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RESEARCH ARTICLE

Potential of indigenous plant species for phytoremediation of metal(loid)-contaminated soil in the Baoshan mining area, China

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Abstract

A field survey was conducted to investigate metal(loid) concentration in soils and native plants in the Baoshan mining area for potential application in phytoremediation. Total concentrations of arsenic (As), cadmium (Cd), lead (Pb), and zinc (Zn) in soil varied from 125 to 6656, 5.10 to 1061, 568 to 49294, and 241 to 17296 mg kg^{-1}, respectively, showing severe contamination. Among 20 species native to this area, *Pteris ensiformis* accumulated 1091 mg kg^{-1} As in the shoot, and its translocation factor (TF) was greater than 1, suggesting potential capacity for As phytoextraction. *Boehmeria nivea*, *Aster prorerus*, and *Hydrocotyle sibthorpioides* showed potential for phytoextraction of Cd due to their high accumulation of Cd in shoots (490.3, 175.4, and 128.5 mg kg^{-1}, respectively) and high TFs (92.0, 22.1, and 6.7, respectively). *Eleusine indica* and *P. ensiformis* were found to contain high concentrations of Pb (7474 mg kg^{-1}) and Zn (1662 mg kg^{-1}) in roots, but with low TFs for Pb (0.4) and Zn (0.2), suggesting potential capability for phytostabilization. There was a positive correlation ($p < 0.01$, $N = 25$) of TFs between the metal(loid)s, indicating a synergic interaction in the uptake of metal(loid)s by these plants. According to metal(loid) concentrations in shoots, bioconcentration factors (BFs), and TFs, as well as the botanical features such as wide occurrence, high biomass yield, and rapid growth of the plants, the five native species identified above have the potential for phytoremediation in the Baoshan mining area.

Keywords Metal(loid)s · Mining pollution · Hyperaccumulators · Phytoextraction · Phytostabilization

Introduction

Currently, 16.1% of Chinese soil is polluted, and 82% of the contaminated soils are related to toxic inorganic pollutants, such as cadmium (Cd), mercury (Hg), arsenic (As), chromium (Cr), and lead (Pb), which are toxic to biota (Chen et al. 2014; MEP and MLR of P. R. China 2014). Soil remediation is required to reduce risks to human and the environment. As a cost-effective, environmentally friendly remediation method, phytoremediation is considered a viable technology and has been widely applied in remediating metal(loid)-contaminated soils (Yoon et al. 2006; Pinto et al. 2015; Sarwar et al. 2017). For example, *Eucalyptus globulus* was reported to have a decontamination capacity of 0.006–0.010 t for Cd, 0.23–0.55 t for Pb, and 0.56–1.13 t for Cu per hectare in two years (Luo et al. 2018).

Phytoremediation technology includes phytoextraction, phytostabilization, phytofiltration, phytovolatilization, phytodegradation, rhizodegradation, and phytodesalination (Alkorta et al. 2004; Hemen 2011; Ali et al. 2013), of which phytoextraction and phytostabilization are more extensively studied. Phytoextraction is the use of live plants to remove metal(loid)s from soil by uptake. Its efficiency depends on the ability of plant roots to absorb, translocate, and accumulate metal(loid)s from soil to the aboveground harvestable parts (Khalid et al. 2017). Phytostabilization decreases the

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bioavailability and mobility of metal(loid)s in soil through root sorption, precipitation, complexation, or reduction in rhizosphere (Ali et al. 2013).

Metallophytes are plants that are specifically adapted to and thrive in heavy metal–rich soils, and good candidates for phytoextraction and phytostabilization. Metallophytes are divided into three categories: metal hyperaccumulators, metal excluders, metal indicators (Ali et al. 2013). Metal hyperaccumulators can be used for phytoextraction and metal excluders for phytostabilization.

According to van der Ent et al.'s (2013) reports, hyperaccumulation threshold criteria for different metal and metalloids in dried foliage are as follows: 100 mg kg^{-1} for Cd and Se; 300 mg kg^{-1} for Co, Cr, and Cu; 1,000 mg kg^{-1} for As, Ni, and Pb; 3,000 mg kg^{-1} for Zn; and 10,000 mg kg^{-1} for Mn, with plants growing in their natural habitats. Some other characteristics to be considered include the following: (1) bioconcentration factor > 1, (2) translocation factor > 1, and (3) extreme metal(loid) tolerance due to effective biochemical detoxification (Baker and Whiting 2002). There are more than 500 plant species from at least 101 families that have been reported to hyperaccumulate metal(loid)s, including members of *Asteraceae*, *Brassicaceae*, *Caryophyllaceae*, *Cyperaceae*, *Cunoniaceae*, *Fabaceae*, *Flacourtiaceae*, *Lamiaceae*, *Poaceae*, *Violaceae*, and *Euphorbiaceae* (Hemen 2011), and the number keeps increasing with further exploration and analysis. The best known metal(loid) hyperaccumulators are *Noccaea caerulescens* (formerly *Thlaspi caerulescens*) for Zn, which accumulate up to 26,000 mg kg^{-1} Zn without showing any injuries (Brown et al. 1995) and *Pteris vittata* L. (Chinese brake fern) for As, which grow normally in soils of 50–4030 mg kg^{-1} As, and even in tailings with As of up to 23,400 mg kg^{-1} (Chen et al. 2007). Root compartments and excluders may be useful for phytostabilization. This strategy of phytoremediation does not remove the pollutants from soils but fixes metal(loid)s in the rhizosphere to limit the spread of metal(loid)s (Bech et al. 2012).

