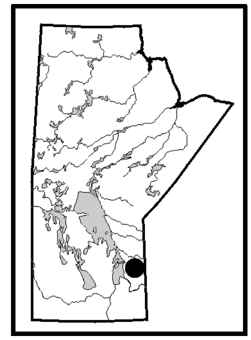
GS-29 PHYTOREMEDIATION OF MINE TAILINGS AND BIO-ORE PRODUCTION: PROGRESS REPORT ON SEED GERMINATION, SURVIVAL AND METAL UPTAKE OF SEEDLINGS PLANTED AT CENTRAL MANITOBA (AU) MINESITE (NTS 52L13)

by S. Renault[1], E. Sailerova[2] and M.A.F. Fedikow[3]



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SUMMARY

A project was initiated in 2000 at the Central Manitoba (Au) minesite in southeastern Manitoba to determine the potential for revegetation, phytoremediation and phytomining of mine tailings through the identification of plant species that can avoid or tolerate the presence of heavy metals. Sixteen plant species, seedlings as well as seeds, were planted on three experimental sites of mine tailings and in the greenhouse on the tailings material. Results have shown that several plant species were able to survive for three growing seasons on two of the three selected sites without any additional treatment. Wheatgrass seeds demonstrated the highest survival rate in both greenhouse and in the field. Capping of tailings with peat on the third site allowed survival of some of the seedlings for at least two growing seasons. Laboratory results indicate a promising enrichment of metals in roots and in some shoots of selected plant species.

INTRODUCTION

Tailings are the waste product of ore processing operations and they can pollute the environment with significant quantities of heavy metals. At present, modern techniques avoid the uncontrolled release of tailings in the environment. However, there are many vast, exposed and untreated tailing sites that desperately need effective remediation and revegetation to avoid significant risk to the environment and to the health of people living in the area.

Most of the heavy metals are released from the tailings to the environment after being oxidized. The oxidation of the tailings in air under moist conditions results in lowering of the pH and leads to an increased solubility of the heavy metals. Metal mobilization from tailings can often be traced into watersheds downstream from active mining sites. Low pH, presence of metals in toxic quantities, the lack of vegetative cover and organic nutrients prevent seed germination and plant growth. Tailings thus form large and bare areas with no vegetation cover. This in combination with their often powdery nature makes them a source of enormous dust production. Affected soil cannot be used for agricultural purposes because of the high metal content and other land uses are limited. Today's practices of removing the contaminated soil (excavation) are very expensive (Giasson and Jaouich, 1998).

Oxidation of the tailings can be controlled by covering the surface with soil and then usually revegetating the site. Establishment of a self-sustaining mat of vegetation is usually an important element in a rehabilitation program for waste-disposal areas. Vegetation stabilizes the soil, prevents new acid-generating material from being exposed and decreases the amount of water available for deep percolation through transpirational water movement. Vegetation is established by controlling pH near the surface with the addition of lime or limestone and by adding peat and fertilizers where necessary. This treatment can increase initial plant survival rate and help to induce adaptation processes. Plant species are usually selected from well-adapted species growing in the region (Bradshaw, 1952). Nevertheless, revegetation alone does not stop acid drainage and does not necessarily remove heavy metals from the contaminated site.

Phytoremediation of soils contaminated with heavy metals is being developed as a potential cost-effective remediation solution for thousands of contaminated sites in the United States and abroad (Salt et al., 1995, 1998; Cunningham et al., 1995; Comis, 1996). Phytoremediation of tailings, however, is a problem that remains to be addressed on a case-specific basis. It might be necessary to revegetate with grass species before introducing the species that are the most effective in extracting metal from the tailings.

A relatively new approach to phytoremediation involves the introduction of highly tolerant species with high biomass production, capable of accumulating 0.5 to 1% of their dry weight in metals. The shoots of these plants are harvested at the end of the growing season and burned, forming a metal-rich bio-ore (Nicks and Chambers, 1998). The choice of hyperaccumulator species must also be climate and site specific, and sensitive to regulations restricting the

[1] Department of Botany, University of Manitoba, Winnipeg, Manitoba, R3T 2N2
[2] M.E.S.S. Consultants, 683 Borebank Street, Winnipeg, Manitoba, R3N 1G1
[3] Mount Morgan Resources Ltd., 34 Wellesley Court, Winnipeg, Manitoba, R3P 1X8

introduction of foreign species.

Phytomining technology offers the possibility of exploiting ores or mineralized soils that are uneconomic by conventional mining methods. Bio-ores are virtually sulphur free and their smelting requires less energy than sulphide ores. The metal content of a bio-ore is usually much greater than that of a conventional ore and therefore requires less storage space, despite lower density. Moreover, phytomining is an environmentally responsible approach to site remediation.

OBJECTIVES

The long-term goal of this study is to define limiting factors for phytoremediation of mine tailings and other sites contaminated with heavy metals. This study will establish the scientific basis for the remediation of mine tailings and extraction of heavy metals by phytomining techniques. Practical experience will be gained in the routine remediation of mine tailings and possibly in the extraction of heavy metals. Plant species selected for the study will include plants native to the surrounding environment and seeds of plants acclimated on-site will be also tested. The suitability of selected species for phytomining for base metals and gold will be tested in terms of the quality and costs of bio-ore production and economic effectiveness.

