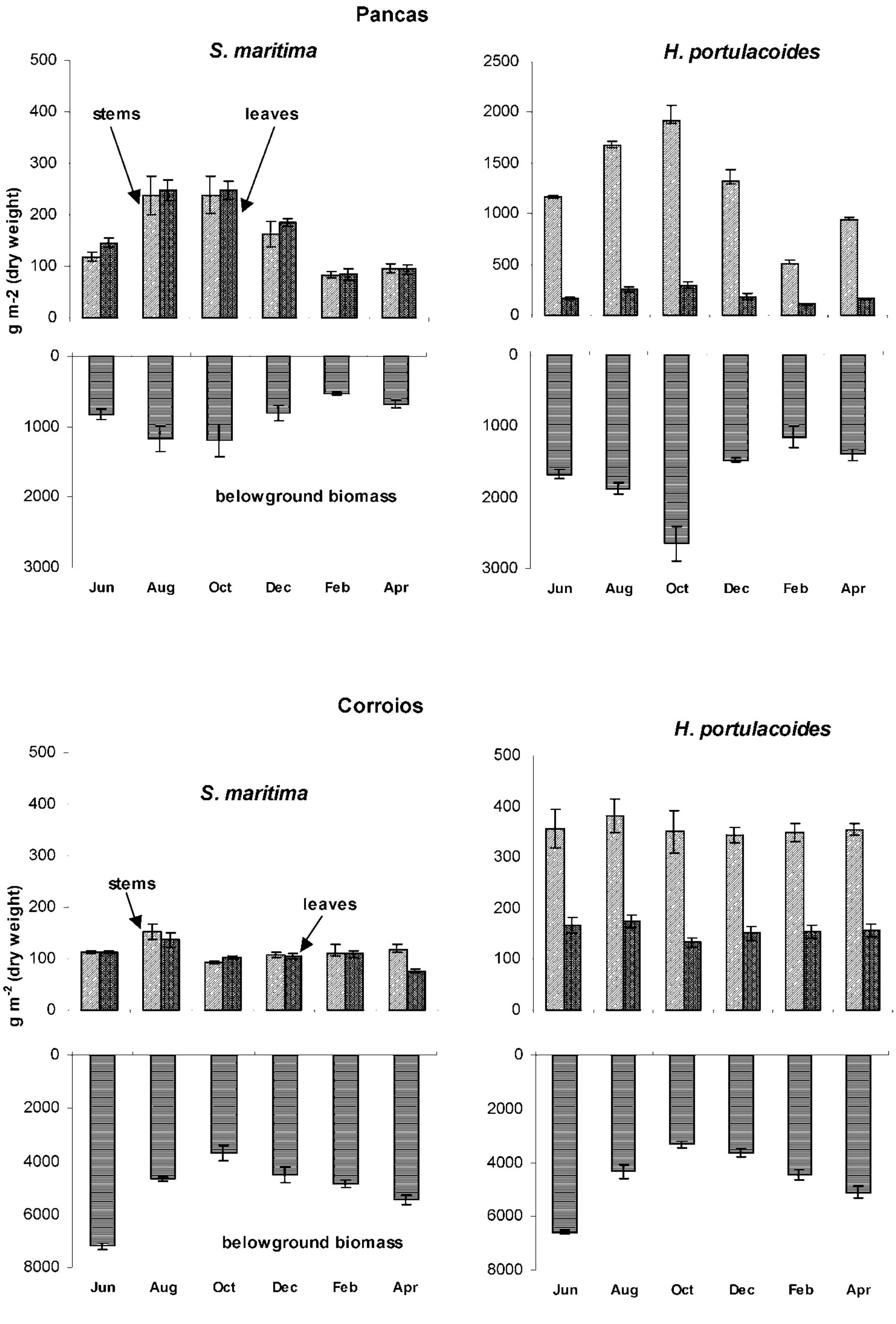

Figure 3. Seasonal variation of aboveground and belowground biomass of *Spartina maritima* and *Halimione portulacoides* in Pancas and Corroios (means ± standard deviations).