Although there are current efforts to enhance phytoremediation with plant growth–promoting bacteria (Novo et al. 2018) and advanced genetic engineering techniques (Basharat et al. 2018), the screening of suitable plants for phytoremediation is still critical. Screening suitable native plants for phytoremediation is of primary importance because these plants are tolerant to metal(loid) pollution in specified soil conditions, and they also perform better in terms of survival, growth, and reproduction, as compared with plants introduced from other environments (Frérot et al. 2006; Yoon et al. 2006; Antosiewicz et al. 2008).

The Baoshan mine is located in Chenzhou, southern Hunan province, and rich in lead, zinc, silver, tungsten, tin, and molybdenum ores. The long history of mining has caused severe pollution of metal(loid)s in the surrounding environment. The average concentrations of Cd and Pb in soybeans collected in the Baoshan mine were 1.59 and 13.08 mg kg^{-1}, respectively (Zhou et al. 2013), which greatly exceeded the limited value of national standards for food safety of China (GB 2762-2017) (NHFPC and NFDASA 2017). In order to give recommendations for mine rehabilitation and reduce pollution to the surrounding environment from the Baoshan mine, a survey on the metal(loid) tolerance of native plants was conducted in this study; the specific objectives were (1) determining the concentrations of metal(loid)s in soil and plant samples, (2) examining the potential interactions between metal(loid)s during plant accumulation, and (3) assessing effectiveness of plants for phytoremediation.

Material and methods

Site characterization

The study area is located in the Baoshan mine, Guiyang County, Hunan province, China, with longitude 112° 13′–112° 55′ E and latitude 25° 27′–26° 13′ N. This is a subtropical humid monsoon climate area, with the annual average temperature of 17.2 °C and the annual rainfall of 1385.2 mm. The region comprises a wide variety of strata spanning from the Sinian to the Quaternary except for the Silurian (Xie et al. 2013), and the strata of the mining area consists of mainly carboniferous carbonate rocks, enriched with non-ferrous metals such as Cu, Pb, Zn, Au, Ag, and Mo. The associated minerals are As, Cd, and S. Both open-cast mining and underground mining were operated in the Baoshan mine.

Sample collection

Samples of soil and plant were collected from two zones in the Baoshan mining area in August 2010, including 7 sites in the smelter area and 5 sites in the tailing pond area (Fig. 1). At each site, one to seven plant samples in an area of 1 m^2 were collected. Soil samples from the rooting zone (0–20 cm) were collected from each site. In order to obtain accurate plant species information, plants were photographed and transported to the laboratory as soon as possible; a plant taxonomist was invited to identify each plant. In total, 20 species from 13 families were collected from 12 sites; their basic information including relative abundance, life form, and grown stage was listed in Table 1. The relative abundances were estimated visually and described as 1–5 (from very rare to abundant).

Soil and plant analysis

After large stones and plant debris were removed, the soil samples were air-dried at room temperature, and ground to < 0.15-mm powder prior to use. Plant samples were separated into shoots and roots, washed carefully with tap water, and

