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Stock and losses of trace metals from salt marsh plants

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ABSTRACT

Pools of Zn, Cu, Cd and Co in leaf, stem and root tissues of *Sarcocornia fruticosa*, *S. perennis*, *Halimione portulacoides* and *Spartina maritima* were analysed for a Tagus estuary (Portugal) salt marsh. Pools of Cu and Cd in the salt marsh were higher in spring/summer indicating a net uptake of these metals during the growing season. Standing stocks of Zn, Cu, Cd and Co in leaf and stem biomass of *S. fruticosa*, *S. perennis* and *H. portulacoides* showed a strong seasonal variation, with higher values recorded in autumn. The metal-containing leaves and stems that shed in the autumn become metal-containing detritus. The amount of this material washed out from the total marsh area (200 ha) was estimated as 68 kg of Zn, 8.2 kg of Cu, 13 kg of Co and 0.35 kg of Cd. The high tidal amplitude, a branched system of channels and semidiurnal tidal cycle greatly favour the export of the organic detritus to adjoining marsh area.

Keywords: halophytes, metals, detritus, salt-marshes, metal-containing litter

1. Introduction

Salt marsh plants are widely recognized to influence the transfer of metals between the aquatic compartments (Rozema et al., 1985; Crowder, 1991). These metals may be immobilized and stored in belowground biomass, sediment or in aboveground tissues (Jacob and Otte, 2003; Weis and Weis, 2004). Several plant species have the remarkable ability to concentrate metals in their tissues and are therefore being used for phytoremediation purposes (Meagher, 2000; Williams, 2002). Plants included in that category have been widely studied and their capacity to accumulate metals in roots is well documented (Almeida et al., 2004; Cundy et al., 2005; Deng et al., 2006). Since most salt marsh plants show low translocation of metals to their aboveground tissues, they have been considered as a long-term sink (McFarlane et al., 2003; Fitzgerald et al., 2003). Nevertheless, some studies on natural marsh plants have shown that a small portion of the accumulated metals may be released back to the aquatic environment through salt glands in living leaves, according to the physiological and morphological properties of plants (Burke et al., 2000; Weis et al., 2002). Furthermore, during the seasonal life cycle of salt marsh plants aboveground plant portions die and fall to the sediment becoming organic-rich detritus (Giblin et al., 1980; Valiela et al., 1985; Weis and Weis, 2004). This detritus can be retained and/or exported out from the marsh according to the flooding regime, elevation gradient, marsh topography and wind (Halupa and Howes, 2004; Neckless and Neill, 2004). Flooding and wind increase the rate of mass loss from aboveground litter (Dame, 1982; Bouchard et al., 1998; Bouchard and Lefevre, 2000). Otherwise, detritus retention increases with the elevation gradient from low marsh (frequently inundated) to higher marsh area (Mitsch and Gosselink, 2000). The branched system of channels across that gradient also promotes the transfer of litter between marsh zones and the export to adjacent areas (Caçador et al., 2004). A number of studies have focused on *in situ* plant litter decay using nylon mesh litter bags (e.g. Valiela et al., 1985; Halupa and Howes, 2004). The decomposition of litter is strongly regulated by climate conditions, litter quality, sediment properties, bacterial and fungal populations (Valiela et al., 1985; Graça et al., 2000). Since metals in aboveground plant parts are likely to persist when tissues die and fall off, the leaching or retention of metals in decaying litter over time has been extensively investigated (Banus et al., 1974; Dorgelo et al., 1995; Zawislanski et al., 2001; Du Laing et al., 2006). Otherwise, metal-containing detritus can also be transported to adjacent marsh areas. The large majority of salt marsh ecosystems

exported energy-rich substances (reduced nitrogen compounds, dissolved and particulate organic matter) to deeper waters (Mitsch and Gosselink, 2000; Valiela et al., 2004). Banus et al. (1974) highlight that substantial amounts of Pb associated with *S. alterniflora* litter may be removed by tides from the marsh surfaces. However, where metal-containing fertilizers were supplied to the marsh a minor export of Pb, Zn and Cd associated with litter was obtained (Banus et al., 1975). Consequently, there is little agreement on the transfer of trace metals to marine environment across the detritus generated by salt marsh plants. The fate of detritus is crucial to the understanding of the metals budgets at the estuarine ecosystem level.

