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Soil characteristics and heavy metal accumulation by native plants in a Mn mining area of Guangxi, South China

Jie Liu · Xue-hong Zhang · Tian-yu Li ·
Qing-xin Wu · Zhen-jiang Jin

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Abstract Revegetation and ecological restoration of a Mn mineland are important concerns in southern China. To determine the major constraints for revegetation and select suitable plants for phytorestoration, pedological and botanical characteristics of a Mn mine in Guangxi, southern China were investigated. All the soils were characterized by low pH and low nitrogen and phosphorus levels except for the control soil, suggesting that soil acidity and poor nutrition were disadvantageous to plant growth. In general, the studied mine soils had normal organic matter (OM) and cation exchange capacity (CEC). However, OM (8.9 g/kg) and CEC (7.15 cmol/kg) were very low in the soils from tailing dumps. The sandy texture and nutrient deficiency made it difficult to establish vegetation on tailing dumps. Mn and Cd concentrations in all soils and Cr and Zn concentrations in three soils exceeded the pollution threshold. Soil Mn and Cd were above phytotoxic levels, indicating that they were considered to be the major constraints for phytorestoration. A botanical survey of the mineland showed that 13 plant species grew on the mineland without obvious toxicity symptoms. High Mn and Cd concentrations have been found in the aerial parts of *Polygonum pubescens*, *Celosia argentea*, *Camellia oleifera*, and *Solanum nigrum*, which would be interesting for soil phytoremediation. *Miscanthus floridulus*, *Erigeron acer*, *Eleusina indica*, and *Kummerowia striata* showed high resistance to the heavy metal and harsh condition of the soils. These species could be well suited to restore local degraded land in a phytostabilization strategy.

Keywords Heavy metals · Nutrient state · Restoration · Phytoaccumulation · Mn mineland

Introduction

Manganese mining can result in significant damage to the local ecosystem. In mining operations, the inevitable removal of the topsoil with its original vegetation leaves a land surface that typically consists of nutrient-poor, skeletal subsoil (Bradshaw 2000). Besides vegetation damage and soil erosion, mining activities also cause toxic metal pollution in soil and water, which pose a high risk to biodiversity and human health (Wang et al. 2008). For instance, long-term mining activities in Dabaoshan, China led to heavy metal contamination in food crops and posed a great health risk to the local population (Zhuang et al. 2009). Therefore, ecological restoration in the mine-damaged land is very important after mining activities have been terminated.

Revegetation offers the most effective method to achieve sustainable site restoration and visual

J. Liu (✉) · X.-h. Zhang (✉) · Q.-x. Wu · Z.-j. Jin
Guangxi Key Laboratory of Environmental Pollution Control Theory and Technology, Guilin University of Technology,
Guilin, Guangxi 541004, China
e-mail: Liu-j7775@163.com
e-mail: Zhangxuehong@x263.net

T.-y. Li
School of Life and Environment Sciences, Guilin University of Electronic Technology,
Guilin, Guangxi 541004, China

improvement of mining-degraded land (Remon et al. 2005). Toxic metals can be immobilized by metal-tolerant plant species through accumulation by roots, adsorption onto roots, or precipitation within the rhizosphere (Wong 2003). Furthermore, as initial vegetation cover grows and dies, significant amounts of organic matter will be added to the soil, thereby enhancing water and nutrient retention. However, after metal mining, the derelict lands usually have unfavorable soil properties that are inimical to plant establishment, such as high metal toxicity (Rotkittikhun et al. 2006; Li et al. 2007), deficiency of major nutrients (Chiu et al. 2006), poor physical structure (Li 2006), and excess salinity and extreme pH (Conesa et al. 2006). Constraints to revegetation vary with the pedological characteristics of minelands. To understand the constraints and opportunities, it is necessary to assess the physicochemical properties of mine-degraded soils (Ye et al. 2002).

The choice of the initial plant species is another critical factor for successful revegetation (Stiles et al. 2011). The plant species selected should not only be able to tolerate toxic metal stress but should also be able to survive the harsh conditions of the degraded site. Furthermore, the plants screened for revegetation should not be considered as exotic or invasive. In this respect, native plants are good choice for phytorestoration. As a result of natural selection, native plants may have evolved tolerance for the environmental stress of a mining area and adapted to the local climate. Therefore, the native plants are often better in terms of survival, growth, and reproduction in the contaminated sites than plants introduced from other environments (Yoon et al. 2006). Moreover, plants living in metalliferous soils can have exceptional properties which make them interesting for phytoremediation (Moreno-Jiménez et al. 2009). In order to screen suitable plants for phytorestoration, it is essential to get information on the vegetation growing on the degraded sites before remedial activities are commenced.

