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Seedling Growth and Heavy Metal Accumulation of Candidate Woody Species for Revegetating Korean Mine Spoils

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Abstract

Selecting plant species that can overcome harsh soil and microclimatic conditions and speed the recovery of degraded minelands remains a worldwide restoration challenge. This study evaluated the potential of three woody species and various organic and inorganic fertilization treatments for revegetating abandoned metalliferous mines in Korea. We compared survival, growth, and heavy metal uptake of species common to Korean minelands in two spoil types and a reference forest soil. Substrate type and fertilization both influenced seedling growth and metal concentrations substantially, but they had little effect on seedling survival. Fertilization increased the growth of all three species when grown in mine spoils but influenced the growth of seedlings grown in forest soil only marginally. Initial seedling survival and growth indicate that the study species can tolerate the heavy metal concentrations and other soil constraints of metalliferous spoil types. We estimate that plants can stabilize 2–22% of various heavy metals contained in spoil materials into plant biomass during 20 years of plantation growth. Combined with the erosion control and site amelioration benefits of mineland reforestation, stabilization of heavy metals in forest biomass justifies this treatment on abandoned Korean metalliferous mines.

Key words: heavy metal contamination, metalliferous mining, minelands, phytoremediation, reclamation, spoils, tailings.

Introduction

The recuperation of degraded minelands has been an ongoing challenge that has stimulated advances in the science of restoration ecology and has highlighted the importance of soils knowledge to the success of restoration practice. Information pertaining to restoring desirable ecological function and species composition to minelands is common to the published restoration literature. For example, of 480 terrestrial research articles published in the journal *Restoration Ecology* from 1993 through 2006, 90 related to minelands. The soils information in this group of articles characterized the nutrient, chemical, physical, and biological conditions that hinder natural revegetation on minelands and evaluated the effectiveness of nutrient and substrate amendments (Clewell 1999; Singh et al. 2000; Stahl et al. 2002) storage (Harris et al. 1993; Parrotta & Knowles 1999) and physical manipulations (Ashby 1997; Montalvo et al. 2002) at overcoming these limitations. Plant cover and growth were the most frequent indicators used to gauge mineland restoration success (Ashby 1997; Ye et al. 2000; Shu et al. 2005; Norman et al. 2006), but soil properties such as nutrient and soil organic matter accretion, microbial activity or abundance (Allen 1993; Harris et al. 1993; Moynahan et al. 2002), and reduction in metal toxicity were also common. An assortment of invertebrate soil fauna (e.g., collembola, millipedes, isopods, ants, beetles) has also been studied to assess their utility as bioindicators of aboveground structure, habitat, and microclimate of recovering minelands (Andersen 1997; Wheater & Cullen 1997; Tajovský 2001; Davis et al. 2003; Ottonetti et al. 2006). Integrated approaches to characterizing post-mining soil recovery (Davis et al. 2003; Heneghan et al. 2008), such as Clewell's (1999) characterization of soil horizon development following reestablishing native vegetation and hydrologic fluctuations on a Florida phosphate mine, remain scarce.

Forest plantations are commonly used to ameliorate harsh mineland soil and microclimatic conditions and speed establishment of native temperate and tropical vegetation (Ashby 1987; Parrotta 1993; Singh et al. 2000). Plantings of native forest species combined with topsoil recovery and careful site preparation has been shown to reduce soil compaction, promote mycorrhizal symbioses, and facilitate colonization of a species-rich forest community (e.g., 86 naturally regenerating native species) on Amazonian bauxite mines (Parrotta et al. 1997; Parrotta & Knowles 1999). Throughout the tropics, forest plantings containing either native or non-native species have been

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promoted as "foster ecosystems" that can modulate microclimatic extremes, improve soil nutrient availability, and provide habitat for seed-dispersing animals on mined (Parrotta 1993) and other degraded lands (Fisher 1995; Feyera et al. 2002; Russell et al. 2007).

Developing species selection and establishment guidelines to ensure rapid revegetation of harsh planting sites is a universal challenge among mine revegetation projects. Unlike restoration of less severely degraded land, the use of non-native plants remains an acceptable option for mineland revegetation (D'Antonio & Meyerson 2002; Li 2006) if they fulfill a temporary successional role to colonize and ameliorate severely degraded sites and facilitate colonization and eventual dominance by native flora. In addition to high heavy metal levels, successful revegetation of metalliferous mine spoils is complicated by soil nutrient deficiency, low organic matter content, and limited water holding capacity, so inorganic fertilizer and organic matter amendments commonly accompany mineland plantings (Piha et al. 1995; Singh et al. 1996; Singh & Singh 2001). The benefits of fertilization should vary across both spoil types and plant species, but specific revegetation guidelines are lacking for most regions.

In Korea, low economic return on minerals caused widespread closure of metalliferous mines during the 1970s. Currently, few of the approximately 2,000 mines abandoned at that time have been remediated to reduce the risk of landslides or heavy metal diffusion from tailings and overburden. Consequently, heavy metal contamination of surface waters, crops, and forest and agricultural soils is an emerging environmental concern in Korean mining regions (Ok et al. 2003; Chang et al. 2005). Establishment of herbaceous and woody plants is widely promoted for long-term stabilization and detoxification of Korean minelands. During the past decade, surveys have compared metal uptake and tolerance of herbaceous species (Kim et al. 1999; Choi & Jang 2003) and assessed their feasibility for mine reclamation (You et al. 1998; Woo 2003), but few studies have evaluated the utility of fast-growing woody species for remediating minelands. This study aims to improve restoration of Korean minelands by (1) evaluating the initial establishment of promising woody species on distinct spoil types and (2) examining the influence of fertilization on seedling growth and metal uptake.

