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Accumulation of Pb, Cu, and Zn in native plants growing on a contaminated Florida site

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Abstract

Contamination of heavy metals represents one of the most pressing threats to water and soil resources as well as human health. Phytoremediation can be potentially used to remediate metal-contaminated sites. This study evaluated the potential of 36 plants (17 species) growing on a contaminated site in North Florida. Plants and the associated soil samples were collected and analyzed for total metal concentrations. While total soil Pb, Cu, and Zn concentrations varied from 90 to 4100, 20 to 990, and 195 to 2200 mg kg^{-1}, those in the plants ranged from 2.0 to 1183, 6.0 to 460, and 17 to 598 mg kg^{-1}, respectively. None of the plants were suitable for phytoextraction because no hyperaccumulator was identified. However, plants with a high bioconcentration factor (BCF, metal concentration ratio of plant roots to soil) and low translocation factor (TF, metal concentration ratio of plant shoots to roots) have the potential for phytostabilization. Among the plants, *Phyla nodiflora* was the most efficient in accumulating Cu and Zn in its shoots (TF = 12 and 6.3) while *Gentiana pennelliana* was most suitable for phytostabilization of sites contaminated with Pb, Cu and Zn (BCF = 11, 22 and 2.6). Plant uptake of the three metals was highly correlated, whereas translocation of Pb was negatively correlated with Cu and Zn though translocation of Cu and Zn were correlated. Our study showed that native plant species growing on contaminated sites may have the potential for phytoremediation.

Keywords: Heavy metals; Plant uptake; Translocation; Bioconcentration; Phytoremediation; Contaminated soil

1. Introduction

Heavy metals are currently of much environmental concern. They are harmful to humans, animals and tend to bioaccumulate in the food chain. Activities such as mining and smelting of metal ores, industrial emissions and applications of insecticides and fertilizers have all contributed to elevated levels of heavy metals in the environment (Alloway, 1994). The threat that heavy metals pose to human and animal health is aggravated by their long-term persistence in the environment.

Several technologies are available to remediate soils that are contaminated by heavy metals. However, many of these technologies are costly (e.g. excavation of contaminated material and chemical/physical treatment) or do not achieve a long-term nor aesthetic solution (Cao et al., 2002; Mulligan et al., 2001). Phytoremediation can provide a cost-effective, long-lasting and aesthetic solution for remediation of contaminated sites (Ma et al., 2001). One of the strategies of phytoremediation of metal-contaminated soil is phytoextraction, i.e. through uptake and accumulation of metals into plant shoots,

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which can then be harvested and removed from the site. Another application of phytoremediation is phytostabilization where plants are used to minimize metal mobility in contaminated soils.

More than four hundreds plants are known as hyperaccumulators of metals, which can accumulate high concentration of metals into their aboveground biomass. These plants include trees, vegetable crops, grasses and weeds. Based on Baker and Brooks (1989), hyperaccumulators are defined as plants that accumulate >1000 mg kg^{-1} of Cu, Co, Cr, Ni or Pb, or >10,000 mg kg^{-1} of Mn or Zn. Hyperaccumulators of Co (26 species), Cu (24), Mn (8), Ni (145), Pb (5), and Zn (4) have been reported (Baker and Brooks, 1989). The five hyperaccumulators of Pb include *Armeria martima*, *Thlaspi rotundifolium*, *Thlaspi alpestre*, *Alyssum wulfenianum*, and *Polycarpaea synandra*. Plant metal uptake is influenced by soil factors including pH, organic matter, and cation exchange capacity as well as plant species, cultivars and age. The mobility and availability of heavy metals in the soil are generally low, especially when the soil is high in pH, clay and organic matter (Jung and Thornton, 1996; Rosselli et al., 2003).

It is important to use native plants for phytoremediation because these plants are often better in terms of survival, growth and reproduction under environmental stress than plants introduced from other environment. There has been a continuing interest in searching for native plants that are tolerant to heavy metals; however, few studies have evaluated the phytoremediation potential of native plants under field conditions (Shu et al., 2002; Mcgrath and Zhao, 2003). Heavy metals can cause severe phytotoxicity, and may act as powerful force for the evolution of tolerant plant populations. Therefore, it is possible to identify metal-tolerant plant species from natural vegetation in field sites that are contaminated with various heavy metals.

