Research Article

Metals Uptake by *Sagittaria montevidensis* in Contaminated Riparian Area of Matanza-Riachuelo River (Argentina)

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Abstract

The objective of this study was to evaluate the accumulation and uptake of Cr, Zn, Cu, Ni and Pb in *Sagittaria montevidensis* growing in highly contaminated riparian soils of Matanza Riachuelo Basin (MRB). It is a native and very abundant riparian plant exposed to heavy metal contamination. Samples of *S. montevidensis*, rhizosphere riparian soil and water were collected at three sites in the lower MR basin. The accumulation and the level of translocation of Cr, Zn, Cu, Ni and Pb in this species were determined. The soils were found to be the main reservoirs of metals (2225 mg Cr kg^{-1} d.w., 367 mg Cu kg^{-1} d.w., 61 mg Ni kg^{-1} d.w., 239 mg Pb kg^{-1} d.w., and 1495 mg Zn kg^{-1} d.w.). All studied metals were uptaken, but Zn and Cu were the most accumulated metals (426 ± 28 mg kg^{-1} d.w. and 129 ± 28 mg kg^{-1} d.w., respectively). *S. montevidensis* was an accumulator species for Cu and Ni (Translocation Factor (TF) > 1) and it showed an exclusionary behavior (TF < 1) for Cr, Pb, and Zn. Cu was mostly accumulated in the aerial biomass. The rest of the metals analyzed were mainly accumulated in the roots. The analyzed plant specimens did not show signs of stress, having completed their phenological states. This native species shows high tolerance of metals. Then the preservation and revegetation of this species in the riparian areas constitute a sustainable alternative for ecological restoration.

Keywords Riverbank degradation · Contaminated riparian soils · Bioconcentration factor · Translocation · Native plants · Heavy metals

1 Introduction

The Matanza Riachuelo River (Buenos Aires, Argentina) is considered one of the most polluted rivers of Latin America [1] and drains into the binational estuary Río de la Plata, which represents the main source of drinking water for Buenos Aires city and environs [2]. This temperate lowland river is 64 km in length and is the main course of the Matanza-Riachuelo Basin (MRB), a densely populated basin of more 3.5 million inhabitants that comprises approximately 2250 km^2. This basin has been contaminated since the beginning of the XIX century by salting and tanning plants [3]. Among the industries currently installed are tanneries, electroplating and chemical factories that use heavy metals in their processes such as chrome (Cr), copper (Cu), zinc (Zn), lead (Pb) and nickel (Ni), among others.

Heavy metals are one of the groups of environmental pollutants of concern, mainly because of their persistence and the low concentrations at which they can manifest their toxic effects [4], resulting in a danger to both human health and ecosystems [5]. In aquatic systems, they eventually become associated with particulate matter settling

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and accumulating in bottom sediments. Some studies have established that most aquatic rooted plants pick up metals primarily from the pore water of the sediment [6]. The roots, stems, leaves, fruits and seeds of most plants, present different levels of concentration and accumulation of heavy metals [7]. When the sediment is the source of heavy metals the levels usually decrease in this order: roots > stems > leaves > fruits > seeds. In general, the tolerance mechanisms are different among different plant species and they will depend on the metal and its concentration.

Those plants that are adapted to and thrive in soils rich in heavy metals are known as metallophytes [8, 9]. In turn, metallophytes can be divided into three categories: metal excluders, metal indicators and metal hyperaccumulators [8]. In the particular case of metal excluders, these accumulate metal in the roots, restricting its translocation to the aerial part [9–11]. Such plants have a low potential for metal extraction but may be efficient for phytostabilization purposes [8, 9].