SIGNIFICANCE OF THE WORK

Soil contamination by heavy metals, and metal leakage and dust production from sulphide tailings represents a significant and widely recognized ecological hazard. Phytoremediation offers the possibility of an ecologically acceptable and cost-effective solution. Phytomining, a new technique for extracting metals from low-grade ore or sulphide tailings, is a promising technique currently being developed for commercialization in the United States. Field experiments in phytomining in Manitoba could provide valuable information regarding the potential of this method to remediate sites contaminated with heavy metals.

GEOLOGICAL SETTING OF THE CENTRAL MANITOBA (AU) DEPOSIT

Tailings associated with the Central Manitoba (Au) deposit were selected for initial phytoremediation and phytomining studies. A description of the geological setting of this deposit is detailed in Renault et al. (2000, 2001).

GEOCHEMICAL CHARACTERIZATION OF TAILINGS AND DESCRIPTION OF EXPERIMENTAL SITES

Three experimental sites were chosen based on the proximity to the tailings edge and vegetation cover, exposure to sun and wind, and drainage conditions (Sailerova, 2000). Site 1 was positioned relatively far from the tailings edge, partially sheltered by sporadic vegetation cover and poorly drained. Site 2 was located in the middle of the tailing mass with no vegetation cover, fully exposed to the wind and sun and well drained. Site 3 was located close to the tailings edge, relatively well sheltered and drained. The pH values were measured at all three experimental sites in 2002. At sites 1 and 2, pH values were in the range of 3.5 to 4 in oxidized zones and 6.5 to 7 in non-oxidized zones. At site 3, pH values ranged from 5 to 7.

Results of geochemical analyses of 20 tailings samples collected from three hand-augered profiles, approximately 1 m deep, were presented in Renault et al. (2000).

RESULTS

Greenhouse Study

Seeds of the following species were planted in the greenhouse: Indian mustard (*Brassica juncea*), white mustard (*Sinapis alba*), slender wheatgrass (*Agropyron trachycaulum*), altai wildrye (*Elymus angustus*), reed canary grass (*Phalaris arundinacea*), creeping foxtail (*Alopecurus arundinaceus*), streambank wheatgrass (*Agropyron riparium*) and tall fescue (*Festuca alatior*). Seeds were planted in trays on tailings collected from the top 15 cm of the three selected sites described above. Seeds of the selected species were also planted on tailings mixed with peat at a ratio of one to one and on a mixture of just peat and sand. The trays were sprayed with distilled water regularly to keep the moisture level relatively constant.

Indian mustard, white mustard and tall fescue seeds planted on tailings from sites 1 and 3 had the highest germination rates followed by slender wheatgrass and altai wildrye (Table GS-29-1). The remaining species (reed canary grass, creeping foxtail and streambank wheatgrass) had relatively low germination rates when planted in tailings from sites 1 and 3, as well as when planted in a mixture of peat and sand. This suggests that these species could just have low germination rates. Although Indian mustard and white mustard germinated well on tailings from sites 1 and 3, they were not able to survive for three months. Addition of peat to the tailings increased germination rates particularly at site 2 and greatly improved the survival rate of the seedlings at all sites (Table GS-29-1). This was in part a result of the increase in pH values. Among the grass species, tall fescue and reed canary grass are the species that produced the highest biomass when grown on site 1 amended with peat (Fig. GS-29-1). These species will be analyzed for metal content to determine their potential as reclamation or remediation species.

Experiments were designed in 2002 to test the efficiency of white mustard to absorb Cu in the presence of various chelators. These chelators will potentially enhance the plants' ability to absorb Cu from the tailings. Results will be available in 2003.

Table GS-29-1: Germination of seeds and survival of plants three months after seeding on tailings in the greenhouse.

	Peat with sand	Site 1	Site 2	Site 3	Site 1 (with peat)	Site 2 (with peat)	Site 3 (with peat)
Plant species							
				Germination (%)			
Indian mustard	100	88	0	88	96	34	96
White mustard	93	95	0	94	84	36	94
Altai wildrye	72	72	7	67	44	34	48
Slender wheatgrass	92	70	0	90	82	54	88
Reed canary grass	44	48	0	48	38	2	60
Creeping foxtail	40	56	0	52	54	4	62
Streambank wheatgrass	64	72	0	50	52	42	74
Tall fescue	88	80	0	86	82	18	76
				Survival (% of germinated seeds)			
Indian mustard	100	0	-	0	100	59	98
White mustard	100	0	-	0	100	50	100
Altai wildrye	100	93	0	69	100	100	100
Slender wheatgrass	100	89	-	41	85	96	98
Reed canary grass	100	42	-	83	89	0	93
Creeping foxtail	100	71	-	88	93	100	97
Streambank wheatgrass	100	94	-	92	96	90	95
Tall fescue	100	100	-	100	100	78	97

