Heavy metals concentrations and accumulation characteristics of dominant woody plants in iron and lead-zinc mining areas in Jiangxi, Southeast China

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Research Article

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Abstract

Phytoremediation using woody plants can effectively reduce heavy metals (HMs) concentrations in soils. However, the remediation capacity of woody plants depends on soil and environmental conditions. To evaluate the HMs remediation potential of woody plants from different mining areas, we analyzed the HMs accumulation characteristics of roots, shoots and leaves of 12 dominant native woody plants in iron and lead-zinc mining areas. The distribution of HMs in plants varied with the type of HMs pollution in the two mining area. Available phosphorus (AP) and available potassium (AK) in soil were potential factors for the uptake of HMs by woody plants. In areas heavily contaminated with Pb, Cd and As, abilities of woody plants to accumulate Pb, Cd and Zn from soil were suppressed by AP, and the abilities to accumulate Pb, Zn, Cr and Ni from soil were suppressed by AK. *Cyclobalanopsis glauca* and *Rhododendron simsii* had strong enrichment and translocation abilities for Cd and Mn, *Pinus elliottii* for Cd, *Liquidambar formosana* for Mn and *Paulownia fortunei* for Zn. *Castanopsis sclerophylla, Rhus chinensis, Rhododendron simsii, Liquidambar formosana, Photinia × fraseri,and Paulownia fortunei* could grow under ultra-high concentration of As. The plants listed above can be used as potential species for phytoremediation in iron and lead-zinc mining areas.

1 Introduction

China is rich in mineral resources which plays an important role in the development of the national economy. However, mineral mining is considered to be the main source of toxic contaminants in the soil (Salomons, 1995; Wei et al., 2009; Li et al., 2017; Zhang et al., 2021). Toxic heavy metals (HMs) in waste rocks, tailings and smelting slags generated by the mining process are transferred to the soil and groundwater in mining areas through oxidation and the impact of natural environment (Salomons, 1995; Kan et al., 2021). The accumulation of toxic HMs in soils reduces soil quality and contaminates crops and groundwater, which, affect ecosystems and human health (Fu et al., 2016; Du et al., 2018). Soil HMs pollution has raised a global concern due to its crypticity, persistence and high toxicity (Ma et al., 2015; Chen et al., 2018).

The remediation methods for soil HMs pollution mainly include physical remediation, chemical remediation and phytoremediation (Ali et al., 2013). However, physical and chemical remediations generally have high costs and result in irreversible soil secondary pollution (Ali et al., 2013). In contrast, phytoremediation has the advantages of high efficiency, economy and ecologically sustainability (Mahar et al., 2016; Xin et al., 2020). The phytoremediation technology include phytostabilization, phytovolatilization and phytoextraction (Sarwar et al., 2017), the core of which is the screening of hyperaccumulator. Hyperaccumulator is defined as plant species that accumulate higher concentrations of specific HMs in the aboveground. To date, more than 500 plant species have been identified as hyperaccumulator, most of which belong to the herbaceous families of *Asteraceae*, *Brassicaceae*, *Caryophyllaceae*, *Poaceae*, *Violaceae* and *Fabaceae* (Luo et al., 2016; Cui et al., 2021). However, the phytoremediation is limited by the low biomass of herbaceous plants (van der Ent et al., 2012). In contrast, woody plants accumulate more HMs in their biomass due to their developed root system, thick branches and fast-growing, and higher above-ground biomass than herbaceous plants (Marmiroli et al., 2011). In addition, planting woody plants with phytoextraction and/or phytostabilization ability can not only reduce the mobility of HMs and effectively prevent the expansion of soil HMs pollution caused by soil erosion, but also produce a large amount of wood or biomass energy, providing economic benefits in terms of wood and bioenergy (Laureysens et al., 2004). Phytoremediation using fast-growing and high-biomass tree species such as poplar, willow, eucalyptus, birch and paulownia is an effective technology to reduce soil HMs contamination (Pajević et al., 2016). The use of nitrogen-fixing woody plants such as *Amorpha fruticosa* to fix nitrogen in the air, improve soil nutrients, enhance plant adaptation to HMs stress in tailings, and revegetate without chemical fertilizers is also an effective plant option (Shi et al., 2011). However, woody hyperaccumulators are regionally dependent, and the phytoremediation capacity depends on soil conditions (Lu et al., 2014; Xiao et al., 2018). Therefore, screening for indigenous dominant plants that are adapted to local soil conditions may have greater remediation potential in future phytoremediation applications (Heckenroth et al., 2016; Madejon et al., 2018; Guarino et al., 2019; Zhong et al., 2021).

To find such plants with HMs remediation potential, we selected the Jiulong iron mine and Yangtiangang lead-zinc mine in Xinyu, Jiangxi Province as our study area. In this study, 12 different species of dominant woody plants planted in the study areas were selected to analyze the concentration and accumulation characteristics of HMs in roots, shoots and leaves. The aim of this study is to analyze the HMs pollution types in different tailing areas, screen woody plants that can enrich or transport HMs, reveal their adaptation to HMs pollution and possible coping strategies, and evaluate their application potential as phytoremediation in the future.

2 Materials And Methods

2.1 Study site description

The study sites are located in two mining areas where phytoremediation experiments are being carried out: Jiulong iron mine (27° 32' N, 114° 43' E) and Yangtiangang lead-zinc mine (27° 51' N, 114° 52' E), Yushui District, Xinyu City, Jiangxi Province, China (Fig. 1). The climate of the two study sites is mid-subtropical monsoon with an annual average temperature of 18.6°C, an annual average precipitation of 1264.5 mm, and an annual sunshine hours of 1753.1 h. Both study sites belong to the Luoxiao Mountains with low hills and hilly terrain. The soil type in the two study sites is red soil developed from granite, metamorphic rocks, gravels and carbonate rocks.