The distribution and behavior of many aquatic plants are often correlated with water quality [12]. They can accumulate contaminants at a level higher than the content in the environment [13]. The emergent aquatic macrophytes of the genus *Sagittaria* (Alismataceae), have a wide worldwide distribution. They can be found in America, Europe, and Asia [14–16]. A particularity of this genus is its phenotypic plasticity [14], it possesses striking variability within and among populations in both vegetative structures, particularly leaf shape [17, 18]. The species *Sagittaria montevidensis* Cham. and Schltdl. (Fig. 1), selected for this study, is native to South America, has rhizomes, and it can reach up to 1.5 m in height [19]. Feijoó and Lombardo [20] and Lopez Van Oosterom et al. [21] recorded this species in different streams of the Pampas region and in particular Basílico et al. [22] did so for the MRB. This species is very abundant in the most degraded sites of the MRB. Despite the fact that it is widely distributed in environments with different degrees of anthropic impact on rivers in South America, there is a lack of studies evaluating the potential of *S. montevidensis* for use in phytoremediation [23]. In this context, the objective of this study was to evaluate the accumulation and uptake of Cr, Zn, Cu, Ni and Pb in *S. montevidensis* growing in highly contaminated riparian soils of MRB.

Fig. 1 Collected specimen of *Sagittaria montevidensis*

2 Material and Methods

2.1 Area of Study

Three sites located in the river banks of the highest urban and industrial concentration area of MRB were chosen for this study. The sites were Puente Vittorino de la Plaza, Puente Uriburu and Puente Bosch (Fig. 2). They record the highest historical values of heavy metals in sediment reported by the Autoridad de Cuenca Matanza Riachuelo [24] in its hydrological data base [25].

2.2 Sample Collection

S. montevidensis was present in all sampled sites. From each place, an isolated adult *S. montevidensis* individual of similar size was collected along with its respective belowground biomass and rhizospheric soil. Also, river surface water samples were taken near the site from which the plants were collected. Both water and riparian soil samples were collected in polyethylene containers previously washed with 50% HNO_3 and rinsed with deionized water. The bottles with the water samples were preserved in the field with HNO_3 at pH <2. The sampling was carried out on August 26, 2016.

2.3 Sample Analysis

Once in the laboratory, the plants were rinsed with tap water to remove any remaining soil and finally with deionized water. Each plant was divided into: belowground part, aerial part (stem and leaves) and flowers. The relationship between the subway part and the aerial one was 70–30, respectively. The clean and dry plant tissue was placed in a stove at 60 °C for one week. It was taken to constant weight and ground to a fine and homogeneous powder with a porcelain mortar.

The samples of water and soil were kept at 4 °C until analysis.

The total metals contents (Cr, Pb, Zn, Cu and Ni) were determined in triplicate in plant tissues, water and soil. The acid digestion was performed by microwave following the protocol established by the EPA 3015, 3051 and 3052 respectively [26–28]. After digestion, the determination of heavy metals was performed by atomic absorption

