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EVALUATION OF SOIL RECLAMATION TECHNIQUES AT KEY LAKE URANIUM MINE

Short title: Soil capping prescriptions

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ABSTRACT

Adequate soil nutrients and water supply are critical to vegetation establishment and creation of sustainable ecosystems in post-disturbed mining sites. This study investigated effects of various amendments and capping techniques on soil quality and moisture distribution on a reclaimed waste rock pile at the Key Lake uranium mine in northern Saskatchewan, Canada. Soil profiles were reconstructed in 2010 using locally available sandy glacial materials to create soil covers of 1 m thickness. The reclamation treatments consisted of a Control plot, commercial peat (Peat), a local lake sediment (Sediment), underlying flax straw (Straw), mulched LFH and Ae (LFH), fertilizer (NPK), manure pellets (Pellets), and a demonstration plot (Demo) comprised of Sediment, LFH and Pellets. Soil amendments were applied by various techniques as broadcast, surface incorporation, below the surface or surface mounding. Annual plot monitoring was conducted from 2011 to 2013 and soil samples were analyzed for pH, electrical conductivity (EC), sodium adsorption ratio (SAR), available nutrients, cation exchange capacity (CEC), total organic carbon (TOC), total nitrogen (TN), and regulated metals. Volumetric moisture contents were measured periodically to examine soil moisture response to growing-season precipitation. In 2013, the topsoil of the Control plot was slightly acidic (pH of 6.3) while the Sediment and Demo plots had the lowest pH of 4.0. EC and SAR values were below 1.0 in all treatment plots. The highest levels of available N, TN, TOC and CEC were in the Sediment and Demo plots, followed by the Peat. The concentration of arsenic was more than the regulatory limit by 3.4- and 2.6-fold in the Sediment and Demo topsoil, respectively, while concentrations of other metals were below the limits in all treatment plots. The Sediment and Demo treatments were most effective in retaining water in the topsoil, while application of soil amendment by mounding enhanced infiltration and water transmission in the profile. In terms of soil fertility and moisture storage, the combination of organic amendments in multi-layers plus surface mounding, as in the Demo plot, is the most promising capping technique for restoring soil health, vegetative cover and ecosystem functions on the waste rock pile.

Key words: soil quality, moisture content, organic amendment, soil capping, soil cover, waste rock

INTRODUCTION

The Key Lake mine is one of the uranium mining facilities operated by Cameco Corporation in northern Saskatchewan, Canada. The extraction of uranium ore by surface mining generates massive waste rock materials which are deposited in above-ground dumps (Cameco 2010; Leskiw et al. 2011). Reclamation of these dumps is challenging given the soil cover materials available in this region are coarse-textured with nutrient and moisture storage limitations.

Resource development and mineral extraction by surface mining are generally accompanied with extensive land disturbance, altering the pre-existing landform attributes, surface drainage, ecological structure, vegetation communities and soil properties (Fung and Macyk 2002; Dale and Bhatti 2012). Following mine closure and decommissioning, a suite of operational management practices are implemented to restore the ecological integrity of post-disturbed mine footprints (Sheoran et al. 2010). The underlying goal of land reclamation is to create a stable landscape with the capability to support diverse, self-sustaining ecosystems and ecological functions equivalent to pre-disturbance conditions or desired end land uses. This requires identification and selection of suitable soil covers and amendments for reconstructing a plant growth medium with adequate nutrient and moisture supply capabilities, and with composition of regulated inorganics below recommended thresholds (MEND 2004). Soil cover is commonly constructed as a single layer or multi layers of earthen material overlying the waste rock, overburden dumps, spoil or mine waste materials such as tailings, which are generally referred to as substrate (MEND 2004; Carrera-Hernandez et al. 2012).

In western Canada, several management practices based on reclamation research have been reported for the oil sands and coal mining operations. In the oil sands reclamation in northeastern Alberta, the final substrates for reconstructing soil profiles comprised mainly of overburden and consolidated tailings sand (Fung and Macyk 2002; Barbour et al. 2007; Carrera-Hernandez et al. 2012). In the past 30 years, the soil capping prescriptions commonly used in the oil sands reclamation include a mixture of peat and mineral soil (peat-mix) or subsoil or both, placed over either tailings sand, overburden, Clearwater shale or lean oil sands (Rowland et al. 2009). The utilization of litter-fibric-humic (LFH) and Ae horizons as topsoil material in the upland boreal forest areas is also a promising technique as was investigated by Mackenzie and Naeth (2010). The LFH material was shown to stimulate diverse ecosystems by providing a viable source of nutrients and propagules for revegetation (Mackenzie and Naeth 2010).

In the coal mining industry in eastern British Columbia and east-central Alberta, reclamation of post-disturbed lands with soil cover is accomplished with various landform configurations comprising of coal waste (fractured rock and coarse coal rejects) as substrate, capped with regolith (unconsolidated B/C horizon), and finally with topsoil consisting of A/B-horizons (O'Brien and Straker. 2010). Unlike in other regions in western Canada, there is limited information addressing reclamation outcomes on post-disturbed uranium sites in northern Saskatchewan.

In addition to creating a plant growth medium, soil covers offer a strategy to reduce infiltration of meteoric waters into the underlying waste rock piles, thereby mitigating the risk of acidic drainage and metal loading to the receiving surface water and groundwater bodies (Ayres et al. 2006). The soil cover also acts as a reservoir for infiltrated waters with subsequent release of moisture for plant uptake. Since mine reclamation requires establishment of stable landscapes and nutrient cycling for plant growth, the soil cover provides the foundation for these processes (Sheoran et al. 2010). Therefore, it is important to monitor the trends in soil quality following soil reconstruction and how the reclaimed soil properties might influence vegetation establishment and ecosystem health.

Indicators of soil quality in mine reclamation are often based on physico-chemical properties (Wong 2003; Shukla et al. 2004) while the assessments of biological processes are also essential for monitoring soil-plant interaction during vegetation establishment (Sheoran et al. 2010; Blecker et al. 2012). The soil chemical properties critical to mine reclamation include pH, salinity, sodicity, nutrient availability and fertility (USEPA 2007). While nitrogen (N) and phosphorus (P) are the two most limiting macronutrients in reconstructed soils, a higher or lower than neutral pH could result in bioavailability of some toxic elements (Wong 2003; USEPA 2007). Changes in soil pH could also result in retention of available P through precipitation with aluminum/iron in acidic soils or with calcium in calcareous soils (Havlin et al. 2005; USEPA 2007). Salinity is an indication of excess salts in the soil, with the potential limitation for plant uptake of water and nutrients, while soils with high sodicity have detrimental effects on plant roots due to toxicity of sodium and associated ions. Soils and waste rock materials in ore mining sites are also often contaminated by heavy metals (MEND 2004; USEPA 2007). The toxicity effect of heavy metals on plants and soil organisms is a function of the total concentration, bioavailability and speciation of metals in the soil environment (Wong 2003).

Soil water supply and temporal fluxes are important physical factors influencing the functionality of a soil cover. The distribution of soil moisture controls key processes such as infiltration, plant water consumption and nutrient uptake, and the overall hydrological and biogeochemical processes driving the transformation of a reclaimed site into a self-sustaining ecosystem (Qualizza et al. 2004; Elshorbagy et al. 2005; Kelln et al. 2008). In cases where the reconstructed soil cover fails to meet regulatory guidelines on soil quality, suitable amendments are utilized as necessary to ameliorate soil degradation.

Types of amendments commonly used in land reclamation vary from organic materials, such as municipal biosolids, manures, compost, plant residue and litters, pulp sludges and wood waste, to inorganic materials, such as synthetic fertilizer for supplying readily available nutrients, and lime or gypsum for modifying the soil pH (USEPA 2007). Given that post-mined lands are commonly prone to extreme physical conditions such as coarse-textured soils, coupled with nutrient deficiency and elevated levels of salts and heavy metals, the combination of these adverse soil characteristics can severely inhibit vegetation establishment on reconstructed soils (MEND 2004). Studies have shown that application of organic amendments is most effective in restoring soil health and ecosystem function in drastically disturbed landscapes (Larney and Angers 2012). In their review of the role of organic amendments in soil reclamation, Larney and Angers (2012) reported that addition of organic-based materials enhanced soil productivity due to the influence of organic matter on microbial activity, nutrient pools and biocycling, pH buffering and retention of chemical contaminants. Addition of organic amendments also improved soil physical attributes such as infiltration, permeability and water holding capacity. In the oil sands region, readily available native peat is often used as a topsoil amendment (Rowland et al. 2009).

As part of the closure plan for the Key Lake uranium facility, field plot trials were established by Paragon Soil and Environmental Consulting (Paragon) in 2010 to investigate the efficacy of eight soil treatments to support revegetation success of various boreal forest plants. This research is also intended to provide an opportunity for advancing knowledge transfer among practitioners, regulators and scientific communities in various reclamation operations. Due to limited information on reclamation outcomes at the Key Lake region, it is important to investigate various methods of rapidly establishing nutrient and moisture regimes that are comparable to the natural forest ecosystems in the area. The objectives of this study were: (1) to evaluate effects of various amendments and capping techniques on the overall soil chemistry as indicated by levels of salinity parameters, available nutrients and fertility, and composition of regulated metals; and (2) to examine the potential of soil treatment to retain water in the upper soil profile and to reduce deep percolation into the underlying waste rock pile, as these have implications on plant water availability and contaminant loading.

The field plot research comprised of two components; one aspect of the study focused on soil quality monitoring while the other was aimed at vegetation assessment. The present study reports findings on the soil monitoring component while the companion study on vegetation aspect is addressed in a separate publication (Cranston and Leskiw 2014). For this study, we hypothesized that addition of organic surface amendments to the reconstructed soil profiles will improve the topsoil quality, promote soil water supply and ultimately facilitate vegetation establishment compared to soil covers without organic materials. In addition to testing the efficacy of surface amendments, the study also examined various techniques for placing amendments on soil covers such as broadcast, surface incorporation, below the surface or surface mounding. It is also hypothesized that placement techniques for the amendments will influence infiltration of meteoric water at the surface and subsequent transmission within the soil covers.

MATERIALS AND METHODS

Site Location and Climate Setting

Cameco's Key Lake Operation (lat. 57°12'55.14"N, long. 105°38'05.99"W) is located at Key Lake, approximately 570 km north of Saskatoon, Canada. The Key Lake region is within the southwestern boundary of the Athabasca Basin, in the Boreal Shield ecozone in northern Saskatchewan (McLaughlan et al. 2010). The dominant forest cover consists of Jack pine (*Pinus banksia* L.), white birch (*Betula papyrifera* M.), blueberry (*Vaccinium myrtilloides* Michx.), alder (*Alnus viridis*), and a variety of moss and lichen species. The region lies within the sub-arctic climatic zone, characterized by a continental climate with warm summers and cold winters. The total annual precipitation averaged 483 mm, with 318 mm occurring as rainfall according to the Environment Canada climate normals from 1981 to 2010 (Fig. 1). Of the 318 mm rainfall, approximately 69% (217 mm) occurs during the frost-free period between June and August. Rainfall data are also monitored at a local weather station on the study site by O'Kane Consultants since 2010. Rainfall events from April to October represent the growing season precipitation for the study site (Fig. 1).

Uranium mining and processing have been in operation at the Key Lake facility since 1983 (Cameco 2010). The waste rock materials are currently stored in piles in designated post-mined areas within the facility. The study site was established on one of the rock piles known as the Deilmann North Waste Rock Pile (DNWRP). The DNWRP site is an 81-ha out-of-pit waste rock pile constructed between 1984 and 1997. The rock pile was excavated prior to uranium mining and is composed of 23% sand/till, 47% sandstone and 30% basement rock by volume (Cameco 2010; Leskiw et al. 2011). The sand and till materials were derived from glacial outwash and sandstone sediments originating from the Athabasca Sandstone. The basement rock refers to the deepest geologic formation and is predominantly granite with traces of graphite and pyrite.

