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Chapter 22

Phytorestoration of metal-contaminated industrial wasteland: A greenhouse feasibility study

Z.-Q. Lin, H. Hussein, Z.H. Ye and N. Terry

Abstract

Metal-contaminated industrial waste sites pose potential toxic impacts on the surrounding environment. Phytostabilization can be a cost-effective and sustainable technology for the restoration of industrial wasteland. This greenhouse study was conducted to demonstrate the feasibility of phytorestoration at a metal-contaminated industrial waste site near San Francisco Bay, California. The contaminated soil in the field was unable to support vegetation systems due to phytotoxicity of contaminants and poor soil quality. Concentrations of arsenic, mercury, lead, and selenium in the contaminated soil were 3030, 1830, 12600, and 2370 $\mathrm{mg\,kg^{-1}}$, respectively, and soil pH ranged from 3.6 to 3.8. To improve soil quality for plant growth, the effects of four soil amendments (dolomitic limestone, mushroom compost, gypsum, and organic fertilizer) on soil acidity reduction, seed germination, and shoot biomass production were evaluated with eight plant species, including Fawn tall fescue (*Festuca arundinacea* Schreber), Perennial ryegrass (*Lolium perenne*), Harding grass (*Phalaris aquatia* var Perla), California brome (*Bromus carinatus*), Carolina poplar (*Populus canadensis* L.), Streaker redtop (*Agrostis gigantean* Roth), Reubens Canada blue grass (*Poa campressa* L.), and Indian mustard (*Brassica juncea* L.). The soil amended with dolomite at 8.8 $\mathrm{g\,kg^{-1}}$ and organic fertilizer at 12.5 $\mathrm{g\,kg^{-1}}$ effectively reduced soil acidity and ameliorated soil conditions for optimum plant growth. Among the tested species, Fawn tall fescue was the most tolerant species to the contaminated soil, and, along with the soil amendments, it can be suitable for phytorestoration at metal-contaminated industrial sites.

22.1. Introduction

High levels of metal contaminants in soils are potentially toxic to plants, animals, and humans (Kabata-Pendias and Pendias, 1992). Metal-contaminated industrial wasteland is often times devoid of vegetation and therefore, aesthetically displeasuring, and becomes hazardous to the surrounding environment. To manage such highly contaminated industrial waste sites, plants can be used to stabilize and inactivate soil contaminants in situ, a process termed phytostabilization (US EPA, 2000). Plants forming dense canopies and large root systems on contaminated sites will physically stabilize the contaminated soil against rain impact or leaching, as well as restrict off-site transport of contaminants through lateral wind erosion. Therefore, establishment of vegetation (i.e., phytorestoration) on industrial wasteland effectively reduces migration of pollutants from the contaminated site (Winterhalder, 1996).

Phytorestoration on industrial wasteland is a sustainable and cost-effective approach for pollution control. It may be achieved by the application of soil amendments and subsequent revegetation of the area with tolerant plant species (Adriano et al., 1997). Soil amendments significantly change the chemical speciation and fractionation of metals in the contaminated soil so as to reduce the chemical and biological availability of the contaminants present, as well as to improve the soil as a medium for plant growth. For example, application of ground limestone to acidic and toxic soils increases soil pH from 3.5 to about 6.5 resulting in immediate detoxification (Winterhalder, 1996). Toxic metals would be precipitated as carbonates or hydroxides. If high-soil acidity is corrected by using dolomitic limestone that contains both calcium and magnesium, the soil also benefits from the additional Ca and Mg supplied in dolomite, because high levels of Ca and Mg protect vegetation against trace element toxicity in acidic soils by reducing Al toxicity (Adriano, 2001).