Methods

Site Descriptions and Soil Materials

This study compared seedling growth in spoils from two abandoned mines and a deciduous forest reference soil. The two spoil types provide a range of metal levels and substrate conditions typical of metalliferous mines in Korea. One site, the Geumjeong mine (lat 37°04′N, long 128°49′E), was mined for gold and silver ores from 1923 to 1988 and the other, the Gahak mine (lat 37°27′N, long 126°51′E), was exploited for lead and zinc from 1912 to 1973. Spoils of the Geumjeong mine exceed Korean toxicity levels (Ross 1994; Kabata-Pendias & Pendias 2001; MOE 2002) for arsenic (As); Gahak mine spoils exceed toxic levels of lead (Pb), zinc (Zn), cadmium (Cd), and copper (Cu). The reference forest is located within 200 km of the two mine sites and is unaffected by heavy industry or mining activities, and soil concentrations of heavy metals are within safe levels (Ross 1994; Kabata-Pendias & Pendias 2001; MOE 2002).

Mineral soil subsamples of the upper 50 cm of the three substrates (reference forest, arsenic spoil, mixed metals spoil) were analyzed for physical and chemical properties as follows (Table 1): pH was determined in a 1:5 soil to distilled water slurry after 1 hour of agitation (Orion pH/ISE meter, model 710A; Thomas 1996); available P was measured by spectrophotometry (U-1100, Hitachi, Japan) after extraction using Bray I reagents and reaction with ammonium molybdate (Kuo 1996); total soil N was analyzed colorimetrically with a continuous flow ion analyzer (Lachat QuickChem AE, Lachat Instrument WI, U.S.A.) following wet digestion in sulfuric acid (Lachat BD-46, Lachat Instrument WI, U.S.A.) (Bremner 1996); organic carbon was measured by the Walkley-Black method (Nelson & Sommers 1996); exchangeable cations (K^+, Na^+, Ca^{2+}, and Mg^{2+}) were extracted using 1N ammonium acetate (pH 7.0) and then measured with inductively coupled plasma atomic emission spectrometry (ICP-AES, ULTIMA 2C, Horiba Jobin Yvon, Japan) (Sumner & Miller 1996); and soil texture was determined using the hydrometer method (Gee & Bauder 1986). Heavy metal (Cd, Cu, Pb, Zn, and As) concentrations were determined as follows: a 10-g soil subsample was extracted in 50 mL of 0.1N HCl (1N HCl for As) after 1 hour of agitation. Soil extracts were filtered (Toyo No. 5B filter paper), and the concentrations were measured by ICP-AES.

Pot Experiment

The three species selected for this study grow rapidly and are common colonizers of Korean mines (Seo et al. 2006). *Pinus densiflora* (Siebold & Zucc.) is native to Korea where it is considered one of the most economically and culturally important species (Lee et al. 2006). Its range extends to China, Japan, and extreme southern Russia (Conifer Specialist Group 1998). *Robinia pseudoacacia* (L.) is native to the southeastern United States that has been widely planted and become naturalized across much of North America, Europe, and Asia. This nitrogen-fixing tree has long been used to revegetate degraded agricultural and mineland (Roach 1965; Ashby & Baker 1968; Vogel 1981). Similar to *R. pseudoacacia*, the shrub *Amorpha fruticosa* (L.) is a North American nitrogen-fixer that has become naturalized in Asia (Li 2006); both species are commonly used to reclaim degraded lands in Korea.

Two-year-old *P. densiflora* seedlings and 1-year-old *R. pseudoacacia* and *A. fruticosa* seedlings were lifted from bareroot nursery beds and transplanted into plastic

Table 1. Physical and chemical characteristics of the reference forest soil and the arsenic and mixed metals spoil types.

Sites	pH	P_2O_5 (mg/kg)	Total N (%)	Organic C (%)	Exchangeable Cations (cmol$^+$/kg)				Heavy Metals (mg/kg)					Texture
					Na	K	Ca	Mg	As	Cd	Cu	Pb	Zn	
Reference forest	7.3 (0.03)	88.7 (0.60)	0.03 (0.00)	0.4 (0.01)	0.5 (0.01)	0.3 (0.01)	5.5 (0.11)	0.7 (0.03)	0.1 (0.0)	<0.1	6.2 (0.6)	9 (1.2)	20 (2.1)	LS
Arsenic spoil	8.0 (0.15)	57.1 (1.35)	0.05 (0.03)	0.8 (0.01)	0.1 (0.01)	0.4 (0.14)	5.8 (0.16)	1.5 (0.05)	219.7 (66.9)	<0.1	3.7 (2.4)	26 (12.4)	20 (8.2)	LS
Mixed metals spoil	7.5 (0.08)	25.7 (3.58)	0.04 (0.06)	0.7 (0.03)	0.0 (0.00)	0.2 (0.01)	5.1 (0.05)	0.1 (0.00)	1.0 (0.7)	33.0 (28.4)	213.8 (52.1)	4,071 (464)	3,832 (243.8)	SL

Data are means with 1 SE in parentheses ($n = 5$). Substrates were sampled from 0 to 50 cm depth with a 5.5-cm-diameter hand-driven corer. LS, loamy sand; SL, sandy loam.

