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Soil pollution assessment and identification of hyperaccumulating plants in chromated copper arsenate (CCA) contaminated sites, Korea

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ABSTRACT

In recent decades, heavy metal contamination in soil adjacent to chromated copper arsenate (CCA) treated wood has received increasing attention. This study was conducted to determine the pollution level (PL) based on the concentrations of Cr, Cu and As in soils and to evaluate the remediative capacity of native plant species grown in the CCA contaminated site, Gangwon Province, Korea. The pollution index (PI), integrated pollution index (IPI), bioaccumulation factors (BAF_{shoots} and BAF_{roots}) and translocation factor (TF) were determined to ensure soil contamination and phytoremediation availability. The 19 soil samples from 10 locations possibly contaminated with Cr, Cu and As were collected. The concentrations of Cr, Cu and As in the soil samples ranged from 50.56–94.13 mg kg^{-1}, 27.78–120.83 mg kg^{-1}, and 0.13–9.43 mg kg^{-1}, respectively. Generally, the metal concentrations decreased as the distance between the CCA-treated wood structure and sampling point increased. For investigating phytoremediative capacity, the 19 native plant species were also collected in the same area with soil samples. Our results showed that only one plant species of *Iris ensata*, which presented the highest accumulations of Cr (1120 mg kg^{-1}) in its shoot, was identified as a hyperaccumulator. Moreover, the relatively higher values of BAF_{shoot} (3.23–22.10) were observed for *Typha orientalis, Iris ensata* and *Scirpus radicans Schk*, suggesting that these plant species might be applicable for selective metal extraction from the soils. For phytostabilization, the 15 plant species with BAF_{root} values > 1 and TF values < 1 were suitable; however, *Typha orientalis* was the best for Cr.

1. Introduction

In the last few decades toxic levels of heavy metals in air, water, soil and plants have been reported worldwide. Heavy metal contaminants are of environmental concern because of their adverse effects on human life (Yang et al., 2007; Ok et al., 2011d). Anthropogenic activities are a primary source of toxic metals in environmental systems (Ok et al., 2007; Ahmad et al., 2012b). Indeed, it is well known that soil acts as a major sink for such inorganic pollutants. Many previous studies have been conducted to evaluate the level of soil contamination with heavy metals derived from anthropogenic sources such as mining and smelting activities, steel and iron manufacturing, waste incineration, cement production, phosphatic fertilizers, pesticides and automobile exhaust (Chen et al., 2005; Moon et al., 2011; Ahmad et al., 2012a).

Chromated copper arsenate (CCA) has been used as a preservative to protect wood products from bacterial, fungal and insect decay (Warner and Solomon, 1990; Chirenje et al., 2003; Saxe et al., 2007). Wood treated with CCA serves as a construction material in surrounding environments, including public/private housing, fences, playground equipment, picnic tables, walkways, sound barriers and other outdoor wood products (Kim et al., 2007). In CCA-treated wood, arsenic (As) and copper (Cu) act as an insecticide and a fungicide, respectively, and the chromium (Cr) fixes the As and Cu into the structures of cellulose or hemicellulose, as well as the lignin of the wood (Dawson et al., 1991). Typically, three forms of CCA, also known as A, B and C types, are commercially available, and the most popular type C is composed of 47.5% CrO_3, 18.5% CuO and 35.0% As_2O_5 (AWPA, 1999).

In many countries, the use of CCA-treated wood has been banned. However, existing structures made of CCA treated wood are leaching CCA into the surrounding environment, resulting in elevated levels of Cr, Cu and As in the soil and subsequently may cause negative effects on the environment and human health (Stilwell and Gorny, 1997; Hingston et al., 2001; Solo-Gabriele et al., 2002; Gezer et al., 2005; Kumpiene et al., 2008). Accordingly, remediation of soils contaminated with CCA is necessary to eliminate risks to humans and the environment.

Several remediation techniques have been adopted to remediate soils contaminated by heavy metals (Isoyama and Wada,

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2007; Ma et al., 2001; Ok et al., 2010, 2011a, 2011b, 2011c); however, they have been restricted due to economic and logistic reasons, as well as possible detrimental effects on sustainable restoration and ecological equilibrium (Cao et al., 2002; Friesl et al., 2003; Yang et al., 2006). Recently, the plant-based remediation technique known as phytoremediation has emerged as a cost effective, environmentally-friendly method of removing heavy metals from the soil. Phytoremediation is the development of plant-based remediation technique and can be categorized into two different approaches: (i) phytoextraction, which is the removal of heavy metals by aboveground parts of the plant (Raskin et al., 1997; Ma et al., 2001; Yoon et al., 2006; Usman and Mohamed, 2009), and ii) phytostabilization, which is the reduction of heavy metal mobility and availability around the rhizospheric soil (Yoon et al., 2006; Antosiewicz et al., 2008).