4.4. Net primary production

Aboveground and belowground net primary production (g C m^{-2}) were estimated as the difference between maximum and minimum biomass, expressed in C units, over the annual period of study:

$$NPP_{Above} = \max\,(leaf\ biomass\ \times\ [C]_l\ +\ stem\ biomass\ \times\ [C]_s)\ -\ \min\,(leaf\ biomass\ \times\ [C]_l\ +\ stem\ biomass\ \times\ [C]_s)$$

and

$$NPP_{Below} = \max\,(belowground\ biomass\ \times\ [C]_b)\ -\ \min\,(belowground\ biomass\ \times\ [C]_b)$$

where $[C]_l$, $[C]_s$ and $[C]_b$ are the concentrations of carbon in leaf, stem and belowground biomass, respectively.

At Corroios, NPP_{Below} was 22 and 32 times higher than NPP_{Above} for *S. maritima* and *H. portulacoides*, respectively (Table I). For both species, NPP_{Above} was higher and NPP_{Below} was lower at Pancas than at Corroios, such that the ratios of NPP_{Below} to NPP_{Above} were only 2 and 0.9 for *S. maritima* and *H. portulacoides*, respectively (Table I). NPP_{Above} at Pancas is comparable to values reported for several tidal marshes in Europe (Bouchard and Lefeuvre, 2000) and in North America (Mendelssohn and Morris, 2000). Total NPP (NPP_{Above} + NPP_{Below}) values for *S. maritima* and *H. portulacoides* of 358 and 1,281 g C m^{-2} a^{-1} at Pancas and 1,054 and 929 g C m^{-2} a^{-1} at Corroios, respectively, are comparable to values reported for several tidal marshes (Wolff *et al.*, 1979) and exceed the values reported for microtidal Mediterranean coastal marshes (Ibañez *et al.*, 2000).

Carbon allocated to belowground biomass at Pancas was between 48 and 65% of total C uptake, while at Corroios it exceeded 95%. These results are in line with studies of *Spartina alterniflora* in US salt marshes (Kostka *et al.*, 2002), and of other species in fen ecosystems (Scheffer and Aerts, 2000). Changes in the proportion of belowground and aboveground biomass may reflect adaptive responses of the plants in stressed environments (Groenendijk and Vink-Lieavaart, 1987). Because Corroios is an old marsh, the increased allocation of biomass to roots of *S. maritima* and *H. portulacoides* may result from intense competition for nutrients.

The ratio between primary production and maximum biomass provides an estimate of annual C turnover rate in plants (Table I). Values for Pancas were higher than for Corroios, indicating that a larger proportion of the biomass is replaced every year in that marsh. Considering the combined areas of the two studied marshes (400 + 800 = 1200 ha), we estimate that 1–10 Gg of C is taken up annually from the atmosphere.

TABLE I

Maximum and minimum content of C (g C m^{-2}) in aboveground and belowground parts of *S. maritima* and *H. portulacoides* from Pancas and Corroios and *NPP* (g C m^{-2}) estimated as the difference between maximum and minimum values. The turnover rate was calculated as the ratio between primary production (NPP_{Above} + NPP_{Below}) and maximum content of C

	Pancas	Corroios
S. maritima		
Maximum aboveground biomass (g C m^{-2})	187	114
Minimum aboveground biomass (g C m^{-2})	69	67
NPP_{Above} (g C m^{-2})	119	46
Turnover rate (%)	63	40
Maximum belowground biomass (g C m^{-2})	445	2610
Minimum belowground biomass (g C m^{-2})	207	1602
NPP_{Below} (g C m^{-2})	239	1008
Turnover rate (%)	54	39
H. portulacoides		
Maximum aboveground biomass (g C m^{-2})	922	210
Minimum aboveground biomass (g C m^{-2})	257	183
NPP_{Above} (g C m^{-2})	665	28
Turnover rate (%)	72	13
Maximum belowground biomass (g C m^{-2})	1100	2281
Minimum belowground biomass (g C m^{-2})	485	1380
NPP_{Below} (g C m^{-2})	616	901
Turnover rate (%)	56	40