Soil may also be ameliorated by other amendments. For instance, the application of fertilizers and organic materials increases the contents of bioavailable nutrients, e.g. N, P, and K, resulting in better plant growth. Higher levels of organic matter in soil increase adsorption and fixation of metal contaminants in soils. In general, toxic elements become less bioavailable through the physical and chemical processes of adsorption, ion exchange, and precipitation in soil. Mohamed et al. (2005) reported that the biomass yield of rice in As-contaminated soil treated with amorphous Fe/Al oxides and cationic polymers increased 5-fold more than in the control soil.

A suitable plant species for the phytorestoration of industrially contaminated soils should have the following general characteristics: (1) *high* *tolerance to a wide range of soil pH*. The selected plant species should be able to grow well with a wide range of soil pH change, if the succeeding lime treatment could not be made promptly or the neutralizing power of the limestone would deplete after lime application; (2) *high tolerance to low-soil fertility*. Industrially contaminated soils generally have low levels of soil fertility, especially deficiency in soil phosphorus (Winterhalder, 1996). After several years of plant growth, the nitrogen deficiency may also become another major limiting factor; (3) *high tolerance to high levels of contaminants in soil*. Industrial waste sites are usually co-contaminated with different metals at high concentrations (oftentimes $>1000\,\mathrm{mg\,kg^{-1}}$). Therefore, the selected plant species needs to be genetically tolerant to such high levels of contaminants in soil; (4) *high-biomass production*. A greater biomass production will ensure broader plant coverage on ground and intensive root systems in soil. Grass species are highly recommended at the early stage of the phytorestoration because of their fast growth and high tolerance to droughts, insects, and diseases; and (5) *least field management*. A cost-effective phytorestoration technique should require less labor, machinery investment, and other site maintenance costs.

The goal of this research was to study the feasibility of revegetating a metal-contaminated industrial waste site. The specific objectives of this greenhouse study were to (1) determine the effective soil amendment and (2) identify the tolerant plant species that will facilitate phytorestoration of metal-contaminated industrial wasteland.

22.2. Materials and methods

22.2.1. Sampling in the field

The metal-contaminated industrial waste site was located near the San Francisco Bay, California. There was no vegetation growing in the contaminated soils. The soil profiles showed that the industrial chemical wastes were mixed with soil, and that the contaminated soil layer extended down to 150 cm in depth. Five randomly selected soil profiles were sampled at 0–20 and 20–40 cm depth, respectively. Soil samples were stored and transported in clean plastic bags.

22.2.2. Greenhouse experiments

The contaminated soil was brought back from the site to the UC Berkeley greenhouse for pot experiments. The soils were air-dried and large-size rocks were removed. The dry contaminated soil was thoroughly mixed with the selected amendment materials (see below). Each plastic pot (6″) contained 1.6 kg the experimental soils. There were three replicates of each treatment.

Soil amendment materials. It was hypothesized that low-soil pH or strong acidity of the contaminated soil, and consequently low levels of soil fertility (e.g., P), might be important factors responsible for the lack of vegetation on the contaminated site. Therefore, the selection of soil amendments was focused on three primary aspects: soil acidity, soil fertility, and soil structure. The soil amendment treatments included the addition of dolomitic limestone, organic fertilizer, mushroom compost, and gypsum. The general properties of the four selected soil amendment materials are as follows: (1) Dolomite: Commercially available GreenAll® (Suisun, CA) dolomite was used. It was derived from natural dolomite limestone, which contained 24.9% of Ca and 11.4% of Mg (or 49% of calcium carbonates and magnesium carbonate). (2) Organic fertilizer: The organic fertilizer used was derived from the bone meals, kelp, alfalfa, dried poultry waste, bat guano, and blood meal. It was a natural organic transplanting fertilizer, containing 2% water insoluble total nitrogen, 4% available phosphorous as P_2O_5, and 2% soluble potassium as K_2O. (3) Mushroom compost: The compost was moist, containing 69.4% of water, and with a pH of 6.8. (4) Gypsum: This was obtained commercially from GreenAll® (Suisun, CA). The gypsum (92% $CaSO_4 \cdot 2H_2O$) contained 21.0% Ca and 17% S.