pots (diameter 35 × diameter 25 × height 30 cm) in April 2005. Seedling shoots and root systems were well developed and structurally sound, but there was no visual evidence of ectomycorrhizae or root nodules on any of the species. Pretrial height (cm) and root collar diameter (mm) were 10.5 (± 0.4) and 3.0 (± 0.2) for *P. densiflora*, 26.0 (± 1.1) and 2.5 (± 0.1) for *R. pseudoacacia*, and 34.8 (± 1.4) and 4.2 (± 0.3) for *A. fruticosa*. Pots were filled with 13 kg of soil and rock from either the reference forest or one of the two mine spoil substrates. The following fertilization treatments were applied at the time of planting and after 1 year of growth: Inorganic (N, P, and K added at 5.6, 7.5, and 1.9 g/pot), Organic (N, P, K, zeolite, and organic matter added at 8, 4, 2, 46, and 140 g/pot), Inorganic plus Organic (combine 200 g of organic and of inorganic fertilizer mixtures described above per pot), and an unfertilized control. Each fertilizer treatment was replicated four times for each species by substrate combination. The 144 pots were watered every 2–3 days throughout the study to maintain adequate soil moisture.

Seedling Survival, Biomass, and Heavy Metal Uptake

Seedling survival, height, and root collar diameter were assessed on all seedlings in September 2005 and 2006. At each sampling date, three seedlings were harvested per treatment (substrate × species × amendment), washed, and dissected into leaf, stem, and root tissues. The subsamples were dried at 65°C to a constant mass and weighed. Dry samples were ground to pass a 850-μm mesh sieve, wet digested in H_2SO_4 and H_2O_2 on block digestor (Lachat BD-46, U.S.A.), and analyzed for heavy metal concentrations as described previously. Heavy metal uptake was calculated by multiplying the biomass and elemental concentrations of each seedling component. Arsenic content was calculated for seedlings grown in the arsenic spoil, and Cd, Cu, Pb, and Zn contents were calculated for those grown in mixed metals spoil.

Statistical Analysis

The influence of the fertilization amendments on final seedling height and root collar diameter, biomass, and heavy metal concentrations were compared separately for the three substrate types after 18 months of growth using analysis of variance (general linear model [GLM] procedure; SAS version 9.1, SAS Institute, Cary, NC, U.S.A.). Duncan's multiple range tests were used to separate means at the 5% probability level.

Results

Seedling Survival

Seedling survivorship varied among species and fertilization treatments (Fig. 1). In general, survival in the mine spoils was no lower than that in the forested reference site. The survival of the N-fixing shrub *Amorpha fruticosa*

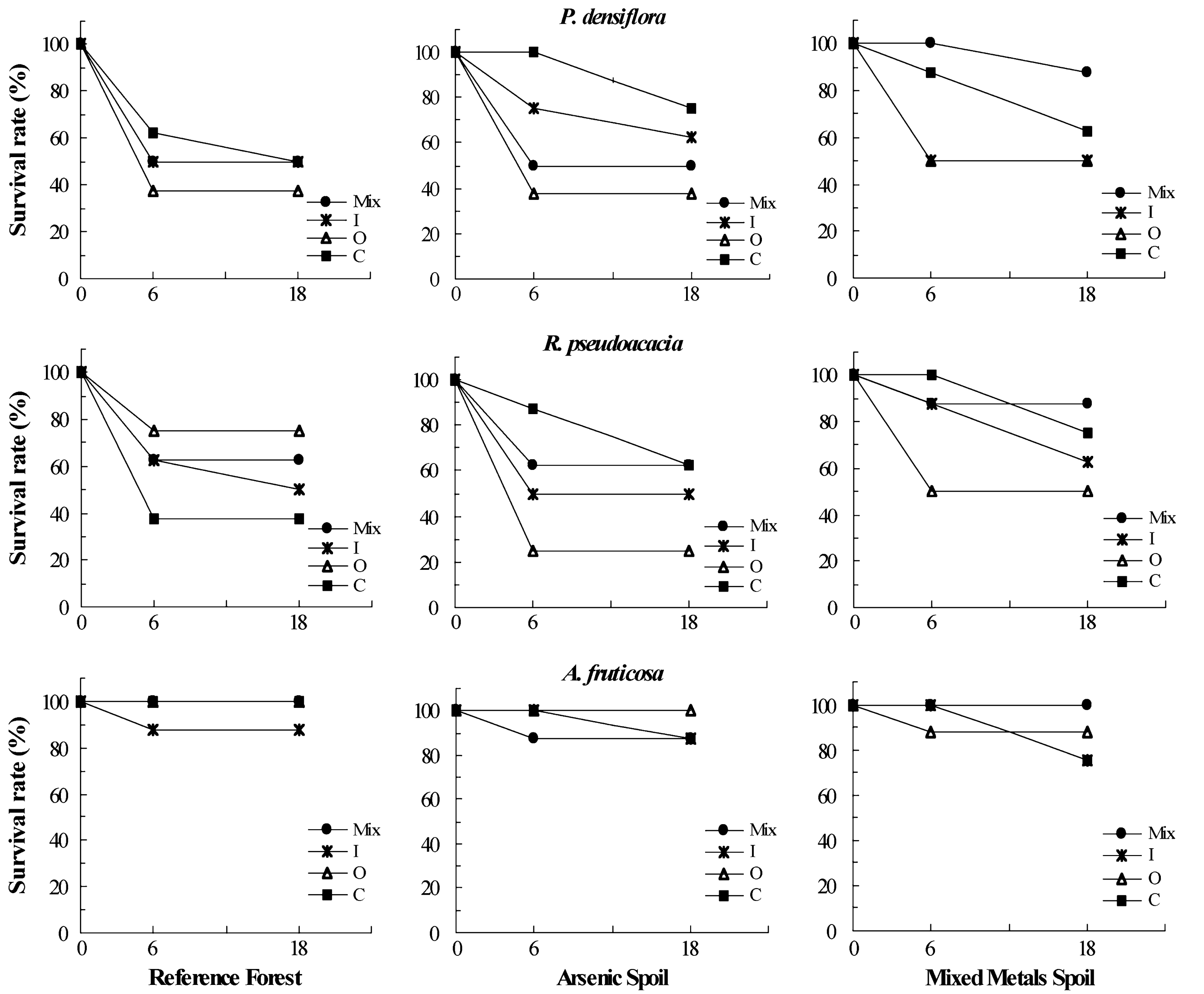

Figure 1. Seedling survival 6 and 18 months (from April 2005 to September 2006) after fertilization. The four treatments were replicated four times on each species and soil type combination ($n = 144$ total seedlings). C, control; O, organic fertilizer; I, inorganic fertilizer; and Mix, organic plus inorganic fertilizer.