Study Design and Plot Construction

Test plots for soil amendment and capping trial were established in September 2010, immediately followed by vegetation establishment. The experimental layout was a randomized complete block design (RCBD) with eight soil treatments in three replicate blocks. The soil treatments included: (1) no amendment (Control); (2) commercial peat (Peat); (3) sediments from a local lake (Sediment); (4) underlying flax straw (Straw); (5) Mulched forest floor and Ae horizon (LFH); (6) synthetic fertilizer (NPK); (7) manure pellets (Pellets); and (8) a demonstration plot (Demo) comprised of the lake sediment, mulched LFH and manure pellets amendments. A brief description of the soil amendments, background characteristics and method of application are shown in Table 1. Though the placement depths of amendments varied among treatment plots (Table 1), the selected depths were based on the practical feasibility of applying the individual amendments. The placement depths are also consistent with those commonly applied in soil capping operations in the oil sands region (Barbour et al. 2007). However, differences in reclamation outcomes among treatments will be attributed solely to properties of the amendment in lieu of depth of application.

Treatment plots were grouped into three replicate blocks denoted as A, B and C. Each block was divided into seven random soil amendment plots and one control plot, each plot measuring 9 m × 9 m dimension (Fig. 2). Each treatment plot (9 m × 9 m) was further divided into nine 2 m × 2 m vegetation subplots. Species planted in the vegetation subplots were Polytrichum moss, LFH turfs, Jack pine (*Pinus banksia* L.), bearberry (*Arctostaphylos uva-ursi* (L.) Spreng.), blueberry (*Vaccinium myrtilloides* Michx.), birch (*Betula papyrifera* M.), willow (*Salix bebbiana* Sarg.), alder (*Alnus viridis*), and aspen (*Populus tremuloides* Michx.). Buffer zones (1 meter wide) were established between subplots as well as between the edges of each treatment plot.

Glacial sandy materials were excavated from a nearby drumlin and hauled to the DNWRP site to create a cover with a nominal thickness of 1 m over the waste rock. The schematic description of soil capping technique in each treatment plot is shown in Fig. 3. Treatment plots were sampled and described in accordance with the Canadian System of Soil Classification procedure (Soil Classification Working Group 1998). The reconstructed soils were classified as Albo Spolic Anthroposols based on the anthroposolic classification system (Naeth et al. 2012).

Description of Soil Treatments

The control plot received no amendment and the soil profile is composed of stony, sand-textured glacial till materials that were used to construct the subsoil layer of the entire test plot.

Peat moss is a valuable soil amendment (Li et al. 2004) and is widely used in oil sands reclamation in the boreal region of northeastern Alberta, where it is salvaged from the mining footprint prior to disturbance. The peat material generally has a high moisture holding capacity and organic matter content. For this trial, commercial bagged peat moss (Sunshine Peat™) was applied to the soil surface at 6 to 12 cm depth and incorporated into the top 10 cm with two passes of a tractor-mounted rototiller. The topsoil (0-10 cm) of the Peat plot is peaty-sand, but the subsoils are sands as in the Control plot.

During uranium mining at Key Lake, several small lakes have been dewatered. The sediments at the bottom of these lakes were considered as a valuable amendment for reclamation due to their fine texture and high organic matter content and hence, high moisture holding capacity. The composition of lake sediments at the Key Lake region range from organic matter dominated deposits to beds of silty-loam and clay material. The sediment used for the plot trial was collected from the edge of a drained lake adjacent to the tailings pond. The lake sediment was transported to the plots using a haul truck, and was spread on the plots using a tractor-mounted front loader. Following spreading, depths of sediment on the soil surface ranged from 6 to 10 cm. The sediment was subsequently incorporated into the top 10 cm soil layer using a tractor-mounted rototiller, resulting in a blend ratio of approximately 1:1 sediment to soil, silty-loam topsoil (0-10 cm).

The flax straw treatment was based on the use of a subsoil capillary break to promote soil moisture storage in the surface horizons. The utilization of this soil capping technique was previously tested in a laboratory column study (Fleming et al 2010; Leskiw et al. 2011). For this study, the Straw plot was constructed with 20 cm layer of flax straw placed at approximately 50 cm below the ground surface (the layer was subsequently compressed). The flax straw was obtained and transported to the study site by Cameco's operations personnel. The top 50 cm depth of the assigned Straw plot was excavated using a track hoe, the straw was placed and the surface material was backfilled. The soil profile attributes in the Straw plot are similar to the Control except for the loosening of soil within the top 50 cm and the presence of straw material at 50 to 70 cm depth.

Forest floor (referred to as LFH) is a rich source of plant propagules, soil microbes and nutrients, and is widely applied in land reclamation in the Alberta oil sands region (Mackenzie and Naeth 2010). Most ecosites within the Key Lake mining footprint are designated as BS6 ecosite (McLaughlan et al.

2010), typically with a shallow LFH over Ae, Bm and C horizons classified as Eluviated Dystric Brunisols. The LFH amendment for this study was a combination of mulched native LFH and surface soil (Ae horizon). These mulched materials were previously stripped in summer of 2010 from an area that had been cleared as part of an ongoing expansion and development at the Key Lake Operations (Leskiw et al. 2011). The LFH amendment was mounded over the assigned plots using a tractor-mounted front loader to create a micro-hummocky surface configuration but the material was not incorporated into the subsoil, i.e. no rototilling. A nominal depth of 20 cm was finally achieved across the replicate LFH plots, resulting in loamy-sand topsoil (0-20 cm) overlying the sand textured subsoil.

The NPK treatment plot was amended with 18-24-11 (N-P-K) fertilizer at a rate of 4 kg per 100 m^2 (equivalent to 400 kg ha^{-1}). The N-P-K fertilizer was spread over the soil surface using a belly seeder without rototilling. The soil texture in the NPK plot was sand at all sampled depths.

The manure pellets were processed livestock manure collected from feedlots, which were manufactured by EarthRenew in Calgary, Alberta. The pellets were applied at a rate of 20 tonnes ha^{-1} using a fertilizer spreader, and were subsequently incorporated into the top 10 cm soil layer using the rototiller. The soil profile texture in the Pellet plot remained sand as in the Control plot.

The objective of the Demonstration plot was to examine effects of multiple amendments on soil properties. The Demo plot profile was constructed as a layered system with 70 cm depth of sand subsoil overlain by 10 cm of lake sediment, followed by 20 cm of LFH at the top, and finally with surface application of manure pellets. Depths of application for the lake sediment and LFH materials in the Demo plot are consistent with those applied in the corresponding Sediment and LFH treatment plots. The use of multiple amendments in the Demo plot was to test the influence of textural heterogeneity and multi-layered soil capping technique on hydrological processes. This soil capping approach has been demonstrated in several studies in the oil sands region (Barbour et al. 2007; Zettl et al. 2011). Both the lake sediment and LFH materials were dumped on the Demo plot and mounded using a loader to create a micro-hummocky surface that is intended to promote surface water infiltration and to create micro-sites for vegetation establishment. As such, the surface configuration of the Demo plot was similar to that in the LFH plot. Finally, manure pellets were applied to the Demo plot surface at a rate of 7 tonnes ha^{-1}, but were not incorporated (i.e. no rototilling). The soil profile texture in the Demo plot was loamy-sand, silty-loam and sand for the LFH layer (0-20 cm), lake sediment (20-30 cm) and subsoils (30-100 cm), respectively.

Soil Monitoring

Following plot construction in 2010, the topsoil in each treatment plot was sampled for baseline characterization. Annual soil monitoring was conducted in August of subsequent years from 2011 to 2013. Samples were collected from three principal horizons at 0-20 cm for topsoil (TS), 20-50 cm for upper subsoil (US), and 50-100 cm for lower subsoil (LS). The exceptions were the Peat, Sediment and Pellets plots where the TS was sampled at 0-10 cm, while the Demo plot TS was sampled at 0-30 cm. In each monitoring year, soil samples were collected from a nearby natural undisturbed area as a reference for soil quality assessment. Three replicate locations in the natural site were sampled at four pedogenic horizons as LFH (4-0 cm), Ae/Aeh (0-15 cm), Bm (15-45 cm), and BC (45-100 cm). The soil texture for the Ae/Aeh horizon was sandy loam while the subsoil horizons were generally sand.

Soil samples were kept cool and transported to a commercial soil-testing laboratory (Exova Canada Inc., Edmonton, Alberta). Samples were analyzed using standard laboratory procedures for salinity package, available nutrients and fertility parameters, and regulated metals and metalloids according to the Canadian Council of Ministers of the Environment (CCME) guidelines for residential/parkland coarse-textured soils (CCME 2007). To avoid ambiguity, the CCME regulated metals and metalloids are generally referred to as “metals” in the present study. The soil parameters and analytical methods are summarized in Table 2. The CCME criteria were used for assessing the indicators of soil quality in the present study in order to be consistent with the findings that have been reported for this site. This is also in accordance with the regulatory approval for evaluating reclamation operations at the Key Lake uranium facility. Other studies in western Canada have implemented CCME criteria for evaluating soil quality parameters. For instance, Gardner et al. (2012) conducted a three-year study to investigate the influence of biosolids and fertilizer amendments on element concentrations and revegetation of copper mine tailings in British Columbia. Elemental concentrations of soil metals were compared with CCME thresholds across varying levels and types of treatments applied in the study (Gardner et al. 2012).

Volumetric moisture contents were measured periodically by O’Kane Consultants using permanently installed access tubes and a portable soil moisture probe (Diviner 2000, Sentek Technologies). Soil moisture measurements were taken to 100 cm depth at 10 cm intervals. The soil moisture was measured only in selected treatment plots which included Control, Peat, Sediment, Straw, LFH and Demo. Soil moisture monitoring was conducted between May 10th and August 30th in 2012, and between May 15th and October 17th in 2013. Temporal distribution of volumetric water contents in each monitoring year were summarized according to the three horizons and other variants of soil depths such as the flax straw layer in the Straw plot and lake sediment and LFH layers in the Demo plot.

The field-measured volumetric water contents were averaged over the sampling periods and were used to determine other soil moisture regimes, referred to as surplus water content (SWC) and available water content (AWC). The SWC was estimated as the average volumetric moisture content (VMC_{ave}) minus moisture content at field capacity (FC), while the AWC was moisture content at FC minus permanent wilting point (PWP). The topsoil in each treatment plot was sampled to determine the FC and PWP moisture contents using the water retention curves procedure (Klute 1986). The FC was measured at soil moisture potential of −0.33 bar while PWP was determined at −15 bar. The FC and PWP data for the Control plot represent those for the subsoils in all treatment plots.

Vegetation Assessment

For this study, indicators of vegetation performance were based on percent survival of plant stands per plot and vegetative growth. The percent survival is the number of existing plant stands relative to the total number of species planted in each plot, while the vegetative growth was estimated as the difference in above-ground heights of plant species between 2012 and 2013 monitoring. Detailed discussions on vegetation assessments and findings have been presented in the companion study (Cranston and Leskiw 2014). Foliar concentrations of metals were also examined in selected treatment plots (Control, Sediment, LFH, Pellets and Demo). Foliar tissue samples were collected only from birch species in each plot and were analyzed for composition of heavy metals. Amounts of metals in the plant tissue were compared with the critical concentrations of trace elements for toxicity, generalized for matured leaf tissues of various terrestrial species (Kabata-Pendias 2011).

Statistical Analyses

Statistical analyses were performed on the topsoil data for all treatment plots to determine the temporal variation in soil quality between 2010 and 2013. The 2010 data represent the baseline or soil quality at Time 0, while the 2013 data represent the soil quality status three years after soil reconstruction. The temporal variations in topsoil properties among treatments were determined by 2-Way analysis of variance (ANOVA) of year × treatment using the PROC MIXED procedure in SAS program (SAS Institute). To examine the vertical distribution of solutes and potential for leaching, the soil salinity data in 2013 were analyzed by 2-Way ANOVA of horizon × treatment effect. Soil profile distribution of CCME metals in 2013 was also analyzed for the Control, Sediment and Demo plots. The average volumetric water contents and other soil moisture regimes were estimated for each sampled horizon depth and were compared among treatment plots using a 2-Way ANOVA of horizon × treatment.