Plant species. Eight plant species were selected, including Fawn tall fescue (*Festuca arundinacea* Schreber), Perennial ryegrass (*Lolium perenne*), Harding grass (*Phalaris aquatia* var Perla), California brome (*Bromus carinatus*), Carolina poplar (*Populus canadensis* L.), Streaker redtop (*Agrostis gigantean* Roth), Reubens Canada bluegrass (*Poa campressa* L.), and Indian mustard (*Brassica juncea* L.). Except Carolina poplar that was cultured from shoot-stakes, seeds of the other selected plant species were sowed into ~0.5 cm below soil surface. Pots were watered with tap water every two days.

Experiment 1. To determine the effectiveness and application rates of amendments, each of the four selected materials was tested with Fawn tall fescue, a plant species that is generally tolerant to poor soil conditions (Duble, 1999). The three application rates were 2.9, 4.8, and 6.7 $\mathrm{g\,kg^{-1}}$ for mushroom compost; 3.8, 6.3, and 8.8 $\mathrm{g\,kg^{-1}}$ for Gypsum; 3.8, 6.3, and 8.8 $\mathrm{g\,kg^{-1}}$ for Dolomite; and 6.3, 9.4, and 12.5 $\mathrm{g\,kg^{-1}}$ for organic fertilizer. The original contaminated soil was used as the control. Germination rates and shoot-biomass yields of Fawn tall fescue and soil pH were determined on Day-140 after seed germination.

Experiment 2. To determine the plant species that is most tolerant to the contaminated soil, a total of 150 seeds of each selected species, except for Indian mustard with 15 seeds and Carolina poplar by three shoot-stakes, were sowed into the contaminated soil amended with dolomite at a rate of 8.8 g kg^{-1}. The eight plant species were also grown in the clean soil (i.e., UCMix, growth medium containing peat moss, 36%, Colma sand, 64%, and 9 kg organic fertilizer m^{-3}, Ye et al., 2003) and the original contaminated soil as controls. The same observations (see Experiment 1) were conducted on Day-80 after seed germination. The tolerance index (%) of each tested species was calculated as the ratio of the total dry shoot biomass on dolomite-amended contaminated soil to the total dry shoot biomass on the clean soil (Lin and Huang, 1990).

Experiment 3. To determine the effectiveness of various combinations of the selected amendments for phytorestoration on the contaminated soil, four combinations of the selected amendments were examined for Fawn tall fescue growth and soil acidity neutralization. The application rate of each amendment was 6.7 g kg^{-1} for mushroom compost, 8.8 g kg^{-1} for Gypsum, 8.8 g kg^{-1} for Dolomite, and 12.5 g kg^{-1} for organic fertilizer. Measurements of soil pH, seed germination, and shoot biomass were conducted on Day-60 after seed germination. The contaminated soil without amendment treatments was used as the control.

22.2.3. Physio-chemical properties of soils

The soil sample (about 1 kg) was air-dried and passed through a 2-mm sieve. Measurements of soil physio-chemical properties were conducted by ANR Analytical Laboratory (University of California, Davis) according to the standard methods (Page et al., 1982), except for organic matter (OM) (Nelson and Sommers, 1982), particle size distribution (Gee and Bauder, 1979), SMP soil buffer pH (a measure of the soil lime requirement) (Shoemaker et al., 1961), and soil test P (Horneck et al., 1989; Diamond, 1995). Soil pH was measured in deionized distilled water (1:1 soil to water, w/w) using a Corning Checkmate Modular Testing System (Corning, NY).