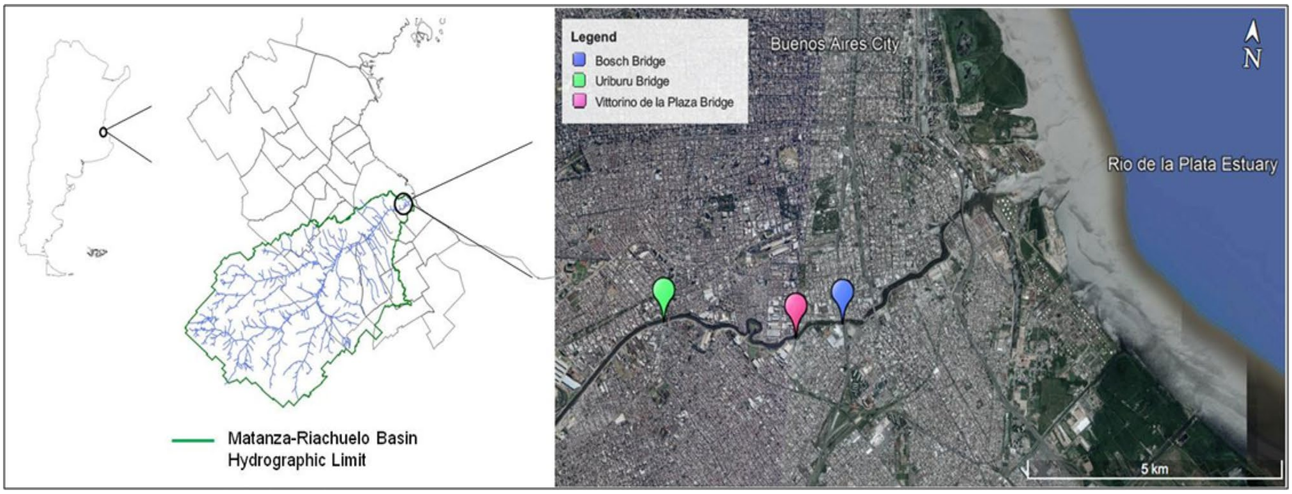

Fig. 2 Map with the location of the sampling sites in the lower Matanza-Riachuelo Basin, Buenos Aires, Argentina

spectrophotometry by the flame method following standardized protocols except for Pb in water which was determined by graphite furnace [29]. The results of metal concentration in soil were expressed as a percentage of dry weight and the water content of the soils samples was determined by measuring weight loss after drying to 105 °C up to constant weight. Traceable certified standards for the analysis of metals were from Merck, Inc. (1000 mg L^{-1} standard stock solutions, in HNO_3, traceable to National Institute of Standards and Technology (NIST), USA) and used the ULTRAcheck® Blind Quality Control Check Standards (certified by ULTRA Scientific and traceable to NIST). Chemicals for sample treatment or analysis of major matrix components were analytical grade. All the glass material used was washed with 50% HNO_3 and rinsed with deionized water.

2.4 Bioaccumulation and Translocation Analysis

The bioconcentration factor (BCF) indicates the efficiency of a plant species in accumulating a metal into its tissues from the surrounding environment and it is the ratio between the concentration of the target metal in the plant harvested tissue and the concentration of the same metal in the soil (substrate) [8]. BCF was calculated as BCF = C_t/C_s, where C_t = Heavy metal concentration in plant tissue (roots, stem, leaves and flowers) (mg kg^{-1} d.w.) and C_s = Heavy metal concentration in soil (mg kg^{-1} d.w.). The Translocation Factor (TF) represents the quotient between the concentration of the metal in the aerial and root organs [30] and indicates the efficiency of the plant in translocating the accumulated metal from its roots to shoots [8]. The translocation factor (TF) was estimated as TF = C_{ap}/C_r, where C_{ap} = Heavy metal concentration in aerial part (leaves and flowers) (mg kg^{-1} d.w.) and C_r = Heavy metal concentration in roots (mg kg^{-1} d.w.).

2.5 Soil Pollution Index

In order to evaluate the degree of contamination of the soils studied we calculated the index used by Kwon and Lee [31] and in particular by Mendoza et al. [32] for the MRB. It is defined as follows:

$$C_f = \frac{C_m}{C_{ref}} \tag{1}$$

where, C_f is the contamination factor, C_m is the concentration of the metal under study in the soil and C_{ref} is the concentration of this metal in the soil used as reference; and:

$$D_c = \sum C_f \tag{2}$$

where D_c is the soil contamination index and represents the sum of each C_f measured in the soil. The reference soil used in this work was the same used by Mendoza et al. [32].

2.6 Statistical Analysis

Pearson correlation coefficients were calculated using R 3.5.0 [33]. The correlations were calculated for three data sets (riparian soil, water and plant tissue), as well as for each analyzed element in the different matrix. Correlation was assumed to be statistically significant at $p < 0.05$.

3 Results and Discussion

3.1 Heavy Metals in the Water Column

The mean concentration of the elements analyzed in water is shown in Table 1. Of the five metals analyzed in water, only Cr exceeded the limits established by the argentine Resolution 283/2019 for the protection of aquatic life [24]. The concentrations obtained followed the same trend as the historical values of the monitoring carried out by ACUMAR between 2008 and 2018 [25] for all metals except Pb where it was not detected.

3.2 Heavy Metals in the Riparian Soil

The concentrations of heavy metals in riparian soil were found in the following order: Cr > Zn > Cu > Pb > Ni (Table 2). The main contaminating metal found in the soils was Cr, which is related to tanneries, one of the main economic activities that have been developed in the basin since 1895 [34].