Guangxi Province ranks first in China in terms of Mn mining, and there are 227 Mn mines in this region (Li et al. 2007). The Xiaotianshan Mn mine is one of the oldest mines in Guangxi Province, which has been exploited since 1958. However, the restoration of this mine has been overlooked for long time. In the present work, the pedological characteristics and metal accumulation by native plants were investigated as the groundwork for the phytorestoration of this area. Our objectives were to identify the limiting factors for plant establishment on the mining-degraded land and to find the potential plant species suitable for phytorestoration of the Mn mineland. Hopefully, the data will provide reference values for the phytorestoration of numerous similar sites in this region.

Materials and methods

Site description

The Xiaotianshan Mn mine is located at longitude 110°37′–111°29′E and latitude 25°29′–26°23′N, 125 km north from Guilin, Guangxi Province, China (Fig. 1). The mine area belongs to the middle subtropical monsoon climatic zone with an annual average rainfall of 1,492.2 mm and an annual average temperature of 17.7 °C. The regional vegetation is the subtropical evergreen broadleaf forest. The landform is hilly land, and zonal soil is loam soil or sandy loam soil.

Sample collection

Field surveys of the higher plants in the mineland were carried out in October 2009. For each species, three to five individual plants were collected randomly. The mineland was divided into seven areas in terms of the dominant plants colonized, and seven soil sampling sites were set up: (1) the local unmined land (control, S0), (2) a mine drainage area dominated by *Polygonum perfoliatum* and *Pteris vittata* L (S1), (3) the bare mining area without vegetation (S2), (4) an abandoned mineland dominated by *Polygonum pubescens* and *Solanum nigrum* (S3), (5) the tailing dump with a few herbs (S4), (6) an abandoned mineland dominated by *Erigeron acer* and *Paspalum orbiculare* (S5), and (7) an abandoned mineland dominated by *Kummerowia striata* and *Glycine soja* (S6). For each sampling site, surface (0–30 cm) soils were sampled separately. Usually, five subsamples were merged into one single sample, and three parallel samples were collected. All soil and plant samples were sealed with polythene bags and transported into the laboratory.

Sample analysis

Soil samples were air-dried and ground to pass through a 2-mm sieve. Soil pH was determined using a 1:2.5 soil-to-water ratio, and cation exchange capacity (CEC)

Fig. 1 Geographic location of the Xiaotianshan Mn mine in Guangxi

was quantified using the barium acetate method (Jackson et al. 1986). Organic matter content was determined using the Walkley and Black procedure (Nelson and Sommers 1982). Total nitrogen (TN) and total phosphorus (TP) were measured using the standard methods of the Soil Science Society of China (SSSC) (1983). Soil texture was analyzed using the hydrometer method (Allen et al. 1974). Soil samples were digested with HNO_3 + HF + $HClO_4$, and the concentrations of Mn, Cr, Cd, Zn, Pb, and Cu were determined using a flame atomic absorption spectrophotometer (FAAS, PE-AA700).

Plant samples were washed with tap water and rinsed three times with deionized water. Samples were then separated into shoots and roots, dried at 70 °C to constant weight, and ground to pass a 2-mm sieve. The triturated plant tissues (about 0.5 g) were digested with a mixture of HNO_3 and $HClO_4$ (5:3, *v*/*v*) in a block heater. After cooling, the extracts were diluted with 0.2 % HNO_3 to 50 ml. Heavy metal (Mn, Cr, Cd, Zn, Pb, and Cu) concentrations of the extracts were determined by FAAS. The bioconcentration factor (BCF) of a plant for a certain metal equals the heavy metal concentration of shoots divided by the same metal content in soil, while the translocation factor (TF) is the heavy metal concentration of shoots divided by the same metal content in roots.

Reagent blanks, a standard reference soil sample (GBW07403), and standard plant samples (GBW10010) were employed in the analysis to ensure accuracy and precision. Results were found within ±5 % of the certified value.

Results

Physicochemical characteristics of soils

The general properties of soils were presented in Table 1. The overall area was characterized by an acidic pH (Table 2); however, the pH value of the control soil (S0) was higher than that of the other six soils. The soil sample from the tailing dump (S4) was the most acidic among all the soils. The CEC ranged from 8.9 to 14.7 cmol/kg, and the minimum was found in S4. The soil CEC classification standard (Table 2) indicated that the nutrient retention of S4 was weak, while those of the rest of the soils were moderate.

