



Differences in Metal Accumulation from Stormwater by Three Plant Species Growing in Floating Treatment Wetlands in a Cold Climate

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Abstract Stormwater is a source of pollutants in urban areas and should be treated to prevent negative environmental effects. A newer technique uses floating rafts with plants, called floating treatment wetlands (FTWs), which are placed in the polluted water. Few earlier studies have examined heavy metal removal by FTWs, and none has examined stormwater in cold climates. This study therefore aimed to determine whether plants growing in FTWs could accumulate heavy metals from stormwater ponds in a cold climate. This study examined the abilities of three native wetland species (i.e., *Carex riparia*, *C. pseudocyperus*, and *Phalaris arundinacea*) to accumulate Cd, Cu, Pb, and Zn. The plants were planted on FTWs, which were placed in two stormwater ponds in Stockholm, Sweden, for 12 weeks. *Phalaris arundinacea* accumulated more Cd, Cu, and Zn than did the *Carex* species, and *C. pseudocyperus* accumulated less Pb than did the other species during the experimental period. In most cases, the roots had higher metal concentrations than did the shoots. *Carex pseudocyperus* had smaller differences between shoot and root metal contents, whereas *P. arundinacea* had higher Cd and Cu contents and lower Zn contents in its roots than in its shoots. The metal content in the plants increased with higher

biomass. The plants that grew in the stormwater pond with a higher Zn concentration had a higher Zn tissue concentration and total Zn content per plant after treatment. This study shows that wetland plants growing on FTWs can accumulate metals from stormwater ponds in a cold climate. *Phalaris arundinacea* appears to be a good candidate for metal removal use in FTWs. Furthermore, high plant biomass positively affects the metal uptake, meaning that good growing conditions could be essential for metal removal.

Keywords Floating treatment wetlands · Rhizofiltration · Heavy metals · Stormwater · *Phalaris arundinacea*

1 Introduction

Human activities in urban areas result in the surface accumulation of pollutants that are washed off by rain and snow, resulting in polluted stormwater. As stormwater pollutants originate from all kinds of human activities (e.g., traffic, industry, and construction), stormwater pollutants vary, commonly including heavy metals, suspended solids, nutrients, chloride, and organic carbon (Makepeace et al., 1995). The stormwater carries the pollutants to the receiving water body. Stormwater plays a main role in the degradation of freshwater ecosystems (Roy et al., 2008), so it is important to treat this water. Traditionally, stormwater management mostly involved diverting

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the water to receiving streams as fast as possible (Ladislav et al., 2015). However, as the problems with stormwater pollution have surfaced, other types of management have been implemented since the 1990s. These newer management techniques are intended to remove pollutants and retain the volumes of runoff water. They include sedimentation ponds, constructed wetlands, swales, biofilters, and infiltration systems (Blecken, 2016).

One type of constructed wetland is floating treatment wetlands (FTWs), which are small rafts planted with emergent wetland plants with their roots submerged in the water (Headley & Tanner, 2012). The roots help reduce water velocity, in turn increasing the particle sedimentation rate. Biofilms form around the roots and, together with the roots, remove pollutants by adsorption, absorption, and biotransformation to less toxic metal forms (Headley & Tanner, 2006; Jasu & Ray, 2021). Metal uptake by the plants and subsequent accumulation in plant tissues also contribute to the treatment of stormwater (Ladislav et al., 2015). Several factors, including pollutant load, raft size and placement, and season (McAndrew & Ahn, 2017; Pavlineri et al., 2017; Van de Moortel et al., 2010), affect the uptake of pollutants by the plants, and the removal capacity is also species dependent. Altogether, the amount of metals that different species in FTWs can remove is still under examination. Most research on FTWs has so far investigated nutrient removal, chemical oxygen demand, biological oxygen demand, and suspended solids. Additionally, most field studies have been performed in warm climates, using plant species that cannot survive in cold climates. Therefore, more knowledge of the metal removal capabilities of floating treatment wetlands in cold climates is required in order to implement FTWs that successfully remove heavy metals from stormwater.

Plants used in FTWs should be able to both tolerate high metal concentrations and accumulate metals from the water to decrease their concentrations in the water. Wetland plants tolerate high metal concentrations and can accumulate metals (Salem et al., 2014). However, as plant species differ in their metal accumulation properties (Rai et al., 1995; Rezanian et al., 2016), it is of interest to further investigate what plant species are best suited for metal removal in FTWs. *Carex riparia* and *C. pseudocyperus* have shown potential for heavy metal removal in FTWs (Schück

& Greger, 2020a), being the best of 34 investigated Swedish wetland species for reducing Cd, Cu, Pb, and Zn levels in a hydroponic microcosm. However, metal accumulation and metal distribution in these plants were not studied. *Phalaris arundinacea* has shown good potential for chloride removal (Schück & Greger, 2022). Since these species showed the ability to remove metal and chloride from water in a laboratory environment, their accumulation capacities should be verified in situ.

When using plants for metal removal purposes, knowledge of the metal accumulation distribution in the plants is important for successful metal removal. If most metals accumulate in the roots, harvest of the roots or whole plants would be necessary, whereas if the plants transport most of the metals to their shoots, shoot harvest would be recommended, which might be both easier to do and allow the same plants to continue to grow for several years on the FTW. To tolerate high levels of metals, plants have evolved different mechanisms that affect where they accumulate metals. Some plants prevent the transport of metals from roots to aerial parts and can accumulate considerable quantities of metals in their roots (Sheoran et al., 2010). Other plants have accumulation mechanisms whereby they take up and transport metals to the shoots, where the metals are detoxified (McGrath et al., 2001). Most studies (e.g., Bonanno, 2011; Polechońska & Klink, 2014; Vymazal et al., 2007) that have evaluated the metal accumulation properties of wetland plants have shown that the plants generally have higher metal concentrations in their roots than in their aboveground tissues. However, the metal concentration in tissues does not necessarily predict the total metal accumulation. It is possible that the aboveground biomass may be greater than the belowground biomass, resulting in higher metal accumulation in one plant part despite lower metal concentrations overall (Liu et al., 2007; Vymazal, 2016).