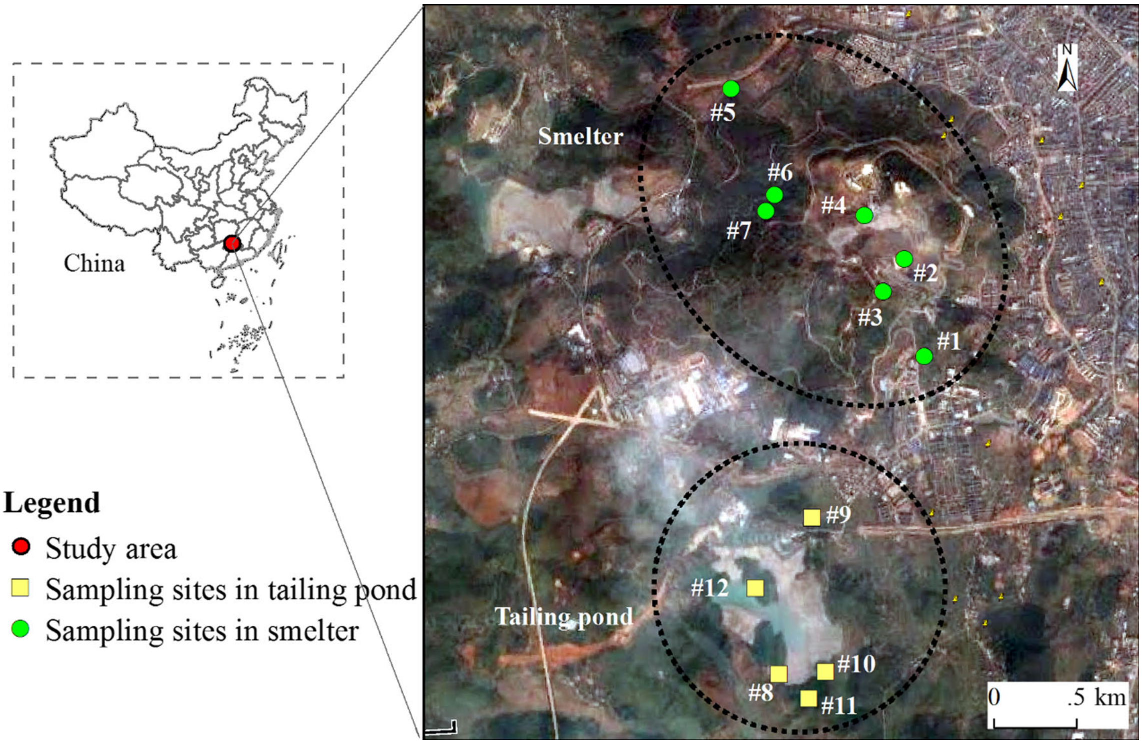

Fig. 1 Study area and sampling sites

Table 1 Basic information of dominant plants from Baoshan mine

Family	Species	Site	Abundance*	Life form	Growing stage
Apiaceae	*Hydrocotyle sibthorpioides* Lam.	Smelter	4	Perennial herb	Vigorous growth
Asteraceae	*Artemisia argyi* H. Lév. & Vaniot	Tailing pond	5	Perennial herb	Vigorous growth
	Artemisia taurica Willd.	Tailing pond	2	Perennial herb	Late growth
	Artemisia japonica Thunb.	Smelter	4	Perennial herb	Vigorous growth
	Aster prorerus Hemsl.	Smelter	2	Perennial herb	Vigorous growth
	Aster subulatus Michx.	Smelter	5	Perennial herb	Flowering
	Chrysanthemum indicum	Smelter/tailing pond	5	Perennial herb	Flowering
	D. morifolium '*Xiaohuangju*' *nom. ined.*	Smelter	4	Perennial herb	Flowering
	Saussurea japonica (Thunb.) DC	Smelter	4	Biennial herb	Flowering
Blechnaceae	*Woodwardia japonica* (L. f.) Sm	Tailing pond	5	Fern	Vigorous growth
Caryophyllaceae	*Dianthus superbus* L.	Smelter	2	Perennial herb	Flowering
Equisetaceae	*Equisetum ramosissimum* Desf.	Tailing pond	3	Fern	Vigorous growth
Euphorbiaceae	*Euphorbia Esula* Linn.	Smelter	3	Perennial herb	Vigorous growth
Gramineae	*Eleusine indica* (L.) Gaertn.	Tailing pond	5	Annual herb	Flowering
Polygonaceae	*Polygonum bungeanum* Turcz	Tailing pond	3	Annual herb	Flowering
Pteridaceae	*Pteris ensiformis* Burm.	Smelter/tailing pond	4	Fern	Vigorous growth
Polygonaceae	*Rumex acetosa* Linn.	Smelter	4	Perennial herb	Vigorous growth
Rosaceae	*Sanguisorba officinalis* L.	Smelter	1	Perennial herb	Flowering
Urticaceae	*Boehmeria nivea* (L.) Gaudich.	Smelter	4	Shrub	Flowering
Valerianaceae	*Valeriana officinalis* L.	Smelter	3	Perennial herb	Fruit
Total: 13 families	Total: 20 species				

*Abundance class: 1, very rare; 2, rare; 3, occasional; 4, frequent; 5, abundant then rinsed with deionized water 3 times to remove soil particles that adhered to the surfaces. The washed plant samples were oven-dried (at 105 °C for 30 min and then at 70 °C for 48 h) and ground to powder. Soil pH was measured using a pH meter with the 1:2.5 soil to water ratio. Soil samples were digested with concentrated HNO_3 and H_2O_2 (USEPA 3050B). Plant samples were digested with a mixture of concentrated HNO_3 and $HClO_4$ (Chen et al. 2002). The concentrations of Cd, Pb, and Zn in digested soil or plant samples were then determined using an inductively coupled plasma optical emission spectrometer (ICP-OES, Optima 5300DV, PerkinElmer Co., USA). The concentration of As in the digested samples was determined using an atomic fluorescence spectrometer (AFS 9800, Haiguang Instrument Co., China). To ensure accuracy and precision, reagent blanks and appropriate standard reference materials (GBW07401 for soil, GBW07603 for plant) from the National Standard Substances Center of China were carried through the digestion and subsequent analysis. The recovery of As, Cd, Pb, and Zn was 90.4–102.7% for GBW07401 and 92.1–103.2% for GBW07603.

Statistical analysis

The bioconcentration factor (BF) was defined as the ratio of a metal(loid) in the plant shoot to that in the soil. The translocation factor (TF) was defined as the ratio of a metal(loid) in the plant shoot to that in the plant root. All data were analyzed by Excel 2016 and SPSS 20.0 (IBM, USA). Data were standardized using log transformation and the statistical differences between the means of pH and metal(loid) concentration of soils from the smelter area and tailing pond area were determined by *t* test at $p < 0.05$ level. The correlation of metal(loid) concentration in soils and plants, and BF and TF in plants, was undertaken by the bi-variation method, with two-tailed significance, and Spearman's correlation coefficients were determined.