2.2 Sample collections

The plant samples were collected in May 2021. Well-grown woody plants from the study area were selected as the dominant plants as shown in Table 1. Three healthy plants of each specie were selected at each site, and the roots, shoots and leaves of each plant were collected separately. Three samples of each organ were mixed to one composite sample. The information of the sampling points was recorded by global positioning system (GPS), and the collected plants were identified and named taxonomically. Also, about 500 g of soil was collected from the root zone of each plant, and stones and branches were removed from the soil samples. All samples were immediately placed in clean polyethylene self-sealing bags, and transported back to the laboratory for HMs concentrations determination.

Table 1
List of dominant plant species growing on the study area

Sample sites		Family	Species	Life form
Jiulong	1	*Anacardiaceae*	*Rhus chinensis* Mill.	Deciduous tree
	2	*Taxodiaceae*	*Cunninghamia lanceolata* (Lamb.) Hook.	Evergreen tree
	3	*Pinaceae*	*Pinus massoniana* Lamb.	Evergreen tree
	4	*Betulaceae*	*Alnus cremastogyne* Burk.	Deciduous tree
	5	*Pinaceae*	*Pinus elliottii* Engelmann	Evergreen tree
	6	*Leguminosae*	*Spatholobus suberectus* Dunn	Evergreen vine
	7	*Fagaceae*	*Cyclobalanopsis glauca* (Thunberg) Oersted	Evergreen tree
Yangtiangang	8	*Pinaceae*	*Pinus massoniana* Lamb.	Evergreen tree
	9	*Fagaceae*	*Castanopsis sclerophylla* (Lindl. et Paxton) Schottky	Evergreen tree
	10	*Anacardiaceae*	*Rhus chinensis* Mill.	Deciduous tree
	11	*Ericaceae*	*Rhododendron simsii* Planch.	Deciduous shrub
	12	*Hamamelidaceae*	*Liquidambar formosana* Hance	Deciduous tree
	13	*Rosaceae*	*Photinia × fraseri* Dress.	Evergreen shrub
	14	*Scrophulariaceae*	*Paulownia fortunei* (Seem.) Hemsl.	Deciduous tree

2.3 Sample analysis

Soil samples were air-dried, ground, and sieved through 2 mm for soil pH, available phosphorus (AP) and available potassium (AK) assays, and 0.149 mm for HMs assays, respectively. Each soil sample (0.1 g) was digested with 8 mL aqua regia (HNO_3:HCl = 1:3) (Chinese national environmental protection standard (HJ 803–2016)). The plant samples were repeatedly washed three times with deionized water to remove the dirt. The samples were treated by high temperature desiccation under 85°C for 30 min, then oven dried under 65°C to constant weight. The dried plant samples were crushed to a size < 2 mm using a grinder. Each plant sample (0.2 g) was digested with 8 mL of 65% HNO_3 (Chinese national standard (GB 5009.268–2016)). Each digested sample was filtered through 0.45 µm aqueous filter membrane and was diluted to 25 mL volume with deionized water. Soil AP and AK were extracted from soil (5 g) using 50 mL solution of a mixture of 0.03 mol·L^{-1} NH_4F and 0.025 mol·L^{-1} HCL and 50 mL solution of 1 mol·L^{-1} NH_4Ac (pH = 7.0), respectively. The concentrations of Pb, Cd, Cu, Zn, Cr, Ni, Mn, AP and AK were measured by an inductively coupled plasma mass spectrometry (ICP-MS, Thermo ICAP-RQ, USA). The concentrations of As was measured by an atomic fluorescence spectrometry (AFS, Persee PF32, China). Soil pH (soil: water = 1: 2.5) was measured with conventional pH meter (Mettler Toledo FE20, China). Three replicates were performed for all samples and a blank test was done, and the analytical precision was accepted when the relative standard deviation was within 5%.

To assess phytoextraction or phytostabilization and to screen plant species with phytoremediation capabilities (Chojnacka et al., 2005), bioconcentration factor (BCF) reflecting the HMs enrichment capacity and translocation factor (TF) indicating the ability of plants to transfer HMs from the below-ground (root) to the above-ground (shoot and leaf) (Ali et al., 2013) were calculated as:

$BCF_{leaf/shoot/root} = C_{leaf/shoot/root} / C_{soil}$

$TF_{leaf/shoot} = C_{leaf/shoot} / C_{soil}$

Where C was the concentration of each heavy metal in each plant organ or soil (Li et al., 2007).

2.4 Statistical analysis

The experimental data were processed by Microsoft Excel (Ver. 2019) for analysis of the means, minimum, maximum and standard deviation, and pearson correlation analysis was performed using SPSS 26.

3 Result

3.1 Soil characteristics

The soil characteristics in study area are shown in Table 2. The soils in study areas were acidic (pH 2.95–5.92). The average concentrations of AP and AK in the soil is less than 10 mg kg^{-1} and 100 kg mg^{-1}, respectively, showing a nutrient-poor state of the soil. The concentrations of all HMs at the Jiulong and Yangtiangang mines were above the background values. The concentrations of Cd, Cu and Mn in Jiulong area exceeded the threshold values by 1.03, 1.07 and 1.89 times. The concentrations of Pb, Cd, Cu, Zn and As in Yangtiangang area exceeded the threshold values by 18.32, 3.20, 1.20, 1.70 and 55.16 times. The soils of the two tailings sites were contaminated with multiple HMs compound. Among the HMs exceeding the threshold values, the coefficients of variation of Cd, Cu and Mn in Jiulong and Pb, Cd, Zn and As in Yangtiangang were all greater than 0.4, indicating that there was a large spatial variability of HMs pollution in the tailings waste sites.