Metal concentrations in stormwater vary, and the metal concentration in the surrounding medium may affect the metal uptake by plants. Laboratory experiments studying the metal removal capacities of aquatic macrophytes have shown that higher metal concentrations in the water increase the metal concentrations in the plants (Miretzky et al., 2004), although this might not be the case for all metals or plant species (Mishra & Tripathi, 2008). However, other studies (Krüger & Gröngröft, 2003; Overesch et al., 2007)

have shown weak or no correlation between plant and soil metal concentrations. This might be due to the difference between water and soil, a more complex matrix where most metals are bound to organic or inorganic soil constituents (Raskin et al., 1994).

This study examined the metal accumulation properties of three wetland plant species, i.e., *Carex pseudocyperus*, *C. riparia*, and *Phalaris arundinacea*, growing in FTWs in stormwater ponds, and their potential use for metal removal in FTWs. It also sought to gain more insight into plant metal uptake during metal removal with FTWs. The specific objectives were to determine:

- the accumulated metal amounts and distributions in the plants in FTWs during the experimental period,

- whether plant species, metal concentrations in the water, and growth affected metal uptake and accumulation, and
- each species' potential for metal removal in an FTW.

2 Materials and Methods

2.1 Study Sites

The study was conducted in two stormwater ponds along a busy highway in the Stockholm area (Fig. 1). The climate of the Stockholm area is characterized by cold winters (average temperature in February, 1991–2020, was -1.1°C) and mild summers (average temperature in July, 1991–2020, was 18.7°C),

Fig. 1 Study sites Lilla Essingen stormwater pond (top image) and Silverdal stormwater pond (bottom image) with the FTWs



whereas precipitation is evenly distributed over the year, averaging 25–65 mm per month (Stockholms stad, 2022).

Study site 1 is located on Lilla Essingen island in central Stockholm (59°19'28.3"N 18°0'2.1"E). The pond is situated under the bridges of highway E4 (eight lanes) and a local street (two lanes), resulting in partial shading by the bridges. The watershed area is estimated to be 17,600 m², and the pond mainly collects water from E4, with the rest coming from surrounding local streets and houses on Lilla Essingen (Renman et al., 2021). The pond has a permanent volume of 150 m³ and an additional detention volume of 180–200 m³. When the total volume is reached, the detention volume is pumped out until the permanent volume is reached again. The pond's area and depth at maximum water volume are 450 m² and 1.4 m. The pond was built in the autumn and winter of 2002–2003 and was dredged three months before the start of this study.

Study site 2, Silverdal, is located approximately 10 km north of Lilla Essingen in the Stockholm suburbs (59°24'16.0"N 17°58'8.3"E). The pond is situated between highway E4 and the tracks of local and national rail lines. The location is exposed to the sun throughout the day. The watershed area is estimated to be 0.11 km², and the pond collects water from highway E4 and surrounding green areas (Emell & Welin, 2015).

The pond volume is 780 m³ at normal water levels and 1330 m³ at high water levels. At high water levels, the pond area is 1700 m² and the depth is 1.4 m. The pond has passive in- and outflows that depend on the amount of precipitation. The pond was built in 2011, and has not been dredged since then.

2.2 Plant Material and Raft Construction

Specimens of three wetland species, i.e., *C. pseudocyperus*, *C. riparia*, and *P. arundinacea*, were used in the study. The plants were 3–4 months old and had been propagated from cuttings from larger plants in a greenhouse (15 °C, 13 h light, and 65% relative humidity). The plants originated from an earlier collection described by Schück and Greger (2020b). The *Carex* species had been collected in Norra Djurgården (*C. pseudocyperus*) and Flemingsberg (*C. riparia*) in the Stockholm area. The *Phalaris* specimens were purchased from Veg-Tech

AB, which collected the seeds in Sweden. The plants were grown in 25% modified Hoagland solution (Eliasson, 1978) for the first month, and thereafter grown in 5% modified Hoagland solution until the start of the experiment. The *Carex* species were in a vegetative stage without flowers, whereas some *Phalaris* plants had flowers. The specimens used in the study came from a large number of original plants and were selected based on their similarity in shape and size.

The rafts measured 0.58 × 1.07 m and consisted of frames made from 75-mm polypropylene drainpipes to provide buoyancy (Fig. 2). Galvanized chicken-wire nets were attached above and below the frame to support a thrice-folded coconut-fiber mat.

2.3 Experimental Setup

The selected plant specimens were weighed, planted on floating rafts, and placed in the two stormwater ponds described above (Fig. 1). One raft planted with six specimens of each species (a total of 18 specimens per raft) was placed in each pond (Fig. 3). Specimens of the same species were placed together to study how they grew as a monoculture and not as a mixed culture. Within the species, the specimens' spatial positions were randomized. The rafts remained in the ponds for 12 weeks (from 7 July to 29 September 2020), after which they were removed from the ponds and the plants were harvested.

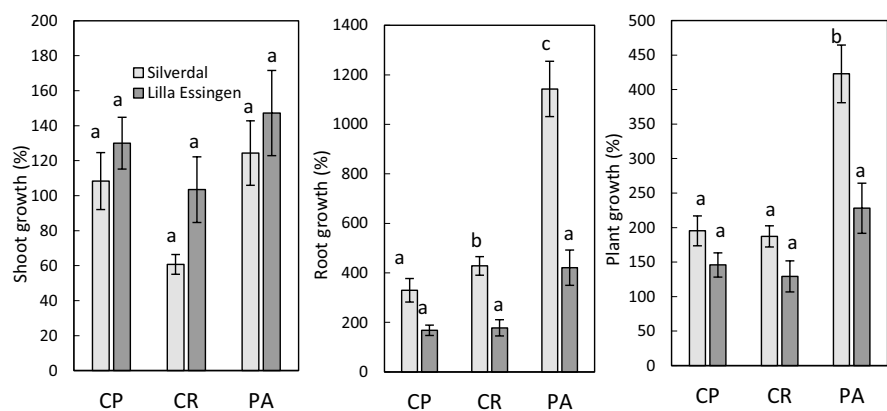
At harvest, the rafts were transported to Stockholm University (ca. 6–7 km away) on large plastic sheets to protect the roots. The rafts were immediately taken apart to remove the plants. A small portion of the roots had grown into the fibre mat and could not be separated. The root and shoot lengths of each specimen were measured. The roots were rinsed with deionized water and dishwashing soap to remove hydrophobic substances, then with deionized water, then with 20 mM EDTA to remove biofilms and loosely adsorbed metals on the root surface, and finally with double deionized water (Nyquist & Greger, 2007). Each rinsing step was conducted for 1 min. Then, all plant parts were dried for 48 h at 105 °C. The plants were weighed before and after drying.