The total P and total N were uniformly low in the different samples except for the S0 (Table 1). According to the classification standard of soil nutrient, nitrogen and phosphorus in the soils were generally deficient, though TN and TP of S0 (control soil) were moderate and very abundant, respectively (Table 2). The organic matters (OM) were also relatively similar in the different soils, falling within the range of moderate to abundant. However, the sample S4 contained a rather low level of OM, being classified as an OM-deficient soil. Carbon/

Table 1 Physicochemical characteristics of the soils

Samples	pH	CEC (cmol/kg)	TN g/kg	TP	OM	C/N	Texture
S0	5.38	14.3	1.48	3.25	45.37	17.78	Sandy clay loam
S1	4.49	11.5	0.41	0.64	27.83	39.37	Sandy clay loam
S2	4.75	13.9	0.78	0.73	25.89	19.25	Sandy clay loam
S3	4.47	14.7	0.32	0.58	29.52	53.51	Sandy clay loam
S4	3.98	8.9	0.34	0.53	7.15	12.20	Sandy
S5	4.56	12.9	0.39	0.59	28.86	42.92	Sandy clay loam
S6	4.97	13.6	0.45	0.68	35.24	45.42	Sandy clay loam

CEC cation exchange capacity, *TN* total nitrogen, *TP* total phosphorus, *OM* organic matter, *C/N* the ratio of soil organic carbon to total nitrogen

nitrogen (C/N) ratio varied from 12.20 to 53.51 in the studied soils with an average of 32.92. The soil texture was consistent with the zonal soil (sandy clay loam) expect for S4 (sandy) which contained a mass of mill tailings (Table 1).

Metal concentrations in soils

The heavy metal levels in the soils are shown in Fig. 2. The most obvious feature of the studied area was its high level of contamination by various heavy metals. The polymetallic pollution was mostly due to Mn, Cd, Cr, and Zn, which exceeded the pollution warning thresholds in the China Environmental Quality Standard for Soils (the pollution threshold for soil Mn was from Wang (1995)). The peak Mn, Cd, Cr, and Zn concentrations in the soils were 125,426, 9.08, 336, and 564 mg/kg, representing 69.7, 30.3, 2.2, and 2.8 times of their maximum allowable concentrations in the China Environmental Quality Standard for Soils. The Cd and Mn levels in all the soils were higher than the pollution warning threshold (indicated by the dotted line in Fig. 2), posing a potential environmental risk. Soil Cr and Zn for several sites (S1, S3, S4 for Cr, and S3, S4, S5 for Zn) were above the pollution warning threshold. However, Pb and Cu levels of all samples satisfied the China Environmental Quality Standard for Soils, which showed no pollution warning.

Metal concentrations in the soils were spatially heterogeneous. At a mining site (S3), Mn and Cu levels in the surface soil were the highest of all sites while Cd was very high, indicating that active mining could cause polymetallic pollution of the mineland. S4 was a tailing dump with low vegetation cover, where Zn and Cd were incomparably higher than those of other soils while Cr was just second to that in S3. The extremely high metal levels in tailings made them a potentially hazardous source of soil and water pollution. As the control site, S0 was 2 km away from the mine area, where Mn, Cd, Zn, and Cu concentrations were lower than those in the other soils. Soil Pb and Cu concentrations were relatively homogenous on the overall area with exception of S2, which showed a Cu concentration about threefold higher than the control soil.

Table 2 Classification standards of soil nutrient, pH, and CEC

Grade[a]	TN (%)	TP (%)	OM (%)	pH	CEC (cmol/kg)
I	<0.3	<0.4	<5.0	<5.0	>20.0
II	0.3–0.8	0.4–0.8	5–15	5.0–6.5	15.4–20.0
III	0.8–1.6	0.8–1.2	15–30	6.5–7.5	10.5–15.4
IV	1.6–3.0	1.2–1.8	30–50	7.5–8.5	6.2–10.5
V	>3.0	>1.8	>50	>8.5	<6.2

[a] The grade criteria were suggested by Guan (2006). Grades I, II, III, IV, and V are very deficient, deficient, moderate, abundant, and very abundant for TN, TP, and OM, and are acidic, slightly acidic, neutral, slightly alkaline, and alkaline for pH. For CEC, grades I, II, III, IV, and V denote that nutrient retention of the soil is very strong, strong, moderate, weak, and very weak

