GS-21 PHYTOREMEDIATION OF MINE TAILINGS AND BIO-ORE PRODUCTION: RESULTS FROM A STUDY ON PLANT SURVIVAL AT THE CENTRAL MANITOBA (AU) MINESITE (NTS 52L/13)

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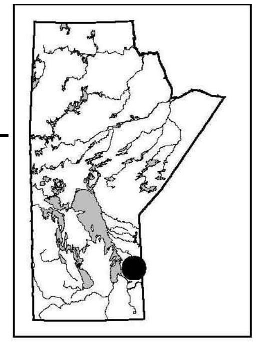

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SUMMARY

A new project to determine the potential for phytoremediation of mine tailings and production of bio-ores, through the identification of plant species that can accumulate heavy metals, was initiated in 2000 at the Central Manitoba (Au) minesite in southeastern Manitoba (Fig. GS-21-1). The first phase of the project involved planting seeds and/or seedlings of 14 plant species on three experimental sites on mine tailings. Preliminary results have shown that several plant species were able to survive and grow for two growing seasons on two of the three selected sites without any remediation of the soil. Capping of tailings with peat allowed survival of all seedlings for at least one growing season on all experimental sites, including one site with very high Cu and Au contents. The growth and survival of Indian mustard in this environment indicates high potential for phytoremediation and possibly phytomining for this species. The amount of extracted base and precious metals from plants growing on tailing sites for two growing seasons should identify plant species that are suitable for phytoremediation and the production of a bio-ore. Preliminary results from analyses of plants growing on tailings for one growing season indicate substantial enrichment in Au in pine and spruce seedlings and enrichment in Zn in willow.

INTRODUCTION

Mining and mineral-processing activities contribute significant quantities of heavy metals to the environment and affect surrounding land, air and water quality. These effects cannot be reversed by nature and require aggressive application of planned reclamation programs.

Metal mines across Canada produce large amounts of tailings that represent the waste products of mine operations. The decreased pH of the tailings, caused by oxidation in air under moist conditions, leads to increased solubility of most heavy metals. Metal mobilization from tailings can often be traced into watersheds downstream from active minesites. Low pH, presence of metals in toxic quantities and the lack of vegetative cover and organic nutrients prevent seed germination and plant growth. Tailings thus form large areas without vegetation cover (Fig. GS-21-2) and are a source of enormous dust production. This dust in turn pollutes vast areas adjacent to the tailings creating additional environmental and possible health hazards. 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 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 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. Plant species and techniques successfully used in tailings remediation could be used to successfully remediate other contaminated soil sites.

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.

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. Anderson et al. (1999) provides a list of hyperaccumulators under investigation. 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). Up to 57 mg/kg Au (dry mass) could be accumulated by Indian mustard (*Brassica juncea*) (Anderson et al., 1998) using induced hyperaccumulation by ammonium thiocyanate, which is biodegraded to ammonia, bicarbonate and sulphate. The choice of hyperaccumulators species must also be climate and site specific, and sensitive to regulations restricting the introduction of foreign species.