In addition to the plants used in the field experiment, four greenhouse specimens of each species

Fig. 2 A FTW module at the start of the experiment in July (top image) and *Carex riparia* roots from Lilla Essingen stormwater pond covered with an oily pollutant at the end of the experiment in September (bottom image)



Fig. 3 Growth (percentage weight gain [fresh weight] during the field treatment) of a) the entire field-treated plants, b) the shoots of the field-treated plants, and c) the roots of the field-treated plants. CP = *Carex pseudocyperus*, CR = *Carex riparia*, and PA = *Phalaris arundinacea*. Small letters indicate significant differences ($p < 0.05$) between plant parts across species and sites



were measured and dried at 105 °C for 48 h before the start of the experiment to serve as a background control for pollutant levels.

To estimate the water quality in the ponds, water samples were collected from each site at three-week intervals starting and ending on the same dates as the field experiment. Each sample consisted of five 500-mL spot samples taken near the outlet and thoroughly mixed. The samples were placed in a 3 °C cold room within hours of sampling.

2.4 Heavy Metal Analysis

Approximately 0.1 g (for shoots) and 0.25 g (for roots) of dried plant material was taken from each shoot and root sample. To this, 10 mL of 65% HNO₃ and 4 mL of 30% H₂O₂ were added, and then the material was wet digested in a microwave oven (Speedwave, Berghof, Germany). The metal concentration of the wet-digested plant samples was then determined using atomic absorption spectrophotometry. For the analysis of Cu, Pb, and Cd, an atomic absorption spectrophotometer (AAS) with a GTA 120 furnace (SpectrAA 240; Agilent, Santa Clara, CA, USA) was used. For the Zn analysis, an AAS with a flame atomizer (SpectrAA 55B; Varian, Palo Alto, CA, USA) was used. Standard additions were used for all samples to prevent matrix effects.

2.5 Calculations

The plant growth of the whole plant was calculated as

$$\text{Plant growth (\%)} = \left(\frac{m_{\text{end(fp)}} - m_{\text{start(fp)}}}{m_{\text{start(fp)}}} \right) \times 100, \quad (1)$$

where plant growth (%) is the weight gain in percent, $m_{\text{end(fp)}}$ is the plant biomass (fresh weight) of the field-treated plants after harvest, and $m_{\text{start(fp)}}$ is the plant biomass (fresh weight) of the field-treated plants before the field treatment.

To determine the growth of the plant parts (i.e., shoots or roots), Eq. 1 was used but with the biomass of the respective plant parts. The starting biomass of the plant parts (before field treatment) was estimated using the (plant part)/(whole plant) biomass ratio of the control

plants (average for each species). The ratio was then multiplied by the whole plant biomass of the field-treated plants to obtain the starting biomass of the plant parts.

The analyzed metal concentration, as the amount of metal (μg)/per dry weight plant biomass (g), was multiplied by the dry weight of each plant part (shoots or roots) to determine the quantity of metal (μg) per plant part.

To determine the net metal amount during the experimental period in the field-treated plants, the metal amount in the control plants was used to calculate the metal concentration as metal amount/fresh weight. For each species, an average concentration was determined, which was then multiplied by the starting fresh weights (i.e., before planting in the rafts) of the field-treated plants to estimate the metal amount in the plants before the field experiment started. This value was then subtracted from the metal amount in the whole plants to obtain the net metal amount during the experimental period:

$$Me \text{ net amount}_{wp} (\mu g) = m_{Me \text{ wp}} - (m_{fp \text{ (fw)}} \times \frac{m_{Me \text{ wp (cp)}}}{m_{cp \text{ (fw)}}}), \quad (2)$$

where $Me \text{ net amount}_{wp}$ is the metal uptake (during the experimental period) of the whole plants, $m_{Me \text{ wp}}$ is the total metal amount in the plants, $m_{fp \text{ (fw)}}$ is the fresh weight of the field-treated plants at the start of the field experiment, $m_{Me \text{ wp (cp)}}$ is the metal amount in the control plants, and $m_{c.p. \text{ (fw)}}$ is the fresh weight of the control plants.

The net metal amount per plant part was determined by

$$Me \text{ net amount}_{pp} (\mu g) = m_{Me \text{ pp}} - m_{fp \text{ (fw)}} \times \text{average} \left(\frac{m_{pp \text{ (cp)}}}{m_{wp \text{ (cp)}}} \right) \times \frac{[Me]_{cp}}{\frac{m_{cp \text{ (fw)}}}{m_{cp \text{ (dw)}}}}, \quad (3)$$

where $Me \text{ net amount}_{pp}$ is the net metal amount (during the experimental period) in each plant part, $m_{Me \text{ pp}}$ is the metal amount in each plant part, $m_{fp \text{ (fw)}}$ is the fresh weight of the field-treated plants (fp), $m_{pp \text{ (cp)}}$ is the dry weight of each plant part of the control plants, $m_{wp \text{ (cp)}}$ is the dry weight of the control plants, $[Me]_{cp}$ is the metal concentration in the control plants, $m_{cp \text{ (fw)}}$ is the fresh weight of the control plants, and $m_{cp \text{ (dw)}}$ is the dry weight of the control plants.