Table 2

Soil characteristics and reference values in Jiulong iron mining areas and Yangtiangang lead-zinc mining areas

Sample sites	Jiulong			Yangtiangang			Reference value	
	Range[a]	Mean	CV	Range	Mean	CV	Background[b]	Threshold[c]
pH	4.49–5.92	4.83	0.10	2.95–4.41	3.70	0.11		
AP	1.24–3.02	2.15	0.25	1.13–15.87	8.72	0.51		
AK	38.89–158.01	86.16	0.52	61.7–140.75	95.17	0.27		
Pb	27.08–47.66	35.24	0.17	67.86–5944.23	1282.57	1.58	32.1	70
Cd	0.12–0.72	0.31	0.57	0.10–2.95	0.96	1.09	0.1	0.3
Cu	17.93–102.94	53.53	0.65	33.41–84.78	59.87	0.27	20.8	50
Zn	61.19–96.42	81.86	0.15	117.25–820.47	339.08	0.75	69.0	200
As	3.36–30.61	15.53	0.64	150.45–4454.35	2206.37	0.65	10.4	40
Cr	31.33–82.73	64.57	0.24	51.75–77.48	64.89	0.15	48.0	150
Ni	29.40–53.51	40.41	0.19	16.06–55.39	34.82	0.30	19.0	60
Mn	470.83–3612.76	2267.58	0.46	678.92–1045.57	856.82	0.15	258.0	1200

a, Element concentration unit: mg kg^{-1}

b, Background values of soil environment in Jiangxi Province, 2006

c, The threshold values of Pb, Cd, Cu, Zn, As, Cr, and Ni refer to the risk screening value of pH ≤ 5.5 in the Chinese standard for soil pollution risk control of agricultural land (GB 15618 – 2018) as, and Mn refer to the standard in the reference of Li et al.(Li et al, 2018)

3.2 HMs concentrations in dominant plants

The elemental concentrations determined in woody plants in the study area are depicted in Fig. 2. The range of various HMs in plants was: 0.404–476 mg kg^{-1} for Pb, 0.025–1.47 mg kg^{-1} for Cd, 2.76–48.8 mg kg^{-1} for Cu, 8.19–200 mg kg^{-1} for Zn, 0–713 mg kg^{-1} for As, 2.11–24.4 mg kg^{-1} for Cr, 1.52–36.1 mg kg^{-1} for Ni and 29.1–2898 mg kg^{-1} for Mn. In Yangtiangang where Pb, Cd, Zn and As pollution is more severe, the corresponding elements were present in higher levels in plants. The concentrations of HMs in different organs of the plant varied. The distribution of different elements in plants was generally as follows: root > leaf > shoot for Pb and As; root > shoot > leaf for Cr; leaf > shoot > root for Zn, Ni and Mn. Cu and Cd differed in plants from two regions, with shoot > leaf > root for Cu; shoot > root > leaf for Cd in plants from Jiulong and root > shoot > leaf for Cu; shoot > leaf > root for Cd in Yangtiangang.

3.3 Correlation analysis between the concentrations of HMs in plant roots and the concentrations of HMs, AP and AK in soil

The results of the correlation analysis between the root HMs concentrations of native dominant woody plants and the concentrations of soil HMs, AP and AK are shown in Fig. 3. The Pb and As concentrations in roots positively correlated with Pb and As concentrations in soils ($p < 0.01$), respectively, while the Zn concentrations in roots negatively correlated with Cr ($p < 0.01$) with the Cr concentrations in soils, in both study areas. It is noteworthy that there was a significant correlation between AP and AK concentrations in soils and some HMs concentrations in plant roots in both study areas. Significant negative correlations were found between AP concentrations and plant root Pb, Cd and Zn concentrations, and between AK and plant root Pb, Cr and Ni concentrations in Yangtiangang lead-zinc mining area. However, such correlations were completely reversed in Jiulong iron mining area.

3.4 Evaluation of HMs accumulation and translocation potential

The BCFs and TFs of woody plants in the study area are depicted in Fig. 4 and Fig. 5. The BCFs of plant roots, shoots and leaves to the six HMs with pollution risk in soil all showed Cd > Mn > Zn > Cu > Pb > As. The TFs of plant shoots and leaves to the six HMs all showed Mn > Zn > Cd ≈ Cu > Pb > As. The enrichment and transport capacities of most of woody plants were more pronounced for Cd. The BCF_{leaf}, BCF_{shoot} and BCF_{root} of *R. simsii* reached 8.41, 7.48, 2.61 and the TF_{shoot} and TF_{leaf} reached 2.87 and 3.23, which far exceeded 1. In addition, the BCF_{shoot}, BCF_{leaf}, Tf_{shoot} and TF_{leaf} for Mn of *C. glauca* and *L. formosana* were greater than 1, and the BCF_{shoot}, BCF_{leaf}, Tf_{shoot} and TF_{leaf} for Zn of *P. fortunei* were greater than 1.

4 Discussion

4.1 Concentrations of HMs in woody plants and factors with potential effects

In general, the normal range of HMs concentrations in plants is 0.1–41.7 mg kg^{-1} for Pb, 0.2–0.8 mg kg^{-1} for Cd, 0.4–45.8 mg kg^{-1} for Cu, 1–160 mg kg^{-1} for Zn, 0–1 mg kg^{-1} for As, 0.2–8.4 mg kg^{-1} for Cr, 0.1–10 mg kg^{-1} for Ni and 1–700 mg kg^{-1} for Mn (Huang et al., 2014; Zhu et al., 2018; Wu et al., 2021; Gou et al., 2021). The HMs concentrations of plants in the study area far exceeded general plants. Some of the plant roots have good adsorption capacity for Pb, As and Cr in the soil, such as Pb concentrations in the roots of *R. chinensis* in Yangtiangang lead-zinc mining areas exceeded the range by 10.95 times, and As concentrations in the roots of *R. simsii* exceeded the range by 709.31 times. The concentrations of Pb, As and Cr metals accumulated in the roots were significantly higher than those in the above-ground shoots and leaves. It has been demonstrated that the uptake of HMs by trees is mainly confined to the roots (Punshon and Dickinson, 1999; Watson et al., 2003), presenting high plant availability of the metals as well as its limited mobility once inside the plant(Deng et al., 2004). The concentrations of Pb, As, Zn, Mn and Ni in the above-ground parts were higher in the leaves than in the shoots (Fig. 2), which could be attributed to the role of the shoots as a transferring tissue for these element (Planquart et al., 1999).