22.2.4. Chemical analysis of metals

Soil samples were ground and passed though a 0.25-mm sieve prior to wet digestion with HNO_3, H_2O_2, and HCl for chemical analysis (Method 3050B, see US EPA, 1996). A total of 25 elements (Al, As, B, Ba, Ca, Cd, Co, Cr, Cu, Fe, Hg, K, Mg, Mn, Mo, Na, Ni, Pb, S, Sb, Sc, Se, Sr, V, and Zn) were determined. Total element concentrations in digests were determined following the procedures described in Method 7742 (US EPA, 1994) by inductively coupled plasma emission spectroscopy, except for Se and Hg determined using atomic absorption spectrophotometry with a hydride generator. The standard reference material of SRM-2709 (the San Joaquin soil) (NIST, 1996) was analyzed as an external quality control.

22.2.5. Statistical analysis

Statistical analysis was performed using the statistical analysis system (SAS Institute, 1988a,b). The multiple comparisons of the means were performed using PROC GLM with *Tukey* option.

22.3. Results and discussion

22.3.1. Physical and chemical properties of soil

The physical and chemical properties of the contaminated soil are compiled in Table 22.1. The soil properties, particularly in the topsoil (0–20 cm depth), are important for evaluating the site for future phytorestoration. The contaminated soil was characterized by low-soil pH varying from 3.6 to 3.8 and low-clay content (from 14 to 16% dry weight). The total and extractable macronutrients in the contaminated soil, such as N, P, K, Ca, and Mg, were found generally within their range of variation in agricultural soils. The low levels of CEC and clay content indicated that the contaminated soil had a low pH-buffering capacity. When soil pH values lay below 4, most plant nutrients would become unavailable in soil, except Fe and Mn (Hewitt and Smith, 1974). The reduced availability of P would be an important limiting factor to plant growth, because it can be bounded strongly by Al- and Fe-oxides in the acidic soils. Additionally, the contaminated soil with low levels of clay content and CEC (i.e., 6 to 10 cmol (+) kg^{-1}) had a low-adsorption capacity to bind metal contaminants.

22.3.2. Soil metal concentrations

The chemical analysis suggested that the potentially phytotoxic metal contaminants in the soil (0–20 cm and 20–40 cm depths) at the

Table 22.1. Soil physio-chemical properties at the contaminated site. Values are means ± standard deviations ($n = 5$)

	Soil depth (cm)	
	0–20	20–40
Soil pH (water) (2:1)	3.8 ± 0.4	3.6 ± 0.2
Organic matter (OM) (%)	2.9 ± 0.2	4.1 ± 1.1
Salinity (EC) (dS m^{-1})	5.42 ± 1.88	4.95 ± 0.71
Cation exchange capacity (cmol (+) kg^{-1})	6.2 ± 4.3	10 ± 11.3
Sand, silt, and clay (%)	33 ± 8; 53 ± 7; 14 ± 1	33 ± 4; 50 ± 5; 16 ± 1
Total $CaCO_3$ (%)	<0.2%	0.2%
Total C (%)	4.3 ± 1.2	0.2 ± 0.1
Total N (%)	0.17 ± 0.03	0.17 ± 0.06
Total P (%)	0.05 ± 0.01	0.07 ± 0.05
Extractable K (cmol (+) kg^{-1})	0.1 ± 0	0.15 ± 0.1
Extractable Ca (cmol (+) kg^{-1})	42.2 ± 24.6	41.0 ± 53.5
Extractable Mg (cmol (+) kg^{-1})	4.1 ± 1.7	5.2 ± 1.1
Soil test P (Bray-2) (μg g^{-1})	13.7 ± 9.9	14.2 ± 5.9

contaminated site include Al, As, Pb, Hg, and Se (Table 22.2). Concentrations of these five selected elements were generally well above 1000 μg g^{-1}. For example, Al concentrations ranged from 23,600 to 38,900 μg g^{-1}, As from 1600 to 3000 μg g^{-1}, Pb from 5790 to 12,600 μg g^{-1}, Hg from 1700 to 1800 μg g^{-1}, and Se from 2000 to 2400 μg g^{-1}. In addition, concentrations of B, Cd, Cu, Mn, Ni, and Zn were also excessively high compared to normal agricultural soils (Angelone and Bini, 1992). The phytotoxicity of metal contaminants in the soil is greatly aggravated by a low-soil pH of <4. Although the contents of bioavailable elements were not determined in the contaminated soil, a low-soil pH likely increases the bioavailability of Al, Mn, Cu, and Ni, this in turn leads to uptake of toxic quantities of these metals in plants (Adriano et al., 1997).