Table 1 Ranges of mean concentrations of metals in water (mg L^{-1}) from sites of Matanza-Riachuelo River ($n = 3$). Detection and quantification limits (mg L^{-1})

		Cr	Cu	Zn	Ni	Pb
Water	Min	0.031	0.030	0.049	0.009	ND[a]
	Max	0.091	0.030	0.101	0.013	
	Mean	0.059	0.030	0.068	0.010	
	S.E.	0.017	0.000	0.016	0.001	
Detection limit		0.012	0.010	0.005	0.002[b]	0.002[b]
Quantification limit		0.050	0.050	0.030	0.005[b]	0.010[b]
Argentine legislation[c]		<0.020	<0.009	<0.120	<0.250	<0.002
Historical values[d]	Min	0.002	0.005	0.003	0.001	0.0002
	Max	0.485	0.100	0.319	0.400	0.102
	Mean	0.058	0.020	0.093	0.022	0.012
	S.E.	0.007	0.002	0.017	0.006	0.002

[a] *ND* no detection level

[b] Determined by graphite furnace [29]

[c] Reference value refers to ACUMAR Resolution 283/2019 [24] (mg L^{-1})

[d] Historical values reported by the Autoridad de Cuenca Matanza-Riachuelo (ACUMAR) in its hydrological data base (2008–2018 period) [25]

Table 2 Ranges of mean concentrations of metals in riparian soils (mg kg^{-1} d.w.) from sites of Matanza-Riachuelo River (n = 3). Detection and quantification limits (mg kg^{-1} d.w.). Values of contamination factor (C_f)[a] and degree of contamination (D_c)[b] by metals for the reference soil[c] for contamination assessment of the soil sites associated to the plants studied

		Cr	Cu	Zn	Ni	Pb
Riparian soils	Min	1548.8	336.5	1388.8	55.2	172.4
	Max	3025.6	426.9	1693.3	65.2	287.5
	Mean	2225.2	366.8	1495.1	61.0	238.9
	S.E.	430.8	30.1	99.2	3.0	34.4
Detection limit		0.5	0.4	0.2	0.1	0.1
Quantification limit		2.0	2.0	1.2	0.2	0.4
PEL[d]		90	197	315	NV[e]	91
Argentine legislation[f]		250	100	500	100	500
Index contamination in soil	C_f[a]	117	32	20	NV[e]	8
	D_c[b]	177 ± 25				

[a] $C_f < 1$ low contamination factor; C_f 1–3 moderate contamination factor, C_f 3–6 high contamination factor, $C_f > 6$ very high contamination factor

[b] $D_c < 6$ low degree of contamination; $6 < D_c < 12$ moderate degree of contamination; $12 < D_c < 24$ considerable degree of contamination; $D_c > 24$ very high degree of contamination $D_c = \Sigma C_f \pm$ S.E

[c] Reference soil (mg kg^{-1}): Cr 19.3, Cu 23.0, Pb 31.0, Zn 74.1

[d] Probable effect level (PEL) of the Canadian Council of Minister of the Environment (CCME) [36]

[e] *NV* no value

[f] Decree 831/93, Annex II, Table 2, regulatory of the Argentinian National Law of Hazardous Waste No. 24051 (Soil quality guide levels for Residential use [35] [mg kg^{-1} d.w.])

A comparative analysis of the results was carried out with the Argentine legislation (guide levels of land quality for residential use [35] (Table 2) due to the fact that there are urban settlements on the riverbanks. With the exception of Pb and Ni, the values of metals found in the riparian soil exceed those allowed for residential use. Thus, these sites present significant risk to human health and the biota, and confirm the deterioration of the environmental quality.

In turn, the contamination degree index (D_c), calculated from Eq. (2), categorizes this soil as very high degree of contamination (Table 2), consistent with what is reported by Mendoza et al. [32].

On the other hand, to evaluate the level of toxicity, the results were compared with the Probable Effect Level (PEL) of the Canadian Council of Minister of the Environment (CCME) [36], which is defined as the level above which adverse biological effects are most likely to occur. For all metals (except Ni where there are no CCME values) the concentrations exceed the PEL (Table 2).