Among all plants, there were differences in the concentrations of HMs in plants, but in general, they showed that the concentrations of Mn, Zn, Cu and Ni in plants was greater than that of Pb, Cd, Cr and As, which was related to the specific roles played by these elements in plants. Mn, Zn, Cu and Ni are essential trace elements for plant growth and development, and are involved in processes such as enzyme and protein synthesis and photosynthesis in plants (Zengin and Munzuroglu, 2005; Kumar et al., 2007; Liu et al., 2020; Kulbat-Warycha et al., 2020). Cd, Pb, Cr and As are not essential for plant growth and can have strong toxic effects on plants (Huihui et al., 2020). These elements can induce free radical production and cause oxidative stress in plants, which interfere with the normal metabolic processes of plant cells and lead to yellowing, leaf necrosis and a reduction in plant biomass (Wagner, 1993; Hall, 2002; Fahr et al., 2013; Gupta et al., 2020).

A general positive correlation between HMs concentrations in plants and soil are reported (Salam et al., 2016; Radojcic Redovnikovic et al., 2017; Ullah and Muhammad, 2020). Similar results were observed in the present study. Both *R. chinensis* and *P. massoniana* showed stronger enrichment ability for Pb, Cd, As and Zn in Yangtiangang, where the pollution of these four HMs was more serious. In Jiulong, where Mn pollution was more pronounced, both *R. chinensis* and *P. massoniana* showed stronger enrichment ability for Mn. The pearson correlation coefficient also showed that the uptake of Pb and As by plant roots mainly depends on the concentrations of the corresponding two elements in the soil, with a significant positive correlation. Significantly, the average concentrations of Pb and As in the soil collected from Yangtiangang have exceeded the pollution risk screening value by 18.32 times and 55.16 times, yet some plants could still grow well under such extreme environment. Plants develop defense strategies against high concentrations of HMs under long-term natural selection, such as the sequestration of HMs by the root system and the activation of antioxidant enzyme systems to reduce oxidative stress caused by HMs in plants (Peco et al., 2020; Song et al., 2020).

Numerous studies have demonstrated that soil pH plays the most important role in determining metal morphology, mineral surface solubility, migration and final bioavailability (Du Laing et al., 2007; Zeng et al., 2011; Zhao et al., 2015). Mobility and bioavailability of HMs will increase as soil pH decreases, thus increasing the uptake of HMs by plants exacerbating their toxicity to plants (Kim et al., 2020). Most soil pH in this study exhibited a strong acidity. Since lower pH usually decrease the sorption of metal ions on soil particles, competition between free metal ions and other cations in solution increases, thus increasing the metal concentrations in the soil solution (Nahmani et al., 2007; Zhong et al., 2020).

Phosphorus and potassium are essential nutrients for plant growth. Reasonable addition of phosphorus and potassium can significantly promote plant growth, and produce a biological dilution effect on HMs in plants by increasing biomass. Phosphate compounds are often used to increase the immobilization of metals, thereby reducing their mobility and bioeffectiveness in the soil (Bolan et al., 2013; Netherway et al., 2019). Potassium could suppress reactive oxygen species helping the anti-oxidant defence of the plant against HMs stress, reducing the toxic effects of HMs such as Pb, Cd, Zn and As on plants (Umar et al., 2013; Song et al., 2015). And it can also immobilize HMs in soils, reducing the concentrations of available heavy metals that plants can absorb (Ruthrof et al., 2017). Chen et al. found that the abilities of wheat to accumulate Zn, Cu, Pb and Ni from soil were suppressed by P addition while of As was enhanced (Chen et al., 2020). Highly similar results were obtained in the Yangtiangang lead-zinc mining area in this study. The negative correlations between AP concentrations in soils and the concentrations of Pb, Cd and Zn in plant roots indicate that AP in soils may be involved in complexation with Pb, Cd and Zn, reducing the concentrations of avaliable HMs elements in soils and lowering the uptake of these elements by plants. In addition, the negative correlations between AK concentrations in soils and the concentrations of Pb, Zn, Cr and Ni in plant roots indicate that AK can reduce the uptake of these elements by plants and reduce the toxic effects of such elements on plants. Interestingly, similar findings to those of previous studies were only found in Yangtiangang, while completely opposite conclusions were obtained in the Jiulong. Firstly, this may be related to the plants selected. The different dominant woody plants selected in two areas may have caused the results to bring a large difference. Secondly, the level of pollution in Jiulong is mild, while Yangtiangang has a high level of contamination and complex elements causing contamination, which may also lead to large differences in the results. However, it is undeniable that AP and AK are also an important factor for the uptake of HMs by woody plants and a reasonable addition of phosphorus and potassium to soil may be helpful for plants to resist the toxic effects of HMs.

4.2 Accumulation and transport characteristics of HMs in woody plants

Some woody plants in this study had good enrichment capacity for a variety of HMs. The additive effect of multi-metal complex pollution may exacerbate the toxic effects of HMs on soil and plants, and affect the ability of plants to take up HMs (Gong et al., 2020). The *R. simsii* could enrich both Cd and As, and *L. formosana* could enrich both As and Mn. Moreover, the concentrations of these elements in plants exceeded the general level more than one and a half times. Thus, these species have potential applications for HMs remediation. The differences in the translocation and uptake of different woody plants may be related to the different dominant plants investigated and also the soil contamination (Li et al., 2016; Chen et al., 2019). It has been reported that differences in phytoextractive capacity may be influenced by the soil mixture of contaminants, which may change relative to a metal that is present in too high a concentration, such as a mixed treatment of Cd and Zn significantly reduced the accumulation of Cd and Zn in poplar and willow, possibly due to the ionic competition between the metals (Dos Santos Utmazian et al., 2007; Nissim et al., 2015). The differences in Pb and As contamination between the two mines were very significant, which may be responsible for the differences in Cu and Cd uptake by plants (Ali et al., 2016).