Depending on the ability of plants used as a phytoremediation medium to absorb, accumulate and tolerate heavy metals, available plants are classified into three categories of hyperaccumulators, indicators and excluders (Ghosh and Singh, 2005). Specifically, hyperaccumulators comprise plant species that are tolerant to extreme levels of heavy metals that can accumulate > 10-mg kg^{-1} Hg, >100-mg kg^{-1} Cd, >1000-mg kg^{-1} Cu, Cr, Co and Pb, and >10,000-mg kg^{-1} Ni and Zn in their aboveground parts (Baker and Brooks, 1989). In a study of Ma et al. (2001), the brake fern (*Pteris vittata*) has been defined as a hyperaccumulator against As in the soil. They found that this plant accumulated > 2% As in its aboveground parts.

Since native plant species can survive better under toxic metal stress relative to invasive plant species, it is possible to identify hyperaccumulators among native species in contaminated areas (Yoon et al., 2006). However, only few studies to identify hyperaccumulators have been conducted under field conditions (Ma et al., 2001; McGrath and Zhao, 2003). Therefore, this study was conducted to evaluate heavy metal concentrations of Cr, Cu, and As in soils near CCA-wood structures and to identify the remediation ability of native plant species.

2. Materials and methods

2.1. Site description

The research area was located at the Gangwon Nature Environmental Research Park in Hongcheon, Gangwon Province, Korea (37°44′57″N lat., 127°51′48″ E long.). This area was designed for recreational purposes and contains many CCA-wood structures including decks, picnic tables, utility poles and boardwalks. Chrome azurol and PAN stains were used to identify CCA-treated wood. When the chrome azurol and PAN (1-[2-pyridylazo]-2-naphthol) were sprayed on the surface of CCA-treated wood, a distinct color change to blue or red was observed (Blassino et al., 2002). Over Korea, there is heavier rainfall during summer season than the rest of the year due to the East Asian monsoon, with up to 40% of the annual precipitation for a period of 30–40 d from late June–July (Lee et al., 1998).

2.2. Soil and plant sampling

The sampling sites were selected near boardwalks made of CCA-treated wood (37°44′27″N lat., 127°51′05″E long.) based on the results of a previous study conducted by Kim et al. (2007). Based on the vegetative state and cover area, a total of 19 plant species and soils at depth of 30 cm were collected from ten locations in July of 2009 (Fig. 1) with three replicates. In particular, 11 and eight plant species were collected adjacent to CCA-treated wood boardwalks and 75 cm away from the boardwalks, respectively (Table 1). The classification developed by Lee (2003) was used to identify the species (Table 1).

2.3. Soil and plant analysis

The collected soil indicated loam texture with 311.30-g kg^{-1} silt and 232.91-g kg^{-1} clay with soil pH 6.15 and 22.7 g kg^{-1} of organic matter content. Soil samples were air-dried and passed through a 2-mm sieve. The total concentration of heavy metals was determined by digestion in 10-mL 60% HNO_3 and microwave oven-drying at 200 ± 5 °C for 20 min (Mars-X, HP-500 plus, CEM Corp.) according to EPA Method 3051 (USEPA, 1994). The concentrations of Cr, Cu and As were determined by inductively coupled plasma/atomic emission spectroscopy (ICP-AES; Perkin Elmer Optima, USA).

The collected plant samples were washed with tap water and thoroughly rinsed with deionized water. The washed plant samples were then divided into shoots and roots and oven-dried at 70 °C for 48 h after being finely ground (Yang et al., 2009). The Cr, Cu and As from the plant tissues were digested using 10-mL 60% HNO_3 and 2-mL 30% H_2O_2 in a microwave oven-drying (1600 watts) at 200 ± 5 °C for 20 min according to EPA Method 3052 (USEPA, 1996). The concentrations of Cr, Cu and As were then analyzed by ICP-AES. To classify the heavy metal pollution level (PL) in soils, the pollution index (PI) and the integrated pollution index (IPI) were calculated as described by Chen et al. (2005). The PI was defined as the ratio of the metal concentration in the soil to the background concentration. The IPI was also determined as the mean value of PI.

2.4. Phytoremediation efficiency

The translocation factor (TF) and bioaccumulation factor (BAF) were calculated to assess the heavy metal phytoextraction efficiency (Ma et al., 2001; Yoon et al., 2006). The TF is the capacity of a plant to transfer metal from its roots to shoots. However, the bioaccumulation factor expresses the ability of a plant to accumulate metal from soils. In the current study, the TF and BAF values for Cr, Cu and As are given by:

$$\mathrm{TF} = (C_{\mathrm{shoot}})/(C_{\mathrm{root}})^{-1} \tag{1}$$

$$\mathrm{BAF}_{\mathrm{shoot}} = (C_{\mathrm{shoot}})/(C_{\mathrm{soil}})^{-1} \tag{2}$$

$$\mathrm{BAF}_{\mathrm{root}} = (C_{\mathrm{root}})/(C_{\mathrm{soil}})^{-1} \tag{3}$$

where C_{shoot} and C_{root} are the metal concentrations in the shoots and roots, respectively, and C_{soil} is the metal concentration in the soil (Ma et al., 2001; Yoon et al., 2006).