Concentrations of metal contaminants generally increased with soil depth at the contaminated site (Table 22.2). In particular, Al, As, B, Fe, Pb, Sc, and V showed the most striking changes (2- to 70-fold) with soil depth (from 0–20 to 20–40 cm depth). For example, Pb concentrations varied from 5790 μg g^{-1} (at 0–20 cm depth) to 12,600 μg g^{-1} (at 20–40 cm). Nickel, V, and Cr concentrations, however, decreased with soil depth. The higher levels of contaminants at a deeper soil depth suggest that the downward movement of contaminants (e.g., As and Pb) may have occurred in the profile of this acidic and light texture soil.

High-soil acidity may cause direct injurious effects on plants by inhibiting root growth. It also indirectly affects bioavailability of P in soil, because of the active P-adsorption to Al- and Fe-oxides at low pH. Such

Table 22.2. Concentrations (mg kg^{-1}) of selected elements in soils collected from the contaminated site in February 1998. Values are means (AVG) and standard deviation (STD)

Element	0–20 cm		20–40 cm	
	AVG	STD ($n = 5$)	AVG	STD ($n = 5$)
Al	23,600	2930	38,900	15,700
As	1590	641	3030	2580
B	75	26	164	47
Ba	153	28	265	119
Ca	8150	3340	12,800	7620
Cd	13	3	18	7
Co	8	1	12	5
Cr	83	7	195	107
Cu	319	25	833	655
Fe	106,000	16,800	149,000	51,500
Hg	1580	570	1830	360
K	2610	233	7420	4220
Mg	3470	512	7850	4570
Mn	152	20	219	82
Mo	21	1	52	29
Na	1710	437	4750	4290
Ni	33	5	53	20
Pb	5790	2270	12,600	11,800
S	13,800	4460	20,400	7690
Sb	110	30	146	43
Sc	10	4	723	656
Se	2090	740	2370	740
Sr	55	14	100	49
V	60	2	170	99
Zn	707	151	1060	459

indirect acidic effects on soil fertility are especially critical at the study site due to the extremely high-soil concentrations of Al and Fe (Table 22.2). The low levels of cation exchange capacity (CEC) and low-clay contents in the contaminated soil could also reduce the water and mineral nutrient capacity of the soil, as well as provided fewer electrostatic adsorbing sites available for the reduction of toxic metals in the soil solution.

22.3.3. Selecting effective soil amendments on contaminated soils

The addition of different amendments to the contaminated soil has different effects on soil acidity, seed germination, and plant biomass production of Fawn tall fescue (Table 22.3). The best soil amendment for improving plant growth was organic fertilizer; an application rate of

Table 22.3. Biomass production of Fawn tall fescue in the contaminated soil treated with different soil amendments. The shoot biomass of Fawn tall fescue and soil pH were determined 140 days after seed germination. Values are means and standard deviations ($n = 3$)

Treatment	Rate ($g\,kg^{-1}$)	pH	Germination (%)	Biomass ($g\,pot^{-1}$)
Unamended soil	Control	3.7±0.3	1±1	ns
Mushroom compost	2.9	4.0±0.0	17±4	ns
	4.8	4.0±0.0	23±6	ns
	6.7	3.8±0.3	23±20	ns
Gypsum	3.8	3.8±0.3	13±12	ns
	6.3	3.8±0.3	15±4	ns
	8.8	3.8±0.3	13±4	ns
Dolomite	3.8	4.5±0.0	37±9	2.5±0.9
	6.3	4.5±0.0	49±12	6.8±2.7
	8.8	4.8±0.3	56±11	9.9±0.8
Organic fertilizer	6.3	4.2±0.6	31±14	11.9±11.9
	9.4	3.8±0.3	43±15	34.3±4.1
	12.5	4.3±0.3	50±16	45.5±1.6

ns, seedlings did not survive after seed germination.