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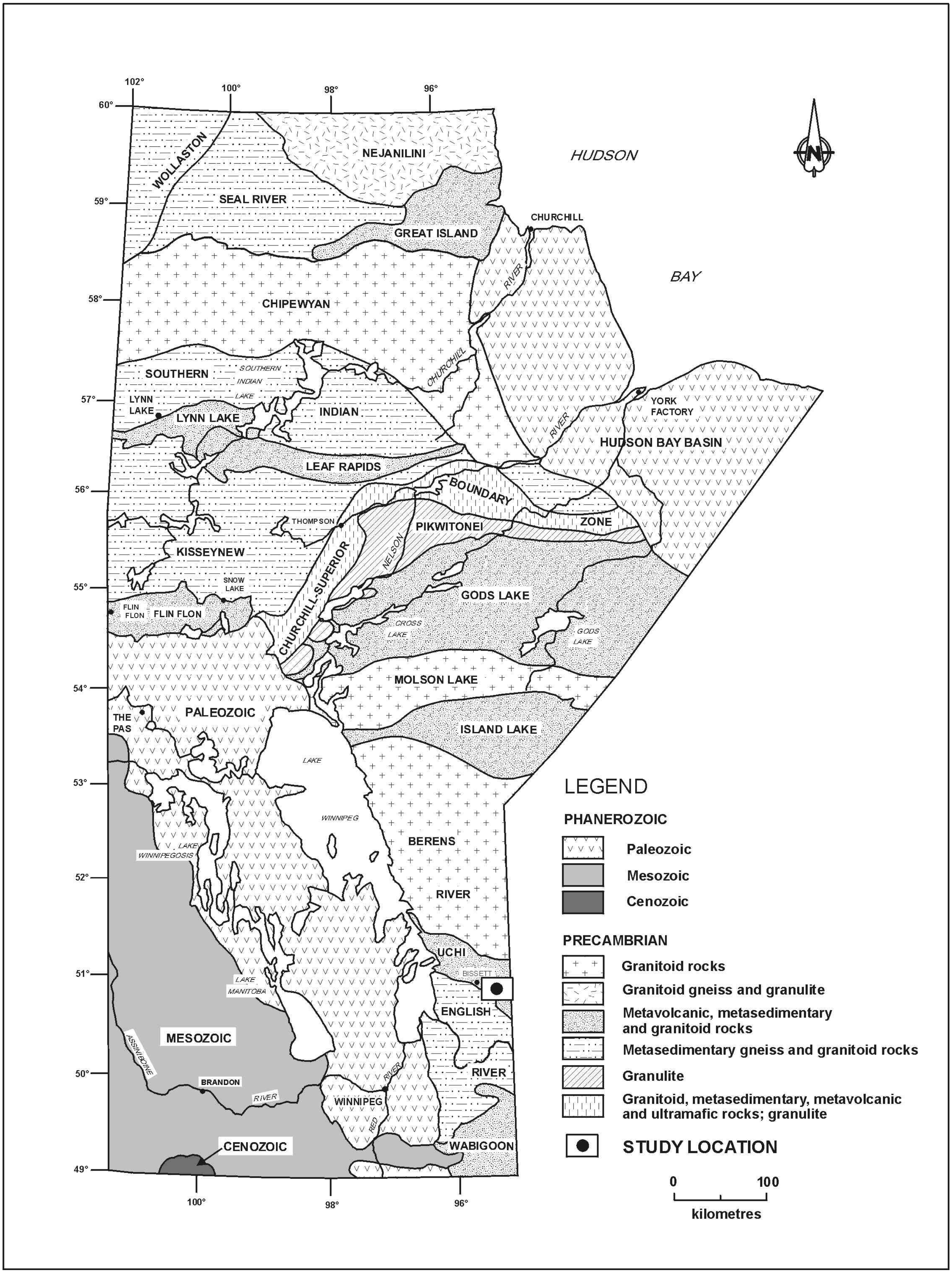

Figure GS-21-1: Location of the phytoremediation and phytomining study area, Central Manitoba gold mine, Bissett area, south-eastern Manitoba.

Figure GS-21-2: Central Manitoba gold mine tailings.

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 would 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 also be 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 gold deposit were selected for initial phytoremediation and phytomining studies. The deposit occurs within the Archean Rice Lake greenstone belt, in the Uchi Subprovince of the Superior Province in southeastern Manitoba (Fig. GS-21-1). The belt is flanked to the north by the Wanipigow River plutonic complex (Marr, 1971; Weber, 1971) and, to the south, is transitional with the Manigotagan gneissic belt (McRitchie and Weber, 1971; Weber, 1971). The Rice Lake belt is fault bounded by the Wanipigow Fault on the north and on the south by the Manigotagan Fault.

Host rocks to the deposit occur within the Bidou Lake subgroup (Poulsen et al., 1996) and comprise arkose, tuff and chert of the Dove Lake Formation. These sedimentary rocks have been intruded by gabbro sills. Gold-bearing quartz veins at the deposit are situated within en échelon shear zones at or close to the contact between the Dove Lake sedimentary rocks and an east-southeast-trending gabbro sill (Stockwell and Lord, 1939). Five veins contributed the bulk of production at the deposit. These were the Kitchener, Eclipse, No.1 Branch, Tene 6 and Hope veins. The quartz veins were mineralized with chalcopyrite, pyrite, pyrrhotite and free gold. Between 1928 and 1938, a total of 347 801 t of ore was milled and 4287 kg of gold produced.

GEOCHEMICAL CHARACTERIZATION OF THE 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 tailings 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 measured at the three experimental sites were 4 to 5 at site 1, 4 at site 2 and 5 to 7 at site 3.

Results of geochemical analyses of 20 tailings samples collected from three hand-augered profiles, each approximately 1 m in depth, were presented in Renault et al. (2000). The instrumental neutron activation analysis (INAA) total data indicate the relative base- and precious-metal enrichment in tailings at the minesite. In particular, Au was elevated in the upper 15 cm of the tailings profile at site 1 (3450 ppb), is consistently enriched throughout the profile at site 2 (1110–2640 ppb) and is somewhat lower but elevated at site 3 (265–958 ppb). Exceptional concentrations of Cu are documented from all three sites (834–5740 ppm at site 1, 1710–10 500 ppm at site 2 and 3150–4510 ppm at site 3). Additional enrichments of Ag (up to 6 ppm) and Bi (up to 127 ppm) are documented at site 1. Arsenic is low (<2-20 ppm) at all three sites.