4.5. Litter production

In the two marshes, litter on the sediment surface follows a seasonal pattern with higher values at the end of summer and a decrease in winter, especially evident for *H. portulacoides* litter at Pancas (Figure 4). The quantity derived from aerial parts of *H. portulacoides* greatly exceeded that from *S. maritima*. Litter production may be estimated by direct or indirect methods (Bouchard and Lefeuvre, 2000), although all procedures have limitations (Hopkinson *et al*., 1978). We choose the simplest method, viz. the difference between maximum and minimum litter pools at different times during a year (Smalley, 1959; Linthurst and Reimold, 1978). Comparing litter production with the corresponding NPP_{Above}, we calculated that only 5% of the NPP_{Above} at Corroios remained at the site versus between 4 and

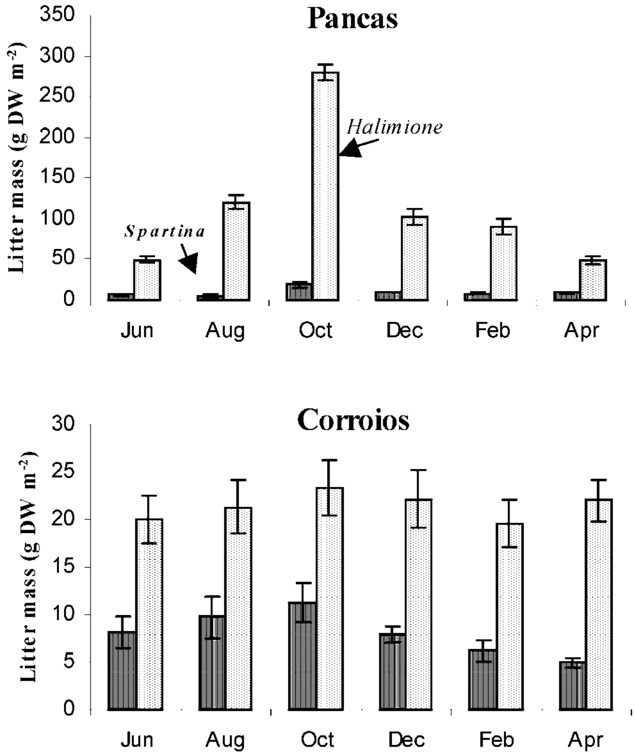

Figure 4. Changes in the litter mass on sediments colonised by *Spartina maritima* and *Halimione portulacoides* in Pancas and Corroios salt marshes (means ± standard deviations).

14% at Pancas. This means that more than 86% of the produced C was exported to the estuary. Detritus being washed over from the marsh by the daily tidal flushing explains the high export in comparison to other studies (Dame, 1982; Wolff *et al.*, 1979; Bouchard and Lefeuvre, 2000). Consequently this exported organic matter is transformed elsewhere in the estuary or coastal zone.

4.6. LITTERBAG EXPERIMENTS

At Pancas and Corroios, belowground litter decomposed rapidly in sediments (Table II). After one month, approximately 50 and 30% of the litter had decomposed at Pancas and at Corroios, respectively, corresponding to *k* values ranging from 0.024 to 0.060 d^{-1}). At each site, *k* values for *S. maritima* roots were lower than for *H. portulacoides* roots. Decomposition was slower in Corroios indicating a tendency for higher accumulation of organic matter than at Pancas. After 4 months, 50 to 70% of the belowground litter still remained in the sediment. Decomposition rates in the Tagus salt marsh sediments are faster than values reported for the salt marshes of Ebre Delta (Curcó *et al.*, 2002) and slower than values reported for

TABLE II

Decomposition rates (k values; k = ln (x_o-x_t)/t, where x_o = initial dry weight (g) and x_t = final dry weight (g) for *S. maritima* and *H. portulacoides* in Pancas and Corroios saltmarshes

	Month of collection	Incubation period, t (d)	k (d^{-1})
Pancas			
S. maritima	March	31	0.037
	April	59	0.020
	May	87	0.012
	June	118	0.011
H. portulacoides	March	31	0.060
	April	59	0.031
	May	87	0.024
	June	118	0.016
Corroios			
S. maritima	March	31	0.024
	April	63	–0.002
	May	93	0.009
	June	119	–0.001
H. portulacoides	March	31	0.045
	April	63	0.018
	May	93	0.011
	June	119	0.012

Spartina in North America marshes (Foote and Reynolds, 1997 and references therein). Carbon concentration of the decomposing belowground material ranged within the same interval (32–40%) that was observed in plant parts. These results are in agreement with other works (Valiela *et al.*, 1985; Benner *et al.*, 1991) indicating that total C concentrations in decaying litter decrease only slightly.