12.5 $g\,kg^{-1}$ yielded the highest biomass of 45.5 g per pot. In addition, the only other effective soil amendment was dolomite, with a yield of 9.9 g per pot at the application rate of 8.8 $g\,kg^{-1}$. The biomass production was significantly ($P < 0.05$) lower at the lowest application rate of dolomite (i.e., 3.8 $g\,kg^{-1}$), compared to the other two application rates. In contrast, the addition of gypsum or mushroom compost did not enable the tested species to grow on the amended soil, even though the treatments had similar germination rates compared with the other treatments of organic fertilizer or dolomite. The addition of dolomite limestone at a rate of 8.8 $g\,kg^{-1}$ significantly increased soil pH from 3.7 to 4.8. The other soil amendments did not change soil pH significantly. Seeds of all tested species were unable to germinate (or $< 1\%$) on the original contaminated soil. Clearly, Fawn tall fescue survived only when the contaminated soil was amended with organic fertilizer or dolomite.

Since plant biomass production increased with increasing the rate of organic fertilizer in Table 22.3, the growth of Fawn tall fescue would have been increased more if the fertilizer had been applied at a higher rate. The addition of fertilizer improved soil fertility by increasing the supply of N, K, and P, as well as an increase of soil pH from 3.7 to 4.3. Although the addition of mushroom compost also provided organic materials for the improvement of soil physical property, it did not improve plant growth because it provided little bioavailable nutrients during the course of this experiment.

There was no significant difference between the 6.3 and $8.8\,\mathrm{g\,kg^{-1}}$ application rates of dolomite (P0.05). This indicates that biomass production would likely not increase significantly if the application rate of dolomite increased. It would appear that the important factors for revegetation of the contaminated soil were soil fertility and acidity. The addition of dolomite provided more Ca and Mg that are known to ameliorate the toxic effects of Al on roots. Possible roles of Ca and Mg ions in the recovery of metal toxicity by dolomitic limestone may be in the competitive exclusion of metal ions from the root-hair exchange complex, and by improving root membrane integrity (Hutchinson and Collins, 1978). Lime application increases soil capacity for metal binding and restricts the solubility of metals in soil. A similar effect can be expected following the application of organic fertilizer (Chaney et al., 1999). Additionally, toxic metals may also precipitate as carbonate or hydroxide compounds when soil pH increases.

22.3.4. Screening plant species for tolerance to the contaminated soil

Different plant species differ in their ability to grow in metal contaminated soils. Eight plant species were tested for germination rates and aboveground biomass production on the soil amended with $8.8\,\mathrm{g\,kg^{-1}}$ of dolomite. Dolomite was selected over organic fertilizer because the dolomite-treatment has less biomass production or greater growth stress than the organic fertilizer treatment (Table 22.3). Results show that the tested plant species were not able to grow on the contaminated soil without soil amendment. With the dolomite treatment, most of the tested plant species had very low-seed germination rates (i.e., $<20\%$), except for Fawn tall fescue and perennial ryegrass (Table 22.4). Indian mustard seeds were not able to germinate on the dolomite-amended contaminated soil. Of the eight plant species tested, Fawn tall fescue had the highest germination rate and produced the highest level of shoot biomass, followed by the perennial ryegrass.