Results

Soil properties and metal(loid) concentrations

Soil pH ranged from 5.78 to7.83. The total concentrations of potentially toxic elements in the soil samples ranged from 125 to 6656 mg kg^{-1} for As, 5.10–1061 mg kg^{-1} for Cd, 568–49294 mg kg^{-1} for Pb, and 241–17296 mg kg^{-1} for Zn (Table 2). To assess the level of contamination, concentrations of total As, Cd, Pb, and Zn in our soil samples were compared with the national soil environmental quality–risk control standard for soil contamination of agricultural land (GB 15618-2018) (MEE and SMSA 2018a) and risk control standard for soil contamination of development land (GB 36600-2018) (MEE and SMSA 2018b). Obviously, concentrations of As, Cd, Pb, and Zn of all sampling sites from the smelter area and tailing pond area exceeded the risk control standard for soil contamination of agricultural land, except for As in site no. 10 from the tailing pond area. They were 1.04–54.5, 1.55–265, 0.14–69.4, and 0.21–68.2 times higher for As, Cd, Pb, and Zn, respectively. According to the risk control standard for soil contamination of development land, all sites from the smelter area exceeded standards (class B) for As and Pb, while 80% and 40% sites from the tailing pond area were above the critical level for As and Pb, respectively. 85.7% sites from the smelter area exceeded the standard (class B) for Cd, but none of the sites from the tailing pond area exceeded that of the critical level of Cd (Table 2). There were significant differences ($p < 0.05$) in soil pH and concentrations of As, Pb, and Zn between the two sampling areas. The average concentration of Cd was significantly higher in the smelter area than in the tailing pond area ($p < 0.05$). These results indicated that Baoshan mine suffered a severe contamination of As, Cd, Pb, and Zn, with Cd contamination level being higher in the smelter than in the tailing pond area.

Metal(loid) concentrations in plants

The concentrations of As, Cd, Pb, and Zn in plants are presented in Table 3. The metal(loid) concentrations varied between plant samples and species. Total As concentration ranged from 7~1091 mg kg^{-1} in shoots and 6~1047 mg kg^{-1} in roots. The highest As concentration occurred in the shoot and root of *Pteris ensiformis* from the smelter area, which was the only plant species that accumulated more than 1000 mg kg^{-1} As in the shoot, meeting the criterion for a hyperaccumulator (Ent et al. 2013).

Total Cd concentration in shoot ranged from 4.7~490.3 mg kg^{-1} and 2.4~157.2 mg kg^{-1}in root, with the highest Cd concentration measured in the shoot of *Boehmeria nivea.* In addition to *B. nivea*, the shoots of *Aster prorerus*, *Hydrocotyle sibthorpioides*, *Chrysanthemum indicum*, *Euphorbia esula*, and *Rumex acetosa* also contained significant amounts of Cd (112.5~215.0 mg kg^{-1}), and they were all above 100 mg kg^{-1}, the criterion for a Cd hyperaccumulator.

The Pb concentration ranged from 90~4462 mg kg^{-1} in the shoot and 23~7474 mg kg^{-1} in the root. The highest Pb concentrations occurred in the shoot of *B. nivea* and in the root of *Eleusine indica*. The criterion for a Pb hyperaccumulator is 1000 mg kg^{-1} in the shoot; 11 species among all the plant samples reached this value, including *B. nivea*, *P. ensiformis*, *A. prorerus*, *Valeriana officinalis, H. sibthorpioides*, *C. indicum*, *D. morifolium* '*Xiaohuangju*' *nom. ined.*, *Saussurea japonica, E. esula*, *R. acetosa*, and *E. indica.*

The Zn concentration in shoot ranged from 152~2506 mg kg^{-1}, and 28~1662 mg kg^{-1} in roots. *R. acetosa* had the highest Zn concentration in the shoot, whereas *P. ensiformis* had the highest Zn concentration in the root. In addition to

Table 2 The pH and metal concentrations (mg kg^{-1}) in soils from polluted areas at the Baoshan mining area

Polluted area	Site number	pH (H_2O)	As	Cd	Pb	Zn
Smelter	1	6.53	830	24.5	10603	1801
	2	7.75	891	101	8021	5594
	3	7.11	245	293	3368	6306
	4	5.8	1232	204	10888	7577
	5	7.83	949	42.1	8028	2682
	6	7.63	651	1061	30062	9671
	7	7.75	1719	1043	27409	12409
Average ± SD		7.20 ± 0.78a	931 ± 460a	395 ± 458a	14054 ± 10356a	6577 ± 3733a
CV (%)		10.76	49.47	115.95	73.69	56.76
Tailing pond	8	7.79	1848	28.2	1692	3054
	9	7.5	479	13	1183	886
	10	5.78	125	5.1	568	241
	11	6.54	6656	83.5	9898	8520
	12	6.68	1143	103	49294	17296
Average ± SD		6.86 ± 0.80a	2050 ± 2658a	46.60 ± 43.97b	12527 ± 20903a	5999 ± 7105a
CV (%)		11.70	129.64	94.35	166.87	118.44
Soil environmental quality	Risk control standard for soil contamination of agricultural land	$5.5 < pH \leq 6.5$	150	2.0	500	200*
		$6.5 < pH \leq 7.5$	120	3.0	700	250*
		$pH > 7.5$	100	4.0	1000	300*
	Risk control standard for soil contamination of development land	Class A**	120	47	800	——
		Class B**	140	172	2500	——

The average is representing in mean ± standard deviation (SD), following by the same letter are not significantly different according to *t* test ($p < 0.05$). Coefficient of variance (CV) is defined as the ration of the standard deviation to the mean and describes the variability of data. *Because of lacking of risk control standard for soil contamination of agricultural land for Zn, its risk screening values were used instead as a reference for determining contamination. **Class A represents residential land, primary and middle school land, medical services land, social welfare facility land, and so on. Class B represents industrial land, warehouse land, commercial service facility land, road and traffic facility land, and so on.