The overall objectives of this research were: 1) to determine the concentrations of Pb, Cu and Zn in plant biomass growing on a contaminated site; 2) to compare metal concentrations in the aboveground biomass to those in roots and in soils, and 3) to assess the feasibility to use these plants for phytoremediation purpose. Information obtained from this study should provide insight for using native plants to remediate metal-contaminated sites.

2. Materials and methods

2.1. Site characterization

The plant and soil samples used in this study were collected from a known metal-contaminated site located in an urban area of northwest Jacksonville, Florida. The

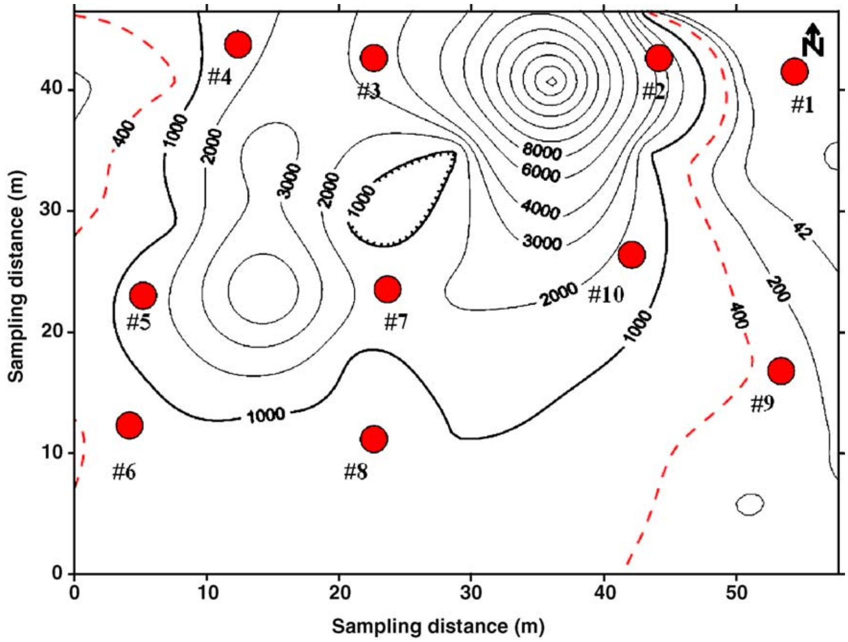

Fig. 1. Total Pb concentrations (mg kg^{-1}) in the top 10-cm soil and sampling locations of the contaminated site (adapted from Chen et al., 2003). The solid circles indicate sampling sites. The numbers associated with each line indicate total lead concentrations. The 400 mg kg^{-1} isopleth marks the boundary of the area requiring Pb cleanup.

site has been vacant, occupies approximately 4047 m^2, and is covered mainly by grasses. Past industrial activities, including a gasoline station, salvage yard, auto body shop, and recycling of lead batteries, have contributed to elevated metal concentrations in this site. Contamination of heavy metals was mainly concentrated in the top 20 cm at the site (Fig. 1). Soil pH was measured using a 1 : 2 soil to water ratio. Selected characteristics of the soil samples collected from this study are shown in Table 1.

2.2. Sample preparation and chemical analysis

Plant samples, based on their coverage at the site, together with the associated soil samples were collected in December of 2002. Sample collections were based on plant coverage of the site as well as plant health. One to six plant samples were collected from each location. A total of 36 plant samples of 17 species were collected and identified from 10 locations at the site (Fig. 1). Soil samples from the rooting zone (0–20 cm) were taken from each location.

Plants samples were divided into roots and shoots, washed gently with deionized distilled water for approximately 3 min to remove soil particles adhered to the plants. After washing, plant samples were air-dried at room temperature for two weeks and then ground to powders using a Wiley Mill. Soil samples were air-dried at room temperature for two weeks and then sieved by 2-mm stainless steel sieve. The plant and soil samples were digested using the hot-block digestion procedure (USEPA Method 3050) for total metal concentration, which were analyzed by a flame atomic adsorption spectrophotometer (AAS, Varian 220 FS with SIPS, Varian, Walnut Creek, CA). For those samples where the flame AAS was insufficiently sensitive, total metals were determined by a graphite furnace AAS (Perkin Elmer SIMMA 6000, Perkin-Elmer Corp, Norwalk, CT). For water-soluble Pb concentration, 25 ml of deionized distilled water was mixed with 2 g of soil and shaken for 12 h. The mixture was then centrifuged for 15 min at 3500 rpm. The supernatant was analyzed for Pb by a flame AAS.