From the net metal amount per plant part (Eq. 3), the net metal concentration in each plant part (roots or shoots) was calculated as

$$Me \text{ net concentration}_{pp} (\mu g/g \text{ dw}) = \frac{Me \text{ net amount}_{pp}}{m_{pp \text{ (dw)}}}, \quad (4)$$

where $Me\ net\ concentration_{pp}$ is the net metal concentration in each plant part, $Me\ net\ amount_{pp}$ is the net metal amount (during the experimental period) in each plant part, and $m_{pp(dw)}$ is the biomass (dry weight) of the field-treated plant parts at the end of the treatment.

The net metal concentrations in shoots and water were used to calculate the accumulation factor (AF):

$$Accumulation\ factor = \frac{Me\ net\ concentration_{shoot}}{Me\ average\ concentration\ during\ the\ period_{water}} \quad (5)$$

2.6 Statistical Analysis

Two-factor ANOVA with Tukey's HSD post hoc test was used to detect any differences in the parameters between species and sites for the statistical tests without control plants. For the tests that included control plants, Welch's test with the Games–Howell post hoc test was used, since the sample size differed between field-treated plants ($n=6$) and control plants ($n=3$). Paired t -tests were used to find differences between shoots and roots. Pearson

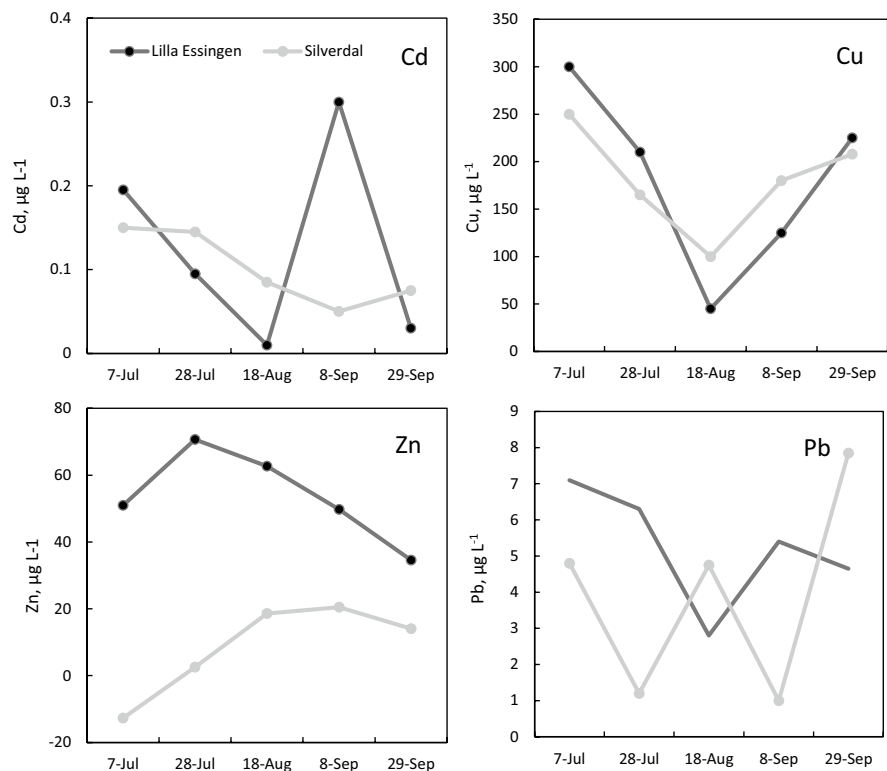
correlations between plant biomass and net metal amount/net metal concentration were calculated.

3 Results

The plants increased their biomass by 30–320%, depending on site and species, in the 12 weeks of the study, mainly resulting from root growth (Figs. 2 and 6). Root growth was generally higher at Silverdal than at Lilla Essingen, whereas the opposite tendency was found for the shoots. The growth of *P. arundinacea* tended to be higher at Lilla Essingen and was significantly higher at Silverdal than that of the *Carex* species, resulting from differences in root growth between the species.

The metal concentrations in the two ponds fluctuated during the experimental period (Fig. 4). The Cd and Cu concentrations were similar in both ponds. The Pb concentration was sometimes higher at Silverdal and sometimes higher at Lilla Essingen. The Zn concentration varied and was higher at Lilla Essingen than at Silverdal, especially at the beginning of the experimental period.

Fig. 4 Metal concentrations in the water of the stormwater ponds on the five sampling days over the 12 weeks of the experiment for a) Cu, b) Pb, c) Cd, and d) Zn. $n=1$



The metal concentration in roots was always significantly higher in field-treated plants than in controls (Table 1). Despite the same tendency in the shoots, not all differences were significant. The Zn and Pb concentrations in shoots were significantly higher in field-treated plants than in controls, with the exception of Pb in *C. pseudocyperus* at Silverdal. The Cu concentration in shoots was significantly higher in *C. pseudocyperus* at both sites and in *C. riparia* at Lilla Essingen. The shoot Cd concentration in the field plants did not differ significantly from that of the controls.

The net concentrations of Cd and Cu were about ten times higher in roots than in shoots, while the net concentrations of Pb and Zn were in the same range (Fig. 5). In most cases, the net metal concentrations in both roots and shoots tended to be higher in plants from Lilla Essingen than from Silverdal.

This was significant in *P. arundinacea* for all metals in roots and for Pb and Zn in shoots. It was also true for Pb in shoots of *C. riparia*.

The accumulation factor (AF) based on the net plant tissue concentration and the concentration in the water of the various metals is shown in Table 2. The AF was highest for Zn at both sites, although lower at Lilla Essingen than at Silverdal. The opposite was found for Pb, for which the AF was higher at Lilla Essingen than Silverdal. In the case of Cu, the AF was similar at both sites. For Cd, the AF was higher at Lilla Essingen for the two *Carex* species, while the opposite was found for *P. arundinacea*. The lowest AF was found for Cu at both sites and for Pb at Silverdal.

