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Role of different salt marsh plants on metal retention in an urban estuary (Lima estuary, NW Portugal)

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The aim of the present work was to understand the role different salt marsh plants on metal distribution and retention in the Lima River estuary (NW Portugal), which to our knowledge have not been ascer-tained in this area yet. The knowledge of these differences is an important requirement for the devel-opment of appropriate management strategies, and is poorly described for Eurosiberian estuaries, like the one selected. In addition it is important to understand the difference among introduced and native salt marsh plants. In this work, metal levels (Cd, Cr, Cu, Fe, Mn, Ni, Pb and Zn) were surveyed (by atomic absorption spectrometry) in sediments from sites vegetated with Juncus maritimus, Spartina patens, Phragmites australis and Triglochin striata (rhizo-sediments), in non-vegetated sediments and in the different tissues of the plants (roots, rhizomes and aerial shoots). In general, rhizo-sediments had higher metal concentrations than non-vegetated sediments, a feature that seems common to sediments colo-nized by salt marsh plants of different estuarine areas. All plants concentrated metals, at least Cd, Cu and Zn (and Pb for T. striata) in their belowground structures ([M]belowground tissues/[M]non-vegetated sediment > 1). However, when considered per unit of salt marsh area, the different selected plants played a different role on sediment metal distribution and retention. Triglochin striata retained a significant metal burden in it belowground structures (root plus rhizomes) acting like a possible phyto-stabilizer, whereas P. australis had an higher metal burden in aboveground tissues acting as a possible phyto-extractor. As for J. maritimus and S. patens, metal burden distribution between above and belowground structures depen-ded on the metal, with J. maritimus retaining, for instance, much more Cd and Cu in the aboveground than in the belowground structures. Therefore, the presence of invasive and exotic plants in some areas of the salt marsh may considerably affect metal distribution and retention in the estuarine region.

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1. Introduction

Estuaries are often considered sinks for pollutants (namely, metals) receiving important anthropogenic inputs from the upstream catchments and from metropolitan areas and industries located on or near those areas. Most estuaries present large salt marsh areas colonized by different plants. Plants are known to be able of oxidizing the sediment through the movement of oxygen towards the roots ([Weis and Weis, 2004](#page7)) or acidifying its rhizo-sphere through the release of root exudates ([Jones, 1998; Mucha](#page7) [et al., 2008](#page7)). Plants can also alter metal speciation in the sediment surrounding its roots ([Almeida et al., 2004; Reboreda and Caçador,](#page7) [2007a; Koretsky et al., 2008](#page7)). If salt marsh plants are able to



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immobilize metals in their belowground structures, they may act as phyto-stabilizers, reducing metals bioavailability. On the other hand, plants that accumulate metals in their aboveground tissues can act as phyto-extractors, although, if these tissues are not removed, metals may return into the salt marsh system, increasing their bioavailability. ([Reboreda and Caçador, 2007b](#page7)). Nevertheless, the role of a plant depends on multiple factors, including environ-mental characteristics and plant species. The aim of the present work was to understand the role different salt marsh plants on metal distribution and retention in an urban-industrialized estuary. The knowledge of these differences is an important requirement for the development of appropriate management strategies, and is poorly described for Eurosiberian salt marshes. Lima River estuary (NW Portugal) is an urban-industrialized estuary, which suffers from several sources of disturbance, such as navigation activity in the lower estuary and a cellulose factory in the upper estuary. In addi-tion, this system is impacted by input of agricultural run off and

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urban and industrial sewage, which discharges nutrients and other substances that are transported from domestic, industrial and agricultural areas into the estuarine area. There is also constant dredging of the navigational channel, fact that can remobilise contaminants into the water column. As far as we know, the level of metal contamination, as well as the possible function of the halo-phyte plants on metals distribution and retention, has not been studied yet in Lima River estuary. The Lima River estuary presents a large Eurosiberian salt marsh ([Costa et al., 2009](#page7)), with an abundant salt meadow where Juncus maritimus is commonly found ([Rede](#page7) [Natura, 2000](#page7)). However, other plant species can also be found, like the exotic, non-native Triglochin striata, the invasive Phragmites australis and the noxious weed Spartina patens, plants that can have distinct behaviour in the salt marsh. Therefore, four different sites and four different plants (J. maritimus, S. patens, P. australis and T. striata) were examined to encompass different vegetated areas of this estuary. Metal levels were determined in vegetated (in contact with plant belowground structures) and in nearby non-vegetated sediments as well as in the different tissues (belowground (roots and rhizomes) and aboveground structures) of the selected plants.

2. Material and methods

2.1. Materials and reagents

To prevent contamination, all sampling and labware materials were soaked in 20% (v/v) HNO3 solution for at least 24 h, rinsed several times with bi-deionised water (conductivity < 0.1 mS cm 1) and dried in a Class 100 laminar flow hood. The sample manipulation was carried out in a clean room with Class 100 filtered air. All reagents used were pro analysis grade or equivalent. Standard solutions for metal analysis were prepared daily from the stock ones (more concentrated, from BDH (Spectrosol)), in polyethylene tubes, by weighing, with filtered bi-deionised water or 1e10% HNO3 solutions.