The aim of this work was to assess the budget of selected metals (Zn, Cu, Cd and Co) exported from a moderately contaminated salt marsh during a one-year growing season. While Zn and Cu are essential metals, and no metabolic functions are known for Cd, less evidence exists on the beneficial effects of Co. The partition of Zn, Cu, Cd and Co concentrations between aboveground plant parts and belowground biomass are also studied. We focused our study on the most common plants of south European salt marshes: *Sarcocornia fruticosa*, *Sarcocornia perennis*, *Halimione portulacoides* and *Spartina maritima*. The standing stock of metals was estimated for plants as a whole and also for the individual plant parts.

2. Materials and methods

2.1 Study area

The Tagus estuary is one of the largest on the Atlantic coast of Europe and subjected to high human pressure with ca. 4 million people living around it. Around 40% of the estuary is composed of intertidal mudflats and its southern and eastern shores contain extensive areas of salt marshes colonised mainly by *Sarcocornia fruticosa* (Caryophyllales, Chenopodiaceae), *Sarcocornia perennis* (Caryophyllales, Chenopodiaceae), *Halimione portulacoides* (Caryophyllales, Chenopodiaceae) and *Spartina maritima* (Poales, Poaceae). One of the marshes (Rosário) located in the southern shoreline of the Tagus estuary (Figure 1) covers an area of 200 ha (Crespo, 1993) and is characterized by a typical zonation with homogeneous stands of *S. maritima* as a pioneer species, colonizing bare mud in the lower marsh area. Across the elevation (20-50 cm) transect pure stands of *H. portulacoides* follow *S. maritima*, while *S. fruticosa* and *S. perennis* are found in the upper salt marsh. This marsh is fully

84 inundated twice a day by tidal action (2-4m of tidal amplitude) through a highly
85 branched system of channels that cross the elevation transect. These channels have 0.5
86 to 1.5 m depth promoting the inundation of the higher marsh even at low amplitude
87 tides. During the ebb tide water is drained into the channels due to the water table
88 difference. The Rosário marsh is located in the proximity of a heavy industrialised area
89 that includes several chemical plants. During the past four decades these industries
90 discharged effluents enriched in several contaminants directly into the estuary.
91 According to Vale (1990) both the semi-diurnal tidal inundation and the proximity to
92 these pollution sources contribute to metal inputs to the Rosário salt marsh. Pore water
93 depth profiles obtained from intertidal sediments will give erroneous information of the
94 metals budgets introduced into the marsh due to post-depositional early diagenetic
95 reactions (Shaw et al., 1990) associated with tidal flushing of pore water solutes
96 (Caetano et al., 1995). Thus, in this particular situation it is inaccurate to estimate the
97 amount of metals flushed to the estuary and establish the pools of metals
98 introduced/retained in the marsh. However, available data on depth profiles of Zn, Cu,
99 Cd and Pb in non-vegetated sediments showed that concentrations in the upper 10 cm
100 layers are up two 10 times higher than pre-industrial levels (Caçador et al., 1993; 1996;
101 Caetano et al., 2007).

102

103 **2.2 Plant material and sampling**

104 Pure stands of *S. fruticosa*, *S. perennis*, *H. portulacoides* and *S. maritima* were sampled
105 bimonthly at Rosário salt marsh at low tide across a growing season, from October 2001
106 to June 2002. The aboveground biomass was assessed for each species by clipping out
107 five squares of 0.3x0.3 m, and storing in plastic bags. In the laboratory plant parts were
108 washed with Milli-Q water (18.2 MΩ.cm) to remove dust and sediment, and separated
109 into photosynthetic and non-photosynthetic tissues. *Sarcocornia fruticosa* and *S.*
110 *perennis* do not have a true shoot system with leaves and stems. From these plants the
111 swollen photosynthetic stems (referred to as “leaves” hereafter) were separated from the
112 dry perennial shoots (referred to as “stems” hereafter). The similar procedure was
113 followed for *S. maritima* where the tillers were divided in leaves and in non-
114 photosynthetic tissues (referred to as “stems” hereafter). Otherwise, the shoot system of
115 *H. portulacoides* allows separating leaves from stems. For all species, no flowering
116 plants were sampled. In each 0.3x0.3 m square all the shedding parts of salt marsh
117 plants (hereafter referred as detritus) found on sediment surface were collected with

118 tweezers and transported to the laboratory in plastic bags. This detritus material
 119 corresponds to the dead plant portions retained within the salt marsh. Samples were
 120 washed with Milli-Q water and oven dried at 60 °C until constant weight. Five sediment
 121 cores were taken at each study site using a core tube, 7 cm in diameter and 100 cm long.
 122 Only the upper layer in each core (0-25 cm) was used since it contains the majority of
 123 belowground components (Gross et al., 1991). The belowground biomass of this layer
 124 was sorted out from the cores and carefully separated from the sediment under a flux of
 125 Milli-Q water using a sieve with 212 µm mesh size to remove any adhering particulate
 126 matter. Plant parts were oven dried at 60 °C and powdered in a grinding ball mill (Glen
 127 CrestomMM2000) (Gross et al., 1991). Sediment samples were oven dried at 60 °C until
 128 constant weight, cleaned of roots with tweezers, passed through a 0.25 mm mesh,
 129 homogenised and ground with an agate mortar (Caçador et al., 1999).