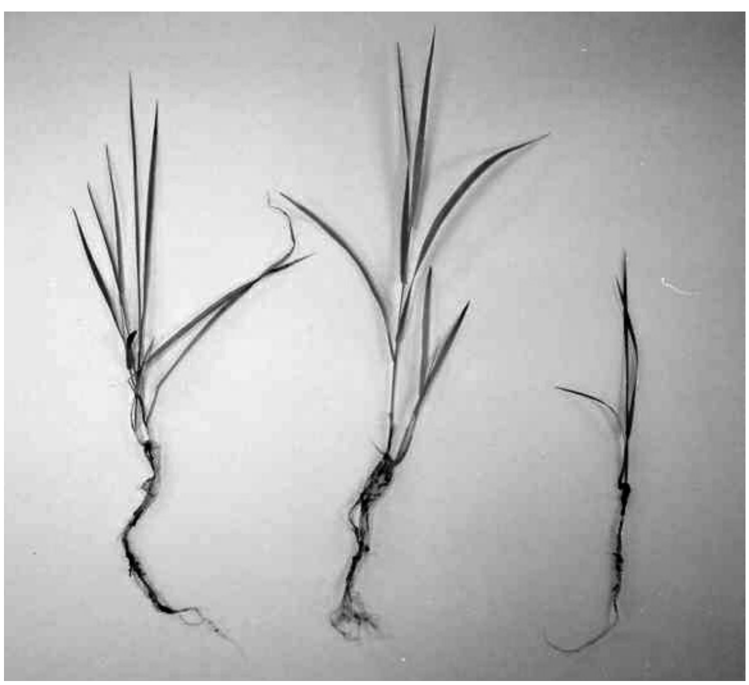

Figure GS-29-1: Reed canary grass grown on peat and sand (left), on site 1 tailings and peat (centre) and on site 3 tailings and peat (right).

Field Study: Plant Species Survival

In 2000, the following native tree species were planted on the three different sites: red-osier dogwood (*Cornus stolonifera*), yellow willow (*Salix lutea*), white spruce (*Picea glauca*), jack pine (*Pinus banksiana*), tamarack (*Larix laricina*) and bog birch (*Betula glandulosa*). In 2001, additional red-osier dogwood (*Cornus stolonifera*), yellow willow (*Salix lutea*), white spruce (*Picea glauca*) and jack pine (*Pinus banksiana*) seedlings were planted on the three sites. Prior to planting in 2001, a layer of peat (5 cm deep) was added on the top of the tailings on site 2. In 2002, additional red-osier dogwood seedlings were planted at sites 1, 2 and 3. Seeds of the following species were also planted (2001 and 2002) directly on tailings or after addition of peat at the three sites: Indian mustard (*Brassica juncea*), white mustard (*Sinapis alba*), slender wheatgrass (*Agropyron trachycaulum*), altai wildrye (*Elymus angustus*), reed canary grass (*Phalaris arundinacea*), creeping foxtail (*Alopecurus arundinaceus*), streambank wheatgrass (*Agropyron riparium*), tall fescue (*Festuca alatior*), tall wheatgrass *(Agropyron elongatum*) and Western wheatgrass (*Agropyron Smithii*).

Results showed that some tree seedlings were able to survive on sites 1 and 3. The tree seedlings rapidly died on the untreated, oxidized zones of site 2 (Table GS-29-2). However, in the areas of site 2 where peat had been added on the top of the tailings or mixed with the tailings matter, some seedlings were still alive after two growing seasons (Fig. GS-29-2, Table GS-29-2). Among the seedlings planted in 2000 at site 1, tamarack (Fig. GS-29-3) and white spruce had the highest survival rate followed by bog birch and jack pine. For the seedlings planted at site 1 in 2001, red-osier dogwood had the highest survival rate. For most seedlings, the survival rate was the highest when growing on site 3, likely due to the higher pH of the site (Table GS-29-2, Fig. GS-29-4, GS-29-5).

Table GS-29-2: Survival of seedlings planted on sites 1, 2 and 3. Measurements were taken in September 2002 after two and three growing seasons.

	Survival (%)		
Plant species (planted in 2000)	**Site 1**	**Site 2**	**Site 3**
Jack pine	50	0	83
White spruce	83	0	67
Tamarack	100	0	100
Red-osier dogwood	42	0	58
Yellow willow	30	0	69
Bog birch	75	0	100
Plant species (planted in 2001)	**Site 1**	**Site 2 (with peat)**	**Site 3**
Jack pine	45	5	94
White spruce	63	0	100
Red-osier dogwood	83	10	90
Yellow willow	38	13	92

Figure GS-29-2: Jack pine on site 2 amended with peat after two growing seasons.

Figure GS-29-3: Tamarack on site 1 after three growing seasons.

Figure GS-29-4: Seedlings planted in 2001 on site 3.

Figure GS-29-5: Yellow willow planted in 2000 on site 3.