2.2. Sample collection and treatment

Salt marsh plants were collected in March 2009 at low tide at four sites (1 to 4) along the Lima River estuary (NW Portugal) ([Fig. 1](#page7)). This estuary has a semidiurnal and mesotidal regime,

exhibiting seasonal vertical stratification of salinity during the winter period. Salt intrusion goes up to 20 km upstream, the flushing rate being in average of 0.40 m s 1 and the residence time being of 9 days ([Ramos et al., 2006](#page7)). Two sites (hence forward called sites 1 and 2) are located in the middle estuary, with salinity ranging from 1 to 34 and turbidity from 2 to 17 NTU, whereas the other two (sites 3 and 4) are located in the lower estuary with salinity ranging from 5 to 35 and turbidity from 1 to 15 NTU. Sites 1 and 2 were colonized mainly by Juncus maritimus. Site 3 was colonized by individual assemblages of J. maritimus, Phragmites australis and Triglochin striata and site 4 was colonized by both J. maritimus and Spartina patens (in mixed and individual assem-blages). Plots of 10 cm long, 10 cm large and 20 cm depth (the depth with the higher belowground biomass) sediment, colonized only by one plant, were sampled. Size plots were selected in order to have sufficient belowground plant biomass for the metal analysis. Only green plants without any signs of senescence and with similar size and age were selected for analysis. At lab, rhizo-sediment (sedi-ment in contact with the plant roots and rhizomes) was carefully separated from the respective plant roots (by washing the roots and rhizomes with deionised water). Plants were then divided into roots and rhizomes (the belowground structures) and aboveground shoots, and the different tissues were put to dry. After drying, roots and rhizomes biomass accounted, respectively, for 4e10% and 12e31% of plant total weight in J. maritimus; for ca. 12% and 20% in S. patens; for ca. 17% and 60% in T. striata; and for ca. 8% and 6% in P. australis. The remaining mass was aboveground tissues. All these halophyte plants are perennial, being from different families and presenting different physiological structures. Juncus maritimus is a sea rush from the family Juncaceae, commonly found in Portu-guese and Eurosiberian estuaries ([Rede Natura, 2000](#page7)). Spartina patens is a cordgrass from the family Poaceae, being considered a noxious weed in some countries, namely in Spain in the Galician salt marshes ([SanLéon et al., 1999](#page7)). Phragmites australis is a common reed also from the family Poaceae, being considered an invasive specie in North America. The presence of this plant in Atlantic salt meadows is considered also an indication of habitat degradation ([Rede Natura, 2000](#page7)). Triglochin striata is an arrowgrass (although it is not in fact a grass) from the family Juncaginaceae, being an exotic plant in this habitat as it is native of Australia. The

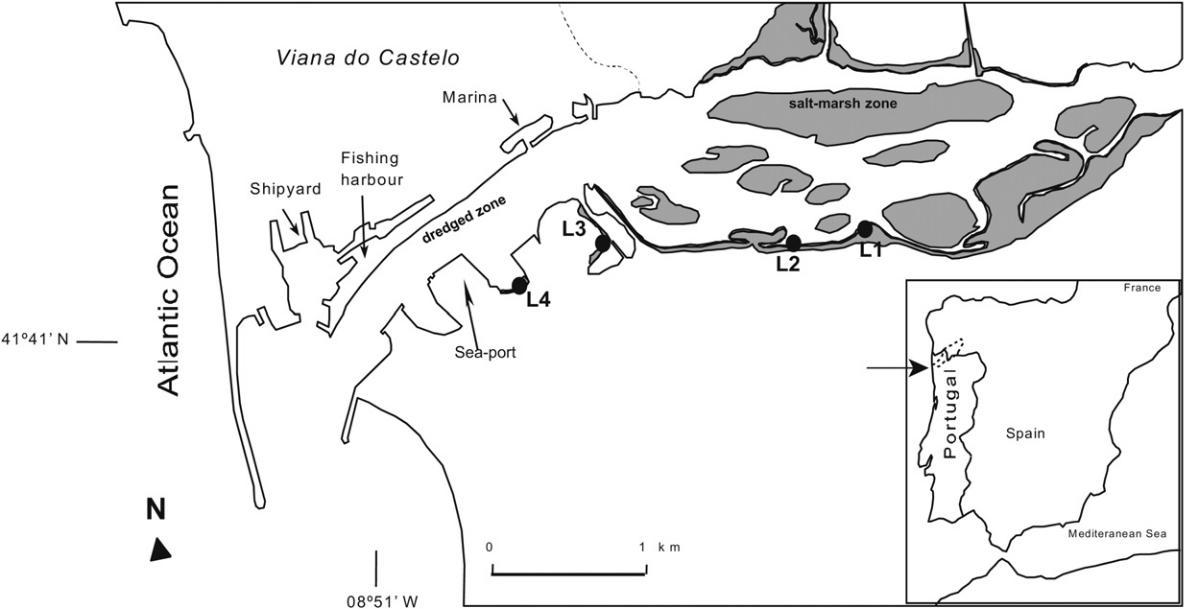


Fig. 1. Location of the four sampling sites (L1, L2, L3 and L4) in the Lima River estuary (NW Portugal).

|  |  |
| --- | --- |
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Table 1

Organic matter content (OM, mean standard deviation, n ¼ 3) and grain size fractions observed in vegetated (rhizo-sediments) and non-vegetated sediments at the different sites (n.d., Not detected).