ranged from 75 to 100% after 18 months, surpassing the average survival of the other species for each substrate. About 50% of the native pine (*Pinus densiflora*) and 40% of the N-fixing tree (*Robinai pseudoacacia*) survived in unfertilized forest soil, but surprisingly both species fared better in the Arsenic and mixed metals spoils. At 6 months, survival was generally lower for fertilized seedlings, but this pattern reversed in the second year when seedling survival declined more for unfertilized seedlings.

Seedling Dimensions

Final height, diameter, and biomass of unfertilized seedlings were highest in the reference forest soil and lowest in the mixed metal spoil (Table 2, Fig. 2). For example, *R. pseudoacacia* seedlings averaged 148.3 cm tall in the reference forest soil compared to 100.3 and 34.8 cm tall in the arsenic and mixed metals spoils, respectively. The biomass of *R. pseudoacacia* seedlings averaged 286.1 g/tree in the reference forest soil compared to 100.7 and 15.2 g/tree in the arsenic and mixed metals spoils, respectively. The growth of *A. fruticosa* was depressed to a similar extent in the two spoil materials (i.e., 30 and 60% lower final height and 62% and >95% lower biomass). Growth of *P. densiflora* seedlings was lower than the other species and the differences between substrate types less pronounced.

Fertilization had no effect on the final height or diameter of seedlings grown in the reference forest soil (Table 2, Fig. 2), but the amendments significantly increased the growth of all three species in mine spoils. In the arsenic spoil, the mixed inorganic and organic treatment produced the largest seedling heights and root collar diameters for

Table 2. Seedling height and root collar diameter following fertilization treatments in three soil types after 18 months growth.

		Reference Forest		*Arsenic Spoil*		*Mixed Metals Spoil*	
Species	*Treatment*	*Height (cm)*	*Diameter (mm)*	*Height (cm)*	*Diameter (mm)*	*Height (cm)*	*Diameter (mm)*
Pinus densiflora	Control	23.0 (4.0)	7.3 (0.3)	18.8 (0.9)b	6.7 (0.5)b	16.5 (1.3)b	5.5 (0.1)
	Organic	25.0 (0.6)	11.2 (0.0)	24.0 (0.9)ab	9.4 (0.0)ab	23.7 (0.9)a	7.7 (0.0)
	Inorganic	26.0 (2.0)	8.1 (1.6)	24.7 (0.9)ab	7.8 (0.4)b	19.5 (0.5)b	6.9 (1.7)
	Mix	28.0 (0.0)	12.2 (2.3)	27.0 (0.0)a	12.1 (0.0)a	17.5 (0.5)b	4.6 (0.2)
Robinia pseudoacacia	Control	148.3 (26.6)	19.5 (2.9)	100.3 (8.9)b	14.5 (1.4)b	34.8 (7.1)b	6.2 (1.3)b
	Organic	161.7 (7.9)	24.2 (1.7)	187.5 (2.5)a	23.2 (2.0)a	160.5 (37.5)a	19.3 (0.0)a
	Inorganic	150.0 (20.8)	23.9 (2.8)	180.5 (3.5)a	18.8 (1.7)ab	110.3 (20.2)ab	13.0 (2.2)ab
	Mix	157.5 (32.5)	22.4 (2.6)	188.7 (16.2)a	26.4 (3.2)a	74.7 (28.3)b	9.8 (3.0)ab
Amorpha fruticosa	Control	144.4 (8.5)	24.8 (1.6)	100.4 (9.8)b	20.4 (1.4)b	54.8 (8.1)b	8.2 (0.9)b
	Organic	174.8 (13.0)	27.4 (4.1)	154.4 (11.2)a	29.2 (2.6)a	102.8 (21.4)a	12.1 (2.7)a
	Inorganic	167.5 (11.6)	26.0 (0.8)	144.4 (13.3)a	27.9 (2.9)ab	91.2 (14.4)a	11.8 (1.6)a
	Mix	169.8 (12.4)	27.0 (0.8)	133.8 (13.0)ab	27.6 (2.9)ab	105.2 (22.7)a	13.5 (2.8)a

One SE of the means is in parentheses ($n = 4$). Different letters indicate significant fertilization treatment differences for a given species and substrate ($p < 0.05$).

