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Soil capping and vegetation trials on waste rock at Cameco Key Lake uranium mine

L.A. Leskiw *Paragon Soil and Environmental Consulting, Canada*

C. Qualizza *Paragon Soil and Environmental Consulting, Canada*

J.D. Zettl *University of Saskatchewan, Canada*

S.L. Barbour *University of Saskatchewan, Canada*

Abstract

Reclamation and revegetation of the Deilmann North Waste Rock Pile (DNWRP) is needed to create a sustainable landscape with stable slopes and a forest cover with diversity that resembles the natural uplands in the area. In addition to providing a suitable landscape, the cover needs to minimise deep percolation of precipitation and the resulting seepage from the underlying waste rock. A research site was established on a waste rock pile at Cameco's Key Lake Mine in Northern Saskatchewan. Test plots to evaluate the efficacy of eight soil amendments to store water and support eight types of boreal forest plants were located within a trial soil cover constructed of locally available sandy glacial till. Two methods of transplanting native moss species were also evaluated. The soil amendments included commercial peat, lake sediments, underlying straw/hay, mulch + forest floor (LFH) layer, inorganic fertiliser, organic pellets and control plots. The surface soil of each plot was sampled for baseline characterisation of soil salinity, pH, soluble ions, available nutrients, total carbon and nitrogen, metals regulated by the Canadian Council of Ministers of the Environment (CCME), cation exchange capacity (CEC) and texture in fall of 2010. Vegetation was planted in September of 2010 and will be monitored for growth characteristics. Preliminary findings include the following: (a) the cover soils have very low nutrient contents and moisture holding capacities; (b) the lake sediment has high total and available nutrients and water holding capacity, but elevated arsenic (As) and nickel (Ni) concentrations; (c) the use of specialised amendments such as straw, lake sediments and peat moss showed a potential to improve water storage within the sandy cover material.

1 Introduction

Creation of adequate soil nutrient and moisture regimes is a prerequisite for successful and sustainable land reclamation and revegetation. Waste rock from uranium mines in northern Saskatchewan is deposited in above ground dumps. Reclamation of these dumps is challenging since available cover soils are coarse textured with soil quality (nutrients) and moisture storage limitations and the conventional approach of direct planting of seedlings onto monolithic cover soils are often unsuccessful. The net percolation into these dumps is also high leading to concerns regarding leaching of dissolved contaminants (Carey et al., 2005). Natural forest ecosystems in the area have established sustainable soil nutrient and moisture conditions (Chapin et al., 1988) by creating suitable hydrological conditions, sufficient soil organic matter and a forest floor community including mosses, lichens and shrubs.

The general objective of this study was to evaluate methods of rapidly establishing comparable nutrient and moisture regimes through the use of amendments. The specific study objectives include the following: (a) evaluate the efficacy of eight soil treatments on revegetation success for eight boreal forest plants; (b) evaluate two methods for transplanting a native moss species (*Polytrichum Sp.*) onto reclaimed soil materials; (c) evaluate the success of transplanting boreal trees and shrubs and (d) evaluate the soil water retention of amended cover soils.

2 Methods

2.1 Site description

The study site is located on the Deilmann North Waste Rock Pile (DNWRP) at Cameco's Key Lake Operation in northern Saskatchewan. DNWRP is an 81 ha out-of-pit waste rock pile constructed between 1984 and 1997 and is composed of approximately 23% sand/till, 47% sandstone and 30% basement rock (by volume). The sand and till are glacially derived sediments originating from the Athabasca Sandstone. Basement rock refers to the mined formation and is predominantly granite with traces of graphite and pyrite. During excavation, the natural sequence of glacial outwash and sandstone overlying basement rock is reversed so that the basement rock is near the surface of the DNWRP.