Indian mustard and white mustard seeds survived in the field when peat was added on the top of the tailings (Table GS-29-3). This is an important finding in light of the suitability of these species for phytoremediation and phytomining. Although biomass production was reduced when seedlings were grown on tailings, the addition of fertilizer to improve growth should be tested. Grass species planted in the spring of 2002 exhibited relatively high germination and survival rates; the highest survival rate was recorded for the wheatgrass species (western wheatgrass, slender wheatgrass, tall wheatgrass and streambank wheatgrass), followed by tall fescue and altai wildrye (Table GS-29-3). The difference in survival rate between seeds planted on an oxidized area of site 2 (pH 3.6) and seeds planted in a non-oxidized area of the same site (pH 7) was drastic (Table GS-29-3). The preliminary results showed that survival rate and the biomass of several plants were much higher in the non-oxidized area (Fig. GS-29-6). This result suggests that oxidation of the tailings, accompanied by a decrease in pH, seriously limits revegetation. However, this result will need to be confirmed by additional studies. The addition of limestone to increase the pH of the tailings at sites 1 and 3 is planned for the next growing season.

Overall survival rates were lower in the field than in the controlled conditions of the greenhouse, suggesting that monitoring of the plant growth at the beginning may be required to ensure successful re-establishment of vegetation on tailings.

Table GS-29-3: Survival of plants three months after seeding on sites 1, 2 and 3 in 2002.

Plant species	Survival (% of planted seeds)						
	Site 1	Site 2	Site 3	Site 1 (with peat)	Site 2 oxidized (with peat)	Site 2 non-oxidized (with peat)	Site 3 (with peat)
Indian mustard	0	0	0	25	8	n.a.	49
White mustard	0	0	0	49	6	n.a.	65
Altai wildrye	26	0	16	22	8	85	36
Slender wheatgrass	44	0	38	30	1	80	25
Reed canary grass	11	0	27	7	1	n.a.	11
Creeping foxtail	0	0	21	0	2	n.a.	3
Streambank wheatgrass	29	0	47	59	11	45	50
Tall fescue	35	0	50	7	10	n.a.	30
Tall wheatgrass	24	0	33	28	19	70	29
Western wheatgrass	50	0	38	37	28	n.a.	52

Note: n.a. - not available

Figure GS-29-6: Planting sites on oxidized (top of photo) and non-oxidized (bottom of photo) zones of site 2.

Elemental Analysis of Plant Tissues

In September 2001, seedlings planted in the field in 2000 (tamarack, white spruce, jack pine, dogwood, willow and birch) and some plants growing naturally on site [white spruce, horsetail (*Equisetum sp.)* and a grass species, Kentucky bluegrass (*Poa pratensis)*] were harvested, washed carefully and freeze-dried prior to elemental analysis. White mustard and Indian mustard, planted in the field and in the greenhouse on tailings amended with peat, were also analyzed for elemental analysis. The results of the analysis showed that plants growing on site 1 had a relatively high level of B (over 100 ppm in tamarack needles and willow shoots) compared to what is normally found in plants, which is 10 to 20 ppm (Table GS-29-4). Although boron is an essential element for plant growth, high levels can cause toxicity to the plant (Dudley, 1994). The level of Cu was elevated in all of the field samples tested (Table GS-29-4). Some plants are able to tolerate a relatively high level of Cu (Jones, Jr., 1998). Further experiments are needed to investigate the extent of Cu accumulation in the selected plants and test their potential role in removal of Cu from the tailings. This removal of Cu from tailings would enable the growth of species that are less tolerant to Cu. Levels of Al, V, Cr, Fe, As and Se were relatively high in the mustard species and some conifers compared to the other planted species (Table GS-29-4). Levels of Cd and Co were also relatively high in willow, dogwood and tamarack, while Ag levels were high in Indian mustard and jack pine (Table GS-29-4). The levels of Na and Mn were within the normal range for plants. On the other hand, the levels of macronutrients such as Mg, Ca and K in the tree species were generally lower than the normal range, suggesting that mineral deficiency might be a limiting factor for plant growth in the tailings. The level of Au in dogwood and willow roots was significantly higher than in the other plant species. No significant Accumulation of gold was found in the mustard shoots (Table GS-29-4), probably due to the small biomass produced. Further work will focus on enhancing the growth rate of the mustard species to determine the potential of these species for phytomining.

Table GS-29-4: Elemental analysis of plant shoots, roots, stems and needles harvested from the field (sites 1, 2 and 3) and from the greenhouse. All values are in ppm, unless otherwise noted.