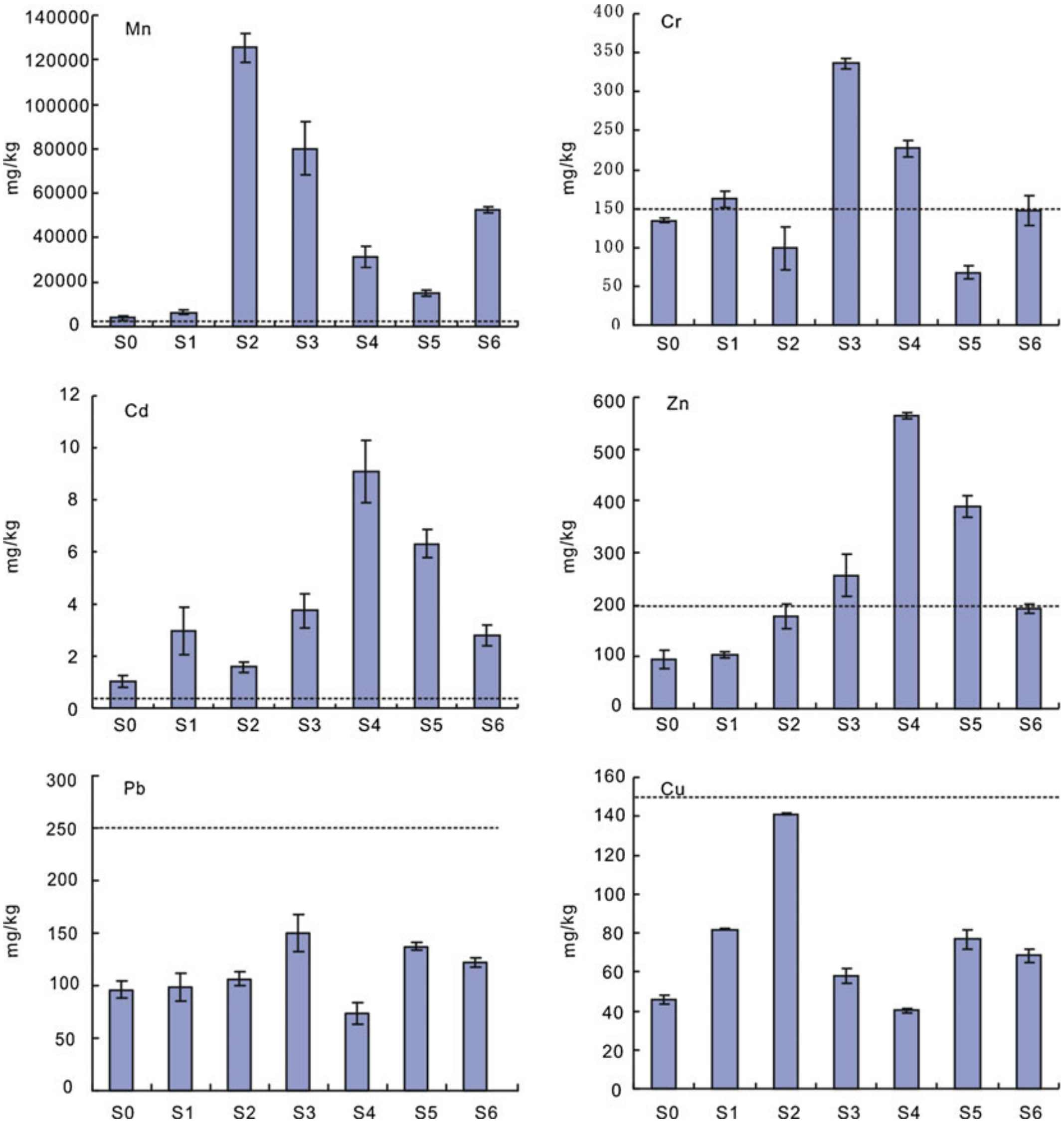

Fig. 2 Heavy metal concentrations in soils from different sampling sites of the studied Mn mineland. The *dotted line* represents the pollution threshold in the China Environmental Quality Standard for Soils (Ministry of Environmental Protection of the People's Republic of China MEP 1995). Because there was no reference value for Mn in this standard, the pollution threshold of Mn was suggested by Wang (1995)