The net metal amount taken up and accumulated during the field treatment in shoots and roots is shown in Fig. 7. The only significant difference found between

Table 1 Metal concentration $\pm$ SE in shoots and roots of the field-treated plants and control plants. * Indicates significant difference from the control group ($p > 0.05$). CP = *Carex pseudocyperus*, CR = *Carex riparia*, and PA = *Phalaris arundinacea*. n = 6

Plant part	Species	Silverdal	Lilla Essingen	Control
Metal				
Shoot				
Cadmium	CP	0.13 ± 0.02	0.27 ± 0.06	0.07 ± 0.02
	CR	0.16 ± 0.02	0.33 ± 0.10	0.14 ± 0.03
	PA	0.33 ± 0.09	0.22 ± 0.02	0.15 ± 0.02
Copper	CP	$65 \pm 2^*$	$76 \pm 4^*$	53 ± 1
	CR	61 ± 3	$74 \pm 5^*$	49 ± 3
	PA	57 ± 2	79 ± 7	58 ± 5
Lead	CP	0.57 ± 0.12	$1.09 \pm 0.08^*$	0.21 ± 0.01
	CR	$1.10 \pm 0.20^*$	$7.29 \pm 1.38^*$	0.16 ± 0.03
	PA	$0.82 \pm 0.14^*$	$10.1 \pm 1.21^*$	0.29 ± 0.04
Zinc	CP	$198 \pm 44^*$	$277 \pm 30^*$	11 ± 1.1
	CR	$110 \pm 16^*$	$431 \pm 53^*$	13 ± 0.9
	PA	$775 \pm 52^*$	$2937 \pm 489^*$	18 ± 3.7
Root				
Cadmium	CP	$0.71 \pm 0.13^*$	$0.54 \pm 0.06^*$	0.16 ± 0.04
	CR	$0.38 \pm 0.03^*$	$0.41 \pm 0.08^*$	0.05 ± 0.02
	PA	$0.87 \pm 0.16^*$	$2.99 \pm 0.45^*$	0.14 ± 0.01
Copper	CP	$75 \pm 5^*$	$177 \pm 9^*$	58 ± 3
	CR	$72 \pm 4^*$	$93 \pm 7^*$	55 ± 1
	PA	115 ± 17	$400 \pm 16^*$	70 ± 5
Lead	CP	$3.07 \pm 0.85^*$	$4.09 \pm 0.25^*$	0.19 ± 0.03
	CR	$4.42 \pm 0.71^*$	$4.80 \pm 0.91^*$	0.14 ± 0.03
	PA	$3.29 \pm 0.37^*$	$8.33 \pm 1.63^*$	0.24 ± 0.03
Zinc	CP	$796 \pm 168^*$	$693 \pm 67^*$	17 ± 2.1
	CR	$344 \pm 29^*$	$833 \pm 105^*$	19 ± 0.6
	PA	$446 \pm 57^*$	$2689 \pm 326^*$	38 ± 6.4

Fig. 5 Net metal concentrations (metal amount taken up by plants during the field treatment/dry weight plant biomass) in shoots and roots of the field-treated plants. Error bars show the standard error. CP = *Carex pseudocyperus*, CR = *Carex riparia*, and PA = *Phalaris arundinacea*. Small letters indicate significant differences ($p < 0.05$) between plant parts across species and sites. $n = 6$