Samples	Pre-ash wt (g)	Ash wt (g)	Ash (%)	B	Na (%)	Mg (%)	Al	K (%)	Ca (%)	V
Tamarack[1]										
Root - site 1	0.99 ± 0.02	0.13 ± 0.06	13.49	31.0 ± 28.8	0.04 ± 0.01	0.10 ± 0.04	309 ± 7	0.26 ± 0.04	1.92 ± 0.82	0
Stem - site 1	0.98 ± 0.03	0.03 ± 0.01	3.06	14.0 ± 2.0	0.02 ± 0.01	0.08 ± 0.02	70 ± 6	0.23 ± 0.03	0.44 ± 0.02	3.67 ± 0.58
Needles - site 1	0.89 ± 0.09	0.06 ± 0.01	6.82	290 ± 167	0.03 ± 0.01	0.18 ± 0.06	40 ± 5	0.68 ± 0.10	0.67 ± 0.09	6 ± 1
Root - site 3	1.00 ± 0.01	0.04 ± 0.01	4.01	9.3 ± 2.3	0.01 ± 0.01	0.06 ± 0.01	117 ± 43	0.27 ± 0.06	0.69 ± 0.10	7.33 ±1.16
Stem - site 3	1.00 ± 0.01	0.02 ± 0.01	2	8.3 ± 0.6	0.01 ± 0.01	0.06 ± 0.01	137 ± 79	0.20 ± 0.02	0.41 ± 0.03	7 ± 0
Needles - site 3	0.78 ± 0.05	0.04 ± 0.01	4.88	18.3 ± 4.5	0.02 ± 0.01	0.12 ± 0.03	73 ± 13	0.46 ± 0.06	0.80 ± 0.27	9 ± 1
White spruce[1]										
Root - site 1	0.99	0.07	7.31	17	0.015	0.076	288	0.155	1.57	11
Shoot - site 1	1.00 ± 0.01	0.03 ± 0.09	2.89	32.3 ± 29.3	0.02 ± 0.01	0.10 ± 0.03	74 ± 14	0.25 ± 0.14	0.38 ± 0.06	0
Root - site 3	1	0.06	6.09	11	0.039	0.156	429	0.281	1.5	0
Shoot - site 3	1.00 ± 0.01	0.03 ± 0.01	3.41	10.0 ± 2.0	0.02 ± 0.01	0.12 ± 0.04	162 ± 96	0.29 ± 0.07	0.55 ± 0.12	0
Jack pine[1]										
Root - site 1	0.66 ± 0.18	0.04 ± 0.02	6.22	21.7 ± 8.4	0.03 ± 0.02	0.09 ± 0.01	193 ± 64	0.43 ± 0.06	1.03 ± 0.29	0
Shoot - site 1	0.99 ± 0.01	0.03 ± 0.03	2.73	36.0 ± 13.5	0.02 ± 0.01	0.13 ± 0.02	129 ± 9	0.35 ± 0.03	0.37 ± 0.15	0
Root - site 3	1.00 ± 0.01	0.03 ± 0.01	3	7.7 ± 1.2	0.02 ± 0.01	0.07 ± 0.03	136 ± 68	0.41 ± 0.08	0.58 ± 0.15	3 ± 0
Shoot - site 3	1.00 ± 0.01	0.02 ± 0.01	2.3	10.0 ± 1.7	0.02 ± 0.01	0.09 ± 0.03	128 ± 18	0.23 ± 0.02	0.47 ± 0.07	0
Red-osier dogwood[1]										
Root - site 1	0.94 ± 0.12	0.03 ± 0.01	3.1	49.0 ± 14.1	0.02 ± 0.01	0.20 ± 0.05	136 ± 26	0.44 ± 0.03	0.52 ± 0.04	0
Shoot - site 1	0.74 ± 0.18	0.03 ± 0.01	4.71	55.7 ± 14.6	0.02 ± 0.01	0.08 ± 0.01	42 ± 8	0.26 ± 0.02	0.91 ± 0.04	0
Root - site 3	1.00 ± 0.01	0.03 ± 0.01	3.2	12.0 ± 0.0	0.02 ± 0.01	0.15 ± 0.04	99 ± 21	0.33 ± 0.07	0.56 ± 0.07	0
Shoot - site 3	0.98 ± 0.03	0.04 ± 0.01	3.96	27.0 ± 3.6	0.02 ± 0.01	0.08 ± 0.02	47 ± 18	0.24 ± 0.04	1.06 ± 0.21	0
Bob birch[1]										
Root - site 1	1.00 ± 0.01	0.03 ± 0.01	2.91	21.0 ± 7.0	0.02 ± 0.01	0.10 ± 0.01	57 ± 27	0.24 ± 0.04	0.61 ± 0.11	0
Shoot - site 1	1.00 ± 0.01	0.03 ± 0.01	3.5	29.0 ± 8.9	0.02 ± 0.01	0.09 ± 0.01	74 ± 22	0.20 ± 0.04	0.88 ± 0.13	0
Root - site 3	0.94 ± 0.07	0.05 ± 0.02	4.89	8.0 ± 1.0	0.02 ± 0.01	0.08 ± 0.01	90 ± 34	0.22 ± 0.04	0.88 ± 0.24	0
Shoot - site 3	0.91 ± 0.13	0.04 ± 0.01	3.97	19.3 ± 10.3	0.03 ± 0.01	0.10 ± 0.05	61 ± 22	0.27 ± 0.15	1.21 ± 0.30	0
Normal range in plants				10 to 20	0.02 to 0.5	0.2 to 0.3	10 to 200	0.5 to 1	0.5 to 1	0.5

[1] seedlings planted in 2000 in the field and harvested after two growing seasons, [2] seedlings growing on tailings, [3] seedlings harvested in the field, 4 seedlings harvested in the greenhouse

Table GS-29-4: Elemental analysis of plant shoots, roots, stems and needles harvested from the field (sites 1, 2 and 3) and from the greenhouse. All values are in ppm, unless otherwise noted. (continued)