Heavy metal phytoaccumulation

Vegetation survey showed that there were 13 species of higher plants in the studied area (Table 3). Despite over 20 years of rehabilitation by natural processes in some area (S6), the naturally invaded species were mostly herbaceous plants (12 species). Only one bush, i.e., *Camellia oleifera*, was found in this mineland. Due to the spatial heterogeneity of pedological characteristics, the vegetation cover was not uniform and, in each sampling site, the dominant species were rather variable. As an abandoned mineland, S3 was characterized by a dense vegetation cover (from 60 to 80 % of ground cover) mainly dominated by *Polygonum pubescens* and *S. nigrum*. However, the tailing dump (S4) was characterized by scarce vegetation (coverage less than 10 %), and only three species (*Miscanthus floridulus*, *Eleusina indica*, and *Celosia argentea*) were found successfully colonizing on the tailing surfaces.

Table 3 Heavy metal concentrations in the plant tissues

Plant species	Location	Life form	Tissues	Heavy metal concentrations (mg/kg)					
				Mn	Cr	Cd	Zn	Pb	Cu
Miscanthus floridulus	S4	P	Shoot	925.2	20.91	1.17	64.28	32.4	16.33
			Root	7,702.8	35.75	1.34	185.31	36.1	7.76
Erigeron acer	S3, S5, S6	A	Shoot	1,887.1	12.04	9.92	165.37	6.11	86.67
			Root	1,986.6	24.15	7.93	80.24	12.98	48.42
Paspalum orbiculare	S5	A	Shoot	1,072.3	66.48	1.34	14.87	45.91	11.75
			Root	952.3	167.09	1.55	15.29	48.15	26.07
Pteris vittata	S1	P	Shoot	876.7	13.01	0.66	45.28	4.02	14.72
			Root	958.6	19.73	0.95	36.34	2.31	9.81
Kummerowia striata	S6	A	Shoot	2,931.5	6.50	2.24	73.25	10.06	29.79
			Root	1,510.6	27.32	3.33	78.15	15.21	17.59
Polygonum perfoliatum	S1	P	Shoot	2,616.1	2.13	1.11	32.21	13.71	6.78
			Root	839.2	4.31	2.2	29.12	7.64	10.21
Polygonum pubescens	S3	A	Shoot	12,528.2	24.45	6.41	120.13	20.61	39.88
			Root	3,616.1	23.24	4.56	81.68	19.56	35.68
Dicranopteris linearis	S5	A	Shoot	1,034.4	12.01	1.26	47.35	20.82	9.33
			Root	647.8	22.23	0.83	26.13	20.91	7.66
Solanum nigrum	S1, S3	A	Shoot	3,959.9	14.41	1.64	56.58	39.13	14.6
			Root	1,388.5	12.01	0.72	31.15	8.64	10.52
Eleusina indica	S4	A	Shoot	1,187.0	17.09	2.28	26.62	88.54	21.92
			Root	1,643.2	24.67	1.76	20.89	48.73	12.2
Glycine soja	S6	A	Shoot	591.2	92.10	0.73	17.62	47.53	5.87
			Root	1,742.4	149.42	0.53	15.65	42.21	9.37
Celosia argentea	S4	A	Shoot	7,659.3	92.12	1.29	86.42	15.43	14.21
			Root	815.5	38.35	0.78	35.16	27.99	6.52
Camellia oleifera	S3	B	Shoot	5,608.3	9.38	1.15	31.05	46.18	7.19
			Root	2,846.1	24.16	1.59	48.53	58.73	8.63

P perennial herb, *A* annual herb, *B* bush

The heavy metal concentrations of the 13 plants are presented in Table 3. There were great variations of metal concentrations among plant species with Mn ranging from 591.2 to 12 528.2 mg/kg, Cr 2.13 to 167.09 mg/kg, Cd 0.53 to 9.92 mg/kg, Zn 14.87 to 185.31 mg/kg, Pb 2.31 to 88.54 mg/kg, and Cu 5.87 to 86.67 mg/kg, respectively. The highest Mn concentration (12,528.2 mg/kg) was found in shoots of *Polygonum pubescens* which showed an extraordinary ability of Mn accumulation. In addition, *Celosia argentea* and *Camellia oleifera* also accumulated markedly higher Mn concentration in shoots than the other species. The lowest and the highest Cd concentrations were in *G. soja* and *Erigeron acer*, respectively; however, they grew on the same soil (S6). The maximum Cr, Zn, Pb, and Cu concentrations were found in *Paspalum orbiculare*, *M. floridulus*, *Eleusina indica*, and *Erigeron acer*, respectively. Taking all plants as a whole, the mean metal contents in shoots were 3,298.2 mg/kg for Mn, 29.43 mg/kg for Cr, 2.40 mg/kg for Cd, 60.08 mg/kg for Zn, 30.03 mg/kg for Pb, and 21.46 mg/kg for Cu, while in roots, the mean values were 2,049.9 mg/kg for Mn, 44.03 mg/kg for Cr, 2.16 mg/kg for Cd, 52.59 mg/kg for Zn, 26.86 mg/kg for Pb, and 16.19 mg/kg for Cu. There were no significantly differences in metal concentrations between roots and leaves (*t* test; $p>$