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
|  |  | % OM |  | % Gravel | % Corse sand | % Fine sand | % Silt and clay |
|  |  |  |  |  |  |  |  |
| Site 1 | Sediment | 2.38 | 0.05 | 0.22 | 4.2 | 95 | 0.62 |
|  | J. maritimus rhizo-sediment | 3.4 | 0.3 | 11 | 40 | 40 | 9.7 |
| Site 2 | Sediment | 4.3 | 0.8 | 6.8 | 22 | 49 | 22 |
|  | J. maritimus rhizo-sediment | 4.65 | 0.02 | 5.3 | 16 | 49 | 29 |
| Site 3 | Sediment | 5.3 | 0.5 | n.d. | 4.5 | 45 | 51 |
|  | J. maritimus rhizo-sediment | 5.53 | 0.09 | n.d. | 3.6 | 36 | 60 |
|  | T. striata rhizo-sediment | 6.30 | 0.02 | n.d | 0.25 | 29 | 70 |
|  | P. australis rhizo-sediment | 5.7 | 0.1 | n.d | 0.70 | 39 | 60 |
| Site 4 | Sediment | 0.60 | 0.01 | 12 | 36 | 46 | 6.7 |
|  | J. maritimus rhizo-sediment | 5.85 | 0.01 | 1.8 | 16 | 30 | 52 |
|  | S. patens rhizo-sediment | 3.41 | 0.01 | n.d | 4.4 | 74 | 21 |
|  |  |  |  |  |  |  |  |

four plants differed significantly in their belowground biomass masses and structures. All plants presented thinner roots than J. maritimus, the only plant with a significant rhizome structure. Most T. striata tissues were located belowground whereas those of P. australis were more concentrated aboveground, being a much taller plant than all the others.

Concomitant sampling of non-vegetated sediment, that is, sediment without plants, but within 50 cm of the plants’ assem-blages, was carried out between 5 and 20 cm depth for all sites. Both rhizo-sediment and non-vegetated sediment were put to dry until constant weight.

Organic matter content (OM) and grain size were determined in all rhizo-sediments and sediments as before ([Almeida et al., 2004](#page7)).

Sample collection and treatment procedures were identical to those described before ([Almeida et al., 2004](#page7)).

2.3. Metal determinations

Total metal content (Cd, Cr, Cu, Fe, Mn, Ni, Pb and Zn) were determined by atomic absorption spectrometry (AAS) after high pressure microwave digestion. Depending on the metal levels either AAS with flame atomization (PU 9200X, Philips) or AAS with electrothermal atomization provided with a Zeeman background correction (4100 ZL, PerkineElmer coupled to an AS-70 autosam-pler) was used. Aqueous matched standards were used for external calibrations as no matrix effects were detected (checked by regular analysis of certified reference material and inter-comparison laboratory results). More details can be found in [Almeida et al.](#page7) [(2004)](#page7). Blank solutions were prepared for each type of sample, following the respective sample treatment.

Three independent replicates of each sample were prepared and analysed and, after blank subtraction, mean values and respective standard deviations were calculated. Statistically significant differences among samples were evaluated through ANOVA tests, using SPSS software.

Table 2

3. Results and discussion

3.1. Sediment characteristics

[Table 1](#page7) presents OM contents and grain size fractions of the different sites. Site 3 sediments (both vegetated and non-vegetated) were, in general, the richest in OM (in general, differences were statistically significant) and silt and clays. As expected, at each site rhizo-sediment was finer than non-vegetated sediments, displaying a higher percentage of the silt and clays fraction, as well as with higher OM. Salt marsh areas have, normally, slow hydrodynamic conditions, which contribute for the retention of particles that come along the Rivers. Plants can increase that retention, including the retention of organic detritus which can increase OM around their roots, leading normally to finer sediments with higher OM than non-vegetated sediments. This was in fact the case for Site 4. At this site Juncus maritimus even contributed much more than Spartina patens for the retention of OM. The fact that Site 4 non-vegetated sediment had a much lower OM than the corresponding vegetated sites (which were within 50 m of each other) clearly shows the effects of plants on particles and organic detritus retention.

3.2. Metal concentration in sediments

3.2.1. Non-vegetated sediments

Metals levels in sediments ([Table 2](#page7)) varied between 5 and 130 mg g 1 for Cr, Cu, Mn, Ni, Pb and Zn, 1 and 2% for Fe and between 20 and 230 ng g 1 for Cd (results are expressed on a dry weight basis). The highest levels were, in general, observed at site 3 (2e13 times higher). This result is compatible with the characteristics of site 3 comparatively to those of the other sites. Sediments with high percentage of fine-grained fractions have relatively high specific surface area for adsorption of metals and, therefore, metal concen-trations normally increases with decreasing grain size ([Chapman](#page7) [and Wang, 2001](#page7)). In addition, sediment with high OM can also

Concentrations of Cd, Cr, Cu, Mn, Ni, Pb and Zn (in mg g 1) and of Fe (in %) observed in non-vegetated sediments in this study as well as in several other Portuguese estuaries and lagoon systems, for comparison (adapted from [Almeida et al., 2008](#page7)) (n.a., Not available).