2.2 Study design

A 1.25 ha trial cover, nominally 1 m in thickness, was constructed on the plateau of the DNWRP in 2010 using glacial till excavated from a nearby drumlin. Three blocks of test plots (A, B, and C) were added to the trial cover with each block divided into seven random soil amendment test plots and one control plot. Each 9 × 9 m test plot was further sub-divided into nine vegetation subplots (2 × 2 m) with a one meter wide buffer zone between each subplot as well as between the edges of each test plot. The following treatments were then applied to the individual plots: Control (C), Commercial peat (CP), Lake sediments (LS), Underlying flax straw (UFS), LFH/mineral (includes the organic litter plus underlying mineral soil), conventional fertiliser treatment (NPK), Organic pellets (OP), and "Demonstration" plots (Demo) (Figure 1).

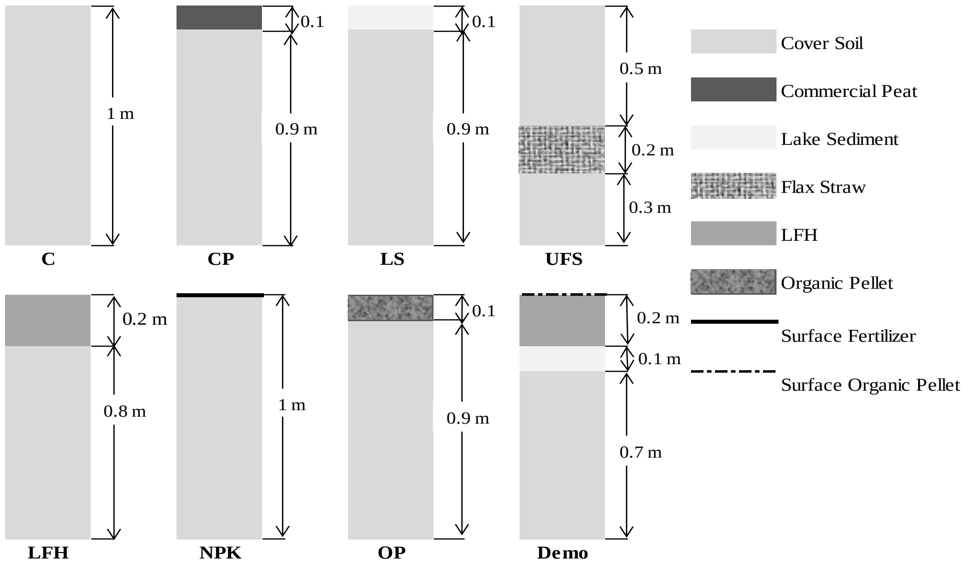

Figure 1 Schematic of simulated treatment profiles. Treatments include control (C), commercial peat (CP), lake sediment (LS), underlying flax straw (UFS), forest floor (LFH), conventional fertiliser (NPK), organic pellets (OP) and demonstration (Demo)

Soil samples were taken in the fall of 2010 to characterise the initial soil conditions. Three samples of the topsoil obtained randomly from each treatment plot for each block were composited to yield a single sample for each treatment. Topsoil was obtained from the 0–10 cm depth increment for all treatment plots except LFH/mineral, where the sample was taken from the 0–20 cm zone due to the depth of the amendment. Samples were kept cool and transported to Exova Laboratories in Edmonton, Alberta. Samples were analysed for: (a) salinity [pH, electrical conductivity (EC), sodium adsorption ratio (SAR), calcium (Ca), magnesium (Mg), sodium (Na), chloride (Cl)], (b) available nutrients [nitrate (NO_3), ammonium (NH_4), phosphorus (P), potassium (K), sulphate (SO_4), copper (Cu), iron (Fe), manganese (Mn), zinc (Zn)], (c) total carbon and nitrogen, (d) CCME metals (strong acid digestible + hot water soluble boron), (e) cation exchange capacity, and (f) soil texture.