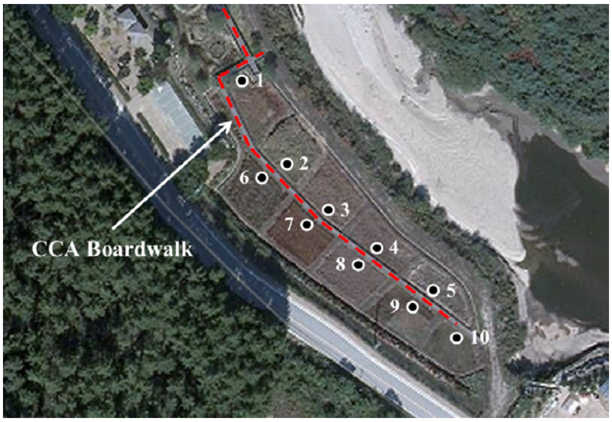

Fig. 1. Locations of soil and plant samples collected along a CCA-treated wood boardwalk near the Gangwon Nature Environmental Research Park, Hongcheon, Korea.

Table 1
Investigated native plant species from soil contaminated with Cr, Cu, and As.

Location	Sampling site	Distance	Order	Family	Scientific name	Common name
1	1	Boardwalk[a]	Papaverales	Papaveraceae	*Chelidonium majus* L.	Greater celandine
2	2	75 cm[b]	Graminales	Gramineae	*Phragmites communis*	Common reed
3	3	Boardwalk	Campanulales	Compositae	*Erigeron canadensis* L.	Horseweed
	4	Boardwalk	Plantaginales	Plantaginaceae	*Plantago depressa* Willd.	Plantain
	5	75 cm	Pandanales	Typhaceae	*Typha orientalis* L.	Bulrush
4	6	Boardwalk	Equisetales	Equisetaceae	*Equisetum arvense* L.	Field horsetail
	7	75 cm	Cyperales	Cyperaceae	*Scirpus tabernaemontani* L.	Glaucus Club-rush
5	8	Boardwalk	Campanulales	Compositae	*Artemisia princeps* Pamp.	Mugwort
	9	Boardwalk	Campanulales	Compositae	*Aster koraiensis* Nakai	Korean starwort
	10	Boardwalk	Campanulales	Compositae	*Lactuca indica* L.	Indian lettuce
	11	75 cm	Graminales	Gramineae	*Zizania latifolia* L.	Wild rice
6	12	Boardwalk	Liliales	Iridaceae	*Iris ensata* Thunb.	Japanese iris
7	13	Boardwalk	Rosales	Rosaceae	*Duchesnea chrysantha*	False strawberry
	14	Boardwalk	Polygonales	Polygonaceae	*Persicaria thunbergii*	Smartweeds
	15	75 cm	Cyperales	Cyperaceae	*Scirpus fluviatilis*	River bulrush
8	16	Boardwalk	Rosales	Leguminosae	*Glycine soja*	Wild soybean
	17	75 cm	Cyperales	Cyperaceae	*Scirpus radicans* Schk	Sharp Club-rush
9	18	75 cm	Umbellales	Umbelliferae	*Oenanthe javanica*	Chinse celery
10	19	75 cm	Tubiflorales	Labiatae	*Mentha arvense* L.	Field mint

[a] Collected adjacent to a CCA-treated wood boardwalk.
[b] Collected 75 cm away from a CCA-treated wood boardwalk.

3. Results and discussion

3.1. Total concentration of heavy metals in soils

The concentrations of Cr, Cu and As in the soils are shown in Table 2. The total concentrations of Cr, Cu and As ranged for 50.56–94.13 mg kg^{-1}, 27.78–120.83 mg kg^{-1}, and 0.13–9.43 mg kg^{-1}, respectively. The concentrations of Cr, Cu and As decreased as the distance from the CCA-treated wood structures increased. The mean concentrations of Cr, Cu and As in the soil samples adjacent to the boardwalk were 8.1%, 50.7% and 195.8% higher, respectively, than those in soil samples collected from 75 cm away from the CCA boardwalk. These findings demonstrated that leaching of Cr, Cu and As from the CCA-treated wood (boardwalk in this study) into the surrounding soil led to higher concentrations of As, Cr and Cu in the vicinity of the structures.