The BCF is higher than 1 indicating that the tree species has a high enrichment capacity for HM and can effectively reduce the concentration of HM in the soil (Midhat et al., 2019). The TF is higher than 1 indicating that the tree species can effectively transfer HM from the below-ground to the above-ground, reduce the toxic effects caused by high concentrations of HM in the plant roots, and have the potential for phytoextraction (Rodriguez et al., 2012; Pandey et al., 2016). Wang et al. concluded that woody plants with BCF greater than 0.4 are hyperaccumulators due to their high biomass, but there is a lack of experimental corroboration (Wang et al., 2011). No matter which of the above criteria is used for evaluation, most of the studied plants had a strong enrichment and transport capacity for Cd. Carmine’s study also showed that plants in two different places were the most enrichment for Cd (Baycu et al., 2015; Guarino et al., 2019).

According to Baker and Brooks, hyperaccumulators refer to plants whose aboveground HM concentration is more than 10 times higher than the typical plants (Baker and Brooks, 1989). Antony van der Ent et al. concluded through experiments and model validation that the criteria for hyperaccumulators of certain metal elements should be set to Cd[illegible]100 mg kg^{-1}, Cu, Cr > 300 mg kg^{-1}, Pb, Ni, As [illegible]1000 mg kg^{-1}, Zn > 3000 mg kg^{-1} and Mn

10000 mg kg^{-1} (van der Ent et al., 2012). Although none of the plants investigated in this study reach the above critical value, some plants with high BCF, high TF or high BCF, low BTF are still found, and such plants have the potential to be applied for phytoextraction or phytostabilization in HMs contaminated area (Yoon et al., 2006). In addition, some plants can avoid excessive intake of HMs ions and have strong stress avoidance and stress tolerance to environments with extremely high concentrations of soil HMs through tolerance of the protoplasm itself (Punz and Sieghardt, 1993). These plant can be used to green the abandoned land of the mine, which can help to conserve water and soil and reduce the migration of HMs. Therefore, this study also classified such plants as one of the types of HMs phytoremediation, which were supposed to grow in soils with ultra-high HMs concentrations, and the plants had low BCF and TF (Punz and Sieghardt, 1993). Based on the following criteria, tree species with HMs remediation potential were classified. Some plants with HMs concentrations in an organ above the normal range and with both BCFs and TFs higher than 1 are considered to have potential of phytoextraction. Some plants are considered to have a ultra-high tolerance to HMs when they are grown in soils exceeding 20 times the threshold value for HMs, despite the fact that plant HMs levels are in the normal range and BCFs are less than 1. The native woody species with potential for remediation of contaminated soil in mining areas were screened in this study (Table 3). *C. glauca*, *R. simsii* and *P. elliottii* have high BCFs and high TFs for Cd, *C. glauca*, *R. simsii* and *L. formosana* have high BCFs and high TFs for Mn, *P. fortunei* has high BCFs and TFs for Zn, and these plants are considered to have the potential of phytoextraction. Caparros et al. also found that *P. fortunei* had a strong ability to accumulate Zn and they had a very high annual increment in biomass, up to 150 t ha^{-1} (Caparros et al., 2008). Among all plants studied, *C. sclerophylla* and *R. chinensis* are extremely tolerant to both Pb and As in the soil, *R. simsii*, *L. formosana*, *Photinia × fraseri*, and *P. fortunei* are extremely tolerant to As in the soil. The specific tolerance mechanisms need to be further studied.

Table 3
Woody plants with potential for remediation of heavy metal pollution in study areas

Function	Heavy metal	Dominant plant
Phytoextraction	Cd	*C. glauca, P. elliottii, R. simsii*
	Mn	*C. glauca, L. formosana, R. simsii*
	Zn	*P. fortunei*
Ultra-high tolerance	Pb,As	*C. sclerophylla, R. chinensis*
	As	*L. formosana, P. fortunei , Photinia × fraseri, R. simsii*

5 Conclusions

The investigation and experimental results showed that soil HMs remediation using native dominant woody plants is an effective remediation in the future. HMs levels in plants tended to be higher in areas with higher levels of pollution. When the soil was heavily contaminated with Pb, Cd and As, AP in the soil may have inhibited the accumulation of Pb, Cd and Zn in plants, and AK in the soil inhibited the accumulation of Pb, Zn, Cr and Ni in plants. The dominant woody plants in the study area exhibited good enrichment ability for HMs. *C. glauca*, *L. formosana, R. simsii*, *P. elliottii* and *P. fortunei* had strong enrichment ability for HMs such as Cd, Mn and Zn, and could be used for phytoextraction. Besides, *C. sclerophylla*, *R. chinensis*, *R. simsii*, *L. formosana*, *Photinia × fraseri* and *P. fortunei* could grow normally under ultra-high concentrations of Pb and As HMs and had strong HMs tolerance, which can help to conserve water and soil and reduce the migration of HMs. The tree species listed above are considered to have potential remediation capacity for HMs contamination.

Declarations

Author contribution

All authors contributed to the study conception and design. Writing—original draft, Validation: Yanglong Li. Investigation: Yanglong Li, Chaowu Yan, Xiangteng Chen and Mansheng Zeng. Formal analysis: Yanglong Li, Shaowen Liu. Resources: Chaowu Yan and Shaowen Liu. Writing – review & editing, Supervision: Chaoqun Wang, Yuhong Dong and Ruzhen Jiao. All authors read and approved the final manuscript.