2.3 Soil treatment description

Following is a description of soil treatments:

1. C – no soil amendments; comprised of the stony, sandy, glacial till used to form the subsoil layer of the entire test plot.
2. CP – peat moss spread to depths ranging from approximately 6 to 12 cm and incorporated into the top 10 cm with two rototiller passes. Commercial bagged peat moss (Sunshine Peat) was used for this trial.
3. LS – 6–10 cm of lake sediments incorporated into the surface resulting in approximately 1:1 sediment: subsoil ratio. Lake sediments were obtained from lakes drained during mining activities and have higher clay and organic matter contents ranging from organically dominated deposits to beds containing silt loam and clay.
4. UFS – incorporated a capillary break at a depth of 40–50 cm created using a layer of ~ 20 cm thick flax straw.
5. LFH – mulched (LFH, Ae and Bm) materials were imported for the LFH treatment from an area that had been cleared as part of an ongoing expansion and development at Key Lake Operations. This material is rich in plant propagules, soil microorganisms and nutrients. Nominal depth was 20 cm although application depths were highly variable. LFH/mineral material was not incorporated into the subsoil (no rototilling). Vegetation was planted directly into the surface layer.
6. NPK – 18-24-11 (NPK) fertiliser was applied at 400 kg/ha by hand using a belly seeder and was not incorporated into the surface soil (i.e. no rototilling).
7. OP – organic pellets (heat treated, dried and pelletised feedlot manure) were broadcast on the surface (20 tonnes/ha) using a fertiliser spreader and were then incorporated into the top 10 cm of subsoil material with a rototiller.
8. Demo-evaluation of multiple amendments and vegetation planting in communities. The plots were constructed as a layered system composed of sandy subsoil overlain by a ~ 10 cm thick layer of lake sediment, overlain by 20 cm thick layer of LFH/mineral. Organic pellets applied at 1/3 the rate for the OP treatment (6.7 T/ha). Pellets were not incorporated on the Demo plots (i.e. no rototilling).

2.4 Revegetation treatment description

The vegetation subplots (2 × 2 m) were laid out randomly within each soil plot and included: (i) Moss 1 (*Polytrichum Sp.*) prepared by chopping live moss in a blender; (ii) Moss 2 (*Polytrichum Sp.)* prepared by feeding live moss through a wood chipper; (iii) Jack Pine (*Pinus banksiana*); (iv) Bearberry (*Arctostaphylos uva-ursi*); (v) Blueberry (*Vaccinium myrtilloides*); (vi) Birch (*Betula papyrifera*); (vii) Willow cuttings (*Salix bebbiana, Salix pseudomonticola* and *Salix exigua*); (viii) Alder (*Alnus viridus spp. crispa*); and (ix) Aspen (*Populus tremuloides*). Seedlings were planted on each vegetation plot using standard silviculture techniques. All seedlings were watered (approximately 1–2 L per plant) following planting. Watering was necessary on the peat and LFH/mineral treatments.

2.5 Evaluation of soil physical properties and water storage

The available water holding capacity (AWHC), defined as the difference between field capacity (FC) and permanent wilting point (PWP), was estimated using five approaches (AWHC 1–5). In AWHC 1, drainage of laboratory columns were used to evaluate the field capacity of a range of different capillary break materials including flax straw. A double ring infiltrometer test was also undertaken on the DNWRP cover in the fall of 2010 (AWHC 2) in drainage of a field saturated wetting front was used to establish field capacity conditions. A permanent wilting point of 30 mm/m estimated from soil texture (Vereecken et al., 1989) was used to estimate AWHC (Zettl, 2011). The AWHC three estimates were obtained using the Land Capability Classification System (LCCS) (CEMA, 2006). The LCCS is a system developed as a tool for assessing land capability of reclaimed lands in the in the oil sands region of northern Alberta, which like the study sites is also located in the Boreal forest.

For AWHC 4 each profile was estimated using the water contents estimated using the Rawls et al. (1982) equation describing soil water contents at a particular suction as a function of soil texture. The water content at 10 kPa was used for FC and at 1,500 kPa for PWP. The soil beneath each of the amendments was assumed to be the same texture and thus have the same water storage capacity as the C treatment. The Rawls et al. (1982) equation is shown:

$$\Theta_P = a + b(\%\ \text{sand}) + c(\%\ \text{silt}) + d(\%\ \text{clay}) + e(\%\ \text{organic matter}) + f(\text{bulk density}) \qquad (1)$$

The % organic matter was estimated to be 1.70 times the % organic carbon (Dane and Topp, 2002). A bulk density of 1.69 $Mg.m^{-3}$ for C was measured by Zettl (2011) and was assumed for all soils. The regression coefficients (a, b, c, d, e, and f) can be found in Rawls et al. (1982).