The ANOVA model was based on the RCBD design with the replicate block as a random factor while soil treatment versus year of monitoring or horizon depth were fixed factors (Littell et al. 2006). The horizon effect was treated as a categorical factor given that the sampling depths were not consistent across experimental units. As such, the horizon depths were computed as nominal variables by assigning sampling intervals of 0-20, 20-50 and 50-100 cm uniformly for all topsoils, upper subsoils and lower subsoils, respectively. Vegetation data for percent survival, growth and foliar metals were tested for treatment effect using a 1-Way ANOVA procedure. However, plant species in the Demo plot were not assessed for survival and growth due to variability in numbers of species established in the treatment plots. Mean separations for the ANOVA tests were determined by the Tukey–Kramer post-hoc method at $P < 0.05$. The data were tested to meet assumptions of normality using the Shapiro-Wilk's test in the UNIVARIATE procedure. In cases where the raw data did not conform to normal distribution, the data were logarithmically transformed prior to analysis and subsequently back-transformed as geometric means.

RESULTS

Treatment Effects on Salinity Parameters

The topsoil chemistry varied among treatments in 2010 and 2013 with significant year × treatment effects for all salinity parameters (Table 3). The mean separation for treatment effect was compared across the row by different letters, while the letters in parentheses indicate significant difference in soil property between 2010 and 2013. In 2010, the lowest baseline pH was 4.1 as measured in the Sediment plot, while the Pellets plot had the highest pH of 7.8. Except for NPK, other treatments also reduced the topsoil pH in 2010 relative to pH of 6.8 in the Control plot ($P < 0.05$). However, soil pH decreased significantly over time in the NPK, Pellets and Demo plots between 2010 and 2013. By 2013, the topsoil of Sediment and Demo plots remained acidic with the lowest pH of about 4.0 while the pH in the Pellets plot was neutral at 7.1 but higher than pH of 6.3 in the Control plot ($P < 0.05$). The soil pH in the Sediment and Demo plots was similar to pH of 4.0 measured in the natural Ae/Aeh horizon but much lower than pH range of 6.0–8.0 in the CCME guidelines for residential/parkland coarse soils (CCME 2007).

Salinity parameters were also analyzed for lake sediment materials sampled from two previously drained natural lakes denoted as Remnant Key Lake and Little Martin, both adjacent to the study site.

The pH of natural lake sediments in the Remnant Key Lake and Little Martin sites was 3.9, similar to that in the Sediment plot and natural Ae/Aeh (Table 3).

The topsoil EC in 2010 was higher in the Pellets, NPK, Demo and Sediment plots than in the Control (*P* <0.05), but EC values were below regulatory threshold of 2.0 dS m^{-1} in most cases (Table 3). The exception was the Pellets treatment where the EC was 2.8 dS m^{-1} in 2010. The baseline EC declined significantly by 2013 only in the NPK and Pellets plots, whereby the highest EC in 2013 was 0.63 dS m^{-1} as measured in the Sediment plot but EC was below the CCME limit in all treatment plots. The topsoil SAR was below the CCME limit of 5.0 in all treatment plots in 2010 while the highest SAR level of 4.2 was in the Pellets plot compared to other treatments (Table 3). By 2013, SAR was less than 1.0 in all treatment plots with a significant temporal decline in the Pellets and Demo plots.

Significant differences in salinity among horizons (topsoil, upper subsoil and lower subsoil) are indicated by the letters in parentheses (Table 4). Soil profile distribution of pH was significantly influenced by horizon depth in all amended plots except for the NPK treatment where the pH was uniform within the profile as in the Control plot (Table 4). In other amended plots, surface application reduced the topsoil pH with the exception of the Pellets plot where the topsoil pH was higher than in the subsoils (*P* <0.05). The average data for all horizons indicated the greatest pH reduction was in the Sediment and Demo plots, followed by the Peat, LFH and NPK plots.

In the treatment plots where horizon effect was significant, the topsoil EC was higher than in the subsoils but EC was invariant with depth in the Straw and NPK profiles (Table 4). Overall, the highest EC was in the Sediment profile, followed by the Demo plot, but EC was less than 1.0 dS m^{-1} in all treatment plots in 2013. There were no statistical effects of treatment and sampling depth on SAR in 2013 as the average SAR in all treatment plots was 0.44 (Table 4). To further investigate effects of soil amendment on salt migration, soil profile distribution of soluble Na was also examined in 2013. Though there was no horizon effect on Na concentration, the mean concentration for the soil profile indicated a higher amount of soluble Na in the Sediment plot compared to other treatments (*P* <0.05).

Treatment Effects on Soil Fertility

Amounts of available nutrients and fertility levels in the topsoil were significantly influenced by year × treatment effect (Table 5). The concentration of available N was estimated as the sum of nitrate-N and ammonium-N. In 2010, the highest concentration of available N was in the NPK plot, followed by that in the Pellets and Sediment plots while amounts of available N in other amended plots were similar to 2.3 mg N kg^{-1} in the Control plot and natural site. Between 2010 and 2013, the amount of available N in the Sediment plot declined by 47% while that in the NPK and Pellets plots decreased by 96 and 94%, respectively. In 2013, as much as 17 mg N kg^{-1} was measured in the Sediment plot which was about 8-fold of that in other plots (P <0.05).

Substantial amounts of available P were in the NPK (55 mg kg^{-1}), Pellets (46 mg kg^{-1}), Demo (15 mg kg^{-1}) and LFH (10 mg kg^{-1}) plots in 2010 compared to about 5.0 mg kg^{-1} in other treatments (Table 5). The concentration of available P in the Control plot was the same as 5.0 mg P kg^{-1} in the natural site. Between 2010 and 2013, P concentration in NPK, Pellets and Demo plots declined by 70, 72 and 67%, respectively (P <0.05).

The manure pellets amendment was rich in potassium as the highest concentration of available K was measured in the Pellets plot in 2010 (Table 5). The initial concentration of K in the Pellets plot in 2010 was 240 mg kg^{-1}, followed by about 60 mg kg^{-1} in the NPK and Demo plots while the average concentration of available K in other plots was 24 mg kg^{-1}, similar to 20 mg kg^{-1} in the natural site. While amounts of available K remained unchanged over time in other treatments, K concentration declined between 2010 and 2013 by 61, 92 and 38% in the NPK, Pellets and Demo plots, respectively.

The highest concentration of available sulphate was in the Sediment (37 mg kg^{-1}) and Pellets (33 mg kg^{-1}) plots in 2010, followed by 25 mg kg^{-1} in the Peat plot and 11 mg kg^{-1} in Demo plot relative to 3.0 mg kg^{-1} in the Control (Table 5). By 2013, concentrations of available SO_4-S in the Sediment (43 mg kg^{-1}) and Demo (36 mg kg^{-1}) plots were consistently higher than in other treatments while amounts of SO_4-S in the Peat and Pellets plots declined by 76 and 95%, respectively. The concentration of SO_4-S in the Sediment plot seemed to increase over time but the difference was not significant. However, SO_4-S concentration increased three folds between 2010 and 2013 in the Demo plot (P <0.05).

In 2010, the cation exchange capacity in the Sediment plot was 14 cmol+ kg^{-1}; three times the CEC of about 4.0 cmol+ kg^{-1} in other plots and natural site (Table 5). By 2013, the CEC in the Demo plot increased from 4.0 to 10 cmol+ kg^{-1} and was similar to that in the Sediment plot (11 cmol+ kg^{-1}) while the CEC was time-invariant in other treatment plots. Baseline levels of total organic carbon (TOC) and total nitrogen (TN) in the Control plot in 2010 was 0.05 and 0.02%, respectively. These amounts of TOC and TN were similar to those in the natural site, indicating low soil fertility for the study area. However, surface application of organic-based amendments enhanced topsoil fertility in the corresponding treatment plots, whereby the TOC in the Peat and Sediment plots was as much as 2.0% in 2010 while TOC content in the LFH and Demo plots was also significantly higher than in the Control (P <0.05). By 2013, the TOC content in the Peat, Sediment, LFH, and Demo plots was still higher than in the Control. Amounts of TOC and TN in the Demo plot increased over time but total N declined in the Sediment plot in 2013. Nonetheless, the total N content in the Sediment and Demo plots in 2013 was 0.14%, compared to about 0.02% in other treatments.

Treatment Effects on Regulated Metals

Temporal variations in topsoil concentrations of metals were examined in 2010 versus 2013 and were compared with the CCME guidelines for coarse-textured soils (Table 6). Of the metals analyzed, only those shown in Table 6 were selected for discussion in this study. There was an elevated amount of arsenic in the Sediment plot in 2010 where the concentration was 45 mg kg^{-1}, about four times the CCME limit of 12 mg kg^{-1}. Amounts of arsenic in the Demo (8.4 mg kg^{-1}), LFH (4.9 mg kg^{-1}) and NPK plots (2.3 mg kg^{-1}) in 2010 were also higher than in the Control plot (1.2 mg kg^{-1}) but less than the CCME threshold while the concentration of arsenic in the natural Ae/Aeh was 0.20 mg kg^{-1}. The concentration of arsenic varied between the sediment samples obtained from the adjacent drained lakes. Arsenic concentration in the Remnant Key Lake site was 22 mg kg^{-1}, which was about twice the CCME limit, while the concentration for the Little Martin site was 2.3 mg kg^{-1}. The concentration of arsenic was statistically invariant over time in all treatment plots as the highest amount remained in the Sediment plot in 2013 (P <0.05), while that in the Demo plot was about 3-fold the CCME limit.

Except for arsenic, the concentration of other metals was below regulatory thresholds. However, substantial amounts of nickel were recovered in the Sediment (40 mg kg^{-1}) and Demo (22 mg kg^{-1}) plots over the years relative to CCME limit of 50 mg kg^{-1} (Table 6). In general, topsoil concentration of most metals was highest in the Sediment plot, followed by the Demo plot which had the highest amounts of lead and uranium (P <0.05). Considerable amounts of metals were also measured in the LFH plot, particularly for chromium, copper and lead. Though there was no significant year effect on composition of metals in most cases, the concentrations of boron and uranium declined over time in the Sediment and Demo plots, respectively (Table 6). On the other hand, the concentration of lead increased between 2010 and 2013 in all treatment plots where there was a significant temporal variation except in the Demo plot where the amount of Pb decreased by 53% over time (P <0.05).

Soil profile distribution of metals in 2013 is presented only for the Control, Sediment and Demo plots (Table 7). There were significant effects of horizon × treatment on most metals except for lead concentration, which was invariant with depth and among treatments. Concentrations of metals were statistically similar with depth in the Control plot but the highest concentration of metals was measured in the topsoil of the Sediment and Demo plots compared to the upper and lower subsoils (P <0.05). The vertical distribution of metals in the Sediment and Demo plots demonstrated the influence of surface application of amendments on metal accumulation in the topsoil. There was virtually no downward migration of metals in the soil profiles of the amended plots as concentrations of metals were similar for the upper and lower subsoil and the values were statistically similar to those in the subsoils.

Treatment Effects on Vegetation Performance

The vegetation data were averaged for all plant species in individual treatment plots. Of the species planted in the Control plot, 85% of the plant stands remained in the plot by 2013 (Fig. 4). This value was statistically similar to percent survival of species in the Peat, Straw, LFH and Pellets but much higher than 69 and 47% survival in the NPK and Sediment plots, respectively (P <0.05). The vegetative growth data were based on geometric means due to lack of normal distribution in the raw data. The highest growth was in the Pellets plot, followed by LFH, while Peat plot had the lowest growth but statistically similar to that in other treatment plots (Fig. 5).

The data for survival and growth both indicated that the Pellets treatment was best-performing in terms of vegetation establishment. In contrast, species in the Sediment plot generally had the poorest performance, particularly in terms of survival relative to the Control. Depending on the plant parameter, other treatments such as the LFH showed the potential to support vegetation establishment. In spite of the high percent survival, the Peat, Straw and NPK treatments did not improve vegetation growth relative to the Control.

