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Accumulation properties of As, Cd, Cu, Pb and Zn by four wetland plant species growing on submerged mine tailings

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Abstract

Plants may reduce element leakage from submerged mine tailings by phytostabilisation. However, high shoot concentrations of elements might disperse them and could be harmful to grazing animals. The aim of this investigation was to find out which of the three properties; low-accumulation, root accumulation or shoot accumulation of elements, occur in four of the most common wetland species growing on an old submerged mine tailings and if their properties can be determined by a hydroponic experiment. Above- and below-ground parts of *Salix* (mixed tissue from *S. phylicifolia* and *S. borealis*), *Carex rostrata*, *Eriophorum angustifolium*, and *Phragmites australis* were sampled and analysed for Cd, Cu, Zn, Pb and As. Differences in uptake and translocation properties of the same plant species were observed between field-grown plants and plants grown in hydroponics. These differences were probably due to processes in the soil–root interface. Thus, hydroponic screening studies should not be used to find suitable species for vegetation of wet-covered mine tailings. Most species were found to have restricted translocation of elements to the shoot, i.e. they were root accumulators, and only the shoot concentrations of *Salix* for Cd and Zn and *E. angustifolium* for Pb might be toxic to grazing animals. Thus, plant establishment on submerged tailings can be a safe method to stabilise the metals.

Keywords: Distribution; Metals; Hydroponics; *Carex rostrata*; *Eriophorum angustifolium*; *Phragmites australis*; *Salix borealis*; *Salix phylicfolia*

1. Introduction

Plants that are tolerant to elements of high concentrations have been found useful for reclamation of dry mine tailings containing elevated levels of metals and other elements (Smith and Bradshaw, 1979; Tordoff et al., 2000). Mine tailings rich in sulphides, e.g. pyrite, can form acid mine drainage (AMD) if it reacts with atmospheric oxygen and water, which may also promote the release of metals and As (Lawrence and Higgs, 1999) from the tailings. To prevent AMD formation, mine tailings rich in sulphides may be saturated with water to reduce the penetration of atmospheric oxygen. An organic layer with plants on top of the mine tailings would consume oxygen, as would plant roots through respiration. Thus, phytostabilisation on water-covered mine

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tailings may further reduce the oxygen penetration into the mine tailings and prevent the release of elevated levels of elements into the surroundings.

Metal tolerance can be evolutionarily developed while some plant species seem to have an inherent tolerance to heavy metals (Wu, 1990). Since, some wetland plant species have been found with the latter property, for example *Thypha latifolia*, *Glyceria fluitans* and *Phragmites australis* (Wu, 1990; McCabe and Otte, 2000), wetland communities may easily establish on submerged mine tailings, without prior development of metal tolerance.

The relationships between element concentrations in plants and concentrations in the substrate differ between plant species. Some plant species have mechanisms that make it possible to cope with high external levels of elements. Low-accumulators are plants that can reduce the uptake when the substrate has high element concentrations, or have a high net efflux of the element in question, thus the plant tissue concentration of the element is low even though the concentration in the substrate is high. Plants with a higher concentration than the substrate of an element are considered accumulators (Baker and Walker, 1990) and the storage capacity of the metal can vary between organ and between species. Some species store elements in the roots, root accumulators, while others store them in the shoots, shoot accumulators. *Armeria maritima halleri* and *Agrostis capillaris* are examples of root accumulators of Zn, Cd, Pb and Cu (Dahmani-Muller et al., 2000). Many metal-tolerant plant species growing on contaminated soils have been found to be root accumulators with restricted translocation of metals to the shoot (Baker and Walker, 1990). Shoot accumulators can translocate the elements to a high extent from the root and accumulate the elements in the shoot. Such properties have been found in *Cardaminopsis halleri* for Zn and Cd (Dahmani-Muller et al., 2000) and *Thlaspi goeingense* for Ni (Krämer et al., 1997). If plants growing on water-saturated mine tailings accumulate Cd, Cu, Zn, Pb and As in the shoot, the elements may be dispersed into the environment through herbivores or at senescence. All five elements are toxic to animals at higher concentrations, the tolerable levels for domestic animals in air dried forage being 500–1000 mg kg^{-1} Zn, 0.5 mg kg^{-1} Cd, 25–80 mg kg^{-1} Cu, 30 mg kg^{-1} Pb and 100 mg kg^{-1} organic As (NRC, 1980).