AWHC 5 relied on numerical simulations of FC. The water retention curves (WRC) for each material were estimated using Equation (1). The ROSETTA neural network model (ROSETTA, 1999) was used to estimate the saturated hydraulic conductivity and van Genuchten (1980) method was used to estimate the hydraulic conductivity function. The flax straw layer is not amenable to estimation methods based on texture; consequently this layer was assigned the hydraulic properties of well-drained gravel. The soil beneath each amendment layer was assumed to have the same hydraulic properties as C. The lake sediment layer (20 to 30 cm depth) in the Demo profile was assigned the hydraulic properties of the top of the LS profile. The surface organic pellets were not modelled as separate layers. For these profiles, the sampled top soil was used to calculate the hydraulic parameters for the amendment layers as in all other simulations.

All simulations were 2 m in depth and had a vertical grid spacing of 0.02 m. For each simulation, the profile was initially saturated by applying a pressure head equal to 0 m to all nodes followed by drainage under a pressure head equal to 0 m applied to the bottom of the profile for 2 days. The PWP for AWHC calculations was assumed to be 1,500 kPa as estimated by Rawls et al. (1982) (same as that used in the AWHC 4 calculations).

3 Results and discussion

3.1 Initial soil nutrient status

For cation exchange capacity (CEC), organic carbon (OC) and total nitrogen (TN), the lake sediment (LS) treatment was significantly higher than all other treatments except the commercial peat (CP) for OC (Table 1). The UFS, conventional fertilised (NPK), organic pellets (OP) and forest floor (LFH) treatments were not significantly different for CEC, OC and TN content than the control (C). The CEC, OC and TN contents in the C, UFS and NPK treatments were generally below the laboratory detection limits. With the exception of the LS treatment, nitrate-nitrogen levels in all treatments were below the detection limit of 2 $mg.kg^{-1}$ (Table 1). Levels of available phosphorus and potassium were also below detection limits in the C, LS and UFS treatments. The NPK treatment had the highest available phosphorus but was not significantly higher than the OP treatment. The OP treatment had the highest available potassium of all treatments and was nine times that of LFH and four times that of NPK. Ammonium nitrogen was highest in the NPK treatment but again, was not significantly higher than the OP treatment. A comparison of overall nutrients showed that the LS treatment is relatively rich in both macro and micronutrients, whereas the C and UFS were poor. High clay and organic matter content in the LS soil resulted in higher total and available nutrient pools. Levels of available nutrients in the CP and OP treatments are expected to increase as the organic material decomposes and mineralises.

Table 1 Initial nutrient status of the different soil treatments

Nutrients	C[z]	CP	LS	UFS	LFH	NPK	OP	Demo
CEC	4.00*b*[y]	5.00*b*	13.7*a*	4.00*b*	4.00*b*	4.00*b*	4.00*b*	4.00*b*
Carbon (%)	0.0500*c*	1.69*ab*	2.04*a*	0.0500*c*	0.823*bc*	0.050*c*	0.143*c*	0.873*bc*
Total N (%)	0.0100*b*	0.0400*b*	0.203*a*	0.0100*b*	0.0167*b*	0.0100*b*	0.0300*b*	0.0200*b*
Available (mg.kg^{-1})								
Nitrate	2.00*b*	2.00*b*	17.0*a*	2.00*b*	2.00*b*	2.00*b*	2.00*b*	2.00*b*
Phosphorus	5.00*c*	5.33*c*	5.00*c*	5.00*c*	9.67*c*	54.7*a*	46.3*ab*	15.3*bc*
Potassium	23.3*b*	25.0*b*	25.0*b*	21.7*b*	26.6*b*	56.7*b*	240.0*a*	61.3*b*
Copper	0.133*b*	0.200*b*	0.133*ab*	0.133*b*	0.367*a*	0.167*b*	0.267*ab*	0.500*b*
Iron	9.53*b*	18.5*b*	218*a*	14.3*b*	35.6*b*	7.60*b*	11.9*b*	48.5*b*
Manganese	0.967*b*	5.70*b*	44.1*a*	1.30*b*	8.83*b*	0.700*b*	1.33*b*	9.83*b*
Zinc	0.500*b*	0.567*ab*	0.500*b*	0.500*b*	0.933*ab*	0.500*b*	0.933*ab*	1.23*a*
Ammonium	0.300*c*	19.5*bc*	14.7*bc*	0.300*c*	0.300*c*	50.0*a*	37.2*ab*	1.10*c*
Calcium	57.7*c*	414*a*	207*bc*	34.3*c*	96.0*bc*	46.7*c*	241*ab*	133*bc*
Magnesium	12.0*c*	70.0*a*	20.0*c*	5.67*c*	22.7*bc*	13.3*c*	58.6*ab*	31.3*bc*
Sodium	20.0*b*	20.0*b*	20.0*b*	20.0*b*	20.0*b*	20.0*b*	60.0*a*	20.0*b*