Samples	Cr	Mn	Fe (%)	Co	Cu	As	Se	Au (ppb)	Ag	Cd
Tamarack[1]										
Root - site 1	23.3 ± 2.1	28 ± 15	0.06 ± 0.02	11.9 ± 7.4	1135 ± 524	1.7 ± 2.3	2.0 ± 4.6	13.8 ± 18.6	5.6 ± 5.5	1.4 ± 0.3
Stem - site 1	23.3 ± 2.1	83 ± 19	0.02 ± 0.01	0.6 ± 0.1	147 ± 54	2.6 ± 0.2	13 ± 1	14.7 ± 9.5	0.4 ± 0.1	0.3 ± 0.1
Needles - site 1	36.7 ± 3.8	224 ± 17	0.02 ± 0.01	1.3 ± 0.9	37 ± 25	6.3 ± 2.6	23.7 ± 1.2	12.8 ± 4.6	0.7 ± 0.1	0.1
Root - site 3	45.7 ± 9.3	26 ± 13	0.03 ± 0.01	1.0 ± 0.9	719 ± 678	6.1 ± 1.3	32.7 ± 7.6	7.2 ± 1.7	0.4 ± 0.1	0.8 ± 0.5
Stem - site 3	44.7 ± 1.5	56 ± 16	0.03 ± 0.01	0.4 ± 0.1	103 ± 24	5.7 ± 0.3	30.3 ± 2.1	8.2 ± 0.9	0.4 ± 0.1	0.2 ± 0.1
Needles - site 3	56 ± 6.2	166 ± 86	0.02 ± 0.01	0.2 ± 0.1	35 ± 23	7.2 ± 0.7	38 ± 2.6	7.4 ± 0.4	0.6 ± 0.1	0.1
White spruce[1]										
Root - site 1	67	39	0.027	2.1	732	8.2	42	22	1.7	0.3
Shoot - site 1	0	50 ± 41	0.03 ± 0.01	0.5 ± 0.1	122 ± 15	0	0	10.3 ± 3.0	0.4 ± 0.1	0.1
Root - site 3	4	20	0.076	1.2	2.17	1.2	8	10.2	0.8	0.8
Shoot - site 3	4 ± 1.7	48 ± 18	0.06 ± 0.03	0.6 ± 0.2	99 ± 15	0	0	4.2 ± 0.8	0.5 ± 0.1	0.1
Jack pine[1]										
Root - site 1	8 ± 12.5	15 ± 10	0.06 ± 0.04	2.8 ± 1.4	915 ± 302	0.5 ± 2.2	4.3 ± 9	36.2 ± 24.6	5.5 ± 4.3	0.6 ± 0.1
Shoot - site 1	15.3 ± 3.5	37 ± 12	0.05 ± 0.01	0.8 ± 0.4	194 ± 82	1.4 ± 0.4	8.7 ± 2.1	20.1 ± 5.6	0.5 ± 0.1	0.1
Root - site 3	21.7 ± 1.2	12 ± 3	0.03 ± 0.01	0.9 ± 0.3	1722 ± 681	1.8 ± 0.3	12 ± 1.7	9.0 ± 3.0	0.3 ± 0.1	0.6 ± 0.3
Shoot - site 3	14.7 ± 6.1	36 ± 17	0.04 ± 0.01	0.4 ± 0.1	78 ± 34	0.5 ± 1.1	4.3 ± 5.5	5.8 ± 0.9	0.3 ± 0.1	0.2 ± 0.1
Red-osier dogwood[1]										
Root - site 1	0	85 ± 11	0.02 ± 0.01	9.8 ± 2.8	1297 ± 595	0	0	206.3 ± 75.7	1.2 ± 0.1	1.8 ± 0.1
Shoot - site 1	0	11 ± 3	0.02 ± 0.01	0.4 ± 0.1	82 ± 3	0	0	6.4 ± 2.6	0.4 ± 0.2	0.1
Root - site 3	0	67 ± 13	0.02 ± 0.01	1.4 ± 0.6	824 ± 428	0	0	6.8 ± 6.0	0.5 ± 0.1	1.1 ± 0.4
Shoot - site 3	1.33 ± 2.89	12 ± 2	0.02 ± 0.01	0.2 ± 0.1	28 ± 7	0	0	2.4 ± 1.0	0.3 ± 0.1	0.1
Bob birch[1]										
Root - site 1	0	16 ± 5	0.02 ± 0.01	2.3 ± 0.5	257 ± 58	0	0	58.0 ± 10.8	0.3 ± 0.1	0.3 ± 0.1
Shoot - site 1	0	57 ± 31	0.03 ± 0.01	3.8 ± 1	103 ± 15	0	0	7.4 ± 2.9	0.2 ± 0.1	0.3 ± 0.1
Root - site 3	0	21 ± 9	0.03 ± 0.01	0.9 ± 0.4	528 ± 218	0	0	10.1 ± 7.4	0.3 ± 0.1	0.5 ± 0.3
Shoot - site 3	0	100 ± 56	0.02 ± 0.01	1.7 ± 0.8	52 ± 22	0	0	5.3 ± 7.5	0.3 ± 0.1	0.4 ± 0.2
Normal range in plants	1.5 to 2	10 to 200	0.01 to 0.02	0.5 to 3	6 to 40	1 to 2	0.02 to 5	1 to 5	0.2 to 2	0.1 to 1

[1] seedlings planted in 2000 in the field and harvested after two growing seasons, [2] seedlings growing on tailings, [3] seedlings harvested in the field, 4 seedlings harvested in the greenhouse