The aim of this investigation was to find out which of the three properties, i.e. low-accumulation, root accumulation or shoot accumulation of Cd, Cu, Pb, Zn and As, occur in four of the most common wetland species growing on an old submerged mine tailings with natural plant establishment. This information would be helpful in determining if those species are suitable, i.e. not shoot accumulators, for plant establishment on mine tailings. The plant uptake from mine tailings was compared with hydroponically grown plants in order to find out if the uptake properties were related to a tailing–root interface communication or if they were directed through pore water uptake. The first hypothesis was that the uptake and translocation properties of metals and As in field plants differ with that in hydroponics. This would show the importance of a soil–root interface for elemental uptake properties and would determine if a hydroponic screening test would be a good method to find plant species suitable for re-vegetation of mine tailings. The second hypothesis was that most of the plant species growing on mine tailings have restricted translocation of metals to the shoot, as do many tolerant species (Baker and Walker, 1990). Thus, plant establishment on wet covered mine tailings would stabilise the metals, not disperse them.

2. Materials and methods

2.1. Materials

A submerged tailings impoundment had received sewage water during the period 1953–1983, which had caused the formation of wetland vegetation at the Boliden mine in Northern Sweden (64° 52′ N, 20° 22′ E). Mine tailings (rich in pyrite) and roots and shoots of *Salix phylicifolia* L. and *S. borealis* Fr. (which were mixed together and will hereafter be called *Salix*), *Carex rostrata* Stokes, *Eriophorum angustifolium* Honk, and

Phragmites australis (Cav.) Steud. were collected from the tailings impoundment. The plant species chosen were four of the most common at the Boliden tailings impoundment. At the time of collection the plants had been growing in the tailings, and thus been exposed to metals and As, for 2.5 months. Seeds from all species were also collected, except for *Salix* where stem cuttings were sampled. The seeds and *Salix* cuttings were stored wet in darkness at +4 °C until use. The seeds were then treated with diurnal fluctuations in both temperature and light (a 12-h dark period with 6 °C, and a 12-h light period of 19 °C) for 3 days, in order to increase the viability of wetland plant seeds (Thompson et al., 1977). After the diurnal treatment, the seeds were left to germinate on wet filter paper for 2 days.

2.2. Field material

The plant parts, collected from the submerged tailings impoundment, were rinsed in redistilled water, dried (at 80 °C for As analyses, and 105 °C for the analyses of the metals) and wet digested in HNO_3:$HClO_4$ (7:3, V/V). Mine tailings were dried in the same way as plant material and wet digested for 30 min in 7 M HNO_3 at 120 °C to obtain the 'total' fraction of heavy metals. The 'bio-available' fraction was obtained when dried tailings were extracted for 16 h in 1 M NH_4OAc, having a pH one unit lower than the tailings samples according to a modified method of Andersson (1976). Samples of plants and tailings were analysed for Cd, Cu, Pb, Zn and As (see below).

2.3. Metal treatment experiment

The germinated seedlings were moved to trays with vermiculite and watered with 1% nutrient solution. The nutrient solution was a modified Hoagland solution (Eliasson, 1978) with an addition of Si (100% Hoagland contained 500 μM Si) the pH was 6.3. After 1 month the seedlings were mounted in styrofoam plates and placed in 3 l pots (about 30 plants in each pot) containing 1% nutrient solution. The concentration of the nutrient solution was gradually increased and changed once a week; after 2 weeks, 20% nutrient solution was added, and after 3 weeks the final concentration of 50% nutrient solution was given to the plants, which continued during the next 4 weeks. At the same time as the seedlings received 50% nutrient solution, the *Salix* stems were cut into 7 cm pieces, mounted in styrofoam plates and placed in 3 l pots with 100 μM Ca $(NO_3)_2$, which were also changed once a week. When the *Salix* cuttings had been growing for 4 weeks and the seeds for approximately 11 weeks, the metal treatment experiment started for all species. During the time before the metal treatment, the plants were kept in a greenhouse (set for 18 ± 1 °C, RH ~ 70%), equipped with supplementary lamps (Osram Daylight lights, HQI-BT 400W); the light period was 12-h.

Six plants of each species, except for *Salix* where four plants were used, were mounted in black styrofoam plates and placed in 1 l plastic pots filled with 30% nutrient solution with or without the addition of heavy metals. In metal-treatment pots, the elements given were 0.12 μM Cd, 2.7 μM Cu, 19.8 μM Pb, 42.3 μM Zn and 6.37 μM As. The elements had the same proportions to each other as in the NH_4OAc-extractable fraction (Table 1) of the mine tailings. Five replicates were used for each treatment and each species. There was no aeration of the solution before or during the metal treatment. The pots were kept in a climate chamber equipped with metal halogen lamps (Osram, Powerstar HQI-R) providing a photon flux density of 200 μmol m^{-2} s^{-1} during the light period of 20 h with 20 °C. The dark period was set to 4 h and 16 °C. Relative humidity was 70%. After 1 week all plants were rinsed in redistilled water, dried (at 80 °C for 48 h) and wet digested in HNO_3:$HClO_4$ (7:3, V/V), and thereafter analysed for Cd, Cu, Pb, Zn and As (see below). Arsenic concentrations in plant parts and tailings were recalculated to obtain the concentrations at 105 °C dry weight for comparability with the metals.