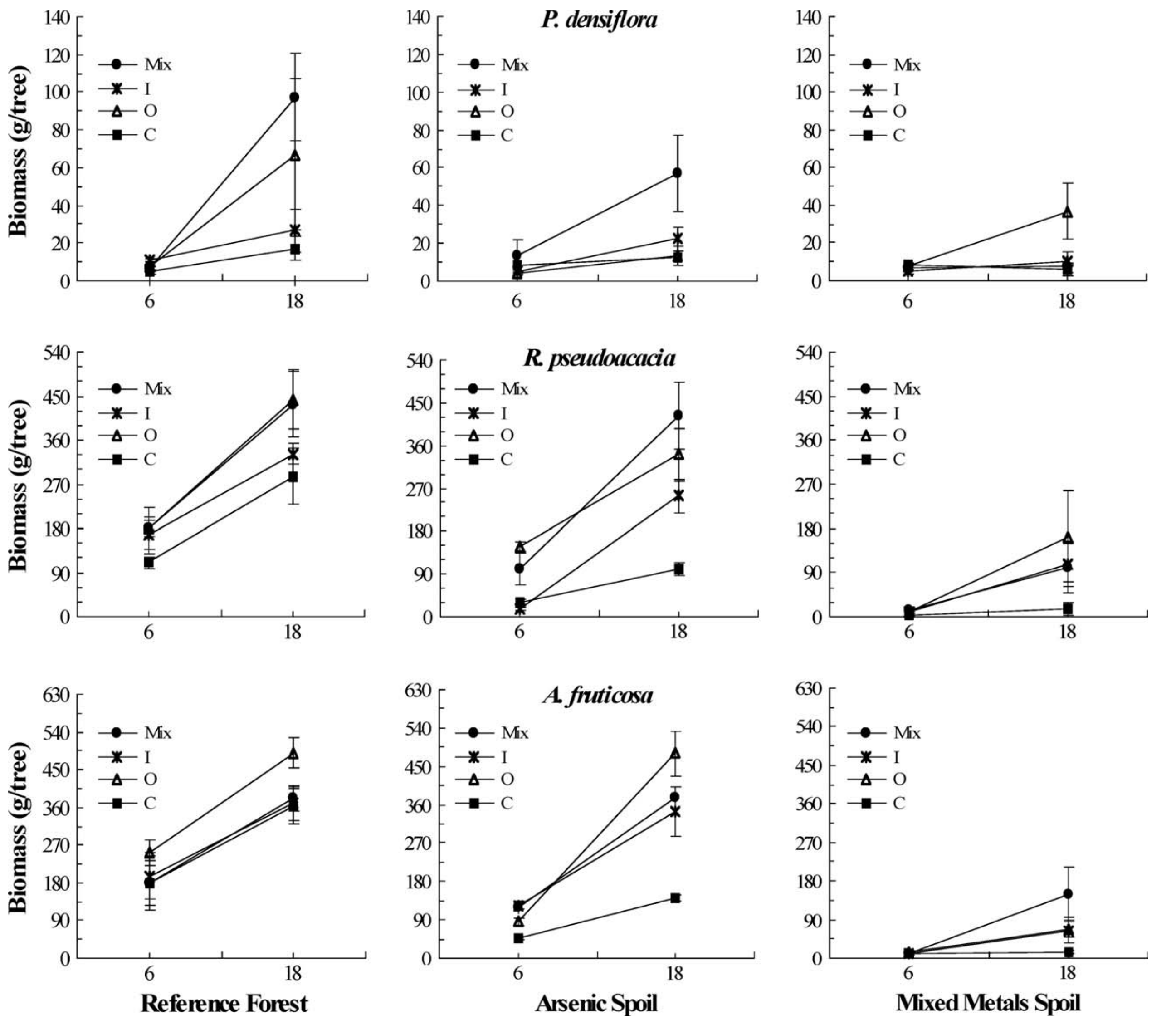

Figure 2. Total seedling biomass (g/tree) 6 and 18 months (from April 2005 to September 2006) after fertilization treatments. Vertical bars represent SEs. C, control; O, organic fertilizer; I, inorganic fertilizer; and Mix, organic plus inorganic fertilizer.

both *P. densiflora* and *R. pseudoacacia*, though the separate inorganic and organic additions also generally increased growth relative to unfertilized seedlings. *Amorpha fruticosa* responded most to the organic fertilizer treatment. Similarly, in the mixed metals spoil, the organic or mixed fertilizer treatments produced the largest seedlings of all three species.

The total biomass of seedlings grown both in the reference forest soil and in the spoil materials was significantly enhanced by the organic or mixed fertilization treatments. Organic fertilization increased the biomass of seedlings of all species grown in the arsenic spoil 2- to 3-fold compared to unfertilized controls. In the mixed metals spoil, where the biomass of unfertilized seedlings was a fraction of that in the other substrates, organic fertilization increased the biomass of *A. fruticosa*, *P. densiflora*, and *R. pseudoacacia* 5-, 6-, and 11-fold, respectively.

Fertilization had a greater effect on *R. pseudoacacia* compared to the other species (Table 2). For example, in the arsenic spoil, the organic treatment increased *R. pseudoacacia* seedling height 1.9-fold over that of unfertilized seedlings compared to 1.3- and 1.4-fold for *A. fruticosa* and *P. densiflora*, respectively. The response of *R. pseudoacacia* to the organic fertilizer treatment was even more notable in the mixed metals spoil. Height and diameter of *R. pseudoacacia* seedlings were 4.6- and 3.1-fold greater than unfertilized seedlings; neither of the other species responded much to organic fertilizer.

Seedling Heavy Metal Uptake

Heavy metal concentrations were significantly higher in root tissue than in aboveground components (leaf and stem), and the three species demonstrated different affinity to take up heavy metals (Table 3). The concentration of all heavy metals was highest in tissues of unfertilized *P. densiflora* and lowest in *R. pseudoacacia* seedlings. For various heavy metals, concentrations ranged from 3- to 12-fold higher in *P. densiflora* compared to *R. pseudoacacia* root tissue. Similar species differences existed for leaf and stem tissue (i.e., 2- to 6-fold higher in *P. densiflora* leaf and 4- to18-fold higher in *P. densiflora* stem). However, the biomass of *P. densiflora* seedlings was approximately one-tenth that of either *R. pseudoacacia* or *A. fruticosa*, so metal uptake differed less among the species.