4.7. Carbon concentrations in sediments

The amount of organic C transferred yearly to sediments and the decomposition rate of organic matter are reflected in the vertical profiles of C concentrations in sediments. Depth variation of C differed considerably between vegetated to non-vegetated sediments (Figure 5). Carbon concentrations in non-vegetated sediments were approximately 20 mg g^{-1} at the surface and decreased gradually with depth. Vegetated sediments exhibited a subsurface C enrichment in layers of higher root biomass, with concentrations reaching 3.3 mg g^{-1} C at Pancas and 7.5 mg g^{-1} at Corroios. This pattern was observed in all surveys and indicates retention of

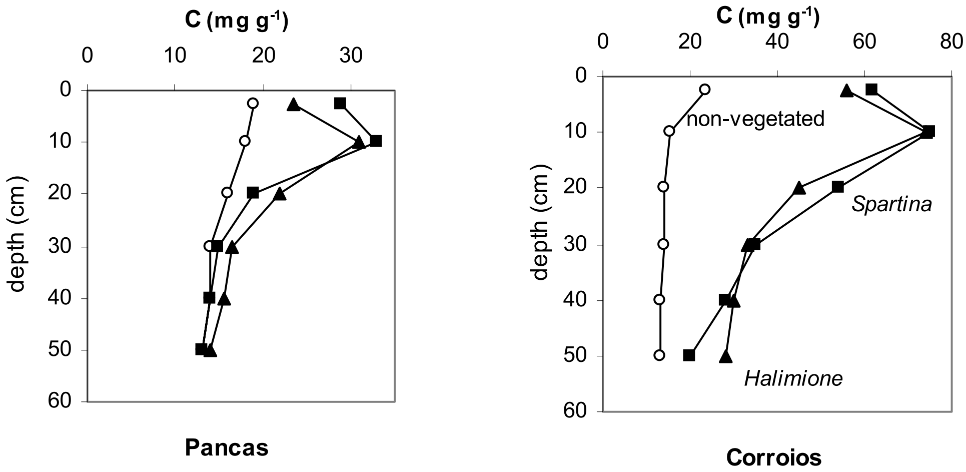

Figure 5. Vertical profiles of total C in non-vegetated sediments and sediments colonised by *Spartina maritima* and *Halimione portulacoides* in Pancas and Corroios (means ± standard deviations).

organic matter as root-derived material. Where belowground biomass was higher and degradation rate slower (Corroios) C accumulation in sediments was greater. Sediment layers of higher root biomass exhibited an increase in C concentration from October to February and a decrease in April. This seasonal variation resulted from the slow decay of belowground components of the plants in winter, along with an increasing allocation of C to rooted sediments. The decrease in C concentration in summer probably results from faster oxidation of particulate organic matter and the escape of dissolved organic constituents.

4.8. Estimation of carbon stored in salt marsh sediments

On the basis of the difference in the quantity of carbon in the top 50 cm of the sediment profile of vegetated and non-vegetated sites, one may estimate that 9 to 10 kg C m^{-2} is stored in Pancas and 21–22 kg C m^{-2} in Corroios due to plant activity. Assuming a sedimentation rate for both marshes of 0.8 cm y^{-1} (Vale, 1990; Caçador *et al.*, 1996), the 50 cm depth corresponds to 62.5 yr. The mean annual amounts of carbon incorporated in the sediments are: 0.15 kg C m^{-2} y^{-1} (9.5 kg C m^{-2} divided by 62.5 yr) in Pancas, and 0.34 kg C m^{-2} y^{-1} (21.5 kg C m^{-2}/62.5 yr) in Corroios. These quantities are comparable to the reported values of carbon content retained in the upper sediments of coastal marshes in Florida (Choi *et al*, 2001), and exceeded largely the sequestration rate of peatlands (Roulet, 2000). Overall, C retention in sediments differed between the two marshes, with greater accumulation in the older marsh (Corroios), attributable to higher NPP_{Below} along with slower root decomposition.

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