Table 1
Selected properties of soil samples from the contaminated site at Jacksonville, Florida

Site #	Soil pH	Total Pb (mg kg^{-1})	Water-soluble Pb (mg L^{-1})	Total Cu (mg kg^{-1})	Total Zn (mg kg^{-1})
1	7.03	90	1.0	20	200
2	7.00	143	3.0	21	195
3	6.62	4100	31.9	990	2200
4	7.06	1375	81.5	980	900
5	7.20	1886	65.1	860	683
6	7.08	767	20.2	314	551
7	6.95	2405	234.0	746	1000
8	6.97	1451	96.4	300	572
9	7.01	333	2.2	29	532
10	6.63	145	1.0	26	720

Standard soil reference materials (1547 Peach leaves, 2709 San Joaquin soil, 2710 Montana soil) from the National Institute of Science and Technology (NIST, Gaithersburg, MD) were carried through the digestion and analyzed as a part of the quality assurance–quality control protocol (accuracies within 100 ± 20%). Reagent blanks and internal standards were used where appropriate to ensure accuracy and precision in arsenic analysis. Differences among means were determined by analyses of variance. The SPSS (Statistic Program for Social Sciences) statistical program package (Release 12.0) was used for statistical analyses of data. Pearson product moment correlation coefficients (r) were used to express the associations of quantitative variables.

3. Results and discussion

3.1. Soil properties and metal concentrations

Previous research has shown that this soil has relatively high organic matter (3.91%) and high pH (6.95) (Cao et al., 2003), which is not typical of Florida soils where low organic matter and pH are common (Chen et al., 1999). The source of the elevated organic matter was probably from the urban waste deposited on the site over the years. The use of lime to reduce soil pH probably caused alkaline pH of this soil (Cao et al., 2001).

Selected properties of the 10 collected soil samples are listed in Table 1. The soil was mainly contaminated with Pb though both elevated Cu and Zn were found (Cao et al., 2003). Total lead concentrations in the soil samples collected from the site were variable, ranging from 90 at site 1 to 4100 mg kg^{-1} at site 3 (Table 1). The mean Pb concentration in Florida soils is 77 mg kg^{-1} (Chen et al., 1999) while the global baseline level of Pb in uncontaminated surface soils is 20 mg kg^{-1} (Kabata-Pendias and Pendias, 1992). In addition to total Pb concentrations, water-soluble Pb was also determined (Table 1). As expected, the concentrations of water-soluble Pb were much lower than those of total Pb concentrations and no correlation was found between the two.

Though the site was predominantly contaminated with Pb, it also contained elevated concentrations of Cu and Zn, ranging from 20 to 990 mg kg^{-1} for Cu, and from 195 to 2200 mg kg^{-1} for Zn (Table 1). Metal concentrations in the soil samples collected from different locations were highly correlated with $r=0.72$ (Cu–Zn, $p<0.05$, $N=10$), 0.84 (Pb–Cu, $p<0.01$, $N=10$) and 0.9 (Pb–Zn, $p<0.01$, $N=10$), respectively. This means a site that had a high Pb concentration also tended to have high Zn and Cu concentrations, which may indicate that all three metals come from similar sources of contamination. Among the 10 locations sampled, sites 3, 4, 5, and 7 were the most contaminated with all three metals (Table 1, Fig. 1).

3.2. Metal concentrations in plants

Metal concentrations in plants vary with plant species (Alloway et al., 1990). Plant uptake of heavy metals from soil occurs either passively with the mass flow of water into the roots, or through active transport crosses the plasma membrane of root epidermal cells. Under normal growing conditions, plants can potentially accumulate certain metal ions an order of magnitude greater than the surrounding medium (Kim et al., 2003). Metal concentrations in plants growing in uncontaminated soils were 0.3–18.8, 1.1–33.1, and 6–126 mg kg^{-1} for Pb, Cu and Zn, respectively, whereas the highest metal concentrations in plants growing in contaminated soils were 1506, 1123 and 710 mg kg^{-1} for Pb, Cu and Zn, respectively (Kabata-Pendias and Pendias, 1992). The combination of elevated soil pH and high organic matter in the study site may have played a role in the limited plant availability of heavy metals in the soil, resulting in low plant uptake of these metals (Jung and Thornton, 1996, Rosselli et al., 2003). However, no significant correlations were found between metal concentrations and soil pH (data not shown).