RESULTS

Field Study: Plant Species Survival

Seedlings of native plant species of the boreal forest were selected for the study. In July 2000, the following tree species were planted on the three different sites described above: 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 June 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 June 2001, a layer of peat (5 cm deep) was added on the top of the tailings on site 2. Seeds of the following species were also planted 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*) and tall fescue (*Festuca alatior*).

Results showed that most tree seedlings were able to survive on sites 1 and 3 (Figs. GS-21-3 and -4), while they rapidly died on the untreated site 2 (Table GS-21-1). However, when peat was added on the top of the tailings or mixed with the

Figure GS-21-3: Seedlings growing on site 1 for two growing seasons.

Figure GS-21-4: Seedlings growing on site 3 for two growing seasons.

Table GS-21-1: Survival of seedlings planted on the tailings in July 2000 and June 2001. Measurements were done in September 2001.

	Survival (%)		
Plant species (planted in 2000)	**Site 1**	**Site 2**	**Site 3**
Jack pine	80	0	87
White spruce	83	0	100
Tamarack	100	0	100
Red-osier dogwood	93	0	80
Yellow willow	38	0	69
Bog birch	86	0	86
Plant species (planted in 2001)	**Site 1**	**Site 2** (with peat)	**Site 3**
Jack pine	55	87	95
White spruce	69	75	100
Red-osier dogwood	100	87	90
Yellow willow	69	50	92

tailings matter at site 2, the seedlings were still alive after three months (Table GS-21-1; Fig. GS-21-5). However, new root growth, a sensitive indicator of successful plant adaptation, was observed only on sites where the peat was not mixed with the heavy metal-rich tailings. Among the seedlings planted in 2000 at site 1, tamarack (Fig. GS-21-6) had the highest survival rate followed by red-osier dogwood, bog birch, white spruce, jack pine and willow (Table GS-21-1). Transpiration rates were measured in red-osier dogwood seedlings to estimate their level of stress (Fig. GS-21-7). Results indicated the importance of drainage conditions and sheltering effects of vegetation at the site, as well as the stress-inducing effect of very high metal contents in the soil.

Indian mustard and white mustard seeds germinated and survived in the field when peat was added on the top of the tailings (Table GS-21-2; Fig. GS-21-8). This is an important finding in light of the suitability of these species for phytoremediation and phytomining. Among the grass seeds tested, tall fescue, streambank wheatgrass and slender wheatgrass had the highest survival rates on the untreated sites (Table GS-21-2).

Several native plant species including manna grass (*Glyceria striata*) and horsetail (*Equisetum sp.*) were identified growing on the tailings. In addition, some fireweed (*Epilobium angustifolium*) plants were found growing on the tailings amended with peat. The metal-accumulating ability and suitability of these species for phytoremediation and phytomining purposes will be tested in future studies.

Greenhouse Study

Seeds of the following species were also 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. The trays were sprayed with distilled water regularly to keep moisture level relatively constant. Seeds of the selected species were also planted on tailings mixed with peat at a ratio of one to one.

Figure GS-21-5: Seedlings growing on site 2 after peat addition.

Germination and survival rates of seeds planted in the greenhouse on the collected tailing material showed similar trends as the field experiments (Table GS-21-3). However, survival rates in the greenhouse were higher, indicating the important role of climatic factors, such as water supply.

Elemental Analyses of Plant Tissues

Table GS-21-4 shows the elemental analyses of plant tissues. The results of the analyses of plant shoots harvested at sites 1 and 3 after one growing season, both in the field and greenhouse, are promising in terms of high metal accumulation by selected plant species. Results from analyses of spruce and pine shoots growing in the field and in the greenhouse indicate a relatively high accumulation rate of gold. Willow seedlings seem to be tolerant to the large amounts of zinc they accumulated during one growing season (Table GS-21-4). Available data also suggest high accumulation rates of Ni, As and Se by all tested species. However, only a few species and a limited number of samples were tested and more detailed study is necessary before any conclusion can be made regarding plant ability to accumulate metals of interest.

Figure GS-21-6: Tamarack growing on site 1 for two growing seasons.

FUTURE WORK

The focus of field 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. Newly identified plant species native to the environment and species with traits induced by adaptation processes derived from seeds collected near tailings will be used for further study. Metal content in plants surviving two growing seasons will be measured to determine the most promising species for phytoremediation purposes. Furthermore, different soil treatment that would enhance the biomass growth of Indian mustard (*Brassica juncea*) – a promising plant species for bio-ore formation – will be investigated. The native fast-growing species, such as horsetail, manna grass and fireweed will be studied for their ability to form a cost-effective bio-ore.

ACKNOWLEDGMENTS

We would like to thank Jennifer Mustard, Mila and Tony Sailer for fieldwork assistance.

Figure GS-21-7: Transpiration rate measurement at site 1.

Table GS-21-2: Survival of plants three months after seeding on tailings in the field.