[z] C = control; CP = commercial peat; LS = lake sediment; UFS = underlying flax straw; LFH = LFH/mineral; NPK = conventional fertiliser; OP = organic pellet; Demo = demonstration plot. The same abbreviations used in all tables and figures from this point forward.

y Common letters are not significantly different at p = 0.05.

3.2 Soil physical properties and water storage

The LS treatment had the lowest proportion of sand compared to all other treatments, and had the highest silt content of all (Table 2). Clay was not significantly different among treatments. Organic matter and moisture content was also highest in the LS treatment. The AWHC 1 values indicate that a flax straw layer (similar to the UFS but at a 30 cm depth) increased the AWHC in the upper 30 cm by 40–126% and 4–29% over the entire 100 cm depth (Fleming et al., 2010). This experiment provided clear evidence of the enhancement of soil water storage using a capillary break material. The control cover alone had an AWHC of 80 mm m^{-1} (AWHC 2). The LCCS estimated AWHC 3 values for C were significantly lower than that estimated for the LS and CP treatments. The LS and CP treatments had AWHC values that were 111% and 105% of C, respectively. It is noted that AWHC 3 for the UFS treatment does not consider layering and capillary break phenomenon. As shown in Fleming et al. (2010), this should substantially enhance water storage in the profile above the straw layer.

As expected the C and NPK treatments had the same AWHC (Table 2). The LS and Demo treatments had the largest AWHC values. In the UFS treatment, AWHC was found to be the same as C indicating that this method does not account for the enhancement of AWHC due to the flax straw capillary break. UFS, Demo, LS and CP treatments show the highest water contents at field capacity (Figure 2) with UFS having the greatest increase in AWHC (28%) over the control case. The simulation captured the increased in AWHC due to the UFS capillary break.

Table 2 Initial physical properties and AWHC estimates of different treatments

Physical Properties	C	CP	LS	UFS	LFH	NPK	OP	Demo
Texture[z]	S	LS	SL	S	S	S	S	S
Sand (%)	88.1*a*[y]	84.7*a*	76.3*b*	88.9*a*	90.3*a*	89.7*a*	87.1*a*	90.4*a*
Silt (%)	8.80*b*	11.7*b*	19.3*a*	7.00*b*	6.00*b*	6.40*b*	9.00*b*	6.87*b*
Clay (%)	3.06	3.53	4.47	4.07	3.73	3.87	3.93	2.73
Organic Matter[x] (%)	0*c*	2.9*ab*	4.7*a*	0*c*	1.4*bc*	0*c*	0.2*c*	1.5*bc*
Moisture	4.73*d*	14.9*bc*	28.5*a*	4.87*d*	4.33*d*	4.70*d*	4.70*d*	5.77*cd*
AWHC1[w] (mm/m)	140 to 173	-	-	180	-	-	-	-
AWHC2[v] (mm/m)	80	-	-	-	-	-	-	-
AWHC3[u] (mm/m)	80	84	89	88	80	80	80	89
AWHC4[t] (mm/m)	113	119	124	113	116	113	114	128
AWHC5[s] (mm/m)	90	96	102	115	94	89	91	105