The organic fertilization treatment had the greatest influence on the heavy metal concentrations of root tissue (Table 4) and equal effect on leaf and stem tissues (data not shown). For *P. densiflora*, the organic amendment resulted in the highest root concentrations of Cu, Pb, and Zn; these were significantly greater than both unfertilized seedlings and those receiving inorganic fertilizer in most cases. Similarly, organic fertilizer resulted in the highest concentrations of As, Pb, and Zn in *A. fruticosa* roots and the highest As and Cu concentrations in *R. pseudoacacia* roots. Inorganic fertilizer improved metal uptake compared to unfertilized seedlings in a few cases (e.g., Pb and Zn by *P. densiflora*) but was consistently less effective than organic fertilization.

Table 3. Heavy metal concentration (mg/kg) in unfertilized seedling tissues ($n = 24$).

	Leaf					Stem					Root				
Species	*As*	*Cd*	*Cu*	*Pb*	*Zn*	*As*	*Cd*	*Cu*	*Pb*	*Zn*	*As*	*Cd*	*Cu*	*Pb*	*Zn*
Pinus densiflora	34.6	10.4	14.6	138.6	402.9	5.6	11.7	16.3	205.1a	212.8	54.6	72.3a	668.2a	359.1a	1425.7a
	(19.3)	(2.1)	(0.7)	(23.6)	(71.2)	(3.7)	(6.2)	(1.4)	(4.4)	(56.5)	(10.2)	(8.8)	(22.0)	(0.3)	(102.2)
Robinia pseudoacacia	5.6	6.4	6.6	29.9	278.6	0.3	2.8	4.0	37.9b	47.7	21.7	9.8b	58.1c	229.0c	487.5b
	(2.2)	(0.0)	(0.0)	(0.0)	(0.0)	(0.0)	(0.0)	(0.0)	(0.0)	(0.0)	(8.7)	(0.0)	(0.0)	(0.0)	(0.0)
Amorpha fruticosa	6.8	6.4	18.2	47.5	358.6	0.3	7.0	5.1	51.2b	67.3	30.2	47.5ab	215.7b	323.0b	644.3ab
	(1.1)	(4.2)	(11.7)	(34.6)	(252.9)	(0.1)	(6.2)	(2.9)	(29.7)	(32.2)	(7.9)	(4.7)	(1.3)	(3.5)	(132.3)

Arsenic concentration was analyzed for the arsenic spoil, and Cd, Cu, Pb, and Zn concentrations were analyzed for the mixed metals spoil. One SE of the means is in parentheses. The small letters indicate significant differences among species within a seedling component ($p < 0.05$).

Table 4. Heavy metal concentration (mg/kg) in 2-year-old seedling root tissue following fertilization treatments.

		As		*Cd*		*Cu*		*Pb*		*Zn*	
Species	*Treatment*	*Arsenic Spoil*	*Mixed Metals Spoil*	*Arsenic Spoil*	*Mixed Metals Spoil*	*Arsenic Spoil*	*Mixed Metals Spoil*	*Arsenic Spoil*	*Mixed Metals Spoil*	*Arsenic Spoil*	*Mixed Metals Spoil*
Pinus densiflora	Control	54.6	1.0	0.6	72.3	32.0c	668.2	10.7b	359.1c	68.6	1425.7b
		(10.2)	(0.2)	(0.0)	(8.8)	(3.1)	(22.0)	(0.7)	(0.3)	(12.7)	(102.2)
	Organic	64.9	1.6	0.8	87.4	67.0a	1073.3	48.7a	454.1a	75.2	2867.5a
		(0.0)	(0.0)	(0.0)	(0.0)	(0.0)	(0.0)	(0.0)	(0.0)	(0.0)	(0.0)
	Inorganic	53.9	1.1	0.9	116.4	48.2b	725.5	12.7b	393.8b	63.8	2352.5a
		(5.8)	(0.0)	(0.2)	(0.0)	(1.0)	(0.0)	(3.0)	(0.0)	(2.8)	(0.0)
	Mix	50.9	1.3	0.8	90.3	45.1b	1034.1	11.1b	363.3c	40.5	2479.9a
		(0.0)	(0.2)	(0.0)	(3.0)	(0.0)	(32.1)	(0.0)	(0.6)	(0.0)	(241.0)
Robinia pseudoacacia	Control	21.7b	0.1	0.0	9.8	21.0b	58.1	14.7	229.0b	18.0	487.5b
		(8.7)	(0.0)	(0.0)	(0.0)	(2.1)	(0.0)	(0.8)	(0.0)	(4.3)	(0.0)
	Organic	186.5a	0.8	0.1	34.2	37.1a	202.0	34.7	286.1ab	25.9	818.4ab
		(83.3)	(0.7)	(0.0)	(3.6)	(4.3)	(48.4)	(28.5)	(7.7)	(1.9)	(49.1)
	Inorganic	58.6ab	1.6	0.1	36.8	22.8b	222.5	15.1	297.1ab	21.4	957.2ab
		(25.8)	(1.1)	(0.1)	(17.0)	(0.6)	(62.1)	(7.8)	(22.4)	(3.1)	(258.2)
	Mix	78.5ab	1.5	0.3	37.1	18.0b	140.7	19.0	363.4a	27.2	1016.9a
		(16.6)	(0.4)	(0.2)	(15.9)	(1.9)	(28.7)	(7.5)	(14.6)	(4.2)	(179.3)
Amorpha fruticosa	Control	30.2b	0.9	0.1	47.5	21.0	215.7	9.6	323.0b	24.6b	644.3
		(7.9)	(0.4)	(0.0)	(4.7)	(0.9)	(1.3)	(1.0)	(3.5)	(1.0)	(132.3)
	Organic	53.2a	0.1	0.1	42.9	17.8	226.9	24.8	356.4a	34.3a	1056.1
		(6.4)	(0.1)	(0.0)	(21.5)	(1.5)	(114.2)	(5.8)	(7.5)	(1.3)	(232.8)
	Inorganic	25.7b	1.6	0.2	61.5	18.8	223.9	19.9	311.4b	21.0b	797.4
		(4.6)	(0.5)	(0.1)	(7.9)	(4.9)	(30.3)	(5.7)	(2.9)	(4.1)	(122.3)
	Mix	29.0b	0.7	0.2	33.8	22.5	131.7	18.0	285.7c	25.4b	628.9
		(3.1)	(0.2)	(0.0)	(11.8)	(5.1)	(37.2)	(2.7)	(8.2)	(2.3)	(104.4)