In this study, a total of 36 plant samples of 17 species was collected from 10 locations at the site. Concentrations of Pb, Cu and Zn in soils and plant biomass are provided in Tables 2 3 and 4. Total Pb concentrations in the plants ranged from non-detectable to as high as 1183 mg kg^{-1}, with the maximum being in the roots of *Phyla nodiflora* from site 4 (Table 2). In addition, the roots of *Paspalum notatum* (Bahia grass), *Bidens alba*, *Rubus fruticosus* and *Gentiana pennelliana* (Wire grass) also contained significant amounts of Pb (575–968 mg kg^{-1}). None of the plant species accumulated Pb above 1000 mg kg^{-1} in the shoots, the criteria for a hyperaccumulator (Baker and Brooks, 1989). In 95% of the plant samples, the root Pb concentrations were much greater than those of the shoot Pb contents, indicating low mobility of Pb from the roots to the shoots and immobilization of heavy metals in roots. Analyzing Pb concentrations in plants collected from a dump site, Pitchtel et al. (2000) showed similar Pb concentrations (non-detectable to 1800 mg kg^{-1}). Stoltz and Greger (2002) reported a range of 3.4 to 920 mg kg^{-1}

Table 2
Lead concentrations in soil and plant samples (mg kg^{-1}) from the Jacksonville site

Scientific name	Common name	Site #	Roots	Shoots	Soil
Paspalum notatum Fluggé.	Bahia grass	4	575	428	1375
		5	397	92	1886
		9	nd *	nd	333
Gentiana pennelliana Fern.	Wire grass	1	968	453	90
		8	881	491	1451
Bidens alba var. *radiata* (Sch. Bip.) Ballard ex Melchert	Romerillo	2	947	91	143
		3	149	23	4100
		5	660	77	1886
Cynodon dactylon (L.) Pers.	Bermuda grass	5	293	88	1886
		6	74.7	52	767
Cyperus esculentus L.	Flatsedge	1	28.1	18	90
		2	15.9	26	143
		8	417	26	1451
Desmodium paniculatum (L.) DC.	Ticktrefoil	2	130	20	143
Equisetum arvense L.	Horsetail	3	284	38	4100
Hydrocotyle americana L.	Hydrocotyle	8	98.8	8.0	1451
		10	nd	nd	145
Phyla nodiflora (L.) Greene	Turkey tangle fogfruit	1	43.9	24	90
		4	1183	73	1375
		7	117	83	2405
		7	451	55	2405
Plantago major L.	Plantain	1	8.73	52	90
		5	294	67	1886
		9	nd	nd	333
Rubus fruticosus L. agg.	Blackberry	3	825	22	4100
		6	127	12	767
		9	51.4	nd	333
Solidago altissima L.	Goldenrod	6	58.8	49	767
		10	nd	nd	145
Sonchus asper (L.) Hill	Sowthistle	7	146	39	2405
Stenotaphrum secundatum (Walt.) Kuntze	St. Augustine grass	1	30.8	14	90
		3	67.5	32	4100
Tradescantia ohiensis Raf.	Bluejacket	5	206	140	1886
Verbena rigida Spreng.	Tuberous vervain	1	22.8	11	90
		8	35.2	11	1451
Sesbania herbacea (P. Mill.) McVaugh	Bigpod sesbania	2	150	nd	143

* nd stands for not detected and the detection limit for Pb=2 mg kg^{-1}.