Previous studies have shown that detrimental heavy metals such as Cr, Cu and As leach out from CCA-treated wood into the soil or water ecosystem when a rainfall event occurs (Zagury et al., 2003; Lebow and Foster, 2005; Robinson et al., 2006; Kim et al., 2007). Kim et al. (2007) evaluated the potential environmental impacts of metal leaching from CCA-treated wood to the soils and found that the Cr, Cu and As concentrations in soil samples collected adjacent to the CCA-wood structures were 79.0, 98.9, and 128 mg kg^{-1} soil, respectively, which was much higher than in uncontaminated soils (48.2 mg kg^{-1} for Cr, 26.9 mg kg^{-1} for Cu and 6.3 mg kg^{-1} for As). Robinson et al. (2006) also found that leaching of Cr, Cu and As from CCA-treated wood into soils was a concern because it may degrade soil quality, contaminate groundwater, and threaten human health.

The level of As contamination in soils observed in the present study may have been lower than that of the Cr and Cu for two reasons: (i) most of the original As was fixed and then bound to the wood and (ii) due to its high mobility, As may have migrated vertically and horizontally into neighboring soils. In particular, the As in the soils exists primarily in either neutral (H_3AsO_3) or anionic

Table 2
Total concentrations of As, Cr and Cu (mg kg^{-1}) in soils contaminated with CCA-treated wood (mean ± SD, $n = 3$).

Locations	Sampling site	Distance	Cr (mg kg^{-1})	Cu (mg kg^{-1})	As (mg kg^{-1})
1	1	Boardwalk[a]	84.25 ± 0.60	62.42 ± 0.13	3.25 ± 0.21
2	2	75 cm[b]	54.27 ± 1.78	38.13 ± 0.39	2.61 ± 0.10
3	3	Boardwalk	60.37 ± 1.24	46.22 ± 0.63	1.99 ± 0.03
	4	Boardwalk	90.29 ± 1.60	120.83 ± 0.36	9.43 ± 0.38
	5	75 cm	52.09 ± 1.68	31.38 ± 0.45	0.68 ± 0.03
4	6	Boardwalk	74.64 ± 0.61	59.33 ± 0.12	1.79 ± 0.01
	7	75 cm	57.96 ± 0.81	31.73 ± 0.34	0.67 ± 0.02
5	8	Boardwalk	86.12 ± 1.34	31.86 ± 0.05	0.94 ± 0.03
	9	Boardwalk	88.39 ± 0.49	44.32 ± 0.26	1.27 ± 0.05
	10	Boardwalk	72.52 ± 1.92	33.80 ± 0.38	1.33 ± 0.06
	11	75 cm	70.14 ± 1.28	32.85 ± 0.27	0.13 ± 0.02
6	12	Boardwalk	50.56 ± 1.20	28.97 ± 0.14	0.69 ± 0.03
7	13	Boardwalk	57.05 ± 1.12	28.53 ± 0.14	0.66 ± 0.02
	14	Boardwalk	51.89 ± 2.20	27.78 ± 0.13	0.61 ± 0.01
	15	75 cm	62.74 ± 0.35	27.94 ± 0.18	0.69 ± 0.05
8	16	Boardwalk	75.53 ± 0.48	46.30 ± 0.30	1.49 ± 0.04
	17	75 cm	65.85 ± 1.94	31.33 ± 0.27	0.34 ± 0.04
9	18	75 cm	75.18 ± 2.46	28.26 ± 0.38	0.29 ± 0.01
10	19	75 cm	94.13 ± 1.97	34.33 ± 0.30	0.63 ± 0.03
Overall mean			69.68	41.38	1.53
Mean of sites adjacent to boardwalk			71.96	48.21	2.13
Mean of sites at 75 cm from boardwalk			66.54	31.99	0.72

[a] Collected adjacent to a CCA-treated wood boardwalk.
[b] Collected 75 cm away from a CCA-treated wood boardwalk.

form ($H_2AsO_3^-$, $H_2AsO_4^-$ or $HAsO_3^{2-}$), and its mobility in soils is higher than in the other metals (Robinson et al., 2006).

Several factors may contribute to the variability in the total concentrations of heavy metals, such as soil characteristics, rainfall rate and intensity, construction practices, structure age, structure type, and runoff patterns (Townsend et al., 2003). Indeed, the mobility of Cr, Cu and As in soils differs, which results in their different behavior (Chirenje et al., 2003).