2.4. Analyses of metals and As

All elements were analysed on the atomic absorption spectrophotometer (Varian Spectr AA-

100). Cadmium, Cu, Pb and Zn were analysed using flame spectrometry, some of the Cd samples were analysed using the furnace technique (GTA-97), and As using the vapour generation technique (VGA-77).

2.5. Calculations and statistics

The shoot and root accumulation factor in relation to the NH_4OAc-extractable concentration in the tailings (AF_{bio}) was calculated for plants from the field as the ratio between $[Element]_{plant}$:$[NH_4OAc\text{-extractable element}]_{in\ tailing}$. The distribution of metals and As within a plant was expressed in the $[Element]_{shoot}$:$[Element]_{root}$ ratio, and was calculated both for the plants from the field, and for the plants treated with metal and As solution.

In the field samples, the means of three replicates for plants and four replicates for tailings were used. In the metal-treated plant experiment, the mean of five replicates was used and each replicate consisted of six plants, except for *Salix* where four plants were used. An analysis of variance (ANOVA) ($\alpha = 0.05$) was performed with STATISTICA'99 (Microsoft). Post Hoc comparisons with Tukey's Honest Significant Different (HSD) test were used to find out differences between groups. To find differences between element concentrations of plants grown in the field and the element accumulation of treated plants, t-tests with separate variance estimates were performed ($\alpha = 0.05$).

3. Results

Table 1 shows the element concentrations in different plant parts from the plant species grown in the mine tailings. In general, the element concentrations of roots were higher than that of shoots. However, the opposite was found for Cd and Zn in the case of *Salix*. Furthermore, *Salix* had the significantly highest Cd concentration in

Table 1
Metal concentration (mg kg^{-1} DW) in different plant parts and mine tailings collected at a mine-tailing impoundment at Boliden mine site

Sample	Part or fraction	Cd	Zn	Cu	Pb	As
Above ground part						
Salix	Leaf	12.5 ± 4.4 a	1130 ± 470 a	7.8 ± 0.5 b	3.4 ± 1.2 b	0.7 ± 0.1 c
Salix	Stem	7.3 ± 1.9 ab	852 ± 344 a	10.9 ± 2.3 b	15.4 ± 4.1 b	0.9 ± 0.3 c
P. australis	Shoot	1.0 ± 0.5 b	68 ± 5 a	6.4 ± 5.8 b	4.1 ± 0.5 b	1.0 ± 0.3 cb
C. rostrata	Shoot	0.4 ± 0.2 b	90 ± 6 a	12.6 ± 1.7 b	12.8 ± 3.0 b	5.7 ± 1.1 ab
E. angustifolium	Shoot	0.7 ± 0.4 b	187 ± 12 a	22.6 ± 0.8 a	38.3 ± 3.7 a	8.4 ± 2.1 a
Below ground part						
Salix	Root	6.2 ± 1.1 x	566 ± 257 x	88.2 ± 38.9 xy	348 ± 285.0 x	127.0 ± 28.2 xy
P. australis	Rhizome	0.1 ± 0.1 y	80 ± 36 x	8.0 ± 2.1 y	8.1 ± 4.5 x	2.6 ± 0.7 y
P. australis	Root	4.6 ± 1.8 xy	1310 ± 901 x	80.1 ± 2.8 xy	523 ± 154.0 x	32.5 ± 7.5 y
C. rostrata	Root	1.4 ± 0.5 xy	656 ± 62 x	74.9 ± 4.1 xy	305 ± 18.4 x	26.9 ± 4.2 y
E. angustifolium	Root	4.3 ± 0.6 x	1630 ± 17 x	160.0 ± 26.7 x	920 ± 357.0 x	276.0 ± 88.9 x
Mine tailings						
	Total	52.4 ± 4.8	14 500 ± 474	1420 ± 171.0	2040 ± 82.0	152 ± 8.1
	NH_4OAc-extractable	1.3 ± 0.3	277 ± 83	17.1 ± 4.9	410 ± 62.1	7.7 ± 1.8

Values are means of three (plants) and four (tailings) replicates ± S.E. Different letters for above-ground (a–c) and below-ground (x–z) tissue show significant differences ($P < 0.05$) between the plant species for each element.

