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Heavy metal accumulation by panicled goldenrain tree (*Koelreuteria paniculata*) and common elaeocarpus (*Elaeocarpus decipens*) in abandoned mine soils in southern China

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Abstract

Phytoremediation can be used as a sustainable technology for mine spoil remediation to remove heavy metals. This study investigated the concentration of 7 heavy metal contamination in soil and plant samples at an abandoned mine site. We found that, after vegetation remediation at the abandoned mine site, the reduction rates for 7 heavy metals were in the range of 4.2%–86%, where reduction rates over 50% were achieved for four heavy metals (Zn, Mn, Cd, Ni). Transfer coefficients of the panicled goldenrain tree (*Koelreuteria paniculata* Laxm) and the common elaeocarpus (*Elaeocarpus decipens*) for Zn, Mn, Ni, and Co were more than 1. Enrichment coefficients of both trees for Mn were higher than 1. Our results suggest that the panicled goldenrain tree and the common elaeocarpus tree may act as accumulators in remediation. Moreover, the woody vegetation remediation in abandoned mining areas play an important role in improving scenery besides removing heavy metal from contaminated soil.

Key words: panicled goldenrain tree (*Koelreuteria paniculata*); common elaeocarpus (*Elaeocarpus decipens*); heavy metal elements; accumulation; abandoned mine sites

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Introduction

Heavy metals, which are ubiquitous environmental contaminants in industrialized societies, cause serious environmental problems. Heavy metals persist in soil much longer than in other ecosystem components (Lasat, 2002; Padmavathiamma and Li, 2007). Sources of heavy metal contaminants in soils include metalliferous mining and smelting, metallurgical industries, sewage sludge treatments, warfare and military training, waste disposal sites, agricultural fertilizers, and electronic industries.

It is well known that heavy metals obtained from mining, such as Mn, Zn, and Pb, adversely affect the soil (Mueller *et al*., 1989). Heavy metals become toxic once they exceed certain concentrations (Babich and Stotzky, 1980), and they constitute major pollutants that destroy original vegetation and pose potential health hazards to humans and animals (Göhre and Uta Paszkowski, 2006). Moreover, when soil is drastically polluted, there is usually a complete absence of soil, in either a pedological or a biological sense, and what is left is just a skeleton full of limiting factors (Bradshaw, 1983). To figure out appropriate method of restoring degraded soil, a number of studies on chemical, physical and biological techniques have been conducted for metal-mined wastelands (Li, 2006; Shu *et al*., 2003, 2005; Shen *et al*., 2004; Hao *et al*., 2004; Xue, 2002; Lagemna, 1993), where phytoremediation holds the greatest promise for persistent metal remediation.

Phytoremediation can be defined as an approach to using plants to remove, transfer and stabilize contaminants from soil (Hughes *et al*., 1997; Salt *et al*., 1998). As a promising, cost-effective, environmentally friendly technology, phytoremediation has become a research hotspot in the field of abandoned mine soil remediation. Many herbaceous species including *Sedum alfredii* H., *Pteris vittata* L., *Typha latifoia* and *Miscanthus floridulus* (Labill) Warb have been observed to be able to stabilize and accumulate heavy metals such as Mn and Pb in mine tailings (Ren *et al*., 2006; Chen *et al*., 2002; Yang *et al*., 2006; Sun *et al*., 2006), and only few trees including *Leucaena leucocephala*, *Acacia auriculiforimis* and *Schima superb* can effectively remove Pb, Zn, and Mn mine tailings (Zhang *et al*., 2001; Song *et al*., 2004; Yang *et al*., 2006). Heavy metal accumulating plants classified as herbs have a shallow root system that limits contamination removal in deep soil (Keller *et al*., 2003). To date, hyperaccumu-

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lator plants (such as *Phytolacca acinosa* Roxb) that can uptake Mn have been discovered and soil characteristics at abandoned manganese mine sites prior to remediation has been examined in Xiangtan Manganese Mine (Yan *et al*., 2006; Fang *et al*., 2006). However, no report on the role of wood vegetation in restoring mine soil in the above area is available.

In this study, we selected panicled goldenrain tree and common elaeocarpus as phytoremediation plants, because they are found to be highly toxicity-tolerated after the successful growth in the mine site and a selection pot experiment. Following the previous study of the biomass, productivity and biological cycles of mineral elements in mixed stands of them at the mine site (Tian *et al*., 2006, 2007), the aims of this study are: (1) to determine the concentrations of Cu, Zn, Mn, Cd, Ni, Pb, Co in plants and soils; (2) to investigate transfer and enrichment in a mixed stand of panicled goldenrain trees and common elaeocarpus trees, which have been planted at the abandoned Mn mine site for over 2 years.