130

131 **2.3 Analytical Methods**

132 Redox potential (Eh) and pH of the sediment between the roots were measured *in situ* in
 133 all sampling periods except October 2001. Five replicate measurements were obtained
 134 between 10 and 15-cm depth. The pH was measured using a combined glass electrode
 135 with one Ag/AgCl reference electrode while for Eh measurements a platinum electrode
 136 with a calomel reference electrode was used. Values of redox potential were corrected
 137 for the reference potential of H₂. Pore water was extracted by centrifugation (3000 rpm,
 138 10 min) to measure salinity using a refractometer (Atago, S/Mill-E). Particle size (sand,
 139 silt, or clay) in each sediment sample was determined by the pipette method (Gee and
 140 Bauder, 1986). The organic matter content of the sediment was determined in dried
 141 samples by loss of ignition (LOI) at 600 °C for 2 hours. Sediment samples (≈100 mg)
 142 were digested with 10 mL of HNO₃/HCl (3:1 v/v) at 130 °C. This procedure was
 143 repeated twice, as described by Otte (1991). Concentrations of Zn were determined by
 144 flame atomic absorption spectrometry (FAAS) with an air-acetylene flame while levels
 145 of Cu, Co and Cd were determined by graphite furnace atomic absorption spectrometry
 146 (GFAAS). Plant samples and detritus (≈200 mg) were digested with 10 mL of
 147 HNO₃/HClO₄ (7:1 v/v) at 130 °C according to the method described by Otte (1991).
 148 Levels of Zn, Cu, Co and Cd were determined by GFAAS and detection limits were
 149 0.01, 0.10, 0.05 and 0.05 µg g⁻¹, respectively, for all the analytical procedures used.
 150 International certified reference materials of sewage sludge (CRM 145 and CRM 146)
 151 and plant material (BCR 62- *Olea europaea*) were used to ensure accuracy of our

152 procedure. For all metals investigated, obtained values were consistently within the
153 ranges of certified values ($p < 0.05$).

154 The area occupied by each plant species in Rosário salt marsh was estimated on the
155 basis of patches from aerial photographs scaling 1:2000. *Halimione portulacoides*
156 colonized 132 ha, the equivalent to 66 % of the total salt marsh area (200 ha), *S.*
157 *maritima* and *S. fruticosa* occupied 37.6 and 28.2 ha, respectively and *S. perennis* was
158 found only in small patches within the marsh.

159

160 **2.4 Data analysis**

161 Statistical analysis was performed using a one-way analysis of variance to detect
162 differences between metal concentrations, plant type and dates. The same test was used
163 to look for differences in the sediment characteristics. One-way ANOVA and Newman-
164 Keuls multiple comparison tests were used to detect differences between standing
165 stocks of metals. To obtain homogeneity of variance, data were log-transformed (Sokal
166 and Rohlf, 1981).

167

168 **2.5 Estimation of aboveground plant detritus**

169 The difference between the maximum and the minimum metal standing stocks for
170 leaves and stems over the annual period of study, allows the estimation of aboveground
171 net metal production of detritus (NMePD; mol m^{-2}) for each plant species (Caçador et
172 al., 2004):

173

$$174 \quad \text{NMePD}_i = (\max \text{Me}_{\text{A-stk}} - \min \text{Me}_{\text{A-stk}})_i \quad (1)$$

175

176 where i is the plant species and $\text{Me}_{\text{A-stk}}$ (mol m^{-2}) is the aboveground metal standing
177 stock for that species. By using the surface area colonized by each plant species in the
178 Rosário marsh, the amount of metal in *aboveground plant detritus* produced in the total
179 marsh area (Q_{Me} ; kg) may be estimated by:

180

$$181 \quad Q_{\text{Me}} = \sum \text{NMePD}_i A_i \quad (2)$$

182

183 where i is the plant species and A is the area colonized by each plant species (m^2).