0.05, *n*=13), indicating that in this plant community, the potential toxic metals in plants were overall in equilibrium between roots and leaves.

To evaluate the ability of plants to translocate metals from roots to shoots, TF was calculated for each species (Table 4). Among the 13 species, *Polygonum pubescens*, *S. nigrum*, and *Celosia argentea* showed higher ability of metal transfer from roots to shoots than the other plants. *Celosia argentea* showed the highest TF for Mn (9.39), Cr (2.40), Zn (2.46), and Cu (2.18), although this species had the lowest TF for Pb (0.55). *S. nigrum* had the highest TF values for Cd and Pb. In the case of *Polygonum pubescens*, TF values for the six metals were all higher than 1. Conversely, *M. floridulus* and *Camellia oleifera* showed low metal transfer rate from roots to their aerial parts. TF values in the two species were generally lower than 1, with the exception of *M. floridulus* for Cu and *Camellia oleifera* for Mn. BCF indicated the capacity of plants to accumulate heavy metals in their aerial parts. For the six metals studied, BCFs were all below 1 except for *Erigeron acer* and *Polygonum pubescens* for Cd and *Erigeron acer* for Cu (Table 4). *Eleusina indica* and *G. soja* showed lower Mn BCF than the other plants, while *M. floridulus* had the lowest Cd BCF.

Discussion

Evaluation of major constraints to revegetation

An obvious feature of the soils from the studied area was low pH. In general, the optimum soil pH range for most plants is between 5.5 and 8.5 (Sun et al. 2002). The soil pH values ranged from 3.98 to 5.38, which were unfavorable for plant growth. Plants grown on excessively acidic soils can experience a variety of symptoms including aluminum and hydrogen toxicity, as well as potential nutrient deficiencies of calcium and magnesium (Brady and Weil 1996). Especially low soil pH could increase solubility and phytotoxicity of manganese, a major pollutant in this mineland (Tack et al. 1996; Hue et al. 2001). Therefore, the low pH values could be considered as important factors determining plant colonization in this mining-degraded land. The pH values in the studied area were slightly lower than those of a restored Mn mineland (4.44–6.69) which was located close to the studied Mn mine, indicating that phytorestoration might ameliorate pH conditions of the soil (Li et al. 2007).

Low fertility was another feature of the soils in the studied area. Except for the control, TN and TP in all the soils were deficient, which was consistent with most metalliferous mine soils (Ye et al. 2002; Boojar and

Table 4 Translocation factor (TF) and bioconcentration factor (BCF) of selected plant species

Plant species	TF[a]						BCF[b]					
	Mn	Cr	Cd	Zn	Pb	Cu	Mn	Cr	Cd	Zn	Pb	Cu
M. floridulus	0.12	0.58	0.87	0.35	0.90	2.10	0.03	0.09	0.13	0.11	0.44	0.41
E. acer	0.95	0.50	1.25	2.06	0.47	1.79	0.06	0.05	1.09	0.29	0.08	2.16
P. orbiculare	1.13	0.40	0.86	0.97	0.95	0.45	0.07	0.99	0.21	0.04	0.33	0.15
P. vittata	0.91	0.66	0.69	1.25	1.74	1.50	0.14	0.08	0.22	0.44	0.04	0.18
K. striata	1.94	0.24	0.67	0.94	0.66	1.69	0.06	0.04	0.80	0.38	0.08	0.44
P. perfoliatum	3.12	0.49	0.50	1.11	1.79	0.66	0.41	0.01	0.37	0.31	0.14	0.08
P. pubescens	3.46	1.05	1.41	1.47	1.05	1.12	0.16	0.07	1.70	0.47	0.14	0.69
D. linearis	1.60	0.54	1.52	1.81	1.00	1.22	0.07	0.18	0.20	0.12	0.15	0.12
S. nigrum	2.85	1.20	2.28	1.82	4.53	1.39	0.62	0.09	0.55	0.55	0.40	0.18
E. indica	0.72	0.69	1.30	1.27	1.82	1.80	0.02	0.12	0.81	0.14	0.73	0.32
G. soja	0.34	0.62	1.38	1.13	1.13	0.63	0.01	0.62	0.26	0.09	0.39	0.09
C. argentea	9.39	2.40	1.65	2.46	0.55	2.18	0.24	0.41	0.14	0.15	0.21	0.35
C. oleifera	1.97	0.39	0.72	0.64	0.79	0.83	0.07	0.03	0.31	0.12	0.31	0.12