R. acetosa, the shoots of *Polygonum bungeanum* and *E. indica* also contained significant amounts of Zn (1133~1427 mg kg^{-1}). However, none of the plant species accumulated Zn above 10000 mg kg^{-1} in the shoot, which is the criterion for a Zn hyperaccumulator.

Bioconcentration and translocation of metal(loid)s

In addition to metal(loid) concentrations suggested by van der Ent et al. (2013) to qualify a hyperaccumulator, bioconcentration factors (BFs) and translocation factors (TFs) are two other key factors used for the screening of potential metal(loid) hyperaccumulators. The BFs and TFs of the plant samples collected from the study sites are listed in Table 4.

Among the 20 plant species, *P. ensiformis* collected from the smelter area was the only species that had the BF higher than 1 for As (BF = 1.31). For 92% of the plant samples, the TFs of As were greater than 1, including *P. ensiformis*. *P. ensiformis* also showed a high accumulation of As (Table 3), and thus this species may be a potential As hyperaccumulator.

B. nivea showed the highest BF for Cd (BF = 20.0). Five other species, i.e., *P. ensiformis*, *A. prorerus*, *Valeriana officinalis*, *H. sibthorpioides*, and *P. bungeanum*, also had BFs greater than 1 for Cd. For 88% of the plant samples, the TFs of Cd were greater than 1, including the 6 plant species mentioned above. *B. nivea* also showed the highest TF for Cd (TF = 92.0). Three of the six plant species, i.e., *B. nivea*, *A. prorerus*, and *H. sibthorpioides*, accumulated Cd in excess of 100 mg kg^{-1} in the shoots, which suggested that they are suitable plants for the phytoextraction of Cd.

Similar to As and Cd, most of the plant species had a value of TFs for Pb and Zn greater than 1. However, only *P. bungeanum* had a BF of 5.91 for Zn. For Pb, *E. indica* had the lowest TF (TF = 0.4, Table 4) but with the highest concentration in the root. In addition, the corresponding soil sample at site 12 had the highest concentration of Pb (49294 mg kg^{-1}, Table 3) with the normal growth of *E. indica*. These findings suggested that *E. indica* has the potential to stabilize Pb. *P. ensiformis* from the tailing pond area had similar characteristics as *E. indica* but for Zn, which included the accumulation of

Table 3 Concentrations (mg kg^{-1} DW) of As, Cd, Pb, and Zn in plant species from polluted area at the Baoshan mining area

Species	Polluted area	As		Cd		Pb		Zn	
		Shoot	Root	Shoot	Root	Shoot	Root	Shoot	Root
Artemisia argyi H. Lév. & Vaniot	Tailing pond	48	7	11.6	2.4	446	23	233	46
Artemisia taurica Willd.	Tailing pond	509	62	22.5	7.6	375	150	808	312
Artemisis japonica Thunb.	Smelter	87	11	54.3	6.5	539	159	444	147
Aster prorerus Hemsl.	Smelter	530	18	175.4	7.9	3677	161	933	39
Aster subulatus Michx.	Smelter	32	9	35.7	16	229	74	239	65
Boehmeria nivea (L.) Gaudich.	Smelter	701	14	490.3	5.3	4462	112	992	28
Chrysanthemum indicum	Smelter	251	14	9.3	2.6	216	133	154	60
	Smelter	221	8	36.7	4.9	1442	112	528	62
	Smelter	178	105	127.6	98.5	568	615	191	329
	Tailing pond	36	9	9.3	0.4	216	49	124	59
Dendranthema morifolium 'Xiaohuangju'nom.ined.	Smelter	336	20	78.2	16.5	1794	248	430	157
Dianthus superbus L.	Smelter	68	26	47.2	36.9	719	406	374	242
Eleusine indica (L.) Gaertn.	Tailing pond	64	143	76.2	47.5	2798	7474	1133	34
Equisetum ramosissimum Desf.	Tailing pond	7	20	4.7	6.8	90	192	152	224
Euphorbia Esula Linn.	Smelter	410	41	112.5	33.8	855	220	894	229
Hydrocotyle sibthorpioides Lam.	Smelter	341	49	128.5	19.3	2328	436	477	106
Polygonum bungeanum Turcz	Tailing pond	36	8	11.9	8.9	273	249	1427	859
Pteris ensiformis Burm.	Smelter	1091	1047	62.7	11.3	1347	114	296	118
	Tailing pond	664	180	12	20.7	1011	590	339	1662
Rumex acetosa Linn.	Smelter	429	10	215	52.4	2112	226	2506	394
Sanguisorba officinalis L.	Smelter	174	19	41.1	23.3	896	247	345	227
	Smelter	86	6	135.5	65.8	1041	161	932	388
Saussurea japonica (Thunb.) DC	Smelter	195	14	96.1	157.2	1255	602	639	408
Valeriana officinalis L.	Smelter	308	16	82.4	8.4	1589	236	386	103
Woodwardia japonica (L. f.) Sm	Tailing pond	62	9	8.6	2.5	436	77	257	143

The abbreviation DW represents dry weight

high amounts of Zn (1662 mg kg^{-1}, Table 3) in the root with a low TF (TF = 0.2, Table 4) and normal growth in soil with a high concentration of Zn (8520 mg kg^{-1}, Table 2). This result suggested that *P. ensiformis* is a suitable species for the phytostabilization of Zn.