184

3. Results and Discussion

3.1 Sediment characteristics

Sediments from the upper layer (0-25cm) were formed mainly of silt (60 ± 0.4 %) and clays (38 ± 0.4 %) in all plots studied and at all sampling times. This suggests that these plants grow in sediment with similar grain size and retained similar suspended matter (Salgueiro and Caçador, 2007). Pore water salinity varied within the salt marsh depending on vegetation species. Pore waters from sediments colonised by high marsh plants (*S. fruticosa* and *S. perennis*) contained more salts (salinity = 42 ± 1.0 and 41 ± 1.7) than those from the lower marsh (*H. portulacoides*: salinity = 36 ± 0.5 and *S. maritima*: salinity = 31 ± 0.2). This difference was observed all over the seasonal survey, although salinity was lower in spring. A seasonal variation of pH was also observed, with lower values in the winter (Table 1). In a previous study, Sundby et al. (2003) showed that the release of oxygen by roots was lower in winter, changing the state of sediment to reduced conditions. Therefore, the reactions involving the $\text{Fe}^{2+}/\text{Fe}^{3+}$, $\text{Mn}^{2+}/\text{Mn}^{4+}$ and $\text{S}^{2-}/\text{SO}_4^{2-}$ pairs prevail in the rhizosphere during the winter. As oxygen reduces in the rhizosphere the decrease of pH appears to be related to the oxidation of iron sulphide compounds by Fe(III) organic complexes (Luther et al., 1996). Since no statistically significant differences of pH were found between plant species, early diagenetic reactions had similar consequences on sediment acidity and metal availability. The redox potential (Table 1) varied irregularly between plants and throughout the year with no seasonal pattern. These results are consistent with previous work done by Caçador et al. (1996) at several salt marshes in the Tagus estuary, showing that pH and Eh variations have no statistical consistency. No seasonal differences were found also for organic matter content. However, sediment colonized by *S. maritima* contained less organic matter (13 ± 1.0 %) than the sediments from areas colonised by the other plant species (*S. fruticosa* = 21 ± 1.4 %; *S. perennis* = 20 ± 1.6 %; and *H. portulacoides* = 20 ± 1.5 %).

Mean concentrations of Zn, Cu, Co and Cd found in sediment between roots of the four plant species included in this study are shown in Table 2. Levels of Cu, Co and Cd were relatively constant during the sampling period as can be inferred by the low standard deviations. Although an enhanced variability was found for Zn concentrations, the standard deviation never exceed 10 % of the mean value. Moreover, no statistically significant differences were found among the metal (Zn, Cu, Co and Cd) concentrations

in sediments coming from areas colonised by the four plant species included in our study. Lack of seasonal variation in the metal concentrations may be attributed to higher non-reactive fraction of these metals in the solids (Caçador et al., 1996). However, it is possible that variations within the sediment layer may have occurred, but this must have been on a scale of a few centimetres only and could not be resolved by our sampling methods.

3.2 Plant biomass

From October 2001 to February 2002, the plant biomass overall was larger in plots of *S. fruticosa*, while areas with *S. maritima* had the lowest biomass values recorded from all the plant species included in this study (Table 3). In April and June total biomass was not statistically different for all the studied species. Root biomass may account for up to 80 % (d.w.) of the total biomass. An exception was recorded in October for *S. fruticosa*, when the aboveground biomass accounted for 50 % of the total biomass. Presumably because dead and live roots are not easily discerned, rather small seasonal variation were observed in the biomass of roots, although higher values were found in the summer for *S. maritima* and in spring for the other species. Results from aboveground biomass showed statistically significant differences between plant species ($p < 0.05$) and also between leaf and stem biomass ($p < 0.05$). Although both *Sarcocornia* species had similar morphology, leaf and stem biomasses of *S. fruticosa* were up to one order of magnitude higher than those calculated for *S. perennis*. The same difference was also found by comparing aboveground plant parts biomass of *S. fruticosa* with those of *S. maritima* and *H. portulacoides* (Table 3). Furthermore, a clear seasonal variation was observed for leaf and stem biomass in all four species. Higher biomass values were observed in October, followed by a logarithmic decrease. However, the decline of biomass was more sharp for *S. fruticosa* (leaf: from 3516 ± 341 to 50 ± 19 g m⁻² and stem: from 1919 ± 195 to 110 ± 29 g m⁻²) than for *S. perennis* (leaf: from 167 ± 39 to 37 ± 5 g m⁻² and stem: from 425 ± 40 to 43 ± 17 g m⁻²) and *H. portulacoides* (leaf: from 212 ± 57 to 46 ± 3 g m⁻² and stem: from 733 ± 122 to 180 ± 49 g m⁻²). Leaf biomass in the latter species was most reduced in December after some senescent leaves had fallen from the standing stems. A different pattern was observed for *S. maritima* since aboveground biomass was lower in December but increased afterwards. Differences in the phenology of plant species attest to specific patterns of carbon allocation to the aboveground tissues, with

S. perennis, *S. fruticosa*, and *H. portulacoides* promoting early leaf production when compared to *S. maritima* (Windham et al., 2003).