Table 2
Accumulation factor in plant species in relation to bioavailable extractable fraction in tailings, AF_{bio} ($[Element]_{plant}$:$[NH_4OAc\text{-extractable element}]_{in\ tailing}$)

Sample	Plant part	AF_{bio}				
		Cd	Zn	Cu	Pb	As
Above ground part						
Salix	Leaf	9.97 ± 3.47 a	4.07 ± 1.70 a	0.45 ± 0.03 b	0.01 ± 0.003 b	0.09 ± 0.02 c
Salix	Stem	5.83 ± 1.48 ab	3.08 ± 1.23 a	0.64 ± 0.13 b	0.04 ± 0.010 b	0.11 ± 0.04 c
P. australis	Shoot	0.77 ± 0.36 b	0.24 ± 0.02 a	0.37 ± 0.16 b	0.01 ± 0.001 b	0.13 ± 0.04 bc
C. rostrata	Shoot	0.34 ± 0.14 b	0.32 ± 0.02 a	0.73 ± 0.10 b	0.03 ± 0.007 b	0.74 ± 0.15 ab
E. angustifolium	Shoot	0.68 ± 0.55 b	0.68 ± 0.04 a	1.32 ± 0.0 5 a	0.09 ± 0.009 a	1.09 ± 0.27 a
Below ground part						
Salix	Root	4.90 ± 0.91 x	2.05 ± 0.93 x	5.15 ± 2.27 xy	0.85 ± 0.690 x	16.60 ± 3.67 x
P. australis	Rhizome	0.06 ± 0.06 y	0.29 ± 0.12 x	0.46 ± 0.12 y	0.20 ± 0.010 x	0.33 ± 0.10 y
P. australis	Root	3.65 ± 1.41 xy	4.73 ± 3.20 x	4.67 ± 0.33 xy	1.28 ± 0.380 x	4.75 ± 1.02 y
C. rostrata	Root	1.14 ± 0.39 xy	2.37 ± 0.22 x	4.37 ± 0.24 xy	0.75 ± 0.040 x	3.51 ± 0.55 y
E. angustifolium	Root	4.82 ± 1.44 x	5.89 ± 0.61 x	9.31 ± 1.55 x	2.25 ± 0.870 x	36.00 ± 11.60 x

Based on data in Table 1. Mean value ± S.E., $n = 3$. Different letters for above-ground (a–c) and below-ground (x–z) tissue show significant differences ($P < 0.05$) between the plant species for each element.

the leaves and stems among the plant species. No significant differences were found for Zn concentration, even though *Salix* had high shoot levels. *E. angustifolium* had the highest shoot concentrations of Cu, Pb and As, although the As concentration was not significantly different from *C. rostrata*. Due to high variation in element concentrations of the belowground plant parts, there were few significant differences in element concentrations of plant roots and rhizomes (Table 1).

None of the element concentrations of the plant parts reached above the total concentration of the same element in the mine tailings, except for *E. angustifolium*, which had higher As concentration in roots than the total As concentration of the tailings (Table 1). However, most of the root metal concentrations exceeded the metal concentration of the NH_4OAc-extractable fraction of the metal in question, $AF_{bio} > 1$ (Tables 1 and 2). The AF_{bio} was significantly higher in above-ground tissues for Cd in *Salix* leaves, and for Cu and Pb in *E. angustifolium* compared with the other species. Shoot of *E. angustifolium* and *C. rostrata* had also significantly higher AF_{bio} for As compared with *Salix*. No significant differences were found for Zn shoot AF_{bio}. In root tissue no significant differences were found for Zn and Pb between the species. The rhizome of *P. australis* had significantly lower AF_{bio} for Cd and Cu compared with *E. angustifolium*. In addition, the Cd AF_{bio} for the rhizomes of *P. australis* were lower compared with *Salix*. For As, *E. angustifolium* had significantly higher AF_{bio} than *P. australis* and *C. rostrata*.

The metal concentrations of the plants treated with metals and As solution, control plants and the difference between treated and control plants, i.e. the accumulation over the treatment time, are shown in Table 3. The following results of the accumulation are statistically significant. *P. australis* had the highest Zn and Pb accumulation in the shoot. *Salix* leaves had lower As concentrations in above-ground parts compared with *P. australis* and *C. rostrata*. No differences were found for Cd shoot accumulation between the various species. The highest accumulation of Zn in roots was found in *P. australis*. *E. angustifolium* had higher root accumulation of Cd compared with *P. australis*. The Cu accumulation was lower in *C. rostrata* and *E. angustifolium* compared with *Salix* and *P. australis*. The two last-mentioned species had higher As concentrations compared with *C. rostrata* and *E. angustifolium*. No differences were found in root Pb accumulation.