Table GS-29-4: Elemental analysis of plant shoots, roots, stems and needles harvested from the field (sites 1, 2 and 3) and from the greenhouse. All values are in ppm, unless otherwise noted. (continued)

Samples	Pre-ash wt (g)	Ash wt (g)	Ash (%)	B	Na (%)	Mg (%)	Al	K (%)	Ca (%)	V
Yellow willow[1]										
Root - site 1	0.51 ± 0.11	0.02 ± 0.01	3.95	21.7 ± 5.0	0.04 ± 0.01	0.12 ± 0.04	87 ± 24	0.45 ± 0.13	0.87 ± 0.06	0
Shoot - site 1	0.55 ± 0.06	0.02 ± 0.01	4.02	120 ± 42	0.04 ± 0.01	0.18 ± 0.04	65 ± 23	0.41 ± 0.11	1.83 ± 0.27	0
White spruce[2]										
Root - site 1	0.91 ± 0.16	0.02 ± 0.01	2.54	21 ± 14	0.02 ± 0.01	0.06 ± 0.03	87 ± 9	0.33 ± 0.05	0.58 ± 0.13	0
Shoot - site 1	1.00 ± 0.01	0.05 ± 0.01	4.79	61 ± 42	0.02 ± 0.01	0.09 ± 0.08	141 ± 58	0.40 ± 0.07	4.39 ± 5.72	0
Horsetail[2]										
Root - near site 3	0.58 ± 0.22	0.06 ± 0.04	10.5	26.3 ± 2.5	0.20 ± 0.02	0.20 ± 0.03	284 ± 76	1.48 ± 0.16	1.24 ± 0.24	0
Shoot - near site 3	0.93 ± 0.12	0.16 ± 0.03	17.28	31.3 ± 4.5	0.13 ± 0.02	0.20 ± 0.04	130 ± 45	2.07	1.69 ± 0.16	0
Kentucky blue grass[2]										
Shoot - site 2	0.91 ± 0.14	0.06 ± 0.01	6.13	6.3 ± 1.2	0.04 ± 0.01	0.30 ± 0.06	158 ± 113	1.15 ± 0.07	0.32 ± 0.14	0
White mustard[3]										
Root - site 3 with peat	0.15 ± 0.01	0.01 ± 0.01	9.03	18 ± 1.7	0.11 ± 0.02	0.18 ± 0.02	488 ± 42	2.84 ± 0.21	1.43 ± 0.12	0
Shoot - site 3 with peat	0.75 ± 0.09	0.12 ± 0.01	15.25	22.7 ± 0.6	0.07 ± 0.01	0.41 ± 0.03	511 ± 55	2.39 ± 0.15	2.86 ± 0.15	0
Indian mustard[3]										
Root - site 3 with peat	0.13 ± 0.02	0.01 ± 0.01	7.94	19.3 ± 0.6	0.11 ± 0.01	0.19 ± 0.02	741 ± 115	2.08 ± 0.06	1.73 ± 0.06	24.67 ± 1.16
Shoot - site 3 with peat	0.79 ± 0.12	0.08 ± 0.02	10.33	27.7 ± 0.6	0.03 ± 0.01	0.31 ± 0.01	224 ± 27	1.39 ± 0.04	2.56 ± 0.05	4.33 ± 0.58
White mustard[4]										
Shoot - site 1 with peat	0.60 ± 0.17	0.08 ± 0.01	12.67	83 ± 15.6	0.42 ± 0.05	0.43 ± 0.02	28 ± 8	2.3 ± 0.25	2.86 ± 0.38	7.33 ± 4.16
Shoot - site 3 with peat	0.62 ± 0.26	0.08 ± 0.03	12.42	21.3 ± 1.2	0.37 ± 0.06	0.31 ± 0.03	23 ± 9	2.17 ± 0.25	2.10 ± 0.29	0
Indian mustard[4]										
Shoot - site 1 with peat	0.59 ± 0.18	0.06 ± 0.02	9.88	43.7 ± 2.5	0.12 ± 0.01	0.25 ± 0.02	16 ± 3	2.16 ± 0.11	2.04 ± 0.15	0
Shoot - site 3 with peat	0.46 ± 0.19	0.06 ± 0.02	11.93	27 ± 1	0.13 ± 0.01	0.29 ± 0.01	18 ± 5	2.44 ± 0.12	2.05 ± 0.14	0
Normal range in plants				10 to 20	0.02 to 0.5	0.2 to 0.3	10 to 200	0.5 to 1	0.5 to 1	0.5

[1] seedlings planted in 2000 in the field and harvested after two growing seasons, [2] seedlings growing on tailings, [3] seedlings harvested in the field, 4 seedlings harvested in the greenhouse

Table GS-29-4: Elemental analysis of plant shoots, roots, stems and needles harvested from the field (sites 1, 2 and 3) and from the greenhouse. All values are in ppm, unless otherwise noted. (continued)