[a] Metal concentration ratio of plant shoot to root

[b] Metal concentration ratio of plant shoot to soil

Goodarzi 2008; Santos et al. 2012). Moreover, the low soil pH values in the studied area may reduce availability of nitrogen and phosphorus (Zhu 2000; Fernández and Hoeft 2009). Therefore, low levels of N and P can be considered strong limiting factors for plant growth. The nutrient state of the soil was also related to the CEC and OM. In this mineland, soil CEC and OM were generally within the normal range of plant growth; however, they were very low in the tailing dump (S4). The low values of CEC and OM in soils from the tailing dump might be caused by the sandy texture. Sandy textured soils typically have a low nutrient holding capacity, thereby resulting in low CEC and OM. Nutrient deficiency and poor physical structure in addition to toxic elements strongly hindered plant establishment on the tailing dump. According to our survey, only three species (*M. floridulus*, *Eleusina indica*, and *Celosia argentea*) grew on S4. In order to successfully remediate the tailing dump, a substrate amendment was suggested to promote plant survival.

According to the China Environmental Quality Standard for Soils (GB15618-1995, grade II for soil pH <6.5: Cr ≤ 250 mg/kg, Zn ≤ 200 mg/kg, Cu ≤ 50 mg/kg, Cd ≤ 0.3 mg/kg, and Pb ≤ 250 mg/kg, indicating a pollution warning threshold), soil Pb and Cu levels satisfied grade II quality, posing no contamination risk. Cr and Zn in several samples showed moderate contamination especially for the samples from the tailing dump, while Cd levels in all samples showed moderate to serious contamination. There was no stipulated figure for Mn in this standard; however, a pollution warning threshold in soil (1,800 mg/kg) suggested by Wang (1995) revealed that all the soils were seriously contaminated by Mn. Of the six metals, Mn and Cd posed higher environmental risk in the studied area; therefore, they were suggested to be the priority targets for phytoremediation. Interestingly, Mn and Cd combined contamination seemed to be a common character in a Mn mineland. In Xiangtan (Wang et al. 2008), Pingle (Yang et al. 2006), Lipu (Li et al. 2007), and Xialei (Tang and Li 2008) Mn mines, Mn and Cd were also reported to be the major contaminants in soils.

In general, total concentrations of 5,000 mg/kg Mn (Alloway 1995), 3–8 mg/kg Cd, 60–125 mg/kg Cu, 70–400 mg/kg Zn (Kabata-Pendias and Pendias 1992), 200–400 mg/kg Cr (Shanker et al. 2005), and 500–1,000 mg/kg Pb (Foy et al. 1978) are considered phytotoxic. In this mineland, soil Mn, Cd, Cu, Zn, and Cr were above or approaching these toxicity thresholds. Therefore, these metals may be limiting factors for phytorestoration. However, the plants inhabiting the mineland did not show obvious symptoms of toxicity, indicating that the native species developed metal resistance and might be suitable for the revegetation on local contaminated soils.

Screening of native plants for phytorestoration

The normal ranges in plants were 1–2,262 mg/kg for Mn (Wang 1995), 0.05–3 mg/kg for Cd (Moreno-Jiménez et al. 2009), 0.006–18 mg/kg for Cr (Gardea-Torresdey et al. 2004), 5–25 mg/kg for Cu (Reeves and Baker 2000), 25–150 mg/kg for Zn (Álvarez et al. 2003), and 0.1–20 mg/kg for Pb (Påhlsson 1989), respectively. In the present study, many species (7 for Mn, 3 for Cd, 11 for Cr, 4 for Cu, and 9 for Pb) showed metal concentrations much higher than the upper normal levels for plants, indicating an abnormal characteristic of phytogeochemistry in the studied area. Compared to the Xiangtan Mn mine (Wang et al. 2008), the concentrations of Cu, Zn, and Cd were similar; however, the Mn concentrations in this area were higher. The Mn concentrations in the plants from this area were also higher than those from the Molango Mn mine, Mexico (Juárez-Santillán et al. 2010). The high levels of metals which accumulated in the plants implied that these species had a great potential to remediate the local contaminated soil.