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Competing interests The authors declare no competing interests.

Availability of data and materials

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

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Figures

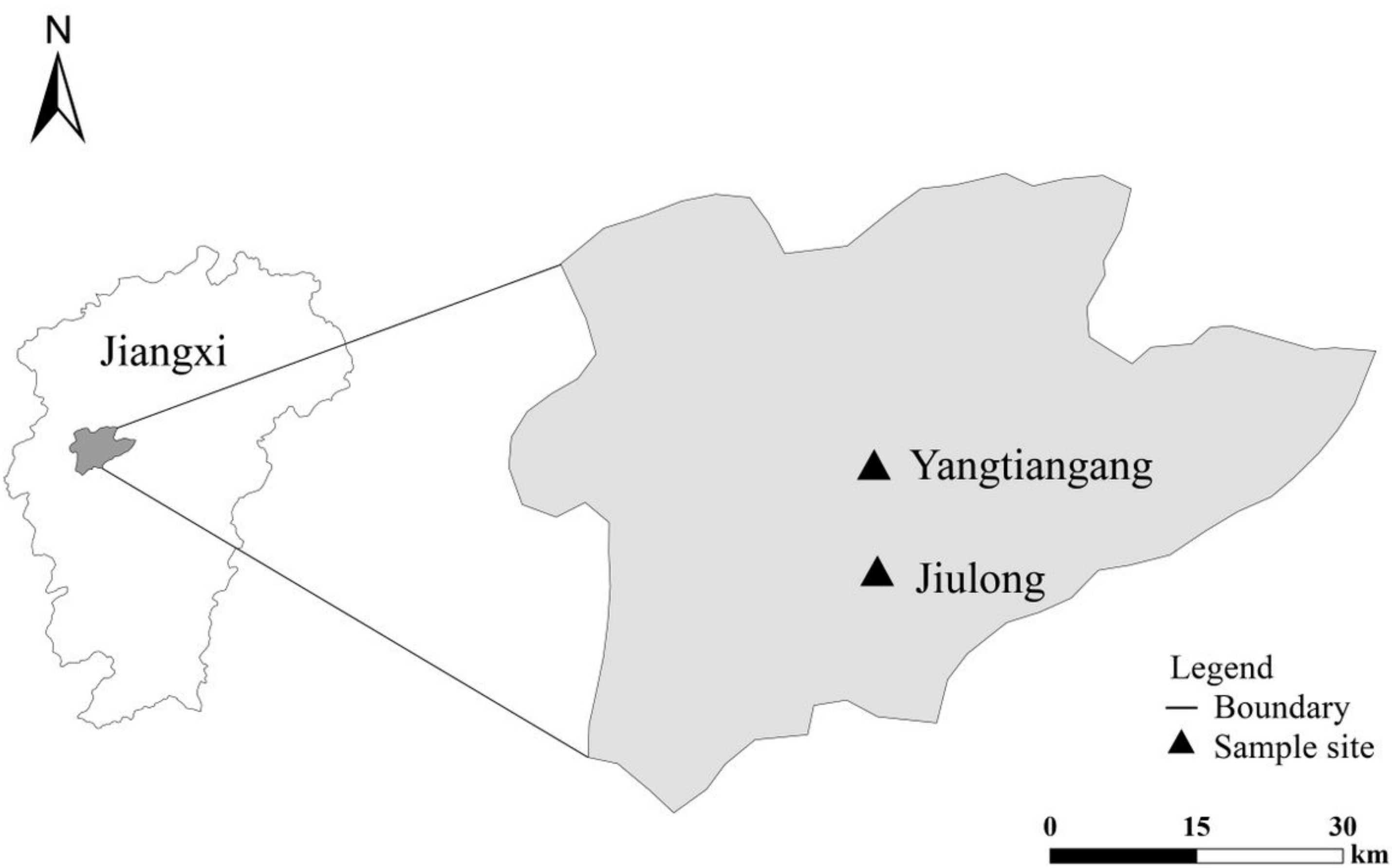

Figure 1

Location map and different sampling sites of investigated mining areas

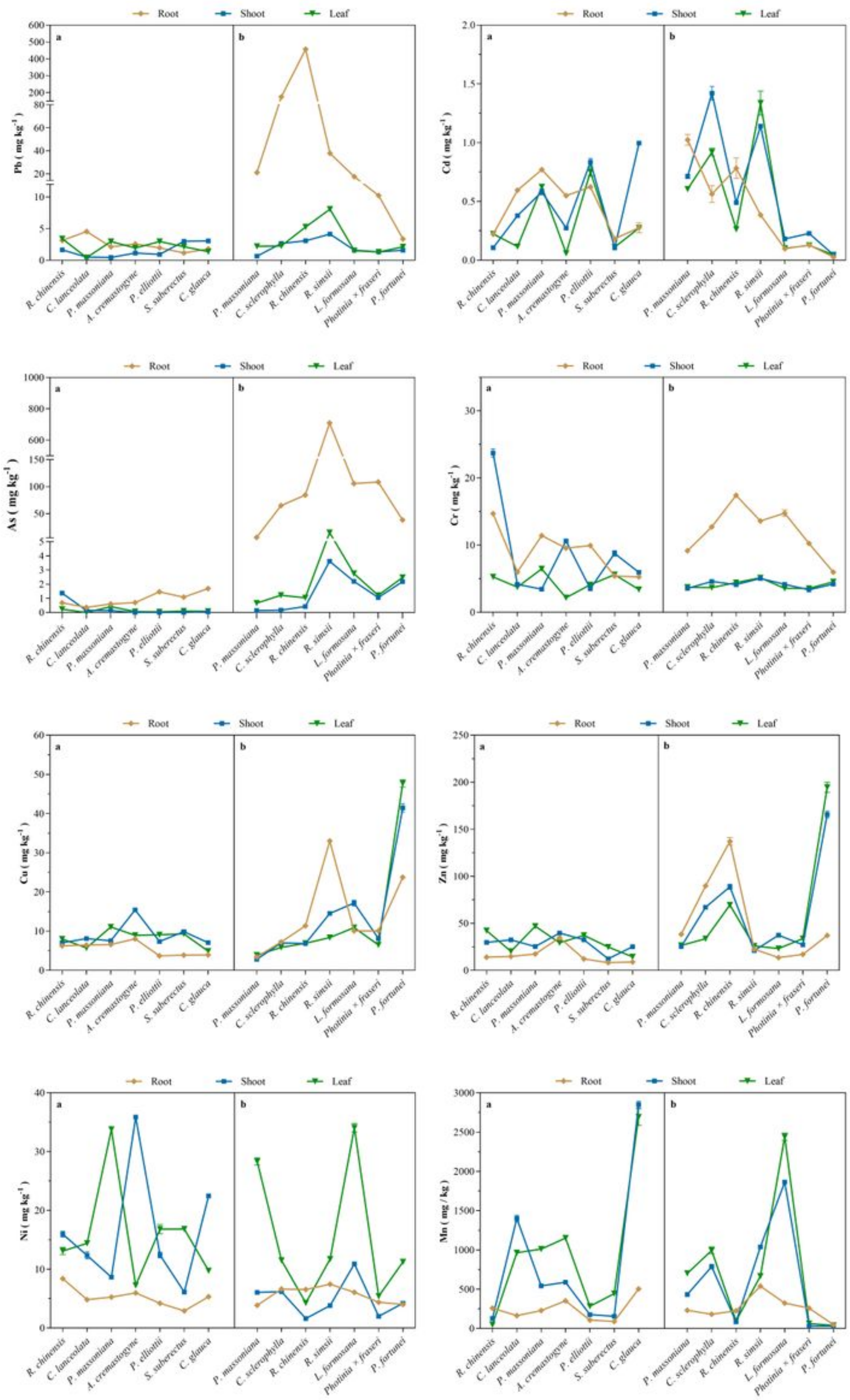

Figure 2