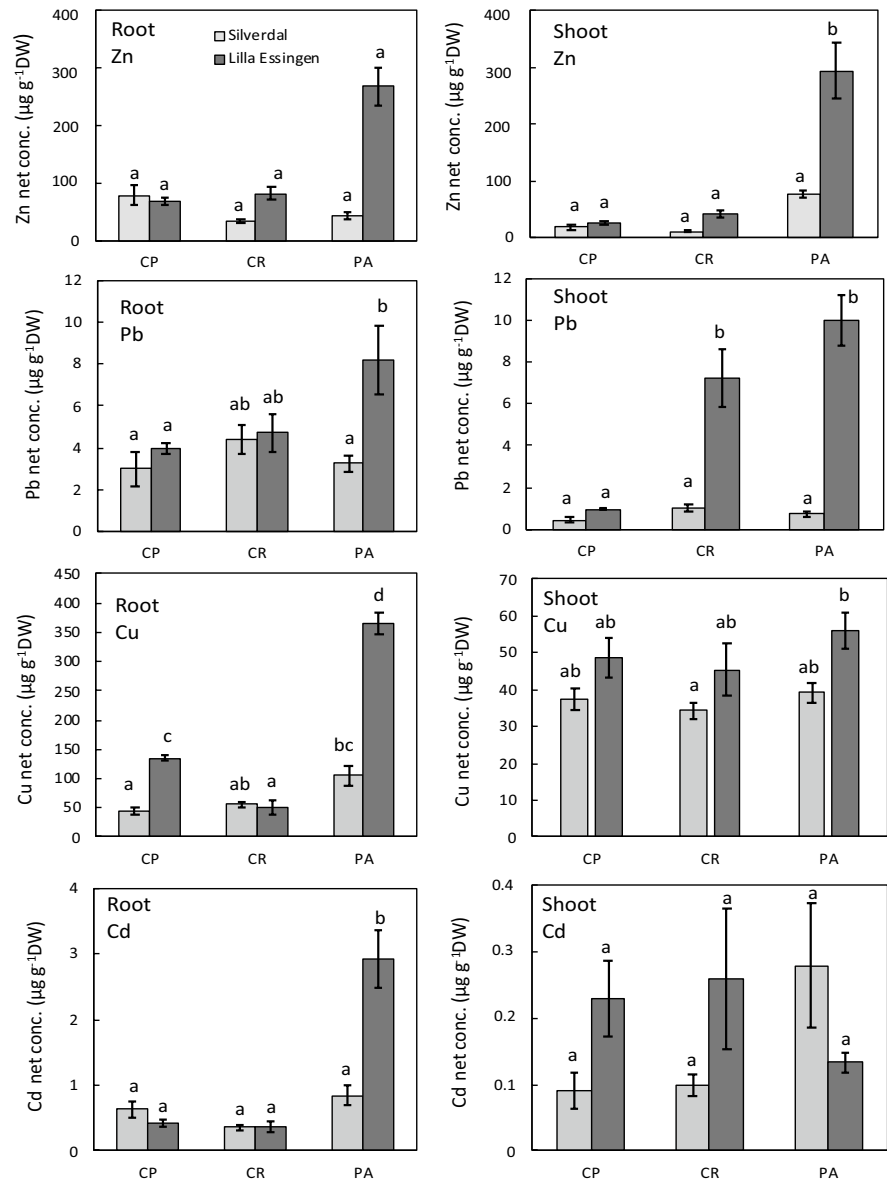


Table 2 Accumulation factor $\pm \text{SE} \leq 5\%$ for the field-treated plants. CP = *Carex pseudocyperus*, CR = *Carex riparia*, PA = *Phalaris arundinacea*, S = Silverdal, LE = Lilla Essingen. $n = 6$

	Cadmium		Copper		Lead		Zinc	
	S	LE	S	LE	S	LE	S	LE
CP	761	1580	194	287	118	186	22,343	5048
CR	837	1777	179	266	262	1378	12,187	7916
PA	2356	916	205	329	190	1909	90,011	54,564

the two sites was in shoots of *P. arundinacea*, in which the Zn and Pb contents were higher in plants from Lilla Essingen; the same difference was also found in shoots of *C. riparia* for Pb.

The effect of biomass growth on metal accumulation was examined using tests of correlation between the net metal amount in the plant parts and the biomass of the same plant parts with all plant species

combined (Table 3). Roots showed the highest positive correlation, which was significant in all cases except for Pb at Silverdal. In the case of shoots, significance was found at Lilla Essingen for Cd and Cu and at Silverdal for Zn.

4 Discussion

This study showed that the studied ecotypes of *C. pseudocyperus*, *C. riparia*, and *P. arundinacea* growing on FTWs could accumulate Cd, Cu, Pb, and Zn from the water in two stormwater ponds over 12 weeks. This finding demonstrates the opportunities to use FTWs for metal removal from stormwater. *Phalaris arundinacea* accumulated an overall higher net amount of all metals than did the *Carex* species. The metal concentration was generally higher in the roots than in the shoots.

The first objective was to determine the accumulated metal amount and the metal distribution in the plants in FTWs during the experimental period. All species were able to take up metals from the stormwater ponds (Tables 1 and 2, Figs. 5 and 7). The metal concentrations were higher in the roots than in the shoots in most cases, corresponding to the results of other studies (Deng et al., 2004; Liu et al., 2007; Stoltz & Greger, 2002) although the differences were smaller in this study. A possible explanation for this is that in environments with high metal concentrations, some plant species have mechanisms preventing the

transport of toxic levels of metals from roots to shoots (Deng et al., 2004), preventing toxic effects on photosynthesis. Additionally, our results show that *C. riparia* and *P. arundinacea* can be shoot accumulators of Pb and that *P. arundinacea* is a shoot accumulator of Zn, as they had higher concentrations of these metals in their shoots than in their roots (Fig. 5).

Overall, the net amounts of Cu and Cd were higher in the roots than in the shoots (Fig. 7). The net accumulated amounts of Pb and Zn were higher in the shoots than in the roots of *P. arundinacea*, whereas the *Carex* species did not display any large differences in net metal amounts between shoots and roots. Although the metal concentration in the tissue was generally higher in roots than in shoots, the total net metal amount was not always higher in the roots. This finding is consistent with the results of other studies (Březinová & Vymazal, 2015; Liu et al., 2007; Vymazal, 2016), which explain this by the larger shoot than root biomass. In this study, the cases in which the net metal amount was higher in the shoots than in the roots can be explained partly by higher shoot biomass and partly by higher shoot metal concentration than the root metal concentration.

Compared with studies that have evaluated metal concentrations in wetland plants (Deng et al., 2004; Kabata-Pendias & Szeke, 2015; Outridge & Noller, 1991; Vymazal et al., 2007), this study found plant concentrations of Cu and Zn that can be considered normal to high, while those of Cd and Pb were low to normal (Table 1). The metal concentrations in the water of the two ponds (Fig. 4) were low to normal for Pb, Cd, and Zn, while the Cu concentration was normal to high, compared with other reports (Shaver et al., 2007; Viklander et al., 2019). Interestingly, the Cu concentrations in the waters at Lilla Essingen and Silverdal were 3 and 22 times higher than the Zn concentrations, respectively (Fig. 4), but the plant concentrations were 3–20 times higher for Zn than for Cu (Table 2, Fig. 5). This implies that these plants are less efficient at restricting the uptake of Zn than of other metals, which can also be seen from the shoot AF reported in Table 2. Table 2 also shows that Cu was the metal that overall was the most efficiently restricted from uptake by the plants.

The second objective was to determine whether plant species, metal concentrations in the water, and growth affected metal uptake and accumulation. In

Table 3 Correlation coefficients and *p*-values for the correlations between net metal amount per plant vs. biomass of whole plant and plant parts. All three plant species are combined. * Indicates significant correlation ($p < 0.05$). S=Silverdal and LE=Lilla Essingen. $n=6$

Metal	Site	Shoot biomass vs. net metal amount		Root biomass vs. net metal amount	
		<i>r</i>	<i>p</i>	<i>r</i>	<i>p</i>
Cadmium	S	0.41	0.098	0.76	0.000*
	LE	0.56	0.023*	0.69	0.003*
Copper	S	0.35	0.151	0.79	0.000*
	LE	0.75	0.001*	0.88	0.000*
Lead	S	0.11	0.697	0.41	0.132
	LE	0.32	0.223	0.59	0.016*
Zinc	S	0.49	0.046*	0.74	0.001*
	LE	0.33	0.192	0.58	0.015*

general, the plant biomass affected the net metal amount per plant (Table 3), which is consistent with other studies (Schück & Greger, 2020b). The root biomass seemed to have a greater impact than did the shoot biomass on the net metal amount per plant (Table 3), at least according to intra-site comparisons. This effect may depend on the fact that the roots are in contact with the water and take up the metal. Growth of the plants, especially the roots, was generally higher at Silverdal than at Lilla Essingen (Figs. 2 and 6), likely because of the shade at Lilla Essingen, which is known to decrease total growth and the root:shoot ratio in *P. arundinacea* and *Carex* species (Perry & Galatowitsch, 2004).