Trends in foliar concentrations of metals were not consistent with those observed for the soil analysis. Unlike for the soil data where the concentration of arsenic in the Sediment and Demo plots was higher than in Control, foliar concentration of arsenic was statistically similar for the Control (0.26 $\mu g\ g^{-1}$), Sediment (0.33 $\mu g\ g^{-1}$) and Demo (0.63 $\mu g\ g^{-1}$) plots while there was a higher uptake (P <0.05) of arsenic in the LFH (2.3 $\mu g\ g^{-1}$) and Pellets (2.1 $\mu g\ g^{-1}$) plots (Table 8). In adjacent natural sites denoted as Oasis and Remnant Key Lake, foliar concentration of arsenic was similar to in the values reported for the Control and Sediment plots. Despite elevated concentration of arsenic in the Sediment and Demo topsoils, foliar concentrations of arsenic were below the critical levels (5–20 $\mu g\ g^{-1}$) for phyto-toxicity (Table 8). However, foliar concentrations of other elements such as boron, cadmium, cobalt, lead, nickel and selenium were significantly higher in the Sediment and Demo plots than in other treatment plots (P <0.05).

Foliar concentrations of some metals were above critical limits (Table 8). For instance, plant uptake of boron was within the critical range in most of the treatment plots. Plant uptake of nickel was also above toxicity thresholds in most cases with the exception of the Pellets plot and Oasis site. Other metals with elevated foliar concentrations in the treatment plots relative to the critical levels were vanadium and zinc. Overall, foliar concentrations of metals in the treatment plots and sampled natural sites were generally below critical levels in most cases with the exception of the results described above.

Temporal Distribution of Soil Moisture

To capture the effect of growing season precipitation on soil water fluxes, profiles of volumetric water contents (VMC) were plotted relative to the cumulative rainfall prior to each sampling date (Fig. 6). For the first sampling date, the cumulative rainfall was estimated as the total rainfall that occurred two weeks before the soil moisture reading, while the cumulative rainfall for subsequent moisture readings was the total rainfall prior to the sampling date. To minimize data clustering and excessive fluctuations in soil water profiles, the volumetric moisture contents were plotted at regular time intervals by selecting the VMC data for every two weeks of sampling or for sampling period closest to two weeks in some cases.

The water contents in the topsoil (0-20 cm) of the Control plot were consistently smaller than in the upper subsoil (20-50 cm) and lower subsoil (50-100 cm) in 2012 and 2013 (Fig. 6a). In 2013, the VMC increased with cumulative rainfall, with a greater accumulation of water in the subsoils relative to the topsoil. The percent VMC in the Control plot profile was below 20% during the sampling period. Unlike in the Control plot, soil water contents in the topsoil (0-10 cm) of the Peat plot were higher than in the deeper horizons, particularly in 5 July 2012 when the peak VMC in the Peat plot was 23% (Fig. 6b). The topsoil of the Peat plot responded more to rainfall in 2013 as indicated by multiple spikes in soil water distribution.

In the Sediment plot, there were greater amounts of water in the topsoil (0-10 cm) than in the subsoils with a marked response to rainfall as the VMC ranged from 20 to 42% in 2012 and from 19 to 35% in 2013 (Fig. 6c). In 2012, the highest water content in the Sediment topsoil was over 40% as measured in July 5th and August 30th, while the peak VMC in 2013 was about 35% as occurred in June 12th and October 17th. There was only a slight response to rainfall in the Straw plot as the temporal trend in VMC was relatively uniform for most part of the monitoring period. However, there was a marked response to rainfall in all three soil horizons of the Straw plot in 5 July 2012, but the water content in the straw layer (50-70 cm) remained unchanged over time (Fig. 6d). The Straw plot horizons also responded to rainfall in 2013 but the response was more noticeable in the topsoil. The imbedded straw layer generally had the smallest VMC, while the lower subsoil (70-100 cm) was wetter than other soil layers in most cases. As in the Control plot, the VMC distribution in the Straw plot also indicated accumulation of water with depth in the soil profile.

Soil water distribution in the LFH plot also indicated water accumulation in the lower subsoil (50-100 cm) relative to the topsoil (0-20 cm) and upper subsoil (20-50 cm) in both monitoring years (Fig. 6e). While there was a marked response to the peak rainfall in all three horizons of the LFH plot in 5 July 2012, only the topsoil showed considerable fluctuations in water content in 2013. The top 30 cm of the Demo plot was wetter than the entire subsoils (30-100 cm) but there was water accumulation in the lower subsoil (50-100 cm) relative to the upper subsoil (30-50 cm) in both monitoring years (Fig. 6f). Surface application of amendments by mounding influenced the VMC distribution in the Demo plot. There was a response in soil moisture to the peak rainfall in 5 July 2012 in all soil layers in the Demo plot where the VMC varied as 55% in the topsoil > 21% in the lower subsoil > 16% in the upper subsoil. In 2013, soil water contents differed remarkably between the two layers of amendment in the Demo topsoil as the VMC ranged from 19 to 36% in the LFH layer (0-20 cm) and 40 to 50% in the lake sediment layer (20-30 cm). In the deeper horizons, the VMC ranged from 10 to 16% in the upper subsoil and 8 to 20% in the lower subsoil (Fig. 6f).

Treatment Effects on Soil Moisture Contents

Statistical differences in soil moisture contents among treatments are presented only for 2013 monitoring using the average of volumetric water content (VMC_{ave}) over the entire sampling period. Soil moisture contents above wilting point in the topsoil indicate water storage and availability for plant uptake, while the water contents above field capacity in the lower subsoil are indicative of deep percolation and potential for leaching below the 100-cm profile. The propensity of a soil treatment to enhance water retention near the soil surface is expected to reduce deep percolation into the underlying waste rock.

In 2013, the topsoil VMC_{ave} in the amended plots was higher than in the Control except for the Straw treatment where the water content was statistically similar to the Control plot (Table 9). This is expected since the topsoil attributes of the Control plot were the same as the Straw plot. Amongst the amended plots, the trend in topsoil VMC_{ave} varied as Demo (37%) > Sediment (26%) > Peat (12%) ≥ LFH (10%) > Straw (5%) (P <0.05). The VMC_{ave} declined significantly in the deeper horizons relative to the topsoil in the Peat, Sediment and Demo plots but water content significantly increased with depth in the Control, Straw and LFH plots. There was water accumulation in the lower subsoil of LFH and Demo as the VMC_{ave} in these plots was consistently higher than in other plots while the smallest VMC_{ave} was in the lower subsoil of the Peat, Sediment and Straw plots. The weighted mean VMC_{ave} for the entire soil profile was estimated based on the horizon segments in each plot. The data indicated that the Demo soil profile was wettest, followed by LFH, while the Peat and Straw plots had the driest profiles.

The surplus water content (SWC), estimated as the difference between VMC_{ave} and field capacity (FC), had negative values in the topsoil of Peat and Sediment plots indicating the greatest potential for water retention in these treatments (Table 9). In contrast, the highest surplus water was in the Demo plot topsoil compared to other treatments (P <0.05). In spite of the small VMC_{ave} in the Control topsoil, the SWC increased with depth as in the amended plots with significantly higher levels of surplus water in the lower subsoil of the Control, LFH and Demo plots compared to other treatments. In the Demo plot, most of the excess water was retained in the topsoil and lower subsoil with 11% SWC relative to 7% in the upper subsoil (P <0.05). The significant accumulation of water in the lower subsoils of the Control, LFH and Demo plots may have implication on deep percolation into the underlying waste rock. According to the weighted mean SWC, the greatest surplus water content was in the LFH and Demo profiles compared to other treatments.

The available water content (AWC) is indicative of plant water supply and was estimated as FC minus permanent wilting point (PWP). The available water levels were influenced by soil amendments only in the topsoil since the Control plot data were used to estimate the water retention values for subsoil layers of all treatment plots (Table 9). The topsoil data indicated that only the Sediment and Demo treatments improved the AWC relative to the Control but there was also a considerable amount of available water in the Peat topsoil where the AWC was statistically similar to that in the Sediment and Demo plots. The AWC results indicated that the Sediment, Demo and Peat treatments had the greatest potential to retain available water in the topsoil for plant uptake.

DISCUSSION

Soil Fertility and Vegetation Performance

While addition of lake sediment amendment to the plots resulted in the lowest soil pH, the manure pellets plot maintained a neutral to slightly alkaline pH relative to the Control. In spite of the presence of the manure pellets in the Demo plot, in addition to lake sediment and LFH layers, the sediment material had a stronger influence on the Demo soil pH. The significant reduction in soil pH by the lake sediment amendment may be attributed to production of hydrogen ion from oxidation of iron and aluminum oxides, hydroxides or sulphides, which are commonly abundant in lake sediment materials (Cummings et al. 2000; Leybourne 2001). Nonetheless, there was no concern with salinity and sodicity in all treatment plots as EC and SAR levels were less than 1.0 and were below regulatory thresholds in 2013.Nitrogen concentration and fertility levels in the Sediment plot were consistently higher than in other treatments, followed by the Demo plot, but the Pellets plot had the highest available P and K contents. As for pH, soil fertility in the Demo plot was largely influenced by inclusion of lake sediment amendment. It is also likely that addition of lake sediment and manure pellets contributed to the higher concentration of SO_4-S in the Demo plot relative to the Control in 2010. However, the manure pellets seemed to contribute to substantial amounts of P and K in the Demo plot while the highest baseline amounts of available N and K in the NPK plot was due to the readily available nutrients in the synthetic fertilizer.

Variations in nutrient composition and soil fertility among treatment plots may be due to differences in the amount applied, forms and reactivity with soil components. As noted earlier, the amendments were applied at varying depths across treatment plots in accordance with operational objectives as opposed to treatment application based on fixed rate of nutrient composition. This could have contributed to variable amounts of nutrients and fertility levels among treatment plots. While nutrients such as NO_3-N, K and SO_4-S are more soluble and mobile, available P could be tied up by Al and Fe under acidic soil conditions where soluble P exists mainly in the mono-phosphate form (Havlin et al. 2005). The retention of available P by Al and Fe is particularly critical in Sediment and Demo plots and other treatments where the pH was significantly lower than in the Control.

It is intuitive that amendments with higher organic matter contents would enhance the CEC, total organic carbon and total N, which are indicative of soil nutrient capital in reclaimed soils (Larney and Angers 2012). The organic-based amendments in this study were peat, lake sediment, mulched LFH and manure pellets. However, only the sediment-amended treatments (i.e., Sediment and Demo plots) improved the CEC level relative to the Control. While the total organic carbon contents in the Peat, Sediment, LFH and Demo plots was higher than in the Control in 2013, the Straw and Pellets treatments did not improve the TOC relative to the Control plot. This is expected for the Straw treatment since the flax straw was buried below 50 cm depth. Though the initial concentrations of available nutrients and TOC in the Pellets plot were higher than in the Control in 2010, differences in fertility levels were not statistically significant in 2013. Nonetheless, the Pellets treatment had a greater potential to improve soil fertility considering its high amounts of available P and K compared to the Control.

The poor performance of the Pellets treatment on TOC relative to the Sediment and Demo plots may be due to rapid mineralization of organic matter in the manure pellets, given that the background TOC of the manure pellets (30%) was higher than 15 and 0.82% characterized for the lake sediment and mulched LFH, respectively (Table 1). In a review of the role of organic amendments in soil reclamation, Larney and Angers (2012) reported that the rate of decomposition of organic amendments and composition of residual soil organic carbon are dependent on the intrinsic quality of the amendment (Lashermes et al. 2009). Therefore, readily bioavailable organic amendments such as manure pellets are less likely to contribute to long-term storage of soil carbon compared to the more recalcitrant, lignin-rich amendments such as the mulched LFH (Larney and Angers 2012). However, there is limited study comparing the influence of lake sediments on organic carbon composition and soil quality relative to other types of amendments.

The LFH treatment did not improve nutrient composition relative to the Control as expected in spite of the higher fertility and nutrient pools often associated with LFH material (Mackenzie and Naeth 2010). This may be due to admixing of the natural LFH with mineral soil in this study. As indicated by soil fertility data for the natural Ae/Aeh horizon, there was a marked nutrient deficiency in the native mineral soil. Overall, the lake sediment appeared to be the best performing amendment with respect to soil fertility despite its characteristic low pH.