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | River estuaries |  |  |  |  |  | Lagoons | |  |  |
|  |  |  |  |  |  |  |  |  |  |  |
|  | Lima (this work) | Minho | Cavado | Douro | Tagus | Sado | Ria de Aveiro | | Ria Formosa | |
|  |  |  |  |  |  |  |  | |  | |
| Cd | 0.02e0.23 | 0.021e0.26 | 0.08e0.25 | 0.07e0.28 | 0.9e11 | 0.30e0.42 | 0.04e1.6 | | 0.04e6 | |
| Cr | 9e29 | 7.1e20 | 27e34 | 1e94 | 35e55 | 74e84 | n.a. | | 11e64 | |
| Cu | 5.5e23 | 2.78e22.4 | 39e57 | 1.0e229 | 10e214 | 59e136 |  | 3.0e45.6 | 10e66 | |
| Fe | 1.0e2.0 | 1.4e3.9 | 2.3e2.7 | 0.27e3.0 | 3.1e5.0 | 3.4e4.5 | n.a. | | 1.6e3.4 | |
| Mn | 80e104 | 74e165 | 184 | 32e93 | n.a. | 122e148 | n.a. | | n.a. | |
| Ni | 5e17 | 3.6e22 | 15 | 11e26 | 25e35 | 32e35 | n.a. | | 9e24 | |
| Pb | 9e58 | 4.75e15.0 | 23e46 | 0.25e192 | 11.8e350 | 56e77 |  | 6.0e26.4 | 40e91 | |
| Zn | 32e129 | 38e92 | 97e104 | 6e457 | 88e1086 | 370e391 |  | 51e589 | 70e151 | |
|  |  |  |  |  |  |  |  |  |  |  |

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retain more metals by complexation ([Chapman and Wang, 2001](#page7)).

Differences in salinity and turbidity can also influence metal levels.

The observed differences among sites could also be related with different metals sources. In fact in Lima River estuary navigation activity and input of agricultural run off and urban and industrial sewage can contribute for the presence of metals in the estuarine area, with the different sources impacting differently the four selected sites. For instance, site 3 seemed to be the one more affected by domestic sewages, presenting the highest levels of faecal coliforms (4750 to 79,000 ufc/100 ml, when the limit for water is 2000 ufc/100 ml) (unpublished results).

In all studied sites metal concentrations were lower than the respective effect range-low (ERL) quality guideline, which repre-sents the concentration above which adverse effects upon sedi-ment-dwelling fauna can be occasionally expected ([Long et al.,](#page7) [1995; Long and MacDonald, 1998](#page7)). The exceptions were Pb and Zn at site 3 sediment with a slightly higher concentration than ERL. So, these sediments probably do not pose a risk to organisms living in them. According to the Portuguese legislation ([Caeiro et al.,](#page7) [2005](#page7)), these sediments can be considered as “clean” in terms of metals, except for Pb and Zn at site 4, which levels correspond to “trace contamination”.

Metal contents observed at Lima River estuary sediments were, in general, lower than those found in several other Portuguese estuaries, most of them considered as polluted by metals ([Table 2](#page7)). In fact, metal levels in the studied area were similar to those observed in the Minho/Coura Rivers estuary, within the northern border with Spain, which is considered a pristine estuary ([Reis](#page7) [et al., 2009](#page7)). Therefore, the intense and diversify activities that take place in this estuary, described above, does not seem to result in significant sediment pollution in terms of metals.

3.2.2. Vegetated versus non-vegetated sediments

[Table 3](#page7) shows that in the rhizo-sediments of all tested plants metals levels were identical to or higher than those found in corre-sponding non-vegetated sediments ([M]rhizo-sediment/[M]sediment between 1 and 2 in most cases). The only exception was the ratio [Cd]rhizo-sediment/[Cd]sediment for Triglochin striata, which was <1. These results were, in general, compatible with the higher OM and silt and clay fractions observed at rhizo-sediments comparatively to non-vegetated sediment ([Table 1](#page7)), which may favour metal adsorption (and formation of metal complexes). In addition, plants take up nutrients and other minor and trace elements from the sediment, causing fluxes of dissolved chemical species from the sediment towards the roots ([Caçador and Vale, 2001](#page7)), which can, therefore, increase metal content around their roots. Such enrichment may occur not only for elements that are essential for plants, like Cu or Zn, but also for elements not recognized as essential, like Pb or Cd ([Almeida et al., 2004](#page7)). Plant uptake of Cd (see section 3.3 below) was probably the reason for [Cd]rhizo-sediment/[Cd]sediment < 1 for T. striata.