One SE of the means is in parentheses ($n = 4$). Different letters indicate significant fertilization treatment differences for a given species and substrate ($p < 0.05$).

Fertilization significantly increased heavy metal accumulation in seedlings of all species and both spoil types (Fig. 3). In the arsenic spoil, organic fertilizer increased As uptake 16.4- and 3.0-fold for *R. pseudoacacia* and *A. fruticosa*, and the mixed fertilizer treatment increased As uptake 3.0-fold for *P. densiflora* compared to unfertilized seedlings. In the mixed metals spoil, organic fertilization increased heavy metal uptake as follows for *P. densiflora* and *R. pseudoacacia*: Cd was 14.3- and 26.1-fold higher, Cu was 35.3- and 24.8-fold higher, Pb was 7.6- and 9.9-fold higher, and Zn was 27.0- and 44.6-fold higher, respectively. The mixed fertilization treatment increased heavy metal uptake by *A. fruticosa* compared to unfertilized control as follows: 10.1-fold higher for Cd, 4.8-fold higher for Cu, 6.9-fold higher for Pb, and 9.7-fold higher for Zn, respectively.

Discussion

Seedling Performance

After 18 months, seedling survival varied among seedling species (*Amorpha fruticosa* > *Pinus densiflora* = *Robinia pseudoacacia*) but did not differ consistently with substrate or fertilizer type. However, both substrate type and fertilization substantially influenced seedling growth. The mixed metals spoil associated with lead and zinc extraction at the Gahak mine presented the greatest obstacle for growth of all three species. The height and biomass of *A. fruticosa* and *R. pseudoacacia* seedlings grown in the mixed metals spoil was about 30% of those grown in the reference forest soil. In contrast, the arsenic spoil from the Geumjeong gold and silver mine reduced seedling growth to a lesser extent. *Pinus densiflora* was less sensitive to planting substrate than either of the non-native N-fixers.

Fertilization improved the growth of all three species grown in both spoil types dramatically and significantly stimulated biomass production by seedlings grown in the reference forest soil. Organic carbon and total nitrogen differed little between substrate types, but extractable phosphorus was substantially lower in both spoil types than the reference forest. In addition to toxic metal concentrations, the arsenic spoil was more alkaline, and the mixed metals spoil contained extremely low levels of some essential plant nutrients (Na and Mg). Our findings agree with many previous studies that have documented positive plant responses to fertilization. For example, Casselman et al. (2006) reported that silvicultural treatments including fertilization improved survival, growth, and biomass of trees planted on reclaimed surface mined lands in the Appalachians, and Conesa et al. (2007) demonstrated that fertilization increased the biomass of three native species grown on neutral mine tailings. The growth of Jeffrey pine seedlings on a Sierra Nevada surface mine was enhanced