Regulated Metals and Vegetation Performance

For soil metal composition, only the concentration of arsenic was above regulatory threshold as the amount remaining in the Sediment and Demo topsoils in 2013 was 3.4- and 2.6-fold more than the CCME limit. Studies have shown that adsorption-desorption process of Fe and Al oxides/sulphides is the main factor controlling arsenic behavior in soil and sediment (John and Leventhal 1995; Kabata-Pendias 2011). Following ion exchange by Al and Fe oxides, the development of acidic and oxidizing conditions in soils tends to release large amounts of arsenic into solution (Leonard 1991; John and Leventhal 1995). In this study, the elemental concentration of Al in the Sediment and Demo plots in 2013 was higher than in other treatments and was twice of that in the Control, while the concentration of Fe in the Control plot was just 2% of that in the sediment-amended plots (data not shown). Therefore, substantial levels of Al and Fe in the sediment-amended plots support the statement above regarding the influence of ion exchange and proton release on arsenic concentration.

While arsenate [As(V)] and arsenite [As(III)] are the dominant forms of arsenic in soils, the bioavailability, mobility and toxicity of As depends on its oxidation state and pH of the soil solution (Masscheleyn et al. 1991; Tu and Ma 2003; Kabata-Pendias 2011). Studies have shown that the solubility of As(V) decreases at low pH with increasing concentration of As(III), whereas the solubility of As(V) increases as the pH increases (Gulens et al. 1979; Tu and Ma 2003; Kabata-Pendias 2011). Although arsenite [As(III)] is more toxic and mobile than arsenate [As(V)] in soils, As(V) is the dominant species in most oxidized environmental conditions with near neutral pH (Kabata-Pendias 2011). Given that the determination of soil concentration of arsenic in this study was based on the elemental composition, it is difficult to ascertain whether the speciation of As in soil pore-water of the sediment-amended plots was largely composed of As(III) or As(V) considering the low pH in these treatments. Even though soil fertility levels were higher in the Sediment and Demo plots, the overall soil quality was compromised by the low pH and elevated concentration of arsenic.

The poor plant survival and growth in the Sediment plot reflected the influence of adverse soil chemistry on vegetation performance. Amongst treatment plots, species in the Pellets plot were best-performing while the LFH plot also had potential to support vegetation establishment. The positive influence of the manure pellets on plant performance may be attributed to its ability to supply nutrients early after planting and to maintain a neutral soil pH that would promote microbial activity and nutrient cycling. In contrast, substantial reduction in soil pH and elevated concentrations of metals in the Sediment plot possibly had implications on plant toxicity, thereby inhibiting species survival and vegetative growth.

Though the topsoil concentration of arsenic in the Sediment plot was above the CCME limit, soil metal data for the adjacent drained lake sediments indicated a marked variability in metal composition as arsenic concentration at the Little Martin site was about one-sixth of the CCME limit while the amount at Remnant Key Lake was twice the regulatory threshold. These results indicated that elevated concentration of arsenic in the Sediment treatment plot is naturally occurring as opposed to contamination resulting from soil reconstruction. It is also likely that the arsenic level may be lower depending on the source of the lake sediment material. More so, the pH of about 4.0 in the sediment-amended plots was similar to that in the natural Ae/Aeh horizon and drained lake sediments (Table 3), suggesting that the native plant species may be tolerant or can adapt to this pH level. Nonetheless, a higher or near neutral pH range is required for optimum soil ecological functions, and for facilitating vegetative growth following plant establishment in boreal forest reclamation (Howat 2000).

Foliar concentrations of metals were determined to examine the implication of metal composition in the amendments on vegetation performance. Unlike for soil analysis, foliar concentration of arsenic was statistically invariant among the Control, Sediment and Demo plots. These results indicated that the total composition of arsenic in the soil did not correspond with plant uptake. In the LFH and Pellets plots where there was better vegetation performance, foliar concentrations of arsenic were higher than in the Sediment plot which had a poor plant survival and growth. More so, foliar concentration of arsenic in the Sediment plot was below the critical level for toxicity (Table 8). This implies that the poor vegetation performance in the Sediment plot may not be entirely consequential to arsenic toxicity. Perhaps other factors such as the low soil pH contributed immensely to adverse effect of arsenic composition on soil microbes, nutrient cycling and root activity, which could ultimately inhibit plant uptake of water and nutrients (Wong 2003). In a phytoremediation study in metal contaminated sites, Sheoran et al. (2012) reported that decrease in rhizosphere pH increased the bioavailability of heavy metals that were tightly bound to the soil, and this could contribute to root stress and toxicity.

Given that low soil pH is commonly associated with arsenic speciation and toxicity (Leonard 1991; John and Leventhal 1995; Kabata-Pendias 2011), the adverse chemistry of the lake sediment amendment can be ameliorated with application of lime such as calcium carbonate (USEPA 2007; Sheoran et al. 2010) in order to raise the pH to the regulatory thresholds.

Soil Water Dynamics and Solute Distribution

The Demo topsoil was most effective in promoting infiltration and retaining infiltrated water compared to other treatment plots. Though the multi-layered amendments enhanced moisture supply in the Demo plot, the silty-loam sediment layer demonstrated a greater potential for water retention than the loamy-sand LFH layer which was relatively more coarse-textured. The volumetric moisture profiles suggested that creation of layering effect with textural contrast, as shown for the LFH and sediment materials in the Demo topsoil, is an effective strategy for improving water retention in reconstructed soil profiles.

In heterogeneous soil layers where a coarse-textured layer is overlying a fine-textured material, the discontinuity in soil texture would result in perched water at the interface of the two soil layers and within the underlying soil layer (Hillel 2004). This multi-layered soil cover configuration has been widely tested in soil capping prescriptions in the oil sands reclamation research (Barbour et al. 2007; Zettl et al. 2011). Based on infiltration tests on seven natural coarse-textured sites within the boreal forest in northeastern Alberta, Zettl et al. (2011) showed that field capacity moisture contents of topsoils increased with textural heterogeneity, and were directly associated with ecosite productivity.

Substantial amounts of surplus moisture in the Demo and LFH plots could be attributed to effects of soil surface configuration on water distribution in the profile. In addition to the multi-layered topsoil, application of amendments to the Demo plot by mounding resulted in a micro-hummocky surface configuration. As such, the presence of localized micro-depressions on the Demo plot surface may be acting as “funnels” or flow channels for collecting water at the soil surface with substantial infiltration into the profile. This may also explain the large amount of surplus water in the LFH soil profile. Unlike in the LFH plot however, the Demo plot was able to retain a larger proportion of infiltrated water near the soil surface compared to volumes of water in the subsoils. The presence of substantial surplus water in the lower subsoil of the Demo plot may be due to water breaking through from the fine-textured topsoil into the coarse-textured upper subsoil, and subsequent accumulation in the lower subsoil. This flow phenomenon, whereby water moves from a finer-textured soil layer into an underlying coarse-textured layer, is known as fingered flow and is associated with by-pass or preferential flow mechanisms in stratified soils (Kung 1990; Parlange et al. 2002; Hillel 2004).

In the Sediment and Peat plots, amendments were added directly to the soil surface and rototilled, thereby modifying the surface condition relative to the Control plot. The high organic matter characteristic of the Sediment and Peat treatments clearly enhanced the moisture holding capacity, as indicated by greater levels of FC and PWP compared to the Control and Straw topsoils. Due to high water retention capacity of the Sediment and Peat topsoil, there was minimal surplus water contents in the soil profile. Relative to other treatments, the lower subsoils of the Control, LFH and Demo plots demonstrate the greatest risk of water percolation and net leaching into the underlying waste rock. As the vegetation community develops over time however, the evapotranspiration process is expected to reduce the surplus water in the LFH and Demo soil profiles, suggesting that these treatment plots will be most resilient to drought.

The Straw plot had the driest soil profile compared to other amended plots, suggesting that the Straw treatment had the least potential for root-zone water storage. This is unlike in a previous study at the DNWRP site by Leskiw et al. (2011), where the Straw and Demo treatments showed the potential to improve soil water storage. Leskiw et al. (2011) found that the placement of flax straw below 50 cm depth improved the available water holding capacity (AWHC) by 10% of that in the Control plot as estimated using the water retention model in the Land Capability Classification System (LCCS) for northern Alberta forest ecosystem (AENV 2007). Their result (Leskiw et al. 2011) agreed with the earlier finding of Fleming et al. (2010) which showed that a flax straw layer buried at 30 cm depth in 100-cm laboratory columns, increased the AWHC by 15% of that in the control column without a capillary barrier. Though estimation of AWHC in the Straw plot by Leskiw et al. (2011) was based on the texture, coarse fragments and layering effect of the soil profile as inferred in the LCCS model (AENV 2007), it is likely that evapotranspiration and other external factors influenced the soil moisture retention of the Straw treatment in the present study.

While the imbedded straw layer is expected to intercept downward transmission of water, the Straw treatment did not improve soil moisture storage relative to the Control and this could be due to soil water depletion by evapotranspiration in the upper soil layer or by net percolation below the straw layer. Unlike in other plots, the top 50 cm of the Straw plot was excavated and the flax straw was imbedded to create a capillary break. Though the soil texture in the Straw plot was sand, other physical attributes such as soil structure and pore geometry in the upper profile had been altered by loosening following soil excavation and replacement. As such, the loose soil matrix would promote infiltration and rapid water transmission in the upper profile of the Straw plot relative to the Control plot.

The differing types of amendments applied to the Demo plot variably influenced its chemical and physical attributes. While the chemical properties and moisture retention in the Demo topsoil were strongly influenced by the presence of lake sediment, soil moisture distribution in the Demo profile was similar to that in the LFH plot. In above-normal rainfall event, with substantial amounts of surplus water in the lower subsoil, the Demo and LFH plots may be prone to deep percolation with a risk of solute migration by baseflow.

Though EC level and metal composition generally declined with depth in the treatment plots in 2013, the EC level in the lower subsoil of the Sediment and Demo plots was greater than in the Control and other amended plots, indicating net downward movement of soluble salts in these sediment-amended plots three years after soil reconstruction. However, this was not the case with the metals which were significantly retained in the topsoil, while the subsoil concentrations of metals were similar across treatment plots. The discrepancy in soil profile distribution of salts and metals could be due to EC being a measure of concentration of soluble salt, while a significant proportion of the metals seemed to be in non-soluble form and hence, were relatively immobile. More so, the higher organic carbon content in the Demo and Sediment topsoils relative to the Control implied the potential for organic matter to retain metals in the topsoil in organically-bound forms (Hsu and Lo, 2001).

Given that the low salinity level in the treatment plots generally indicates “good” soil quality, substantial concentrations of metals in the topsoil also suggested that the metals were largely immobile; hence, there is a minimal risk of solute migration below the reconstructed soil profile. It is also important to acknowledge the role of plant uptake on soil moisture and solute distribution in the long-term. In mature vegetation stands, it is expected that evapotranspiration will reduce surplus water in the soil profile, and subsequently reducing the extent of solute leaching.

Recommendations for Future Reclamation

The overall goal of the plot trial is to develop recommendations on soil amendments and capping techniques for the DNWRP waste rock pile at the Key Lake uranium facility. The greatest limitations to re-establishing vegetation on the rock pile are nutrient deficiency and low moisture supply, which are typical of the coarse-textured soil cover materials available at this region. Considering the best performing attributes of the Demo treatment on soil fertility and moisture retention, these findings suggest that recommendations for future soil capping at the DNWRP site should be based on a combination of organic-based materials.

The positive influence of combining multiple amendments on mine reclamation was demonstrated by de Varennes et al. (2010). The study investigated application of mineral fertilizers, compost and polyacrylate polymers to pyrite mine spoils in an attempt to promote the growth of indigenous plant species (de Varennes et al. 2010). The greatest biomass was obtained in the fertilized soil receiving both the compost and polymers amendments compared to the unamended soil (control), fertilizer only, fertilizer plus compost, or fertilizer plus polyacrylate polymers (de Varennes et al. 2010).

The organic materials used as surface amendments in the present study were commercial peat moss, lake sediment, mulched LFH and manure pellets. Unlike the surface amendments, the underlying straw treatment was not effective at improving soil fertility, moisture storage and vegetation growth relative to the Control. While peat is widely used as amendment and soil cover material in the Alberta oil sands reclamation, the commercial peat moss used in this study had no significant contribution to soil fertility and vegetation performance relative to the Control. Therefore, the peat treatment may not be considered as a future soil amendment based on these findings.