1 Materials and methods

1.1 Study site

The study site was located at a Mn mine site, approximately 50 km north of Xiangtan, Hunan, China. Annual mean temperature for this region is 17.4°C and annual precipitation is 1431.4 mm. The area of the study plot is 0.67 hm^2. The dominant herb species under the planted trees in this abandoned mine site are *Gynura crepidioides*, *Phytolacca acinosa*, *Erigeron annuns*, and *Imperata cylindrical*. The young mixed stand of trees comprised panicled goldenrain trees and common elaeocarpus, which were planted with 2 year old saplings on the site in 2004. Description of the experimental stand is presented in Table 1.

1.2 Sampling method

In April of 2007, plant samples were collected separately from leaves, twigs, stem, wood, and root systems (coarse roots, fine roots, and root heads) of panicled goldenrain tree and the common elaeocarpus tree. There were three replications for each tree species. Herbs (understory) were collected separately, as aboveground and underground components. Plant samples were brought to the laboratory, rinsed with distilled water, and oven dried at 80°C for 48 h.

Table 1 Description of panicled goldenrain, and common elaeocarpus in the study stands

Characteristic	Panicled goldenrain tree	Common elaeocarpus tree	Total
Age (year)	4.5	4.5	
Density (trees/hm^2)	2160	1080	
Average height of tree (m)	4.5	1.8	
Average DBH (cm)	7.0	2.5	
Biomass of individual plant (g)	1958	909	
Stand biomass (kg/hm^2)	4229.28	981.72	5211.00
Stand productivity (kg/(hm^2·year))	2296.08	394.20	2690.28

DBH: diameter at breast height.

Twelve soil samples were taken from the rhizosphere soil of the mixed stand at depths of 0 to 20 cm. In addition, four soil samples were taken from control plots located 1 km away from the mixed stands sites to eliminate the roots systems interference. The soil samples from control site were taken at depths of 0–15, 15–30, 30–45 cm. There were five soil sample types including rhizosphere and non-rhizopshere of panicled goldenrain tree, rhizosphere and non-rhizopshere of common elaeocarpus tree, and controls. Soil samples were air dried and passed through a 0.149-mm mesh sieve, then stored at –5°C for later analysis.

1.3 Chemical analysis

Soil pH was determined in a saturated soil water paste. Zn, Mn, Cd, Ni, Pb, and Co concentrations in plant and soil samples were determined using an HP3510 flame atomic absorption spectrophotometer (Shanghai Hewlett-Packard Company, China).

1.4 Data analyses

The effects of treatments were statistically tested using the Analysis of Variance (ANOVA). The mean value of three replications was calculated. Heavy metal reduction ratio (*R*) was calculated by the following:

$$R = \frac{C_\mathrm{i} - C_\mathrm{f}}{C_\mathrm{i}} \times 100\% \quad (1)$$

where, C_i (mg/kg) and C_f (mg/kg) is the heavy metal concentration in the soil before and after 2 years of tree planting, respectively.

The transfer coefficient is the heavy metal concentration in the shoot divided by the same metal content in the root. The enrichment coefficient refers to the ratio of the heavy metal concentration of aboveground vegetation to heavy metal concentration in the soil.

2 Results

2.1 Soil concentrations of heavy metal elements

The most abundant heavy metals in the abandoned mine soil without phytoremediation were Zn, Mn, and Cd, with a mean concentration 640.32, 7990.21, and 13.15 mg/kg, respectively. Heavy metal concentration decreased to varying extents after 2.5 years of forestation, with the greatest decrease in Mn (from 7990.21 to 1103.35 mg/kg), accounting for 86.19% of total reduction, followed by Cd, Ni, and Zn, which accounted for 75.67%, 75.59%, and 70.39% of total reduction, respectively. The least reduction was found in Pb, which accounted for 4.20% of total reduction. Comparison of soil heavy metal concentration and pH values between vegetated and non-vegetated land indicated that phytoremediation could greatly absorb heavy metal from soil and decrease soil pH value (Table 2).