3.2. Soil heavy metal pollution levels

Various methods have been suggested to quantify heavy metal PLs in soils. In this study, the PI and the IPI were calculated to evaluate the heavy metal contamination levels in soils according to the method described by Chen et al. (2005). Specifically, the PI is classified into three levels of low ($PI \leqslant 1$), moderate ($1 < PI < 3$) and high ($PI \geqslant 3$). In the present study, the mean concentrations of Cr (68 mg kg^{-1}), Cu (22 mg kg^{-1}) and As (5 mg kg^{-1}) in non-contaminated soils collected worldwide were selected as the background (Callender, 2003; Reimann and Garrett, 2005). Our results showed that the values of PI for Cr in all of the investigated sites were widely distributed from low to moderate PLs (Table 3). The values of PI for Cu belong to the category of moderate PL, except for those from site 4, which were highly polluted. However, the values of PI for As were classified as having a low PL, except for those from site 4, which had a moderate PL. The IPI was also determined as the mean of the PI for Cr, Cu, and As, and was classified as low ($IPI \leqslant 1$), moderate ($1 < IPI < 2$) or high ($IPI \geqslant 2$) PLs. Our results revealed that all of the investigated sites showed low or moderate PLs, except for site 4, which had a high PL (IPI value of 2.90).

3.3. Metal accumulation in plant tissues

Plant communities respond differently to heavy metal contaminated soils depending on their ability to accumulate and detoxify various heavy metals (Lee et al., 2008). The results of this study indicated that the extent of heavy metal accumulation differed among the plant species investigated, tissue bodies and types of heavy metal (Table 4). Relatively high concentrations of heavy metals were observed in the shoots of *Iris ensata* and *Typha orientalis*, in the following order of Cr > Cu > As. However, the high root concentrations of these metals were observed in *Typha orientalis* and *Equisetum arvense* in the following order of Cr > Cu > As, and *Scirpus radicans* Schk. and *Iris ensata* in the following order of Cu > Cr > As.

It has been reported that the critical concentration of the aboveground biomass of hyperaccumulators of Cu, Cr and As should be higher than 1000 mg kg^{-1} dry matter (Baker and Brooks, 1989; Srivastava et al., 2006). Based on this definition, *Iris ensata* had the highest concentration of Cr (1120 mg kg^{-1}) in its shoots among all plant species evaluated in this study, and this value was much higher than the Cr concentration in its roots (249.9 mg kg^{-1}). Moreover, *Typha orientalis* ranked second in the Cr concentration of its shoots (934.3 mg kg^{-1}) among all other plant species; however, its Cr concentration was highest (1232.7 mg kg^{-1}) in its roots and was greater than in its shoots. For other heavy metals, the highest concentrations of Cu and As in shoots were observed in *Iris ensata* (257.2 mg kg^{-1}) and *Scirpus radicans* Schk. (1.1 mg kg^{-1}), respectively. The highest concentrations of Cu and As in roots were also observed in *Scirpus radicans* Schk. (300.2 mg kg^{-1}) and *Plantago depressa* Willd. (7.0 mg kg^{-1}), respectively. Taken together, these findings suggest that these plant species had different potentials to accumulate each heavy metal and may be selectively used for phytoextraction or phytostabilization of metal-contaminated soils.

The results of this study agreed with the study conducted by Baker (1981) who showed that plant species may effectively and selectively act as accumulators and indicators. However, the total concentrations of heavy metals in the investigated plant species were not correlated with those in the soils except for the Cu concentration in the roots of the investigated plant species ($r = 0.61$; data not shown). These findings partially agreed with other studies indicating that the total metal concentration is a weak predictor of metal availability for plants (Kabata-Pendias and Pendias, 1992; Yoon et al., 2006). Indeed, metal uptake by plants can be influenced

Table 3
Pollution index (PI), integrated pollution index (IPI), and pollution level (PL) in soils sampled adjacent to CCA-treated wood structures.

Location	Sampling Site	Distance	Pollution Index (PI)			IPI	PL
			Cr	Cu	As		
1	1	Boardwalk[a]	1.24	2.84	0.65	1.58	M[d]
2	2	75 cm[b]	0.80	1.73	0.52	1.02	M
3	3	Boardwalk	0.89	2.10	0.40	1.13	M
	4	Boardwalk	1.33	5.49	1.89	2.90	H[e]
	5	75 cm	0.77	1.43	0.14	0.78	L[c]
4	6	Boardwalk	1.00	2.70	0.36	1.38	M
	7	75 cm	0.85	1.05	0.13	0.68	L
5	8	Boardwalk	1.27	1.45	0.19	0.97	L
	9	Boardwalk	1.30	2.01	0.25	1.19	M
	10	Boardwalk	1.07	1.54	0.27	0.96	L
	11	75 cm	1.03	1.49	0.02	0.85	L
6	12	Boardwalk	0.74	1.32	0.14	0.73	L
7	13	Boardwalk	0.84	1.30	0.13	0.76	L
	14	Boardwalk	0.76	1.26	0.12	0.72	L
	15	75 cm	0.92	1.27	0.14	0.78	L
8	16	Boardwalk	1.11	2.10	0.30	1.17	M
	17	75 cm	0.97	1.42	0.07	0.82	L
9	18	75 cm	1.11	1.28	0.06	0.82	L
10	19	75 cm	1.38	1.56	0.13	1.02	M
Overall mean			1.02	1.86	0.31	1.07	M
Mean of sites adjacent to boardwalk			1.06	2.19	0.43	1.23	M
Mean of sites 75 cm away from boardwalk			0.98	1.41	0.15	0.84	L

[a] Collected adjacent to a CCA-treated wood boardwalk.
[b] Collected 75 cm away from a CCA-treated wood boardwalk.
[c] Low pollution level.
[d] Moderate pollution level.
[e] High pollution level.