Samples	Cr	Mn	Fe (%)	Co	Cu	As	Se	Au (ppb)	Ag	Cd
Yellow willow[1]										
Root - site 1	0	35 ± 8	0.06 ± 0.07	7.9 ± 5.8	473 ± 282	0	0	211 ± 170.9	0.8 ± 0.2	1.7 ± 0.7
Shoot - site 1	0	94 ± 37	0.03 ± 0.01	2.7 ± 0.6	152 ± 88	1.33 ± 0.587	0	16.4 ± 9.8	0.7 ± 0.1	1.7 ± 0.6
White spruce[2]										
Root - site 1	0	50 ± 34	0.03 ± 0.01	3.3 ± 1.9	664 ± 352	0	0	89.0 ± 22.6	1.9 ± 2.0	0.2 ± 0.1
Shoot - site 1	2 ± 3.6	87 ± 39	0.05 ± 0.02	1.4 ± 1.4	299 ± 183	0.47 ± 1.04	3.7 ± 1.2	29.5 ± 8.0	0.7 ± 0.1	0.2 ± 0.1
Horsetail[2]										
Root - near site 3	5.3 ± 8.9	62 ± 15	0.10 ± 0.03	5.6 ± 1.2	1010 ± 65	0.27 ± 2.00	2.3 ± 6.4	113 ± 16.5	0.6 ± 0.1	0.5 ± 0.1
Shoot - near site 3	9 ± 4.4	65 ± 4	0.05 ± 0.01	1.7 ± 0.3	88 ± 36	1.53 ± 0.61	6 ± 2	10.2 ± 5.6	0.3 ± 0.1	0.1
Kentucky blue grass[2]										
Shoot - site 2	13 ± 3	130 ± 12	0.06 ± 0.04	0.7 ± 0.4	120 ± 98	1.67 ± 0.35	6.3 ± 1.5	20.2 ± 11.9	0.4 ± 0.2	0.1
White mustard[3]										
Root - site 3 with peat	97 ± 13.4	30 ± 2	0.12 ± 0.01	1.1 ± 0.1	174 ± 15	10 ± 1.73	42 ± 7.9	39.7 ± 7.6	1.5 ± 0.3	0.4 ± 0.1
Shoot - site 3 with peat	33 ± 1.7	37 ± 3	0.14 ± 0.01	1.2 ± 0.1	139 ± 14	4.63 ± 0.55	20.3 ± 1.2	17.6 ± 9.1	0.5 ± 0.1	0.62 ± 0.10
Indian mustard[3]										
Root - site 3 with peat	206.3 ± 11.0	30 ± 3	0.17 ± 0.03	1.3 ± 0.2	197 ± 27	24.3 ± 3.5	97.3 ± 3.2	58 ± 5.3	3.4 ± 0.1	0.2 ± 0.1
Shoot - site 3 with peat	35.3 ± 3.8	17 ± 1	0.06 ± 0.01	0.5 ± 0.1	75± 8	4.7 ± 0.52	20.3 ± 2.1	8.2 ± 0.4	0.5 ± 0.1	0.3 ± 0.1
White mustard[4]										
Shoot - site 1 with peat	65.3 ± 36.1	39 ± 4	0.02 ± 0.01	0.8 ± 0.2	52 ± 12	9.33 ± 5.13	40 ± 21.6	9.8 ± 2.3	0.5 ± 0.1	0.4 ± 0.1
Shoot - site 3 with peat	35 ± 14	44 ± 22	0.02 ± 0.01	0.3 ± 0.1	34 ± 15	5.57 ± 1.91	31.3 ± 3.8	3.3 ± 2.4	0.5 ± 0.3	0.3 ± 0.1
Indian mustard[4]										
Shoot - site 1 with peat	24 ± 6.6	37 ± 7	0.02 ± 0.01	0.4 ± 0.1	29 ± 4	4.13 ± 0.81	28.3 ± 5.0	4.6 ± 1.2	0.6 ± 0.1	0.4 ± 0.1
Shoot - site 3 with peat	33.7 ± 13.1	36 ± 3	0.02 ± 0.01	0.2 ± 0.1	34 ± 8	5.67 ± 2.52	36.7 ± 14.3	1.8 ± 0.3	0.8 ± 0.3	0.3 ± 0.1
Normal range in plants	1.5 to 2	10 to 200	0.01 to 0.02	0.5 to 3	6 to 40	1 to 2	0.02 to 5	1 to 5	0.2 to 2	0.1 to 1

[1] seedlings planted in 2000 in the field and harvested after two growing seasons, [2] seedlings growing on tailings, [3] seedlings harvested in the field, 4 seedlings harvested in the greenhouse

FUTURE WORK

The focus of the field and greenhouse experiments in the coming growing season will be the determination of the best combination of different amendments to the tailings surface layer to increase the long-term survival rate of selected plant species. These amendments will include lime or limestone, to adjust the pH of the tailings, peat and humic substances. Revegetation of the tailings with selected grass species will be further investigated focusing on increasing the survival rate and biomass production and possibly identifying those species that accumulate metals effectively. The metal content in plants that survive three growing seasons will be measured to determine the most promising species for phytoremediation purposes. In addition, the Cu content of the plants that were treated with chelators will be determined. Copper is the most abundant heavy metal present in the studied tailings. The fast-growing native species, such as horsetail, willow, poplar and fireweed, will be studied for their ability to form a cost-effective bio-ore.

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