3.3 Metal concentrations in plant parts

Concentrations of Zn, Cu, Co and Cd in plant tissues of *S. fruticosa*, *S. perennis*, *H. portulacoides* and *S. maritima* are presented in Table 4. Seasonal and tissue allocation patterns of Zn, Cu, and Cd differed from Co in the four plant species studied under field conditions. For all metals except Co, the concentrations in roots were, in general, up to one order of magnitude higher than levels found in the aboveground tissues. The partitioning indicates that for *S. fruticosa*, *S. perennis*, *H. portulacoides* and *S. maritima* the dominant uptake of metals was via the root system with only small amounts being translocated to the aerial plant parts (Fitzgerald et al., 2003; MacFarlane et al., 2003; Weis and Weis, 2004). Metal concentrations in leaves showed no statistically significant differences when compared to equivalent levels in stems within the same plant or between plant species. The similarity of metal accumulation in aboveground plant parts of *S. maritima* and of both *Sarcocornia* species may result from the undistinguished shoot system of these plants. Moreover, we may suggest that photosynthetic tissues play a minor role on the storage of metals in aboveground plant parts. No seasonal pattern was observed for the concentration of essential elements, Zn and Cu in the aboveground parts of the four species. However, concentrations of Cd in leaf and stem biomass of the same plant species showed a distinct seasonal variation, with increased accumulation in February. The accumulation of Co in the tissues of the studied plants showed a distinctive pattern, quite different from that observed for the remaining elements. Up to 50 % of the total metal pool was retained in the aboveground parts. While for Zn, Cu and Cd the roots act as a barrier for upward translocation this retention was not observed for Co. Detoxification of those metals by plants are associated with the phytochelatins in plant cells (Zenk, 1996). However, Co does not activate the phytochelatin synthase (Oven et al., 2002) suggesting that this metal may induce other detoxification mechanisms or play a physiological role similar to that described for algae. The coenzyme cobalamin has cobalt as component and is essential for *Euglena gracilis* growth, being located in several subcellular compartments, including the tilakoids of the chloroplasts (Marschner, 1995).

3.4 Metal stocks in plants

Our data of metal concentrations in plant parts combined with biomass allow us to compare the standing stocks of given elements in whole plant tissues and subsets, or to compare between plant species and for different seasons. Considering the standing stocks in the whole plant structure for all species in our study (Figure 2), metal pools were generally lower in *S. maritima* as a consequence of comparatively smaller biomass values. Standing stocks of Cu and Cd were higher for all plants in spring/summer ($p<0.05$) indicating a net uptake of these metals in the growing season. When standing stocks of metals were analysed in leaves and stems two different patterns were observed (Figure 3). In the cases of *S. perennis*, *H. portulacoides* and *S. maritima*, stems contained comparatively higher aboveground standing stocks of Zn, Cu, Co and Cd ($p<0.05$) while for *S. fruticosa* leaves emerge as the major contributor ($p<0.05$). These different patterns observed for standing stocks are explained by the higher aboveground biomass of *S. fruticosa* (Table 3). There were also differences in the seasonality of aboveground metal standing stocks. While *S. perennis*, *S. fruticosa* and *H. portulacoides* showed a strong seasonal variation with higher values occurring in the autumn ($p<0.05$; Figure 3), the standing stocks of metals in *S. maritima* were higher in February ($p<0.05$; Figure 3). The early leaf production of *S. maritima* seems to be coupled to an increased transfer of some metals into the aboveground tissues. Belowground standing stocks in all plant species showed small irregular variability throughout the seasonal survey (not shown), but values were considerably higher than aboveground. This result is consistent with other investigations elsewhere showing difficulty in observing well-defined seasonal patterns for metal concentrations in roots (Gleason et al., 1979; Heller and Weber, 1998; Windham et al., 2003).