2.2 Concentration of heavy metals in rhizosphere and non-rhizosphere soil

Rhizosphere, an important interface for soil and plant interaction, plays a significant role in nutrient cycling and

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Table 2 Concentrations of heavy metal elements in soil before and after afforestation (mg/kg)

Item	Soil without phytoremediation				Soil with phytoremediation				
	Minimum	Maximum	Mean	Variation coefficient	Minimum	Maximum	Mean	Variation coefficient	Reduction ratio (%)
pH	6.30	8.08	7.49	9.80	4.06	7.92	6.69	26.67	
Zn	210.91	1801.00	640.32	93.41	100.17	280.93	189.63	41.54	70.39
Cu	32.30	128.12	66.38	50.39	36.25	43.08	39.44	7.10	40.58
Mn	1269.60	30178.36	7990.21	132.88	733.16	1789.60	1103.35	43.15	86.19
Cd	2.10	38.25	13.15	94.42	2.91	3.53	3.20	9.68	75.67
Pb	223.67	622.11	401.15	92.64	327.32	457.96	384.30	17.10	4.20
Ni	23.66	210.88	91.33	31.16	25.04	31.09	22.29	10.13	75.59
Co	12.73	32.83	20.90	50.54	12.04	20.73	16.52	23.68	20.96

energy transfer (Rovira and McDougall, 1967; O'Connell *et al*., 1996). Soil physicochemical and biological characteristics are highly influenced by certain organic materials excreted by the root system. Therefore, stable rhizosphere condition will enhance the capacity to remedy heavy metal contamination.

As shown in Table 3, the Zn, Cu, Mn, Cd, Ni and Co concentrations in rhizosphere soil were 1–4 times of that in non-rhizosphere soil, except for Pb. Moreover, concentrations of Cu, Cd, Pb and Ni in rhizosphere soil of common elaeocarpus tree were 97.6%, 31.2% and 1.02% higher than that of panicled goldenrain tree, respectively. In contrast, the Zn, Mn and Co concentrations in the rhizosphere soil of the panicled goldenrain tree were 25.4%, 5.4% and 1.0% lower than that in the common elaeocarpus tree, respectively. This could be explained by the fact that the panicled goldenrain tree is a broad-leaf deciduous species, whereas the common elaeocarpus is a broad-leaf evergreen species.

2.3 Distribution of heavy metals in trees

Distribution of heavy metals varied with the components of the trees (Table 4). The total amounts of heavy metals found in rhizosphere soils of the common elaeocarpus and the panicled goldenrain tree were 3908.13 and 2490.72 mg/kg, respectively. Mn was the most abundant in both trees, accounting for 56.1% and 63.7% of the accumulation (2490.719 mg/kg) in the panicled goldenrain tree and (3908.13 mg/kg) in the common elaeocarpus. Heavy metal concentrations in trees were ranked as Mn > Zn > Cu > Ni > Pb > Co > Cd for panicled goldenrain tree and Mn > Zn > Cu > Pb > Ni > Cd > Co for common elaeocarpus tree. The accumulation of heavy metals distribution in the different tree components followed the same pattern as leaf > fine root > twig > coarse root > root head > stem.

2.4 Accumulation of heavy metals in trees

The transfer coefficient quantifies the relative differences in bioavailability of metals to plant shoots and

Table 3 Concentrations of heavy metal elements in rhizosphere and non-rhizosphere soils (mg/kg)

Soil	Rhizosphere of panicled goldenrain tree				Rhizosphere of common elaeocarpus				Non-rhizosphere			
	Minimum	Maximum	Mean	Variation coefficient	Minimum	Maximum	Mean	Variation coefficient	Minimum	Maximum	Mean	Variation coefficient
Zn	124.51	435.79	240.00	57.17	271.50	371.71	321.57	12.75	100.17	280.93	189.63	41.54
Cu	32.01	213.72	80.73	109.91	29.69	60.41	40.85	33.01	36.25	43.08	39.44	7.10
Mn	2425.53	5233.40	3959.58	33.42	3599.78	4352.30	3987.93	7.72	733.16	1789.60	1103.35	43.15
Cd	4.93	8.81	7.19	26.54	3.11	8.16	5.48	37.79	2.91	3.53	3.20	9.68
Pb	110.25	599.66	251.96	92.36	141.25	454.32	233.99	63.09	327.32	457.96	384.30	17.10
Ni	44.97	65.80	56.49	15.22	3.78	66.00	44.97	62.15	25.04	31.09	22.29	10.13
Co	26.45	41.85	34.67	20.03	27.52	39.22	35.03	15.34	12.04	20.73	16.52	23.68

Table 4 Concentrations of heavy metals in different tree components (mg/kg)