The accumulation of metals in the rhizosphere of salt marsh plants has been observed before, not only for Juncus maritimus in another estuary ([Almeida et al., 2006b](#page7)), but also for other plants in other estuaries like, for instance, Scirpus maritimus in Douro River

Table 3

estuary ([Almeida et al., 2006a](#page7)), Halimione portulacoides in Cavado River estuary ([Almeida et al., 2008](#page7)) and Spartina maritima and Sarcocornia fruticosa in Guadiana River estuary ([Silva, 2008](#page7)). Therefore, higher metal levels in the sediment surrounding plant belowground structures comparatively to non-vegetated sedi-ments seems to be common in salt marshes.

However, the accumulation around the roots can vary accordingly to the plant species, the sediment characteristics and the metal nature. If fact, as mentioned above, Triglochin striata [Cd]rhizo-sediment/ [Cd]sediment ratio was significantly different than that of the remaining plants. In addition, for all metals, ratios [M]rhizo-sediment/[M]sediment at site 4 were higher than those observed in the other sites. This was evident particularly for Juncus maritimus, as this plant occurred in all sites. Possible causes for this fact may be, for instance, differences in OM, namely in terms of humic substances and exudates capable of complexing metals, differences in the percentage of the thinner fractions and the presence of variable concentrations of Fe and Mn (hydr)oxides, which are capable of adsorbing metals. These oxides have been frequently found in the rhizosphere involving plant roots ([Caetano et al., 2003](#page7)). Levels of Mn and Fe observed at site four rhizo-sediments were higher or similar to those found at site 3, a feature not observed for the remaining metals.

3.3. Metals in plant tissues

Despite the observation that the salt marsh of Lima River estuary could not be considered polluted by metals, the presence of different halophyte plants prompted us to compare their potential for retaining metals. For this purpose, metals were quantified in both belowground (roots and rhizomes) and aboveground biomass.

Metal levels accumulated by plant tissues depended on both metal nature (which is also related with metal concentrations and metal sources) and plant species as expected ([Fig. 2](#page7)).

Enrichment factors were calculated as EF ¼ [M]belowground tissues/ [M]non-vegetated sediment ([Table 4](#page7)). All plants concentrated Cd, Cu and Zn in their belowground structures (EF > 1) and Triglochin striata also seemed to be able to concentrate Pb slightly. Therefore, present results indicated that all plants contribute for the retention of metals in the salt marsh vegetated area, reducing the possibility of those metals reaching shallow coastal waters seawards and eventually the sea. Unlike Cu and Zn, Cd is not to an element essential to the plant. It has been hypothesized ([Raskin and Ensley, 2000](#page7)) that Cd may enter root cells by means of the same uptake processes that move essential micronutrient metal ions. Cd and Zn have similar chemical properties and compounds released by the plant for facilitating Zn uptake may promote Cd uptake too. Plants show a range of different mechanisms for protecting themselves against uptake of toxic elements and for restricting their transport within the plant ([Ross and Kaye, 1994](#page7)). However, in the case of Cd, none of the plants seems to restrain Cd uptake by their belowground tissues, particularly roots.

In general, difference in the EFs values among sites for the same plant (Juncus maritimus) or among plants were not very marked and, in most cases, they were not statistically significant. However, in general these ratios were higher at site 4, probably related with

Ratios [M]rhizo-sediment/[M]sediment observed for the different plants and sites (mean and standard deviation, n ¼ 3).

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Plant | Site | Cd |  | Cr |  | Cu |  | Fe |  | Mn |  | Ni |  | Pb |  | Zn |  |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| J. maritimus | 1 | 1.3 | 0.6 | 0.9 | 0.2 | 1.2 | 0.2 | 0.9 | 0.1 | 1.0 | 0.1 | 1.4 | 0.6 | 1.1 | 0.2 | 1.1 | 0.2 |
|  | 2 | 1.31 | 0.03 | 1.11 | 0.07 | 1.6 | 0.2 | 1.2 | 0.2 | 1.08 | 0.06 | 1.23 | 0.08 | 1.1. | 0.2 | 1.32 | 0.09 |
|  | 3 | 1.15 | 0.05 | 1.04 | 0.02 | 1.24 | 0.05 | 1.3 | 0.3 | 1.06 | 0.06 | 1.10 | 0.04 | 1.0 | 0.1 | 1.08 | 0.05 |
|  | 4 | 2.7 | 0.5 | 2.8 | 0.5 | 2.8 | 0.2 | 1.52 | 0.08 | 1.38 | 0.4 | 1.7 | 0.1 | 4 | 1 | 2.1 | 0.1 |
| T. striata | 3 | 0.6 | 0.1 | 1.19 | 0.09 | 1.18 | 0.07 | 1.2 | 0.1 | 1.15 | 0.09 | 0.9 | 0.1 | 1.17 | 0.07 | 1.00 | 0.09 |
| P. australis | 3 | 1.14 | 0.2 | 1.12 | 0.06 | 1.27 | 0.05 | 1.05 | 0.07 | 0.98 | 0.05 | 1.19 | 0.06 | 1.36 | 0.07 | 1.09 | 0.01 |
| S. patens | 4 | 1.9 | 0.2 | 2.4 | 0.2 | 2.1 | 0.11 | 1.9 | 0.3 | 1.66 | 0.08 | 1.8 | 0.1 | 2.3 | 0.6 | 2.4 | 0.2 |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |

|  |  |
| --- | --- |
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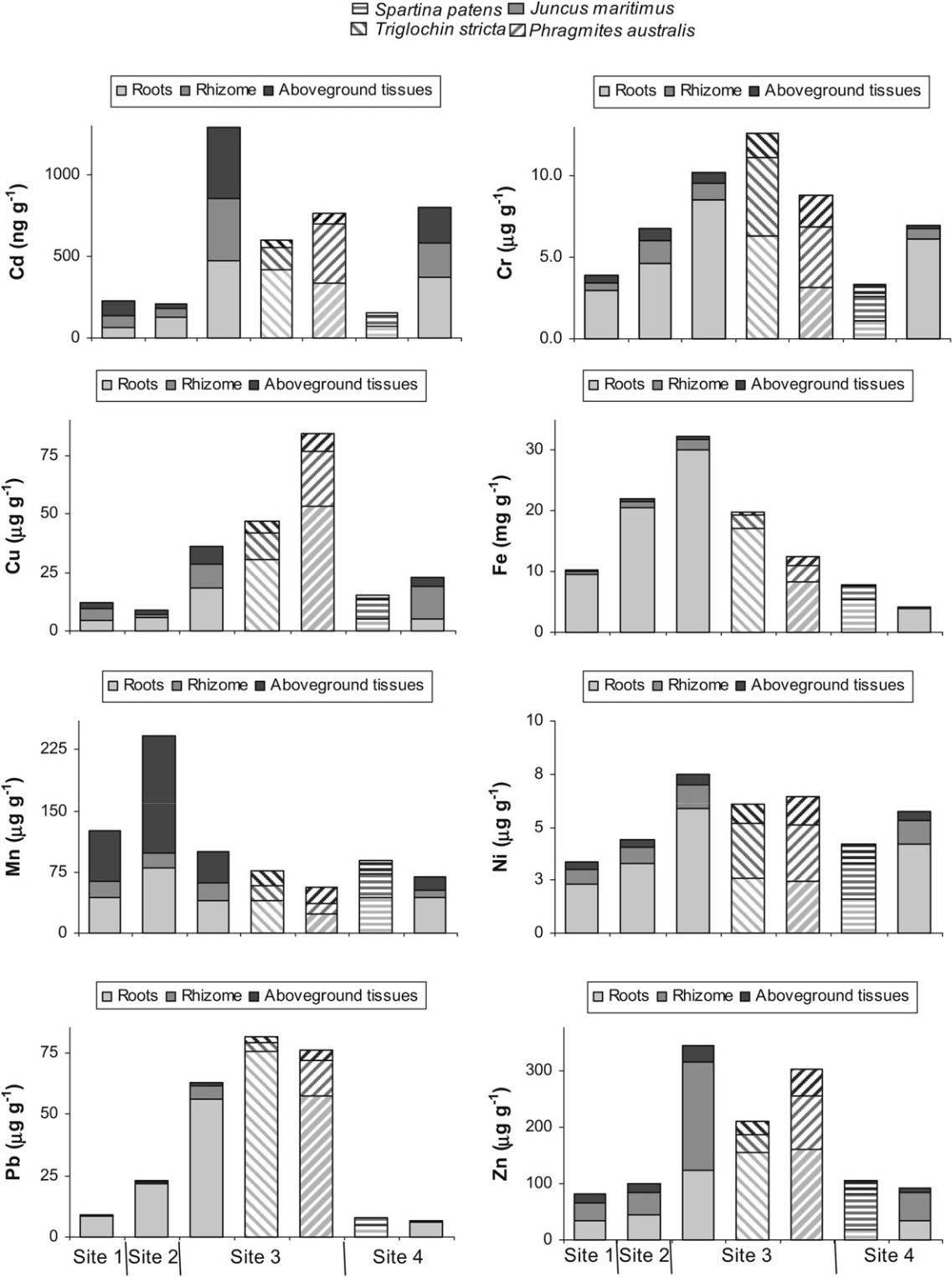


Fig. 2. Metal levels in the roots, rhizomes and aboveground tissues of the selected plants at the four selected sites.

the also slightly higher ratios [M]rhizo-sediment/[M]sediment observed at this site.

Despite the fact that EFs values were identical among the different plants, one should look to the biomass of each plant in a given area of vegetated salt marsh in order to compare the metal retention potential among different plants. In fact, one plant might have a high concentration of metal in its belowground tissues but if

it has a low belowground biomass the metal store in a given area of salt marsh will be low. Therefore, metal concentrations in each plant biomass were calculated per area of salt marsh, taking into consideration the biomass determined in the plots collected for each plant. As [Table 5](#page7) shows, Triglochin striata and Phragmites australis accumulated much more metal in their belowground tissues (sum of roots and rhizomes metal concentrations) in the

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Table 4

Enrichment factorsa observed for the different plants and sites (mean and standard deviation, n ¼ 3).