3.5 Metal containing detritus

Metals in aboveground tissues are likely to remain when these tissues die and turn into detritus. The seasonal variation of the metal standing stocks in *S. perennis*, *S. fruticosa* and *H. portulacoides* was mainly associated with aboveground biomass production. Therefore the *aboveground plant detritus* – *QMe* may be estimated for a growing season using equations 1 and 2. Results show that plants in our study area (200 ha) generate organic detritus containing 96 kg of Zn, 13 kg of Cu, 18 kg of Co and 0.51 kg of Cd during one growing season. However, the pool of organic material derived from aerial plant parts greatly exceeds the litter pool found in the sediment surface. The detritus on the sediment surface follows a seasonal pattern with higher values at the end

of the growing season (*S. fruticosa* – 1020 g m⁻²; *S. perennis* – 212 g m⁻²; *H. portulacoides* – 134 g m⁻²; *S. maritima* – 45 g m⁻²) and a decrease in winter (*S. fruticosa* – 146 g m⁻²; *S. perennis* – 25 g m⁻²; *H. portulacoides* – 62 g m⁻²; *S. maritima* – 21 g m⁻²). This is in line with the findings of Caçador et al. (2004) where more than 86% of the produced carbon from aboveground plant parts was exported from two different salt marshes in the Tagus estuary. The hydrological conditions of Rosário salt marsh (branched system of channels and semidiurnal tidal cycle) greatly favour the transport of organic detritus to adjoining marsh areas. The litter production may be estimated by different methods (Bouchard and Lefeuvre, 2000), although all have limitations (Hopkison et al., 1978). Thus, we chose the simple method, viz. the difference between maximum and minimum litter pools (Caçador et al., 2004). By comparing the aboveground biomass production (Table 3) with the litter pool we calculate that only 5% (*S. maritima*), 21 % (*H. portulacoides*) 17 % (*S. perennis*) and 46 % (*S. fruticosa*) of the detritus produced by aboveground plant parts remain at the site. By apply these proportions to the pool of the metal-containing detritus (Q_{Me}) we found that most of the metal containing detritus was flushed out from the marsh. During one growing season 68 kg of Zn, 8.2 kg of Cu, 13 kg of Co and 0.35 kg of Cd was exported to areas adjoining the Rosário salt marsh. This metal containing detritus may act as a source for these metals before being buried in the sediments since they are easily degraded by decomposers and weathering (Weis and Weis, 2004; Du Laing et al., 2006).

4. Conclusions

There is an important export of trace metals associated with marsh detritus to the estuary, even considering that all plant species included in this study have much higher belowground than aboveground biomass. The export route involves uptake of metals from sediment by roots, translocation to the aerial parts of plants, and return to the soil after senescence and fall of aerial plant parts. The major fraction of the metal-containing detritus is not retained within the marsh. Therefore, when assessing remediation techniques in a contaminated marsh we must take into account the balance between retention and export of metals from the marsh, the biology of the plant species involved and the marsh ecology.

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356

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Figure Captions

Figure 1 – Location of the Tagus estuary and Rosário salt marsh.

Figure 2 – Whole plant standing stock of each metal. Values presented as mean $\pm$ SD.

Figure 3 – Standing stocks of Zn, Cu Co and Cd for aboveground tissues of *S. fruticosa*,
S. perennis, *H. portulacoides* and *S. maritima*. Values presented as mean $\pm$ SD.
Dissimilar letters denote significant differences ($p<0.05$).

Figure 1

Figure 2

Figure 3

Table 1 - Average ($n=5$) pH and redox potential (Eh, mV) in rooting sediment of *S. fruticosa*, *S. perennis*, *H. portulacoides*, and *S. maritima*.

		pH	Eh (mV)
<i>Sarcocornia fruticosa</i>	Dec.	6.9	17±11
	Feb.	7.3±0.1	-6±10
	Apr.	7.4±0.1	-25±9
	Jun.	7.9	34±13
<i>Sarcocornia perennis</i>	Dec.	6.3±0.3	43±10
	Feb.	7.7	34±14
	Apr.	7.5±0.1	73±7
	Jun.	7.9	125±19
<i>Halimione portulacoides</i>	Dec.	7.0	44±10
	Feb.	7.9	67±8
	Apr.	7.7	84±7
	Jun.	8.0	0±10
<i>Spartina maritima</i>	Dec.	6.6±0.1	91±7
	Feb.	7.8	98±7
	Apr.	7.7	93±8
	Jun.	7.8	90±12

Table 1

Table 2 – Average concentrations ($n=5$) and standard deviations of Zn, Cu, Co and Cd ($\mu\text{mol g}^{-1}$) in rooting sediment of *S. fruticosa*, *S. perennis*, *H. portulacoides*, and *S. maritima* all over the seasonal survey.