Table 3
Copper concentrations in soil and plant samples (mg kg^{-1}) from the Jacksonville site

Scientific name	Common name	Site #	Roots	Shoots	Soil
Paspalum notatum Fluggé.	Bahia grass	4	250	352	980
		5	360	60	860
		9	10	11	30
Gentiana pennelliana Fern.	Wire grass	1	432	200	20
		8	375	210	300
Bidens alba var. *radiata* (Sch. Bip.) Ballard ex Melchert	Romerillo	2	10	8.0	21
		3	44	17	990
		5	400	32	860
Cynodon dactylon (L.) Pers.	Bermuda grass	5	310	52	860
		6	36	21	314
Cyperus esculentus L.	Flatsedge	1	16	10	20
		2	10	28	21
		8	150	20	300
Desmodium paniculatum (L.) DC.	Ticktrefoil	2	6.0	6.0	21
Equisetum arvense L.	Horsetail	3	110	23	990
Hydrocotyle americana L.	Hydrocotyle	8	32	13	300
		10	21	16	26
Phyla nodiflora (L.) Greene	Turkey tangle fogfruit	1	31	14	20
		4	460	20	516
		7	nd *	47	746
		7	180	23	746
Plantago major L.	Plantain	1	23	10	20
		5	150	27	860
		9	24	12	29
Rubus fruticosus L. agg.	Blackberry	3	30	46	990
		6	65	13	314
		9	47	265	29
Solidago altissima L.	Goldenrod	6	277	241	314
		10	20	10	26
Sonchus asper (L.) Hill	Sowthistle	7	46	34	746
Stenotaphrum secundatum (Walt.) Kuntze	St. Augustine grass	1	22	17	20
		3	42	15	990
Tradescantia ohiensis Raf.	Bluejacket	5	194	117	860
Verbena rigida Spreng.	Tuberous vervain	1	14	10	20
		8	25	18	300
Sesbania herbacea (P. Mill.) McVaugh	Bigpod sesbania	2	12	48	21

* nd stands for not detected and the detection limit for Cu = 2 mg kg^{-1}.

of Pb concentrations in different wetland plant species collected from mine tailings.

Copper concentrations in the plants varied from 6 to 460 mg kg^{-1} (Table 3). Like Pb, the maximum value was found in the roots of *P. nodiflora* from site 4 and no plant species accumulated Cu above 1000 mg kg^{-1}. In addition to *P. nodiflora*, the roots of *B. alba*, *G. pennelliana* and *Cynodon dactylon* (Bermuda grass) also contained significant amounts of Cu (310–432 mg kg^{-1}). On the other hand, *P. notatum* and *G. pennelliana* had high Cu concentrations in both the shoots (200–352 mg kg^{-1}) and roots (250–432 mg

Table 4
Zinc concentrations in soil and plant samples (mg kg^{-1}) from the Jacksonville site

Scientific name	Common name	Site #	Roots	Shoots	Soil
Paspalum notatum Fluggé.	Bahia grass	4	450	316	900
		5	260	166	683
		9	250	200	532
Gentiana pennelliana Fern.	Wire grass	1	524	250	200
		8	310	359	572
Bidens alba var. *radiata* (Sch. Bip.) Ballard ex Melchert	Romerillo	2	25	20	195
		3	143	230	2200
		5	462	17	683
Cynodon dactylon (L.) Pers.	Bermuda grass	5	244	171	683
		6	231	162	551
Cyperus esculentus L.	Flatsedge	1	172	80	200
		2	162	165	195
		8	260	290	572
Desmodium paniculatum (L.) DC.	Ticktrefoil	2	44	63	195
Equisetum arvense L.	Horsetail	3	246	160	2200
Hydrocotyle americana L.	Hydrocotyle	8	267	50	572
		10	62	36	720
Phyla nodiflora (L.) Greene	Turkey tangle fogfruit	1	191	86	200
		4	598	110	906
		7	32	200	1000
		7	400	453	1000
Plantago major L.	Plantain	1	137	70	200
		5	256	161	683
		9	213	169	532
Rubus fruticosus L. agg.	Blackberry	3	340	400	2200
		6	173	93	551
		9	213	169	532
Solidago altissima L.	Goldenrod	6	111	86	551
		10	90	200	720
Sonchus asper (L.) Hill	Sowthistle	7	134	250	1000
Stenotaphrum secundatum (Walt.) Kuntze	St. Augustine grass	1	164	100	200
		3	516	320	2200
Tradescantia ohiensis Raf.	Bluejacket	5	220	211	683
Verbena rigida Spreng.	Tuberous vervain	1	176	130	200
		8	155	198	572
Sesbania herbacea (P. Mill.) McVaugh	Bigpod sesbania	2	283	239	195

kg^{-1}). As expected, the Cu concentrations in the roots were greater than those in the shoots. Copper concentrations of 6.4–160 mg kg^{-1} in the plant biomass were reported by Stoltz and Greger (2002), which were lower than those in our research. Shu et al. (2002) reported Cu concentrations of 7–198 mg kg^{-1} in plant biomass of *Paspalum distichum* and *C. dactylon*.