Though the lake sediment amendment had low pH and elevated metal composition, it clearly contributed to the soil fertility status, particularly in the Demo plot. The high water retention characteristic of the lake sediment also contributed to soil moisture storage capacity of the Demo plot. Despite the poor vegetation performance in the Sediment plot, the lake sediment material has valuable properties as a potential amendment for future reclamation provided the low pH can be ameliorated by liming in order to raise the pH level. Addition of other organic amendments with lake sediment may also help to dilute the composition of arsenic in the material as in the Demo plot, where the inclusion of manure pellets and mulched LFH reduced the topsoil concentration of arsenic by one-half over the years relative to that in the Sediment plot (Table 6).

While the fertility status in the LFH treatment was only superior to the Control based on the total organic carbon, there was a greater moisture supply and vegetation growth in the LFH plot. As such, the superior vegetation performance of LFH treatment relative to the Control may be due to its higher organic carbon content and the potential of the mounded surface amendment to promote localized microsites and infiltration in the topsoil. Therefore, the mulched LFH amendment, coupled with the capping technique by surface mounding, has the potential to support reclamation and vegetation establishment at the Key Lake site.

Of the organic amendments applied in this study, the manure pellets had the highest pH and greatest amounts of available N, P and K following soil reconstruction in 2010. This implies that the manure treatment was capable of supplying adequate nutrients during early growth stage as indicated by the best vegetation performance in the Pellets plot compared to other treatments. Addition of manure pellets to the Demo plot also improved the available P and K contents. Though the Pellets plot was not tested for soil moisture distribution, the rich source of nutrients in the manure pellets will enhance its ability to support vegetation establishment, especially if combined with other amendments with high moisture retention capacity.

According to the foregoing, a combination of two or three of the organic amendments is the best strategy for achieving adequate nutrient and water supply, and ultimately vegetation establishment on the waste rock pile. This was demonstrated in the Demo treatment plot which was best-performing in terms of overall fertility and soil moisture storage. Although vegetation performance of the Demo plot was not included in the data analysis due to inherent variability in number of planted species, visual assessment of the Demo plot indicated adequate plant growth and species survival. For future reclamation, we therefore recommend that the soil profile be capped by surface mounding with multiple layers of organic amendments such as lake sediments, LFH material and manure pellets. The rates of individual amendments can be refined effectively in future application by estimating the composition of nutrients and metals accompanying various amounts of materials to be added.

CONCLUSIONS

Effects of various amendments and capping techniques on soil quality were evaluated in profiles reconstructed on a waste rock pile at Cameco's Key Lake uranium facility. Treatment plots were denoted as Control, Peat, Sediment, Straw, LFH, NPK, Pellets and Demo. The composition of soluble salts was very low in the reconstructed soils as EC and SAR values were below CCME limits three years after reclamation. Of the treatments applied, organic amendments such as lake sediment, mulched LFH and manure pellets had the greatest potential to improve nutrient supply and soil fertility, while the manure pellets plot had the best vegetation performance. As for soil moisture supply, the Sediment and Demo plots were most effective in retaining water in the topsoil, while application of amendment by surface mounding in the LFH and Demo plots enhanced infiltration and water transmission into the profile.

Though vegetation performance was generally poor in the Sediment plot, coupled with low pH and elevated levels of metals, the lake sediment material had a substantial fertility and water retention capacity to be considered as a favourable amendment for future soil capping. The LFH amendment also had higher organic carbon content than the Control and may be beneficial for promoting infiltration if applied by surface mounding. For optimum nutrient supply, manure pellets can be applied over the topsoil constructed with LFH and lake sediment layers without rototilling. Based on soil fertility and moisture retention capacity, application of multiple amendments plus surface mounding, as in the Demo plot, is the most promising capping technique for restoring soil quality, vegetation community and ecosystem functions on the waste rock pile.

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Table 1. Soil treatments comprising of various amendments, characteristics and methods of application

Treatment	Amendment	Background characteristics[z]			Method of application	Topsoil thickness (cm)
		TOC (%)	Total N (%)	pH		
Control	No amendment	–	–	–	No disturbance	20
Peat	Commercial peat moss (Sunshine Peat™)	38	0.8	4.5	Applied at 6-12 cm depth, incorporated using a rototiller	10
Sediment	Lake sediment from a former lake bottom	15	1.6	3.9	Applied at 6-10 cm depth, incorporated by rototilling at 1:1 sediment to soil ratio	10
Straw	Flax straw	–	–	–	20 cm layer of flax straw placed as a capillary break below the surface at 50-70 cm	20
LFH	Mulched native LFH (forest floor) and Ae materials	0.82	0.02	4.9	Mounded to create micro-hummocky surface configuration (no rototilling)	20
NPK	18-24-11 (N-P-K) fertilizer	–	–	–	Broadcast on soil surface at 400 kg ha^{-1} (no rototilling)	20
Pellets	Processed manure pellets (EarthRenew™)	30	1.8	>8.0	Broadcast at 20 tonnes ha^{-1} and incorporated using a rototiller	10
Demo	Demonstration plot with multiple amendments	–	–	–	10 cm layer of lake sediment + 20 cm of LFH, mounded to create a micro-hummocky surface + manure pellets by broadcast on soil surface at 6.7 tonnes ha^{-1} (no rototilling)	30

[z]Background characteristics of amendments based on total organic carbon, total N and pH prior to application to the plot. The characteristics of peat moss and manure pellets were obtained from the product analysis, while properties of natural lake sediment and mulched LFH were lab analysis of local materials sampled from similar sources in 2014.

Table 2. Soil parameters and analytical methods

Soil property	Parameter	Analytical method[y]	Equipment[x]	Reference
Salinity	pH, electrical conductivity (EC), sodium adsorption ratio (SAR), and soluble Na	Saturated paste extract	Ion Selective Electrode with pH/EC meter; ICP-AES for soluble ions	Hendershot et al. 2008; Miller and Curtin 2008
Fertility	Available nitrogen (sum of nitrate-N and ammonium-N), available phosphorus, potassium and sulphate, cation exchange capacity (CEC), total organic carbon (TOC), and total nitrogen (TN)	NO_3-N and NH_4-N extracted with 2.0 M KCl	CFC	Maynard et al. 2008
		Available P and K by Modified Kelowna Soil Test	CFC	Ashworth and Mrazek 1995
		SO_4-S extracted with 0.1 M $CaCl_2$	ICP-AES	McKeague 1978
		CEC and exchangeable cations with 1.0 M NH_4OAc extraction at pH 7	ICP-AES for exchangeable cations; CFC for NH_4^+	McKeague 1978
		Total organic C and total N by combustion method	LECO combustion analyzer	Nelson and Sommers 1996; Bremner 1996
Metals[z]	Arsenic (As), boron (B), cadmium (Cd), chromium (Cr), cobalt (Co), copper (Cu), lead (Pb), nickel (Ni), selenium (Se), tin (Sn), uranium (U), vanadium (V), and zinc (Zn)	Boron extracted in hot water using the azomethine-H method	ICP-MS	Gupta 1967; McKeague 1978
		Other metals extracted by strong acid digestion (SW-846 Method 3050B)	ICP-MS	USEPA 1996

[z]The following are regulated metals selected for discussion in the present study.
[y]Analytical methods according to Exova Canada Inc. Edmonton, Alberta.
[x]Equipment: pH meter (Fisher Scientific Accumet AR15 pH meter); EC meter (Radiometer Analytical CDM210 Conductivity meter); ICP-AES = Inductively Coupled Plasma-Atomic Emission Spectroscopy (Thermo Fisher ICAP6500); CFC = Continuous Flow Colorimetry (Astoria Pacific A2 Autoanalyzer); LECO = Laboratory Equipment Corporation (TruMac CNS Macro Determinator); ICP-MS = Inductively Coupled Plasma-Mass Spectrometry (Perkin Elmer Elan 9000).

Table 3. Temporal variations in topsoil salinity among treatments

Parameter	Effect	*P*-value	Year	Treatment[y]								Natural Ae/Aeh	Little Martin[x]	Rem. Lake[w]	CCME limit[v]
				Control	Peat	Sediment	Straw	LFH	NPK	Pellets	Demo				
pH	Year(Y)	<0.001	2010	6.8*b*(*a*)	4.8*d*	4.1*e*	5.9*c*	4.9*d*	7.0*b*(*a*)	7.8*a*(*a*)	5.3*cd*(*a*)	4.0	3.9	3.9	6.0-8.0
	Treatment(T)	<0.001	2013	6.3*b*(*b*)	5.0*c*	3.9*d*	5.7*b*	5.0*c*	5.8*b*(*b*)	7.1*a*(*b*)	4.3*cd*(*b*)				
	Y × T	0.010	Mean	6.6*b*	4.9*d*	4.0*e*	5.8*c*	5.0*d*	6.4*b*	7.4*a*	4.8*d*				
EC ($dS\ m^{-1}$)	Year(Y)	<0.001	2010	0.17*d*	0.39*cd*	0.58*c*	0.11*d*	0.19*d*	1.2*b*(*a*)	2.8*a*(*a*)	0.61*c*	0.12	0.33	0.29	2.0
	Treatment(T)	<0.001	2013	0.070*d*	0.15*cd*	0.63*a*	0.060*d*	0.13*cd*	0.09*cd*(*b*)	0.21*c*(*b*)	0.41*b*				
	Y × T	<0.001	Mean	0.12*c*	0.27*bc*	0.61*b*	0.088*c*	0.16*c*	0.66*b*	1.5*a*	0.51*b*				
SAR[z]	Year(Y)	0.001	2010	0.57*b*	0.20*b*	0.17*b*	0.47*b*	0.20*b*	0.73*b*	4.2*a*(*a*)	0.97*b*(*a*)	0.40	0.15	0.30	5.0
	Treatment(T)	<0.010	2013	0.33	0.17	0.38	0.37	0.20	0.30	0.17(*b*)	0.17(*b*)				
	Y × T	0.001	Mean	0.45*b*	0.18*b*	0.27*b*	0.42*b*	0.20*b*	0.52*b*	2.2*a*	0.57*b*				

[z]Treatment means are geometric means derived by back-transformation of natural log values of the raw data.
[y]Treatment means with the same letter(s) across the row are not statistically different at *P* <0.05. Significant differences between 2010 and 2013 are indicated by letters in parentheses.
[x]Salinity parameters in sediments of a previously drained lake known as Little Martin.
[w Y]Salinity parameters in sediments of a previously drained lake known as Remnant Key Lake.
[v]CCME limit according to the guidelines for coarse-textured soil in residential/parkland sites (CCME 2007).

Table 4. Soil profile distribution of salinity and soluble sodium among treatments in 2013

Parameter	Effect	*P*-value	Horizon[y]	Treatment[x]							
				Control	Peat	Sediment	Straw	LFH	NPK	Pellets	Demo
pH	Horizon (H)	<0.001	TS	6.3*b*	5.0*c*(*b*)	3.9*d*(*b*)	5.7*b*(*b*)	5.0*c*(*b*)	5.8*b*	7.1*a*(*a*)	4.3*cd*(*b*)
	Treatment (T)	<0.001	US	6.1*a*	5.8*ab*(*a*)	5.7*ab*(*a*)	6.0*a*(*ab*)	5.9*ab*(*a*)	5.4*b*	6.4*a*(*b*)	5.2*b*(*a*)
	H × T	<0.001	LS	6.0*a*	5.8*ab*(*a*)	5.1*b*(*a*)	6.3*a*(*a*)	5.8*ab*(*a*)	5.5*b*	6.1*a*(*b*)	5.3*b*(*a*)
			Mean	6.1*ab*	5.5c	4.9*d*	6.0*b*	5.6c	5.6c	6.5*a*	4.9*d*
EC (dS m^{-1})	Horizon (H)	<0.001	TS	0.07*d*	0.15*cd*(*a*)	0.63*a*(*a*)	0.06*d*	0.13*cd*(*a*)	0.09*cd*	0.21*c*(*a*)	0.41*b*(*a*)
	Treatment (T)	<0.001	US	0.05	0.06(*b*)	0.12(*b*)	0.05	0.05(*b*)	0.05	0.07(*b*)	0.13(*b*)
	H × T	<0.001	LS	0.06*b*	0.07*b*(*b*)	0.19*a*(*b*)	0.07*b*	0.07*b*(*b*)	0.06*b*	0.08*b*(*b*)	0.15*ab*(*b*)
			Mean	0.06*d*	0.09*c*	0.31*a*	0.06*d*	0.08*c*	0.07*cd*	0.12*c*	0.23*b*
SAR[z]	Horizon (H)	0.371	TS	0.33	0.17	0.38	0.37	0.20	0.30	0.17	0.17
	Treatment (T)	0.105	US	0.50	0.40	1.9	0.47	0.43	0.50	0.60	0.30
	H × T	0.832	LS	0.53	0.33	0.53	0.43	0.37	0.43	0.43	0.27
			Mean	0.46	0.30	0.94	0.42	0.33	0.41	0.40	0.24
Soluble Na (mg kg^{-1})[z]	Horizon (H)	0.233	TS	0.67	1.3	4.7	0.67	1.0	0.67	1.0	1.7
	Treatment (T)	<0.001	US	1.0	0.67	2.7	1.0	0.33	0.00	1.0	1.0
	H × T	0.899	LS	0.67	0.67	2.3	1.0	0.67	0.67	1.0	0.67
			Mean	0.78*b*	0.89*b*	3.2*a*	0.89*b*	0.67*b*	0.44*b*	1.00*b*	1.1*b*

[z]Treatment means are geometric means derived by back-transformation of natural log values of the raw data.
[y]Horizon depths, where TS = Topsoil (0-10 cm), US = Upper Subsoil (10-50 cm), and LS = Lower Subsoil (50-100 cm).
[x]Treatment means with the same letter(s) across the row are not statistically different at *P* <0.05. Significant differences among horizons are indicated by letters in parentheses.