Correlation analysis

To identify whether synergism or antagonism between heavy metal(loid)s existed in the plant absorption process, correlation analysis was conducted, and Spearman's correlation coefficients are listed in Table 5. Significant correlations were found in soil samples between the concentrations of Cd and Pb ($r = 0.699$, $p < 0.01$, $N = 12$), Cd and Zn ($r = 0.853$, $p < 0.01$, $N = 12$), and Pb and Zn ($r = 0.825$, $p < 0.01$, $N = 12$). In the plant samples, strong correlations were found between the concentrations of As and Pb, Cd and Pb, Cd and Zn, and Pb and Zn ($r = 0.628, 0.805, 0.633, 0.632$, respectively, $p < 0.01$, $N = 25$), and a significant correlation was also found between the concentrations of As and Cd ($r = 0.561$, $p < 0.01$, $N = 25$). For BFs, highly significant correlations were found between the concentrations of Cd and Pb ($r = 0.620$, $p < 0.01$, $N = 25$), and Cd and Zn ($r = 0.663$, $p < 0.01$, $N = 25$). While for TFs, all of the four metal(loid)s had highly significant correlations, with correlation coefficients ranging from 0.507 to 0.769 ($p < 0.01$, N = 25).

Discussion

Contamination features of the Baoshan mining area

The present study clearly showed that concentrations of As, Cd, Pb, and Zn in the Baoshan mine greatly exceeded the national soil environmental quality–risk control standard for soil contamination of agricultural land (GB 15618-2018) and development land (GB 36600-2018). This result agreed with other reports for the same area (Liu et al. 2005; Zhou et al. 2013). There were no significant

Table 4 Bioconcentration (BF) and translocation (TF) factors of As, Cd, Pb, and Zn in plant species from polluted areas at the Baoshan ming area

Species	Polluted area	BF				TF			
		As	Cd	Pb	Zn	As	Cd	Pb	Zn
Artemisia argyi H. Lév. & Vaniot	Tailing pond	0.1	0.89	0.38	0.26	6.8	4.9	*19.2*	5.1
Artemisia taurica Willd.	Tailing pond	0.28	0.8	0.22	0.26	8.2	3	2.5	2.6
Artemisia japonica Thunb.	Smelter	0.1	0.54	0.07	0.08	7.9	8.4	3.4	3
Aster prorerus Hemsl.	Smelter	0.64	*7.16*	0.35	0.52	*30*	*22.1*	*22.8*	*23.8*
Aster subulatus Michx.	Smelter	0.03	0.85	0.03	0.09	3.6	2.2	3.1	3.7
Boehmeria nivea (L.) Gaudich.	Smelter	0.84	*20*	0.42	0.55	*49.7*	*92*	*40*	*35.8*
Chrysanthemum indicum	Smelter	0.3	0.38	0.02	0.09	17.5	3.6	1.6	2.6
	Smelter	0.25	0.36	0.18	0.09	26.8	7.5	12.8	8.5
	Smelter	0.73	0.44	0.17	0.03	1.7	1.3	0.9	0.6
	Tailing pond	0.08	0.71	0.18	0.14	4.2	*23.2*	4.4	2.1
Dendranthema morifolium '*Xiaohuangju*' *nom. ined.*	Smelter	0.38	0.78	0.22	0.08	16.8	4.7	7.2	2.7
Dianthus superbus L.	Smelter	0.06	0.23	0.07	0.05	2.6	1.3	1.8	1.5
Eleusine indica (L.) Gaertn.	Tailing pond	0.06	0.74	0.06	0.07	0.4	1.6	0.4	*33.3*
Equisetum ramosissimum Desf.	Tailing pond	0.01	0.36	0.08	0.17	0.3	0.7	0.5	0.7
Euphorbia Esula Linn.	Smelter	0.24	0.11	0.03	0.07	10.1	3.3	3.9	3.9
Hydrocotyle sibthorpioides Lam.	Smelter	0.41	*5.24*	0.22	0.26	7	6.7	5.3	4.5
Polygonum bungeanum Turcz	Tailing pond	0.29	*2.33*	0.48	*5.91*	4.5	1.3	1.1	1.7
Pteris ensiformis Burm.	Smelter	*1.31*	*2.56*	0.13	0.16	1	5.5	11.9	2.5
	Tailing pond	0.1	0.14	0.1	0.04	3.7	0.6	1.7	0.2
Rumex acetosa Linn.	Smelter	0.25	0.21	0.08	0.2	*42.9*	4.1	9.3	6.4
Sanguisorba officinalis L.	Smelter	0.19	0.41	0.11	0.06	9.1	1.8	3.6	1.5
	Smelter	0.13	0.13	0.03	0.1	14.4	2.1	6.5	2.4
Saussurea japonica (Thunb.) DC	Smelter	0.3	0.09	0.04	0.07	14	0.6	2.1	1.6
Valeriana officinalis L.	Smelter	0.37	*3.36*	0.15	0.21	19.2	9.9	6.7	3.7
Woodwardia japonica (L. f.) Sm	Tailing pond	0.03	0.3	0.26	0.08	6.9	3.4	5.7	1.8