Tree	Components	Cu	Zn	Mn	Cd	Ni	Pb	Co	Total
Panicled goldenrain tree	Stem	5.69	10.98	2.73	0.19	0.99	0.63	ND	52.58
	Twig	9.08	21.40	259.09	0.54	2.32	1.68	0.96	403.08
	Leaf	9.97	22.74	1037.10	0.51	3.11	2.66	1.02	1341.35
	Stump	7.38	9.73	2.74	0.21	0.79	0.71	ND	70.03
	Coarse root	10.84	18.29	11.10	0.29	1.34	1.04	ND	207.88
	Fine root	13.03	24.42	84.84	0.41	1.74	2.11	0.71	415.80
	Total	55.98	107.56	1397.60	2.15	10.28	8.82	2.70	2490.72
Common elaeocarpus tree	Stem	7.29	11.51	40.26	0.24	1.18	1.75	ND	122.86
	Twig	20.95	25.96	359.22	0.58	2.60	2.68	0.95	553.78
	Leaf	9.67	36.08	1389.18	0.92	3.50	2.64	1.48	1743.24
	Stump	3.08	10.32	54.52	0.31	1.37	2.26	ND	169.30
	Coarse root	7.92	13.77	235.91	0.34	1.43	4.78	ND	487.53
	Fine root	11.48	33.82	409.10	2.03	3.00	16.65	0.87	831.42
	Total	60.39	131.47	2488.19	4.42	13.09	30.75	3.29	3908.13

ND: undetected.

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roots. The high transfer coefficients reflect great transfer efficiency of heavy metals from root to shoot. The range of calculated transfer coefficients (Mn, Zn, Cu, Ni, Pb, Co, and Cd) for each tree is shown in Fig. 1. The larger transfer coefficients (> 1) for Zn, Mn, Ni, and Co imply a strong transfer capacity for both trees. The order of transfer coefficients for the panicled goldenrain tree was Mn > Co > Ni > Cd > Pb > Zn > Cu, and for the common elaeocarpus it was Co > Mn > Cu > Zn > Ni > Cd > Pb.

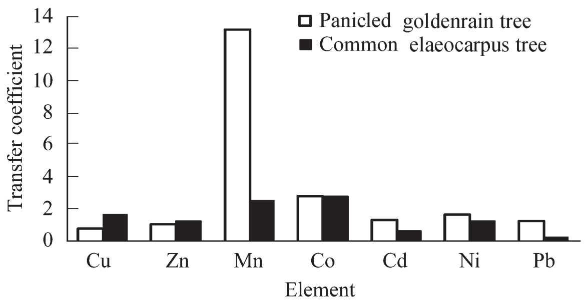

Fig. 1 Transfer coefficients of heavy metals for panicled goldenrain and common elaeocarpus tree.

Moreover, the order of enrichment coefficients for both trees was consistent as: Mn > Cu > Cd > Zn > Ni > Co > Pb, with enrichment of Mn only (>1) (Table 5). The lowest enrichment coefficients of Pb (0.013 and 0.018) showed that the roots absorbed less Pb, even at high concentration in soil.

3 Discussion

Using phytoremediation, there are two ways to remove metals: (1) phytoextraction, a way that the metal-accumulating plants can extract metals from soils and concentrate them into different plant parts, such as roots, stems, leaves and so on (Nanda *et al*., 1995), and (2) phytostabilisation, a way that metal-tolerant plants can reduce the mobility of metals, thereby reducing risks of further environmental degradation, such as by leaching into the ground-water or by airborne spread (Salt *et al*., 1995). A number of high plant species can survive and reproduce in soil heavily polluted by heavy metals, like Zn, Pb, Cu, Cd, and As (Baker, 1987), but some of them may restrict metals from entering their tissues or transferring from roots to shoots. Therefore, accumulators rely on their ability not only to absorb metal contaminants as nutrient from soil, but also to regulate metal concentrations to avoid toxication via a wide variety of metal influx and efflux transporters (Williams *et al*., 2000; Hall and Williams, 2003)

According to the Environmental Quality Standard for Soils in China (GB15618-1995), in which the Grade II levels for soil are as follows: pH in the range of 6.5–7.5, Cu ⩽ 100 mg/kg, Cd ⩽ 0.6 mg/kg, Ni ⩽ 50 mg/kg, Pb ⩽ 300 mg/kg, and Zn ⩽ 250 mg/kg, indicating a pollution warning limitation. In this study, the soil showed serious Zn, Ni, Pb, and Cd pollution, whereas Cu concentrations met grade II. Although there is no stipulated figure for Mn in this standard, the Mn concentration was 1.1–25.2 times of the upper limit of the acceptable range (170–1200 mg/kg) (Wang, 1995). After phytoremediation, Zn, Ni, and Cu soil concentrations were below the standard limit, and soil Mn concentration was reduced to the acceptable level.