Phalaris arundinacea had the highest growth of the studied species, resulting in the highest biomass (Fig. 2). A large biomass affects the metal uptake positively, according to both this study (Table 3) and other studies (Ladislav et al., 2015; Schück & Greger, 2020b; Wang et al., 2014). However, *P. arundinacea* grew better at Silverdal than at Lilla Essingen (Fig. 2) but accumulated a higher net amount of Pb and Zn at Lilla Essingen (Fig. 7). Also, *P. arundinacea* differed more in growth from the *Carex* species at Silverdal than at Lilla Essingen (Fig. 2), but it did not have a correspondingly higher net amount of Pb and Zn at Silverdal (Fig. 7). This finding suggests that larger biomass may not be the only explanation for higher metal uptake.

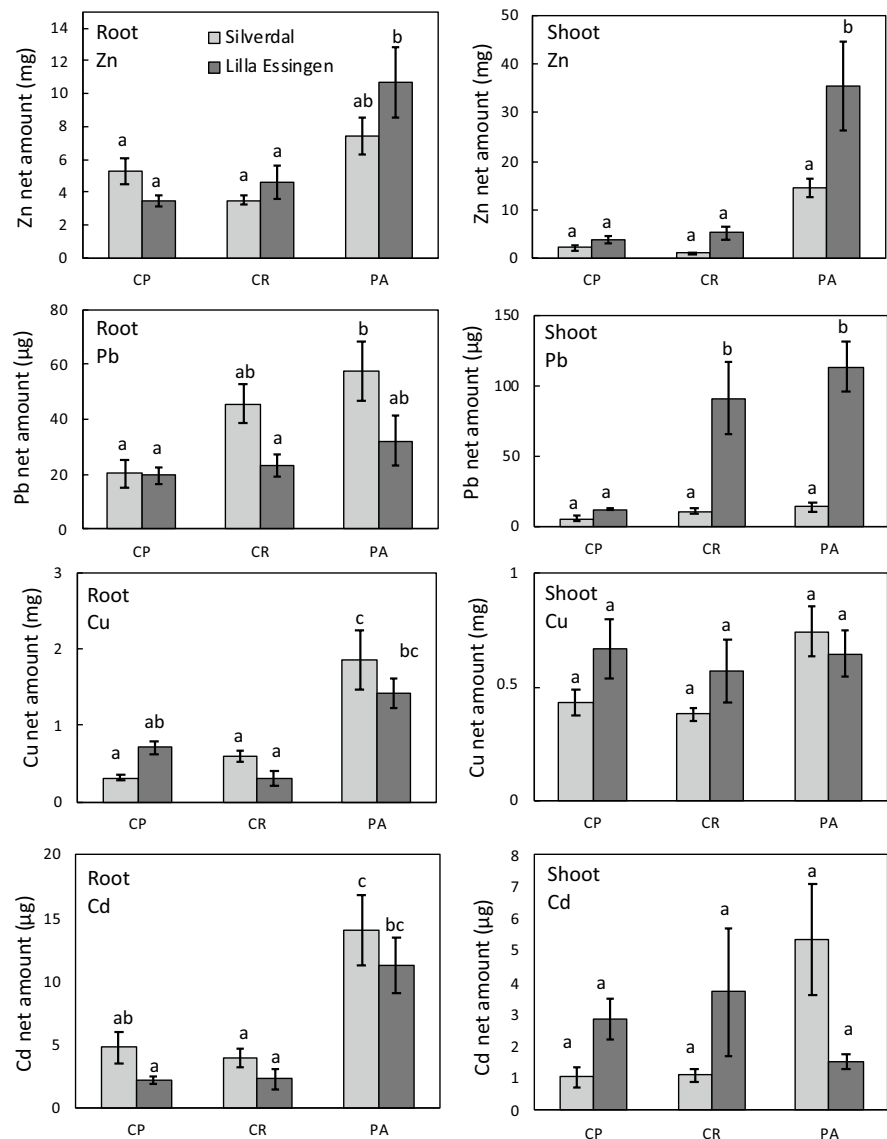
Additionally, *P. arundinacea* plants had the highest amount of fine roots, a trait that positively affects metal removal from water (Schück & Greger, 2020b). This factor might contribute to the better metal uptake by *P. arundinacea* than by the *Carex* species. The young thin roots lack an exodermis, resulting in higher diffusion into the apoplast (Hose et al., 2001). A large root network will also decrease the water flow velocity and thus increase sedimentation (Marchand et al., 2010). Also, fine root networks have larger surface areas that can absorb and adsorb more metals (Li et al., 2015). However, this could also mean that these plants are less tolerant of heavy metals, which could be a problem in the long term (Ali et al., 2019).