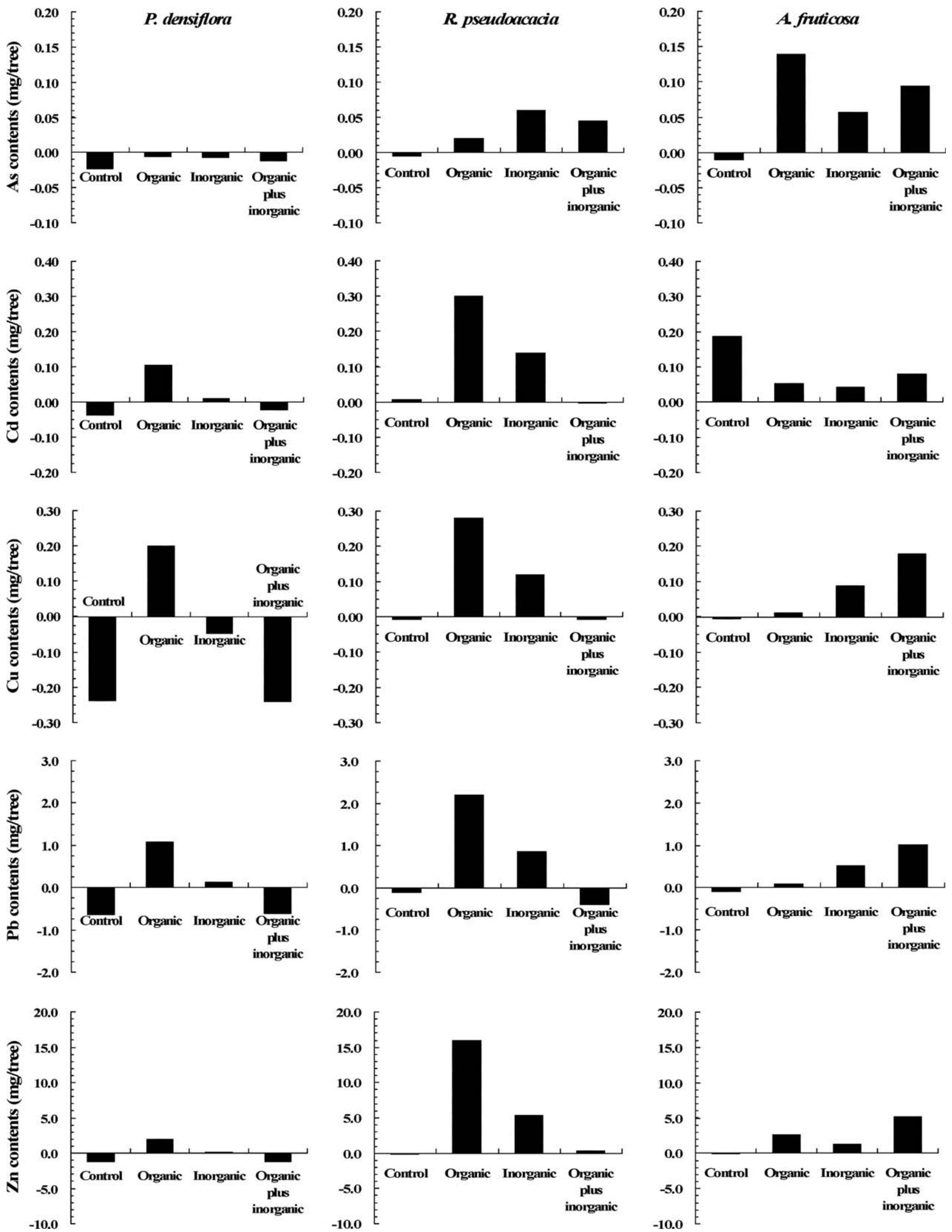

Figure 3. The change in stem heavy metal content between the first and second year of the study. Arsenic content was analyzed for the Geumjeong mine (arsenic spoil); Cd, Cu, Pb, and Zn contents were analyzed for the Gahak mine (mixed metals spoil).

by fertilization applied 3 years after plantation establishment (Walker 2002, 2005). In contrast to the response of *R. pseudoacacia* in our study, fertilizer was shown to have a greater positive effect on non-N-fixers than N-fixers on reclaimed Indian coalfields (Singh & Singh 2001); height and diameter of non-N-fixers increased 3–50% and 9–40% by fertilization compared to 7–15% and 4–27% increases for N-fixers (Singh & Singh 2001).

Heavy Metal Uptake by Tree Seedlings

To assess the long-term potential for woody species to stabilize heavy metals on Korean minelands, we extrapolated the growth of a typical *R. pseudoacacia* plantation (1,000 trees/ha) over an entire rotation. Previous research on *R. pseudoacacia* in Korea measured 33, 65, and 111 mg/ha of aboveground biomass at 8, 13, and 20 years (Kim et al. 1985). In our study, unfertilized *R. pseudoacacia* stem tissue contained 0.25, 3.7, 3.7, 38.8, and 48.0 mg/kg of As, Cd, Cu, Pb, and Zn, respectively. Assuming that tissue metal concentrations remain constant over time, an unfertilized 20-year-old *R. pseudoacacia* plantation would contain approximately 0.04 kg of As, 0.60 kg of Cd, 0.60 kg of Cu, 6.33 kg of Pb, and 7.83 kg of Zn per hectare in stem tissue. This storage is equivalent to about 0.2% of the As, Cu, Pb, and Zn and 1.4% of the Cd contained in the top 50 cm of spoil material. However, our study demonstrated that organic fertilizer increases the heavy metal content of *R. pseudoacacia* stem tissue 15- to 150-fold, so the amount contained in stem biomass of a fertilized plantation would offset 0.03% of the As, 21.6% of the Cd, 3.7% of the Cu, 1.6% of the Pb, and 10.0% of the Zn in spoil material. Accounting for the metals stored in *R. pseudoacacia* root biomass could increase this estimate by an additional 25% or more.

Implications for Practice

- Each of the study species has attributes that are favorable for revegetating Korean minelands: Survival was greatest for *Amorpha fruticosa*, growth was greatest for *Robinia pseudoacacia*, and metal concentrations were greatest for *Pinus densiflora*. Planting recommendations should consider each of these attributes and how they may change as seedlings and plantations develop.
- Fertilization had a positive influence both on seedling growth and on heavy metal uptake for these species and spoil types. The optimal fertilizer treatment differed somewhat, but the organic and mixed organic and inorganic fertilizers were generally most effective. The varying responses to fertilization probably relate to differences in nutrient and heavy metal concentrations as well as the physical properties of the different spoil materials. Adequate fertilization should accompany plantation establishment, and further research should evaluate the importance of maintaining the fertility of mineland plantings.
- Uptake by *R. pseudoacacia* plantings could remove 2, 4, 10, and 22% of the Pb, Cu, Zn, and Cd contained in the upper 50 cm of mine spoils during a 20-year rotation. Though forest biomass accumulates only a fraction of the heavy metals found in mine spoils, the erosion control benefits of reforestation justify this reclamation treatment on abandoned Korean metalliferous mines.
- One of the species evaluated is a Korean native, and the other two are non-native N-fixers. Both the successional role of N-fixing plants in facilitating the recovery of Korean minelands and the identification and examination of native N-fixers deserve additional study.

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