BF > 1 and top 3 TFs are in italics

differences between the smelter area and tailing pond area in terms of As, Pb, and Zn concentrations, which may be a result of contaminant dispersion. Airborne particles and aerosols contributed most to As, Cd, Pb, Zn, and Cu inputs in the Shuikoushan mining area (Wei et al. 2009), which is also located in Zhuzhou city, Hunan province in China, with the same climate characteristics and a similar mining history and mining system as the Baoshan mining area. The deposition fluxes of As, Pb, and Zn in Zhuzhou city were 56.69, 1074.9, and 6295.1 mg $(m^2\ year)^{-1}$ according to Ke (2015), which was much higher than those in other cities in China. The atmospheric As deposition could be an important source of As, as evidenced by the higher concentration of As in shoots than the roots of vegetables, since soil As was low (Liao et al. 2005). Therefore, atmospheric deposition may be an important pollution patterns in the Baoshan mining area, which resulted in no significant difference in the pollution levels between the smelter area and its adjacent tailing area for As, Pb, and Zn.

Characteristics of metal(loid) uptake and accumulation by plants

Plants grown in mining areas often show a strong tolerance to metal(loid)s. Normal heavy-metal contents of terrestrial plants growing in uncontaminated soils of Hunan province were 0.04 mg kg^{-1} for Cd, 0.09 mg kg^{-1} for Pb, and 18.0 mg kg^{-1} for Zn (Wang and Stuanes 2003), whereas in the present study, the concentrations of these metals in most of the plant species were much higher than those in the plants growing in uncontaminated soils. The high level of metal(loid) concentrations in soils was the main cause of elevated metal(loid) concentrations in plants, which could be demonstrated by the significant correlations between concentrations of As, Cd, and Pb in plants and soils (Table S1). Liang et al. (2016) also showed that metal(loid) concentrations in plants were proportional to their concentrations in soil, which fitted well a regression model with a high correlation coefficient (0.9417).

Table 5 Spearman's correlation coefficients between concentrations of As, Cd, Pb, and Zn for soils and plants from the Baoshan mining area, and for bioconcentration (BF) and translocation factor (TF)

		As	Cd	Pb	Zn
Soils ($N = 12$)	As	1			
	Cd	0.217	1		
	Pb	0.406	0.699*	1	
	Zn	0.085	0.853**	0.825**	1
Plants ($N = 25$)	As	1			
	Cd	0.561*	1		
	Pb	0.628**	0.805**	1	
	Zn	0.369	0.633**	0.632**	1
BFs ($N = 25$)	As	1			
	Cd	0.453*	1		
	Pb	0.348	0.620**	1	
	Zn	0.316	0.663**	0.560*	1
TFs ($N = 25$)	As	1			
	Cd	0.513**	1		
	Pb	0.618**	0.769**	1	
	Zn	0.507**	0.678**	0.586**	1

Correlation was described using Spearman's correlation coefficients according to bi-variation method with two-tailed significance. *and ** indicate significant correlations at level $p < 0.05$ and $p < 0.01$, respectively.

Most of the plants exhibited higher concentrations of As, Cd, Pb, and Zn in the shoots than in the roots, and their TFs were higher than one. Two reasons may explain this phenomenon. Firstly, native plants evolved a high transport ability for metals from the root to the shoot. Baoshan mining started in 1966 and has a long history of constant contamination. Plants grown in this area from generation to generation have evolved into metallophytes, which are specifically adapted to and thrive in metal(loid)-polluted environments (Sheoran et al. 2010; Sherameti and Varma 2011). The potential mechanisms may include a strong ability of metal uptake with large quantities of small organic molecules as metal-bonding ligands, and an enhanced xylem loading capacity for metal(loid)s (Rascio and Navariizzo 2011). Secondly, atmospheric deposition of metal(loid)s may be another factor that resulted in the high concentrations of aboveground plant parts. Several previous studies indicated that plants growing near smelters exhibited high foliar levels of metal(loid)s (Shahid M et al. 2013, 2016; Xiong et al. 2014), and the concentrations of metal(loid)s in leaves are significantly related to atmospheric deposition (De Temmerman et al. 2012, 2015). According to Hu et al. (2011), the approximate contributions of airborne Pb to levels found in leaves of plant (*Aster subulatus*) were 65.1~72.2%.

When the plants grow in multiple metal(loid)-contaminated soils, they usually show a characteristic of mutual promotion of translocation in metal(loid) accumulation. The concentrations in plants and enrichment coefficients indicated significant relationships between Pb and Cd, Pb and Zn, and Cd and Zn in a lead–zinc mine area (Zu et al. 2004). Zinc and Cu also interacted in terms of promoting accumulation in plants growing in a contaminated site in Florida (Yoon et al. 2006), while in this study it was found that the concentrations of As, Cd, and Pb and their TFs in plants were significantly related to each other ($p < 0.01$).