	Survival (%)					
Plant species	**Site 1**	**Site 2**	**Site 3**	**Site 1** (with peat)	**Site 2** (with peat)	**Site 3** (with peat)
Indian mustard	0	0	0	25	8	49
White mustard	0	0	0	49	6	65
Altai wildrye	26	0	16	n.a.	8	n.a.
Slender wheatgrass	44	0	38	n.a.	1	n.a.
Reed canary grass	n.a.	n.a.	27	n.a.	n.a.	n.a.
Creeping foxtail	0	n.a.	21	n.a.	n.a.	n.a.
Streambank wheatgrass	29	n.a.	47	n.a.	n.a.	n.a.
Tall fescue	n.a.	n.a.	50	n.a.	n.a.	n.a.

Note: n.a. - not available

Figure GS-21-8: Indian mustard seedling growing on site 3 for one growing season.

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Table GS-21-3: Survival of plants three months after seeding on tailings in the greenhouse.

	Survival (%)					
Plant species	**Site 1**	**Site 2**	**Site 3**	**Site 1** (with peat)	**Site 2** (with peat)	**Site 3** (with peat)
Indian mustard	0	0	0	96	40	98
White mustard	0	0	0	100	50	98
Altai wildrye	96	0	67	n.a.	58	n.a.
Slender wheatgrass	89	0	40	n.a.	100	n.a.
Reed canary grass	38	n.a.	87	n.a.	n.a.	n.a.
Creeping foxtail	77	n.a.	88	n.a.	n.a.	n.a.
Streambank wheatgrass	94	n.a.	91	n.a.	n.a.	n.a.
Tall fescue	100	n.a.	100	n.a.	n.a.	n.a.

Note: n.a. - not available

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Table GS-21-4: Vegetation geochemical data for ashed samples collected from sites 1 and 3 at the study site and in the greenhouse. All values in ppm unless otherwise noted. A value of 999999 indicates a concentration greater than the range of the instrument. A negative value indicates a concentration less than the lower limit of determination.