The main reservoir of heavy metals in the system was the soil. The presence of metals in riparian soils above the reference values are a direct consequence of effluent dumping without adequate treatment. The accumulation of metals in sediments has also been reported by other authors in similar environments [37–39].

3.3 Heavy Metals in Plant Tissue

Although metals can accumulate in plants both through root [40] and through foliar absorption [41, 42], the transfer of metals from the soil root is the main route by which heavy metals enter the plant [43]. Given the associated difficulty in discriminating these two pathways of entry as well as the high concentration of metals present in the soil, this study was approached from the premise that the metals found in the plant tissue came from the soil.

S. montevidensis absorbed the metals studied in the following order: Zn >> Cu > Cr > Ni = Pb, similar results were reported by [44] for this species. However, the collected individuals for this study were in bloom, without chlorotic leaves or signs of stress. Concentrations of Pb and Ni measured in the total plant exceeded reference levels for plant species in general [45] (Table 3). On the other hand, the concentrations of Cr, Zn and Cu in total plant were above the limits considered excessive or toxic [45] (Table 3). The ability to tolerate and accumulate these metals without visible damage, could be provided by the presence of this species in an environment polluted with these metals for more than 100 years. Similar results were found by Demarco et al. [23]. They found individuals of *S. montevidensis* with concentrations of Cu, Mn and V higher than the levels considered toxic, confirming the ability of this species to grow in deteriorated environments and in the presence of different contaminants. In the MRB, de

Table 3 Ranges of mean concentrations of metals [mg kg^{-1} d.w.] in belowground plant parts, stem and leaves, flowers and total plant of *Sagittaria montevidensis* from sites Matanza-Riachuelo River (n = 3). Detection and quantification limits and reference value [mg kg^{-1} d.w.] basis [45]

Organs of *Sagittaria montevidensis*		Cr	Cu[a]	Zn[a]	Ni	Pb
Belowground plant parts	Min	19.6	41.6	195.2	7.2	9.3
	Max	46.5	59.2	339.3	10.7	25.5
	Mean	30.8	47.9	251.8	8.9	16.7
	S.E.	8.1	5.7	44.4	1.0	4.7
Stem and leaves	Min	9.3	51.5	103.6	5.8	0.9
	Max	11.6	73.8	149.0	6.9	1.8
	Mean	10.4	62.1	133.3	6.3	1.5
	S.E.	1.1	6.5	14.9	0.3	0.3
Flowers	Min	0.0	24.1	40.9	2.0	0.5
	Max	1.7	49.8	50.4	3.3	0.8
	Mean	0.6	33.3	46.5	2.7	0.6
	S.E.	0.6	8.3	2.9	0.3	0.1
Total plant	Min	19.6	110.8	392.6	16.5	11.0
	Max	59.8	165.1	483.7	19.7	27.5
	Mean	38.3	129.1	426.4	17.6	18.7
	S.E.	11.7	18.0	28.8	1.0	4.8
Detection limit		0.6	0.5	0.3	0.1	0.1
Quantification limit		2.5	2.5	1.5	0.3	0.5
Reference values for species in general	Sufficient or normal	0.1–0.5	5–30	27–150	0.1–5	5–10
	Excessive or toxic	5–30	20–100	100–400	10–100	30–300

[a]Micronutrients

Cabo et al. [46] and Mendoza et al. [32] found levels of Cr, Cu and Zn in individuals of *Tradescantia fluminensis* and Cr, Cu, Zn and Pb in individuals of *Hydrocotyle bonariensis* and *Eleocharis montana,* respectively, higher than reference values of terrestrial plants in unpolluted areas. These individuals showed tolerance to high levels of contamination in the sites belonging to the basin studied in this work. Plants adapt to stress situations such as those caused by the presence of metals in the environment by developing detoxification mechanisms such as chelation and sub-cellular compartmentalization [47]. Although this has been described mainly for species of the family Brassicaceae and very little is known about this type of behavior in native plants of other families, it could be expected that the mechanisms are similar. Plants develop mechanisms to control the uptake and accumulation of metal through the overexpression of genes related to the tolerance and accumulation of metals in their tissues [48]. Overexpression of these genes is more likely to occur in the *S. montevidensis* population because it has been in contact with elevated levels of heavy metals for more than 100 years explaining the tolerance to contamination observed for *S. montevidensis* in MRB. The phenotypic plasticity of the vegetative and reproductive features of this genus should be highlighted. For example, [49] reported that *Sagittaria latifolia* populations are self-compatible and monoecious or dioecious occurring in wetland habitats where disturbance and competition, respectively, are most important. These contrasting life-history strategies allow the species to respond to variations in environmental conditions and disturbances [14] as in the case of *S. montevidensis* resistance to herbicides (penoxsulam and betazon) [50] or to metal contamination as reported by Demarco et al. [23] and in the present paper.