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Plant | Site | Cd |  | Cr |  | Cu |  | Fe |  | Mn |  | Ni |  | Pb |  | Zn |  |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| J. maritimus | 1 | 4.0 | 0.2 | 0.33 | 0.08 | 1.7 | 0.1 | 1.0 | 0.6 | 0.8 | 0.2 | 0.58 | 0.06 | 0.5 | 0.1 | 1.6 | 0.4 |
|  | 2 | 2.1 | 0.5 | 0.3 | 0.1 | 1.0 | 0.2 | 1.6 | 0.9 | 1.1 | 0.2 | 0.5 | 0.2 | 0.9 | 0.4 | 1.4 | 0.2 |
|  | 3 | 3.7 | 0.7 | 0.3 | 0.2 | 1.19 | 0.08 | 1.6 | 0.9 | 0.60 | 0.04 | 0.4 | 0.1 | 1.1 | 0.6 | 2.5 | 0.6 |
|  | 4 | 17 | 1 | 0.7 | 0.3 | 4 | 2 | 0.4 | 0.3 | 0.6 | 0.3 | 0.7 | 0.3 | 0.7 | 0.6 | 2.6 | 0.5 |
| T. striata | 3 | 2.4 | 0.3 | 0.38 | 0.06 | 1.8 | 0.2 | 0.15 | 0.06 | 0.56 | 0.07 | 0.3 | 0.1 | 1.4 | 0.1 | 1.5 | 0.2 |
| P. australis | 3 | 3 | 1 | 0.23 | 0.08 | 3.2 | 0.6 | 0.14 | 0.02 | 0.36 | 0.04 | 0.30 | 0.08 | 1.2 | 0.3 | 2.0 | 0.6 |
| S. patens | 4 | 4 | 3 | 0.3 | 0.2 | 3 | 1 | 0.22 | 0.05 | 0.9 | 0.5 | 0.2 | 0.2 | 0.8 | 0.5 | 2.5 | 0.7 |

a EF ¼ [M]belowground tissues/[M]non-vegetated sediment. Belowground tissues include plants’ roots and rhizomes.

considered area than the other two plants. In fact, these results indicate that T. striata concentrates a greater amount of metal in their belowground tissues than P. australis. Taking in consideration that the metal accumulated in the rhizo-sediments comparatively to that in the non-vegetated sediment ([M]rhizo-sediment/[M]sediment) was more or less identical among the different plants, these last two plants seem to have an higher metal retention potential, at least for Cd, Cu and Zn (and Pb for T. striata), for which EF > 1.

In general, it is consensual that salt marsh plants accumulate large amounts of metals in their belowground tissues, particularly in their roots, preventing metal translocation. Metal levels in rhizomes (another belowground plant structure) are usually considerably lower than in roots (e.g. [Almeida et al., 2006a;](#page7) [Windham et al., 2003](#page7)). Metal burden in the aboveground struc-tures is frequently lower as have been demonstrated in several studies (e.g., [Windham et al., 2003; Almeida et al., 2004, 2006a;](#page7) [Reboreda and Caçador, 2007b; Suntornvongsagul et al., 2007;](#page7) [Caetano et al., 2008; Cambrollé et al., 2008](#page7)). [Suntornvongsagul](#page7) [et al. (2007)](#page7) reported that Spartina patens could accumulate metals in its roots without significant translocation to shoots. Jun-cus maritimus is also known to displays, in general, a low trans-location metal potential, with most of the metal burden remaining in its roots ([Almeida et al., 2004, 2006b](#page7)). The same has been reported for common red Phragmites australis ([Windham et al.,](#page7) [2003](#page7)). As for Triglochin striata no results have been reported to our knowledge. In the present work, in general, significantly lower levels of metals in aboveground structures comparatively to belowground ones and a higher metal accumulation in roots than in the remaining tissues were also observed ([Fig. 2](#page7)). Cd in Juncus maritimus seemed to be an exception, as similar levels were observed for roots, rhizomes and aboveground shoots. In fact, Cd was concentrated in the shoots of J. maritimus ([M]shoots/[M]non-vegetated sediment > 1) at all sites with the exception of site 2.

However, when the aboveground biomass of a plant in a given area of vegetated salt marsh is taken into consideration, the metal

Table 5

burden in these tissues can be rather relevant ([Table 5](#page7)). In fact, in

1. given area, for Phragmites australis, [M]aboveground shoots > [M]be-lowground structures, and in the case of Cd, Cu and Mn for Juncus maritimus the same was observed.

One should be aware that despite accumulating metals in their tissues, which can contribute for metal retention, plant detritus can also release those metals into the environment during litter degra-dation or during plant litter dispersion. In fact, the role of plants on metal sequestration will depend on the rate of uptake into the plant, rates of translocation and retention within individual tissue types, and the rate, mode and dispersion of tissue decomposition ([Du Laing](#page7) [et al., 2006](#page7)). However, [Duarte et al. (2010)](#page7) have concluded that although high amounts of metal return to the sediments, due to root senescence, salt marshes can still be considered sinks of metals, cycling metals mostly between sediment and roots and [Du Laing](#page7) [et al. (2006)](#page7) concluded that Phragmites australis aboveground biomass litter could be also a trap of metals in the sediments. Also, it must be noted that P. australis is a plant that is extensively used in constructed wetlands (e.g. [Bragato et al., 2006; Yet et al., 2009](#page7)), where its capacity to translocate metals, demonstrated in the present study, could be a very advantage feature.