In the remediation of metal-mined wasteland, agricultural utilization is applied more frequently than other plantation types. Therefore, the question arises as whether some toxic metals could enter the human body through the food chain. In this study, the order of metal distribution in tree components (leaf > fine root > twig > coarse root > root head > stem) indicates that stems should be preferred for use as food products, since they accumulate fewer/less metals in the biomass. In addition, Zn, Cu, Mn, Cd, Ni, and Co concentrations in rhizosphere soil were higher than those in non-rhizosphere soil. We can postulate that these soluble heavy metals move towards plant roots by mass flow and by diffusion when the roots absorb water or nutrient from the soil. Generally, heavy metal solubilities are relatively low under the edaphic properties of the tailing, because the solubilities of most metals in soils are inversely related to pH (Kabata-Pendias and Pendias, 1992). In our study, the pH decreased from 7.49 before afforestation to 6.69 in 2.5 years after afforestation. As a result, the pH change could be responsible for the high metal mobility.

Trees are different in their ability to translocate heavy metals from the root to shoot (Pulford and Watson, 2003). Lepp and Eardley (1978) found concentrations of heavy metals in the stems and leaves to be an order of magnitude less than the corresponding root levels in sycamore seedlings grown in sludge-amended soil. Morin (1981) reported that root tissues of several tree species grown on sludge-amended soil had the highest concentrations of Cd, Cu, Ni, and Zn. However, Drew *et al*. (1987) found Zn and Cd concentrations to be the highest in foliage of poplar clones that grew in sludge-amended soil. The current investigation showed that panicled goldenrain trees

Table 5 Enrichment coefficients of heavy metals in panicled goldenrain tree and common elaeocarpus tree (mg/kg)

	Panicled goldenrain tree			Common elaeocarpus tree		
	Shoot	Soil	Enrichment coefficient	Shoot	Soil	Enrichment coefficient
Cu	24.74	39.44	0.627	37.91	39.44	0.961
Zn	55.12	189.63	0.291	73.55	189.63	0.388
Mn	1298.92	1103.35	1.177	1788.66	1103.35	1.621
Cd	1.24	3.2	0.388	1.75	3.2	0.547
Ni	6.42	22.29	0.288	7.28	22.29	0.327
Pb	4.97	384.3	0.013	7.07	384.3	0.018
Co	1.99	16.52	0.12	2.43	16.52	0.147

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and the common elaeocarpus trees are tolerant to heavy metals, and that they may accumulate these elements without showing any abnormities in terms of life history in a period of 2.5 years.

The results show that phytoremeditation was significantly effective to remove metals from contaminated soil at a mine site, with reduction ratios of 7 heavy metals in soil ranging from 86.19% to 4.20%. The distribution pattern of heavy metals in tree components is similar to that of nutrient elements (N, P, K, Ca, Mg) at this study site (Tian *et al*., 2007), i.e.,leaves had the highest heavy metal concentration, followed by twigs, fine roots, coarse roots and stem wood,.

According to Cunningham and Berti (1993), plants may be suitable for phytoextraction purposes if they contain more than 10000 mg toxic elements per kg of dry matter. *P. acinosa* and *Arthraxon hispidus* are considered hyperaccumulators because they contain more than 10000 mg/kg Mn and the shoot-to-root ratio for Mn concentration is greater than 1. On the other hand, it must be implied that the transfer and enrichment coefficients of the panicled goldenrain tree and the common elaeocarpus tree for Mn are greater than 1. Therefore, both trees may be considered accumulators and are able to effectively lower the concentrations of heavy metals in the contaminated soils. Our results suggested that afforestation played a significant role in removing pollutants and decreasing concentrations of heavy metals from soil in abandoned mining areas.

4 Conclusions

The concentrations of seven heavy metals in different soil and tree species at an abandoned mine site were measured before and after restoration. Our results suggest that panicled goldenrain tree and the common elaeocarpus tree are tolerant to heavy metals and act as accumulators. Phytoremeditation is an effective technique for reducing metal concentrations in contaminated soil at a mine site, with reduction ratios of seven heavy metals in soil ranging from 0.04 to 0.86. The distribution of heavy metal was significantly different among tree components. Leaves usually had the highest concentrations, followed by twigs, fine roots, coarse roots, and stem wood. Vegetation remediation via afforestation in abandoned mining areas played an important role in removing metals from contaminated soil.

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