Although concentrations of Cr in the riparian soil were higher than those of the rest of the metals, higher concentrations of Cu and Zn were determined in the tissues, since they are micronutrients and the organisms need them for their growth and metabolic functions [51]. In contrast, Cr, Pb and Ni were incorporated to a lesser extent by the plant. Both Cr and Pb have no known biological functions for physiological and biochemical processes in cells and are toxic to living organisms even when they are present in low concentrations [52].

BCF values <0.5 were obtained for all metals. Although the plant incorporated all the metals in its biomass, it may not be reflected in BCF values, due to the high concentration of the metals in the soil. Ali et al. [8] described that high metal concentrations in soil could result in a BCF < 1 even though the plant had incorporated high concentrations, for example soils with 3000 mg kg^{-1} Ni and 2000 mg kg^{-1} Ni in a plant. Kickhöfel Ferrer et al. [16] worked with this same species in sites contaminated by heavy metals and they obtained a BCF < 1 in those sites where the concentration of Zn was higher than 200 mg kg^{-1} d.w. and the concentration of Cu was higher than 18 mg kg^{-1} d.w. In contrast, they obtained a BCF > 1 when Zn concentration in the soil was 26.7 ± 0.7 mg kg^{-1} d.w. and also in soils which Ni concentration range was between 2.3–5.1 mg kg^{-1} d.w. For sites with a high degree of contamination within the MRB, de Cabo et al. [46] obtained BCF values of 1 for Zn, Pb, Cu and Ni in *T. fluminensis,* while for Cr they obtained values of 6.5.

S. montevidensis showed a low level of translocation towards the aerial structures (TF < 1) was observed for Cr, Pb and Zn. This result is in line with Baker [11], for which metal excluders are plants which effectively limit the levels of heavy metal translocation within them and maintain relatively low levels in their shoot over a wide range of soil levels; however, they can still contain large amounts of metals in their roots. TF >1 was obtained for Cu and Ni, behaving as a metal accumulator for these elements. The TFs for Cu, Ni and Zn obtained in this work were lower than those reported by Kickhöfel Ferrer et al. [16] for this species. For Cr and Pb they were similar to those detected by Demarco et al. [23] (0.4 and 0.5, respectively).

Table 3 shows the distribution of metals in the plant's organs. The analyzed metals were found in all plant structures. Cr, Zn, Ni and Pb were mainly accumulated in the root. The lowest levels of metals were detected in the flowers. Cu was accumulated mainly in the aerial biomass. The translocation of Cu was due to the fact that it is an essential micronutrient for plant metabolism [53] and it is involved in the processes of photosynthesis, respiration and protein metabolism [51], although its excessive accumulation in plant tissue can be toxic for plants [54].

Zn was the metal that was mostly incorporated by the plant (Table 3). This metal is an essential micronutrient for plants. In contrast to Fe, Mn, Cu and Mo, Zn is a transition element that is not subject to valence changes and it is present in plants only as Zn (II) [55]. Within the main functions of this micronutrient are stress tolerance, reproductive growth (induction to flowering, pollination, fruit establishment) and to be a constituent of cell walls and membrane. The highest concentration of this metal was found in the roots (252 ± 44 mg kg^{-1} d.w.) and it was distributed within the plant in the following decreasing order: root > stem and leaves > flower. Kickhöfel Ferrer et al. [16] found Zn values in roots in a range between 41.3 and 168.8 mg kg^{-1} d.w. while Demarco et al. [23] found concentrations of 235 ± 33 mg kg^{-1} d.w. in the total plant.