The tolerance indexes of the eight plant species to the contaminated soil were shown in Fig. 22.1, indicating that the Fawn tall fescue was a good candidate for phytorestoration at the contaminated site. Tolerance is thought to be the constitutive property presenting in every cell, tissue, organ of the plant, and/or the whole plant (Ernst et al., 1992). Plant tolerance to metal contaminants can be demonstrated at different levels of integration. For phytorestoration of the contaminated sites, high levels of the aboveground biomass production are desired, because they would generate effective plant coverage of the contaminated soil. Therefore, our

Table 22.4. Tolerance of the tested plant species to the contaminated soil amended with 8.8 g dolomite per kg soil. The shoot biomass and soil pH were measured at Day-80 after seed germination. Values are means ± standard deviations ($n = 3$)

Species	pH	Germination (%)	Biomass (g pot^{-1})
Fawn tall fescue (*Festuca arundinacea* Schreber)	5.0±0.2	35±5	4.0±2.3
Perennial ryegrass (*Lolium perenne*)	4.9±0.1	27±11	1.2±0.9
Harding grass (*Phalaris aquatia var Perla*)	4.9±0.1	4±2	0.9±0.6
California brome (*Bromus carinatus*)	4.8±0.1	14±4	0.4±0.3
Carolina poplar (*Populus canadensis* L.)	4.9±0.1	N/A	0.3
Streaker redtop (*Agrostis gigantean* Roth)	4.9±0.1	1±1	0.1±0.1
Reubens Canada bluegrass (*Poa campressa* L.)	4.8±0.1	18±10	0.1±0.1
Indian mustard (*Brassica juncea* L.)	5.0±0.2	0	0

N/A, not applicable.

selection of high-tolerant plant species to the contaminated soil was primarily based on aboveground biomass production, and the tolerance index was defined as the ratio (%) of the total dry shoot biomass on the dolomite-treated contaminated soil to the total dry shoot biomass on the clean soil. Clearly, a dense vegetative groundcover can greatly reduce soil erosion and human exposure to metal contaminants from the contaminated site (US EPA, 2000).

22.3.5. Interactive effects of selected amendments on growth of Fawn Tall Fescue

Effects of different interactions between the dolomite and organic fertilizer, as well as with other two selected soil amendments (i.e., mushroom compost and Gypsum), on seed germination, soil pH, and shoot biomass production of Fawn tall fescue are compiled in Table 22.5. Different combinations of the four selected amendment materials showed different

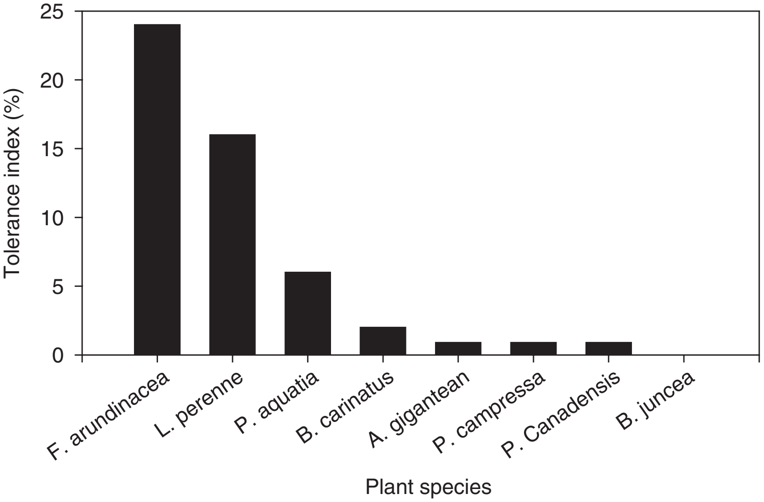

Figure 22.1. Tolerance index of the tested plant species to the contaminated soil amended with 8.8 g dolomite per kg soil. The dry plant biomass on the clean soil (i.e., UCMIX®, containing peat moss, 36%, Colma sand, 64%, and 9 kg organic fertilizer m^{-3}) is not shown.