Table 5. Temporal variations in topsoil fertility among treatment plots

Parameter	Effect	*P*-value	Year	Treatment[y]								Natural Ae/Aeh
				Control	Peat	Sediment	Straw	LFH	NPK	Pellets	Demo	
				mg kg^{-1} soil								
Available N[z]	Year(Y)	<0.001	2010	2.3*c*	8.1*c*	32*b*(*a*)	2.3*c*	2.3*c*	52*a*(*a*)	39*b*(*a*)	3.1*c*	2.3
	Treatment(T)	<0.001	2013	2.3*b*	2.3*b*	17*a*(*b*)	2.3*b*	2.3*b*	2.3*b*(*b*)	2.3*b*(*b*)	2.5*b*	
	Y × T	<0.001	Mean	2.3*b*	5.2*b*	24*a*	2.3*b*	2.3*b*	27*a*	21*a*	2.8*b*	
Available P[z]	Year(Y)	<0.001	2010	5.0*d*	5.3*d*	5.0*d*	5.0*d*	10*cd*	55*a*(*a*)	46*b*(*a*)	15*c*(*a*)	5.0
	Treatment(T)	<0.001	2013	5.0*b*	5.0*b*	5.0*b*	5.0*b*	7.0*b*	17*a*(*b*)	13*a*(*b*)	5.0*b*(*b*)	
	Y × T	<0.001	Mean	5.0*b*	5.2*b*	5.0*b*	5.0*b*	8.3*b*	36*a*	30*a*	10*b*	
Available K[z]	Year(Y)	<0.001	2010	23*c*	25*c*	25*c*	22*c*	27*c*	57*b*(*a*)	240*a*(*a*)	61*b*(*a*)	20
	Treatment(T)	<0.001	2013	20*b*	20*b*	23*b*	20*b*	22*b*	22*b*(*b*)	20*b*(*b*)	38*a*(*b*)	
	Y × T	<0.001	Mean	22*c*	23*c*	24*c*	21*c*	24*c*	39*bc*	130*a*	50*b*	
Available SO_4-S[z]	Year(Y)	0.108	2010	3.0*c*	25*ab*(*a*)	37*a*	2.3*c*	4.0*c*	6.7*c*	33*a*(*a*)	11*b*(*b*)	1.7
	Treatment(T)	<0.001	2013	1.7*c*	6.0*bc*(*b*)	43*a*	2.3*c*	2.7*c*	2.3*c*	1.7*c*(*b*)	36*b*(*a*)	
	Y × T	<0.001	Mean	2.3*c*	16*b*	40*a*	2.3*c*	3.3*c*	4.5*c*	17*b*	24*b*	
				cmol+ kg^{-1}								
CEC	Year(Y)	0.411	2010	4.0*b*	5.0*b*	14*a*	4.0*b*	4.0*b*	4.0*b*	4.0*b*	4.0*b*(*b*)	4.0
	Treatment(T)	<0.001	2013	4.0*b*	5.0*b*	11*a*	4.0*b*	4.0*b*	4.0*b*	4.0*b*	10*a*(*a*)	
	Y × T	0.026	Mean	4.0*b*	5.0*b*	12*a*	4.0*b*	4.0*b*	4.0*b*	4.0*b*	7.2*b*	
				% Dry weight								
Total Organic C	Year(Y)	0.867	2010	0.05*c*	1.7*a*	2.0*a*	0.05*c*	0.82*b*	0.05*c*	0.14*bc*	0.87*b*(*b*)	0.26
	Treatment(T)	<0.001	2013	0.05*c*	0.94*b*	1.7*ab*	0.05*c*	0.71*b*	0.05*c*	0.06*c*	2.0*a*(*a*)	
	Y × T	0.034	Mean	0.05*c*	1.3*ab*	1.9*a*	0.05*c*	0.77*b*	0.05*c*	0.10*bc*	1.5*a*	
Total N	Year(Y)	0.158	2010	0.01*b*	0.04*b*	0.20*a*(*a*)	0.01*b*	0.02*b*	0.01*b*	0.03*b*	0.02*b*(*b*)	0.02
	Treatment(T)	<0.001	2013	0.02*b*	0.03*b*	0.14*a*(*b*)	0.02*b*	0.03*b*	0.02*b*	0.02*b*	0.14*a*(*a*)	
	Y × T	<0.001	Mean	0.02*c*	0.04*bc*	0.17*a*	0.02*c*	0.02*c*	0.02*c*	0.02*c*	0.08*b*	

[z]Treatment means are geometric means derived by back-transformation of natural log values of the raw data.

[y]Treatment means with the same letter(s) across the row are not statistically different at *P* <0.05. Significant differences between 2010 and 2013 are indicated by letters in parentheses.

Table 6. Temporal variations in topsoil concentrations of selected metals among treatments

Metal	Effect	P-value	Year	Treatment[y] Control	Peat	Sediment	Straw	LFH	NPK	Pellets	Demo	Natural Ae/Aeh	Little Martin[x]	Remnant Key Lake[w]	CCME limit[v]
				mg kg^{-1} soil											
As[z]	Year(Y)	0.347	2010	1.2	0.50	45	0.60	4.9	2.3	0.50	8.4	0.20	2.3	22	12
	Treatment(T)	<0.001	2013	1.1	1.0	41	0.40	5.0	0.83	0.63	31				
	Y × T	0.163	Mean	1.1*c*	0.77*c*	43*a*	0.50*c*	5.0*c*	1.6*c*	0.57*c*	20*b*				
B	Year(Y)	0.931	2010	0.20*b*	–	1.3*a*(*a*)	–	–	–	–	0.37*b*	–	0.60	0.87	–
	Treatment(T)	<0.001	2013	0.20*b*	–	0.92*a*(*b*)	–	–	–	–	0.75*a*				
	Y × T	0.044	Mean	0.20*b*	–	1.1*a*	–	–	–	–	0.56*b*				
Cd	Year(Y)	0.851	2010	0.01	0.01	0.097	0.01	0.01	0.01	0.01	0.02	0.01	0.25	0.11	10
	Treatment(T)	<0.001	2013	0.01	0.01	0.07	0.01	0.01	0.01	0.01	0.06				
	Y × T	0.101	Mean	0.01*b*	0.01*b*	0.08*a*	0.01*b*	0.01*b*	0.01*b*	0.01*b*	0.04*ab*				
Cr[z]	Year(Y)	0.212	2010	1.0	0.73	2.6	0.70	1.7	1.2	0.87	1.8	0.50	8.9	8.6	64
	Treatment(T)	<0.001	2013	0.93	0.73	1.8	0.63	0.90	0.90	0.80	2.5				
	Y × T	0.301	Mean	0.97*b*	0.73*b*	2.2*a*	0.67*b*	1.3ab	1.1*b*	0.83*b*	2.2*a*				
Co[z]	Year(Y)	0.571	2010	0.33	0.13	5.2	0.13	0.93	0.30	0.13	1.2	0.10	1.4	3.2	50
	Treatment(T)	<0.001	2013	0.27	0.20	4.0	0.13	0.80	0.20	0.23	3.8				
	Y × T	0.143	Mean	0.30*c*	0.17*c*	4.6*a*	0.13*c*	0.87*c*	0.25*c*	0.18*c*	2.5*b*				
Cu	Year(Y)	0.267	2010	1.3	1.0	2.0	1.0	1.7	1.0	1.0	2.7	1.0	5.4	10	63
	Treatment(T)	<0.001	2013	1.0	1.0	1.9	1.0	1.3	1.0	1.0	2.2				
	Y × T	0.970	Mean	1.2*b*	1.0*b*	2.0*a*	1.0*b*	1.5*ab*	1.0*b*	1.0*b*	2.5*a*				
Pb	Year(Y)	<0.001	2010	1.0*b*(*b*)	0.63*b*(*b*)	1.9*b*(*b*)	0.63*b*(*b*)	6.9*a*	1.8*b*(*b*)	0.63*b*(*b*)	11*a*(*a*)	5.0	5.0	5.0	140
	Treatment(T)	<0.001	2013	5.0(*a*)	5.0(*a*)	5.0(*a*)	5.0(*a*)	5.4	5.0(*a*)	5.0(*a*)	5.2(*b*)				
	Y × T	<0.001	Mean	3.0*b*	2.8*b*	3.4*b*	2.8*b*	6.2*ab*	3.4*b*	2.8*b*	8.1*a*				
Ni	Year(Y)	0.923	2010	3.7	1.3	45	0.93	8.2	3.6	1.3	13	0.50	5.2	22	50
	Treatment(T)	<0.001	2013	1.9	1.5	34	0.90	5.8	1.4	1.2	32				
	Y × T	0.051	Mean	2.8*c*	1.4*c*	40*a*	0.92*c*	7.0*c*	2.5*c*	1.3*c*	22*b*				
U[z]	Year(Y)	<0.001	2010	1.0*b*	–	1.3*b*	–	–	–	–	11*a*(*a*)	–	1.2	2.1	23
	Treatment(T)	<0.001	2013	0.97*b*	–	0.90*b*	–	–	–	–	6.1*a*(*b*)				
	Y × T	<0.001	Mean	1.0*b*	–	1.1*b*	–	–	–	–	8.6*a*				
Zn[z]	Year(Y)	0.510	2010	1.0	1.0	13	1.0	4.0	1.0	1.3	6.7	1.0	14	26	200
	Treatment(T)	<0.001	2013	1.0	1.3	12	1.0	3.3	1.0	1.3	11				
	Y × T	0.447	Mean	1.0*b*	1.2*b*	13*a*	1.0*b*	3.7*b*	1.0*b*	1.3*b*	9.0*a*				

[z]Treatment means are geometric means derived by back-transformation of natural log values of the raw data.

[y]Treatment means with the same letter(s) across the row are not different at P <0.05. Significant differences between 2010 and 2013 are indicated by letters in parentheses.

[x]Concentration of metals in sediments of a previously drained lake known as Little Martin.

[w]Concentration of metals in sediments of a previously drained lake known as Remnant Key Lake.

[v]CCME limit according to the guidelines for coarse-textured soil in residential/parkland sites (CCME 2007).