The Zn contents in the plants ranged from 17 to 598 mg kg^{-1} (Table 4). Like Pb and Cu, the maximum values were again found in the roots of *P. nodiflora* from site 4 and no plant species accumulated Zn above 1000 mg kg^{-1}. Also the roots of *P. notatum*, *G. pennelliana*, *B. alba* and *Stenotaphrum secundatum* (St. Augustine grass) contained significant amounts of Zn (462–524 mg kg^{-1}). Three of the five plants species that accumulated high amounts of Zn in the roots were grasses. Similar to Pb and Cu, Zn concentrations were greater in the roots than the shoots. Research conducted by Stoltz and Greger (2002) showed Zn concentrations of 68–1630 mg kg^{-1} in plant biomass while those by Shu et al. (2002) showed 66–7607 mg kg^{-1} in plant biomass.

Among the 36 plants collected from 10 locations, *P. nodiflora* from site 4 accumulated the highest Pb, Cu and Zn in the roots (1183, 460, and 598 mg kg^{-1}, respectively). In addition, *G. pennelliana* and *B. alba* showed higher concentrations of Pb, Cu and Zn than other species. Though metal concentrations in the soil were correlated ($r=0.72$–90), metal concentrations in the plants were poorly correlated with metal concentrations in the soil, which is expected since total metal concentrations have been considered poor indicators of metal availability to plants (Kabata-Pendias and Pendias, 1992). However, Zn concentrations in the shoots ($r=0.47$, $p<0.01$, $N=36$) and Cu concentrations in the roots ($r=0.36$, $p<0.05$, $N=36$) were weakly correlated with soil concentrations.

Among the five plant species that had the highest metal concentrations in their roots, up to four species were grasses, with Bahia and Wire grasses being effective for all three metals whereas St. Augustine grass for Zn and Bermuda grass for Cu. The suitability of these grasses for phytostabilization of metal-contaminated soils, especially in sub-tropical and tropical areas, may warrant further examination.

3.3. Accumulation and translocation of metals in plants

In this study, none of the plant species showed metal concentrations >1000 mg kg^{-1} in the shoots (Tables 2, 3 and 4), i.e. none of them are hyperaccumulators (Baker and Brooks, 1989). However, the ability of these plants to tolerate and accumulate heavy metals may be useful for phytostabilization. Both bioconcentration factors (BCF) and translocation factors (TF) can be used to estimate a plant's potential for phytoremediation purpose.

A plant's ability to accumulate metals from soils can be estimated using the BCF, which is defined as the ratio of metal concentration in the roots to that in soil. A plant's ability to translocate metals from the roots to the shoots is measured using the TF, which is defined as the ratio of metal concentration in the shoots to the roots. Enrichment occurs when a contaminant taken up by a plant is not degraded rapidly, resulting in an accumulation in the plant. The process of phytoextraction generally requires the translocation of heavy metals to the easily harvestable plant parts, i.e. shoots. By comparing BCF and TF, we can compare the ability of different plants in taking up metals from soils and translocating them to the shoots. Tolerant plants tend to restrict soil–root and root–shoot transfers, and therefore have much less accumulation in their biomass, while hyperaccumulators actively take up and translocate metals into their aboveground biomass. Plants exhibiting TF and particularly BCF values less than one are unsuitable for phytoextraction (Fitz and Wenzel, 2002). A few species growing at the site were capable of accumulating heavy metals in the roots, but most of them had low TF and BCF values, which means limited ability of heavy metal accumulation and translocation by the plants (Table 5).