Table 22.5. Interactive effects of different soil amendments on soil pH, seed germination, and shoot biomass production of Fawn tall fescue. The biomass and soil pH were determined 60 days after seed germination. The data are presented in means with the standard deviations ($n = 3$). The means with different letters in the same column are significantly different ($P < 0.05$)

Combination of amending materials	pH	Germination (%)	Biomass ($g\,pot^{-1}$)
Control (the contaminated soil)	3 ± 0.2^c	0.5 ± 1.0	ns
Dolomite	4 ± 0.3^{ab}	57 ± 9	4.9 ± 0.5^b
Organic fertilizer	4.1 ± 0.2^b	44 ± 18	12.1 ± 2.3^a
Dolomite + organic fertilizer	5.3 ± 0.1^a	45 ± 18	10.1 ± 0.5^a
Dolomite + organic fertilizer + gypsum	4.8 ± 0.5^{ab}	81 ± 7	6.5 ± 1.3^b
Dolomite + organic fertilizer + compost	5.4 ± 0.1^a	59 ± 11	13.9 ± 1.6^a
Dolomite + organic fertilizer + gypsum + compost	5.3 ± 0.1^a	69 ± 9	11.1 ± 0.4^a

ns, seedlings did not survive after seed germination.

effects on the ability to support Fawn tall fescue growth. Data in Table 22.5 show that soil acidity was reduced significantly when the soil was treated with both dolomite and organic fertilizer. The biomass production data showed that the addition of organic fertilizer most effectively improved the soil quality for plant growth. Shoot biomass productions on the contaminated soils amended with dolomite or with dolomite + gypsum + organic fertilizer were significantly lower than on the soils treated with organic fertilizer, dolomite + organic fertilizer, or dolomite + organic fertilizer + mushroom compost. The addition of gypsum did not show any beneficial effects compared to the other three amendments, likely due to low-soil acidity and Al-toxicity to plant roots. The most cost-effective soil amendment, therefore, was the combination of the dolomite and organic fertilizer.

Fawn tall fescue is a variety of tall fescue, a cool-season bunchgrass that is native to Europe and North Africa. Tall fescue (*Festuca arundinacea* Schreb.) was introduced into the United States in the early 1800s, and Fawn tall fescue was first developed in Oregon in 1954 (Duble, 1999). Fawn tall fescue was found to be the best plant species among the eight plant species screened in our greenhouse experiments. It meets the criteria (see Introduction) for selecting suitable plant species for the phytorestoration of the contaminated site. Fawn tall fescue grows well in soil with a pH of 4.7–9.5, although forage production is best when soil pH is maintained between 5.5 and 8.5 (Duble, 1999). Furthermore, it can adapt to a wide range of soils and is tolerant of low-soil fertility. Fawn tall fescue has a massive root system that aids in erosion control, and in surviving drought and flood. It has greater forage and seed yield, compared to other fescue varieties. Although tolerant of low-fertility conditions, fescue requires moderate fertility levels for good production; it is very responsive to nitrogen fertilization (Duble, 1999). Proper watering is important to the survival of Fawn tall fescue, as it requires frequent watering during the summer months (Duble, 1999).

22.4. Conclusions

The limitation for the phytorestoration of the metal contaminated site can be overcome by increasing soil fertility and decreasing soil acidity through the applications of soil amendments. The application of dolomitic limestone at 8.8 g kg^{-1} or organic fertilizer at 12.5 g kg^{-1} in the topsoil layer was essential for plant growth on the contaminated soil. The combination of dolomite and organic fertilizer was suggested to be a cost-effective soil amendment for the phytorestoration of the contaminated site. Fawn tall fescue was identified to be the best plant species for the revegetation, due to its highest tolerance to contaminants in the contaminated soil, and a high aboveground biomass production. Further field trials are needed to validate the findings from this greenhouse study and to implement the phytorestoration technology under field conditions.

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