For an effective phytoremediation of a mine wasteland, identification and characterization of native plant species on minelands are essential to develop phytoextraction and phytostabilization technologies. A desired species for phytoextraction must be fast growing, have high biomass, and should tolerate and accumulate a range of heavy metals in their aerial and harvestable parts (Clemens et al. 2002). In the present work, *Polygonum pubescens* contained 12,528.2 mg/kg Mn in shoots and demonstrated TF larger than 1 (3.46); thereby, it could be qualified as a hyperaccumulator, which was consistent with a previous literature (Deng et al. 2010). In addition, *Celosia argentea*, *Camellia oleifera*, and *S. nigrum* also showed high Mn accumulation and transfer ability of Mn. *Celosia argentea*, an annual herb, was a successful colonizer on the tailing dump. The high metal tolerance and fast growth rate makes it a very suitable species for use in phytoremediation. *Camellia oleifera*, the only woody plant found in the studied area, could be a good candidate for recovery of the biogeochemical cycles in a Mn mine wasteland due to its high biomass and deep root system. Although *S. nigrum* was reported to be a Cd hyperaccumulator (Wei et al. 2005), it also could be considered as an accumulator for Mn here.

Successful phytoextraction depends not only on the metal concentration in the plants but also on the ability of metal transference from the soil to the plants. In the present study, BCF values for Mn, Cr, Cd, Cu, Pb, and Zn in most plants were below 1. Thus, it can be assumed that metals present in the studied area are relatively difficult to transfer from the soil to the aboveground plant parts. The low BCF values implied that the phytostabilization technologies rather than phytoextraction were suitable for the remediation in this area (Li et al. 2007). To control erosion of the soil, an overall and self-sustainable vegetation cover should be established. It is worth noting that *M. floridulus*, *Erigeron acer*, *Eleusina indica*, and *K. striata*, the pioneer plants in the studied area, grow well on poor and harsh soils, develop the vegetation cover in a relatively short time, and accumulate biomass rapidly. Therefore, these species hold great promise for phytostabilization of the Mn mining area. *M. floridulus* and *Erigeron acer* with light seeds can be easily distributed by the wind. They had a high ability to colonize on bare land caused by mining activities. *Eleusina indica*, a rhizomatous species, demonstrated a good ability to establish cover on the loose mine soils as well as tailing dams. As a Leguminosae plant, *K. striata* could improve the nutrient state of the soil due to its nitrogen fixation (Chen et al. 2004).

It is well known that plant diversity and niche complementarity have great influence on ecosystem functioning. Therefore, the diversity of the candidate species is of great importance in ecological restoration (Martínez-Ruiz et al. 2007). For the Mn mine wasteland in Guangxi, the local pioneer species *M. floridulus*, *Erigeron acer*, *Eleusina indica*, and *K. striata* can be used first to colonize the wasteland, and then, the accumulating and tolerance species *Polygonum pubescens*, *Celosia argentea*, *Camellia oleifera*, and *S. nigrum* can be combined to remedy and restore to some ecological function. The establishment of initial vegetative cover can eventually modify the man-made habitat and render it more suitable for subsequent plant communities. By natural succession, it is hoped to create a diverse and completely sustainable ecosystem.

Conclusion

The surface soils in the Xiaotianshan Mn mine were characterized by acidity, low fertility, poor physical structure, and toxic metals. These characters indicated that phytorestoration was necessary to prevent possible erosion and reduce the risk of toxic metals. Low pH and deficiency of N and P may be the major constraints for plant growth on the degraded soil. The high levels of Mn and Cd may also be limiting factors for revegetation of this site. Many of the native plants grown in this site can tolerate metal toxicity, as well as acidic soil and the lack of nutrients. Among them, *M. floridulus*, *Erigeron acer*, *Eleusina indica*, and *K. striata* were suggested to be the potential pioneers for restoration of mined wastelands. *Polygonum pubescens*, *Celosia argentea*, *Camellia oleifera*, and *S. nigrum* showed high abilities of metal accumulation and could contribute to remediate toxic metal-contaminated soils. To achieve a self-sustainable plant community on this degraded site, it is essential to establish a diversified initial vegetative cover.

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