Pb is not an essential element for plant growth [56]. It is firmly bound to soil particles from immobilisation processes such as adsorption, precipitation, complexation and redox reactions [57] making it poorly bioavailable. Also, its transport from roots to aerial structures is usually negligible in most plants [58]. Once this metal has penetrated roots, it can accumulate there and only a small fraction is translocated to aerial parts of the plant [59]. The results of this work agree with these authors since the highest concentration of Pb was found in the roots (16.7 ± 4.7 mg kg^{-1} d.w.) (Table 3). The concentration of Pb assimilated by the whole plant was 18.7 ± 4.8 mg kg^{-1} d.w. Demarco et al. [23] have reported similar concentrations (13.7 ± 3.4 mg kg^{-1} d.w.) in the *S. montevidensis* tissue.

Ni is an essential element in plant metabolism; however at excessive levels many biological processes can be disrupted [51, 52] including photosynthesis and transpiration [45]. The mobility of Ni in plants varies from mobile in some plants to immobile in other species [55]. We found that Ni has mobility within *S. montevidensis* despite of the maximum concentration of Ni was observed in the root (17.7 ± 1.0 mg kg^{-1} d.w.) (Table 3).

Cr is an element considered toxic to plants [53]. The highest concentration of this metal was found in the root (30.8 ± 8.1 mg kg^{-1}) (Table 3). It is probable that the plant concentrates and confines Cr in the roots as a defense strategy to face the toxicity of this metal [51, 60, 61]. Other authors have also recorded higher concentrations of this metal in roots in emerging aquatic plant species than in other [62]. However, concentrations of this metal were also observed in the aerial part (10.4 ± 1.1 mg kg^{-1} d.w.). Once it is translocated to the aerial tissues, the plant might activate physiological and biochemical mechanisms to counteract its toxicity as has been observed for other species [63].

The results obtained indicate that this species can be used to phytoremediate soils and sediments. It showed ability to phytoextract Cu and Ni from the soil and translocate them to the aerial part, facilitating their elimination by harvest. In highly contaminated soils as the study sites, the plants that can extract and translocate metals could be considered accumulator although the BCFs were less than 1. In fact, the values found in tissue were excessive or toxic. For Cr, Pb and Zn, the plants behaved as metal excluders since it accumulated them in its underground structures and practically did not translocate them to the aerial biomass as a defense mechanism of the photosynthetic structures [8, 64]. Therefore, this species can be used to stabilize Cr, Pb and Zn in riparian soil by preventing their passage by runoff into the water column [65], limiting mobility to groundwater and decreasing their bioavailability.

3.4 Comparison of Metal Contents in Water, Riparian Soil, and Plants

The riparian zone is a major part of most riverine systems, providing ecotones with high biodiversity [66]. This in turn is influenced by the associated vegetation exposed to the flood pulse of the river. Therefore, vegetation, riparian soil, and water are in close contact and interaction. In this sense, the Pearson correlation coefficients of the heavy metals in the three matrices were evaluated (Fig. 3). The metal content in the plant tissue correlated positively with the metals present in the water (r = 0.560, $p < 0.05$). The metals in the soil showed a positive but not significant (r = 0.340, $p > 0.05$) trend with those incorporated in