Heavy metals in the roots, shoots and leaves of each woody plant in Jiulong iron mining areas (**a**) and Yangtiangang lead-zinc mining areas (**b**)

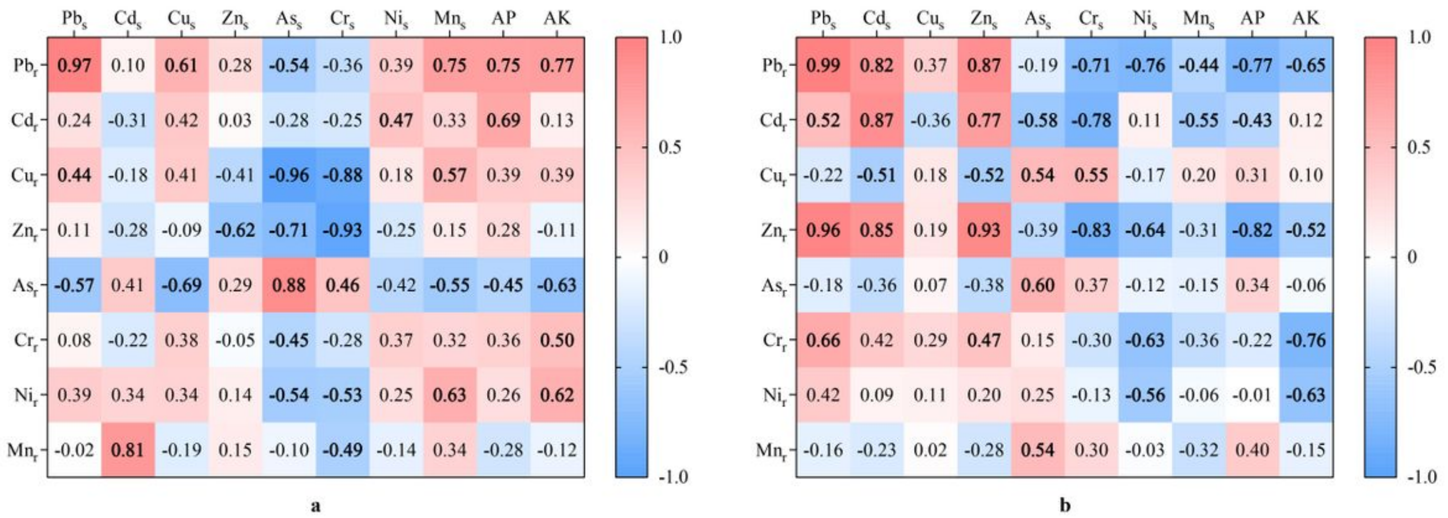

Figure 3

Pearson correlation coefficients between plants root HMs concentrations and soil HMs, AP and AK concentrations in Jiulong iron mining areas (**a**) and Yangtiangang lead-zinc mining areas (**b**). The 's' and 'r' in the subscript denote soil and root respectively. Bold numbers indicate the statistically significant ones and correlation is significant at the 0.05 level (2-tailed)