Table 3
Metal concentrations (mg kg^{-1}DW) in different parts of plants of plants treated with a solution containing 0.12 μM Cd, 42.3 μM Zn, 2.7 μM Cu, 19.8 μM Pb and 6.37 μM As during 1 week (*T*), control plants grown in nutrient solution (*C*) and the difference between the treated and controls (*T*−*C*)

Species	Plant part	Cd			Zn			Cu			Pb			As		
		T	*C*	*T*−*C*	*T*	*C*	*T*−*C*	*T*	*C*	*T*−*C*	*T*	*C*	*T*−*C*	*T*	*C*	*T*−*C*
Salix	Leaf	5.7	2.6	3.1 a	302	141	162 b	9.5	5.7	3.8 b	11.0	1.8	9.3 b	0.5	0.11	0.4 b
P. australis	Shoot	2.5	1.2	1.8 a	439	51	388 a	18.7	10.5	8.2 a	28.8	2.3	26.4 a	1.2	0.06	1.2 a
C. rostrata	Shoot	2.6	0.5	2.1 a	212	32	180 b	16.0	7.7	8.4 b	12.9	2.3	10.6 b	1.1	0.02	1.1 a
E. angustifolium	Shoot	4.2	2.6	3.1 a	232	44	188 b	15.7	8.6	7.1 ab	12.0	0.6	11.4 b	0.8	0.03	0.6 ab
Salix	Root	66.4	3.3	63.1 xy	1114	153	961 y	322.7	8.2	314.5 x	2858	24	2833 x	1.1	0.7	45.1 x
P. australis	Root	40.7	6.8	38.3 y	5608	46	5562 x	485.0	20.3	464.7 x	1619	28	1591 x	42.0	0.1	41.9 x
C. rostrata	Root	42.8	2.2	40.6 xy	1631	44	1587 y	118.4	7.2	111.2 y	1169	25	1144 x	9.4	0.4	9.4 y
E. angustifolium	Root	72.1	3.6	68.4 x	1453	48	1405 y	100.1	11.9	88.1 y	1330	12	1318 x	6.3	0.1	6.6 y

Values are means of five replicates. Different letters for above-ground (a–c) and below-ground (x–z) tissue show significant differences ($P<0.05$) of *T*−*C* values between the plant species for each element.

The distribution of the elements within the plant is presented in Fig. 1. *Salix* was the only species having higher concentrations of an element in the shoot compared with the roots, i.e. for Zn and Cd. *C. rostrata* had significantly higher $[\text{Element}]_{\text{shoot}}$:$[\text{Element}]_{\text{root}}$ ratio in the field collected plants of Cd, Cu and Pb than in the treated plants. The same phenomenon was shown for Cd in *Salix*. No significant differences in the $[\text{Element}]_{\text{shoot}}$:$[\text{Element}]_{\text{root}}$ ratio were found between field and treated plants for any of the metals in *E. angustifolium* and *P. australis*.

Based on the field results above, the metal uptake and translocation properties of the different plant species have been summarised in Table 4. Most species were found to be root accumulators, and all species were root accumulators for Cu, Zn and As. The few shoot accumulators that appeared were *Salix* for Cd and Zn and *E. angustifolium* for Cu and As. Lead was the only metal that was low-accumulated by *C. rostrata* and *Salix*.