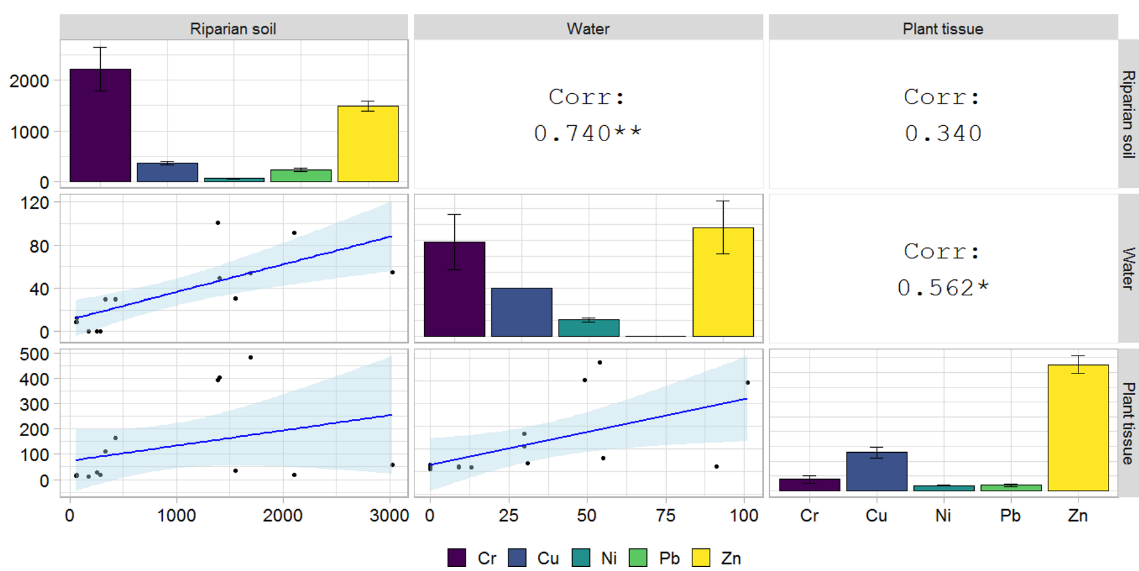

Fig. 3 Relationship of the total content of heavy metals (Cr (violet), Cu (blue), Ni (light blue), Pb (green), and Zn (yellow)) in riparian soil, plant tissue (*Sagittaria montevidensis*), and water. (*) indicates significant correlations ($p < 0.05$), (**) indicates significant correlations ($p < 0.01$). Distribution of heavy metals in each matrix: riparian soil (mg kg^{-1} d.w.), water (μg L^{-1}), and plant tissue (mg kg^{-1} d.w.)

the plant tissue while the concentration of metals in the water correlated positively with that of the riparian soil (r = 0.740, $p < 0.01$). The presence of metals in the riparian soil is given by the influence that the aquatic system has on the terrestrial one (and vice versa), the discharge of effluents without an adequate treatment not only contaminated the body of water but also impacted the riverbank. The correlation analysis responds to the close interconnection between the soil and riparian vegetation with the river system.

Likewise, the low correlation between the concentrations found in the plants with respect to those present in the riparian soil shows a trend that supports the observed results, since the percentage of metal uptake by the plants with respect to that present in the soil varies for each element. The uptake percentages were 2% Cr; 35% Cu; 29% Zn and Ni and 8% Pb.

4 Conclusions

The riparian zone is a major part of most riverine systems. Provide many ecological functions and services as biological corridors and buffer zones to retain pollutants that may enter from urban runoff while mitigating flooding. In the particular case of MRB, the lower basin is the most contaminated with Cr, Ni, Zn, Pb, and Cu as a result of the industrial impact and effluent discharge without adequate treatment. In this sense, aquatic vegetation plays a key role in the retention and immobilization of heavy metals. *S. montevidensis* proved to be a native species with the capacity to retain, immobilize, and tolerate these metals. Despite the damage that heavy metals can cause in plant species, *S. montevidensis* analyzed specimens that did not present signs of stress and having completed their phenological states. All the metals were uptake by the *S. montevidensis*. It is an accumulator for Cu and Ni, while it behaves as a metal excluder for Cr, Pb, and Zn. Zn and Cu were the most assimilated elements because they are essential micronutrients for plant development. Cu was the only metal that was distributed in different organs. Despite its toxicity, concentrations of Ni and Cr were detected in the aerial part while Pb was practically confined to the roots. From an environmental point of view, this native species is adapted to the degraded environment in which it grows. In this context, the preservation and revegetation of this species in the riparian areas constitute a sustainable alternative for ecological restoration due to its tolerance and its availability to accumulate and stabilize heavy metals present in the riparian soil.

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Compliance with ethical standards

Conflict of interest The content of this manuscript has not been published or submitted for publication, in whole or in part, elsewhere. There are no conflicts of interest to declare.

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