Among the 36 plants screened, *G. pennelliana* growing at site 1 had the highest BCF for Pb (BCF = 11; Table 5), though its total Pb concentration in the plant was <1000 mg kg^{-1} (Table 1). Though *P. nodiflora* showed the highest Pb concentration in the roots (1183 mg kg^{-1}; Table 1), its BCF was less than one (Table 5). The BCF of Pb in this study was lower than that found by Kim et al. (2003) in *P. thunbergii* (BCF = 5–58), and higher than those (BCF = 0.004–0.45) reported by Stoltz and Greger (2002). Shu et al. (2002) reported a BCF of 0.1 for Pb in *P. distichum*.

Similar to Pb, no plant species accumulated Cu above 1000 mg kg^{-1} (Table 3). Though several plant species showed BCFs or TFs greater than one for Cu, only *R. fruticosus* growing at site 9 had both the BCF (1.6) and TF (5.6) greater than one (Tables 3 and 5). However, the soil Cu concentration at this site was relatively low, at 29 mg kg^{-1}. The BCF values for these species were lower than those found in *P. thunbergii* (41–160) reported by Kim et al. (2003), higher than those (BCF = 0.1–0.2) reported by Stoltz and Greger (2002).

Table 5
Accumulation and translocation of Pb, Cu and Zn in selected plants

Scientific name	Site #	Bioconcentration factor (BCF)[a]			Translocation factor (TF)[a]		
		Pb	Cu	Zn	Pb	Cu	Zn
Gentiana pennelliana Fern.	1	**11.0**	22.0	2.6	0.47	0.46	0.48
	8	0.61	**1.3**	0.54	0.56	0.56	**1.2**
Cyperus esculentus L.	2	0.11	0.48	0.83	**1.6**	2.8	1.0
	8	0.29	0.50	0.45	0.06	0.13	**1.1**
Phyla nodiflora (L.) Greene	7	0.05	0.01	0.03	0.71	**12.0**	6.3
	7	0.19	0.24	0.40	0.12	0.13	**1.1**
Rubus fruticosus L. agg.	3	0.20	0.03	0.15	0.03	**1.5**	1.2
	9	0.15	1.6	0.40	0.04	**5.6**	0.79
Sesbania herbacea (P. Mill.) McVaugh	2	**1.1**	0.57	**1.5**	0	**4.0**	0.84
Stenotaphrum secundatum (Walt.) Kuntze	1	0.34	**1.1**	0.82	0.45	0.77	0.61
Plantago major L.	1	0.1	**1.2**	0.69	6.0	0.43	0.51
Bidens alba var. *radiata* (Sch. Bip.) Ballard ex Melchert	2	**6.6**	0.48	0.13	0.1	0.8	0.8

[a] BCF = metal concentration ratio of plant roots to soil and TF = metal concentration ratio of plant shoots to roots. Values >1 are in bold font.

The highest plant Zn concentration was 598 mg kg^{-1}, which was in the roots of *P. nodiflora* (Table 4). Both *G. pennelliana.* and *Sesbania exaltata* showed a BCF greater than one, while eight plant species (*G. pennelliana*, *B. alba*, *Cyperus esculentus*, *D. paniculatum*, *P. nodiflora*, *S. asper*, *V. rigida* and *R. fruticosus*) showed TFs greater than one, with *P. nodiflora* having the highest TF of 6.3. The highest BCF for Zn was 2.6 in *G. pennelliana*, lower than those reported by Kim et al. (2003) in *P. thunbergii* (22 to 136) but higher than those (0.005–0.11) reported by Stoltz and Greger (2002). Research conducted by Shu et al. (2002) showed the highest BCF for Zn for *P. distichum* was 0.2.

Though none of the plants sampled were metal hyperaccumulators, some interesting observations were noted. Based on the average BCFs of all plant samples, plant roots were most efficient in taking up Cu (BCF = 1.1), followed by Pb (0.79) and Zn (0.50). Based on the average TFs of all plant samples, the plants were most efficient in translocating Cu (TF = 1.2), followed by Zn (0.98) and Pb (0.58). Among the three metals tested, the plants growing on the site were most efficient in taking up and translocating Cu. Low translocation of Pb indicates that plants were unwilling to transfer Pb from their roots to shoots possibly due to Pb toxicity. Lead can be toxic to photosynthetic activity, chlorophyll synthesis and antioxidant enzymes (Kim et al., 2003). Baker and Brooks (1989) also discussed restriction of metal uptake by plants from contaminated soils and the presence of exclusion mechanisms in such plant species. Since Zn and Cu are essential nutrients for plant systems, higher translocation from roots to shoots is understandable. Thomas and Eong (1984) treated established *Rhizophora mucronata* Lam. and *Avicennia alba* Bl. seedlings in sediment with Pb and Zn. For these two species, root accumulation and reduced translocation from roots to shoots were observed for both metals.