[z] Texture notation: S = sand; SL = Sandy Loam; LS = Loamy Sand. [y] Common letters are not significantly different at $p = 0.05$. [x] Organic Matter estimated by 1.7*[Organic Carbon] (Dane and Topp, 2002). [w] AWHC1 estimated from laboratory column study (Fleming et al., 2010). [v] AWHC2 measured by field double ring infiltration test (Zettl, 2011). [u] AWHC3 estimated by LCCS method (CEMA, 2006). [t] AWHC4 estimated using Rawls et al. (1982) 10 kPa (FC) – 1,500 kPa (PWP). [s] AWHC5 estimated from SEEP/W simulations.

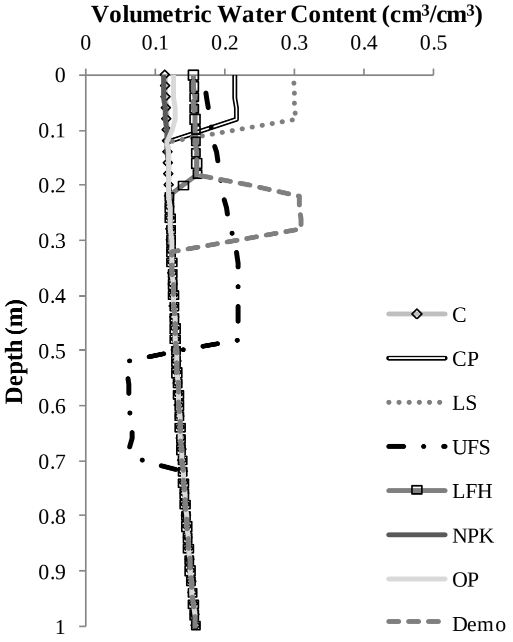

Figure 2 Simulated volumetric water content at field capacity (i.e. after 2 days drainage)

3.3 Salinity

Soil pH was acidic (pH <5) in the LS, CP and LFH treatments (Table 3). The UFS and Demo treatments had a pH range similar to that of the C (between 5 and 7); whereas NPK and OP had a slightly alkaline pH range (7 to 8). The OP treatment was the most alkaline of all treatments. Soil EC (dS.m^{-1}) and SAR in all treatments were below 2 and 1, respectively, except in OP, where mean soil EC and SAR were 2.8 and 4.2, respectively, and higher than all other treatments. The OP treatment also had higher chloride and sulphate levels than all other treatments. The high chloride concentration in the OP treatment implies that the EC and

SAR observed in this treatment was the result of high NaCl salt concentration. As this salt will dissolve and flush down in the sandy profile, it may not pose a persistent problem to revegetation.

Table 3 Initial salinity, pH and regulated inorganic elements of the different soil treatments