Sample ID	Pre-ash wt (g)	Ash wt (g)	Ash (%)	Li	Be	B	Na (%)	Mg (%)	Al	Si	K (%)	Ca (%)	Sc	Ti	V	Cr	Mn	Fe (%)	Co	Ni
Plants growing in the field																				
D-site 1, planted	0.273	0.008	2.93	12	0.058	898	2.10	5.22	4,430	10,900	19.0	28.7	6.2	164	-6	-6	1,330	1.92	67.0	131
S-site 1, wild	0.946	0.068	7.19	15.0	0.046	432	0.23	0.868	6,000	2,530	8.37	23.1	4.0	142	6.2	1.1	2,520	2.46	19.1	94.6
S-site 1, planted	0.54	0.038	7.04	15.3	0.032	262	0.46	4.29	4,020	3,780	12.7	16.9	3.9	129	-1	-1	2,980	1.60	25.2	35.7
A-site 1, wild	0.924	0.075	8.12	5.1	0.011	411	0.23	0.937	1,930	2,230	7.77	29.8	2.1	56	1.1	-0.7	379	0.965	56.8	41.1
W-site 1, planted	0.372	0.023	6.18	8	0.024	506	0.83	3.91	2,530	4,690	13.2	19.4	3.0	98	-2	-2	2,860	1.13	29.3	40.8
W-site 1, wild	0.330	0.026	7.88	1	0.010	464	0.50	0.654	1,210	2,840	7.30	37.8	1.8	42	6	8	376	0.707	41.2	72.7
D-site 3, planted	0.274	0.015	5.47	3	0.020	204	0.78	2.23	4,700	6,600	5.03	26.4	4.3	114	13	19	425	1.91	16.9	54.6
P-site 3, planted	0.969	0.038	3.92	16.9	0.024	169	0.54	3.18	9,270	4,510	13.6	7.96	5.5	143	17	23	1,430	3.18	35.5	62.9
W-site 3, planted	0.394	0.020	5.08	4	0.012	195	0.68	3.21	3,550	4,200	10.4	26.9	2.9	85	10	14	1,000	1.49	18.1	60.1
Plants growing in the greenhouse																				
D-site 1	1.157	0.039	3.37	9.6	0.006	438	0.44	1.08	616	1,940	11.5	36.5	1.3	27	16	23	192	0.316	2.76	32.9
D-site 1	0.961	0.030	3.12	22.9	0.006	730	0.49	1.39	412	2,030	15.0	33.0	1.1	29	28	38	122	0.299	2.35	26.9
D-site 1	1.222	0.0276	2.26	4.8	-0.002	142	0.04	0.314	32.9	300	1.9	6.31	0.3	5	2.8	4.0	39.1	0.059	0.644	6.03
D-site 1	0.960	0.035	3.65	17.8	0.004	504	0.55	1.25	271	1,830	13.9	31.9	1.3	22	21	29	108	0.266	2.30	29.6
Wildrye-site 1	1.012	0.071	7.02	44.2	0.006	768	0.82	2.26	664	3,080	999999	12.5	2.1	29	12.1	16.7	250	0.317	3.43	13.0
Slender Wheatgrass-site 1	0.786	0.068	8.65	16.9	0.008	814	0.35	1.18	1,050	2,900	15.8	14.6	2.1	35	6.9	9.5	236	0.509	6.00	21.7
P-site 1	0.698	0.030	4.30	95.6	0.010	3,030	1.05	3.04	1,250	3,260	23.1	20.6	1.8	65	16	23	1,410	0.571	8.94	37.1
S-site 1	0.191	0.006	3.14	109	0.013	2,430	2.08	2.85	1,990	7,610	26.9	26.0	3.3	84	102	152	1,360	0.664	10.0	75.4
D-site 3	1.031	0.037	3.59	1.0	0.002	269	0.25	1.42	196	1,310	13.2	30.4	1.0	23	23	33	196	0.272	2.08	31.5
D-site 3	0.957	0.036	3.76	1.2	0.004	290	0.33	1.31	171	1,280	11.4	33.5	1.0	26	27	37	200	0.277	2.01	27.4
D-site 3	0.996	0.045	4.52	1.4	0.006	280	0.31	1.86	294	1,460	14.4	29.6	1.1	33	21	31	280	0.303	2.51	25.8
D-site 3	1.009	0.029	2.87	2.2	0.007	375	0.54	1.42	279	2,180	14.9	31.6	1.2	35	30	42	269	0.260	2.24	43.9
Wildrye-site 3	1.030	0.064	6.21	5.3	0.011	92	1.14	1.43	999	2,440	999999	11.0	1.9	53	11.1	15.0	318	0.381	4.42	17.2
Slender Wheatgrass-site 3	0.896	0.070	7.81	3.5	0.010	105	0.47	0.869	1,400	2,360	21.4	14.0	1.8	49	6.6	8.6	328	0.655	6.52	17.6
P-site 3	0.725	0.024	3.31	10	0.011	359	0.88	2.15	1,530	3,340	18.9	21.6	1.8	76	20	29	1,860	0.664	5.68	35.2
S-site 3	0.099	0.002	2.02	24	0.06	616	4.2	3.90	3,310	16,200	30.3	44.1	8	172	351	503	3,110	0.95	10.2	168
Control material V7A				4.4	0.454	254	0.10	3.50	4,790	4,020	11.3	19.3	2.8	234	4.3	4.3	11,300	3.09	54.3	1,680
Standard reference data V7A				**4.6**	**0.52**	**198**	**0.10**	**4.07**	**5,125**	**553**	**10.1**	**21.2**	**2.3**	**362**	**8.3**	**10.5**	**10,077**	**1.46**	**48.8**	**1,451**
+/-				**2.0**	**0.16**	**93**	**0.02**	**0.949**	**1,170**	**386**	**1.94**	**4.37**	**1.7**	**69**	**2.8**	**5.5**	**1,799**	**0.321**	**5.67**	**201**

D-dogwood, S-white spruce, A-aspen, W-willow, P-jack pine

Table GS-21-4: Vegetation geochemical data for ashed samples collected from sites 1 and 3 at the study site and in the greenhouse. All values in ppm unless otherwise noted. A value of 999999 indicates a concentration greater than the range of the instrument. A negative value indicates a concentration less than the lower limit of determination. (continued)