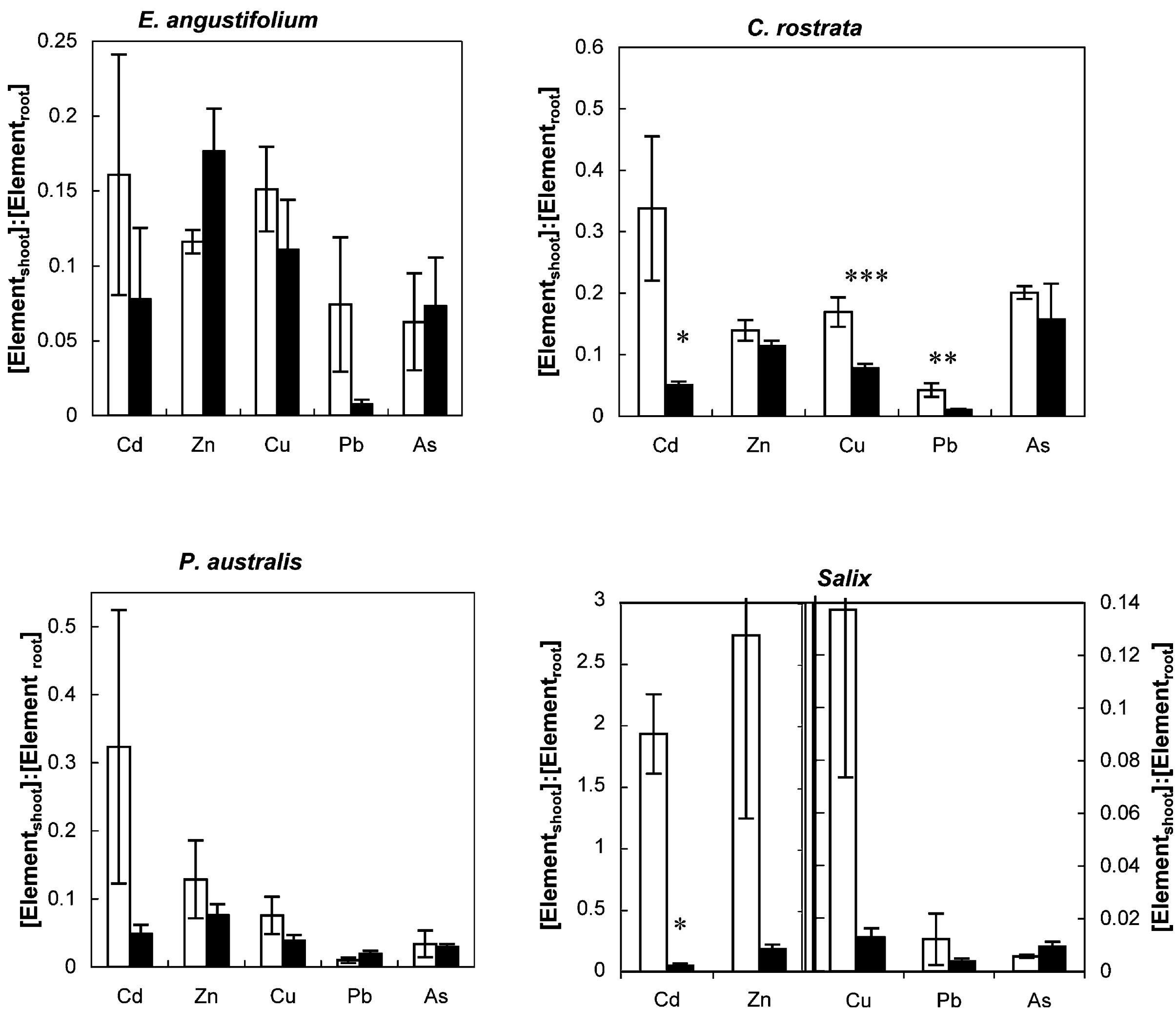

Fig. 1. $[\text{Element}]_{\text{shoot}}$:$[\text{Element}]_{\text{root}}$ ratios in field plants (white bars) and in plants treated for 1 week with a solution containing 0.12 μM Cd, 2.7 μM Cu, 19.8 μM Pb, 42.3 μM Zn and 6.37 μM As (black bars). Values are means of 3 (field) and 5 (treated), ± S.E. *; $P < 0.05$, **, $P < 0.01$ and ***, $P < 0.001$ show where there are significant differences between field and treated plant ratios.

Table 4
Accumulation properties of Cd, Cu, Zn, Pb and As by the four investigated plant species

Trace element	*Carex rostrata*	*Salix*	*Phragmites australis*	*Eriophorum angustifolium*
Cadmium	Intermediate	Root accumulator Shoot accumulator	Root accumulator	Root accumulator
Copper	Root accumulator	Root accumulator	Root accumulator	Root accumulator Shoot accumulator
Zinc	Root accumulator	Root accumulator Shoot accumulator	Root accumulator	Root accumulator
Lead	Low-accumulator	Low-accumulator	Intermediate	Root accumulator
Arsenic	Root accumulator	Root accumulator	Root accumulator	Root accumulator Shoot accumulator

The different properties were defined as: 'Low-accumulator'—plants with lower tissue concentrations, 'Root accumulators'—plants with higher root concentrations, 'Shoot accumulators'—plants with higher shoot concentrations than the NH_4OAc-extractable fraction of the mine tailings and 'Intermediate'—plants with properties in between the different properties.

4. Discussion

The first hypothesis, that uptake and translocation properties of metals and As might be different in field plants compared with hydroponically grown plants, was confirmed by the results. In the field, *Salix* for Cd and *E. angustifolium* for Cu, Pb and As, showed the highest shoot concentrations (Table 1). In hydrophonics, however, the same pattern was not seen; *P. australis* had the highest Zn and Pb concentrations and *Salix* and *E. angustifolium* did not show any shoot-accumulation properties (Table 3). In addition, there are differences in plant element distribution in *C. rostrata* and *Salix* between the two treatments (Fig. 1). These differences are probably due to the fact that the growth conditions were different. In the field, there are interactions between root–soil particles, root–bacteria and/or root–mycorrhiza (Burd et al., 2000; Khan et al., 2000), which are not present in solution and might affect the metal uptake and translocation. Moreover, the effects of e.g. oxygen or proton release from roots in metal availability may have different effects in the field compared with that in hydroponics (Chen and Barko, 1988; Armstrong et al., 1992; Brix, 1993; Murányi et al., 1994). Thus, a simple hydroponic screening experiment is not a suitable method to investigate plant species uptake and accumulation properties.