Table 4
Concentrations of Cr, Cu and As (mg kg^{-1}) in shoots and roots of selected native plant species in soils contaminated by CCA-treated wood (mean ± SD, $n = 3$).

Species	Metal concentration in shoots			Metal concentration in roots		
	Cr (mg kg^{-1})	Cu (mg kg^{-1})	As (mg kg^{-1})	Cr (mg kg^{-1})	Cu (mg kg^{-1})	AS (mg kg^{-1})
Artemisia princeps Pamp.	28.84 ± 3.8	23.82 ± 0.49	0.19 ± 0.02	10.68 ± 3.80	41.85 ± 0.51	0.19 ± 0.04
Aster koraiensis	4.89 ± 2.0	33.16 ± 1.8	0.31 ± 0.002	6.02 ± 4.40	59.28 ± 3.21	0.13 ± 0.04
Chelidonium majus	4.68 ± 1.7	23.74 ± 1.7	0.31 ± 0.09	8.90 ± 2.79	68.63 ± 0.30	1.00 ± 0.10
Duchesnea chrysantha	16.26 ± 0.29	16.94 ± 1.2	0.32 ± 0.02	65.76 ± 3.79	46.19 ± 0.89	0.06 ± 0.02
Equisetum arvense L.	32.98 ± 0.67	16.68 ± 0.51	0.09 ± 0.03	220.50 ± 30.1	63.53 ± 0.80	2.03 ± 0.01
Erigeron canadensis L.	6.34 ± 5.3	25.18 ± 1.9	0.94 ± 0.06	5.59 ± 3.96	119.20 ± 13.8	0.45 ± 0.15
Glycine soja	BDL[a]	15.35 ± 1.3	BDL	24.83 ± 0.86	58.52 ± 3.41	1.08 ± 0.07
Iris ensata	1120.00 ± 48.6	257.20 ± 4.8	BDL	249.92 ± 13.2	263.80 ± 16.4	0.24 ± 0.01
Lactuca indica L.	6.58 ± 6.0	24.97 ± 1.4	0.24 ± 0.01	69.36 ± 17.1	51.31 ± 4.03	0.47 ± 0.12
Mentha arvense L.	32.98 ± 0.67	16.68 ± 0.51	0.22 ± 0.03	31.51 ± 6.00	60.76 ± 5.57	0.38 ± 0.05
Oenanthe javanica	32.54 ± 1.0	17.36 ± 0.62	BDL	15.04 ± 4.46	50.22 ± 13.1	0.52 ± 0.04
Persicaria thunbergii	1.79 ± 0.56	15.00 ± 0.16	0.10 ± 0.01	191.4 ± 72.3	50.65 ± 6.20	0.35 ± 0.07
Phragmites communis	9.86 ± 2.1	15.21 ± 1.1	0.06 ± 0.04	10.87 ± 5.87	24.30 ± 3.02	0.04 ± 0.02
Plantago depressa Willd.	2.33 ± 1.3	36.09 ± 0.43	0.11 ± 0.06	76.69 ± 11.3	118.50 ± 5.07	7.00 ± 0.35
Scirpus fluviatilis	BDL	25.63 ± 2.1	0.02 ± 0.01	66.73 ± 16.0	26.60 ± 1.16	0.02 ± 0.01
Scirpus radicans Schk.	2.92 ± 0.23	12.15 ± 0.46	1.09 ± 0.11	255.90 ± 7.26	300.20 ± 16.5	0.06 ± 0.02
Scirpus tabernaemontani	34.54 ± 1.2	10.55 ± 0.26	0.04 ± 0.03	47.01 ± 25.4	31.22 ± 3.04	1.40 ± 0.76
Typha orientalis	934.30 ± 194.4	184.50 ± 12.2	BDL	1232.70 ± 34.9	174.7 ± 6.98	BDL
Zizania latifolia	2.65 ± 2.9	22.93 ± 2.4	BDL	80.62 ± 1.92	34.80 ± 0.98	0.11 ± 0.03

[a] Below detection limit.

by many factors including soil pH, cation exchange capacity, clay content, organic matter content and the presence of other ions (Kabata-Pendias and Pendias, 1992; Jung et al., 2011).