Sample ID	Cu	Zn	Ga	Ge	As	Se	Rb	Sr	Y	Zr	Nb	Mo	Pd (ppb)	Ag	Cd	In (ppb)	Sn	Sb	Te	Cs
Plants growing in the field																				
D-site 1, planted	8,270	620	0.602	-0.006	76	-6	53.6	755	9.93	28.4	0.784	8.00	-19	26.2	3.38	132	-6	0.416	15.7	0.267
S-site 1, wild	8,430	501	2.30	0.172	11.7	24.6	20.0	565	9.03	4.78	0.917	4.18	57	9.75	1.89	131	2	0.476	19.9	0.236
S-site 1, planted	5,910	938	1.75	0.060	5	5	78.3	781	6.29	6.70	0.695	11.0	103	9.62	1.51	83.2	-1	0.336	13.9	0.339
A-site 1, wild	3,820	693	0.689	0.084	16.8	57.7	13.3	193	1.62	4.75	0.797	2.77	57	3.22	15.2	33.7	-1	0.223	6.43	0.058
W-site 1, planted	2,900	1,570	0.815	-0.002	4	8	43.2	391	3.91	13.1	0.509	3.11	-7	9.40	20.1	58.6	-2	0.355	8.79	0.230
W-site 1, wild	1,330	1,780	0.093	-0.002	28	103	5.71	189	1.80	12.8	0.954	2.84	-6	5.65	57.0	25.4	-2	0.140	4.37	0.049
D-site 3, planted	1,780	426	0.800	-0.003	17	69	16.1	436	1.37	13.9	0.712	6.53	-10	15.6	1.86	58.2	-3	0.249	8.34	0.152
P-site 3, planted	3,700	421	2.50	0.438	5	17	343	118	2.31	5.62	0.731	6.38	91	9.55	4.34	116	-1	0.283	8.94	0.395
W-site 3, planted	1,500	980	0.814	-0.003	17	77	74.9	397	1.13	12.0	0.738	4.00	-8	8.38	22.0	44.8	-3	0.193	6.50	0.300
Plants growing in the greenhouse																				
D-site 1	200	281	0.512	0.366	41	140	15.7	313	0.164	7.27	1.08	2.53	95	5.05	0.445	9.43	-1	0.103	3.46	0.073
D-site 1	155	245	0.143	0.114	49	172	14.4	255	0.127	6.32	0.898	2.35	-5	3.71	0.518	4.15	-2	0.131	3.01	0.044
D-site 1	45.6	46.3	0.067	0.061	7.6	27.2	2.82	37.3	0.006	0.700	0.084	0.303	11	-0.04	0.146	3.04	-2	0.018	0.507	0.010
D-site 1	169	305	0.364	0.373	42	142	15.1	264	0.124	10.7	0.899	2.79	128	5.73	0.562	7.69	-1	0.234	2.56	0.036
Wildrye-site 1	519	388	0.481	0.466	19.2	68.1	43.2	290	0.315	7.38	0.412	2.90	78	1.41	7.36	15.4	-1	0.157	4.25	0.061
Slender Wheatgrass-site 1	733	320	0.434	0.268	15.2	51.1	17.6	179	0.526	3.97	0.421	7.17	47	3.43	3.81	15.1	-1	0.154	4.71	0.041
P-site 1	871	1,180	0.471	-0.002	26	97	31.4	136	0.478	18.7	0.616	10.2	68	7.37	9.84	15.8	-2	0.275	3.74	0.051
S-site 1	1,280	798	0.361	-0.008	79	302	38.8	844	0.875	59.6	0.499	17.9	-25	28.5	3.29	28.6	-8	0.405	11.3	0.073
D-site 3	137	363	0.482	0.650	40	141	18.8	278	0.094	7.33	0.936	4.73	90	3.25	0.324	6.31	-1	0.077	3.24	0.049
D-site 3	116	176	0.513	0.640	48	179	23.4	355	0.078	8.90	1.05	5.64	111	4.10	0.352	6.49	-1	0.098	3.54	0.081
D-site 3	222	265	0.495	0.444	40	146	21.4	251	0.186	7.31	0.915	6.35	86	3.83	0.317	8.16	-1	0.107	3.47	0.093
D-site 3	181	437	0.165	0.146	47	158	18.3	269	0.117	11.3	0.890	4.71	-5	3.23	0.618	1.10	-2	0.095	3.00	0.062
Wildrye-site 3	702	276	0.647	0.500	16.8	61.2	67.7	135	0.731	9.42	0.426	7.74	133	2.90	3.54	20.8	-1	0.148	5.00	0.152
Slender Wheatgrass-site 3	967	259	0.652	0.298	14.1	51.9	37.1	115	0.901	7.08	0.456	14.2	94	2.93	2.47	21.3	-1	0.157	7.91	0.140
P-site 3	1,230	583	0.548	-0.002	28	110	39.9	118	0.808	21.5	0.638	45.0	98	5.80	5.86	22.5	-2	0.277	7.48	0.115
S-site 3	995	1,090	1.95	-0.03	264	945	59.9	965	1.50	157	0.78	192	-75	72.8	3.8	57.7	-25	13.2	23.1	0.12
Control material V7A	457	2,340	3.23	0.586	9.6	29.4	435	1,860	4.71	1.58	1.42	2.17	85	1.79	1.62	14.6	2	0.590	0.762	1.30
Standard reference data V7A	**394**	**1,709**	**2.70**	**0.143**	**11.9**	**39.9**	**421**	**1,735**	**4.86**	**0.488**	**0.600**	**1.52**	**82**	**1.81**	**1.50**	**14.9**	**-1**	**0.240**	**1.26**	**1.39**
+/-	**68**	**368**	**1.22**	**0.116**	**4.80**	**14.4**	**74.3**	**304**	**0.383**	**0.436**	**0.074**	**0.143**	**15**	**0.09**	**0.189**	**2.12**	**-**	**0.044**	**0.459**	**0.111**