The second hypothesis was that most of the plant species growing on mine tailings have a restricted translocation of metals and As to the shoot. This hypothesis was supported by the results since most species were found to be root accumulators (Table 4). A low distribution of elements to the shoots compared with the root was found in most of the species and elements, both in plants grown in solution culture and those collected from the mine tailings (Fig. 1; Table 4). Coughtrey and Martin (1978) showed that the translocation of metals to the shoot of *Holcus lanatus* is prevented in ecotypes from metal-contaminated sites, and Landberg and Greger (1996) found the same results for different *Salix* species. The suggested reason was the protection of photosynthesis from toxic levels of trace elements. Baker (1981) also discussed restriction of shoot metal uptake in plants from contaminated soils, and the presence of exclusion mechanisms in such species was suggested. However, the high leaf concentrations of Cd in *Salix* can be explained by the Cd shoot accumulation ability that many *Salix* species have (Greger and Landberg, 1995).

The shoot concentrations of plant species growing on wet-covered mine tailings are elevated in *Salix* and *P. australis* (Table 5) compared with other studies of the same species (Peverly et al., 1995; Landberg and Greger, 1996). The question arises if the shoot accumulator plants are poten-

Table 5
Metal concentrations in plants growing in mine tailings, in plants growing in unpolluted soil (Pais and Jones, 2000) and the maximum tolerable levels of daily intake by animals (NRC, 1980)

Metal	Concentrations in plants growing on mine tailings, (mg kg^{-1} DW)		Concentrations in normal plant, (mg kg^{-1} DW)	Tolerable levels for animal, (mg kg^{-1} air dried forage)
	Salix (leaf)	*E. angustifolium* (shoot)		
Cadmium	12.5	–	0.2–0.8	0.50
Zinc	1126	–	15–200	500–1000
Arsenic	–	8.4	0.1–5	100[a]
Copper	–	22.6	4–15	25–800
Lead	–	38.3	0.1–10	30

[a] For organically bound As.

tial risks to the environment. *Salix* was found to have properties of a shoot accumulator of Cd and Zn and Table 5 shows that the concentrations in *Salix* shoot of Zn and Cd are high compared with a 'normal' plant. Reindeer (*Rangifer tarandus*) and moose (*Alces alces*) are two species existing in the North part of Sweden, where also many mining sites are situated. Both animal species have been found to consume *Salix* (Oldemeyer and Regelin, 1987; Warenberg et al., 1997) furthermore; reindeer and lesser snow geese (*Anser caerulescens caerulescens*) can graze on *E. angustifolium* (Hupp et al., 2000; Warenberg et al., 1997). The tolerable metal levels for domestic animals (cattle, sheep, swine, poultry, horse and rabbit) were used in Table 5, since no such criteria for wild animals were found. Table 5 shows that *Salix* should be avoided for plant establishment on mine tailings containing high levels of Cd and Zn. Furthermore, *E. angustifolium* showed tendencies to have shoot accumulator properties for As and Cu, however, the levels were not too high (Table 5) and unlikely to cause harm to animals. Even though no shoot-accumulation properties were found some plants could have high shoot metal concentrations that it might be toxic to animals, e.g. the Pb concentration in *E. angustifolium* (Table 5). *P. australis* and *C. rostrata* had properties of root accumulators for all metals except Pb, where they were low-accumulators (Table 4) also the concentrations were not exceeding the concentrations of 'normal plants', hence, they are suitable for plant establishment on mine tailings.

We conclude that most of the plant species in this study can be used for phytostabilisation on wet-covered mine tailings. However, to find out if a plant species is suitable for this purpose, the trace element concentration of the plant shoot when growing in the tailings must be known.

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References

Andersson, A., 1976. On the determination of ecologically significant fractions of some heavy metals in soil. Swed. J. Agric. Res. 6, 19–25.

Armstrong, J., Armstrong, W., Beckett, P.M., 1992. *Phragmites australis*: Venturi- and humidity-induced pressure flows enhance rhizome aeration and rhizosphere oxidation. New Phytol. 120, 107–207.