The metal concentrations in the water of the storm-water ponds differed significantly only for Zn (Fig. 4). The Zn tissue concentrations and net Zn amounts in the plants were generally higher in the plants at Lilla Essingen (Table 1, Figs. 5 and 7), which had the higher Zn concentration in the water. The only exception was that Zn concentrations and net Zn amounts in the roots of *C. pseudocyperus* were similar at Silverdal and Lilla Essingen. These findings suggest that the metal concentration of the water likely positively affected the metal uptake by the plants, in agreement with other studies (e.g., Deng et al., 2004). In general, the plants had higher metal concentrations at Lilla Essingen in both shoots and roots, although there were some differences between species, plant

Fig. 6 Root and shoot growth of the plants on the FTWs. Order of the plants, left–right: *Carex riparia*, *Phalaris arundinacea*, and *Carex pseudocyperus* at Lilla Essingen FTW (left image) and *Carex pseudocyperus*, *Phalaris arundinacea*, and *Carex riparia* at Silverdal FTW (right image)



Fig. 7 Net metal amounts (amount of metal that plants took up during the field treatment) per plant and per plant parts (shoots and roots) in the field-treated plants. Error bars show the standard error. Observe that Zn and Cu amounts are given in mg and Cd and Pb amounts in μg . Small letters indicate significant differences ($p < 0.05$) between plant parts across species and sites. CP = *Carex pseudocyperus*, CR = *Carex riparia*, and PA = *Phalaris arundinacea*. $n = 6$



parts, and metals. Lead differed the most in shoot concentrations between the ponds, while it differed the least in root concentrations. Regarding root concentrations, *P. arundinacea* was consistent in having multiple times higher concentrations of all metals at Lilla Essingen than at Silverdal, while this was not the case for the *Carex* species. This finding could be explained by the higher growth of *P. arundinacea* roots at Silverdal than at Lilla Essingen, which could have resulted in a dilution effect for the root concentration. The increased growth also promoted a higher net uptake of metals due to the increased root area, resulting in smaller differences between sites in the

net amount per root (Fig. 7) than in tissue concentration (Fig. 5).

In contrast to the positive effect of biomass on metal accumulation shown within each site, the plants at Silverdal did not contain overall higher net metal amounts than did the plants at Lilla Essingen despite their increased growth. The metal concentrations in the ponds were similar except for Zn, which was lower in concentration at Silverdal. Therefore, other environmental factors likely influenced the metal uptake. Upon harvesting, the roots at Lilla Essingen were covered with an oily pollutant (Fig. 3), which might have affected the plant growth and metal uptake

at this site. Other factors influencing metal uptake not measured in this study include light conditions (van Gelderen et al., 2018), water quality besides metal content (e.g., nutrient levels; (Göthberg et al., 2004), pH (Li et al., 2015), and water velocity (Weiss et al., 2014)).

The third objective was to study the species' potential for metal removal in an FTW. *Phalaris arundinacea* contained the highest overall net amounts of metals (Fig. 7) and would therefore be the most suitable species for metal removal in FTWs. It could potentially remove, by uptake, 0.58 mg and 0.40 mg of Cd, 71 and 53 mg of Cu, 1.8 and 4.2 mg of Pb, and 629 and 1339 mg of Zn per m² FTW at Silverdal and Lilla Essingen, respectively, over 12 weeks. Annual loadings of heavy metals vary greatly depending on the land use (Sakson et al., 2018). Comparing the annual metal loadings in denser urban areas (Huber & Helmreich, 2016; Järveläinen et al., 2017; Wang et al., 2013) with the metal uptake in this study, 100 m² of *P. arundinacea* would remove 0.59 g of Cd, i.e., 11.9%, 0.8 g of Cu, i.e., 89%, 0.009 g of Pb, i.e., 1.05%, and 3 g of Zn, i.e., 418% of the annual loading per hectare of catchment area over 12 weeks.

The studied species were selected based on their ability to remove metals (the *Carex* species) and chloride (*P. arundinacea*). Schück and Greger (2020a) found that the *Carex* species removed more metal than did *P. arundinacea* for all metals after 0.5 h of metal exposure, but that after five days of metal exposure, *P. arundinacea* had removed more Cd, Pb, and Zn than had the *Carex* species. This finding implies that *P. arundinacea* is better at metal removal in the long term, which is in line with the present study, showing that *P. arundinacea* overall took up more metals than did the *Carex* species (Fig. 7). The better removal by the *Carex* species during the first 0.5 h could be explained by the involvement of other mechanisms in addition to those considered here. Schück and Greger (2020a) measured the metal concentration decrease in water where plant metal uptake, sedimentation, adsorption, and precipitation all contributed to the metal removal, but in the present study, only plant metal uptake and adsorption were measured. This implies that *P. arundinacea* is a better species than the *Carex* species for metal removal by plant uptake, while the *Carex* species might be better in promoting the sedimentation, biofilm sorption, and precipitation of metals.

The next step would be to investigate how the plants perform over a whole growing season and whether harvesting during the season is beneficial for the total net metal uptake by the plants. Březinová and Vymazal (2015) showed that the quantity of metals in *P. arundinacea* varies over the growing season, with different metals reaching their maximum quantities at different times of year. This makes it difficult to predict the time of a harvest that would give the maximum metal removal. A large-scale experiment with a larger area of FTWs is also necessary, as the plant roots slow down the water velocity (Marchand et al., 2010). This effect increases the retention time of the metals in the water, which would increase sedimentation and give more time for interaction between plants and metals. Moreover, a large-scale experiment should include the monitoring of metal concentrations in inlet and outlet water, sediment, and plant parts to quantify the different metal removal pathways related to FTWs. Finally, the impact of shading on FTW metal removal efficacy remains to be elucidated.

5 Conclusions

The study showed that all three investigated plants were able to remove heavy metals Cd, Cu, Pb, and Zn and that the plant roots generally contained the highest metal concentration. The plants accumulated metals in the order Zn > Cu > Pb > Cd. The amount of accumulated metal per plant was also affected by plant biomass, especially root biomass, plant species, and the concentration of the metals in the water. The influence of plant biomass on accumulation stresses the importance of good growing conditions and well-adapted plants for these specific site conditions for each FTW. In this study, *Phalaris arundinacea* had the highest metal uptake, implying that this species could be a good candidate for use in FTWs. From this study, we can conclude that wetland plants growing in FTWs take up metals from water in stormwater ponds, making FTWs a possible technique for heavy metal removal from stormwater in cold climates.

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Data Availability The datasets analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of Interest The authors have no relevant financial or non-financial interests to disclose. Data will be made available on reasonable request.

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