	Species	Sediment
Zn ($\mu\text{mol g}^{-1}$)	<i>S. fruticosa</i>	3.6 $\pm$ 0.2
	<i>S. perennis</i>	5.4 $\pm$ 0.5
	<i>H. portulacoides</i>	4.5 $\pm$ 0.2
	<i>S. marítima</i>	4.0 $\pm$ 0.4
Cu ($\mu\text{mol g}^{-1}$)	<i>S. fruticosa</i>	0.62 $\pm$ 0.03
	<i>S. perennis</i>	0.63 $\pm$ 0.02
	<i>H. portulacoides</i>	0.63 $\pm$ 0.03
	<i>S. marítima</i>	0.72 $\pm$ 0.02
Co ($\mu\text{mol g}^{-1}$)	<i>S. fruticosa</i>	0.48 $\pm$ 0.01
	<i>S. perennis</i>	0.57 $\pm$ 0.02
	<i>H. portulacoides</i>	0.57 $\pm$ 0.02
	<i>S. marítima</i>	0.70 $\pm$ 0.01
Cd ($\mu\text{mol g}^{-1}$)	<i>S. fruticosa</i>	0.029 $\pm$ 0.001
	<i>S. perennis</i>	0.027 $\pm$ 0.001
	<i>H. portulacoides</i>	0.026 $\pm$ 0.0003
	<i>S. marítima</i>	0.028 $\pm$ 0.0002

Table 2

Table 3 – Average ($n=5$) dry weight biomass (g m^{-2}) and standard deviations for total and individual plant tissues of *S. fruticosa*, *S. perennis*, *H. portulacoides*, and *S. maritima*.

		Leaf biomass	Stem biomass	Root biomass (g m^{-2})	Total biomass
<i>Sarcocornia fruticosa</i>	Oct.	3516±341	1919±195	4366±225	9010±1753
	Dec.	630±151	704±215	4574±176	6023±277
	Feb.	50±19	212±67	7176±366	7287±219
	Apr.	67±20	123±50	5354±466	5172±96
	Jun.	82±16	110±29	4252±163	4444±178
<i>Sarcocornia perennis</i>	Oct.	167±39	425±40	3900±329	4594±194
	Dec.	59±18	148±56	4172±429	4179±209
	Feb.	37±5	85±2	4550±206	4725±195
	Apr.	43±6	43±17	4860±94	4946±103
	Jun.	64±12	82±17	4090 146	4287±105
<i>Halimione portulacoides</i>	Oct.	211±57	733±122	4128±111	5072±264
	Dec.	65±16	320±50	3576±283	4183±159
	Feb.	56±11	189±51	4476±276	4623±110
	Apr.	46±3	180±49	4416±75	4642±61
	Jun.	60±16	188±31	4386±227	4643±15
<i>Spartina maritima</i>	Oct.	154±56	254±62	2556±596	2998±162
	Dec.	61±16	148±29	1510±62	1751±21
	Feb.	127±30	363±77	3678±492	4360±353
	Apr.	104±18	271±53	3386±620	3730±127
	Jun.	79±20	181±80	4268±360	4379±191

Table 3

Table 4 - Metal concentrations for individual plant tissues of *S. fruticosa*, *S. perennis*, *H. portulacoides*, and *S. maritima*.