Baker, A.J.M., 1981. Accumulators and excluders—strategies in response of plants to heavy metals. J. Plant Nutr. 3, 643–654.
Baker, A.J.M., Walker, P.L., 1990. Ecophysiology of metal uptake by tolerant plants. In: Shaw, A.J. (Ed.), Heavy Metal Tolerance in Plants: Evolutionary Aspects. CRC Press, Boca Raton, FL, pp. 155–177.
Brix, H., 1993. Macrophyte-mediated oxygen transfer in wetlands: transport mechanisms and rates. In: Moshiri, G.A. (Ed.), Constructed Wetland for Water Quality Improvement. Lewis Publishers, Boca Raton, London, Tokyo, pp. 391–398.
Burd, G.I., Dixon, D.G., Glick, B.R., 2000. Plant growth-promoting bacteria that decrease heavy metal toxicity in plants. Can. J. Microbiol. 46, 237–245.
Chen, R.L., Barko, J.W., 1988. Effects of freshwater macrophytes on sediment chemistry. J. Freshw. Ecol. 4, 279–289.
Coughtrey, P.J., Martin, M.H., 1978. Cadmium uptake and distribution in tolerant and nontolerant populations of *Holcus lanatus* grown in solution culture. Oikos 30, 555–560.
Dahmani-Muller, H., van Oort, F., Gélie, B., Balabane, M., 2000. Strategies of heavy metal uptake by three plant species growing near a metal smelter. Environ. Pollut. 109, 231–238.
Eliasson, L., 1978. Effects of nutrients and light on growth and root formation in *Pisum sativum* cuttings. Physiol. Plant. 43, 13–18.
Greger, M., Landberg, T., 1995. Cadmium accumulation in *Salix* in relation to cadmium concentration in the soil. Report 1995/9 from Vattenfall Utveckling AB. (English summary).
Hupp, J.W., Robertson, D.G., Schmutz, J.A., 2000. Recovery of tall cotton-grass following real and simulated feeding by snow geese. Ecography 23, 367–373.
Khan, A.G., Kuek, C., Chaudhry, T.M., Khoo, C.S., Hayes, W.J., 2000. Role of plants, mycorrhizae and phytochelators in heavy metal contaminated land remediation. Chemosphere 41, 197–207.
Krämer, U., Smith, R.D., Wenzel, W.W., Raskin, I., Salt, D.E., 1997. The role of metal transport and tolerance in Nickel hyperaccumulation by *Thlaspi goesingense* Hálácsy. Plant Physiol. 115, 1641–1650.
Landberg, T., Greger, M., 1996. Differences in uptake and tolerance to heavy metal in *Salix* from unpolluted and polluted areas. Appl. Geochem. 11, 175–180.
Lawrence, R.W., Higgs, T.W., 1999. Removing and stabilizing As in acid mine water. J. Min. Met. Mater. Soc. 51, 27–29.
McCabe, O.M., Otte, M.L., 2000. Revegetation of metal mine tailings under wetland conditions. In: Brandt, J.E., Galevotic, J.R., Kost, L., Trouart, J. (Eds.), Proceedings of the 14th Annual National Meeting—Vision 2000: an Environmental Commitment. American Society for Surface Mining and Reclamation, Austin, TX, pp. 99–103.
Murányi, A., Seeling, B., Ladewig, E., Jungk, A., 1994. Acidification in the rhizosphere of rape seedlings and in bulk soil by nitrification and ammonium uptake. Z. Pflanzenernähr. Bodenk. 157, 61–65.
NRC (National Research Council), 1980. Mineral Tolerance of Domestic Animals. National Academy of Science, Washington, DC, USA.
Oldemeyer, J.L., Regelin, W.L., 1987. Forest succession, habitat management, and moose on the Kenai national wildlife refuge. Swed. Wildlife Res. Suppl. 1, 163–179.
Pais, I., Jones, J.B. Jr, 2000. The Handbook of Trace Elements. CRC Press, Boca Raton, USA.
Peverly, J.H., Surface, J.M., Wang, T., 1995. Growth and trace metal absorption by *Phragmites australis* in wetlands constructed for landfill leachate treatment. Ecol. Engin. 5, 21–35.
Smith, R.A.H., Bradshaw, A.D., 1979. The use of metal tolerant plant populations for the reclamation of metalliferous wastes. J. Appl. Ecol. 16, 595–612.
Thompson, K., Grime, J.P., Mason, G., 1977. Seed germination in response to diurnal fluctuations of temperature. Nature 267, 147–149.
Tordoff, G.M., Baker, A.J.M., Willis, A.J., 2000. Current approaches to the revegetation and reclamation of metalliferous mine wastes. Chemosphere 41, 219–228.
Warenberg, K., Danell, Ö., Gaare, E., Nieminen, M., 1997. Flora i Renbetesland. Werner Söderström Osakeyhtiö—WSOY, Finland In Swedish.
Wu, L., 1990. Colonization and establishment of plants in contaminated sites. In: Shaw, A.J. (Ed.), Heavy Metal Tolerance in Plants: Evolutionary Aspects. CRC Press, Boca Raton, FL, pp. 269–284.