3.4. Phytoremediation efficiency

Ability of a plant to accumulate metals from contaminated soils was evaluated by the BAF, according to studies of Ma et al. (2001) and Yoon et al. (2006) (Table 5). This study assumed that plants with $\mathrm{BAF}_{\mathrm{shoot}}$ values > 1 are accumulators, while plants with $\mathrm{BAF}_{\mathrm{shoot}}$ values < 1 are excluders (Baker, 1981). Additionally, plants were classified as potential hyperaccumulators if the $\mathrm{BAF}_{\mathrm{shoot}}$ values were >10 (Ma et al., 2001).

Our results showed that two plant species (*Iris ensata* and *Typha orientalis*) had $\mathrm{BAF}_{\mathrm{shoot}}$ values > 1, indicating that they had the potential for use as accumulators or hyperaccumulators of Cr and Cu, while only one plant species (*Scirpus radicans* Schk.) had a $\mathrm{BAF}_{\mathrm{shoot}}$ value > 1 for As (Table 5). The success of the phytoextraction process depends on heavy metal removal by the shoots (Usman and Mohamed, 2009). Therefore, we suggested that the plant species having the higher metal concentrations in their shoots than in their roots can be considered as accumulators or hyperaccumulators for phytoremediation.

The $\mathrm{BAF}_{\mathrm{root}}$ values of >1 indicate high efficacy in the phytostabilization of metal-contaminated soils. For Cr, our results revealed that eight plant species (*Duchesnea chrysantha*, *Equisetum arvense*, *Iris ensata*, *Persicaria thunbergii*, *Scirpus fluviatilis*, *Scirpus radicans* Schk., *Typha orientalis*, and *Zizania latifolia*) had $\mathrm{BAF}_{\mathrm{root}}$ values > 1 and that *Typha orientalis* had the highest $\mathrm{BAF}_{\mathrm{root}}$ value of 23.7 among all plant species investigated in this study. All plant species except for *Phragmites communis*, *Plantago depressa* Willd., *Scirpus fluviatilis*, and *Scirpus tabernaemontani* for Cu, and *Equisetum arvense*, *Oenanthe javanica*, and *Scirpus tabernaemontani* for As were found to have $\mathrm{BAF}_{\mathrm{root}}$ values > 1.

The ability of phytoremediation has commonly been characterized by a TF (Baker, 1981; Srivastava et al., 2006; Yoon et al., 2006; Usman and Mohamed, 2009), which is defined as the ratio of the metal concentration in the shoots to that in the roots. Plants with TF values > 1 are classified as high-efficiency plants for metal translocation from the roots to shoots (Ma et al., 2001). Four plant

Table 5
Bioaccumulation factor in shoots ($\mathrm{BAF}_{\mathrm{shoot}}$) and roots ($\mathrm{BAF}_{\mathrm{root}}$), and translocation factor (TF) of investigated native plant species in soils contaminated by CCA-treated wood.

Species	$\mathrm{BAF}_{\mathrm{shoot}}$			$\mathrm{BAF}_{\mathrm{root}}$			TF		
	Cr	Cu	As	Cr	Cu	As	Cr	Cu	As
Artemisia princeps Pamp.	0.33	0.75	0.21	0.12	1.31	0.20	2.70	0.57	1.03
Aster koraiensis	0.06	0.75	0.25	0.07	1.34	0.10	0.81	0.56	2.35
Chelidonium majus	0.06	0.38	0.10	0.11	1.10	0.31	0.53	0.35	0.31
Duchesnea chrysantha	0.28	0.59	0.48	1.15	1.62	0.09	0.25	0.37	5.48
Equisetum arvense L.	0.44	0.28	0.05	2.95	1.07	1.13	0.15	0.26	0.04
Erigeron canadensis L.	0.10	0.54	0.47	0.09	2.58	0.22	1.13	0.21	2.11
Glycine soja	0.00	0.33	0.00	0.33	1.26	0.67	0.00	0.26	0.00
Iris ensata	22.1	8.88	0.00	4.94	9.11	0.35	4.48	0.97	0.00
Lactuca indica L.	0.09	0.74	0.18	0.96	1.52	0.35	0.09	0.49	0.50
Mentha arvense L.	0.33	0.45	0.35	0.33	1.77	0.61	0.99	0.25	0.58
Oenanthe javanica	0.43	0.61	0.00	0.20	1.78	1.83	2.16	0.35	0.00
Persicaria thunbergii	0.03	0.54	0.17	3.69	1.82	0.58	0.01	0.30	0.29
Phragmites communis	0.18	0.40	0.02	0.20	0.64	0.01	0.91	0.63	1.55
Plantago depressa Willd.	0.03	0.30	0.01	0.85	0.98	0.74	0.03	0.30	0.02
Scirpus fluviatilis	0.00	0.92	0.02	1.06	0.95	0.03	0.00	0.96	0.89
Scirpus radicans Schk.	0.04	0.39	3.23	3.89	9.58	0.16	0.01	0.04	19.8
Scirpus tabernaemontani	0.60	0.33	0.06	0.81	0.98	2.10	0.73	0.34	0.03
Typha orientalis	17.9	5.88	0.00	23.7	5.57	0.00	0.76	1.06	0.00
Zizania latifolia	0.04	0.70	0.00	1.15	1.06	0.86	0.03	0.66	0.00