		leaf				stem				root			
		Zn	Cu	Co	Cd	Zn	Cu	Co	Cd	Zn	Cu	Co	Cd
		(μmol.g ⁻¹)				(μmol.g ⁻¹)				(μmol.g ⁻¹)			
<i>Sarcocornia fruticosa</i>	Oct.	0.36±0.05	0.071±0.011	0.051±0.008	0.00089±0.0001	0.45±0.14	0.076±0.017	0.097±0.008	0.0021±0.0001	8.1±3.9	4.8±0.87	0.26±0.06	0.087±0.024
	Dec.	0.83±0.20	0.089±0.008	0.085±0.004	0.0014±0.0001	1.0±0.3	0.11±0.01	0.14±0.01	0.0023±0.0001	10±1	4.0±0.54	0.29±0.05	0.048±0.014
	Feb.	0.12±0.03	0.095±0.013	0.15±0.01	0.0040±0.0004	0.21±0.07	0.13±0.03	0.14±0.01	0.0045±0.0007	8.7±3.0	3.8±0.38	0.31±0.06	0.049±0.008
	Apr.	0.31±0.05	0.067±0.014	0.16±0.01	0.0014±0.0002	0.24±0.04	0.057±0.011	0.23±0.05	0.0023±0.0003	26±3	4.5±0.94	0.29±0.08	0.038±0.007
	Jun.	0.22±0.05	0.14±0.02	0.11±0.01	0.0017±0.0003	0.23±0.05	0.14±0.02	0.096±0.007	--	23±6	5.7±0.64	0.20±0.05	0.091±0.020
<i>Sarcocornia perennis</i>	Oct.	0.59±0.11	0.12±0.01	0.069±0.013	0.0013±0.0002	0.74±0.16	0.12±0.01	0.14±0.02	0.0022±0.0003	8.2±2.7	6.8±1.9	0.19±0.04	0.065±0.007
	Dec.	0.90±0.20	0.11±0.03	0.095±0.003	0.0012±0.0003	1.2±0.3	0.15±0.04	0.092±0.017	0.0016±0.0001	5.6±1.3	3.6±2.0	0.37±0.09	0.069±0.012
	Feb.	0.34±0.11	0.18±0.05	0.083±0.023	0.0047±0.0008	0.29±0.04	0.16±0.01	0.14±0.01	0.0045±0.0009	5.8±2.7	5.1±0.21	0.29±0.11	0.037±0.012
	Apr.	0.47±0.05	0.13±0.01	0.13±0.06	0.0017±0.0002	0.29±0.06	0.077±0.017	0.18±0.04	0.0026±0.0006	9.8±2.9	5.1±0.27	0.44±0.12	0.059±0.011
	Jun.	0.22±0.07	0.15±0.06	0.15±0.02	0.0022±0.0003	0.17±0.04	0.14±0.02	0.13±0.02	--	9.5±1.6	6.8±0.77	0.22±0.03	0.090±0.010
<i>Halimione portulacoides</i>	Oct.	0.77±0.19	0.083±0.017	0.14±0.01	0.00087±0.0002	0.77±0.23	0.046±0.009	0.14±0.01	0.0020±0.0003	9.5±3.4	4.4±1.5	0.27±0.08	0.074±0.007
	Dec.	0.62±0.16	0.080±0.019	0.10±0.01	0.0008±0.0001	0.79±0.19	0.063±0.018	0.10±0.02	0.0018±0.0002	8.5±2.6	4.8±1.4	0.28±0.06	0.042±0.001
	Feb.	0.31±0.09	0.11±0.02	0.11±0.01	0.0049±0.0002	0.50±0.09	0.13±0.03	0.16±0.03	0.0050±0.0006	8.2±1.5	4.8±1.3	0.25±0.09	0.075±0.016
	Apr.	0.71±0.26	0.11±0.03	0.21±0.02	0.0023±0.0005	0.71±0.15	0.088±0.014	0.23±0.03	0.0029±0.0006	12±2	6.7±0.7	0.21±0.05	0.066±0.092
	Jun.	0.53±0.08	0.16±0.02	0.067±0.004	0.0017±0.0003	0.71±0.24	0.14±0.03	0.14±0.03	0.0010±0.0002	17±1	7.5±1.0	0.28±0.05	0.082±0.017
<i>Spartina maritima</i>	Oct.	0.78±0.21	0.051±0.008	0.11±0.02	0.0010±0.0002	0.48±0.07	0.066±0.008	0.079±0.019	0.0013±0.0004	2.4±0.4	2.0±0.2	0.37±0.04	0.15±0.02
	Dec.	0.71±0.15	0.075±0.008	0.091±0.006	0.00094±0.0001	0.68±0.10	0.12±0.03	0.063±0.014	0.0010±0.0002	6.5±1.6	1.3±0.3	0.41±0.06	0.045±0.017
	Feb.	0.48±0.15	0.12±0.01	0.13±0.01	0.00051±0.0005	0.27±0.02	0.12±0.02	0.16±0.01	0.0043±0.0002	7.2±1.8	1.4±0.3	0.39±0.05	0.041±0.009
	Apr.	1.00±0.19	0.091±0.009	0.35±0.03	0.0020±0.0003	0.79±0.04	0.10±0.01	0.23±0.01	0.0020±0.0001	3.4±0.6	2.2±0.3	0.26±0.06	0.11±0.03
	Jun.	0.49±0.15	0.12±0.03	0.070±0.009	0.0014±0.0004	0.51±0.22	0.22±0.13	0.11±0.01	0.0022±0.0006	6.7±1.9	2.3±0.9	0.29±0.08	0.049±0.015

Table 4