Considering results overall, it can be concluded that the different plants studied play a different role on metal distribution and retention in the salt marsh. In fact, the presence of invasive and exotic plants in some areas of the salt marsh may considerably affect metal distribution and retention in the estuarine region. Triglochin striata can have an important role in metal phyto-stabi-lization, as this plant retain more metal per unit of salt marsh area in its belowground tissues, leading to an eventual decrease in metal bioavailability. As for Spartina patens and Juncus maritimus metal burden distribution and retention between above and below-ground structures depended on the metal. For instance, J. maritimus significantly retained more Cd and Cu in its aboveground struc-tures, whereas Cr and Pb metal burdens were higher in its below-ground tissues. Concerning Phragmites australis, this plant can not

Metal in belowground tissues (roots plus rhizomes) and aboveground shoots per unity of vegetated area (mean and standard deviation, n ¼ 3) (n.d., Not detected as levels in shoots were below the detection limit).

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Plant | Site |  | Cd (ng dm 2) | | Cr (mg dm 2) | | Cu (mg dm 2) | | Fe (mg dm 2) | | Mn (mg dm 2) | | Ni (mg dm 2) | | Pb (mg dm 2) | | Zn (mg dm 2) | |
| J. maritimus | 1 | Belowground | 387 | 5 | 5.9 | 0.5 | 24.8 | 0.7 | 15 | 2 | 142 | 20 | 5.8 | 0.2 | 13 | 1 | 170 | 30 |
|  |  | Aboveground | 726 | 281 | 3.6 | 0.1 | 24.8 | 0.2 | 2.0 | 0.1 | 485 | 54 | 3.1 | 0.1 | 2.1 | 0.9 | 122 | 2 |
|  | 2 | Belowground | 202 | 24 | 6 | 1 | 7.6 | 0.8 | 16 | 2 | 94 | 9 | 3.9 | 0.6 | 14.7 | 0.4 | 118 | 14 |
|  |  | Aboveground | 375 | 44 | 10 | 4 | 21 | 7 | 6 | 4 | 1991 | 70 | 5 | 3 | 8 | 6 | 218 | 62 |
|  | 3 | Belowground | 814 | 66 | 6 | 1 | 23.9 | 0.9 | 17 | 2 | 54 | 2 | 4.6 | 0.7 | 35 | 6 | 357 | 67 |
|  |  | Aboveground | 3106 | 1063 | 4 | 1 | 56 | 6 | 3.1 | 0.9 | 266 | 94 | 3.3 | 0.5 | 8 | 2 | 193 | 10 |
|  | 4 | Belowground | 1079 | 29 | 10 | 2 | 44 | 12 | 6 | 2 | 83 | 18 | 9 | 1 | 11 | 3 | 181 | 22 |
|  |  | Aboveground | 4015 | 628 | 2.5 | 0.2 | 76 | 37 | 2.05 | 0.01 | 309 | 53 | 7 | 1 | n.d |  | 161 | 26 |
| T. striata | 3 | Belowground | 3121 | 223 | 87 | 7 | 248 | 18 | 88 | 9 | 375 | 22 | 42 | 4 | 297 | 25 | 946 | 72 |
|  |  | Aboveground | 159 | 18 | 4.3 | 0.1 | 15 | 1 | 1.4 | 0.9 | 58 | 5 | 2.7 | 0.3 | 7.7 | 0.4 | 66 | 3 |
| P. australis | 3 | Belowground | 1442 | 318 | 14 | 3 | 164 | 17 | 24 | 2 | 79 | 3 | 11 | 1 | 156 | 22 | 540 | 76 |
|  |  | Aboveground | 1620 | 57 | 50 | 7 | 186 | 70 | 33.8 | 0.1 | 487 | 101 | 34.0 | 0.3 | 98 | 8 | 1122 | 145 |
| S. patens | 4 | Belowground | 518 | 167 | 10 | 5 | 54 | 15 | 25 | 5 | 257 | 75 | 12 | 4 | 26 | 7 | 347 | 43 |
|  |  | Aboveground | 230 | 72 | 12 | 4 | 29 | 9 | 7 | 2 | 290 | 44 | 16 | 2 | 6 | 1 | 381 | 24 |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |

|  |  |
| --- | --- |
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only concentrate metals in its roots, but also accumulate significant metals amounts in their aboveground tissues acting as a possible phyto-extractor. In general, in salt marsh areas mechanical aspects of harvesting plants could be destructive to salt marshes ([Weis and](#page7) [Weis, 2004](#page7)), although a carefully planned periodical removal of the aboveground tissues could be considered. While the translocation of metals can increase metals bioavailability by returning them into the salt marsh system if the tissues are not removed, it is an advantage feature in the case of constructed wetlands.

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