species (*Artemisia princeps* Pamp., *Erigeron Canadensis*, *Iris ensata*, and *Oenanthe javanica*) and one plant species (*Typha orientalis*) had TF values > 1 for Cr and Cu, respectively. For As, *Artemisia princeps* Pamp., *Duchesnea chrysantha*, *Erigeron Canadensis*, *Phragmites communis*, and *Scirpus radicans* Schk. were found to have TF values > 1. Wei and Chen (2006) suggested that plant species with TF values > 1 actively take up metals from the soil and accumulate them in their aboveground parts, therefore, can be good phytoremediators.

Generally, the higher metal accumulation in the aboveground components with BAF_{shoot} and TF values > 1 have been shown to be likely to explain the higher potential for metal extraction from contaminated sites (Wei and Chen, 2006). In this study, the concentration of Cr in the shoots of *Iris ensata* exceeded its critical level, being as high as 1120 mg kg^{-1} with BAF_{shoot} and TF values > 1 (BAF_{shoot} = 22.10 and TF = 4.48). Therefore, this species could be considered a Cr hyperaccumulator. However, the shoot concentrations of Cu in *Iris ensata*, Cu and Cr in *Typha orientalis* and As in *Scirpus radicans* Schk. were lower than their critical levels of 1000 mg kg^{-1}, even though the values of BAF_{shoot} and/or TF were >1. Therefore, these plant species could be metal accumulators. Even though all of the investigated sites were regarded as low or moderately metal-polluted soils except for site 4, which had a high PL, certain hyperaccumulating and accumulating native plant species were identified from these sites. These findings suggest that these native plant species may also accumulate high concentrations of heavy metals when planted on highly metal-polluted soils. In general, natural metal hyperaccumulators can accumulate large amounts of heavy metals in their aboveground tissues and should be tolerant of metal contaminants and other site conditions that may limit plant growth (Padmavathiamma and Li, 2007). Ma et al. (2001) and Srivastava et al. (2006) identified the fern *Pteris vittata* as a novel hyperaccumulator for As, and it has received the most attention in the phytoremediation field to date. They explained that the efficacy of phytoextraction in metal-contaminated soil is mainly determined by root uptake, translocation from the roots to shoots, accumulation in the aboveground components, and plant tolerance of metals.

It is an important note that plant species with a higher BAF_{root} value combined with a lower TF value can be suitable for phytostabilization of soils contaminated with heavy metals (Yoon et al., 2006; Padmavathiamma and Li, 2007). The 15 plant species among the 19 plant species investigated in this study showed BAF_{root} values > 1 and TF values < 1, indicating strong potential for use in phytostabilization. *Typha orientalis* having the highest BAF_{root} value of 23.7 and the lowest TF value of 0.76 was the most promising plant species for Cr phytostabilization. Our results agreed with a study conducted by Yoon et al. (2006) who evaluated the accumulation potential of 36 native plants growing on a heavy metal contaminated site. They found that *Gentiana pennelliana*, *Bidens alba* var. *radiata*, *Plantago major* and *Sesbania herbacea*, having a relatively high metal bioaccumulation in their roots and a relatively low TF, had the potential to stabilize Cu, Pb and Zn in the soils. Conversely, plant species *Phyla nodiflora*, which had relatively low metal bioaccumulation in its roots and a high TF, might be useful for phytoextraction because it would likely increase metal bioaccumulation in its shoots. Overall, we found that three native plant species of *Iris ensata*, *Typha orientalis* and *Scirpus radicans Schk* are suitable for phytoextraction of one or two metal, and *Typha orientalis* might be best for phytostabilization of Cr and Cu in the soils.

4. Conclusions

This study evaluated the contamination level of soils possibly polluted by CCA-treated wood and investigated 19 native plant species to determine their phytoremediation capacity. Our results revealed that most of the investigated sites were characterized by a low or a moderate PL. Additionally, plant species of *Iris ensata* as a hyperaccumulator, *Typha orientalis, Iris ensata*, and *Scirpus radicans* were suitable for phytoextraction of heavy metals from soils contaminated with CCA-treated wood. Conversely, plant species of *Typha orientalis* would be applicable for phytostabilization because it had the highest BAF_{root} value and a relatively low TF value. Taken together, these findings indicate that phytoremediation may provide a sustainable option to remediate heavy metal contaminated soils, but the proper selection of plant species for specific target metals must be achieved before implementation of phytoremediation technique. Future studies are necessary to evaluate the phytoremediation efficacy of identified plant species against various types and concentrations of Cu, Cr and As, and to investigate the mechanisms of phytostabilization or phytoextraction of heavy metals.

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