D-dogwood, S-white spruce, A-aspen, W-willow, P-jack pine

Table GS-21-4: Vegetation geochemical data for ashed samples collected from sites 1 and 3 at the study site and in the greenhouse. All values in ppm unless otherwise noted. A value of 999999 indicates a concentration greater than the range of the instrument. A negative value indicates a concentration less than the lower limit of determination. (continued)

Sample ID	**Ba**	**La**	**Ce**	**Pr**	**Nd**	**Sm**	**Eu**	**Gd**	**Tb**	**Dy**	**Ho**	**Er**	**Tm**	**Yb**	**Lu**	**Hf**	**Ta**	**W**	**Re (ppt)**
Plants growing in the field																			
D-site 1, planted	841	19.3	97.2	6.41	26.5	5.44	1.22	5.07	0.595	2.56	0.419	1.04	0.119	0.807	0.174	0.651	0.007	-0.6	26,600
S-site 1, wild	139	17.7	42.1	5.08	21.6	4.20	0.878	4.10	0.485	2.08	0.346	0.867	0.093	0.599	0.110	0.175	0.008	1.0	44,200
S-site 1, planted	860	10.1	32.7	2.99	12.7	2.55	0.665	2.71	0.308	1.39	0.234	0.607	0.077	0.655	0.169	0.182	0.007	0.7	10,100
A-site 1, wild	77.8	1.90	9.41	0.482	2.02	0.398	0.103	0.483	0.061	0.288	0.052	0.143	0.019	0.146	0.036	0.120	0.002	0.4	23,500
W-site 1, planted	418	7.50	41.4	2.16	8.71	1.74	0.397	1.78	0.195	0.854	0.143	0.360	0.042	0.309	0.075	0.290	0.003	0.4	14,100
W-site 1, wild	244	3.54	33.4	1.07	4.29	0.856	0.198	0.993	0.097	0.419	0.069	0.182	0.022	0.177	0.057	0.304	-0.002	-0.2	11,200
D-site 3, planted	468	0.754	33.9	0.273	0.815	0.184	0.109	0.426	0.042	0.233	0.048	0.139	0.023	0.204	0.065	0.290	-0.003	0.5	12,900
P-site 3, planted	198	0.983	12.9	0.292	1.19	0.290	0.106	0.474	0.064	0.399	0.080	0.232	0.035	0.272	0.062	0.124	0.002	2.1	17,700
W-site 3, planted	415	0.815	30.9	0.279	0.824	0.186	0.092	0.406	0.037	0.197	0.037	0.113	0.017	0.179	0.058	0.246	-0.003	0.6	2,970
Plants growing in the greenhouse																			
D-site 1	222	0.298	15.8	0.113	0.259	0.055	0.042	0.207	0.011	0.040	0.006	0.018	0.004	0.087	0.042	0.156	-0.001	0.3	12,300
D-site 1	165	0.170	11.8	0.067	0.164	0.038	0.034	0.155	0.008	0.024	0.004	0.012	0.003	0.055	0.026	0.140	-0.002	-0.2	6,350
D-site 1	19.1	0.021	1.60	0.011	0.027	0.005	0.003	0.021	-0.002	0.003	-0.002	0.002	-0.002	0.008	0.004	0.017	-0.002	-0.2	-2
D-site 1	297	0.161	24.3	0.109	0.157	0.032	0.050	0.294	0.010	0.024	0.004	0.011	0.005	0.097	0.051	0.216	0.002	0.4	5,560
Wildrye-site 1	349	0.290	17.6	0.116	0.291	0.060	0.063	0.230	0.014	0.053	0.011	0.032	0.009	0.141	0.059	0.169	0.002	0.3	255,000
Slender Wheatgrass-site 1	270	0.417	12.6	0.135	0.430	0.102	0.057	0.223	0.019	0.082	0.017	0.048	0.010	0.129	0.046	0.085	0.001	0.3	179,000
P-site 1	564	0.712	69.2	0.354	0.675	0.134	0.106	0.698	0.030	0.089	0.017	0.050	0.012	0.203	0.099	0.436	-0.002	-0.2	190,000
S-site 1	1,290	0.883	141	0.606	0.846	0.189	0.176	1.08	0.044	0.152	0.028	0.084	0.020	0.319	0.150	1.35	-0.008	-0.8	186,000
D-site 3	224	0.122	15.3	0.069	0.104	0.025	0.039	0.194	0.007	0.014	0.003	0.008	0.004	0.086	0.038	0.154	0.002	0.5	7,660
D-site 3	280	0.114	18.8	0.077	0.086	0.019	0.047	0.228	0.007	0.013	0.003	0.007	0.004	0.103	0.050	0.182	0.002	0.3	4,790
D-site 3	216	0.215	15.6	0.087	0.185	0.040	0.041	0.204	0.009	0.031	0.006	0.019	0.005	0.094	0.041	0.156	0.001	0.3	10,700
D-site 3	384	0.151	29.3	0.120	0.134	0.025	0.064	0.314	0.010	0.017	0.003	0.012	0.005	0.120	0.058	0.248	-0.002	-0.2	9,720
Wildrye-site 3	513	0.660	30.4	0.251	0.687	0.150	0.109	0.464	0.030	0.124	0.024	0.069	0.016	0.241	0.094	0.213	0.003	0.4	498,000
Slender Wheatgrass-site 3	388	0.876	18.9	0.270	0.969	0.198	0.100	0.397	0.036	0.162	0.030	0.087	0.016	0.207	0.073	0.170	0.002	0.5	447,000
P-site 3	522	0.968	66.3	0.408	1.01	0.204	0.110	0.642	0.038	0.145	0.027	0.079	0.015	0.191	0.084	0.475	-0.002	0.3	463,000
S-site 3	2,690	2.02	320	1.34	1.96	0.40	0.37	2.68	0.09	0.26	0.04	0.14	0.04	0.69	0.37	3.54	-0.03	3	593,000
Control material V7A	242	24.2	28.5	2.51	7.57	1.05	0.248	1.31	0.149	0.693	0.124	0.330	0.039	0.282	0.042	0.046	0.024	0.2	6,660
Standard reference data V7A	**423**	**25.8**	**30.3**	**2.64**	**7.98**	**1.20**	**0.295**	**1.48**	**0.161**	**0.712**	**0.127**	**0.349**	**0.039**	**0.228**	**0.033**	**0.026**	**0.007**	**0.3**	**7,650**
+/-	**467**	**3.81**	**6.94**	**0.189**	**0.541**	**0.101**	**0.051**	**0.196**	**0.014**	**0.052**	**0.010**	**0.028**	**0.003**	**0.020**	**0.004**	**0.018**	**0.006**	**0.1**	**901**