	C	**CP**	**LS**	**UFS**	**LFH**	**NPK**	**OP**	**Demo**
Soil pH and salinity								
pH	6.80*b*[z]	4.80*d*	4.07*e*	5.87*c*	4.93*d*	7.00*b*	7.80*a*	5.30*cd*
EC (dS.m^{-1})	0.170*c*	0.387*bc*	0.583*bc*	0.113*c*	0.190*c*	1.22*b*	2.76*a*	0.610*bc*
SAR	0.567*b*	0.200*b*	0.167*b*	0.467*b*	0.200*b*	0.733*b*	4.20*a*	0.967*b*
Chloride (Cl) (mg.kg^{-1})	1.67*b*	52.3*b*	2.67*b*	1.33*b*	2.33*b*	41.3*b*	113*a*	22.3*b*
Sulphate (SO$_4$) (mg.kg^{-1})	2.73*c*	3.33*c*	19.2*ab*	2.03*c*	3.97*bc*	6.53*bc*	31.4*a*	11.6*bc*
Regulated inorganics (mg.kg^{-1})								
Boron (B)	0.200*b*	0.233*b*	1.33*a*	0.200*b*	0.233*b*	0.233*b*	0.200*b*	0.367*b*
Mercury (Hg)	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100
Antimony (Sb)	0.200	0.200	0.200	0.200	0.200	0.200	0.200	0.233
Arsenic (As)	1.20*b*	0.500*b*	44.7*a*	0.600*b*	4.90*b*	2.33*b*	0.500*b*	8.40*b*
Barium (Ba)	4.67*b*	5.33*b*	10.3*a*	4.33*b*	6.00*b*	4.33*b*	5.00*b*	7.67*ab*
Beryllium (Be)	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.133
Cadmium (Cd)	0.0100*b*	0.0100*b*	0.097*a*	0.0100*b*	0.0133*b*	0.0100*b*	0.0100*b*	0.0200*b*
Chromium (Cr)	1.00*b*	0.733*b*	2.60*a*	0.700*b*	1.73*ab*	1.23*ab*	0.867*b*	1.83*ab*
Cobalt (Co)	0.333*b*	0.133*b*	5.17*a*	0.133*b*	0.933*b*	0.300*b*	0.133*b*	1.23*b*
Copper (Cu)	0.133*ab*	0.100*b*	0.200*ab*	0.100*b*	1.67*ab*	1.00*b*	1.00*b*	2.67*a*
Lead (Pb)	1.00*b*	0.633*b*	1.87*b*	0.633*b*	6.93*ab*	1.77*b*	0.633*b*	10.9*a*
Nickel (Ni)	3.70*b*	1.27*b*	45.1*a*	0.933*b*	8.17*b*	3.63*b*	1.30*b*	12.8*b*
Selenium (Se)	0.300*b*	0.300*b*	0.400*a*	0.300*b*	0.300*b*	0.300*b*	0.300*b*	0.300*b*
Silver (Ag)	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100
Thallium (TI)	0.0500	0.0500	0.0500	0.0500	0.0500	0.0500	0.0500	0.0500
Tin (Sn)	1.00	1.33	1.00	1.00	1.00	1.00	1.00	1.00
Uranium (U)	1.03*c*	0.533*c*	1.27*c*	0.500*c*	8.50*b*	1.17*c*	0.500*c*	11.2*a*
Vanadium (V)	2.23*ab*	1.00*b*	0.233*b*	0.933*b*	4.27*ab*	2.03*ab*	0.933*b*	7.50*a*
Zinc (Zn)	1.00*c*	1.00*c*	13.0*a*	1.00*c*	4.00*bc*	1.00*c*	1.33*c*	6.67*b*

[z] Common letters are not significantly different at $p = 0.05$.

3.4 Regulated inorganics

Except in the LS treatment, all regulated inorganics and metals were well below CCME (2007) limits and there were no substantial differences between other treatments (Table 3). The levels of most regulated inorganics (other than Hg, Sb, Ag, TI, SN and V) were significantly higher in LS than all other treatments. For example, As and Ni were above CCME threshold levels for these elements, although these levels are consistent with background levels in lake sediments in the area prior to disturbance. In composite samples of

LS blended with surface sands the levels of some regulated inorganics were reduced approximately by 50%. Arsenic levels still exceeded CCME (2007) guidelines in the sediment/sand composite samples.

4 Summary

Initial and preliminary evaluation of the different soil and vegetation treatments showed the following:

- The cover soil being reclaimed has a very low nutrient content and moisture holding capacity.
- The lake sediment amendment has relatively high total and available nutrients as well as moisture holding capacity, but the high As and Ni concentrations in this material my pose a challenge.
- The UFS, Demo, LS and CP treatments, in order of declining amounts, showed a potential to improve AWHC of the sandy cover material. Vegetation growth will be monitored to measure response to the various amendments.
- The UFS and Demo treatments have the greatest potential to provide adequate soil nutrients and moisture.

The variability in the results demonstrates how each treatment will provide unique soil and nutrient regimes. Nonetheless, climatic and future management conditions could also affect the development path of these plots.

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