Potential for phytoremediation

Phytoextraction, the use of plants to extract toxic metal(loid)s from contaminated soil, has emerged as a cost-effective, environmentally friendly cleanup alternative (Pinto et al. 2015; Sarwar et al. 2017). Hyperaccumulators are often applied for phytoextraction due to their effective uptake of toxic metal(loid)s and accumulation of metal(loid)s in the harvestable parts of plants (Sainger et al. 2011). The plants in the present study grew normally and exhibited strong tolerance to metal(loid)s. Four species accumulated metal(loid)s in the shoots above the thresholds defined by Ent et al. (2013), meeting the basic requirement for hyperaccumulation, i.e., *P. ensiformis* for As, and *B.* nivea, *A. prorerus*, and *H. sibthorpioides* for Cd. The results suggested that these species are potential hyperaccumulators for As and Cd, respectively. The "potential" means that some characteristics remain to be verified. As discussed above, atmospheric deposition might affect metal(loid) concentrations in plant aboveground. Hyperaccumulator should imply only active accumulation inside the plant leaf tissue, via the root; passive accumulation via airborne deposition on plant leaves should not be considered hyperaccumulation (Ent et al. 2013). An interesting contradiction was found when compared with other study. *P. ensiformis* was identified as a potential As hyperaccumulation in our study, but this species was considered a non-arsenic hyperaccumulator and sensitive to As by Singh and Ma (2006). For this reason, an experiment should be conducted to distinguish between As entering *P. ensiformis* via the root system and foliar absorption, under glasshouse conditions. Moreover, variation between different populations could be another explanation for this contradictory result. As described in Wan et al. (2013) study, four *Pteris vittata* populations showed differences in root As uptake and As species transformation. The As-tolerant populations of *P. vittata* displayed the tendency to sequester As by coordinating with a chelating agent (inactive form like As-GSH), while the As hyperaccumulators exhibited stronger affinities for As and were thus able to absorb As even at low concentrations. Different *P. vittata* populations can result in an approximately eightfold difference in terms of As accumulation (Wan et al. 2013). *P. ensiformis* in Singh and Ma's research and this study were collected at different places and belonged to different populations, so we speculated that they may also have different abilities to accumulate As. But further experimental studies should be conducted to confirm this assumption. *B. nivea* was hypertolerant to Cd, which is consistent with a previous study that revealed *B. nivea* possesses a certain degree of constitutional metal(loid) tolerance to Pb, Zn, Cd, and As (Yang et al. 2010). Furthermore, the feasibility of phytoremediation of Cd-contaminated farmland by *B. nivea* has been proven (She et al. 2011). All of the data in the present study and the cited references suggested that *B. nivea* is a good choice for mining restoration.

E. indica and *P. ensiformis* were found to be enriched with Pb (7474 mg kg^{-1}) and Zn (1662 mg kg^{-1}) in the roots, and the corresponding soils contained high concentrations of Pb (49294 mg kg^{-1}) and Zn (8520 mg kg^{-1}), respectively. And their TF values were less than 1. The above findings suggested that *E. indica* and *P. ensiformis* are hypertolerant, and they accumulated metal(loid)s from soil in their roots but restricted metal(loid) transporting to aerial parts. Plants with these features are considered to be an effective material for phytostabilization purposes (Mendez and Maier 2008; Ali et al. 2013). Other features such as a dense and tough root system is also important (Pinto et al. 2015). *E. indica* has a notoriously tough root system (Zhang et al. 2016); this botanical characteristic makes it a good candidate for Pb phytostabilization.

In addition to the characteristics of enrichment or fixation of metal(loid)s by plants, there are some other botanical features, such as abundance, a high growth rate, and good biomass yields (McGrath and Zhao 2003; Ali et al. 2013) that should be considered for determining whether a plant is suitable for mine restoration. The five indigenous plant species, including *P. ensiformis*, *B. nivea*, *A. prorerus*, *H. sibthorpioides*, *and E. indica*, have high abundance in the Baoshan mining area; their abundance ranked 4 or 5, which means frequent or abundant distribution. Moreover, *B. nivea* is a vigorous, high-yielding plant (Wang et al. 2008); *A. prorerus* and *H. sibthorpioides* are perennial herb that can be mowed in succession; and *E. indica* has a high reproductive capacity and a developed root system (Zhang et al. 2016). They should have good potential for phytoremediation in mining restoration. In addition, the plants that showed greater fitness for phytoextraction should be subjected to further investigation regarding their potential for phytomining of valuable metal(loid)s (Novo et al. 2017).

Conclusion

This study was conducted to investigate metal(loid) concentrations in soils and native plant species from the Baoshan mining area and to determine the potential capacity of these plants for phytoremediation. The concentrations of As, Cd, Pb, and Zn in all the study sites exceeded the soil environmental quality–risk control standard in China, indicating severe pollution. According to metal(loid) concentrations in shoots, BFs, and TFs, of the 20 plant species examined, as well as their botanical features such as high abundance, good biomass yielding, and high growth rate, *P. ensiformis* is identified as potentially useful for phytoextraction of As and *B. nivea*, *A. prorerus*, and *H. sibthorpioides* potentially useful for phytoextraction of Cd, while *E. indica* and *P. ensiformis* can be considered for the potential application to phytostabilization of Pb and Zn, respectively.

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