In general, all three heavy metals occurred at elevated levels in plant biomass collected from the site. Normal and phytotoxic concentrations of Pb, Zn and Cu were reported by Levy et al. (1999), which were 0.5–10 and 30–300 mg kg^{-1} for Pb, 3–30 and 20–100 mg kg^{-1} for Cu, and 10–150 and >100 mg kg^{-1} for Zn. Almost all collected plant species showed heavy metal concentration higher than the normal or phytotoxic levels. These results may indicate that plant species growing on the site contaminated with heavy metals were tolerant of these metals. Restriction of upward movement from roots into shoots can be considered as one of the tolerance mechanism (Verkleij and Schat, 1990).

In addition, the relationships of BCFs and TFs among the three metals were determined through simple correlation. Few studies have been published to show the relationships between metal concentrations and translocations in plants (Kabata-Pendias and Pendias, 1992, Wenzel and Jockwer, 1999). The correlation of BCFs of all plant samples between two metals ranged 0.63 to 0.84 ($p<0.01$, $N=36$), i.e. a plant, which was effective in taking up Pb, was very likely to be effective in taking up Cu and Zn. However, the relationship between TFs was different. Only TFs of all plants between Zn and Cu were correlated with $r=0.79$ ($p<0.01$, $N=36$), whereas no correlations of TFs were found between Pb and Cu, or Pb and Cu. This means a plant, which was effective in translocating Zn, was also effective in translocating Cu and vice versa. However, Cu and Zn translocation in these plants were not related to Pb translocation. Poor correlation between the TFs of Pb–Zn and Pb–Cu and good correlation between the TFs of Zn–Cu may indicate that elevated Pb concentration can inhibit transfer of essential nutrient in plant biomass.

Although no heavy metal hyperaccumulators were found, heavy metal-tolerant species with high BCF and low TF can be used for phytostabilization of contaminated site, together with a vegetative cover. Examples of such plants in our study included *G. pennelliana* for Pb, Cu and Zn, *B. alba* for Pb, *Plantago major* for Cu, and *S. exaltata* for Zn (Table 5). Phytostabilization can be used to minimize migration of contaminants in soils (Susarla et al., 2002). This process uses the ability of plant roots to change environmental conditions via root exudates. Plants can immobilize heavy metals through absorption and accumulation by roots, adsorption onto roots, or precipitation within rhizosphere. This process reduces metal mobility and leaching into ground water, and also reduces metal bioavailability for entry into the food chain. One advantage of this strategy over phytoextraction is that the disposal of the metal-laden plant material is not required (Susarla et al., 2002). By using metal-tolerant plant species for stabilizing contaminants in soil, particularly metals, it could also provide improved conditions for natural attenuation or stabilization of contaminants in the soil. Metals accumulated in the roots are considered relatively stable as far as release to environment is concerned. However, studies are needed regarding the turnover of nutritive roots and the potential release of metals from decomposing roots (Weis and Weis, 2004). Also, effects of plant–bacteria or plant–mycorrhizae interactions, which might affect the metal uptake and translocation merit further investigation.

4. Conclusion

This study was conducted to screen plants growing on a contaminated site to determine their potential for metal accumulation. Only species with both BCFs and TFs greater than one have the potential to be used for phytoextraction. Among the 36 plant samples of 17 plant species screened, no plant species were identified as metal hyperaccumulators. However, several plants had BCFs or TFs greater than one. *G. pennelliana* was most effective in taking up all three metals, with BCFs ranging from 1.1 to 22 (Table 5). *C. esculentus* was most effective in translocating all three metals (Table 5). Among those plant species collected from the contaminated site, *G. pennelliana* was considered as the most promising species for phytoextraction of heavy metal-contaminated sites. The phytoremediation potential of these plant species, especially for use in sub-tropical and tropical areas, needs to be investigated.

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