D-dogwood, S-white spruce, A-aspen, W-willow, P-jack pine

Table GS-21-4: Vegetation geochemical data for ashed samples collected from sites 1 and 3 at the study site and in the greenhouse. All values in ppm unless otherwise noted. A value of 999999 indicates a concentration greater than the range of the instrument. A negative value indicates a concentration less than the lower limit of determination. (continued)

Sample ID	**Pt (ppb)**	**Au (ppb)**	**Tl**	**Pb**	**Bi**	**Th**	**U**
Plants growing in the field							
D-site 1, planted	-13	642	0.277	29.4	39.7	0.454	0.374
S-site 1, wild	9	971	0.276	29.3	46.0	0.450	0.336
S-site 1, planted	5	310	0.349	18.1	27.9	0.353	0.657
A-site 1, wild	4	484	0.161	10.1	13.5	0.154	0.387
W-site 1, planted	-4	343	0.123	10.7	23.3	0.229	0.116
W-site 1, wild	-4	174	0.009	7.01	8.66	0.125	0.065
D-site 3, planted	-7	91	0.082	32.1	32.4	0.095	0.095
P-site 3, planted	8	123	0.412	44.1	44.8	0.137	0.077
W-site 3, planted	-5	93	0.125	26.9	21.4	0.122	0.162
Plants growing in the greenhouse							
D-site 1	5	141	0.020	2.68	1.13	0.060	0.033
D-site 1	-3	65	0.031	3.28	1.43	0.036	0.020
D-site 1	-4	8	0.005	0.32	0.08	0.004	0.006
D-site 1	4	125	0.057	8.23	1.12	0.034	0.030
Wildrye-site 1	3	50	0.035	4.92	5.00	0.056	0.127
Slender Wheatgrass-site 1	-2	123	0.031	5.05	6.07	0.095	0.274
P-site 1	5	253	0.038	8.79	7.48	0.088	0.220
S-site 1	-17	1,580	0.073	16.9	14.7	0.139	0.414
D-site 3	-3	-3	0.041	4.27	0.80	0.026	0.016
D-site 3	4	4	0.024	3.13	0.55	0.022	0.058
D-site 3	5	6	0.034	4.22	1.51	0.047	0.090
D-site 3	-3	5	0.068	4.37	0.88	0.026	0.027
Wildrye-site 3	3	30	0.056	14.5	6.13	0.156	0.277
Slender Wheatgrass-site 3	-2	34	0.066	17.5	8.11	0.218	0.353
P-site 3	-4	122	0.089	23.4	10.2	0.176	0.186
S-site 3	70	232	0.31	224	23.1	0.37	0.40
Control material V7A	44	8	**0.023**	23.0	0.06	0.517	0.411
Standard reference data V7A	**40**	**11**	**0.023**	**22.9**	**0.18**	**0.522**	**0.394**
+/-	**16**	**8**	**0.009**	**2.1**	**0.14**	**0.048**	**0.031**

D-dogwood, S-white spruce, A-aspen, W-willow, P-jack pine