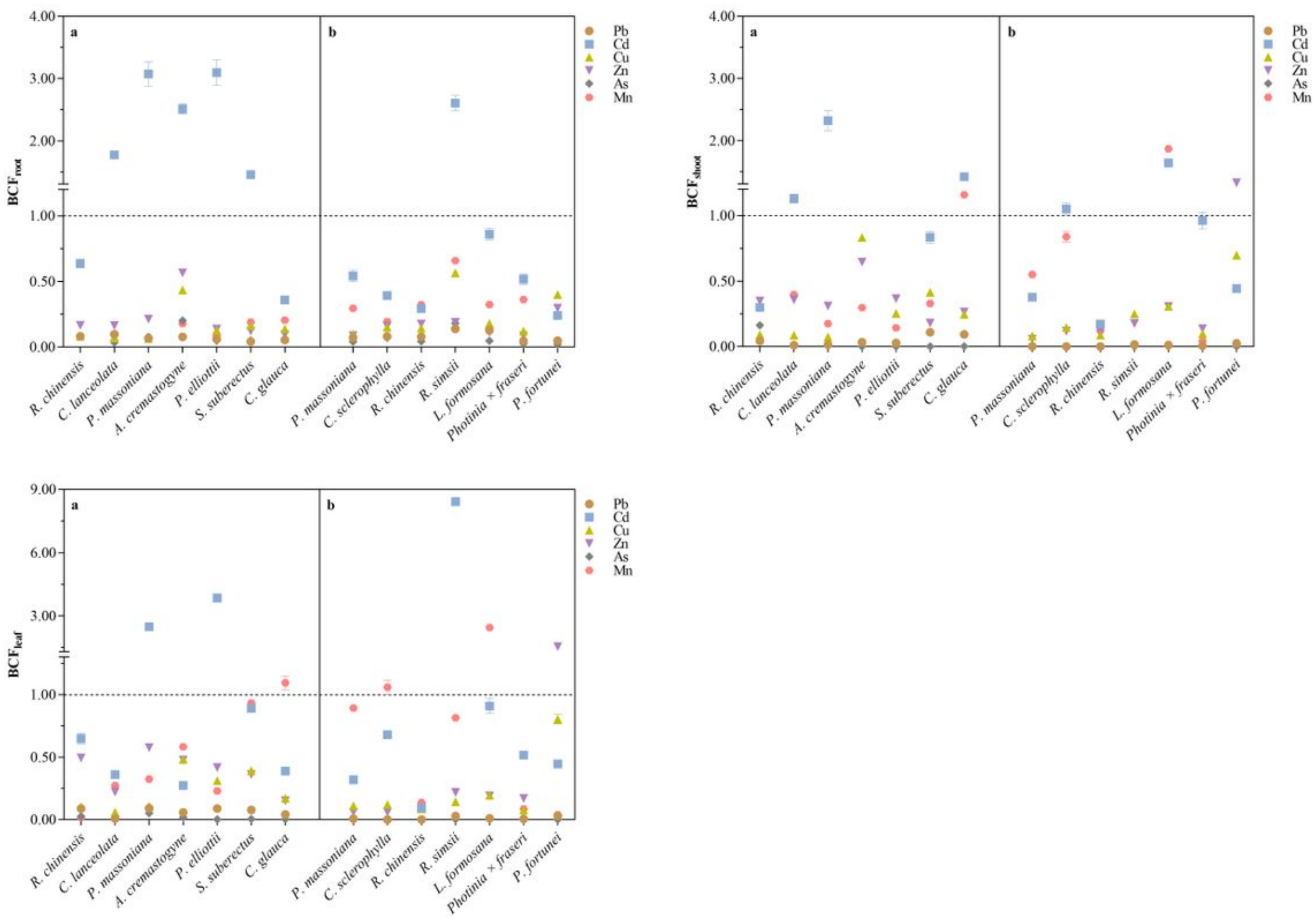

Figure 4

BCFs of heavy metals in the roots, shoots and leaves of each woody plant in Jiulong iron mining areas (**a**) and Yangtiangang lead-zinc mining areas (**b**)

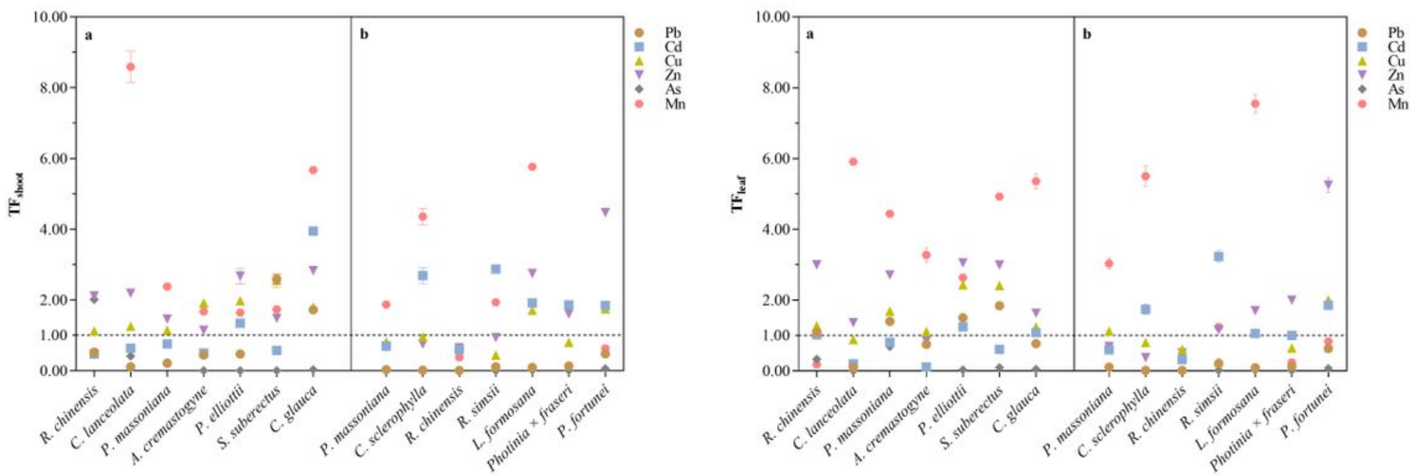

Figure 5

TFs of heavy metals in the roots, shoots and leaves of each woody plant in Jiulong iron mining areas (**a**) and Yangtiangang lead-zinc mining areas (**b**)