Metal	Effect	*P*-value	Horizon[y]	Treatment[x]		
				Control	Sediment	Demo
				mg kg^{-1} soil		
Arsenic	Horizon (H)	<0.001	TS	1.1*b*	41*a*(*a*)	31*a*(*a*)
	Treatment (T)	0.020	US	0.20	0.43(*b*)	0.50(*b*)
	H × T	0.011	LS	0.20	1.3(*b*)	1.1(*b*)
Boron	Horizon (H)	<0.001	TS	0.20*b*	0.92*a*(*a*)	0.75*a*(*a*)
	Treatment (T)	0.009	US	0.20	0.20(*b*)	0.20(*b*)
	H × T	0.003	LS	0.20	0.20(*b*)	0.20(*b*)
Cadmium	Horizon (H)	<0.001	TS	0.01*b*	0.07*a*(*a*)	0.06*a*(*a*)
	Treatment (T)	0.056	US	0.01	0.01(*b*)	0.01(*b*)
	H × T	0.031	LS	0.01	0.01(*b*)	0.01(*b*)
Chromium[z]	Horizon (H)	<0.001	TS	0.93*b*	1.8*ab*(*a*)	2.5*a*(*a*)
	Treatment (T)	0.080	US	0.70	0.70(*b*)	0.73(*b*)
	H × T	0.045	LS	0.67	0.70(*b*)	0.83(*b*)
Cobalt[z]	Horizon (H)	<0.001	TS	0.27*b*	4.0*a*(*a*)	3.8*a*(*a*)
	Treatment (T)	0.008	US	0.10	0.17(*b*)	0.23(*b*)
	H × T	0.005	LS	0.10	0.23(*b*)	0.17(*b*)
Copper	Horizon (H)	0.001	TS	1.0*b*	1.9*a*(*a*)	2.2*a*(*a*)
	Treatment (T)	0.106	US	1.0	1.0(*b*)	1.0(*b*)
	H × T	0.010	LS	1.0	1.0(*b*)	1.0(*b*)
Lead	Horizon (H)	0.387	TS	5.0	5.0	5.2
	Treatment (T)	0.387	US	5.0	5.0	5.0
	H × T	0.433	LS	5.0	5.0	5.0
Nickel[z]	Horizon (H)	<0.001	TS	1.9*b*	34*a*(*a*)	32*a*(*a*)
	Treatment (T)	0.007	US	0.73	0.93(*b*)	2.0(*b*)
	H × T	0.004	LS	0.60	1.8(*b*)	2.0(*b*)
Uranium[z]	Horizon (H)	<0.001	TS	0.97*b*	0.90*b*	6.1*a*(*a*)
	Treatment (T)	<0.001	US	0.50	0.50	0.50(*b*)
	H × T	<0.001	LS	0.50	0.50	0.73(*b*)
Zinc[z]	Horizon (H)	<0.001	TS	1.0*b*	12*a*(*a*)	11*a*(*a*)
	Treatment (T)	0.004	US	1.3	1.3(*b*)	1.0(*b*)
	H × T	0.008	LS	2.0	6.0(*b*)	2.0(*b*)

Table 7. Soil profile distribution of selected metals in the Control, Sediment and Demo plots in 2013

[z]Treatment means are geometric means derived by back-transformation of natural log values of the raw data.
[y]Sampled horizon; TS = Topsoil (0-20 cm), US = Upper Subsoil (20-50 cm), and LS = Lower Subsoil (50-100 cm).
[x]Treatment means with the same letter(s) across the row are not statistically different at *P* <0.05. Significant differences among horizons are indicated by letters in parentheses.

Table 8. Foliar concentrations of metals in birch species among treatment plots and in adjacent natural sites.

Metal	Treatment					Oasis[y]	Remnant Key Lake[x]	Critical Level[w]
	Control	Sediment	LFH	Pellets	Demo			
	μg g^{-1} tissue							
Arsenic	0.26*b*[1]	0.33*b*	2.3*a*	2.1*a*	0.63*b*	0.20	0.39	5–20
Boron	61*b*	120*a*	79*b*	48*b*	123*a*	42	109	50–200
Cadmium[z]	0.36*b*	1.4*a*	0.65*b*	0.06*b*	1.7*a*	0.15	0.05	5–30
Chromium[z]	0.03[1]	0.03	0.04	0.04	0.03	0.36	0.03	5–30
Cobalt[z]	0.11*c*	3.1*a*	0.93*b*	0.06*c*	1.8*ab*	0.18	0.05	15–50
Copper	2.5	3.6	3.7	2.9	2.9	4.1	9.9	20–100
Lead[z]	0.37*b*	1.8*a*	0.39*b*	0.36*b*	1.2*a*	0.54	0.25	30–300
Nickel	20*b*	161*a*	41*b*	5.0*b*	147*a*	4.7	31	10–100
Selenium	0.89*b*	4.5*a*	0.83*b*	0.49*b*	2.1*ab*	1.1	0.25	5–30
Tin[z]	0.20	0.20	0.22	0.25	0.20	0.20	0.20	60
Uranium[z]	0.90	0.93	0.80	0.80	0.77	0.50	0.50	–
Vanadium	15*a*	5.9*b*	15*a*	16*a*	8.2*b*	7.7	1.4	5–10
Zinc	238*ab*	126*b*	375*a*	343*a*	263*ab*	189	65	100–400

[z]Treatment means are geometric means derived by back-transformation of natural log values of the raw data.
[y]Oasis is foliar concentration of metals in birch stands in a naturally revegetated adjacent site with soils dumped 20 years ago.
[x]Foliar concentration of metals in birch stands in a previously drained lake denoted as Remnant Key Lake.
[w]Critical concentrations of metals and trace elements in mature leaf tissues of various species (Kabata-Pendias 2011).

Table 9. Treatment effects on soil moisture contents in 2013 (15 May - 17 October 2013)

Moisture content	Effect	*P*-value	Horizon	Treatment[v]					
				Control	Peat	Sediment	Straw	LFH	Demo
						$cm^3\ cm^{-3}$			
Volumetric moisture content (VMC_{ave})[z]	Horizon (H)	<0.001	TS	0.089*d*(*b*)	0.12*c*(*a*)	0.26*b*(*a*)	0.054*d*(*b*)	0.10*c*(*b*)	0.37*a*(*a*)
	Treatment (T)	<0.001	US	0.13*a*(*a*)	0.12*a*(*a*)	0.069*b*(*b*)	0.073*b*(*ab*)	0.12*a*(*b*)	0.12*a*(*c*)
	H × T	<0.001	LS	0.13*b*(*a*)	0.067*c*(*b*)	0.079*c*(*b*)	0.094*c*(*a*)	0.18*a*(*a*)	0.16*ab*(*b*)
			Mean[w]	0.122*c*	0.093*d*	0.11*c*	0.079*d*	0.145*b*	0.190*a*
Surplus water content (SWC)[y]	Horizon (H)	<0.001	TS	0.039*b*(*b*)	-0.011*c*(*c*)	-0.013*c*(*b*)	0.004*c*(*b*)	0.051*b*(*b*)	0.11*a*(*a*)
	Treatment (T)	<0.001	US	0.076*a*(*a*)	0.066*a*(*a*)	0.019*b*(*a*)	0.024*b*(*ab*)	0.072*a*(*b*)	0.071*a*(*b*)
	H × T	<0.001	LS	0.084*b*(*a*)	0.018*c*(*b*)	0.029*c*(*a*)	0.045*c*(*a*)	0.13*a*(*a*)	0.11*ab*(*a*)
			Mean[w]	0.073*b*	0.026*c*	0.018*c*	0.030*c*	0.096*a*	0.099*a*
Available water content (AWC)[x]	Horizon (H)	<0.001	TS	0.039*b*	0.073*ab*	0.12*a*(*a*)	0.039*b*	0.026*b*	0.12*a*(*a*)
	Treatment (T)	0.029	US	0.039	0.039	0.039(*b*)	0.039	0.039	0.039(*b*)
	H × T	0.010	LS	0.039	0.039	0.039(*b*)	0.039	0.039	0.039(*b*)
			Mean[w]	0.039	0.046	0.055	0.039	0.036	0.054
Field capacity (FC)	Treatment (T)	0.013	TS	0.05*b*	0.13*ab*	0.27*a*	–	0.05*b*	0.26*a*
Permanent wilting point (PWP)	Treatment (T)	0.019	TS	0.01*b*	0.06*b*	0.15*a*	–	0.02*b*	0.14*a*

[z]VMC_{ave} = average volumetric water contents of individual two-week sampling intervals.
[y]SWC = VMC_{ave} − Field capacity (FC) at −0.33 bar
[x]AWC = FC – Permanent wilting point (PWP) at −15 bar
[w]Weighted mean for the entire profile (0-100 cm depth), where TS = Topsoil (0-20 cm), US = Upper Subsoil (20-50 cm), and LS = Lower Subsoil (50-100 cm). The TS depth for Peat and Sediment plots was 0-10 cm and Demo plot was 0-30 cm.
[v]Treatment means with the same letter(s) across the row are not statistically different at *P* <0.05. Significant differences among horizon depths are indicated by letters in parentheses.

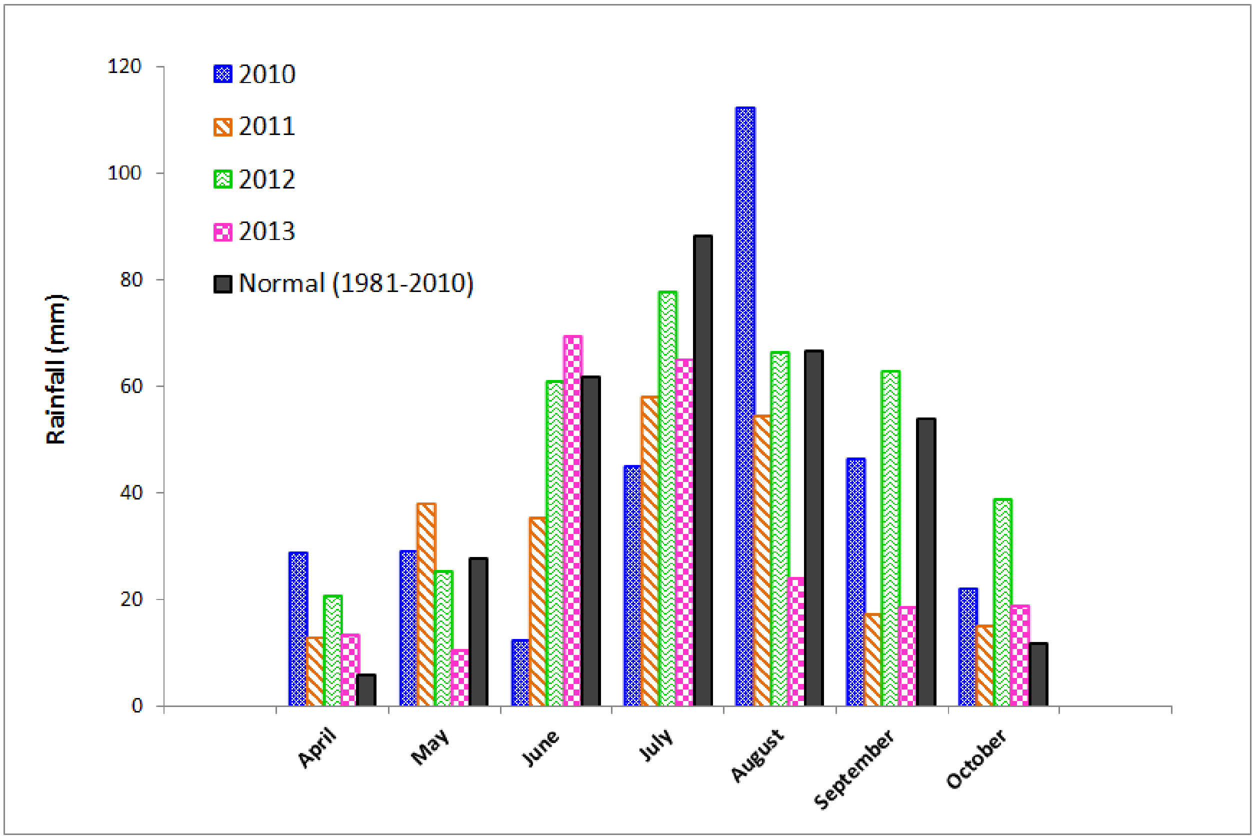

Fig. 1. Monthly cumulative rainfall from April to October in 2010, 2011, 2012 and 2013 were plotted with the normal rainfall data (1981-2010) for the Key Lake region, Saskatchewan. The local weather data (2010-2013) were obtained from O'Kane Consultants while the 30-year normal data were obtained from Environment Canada.

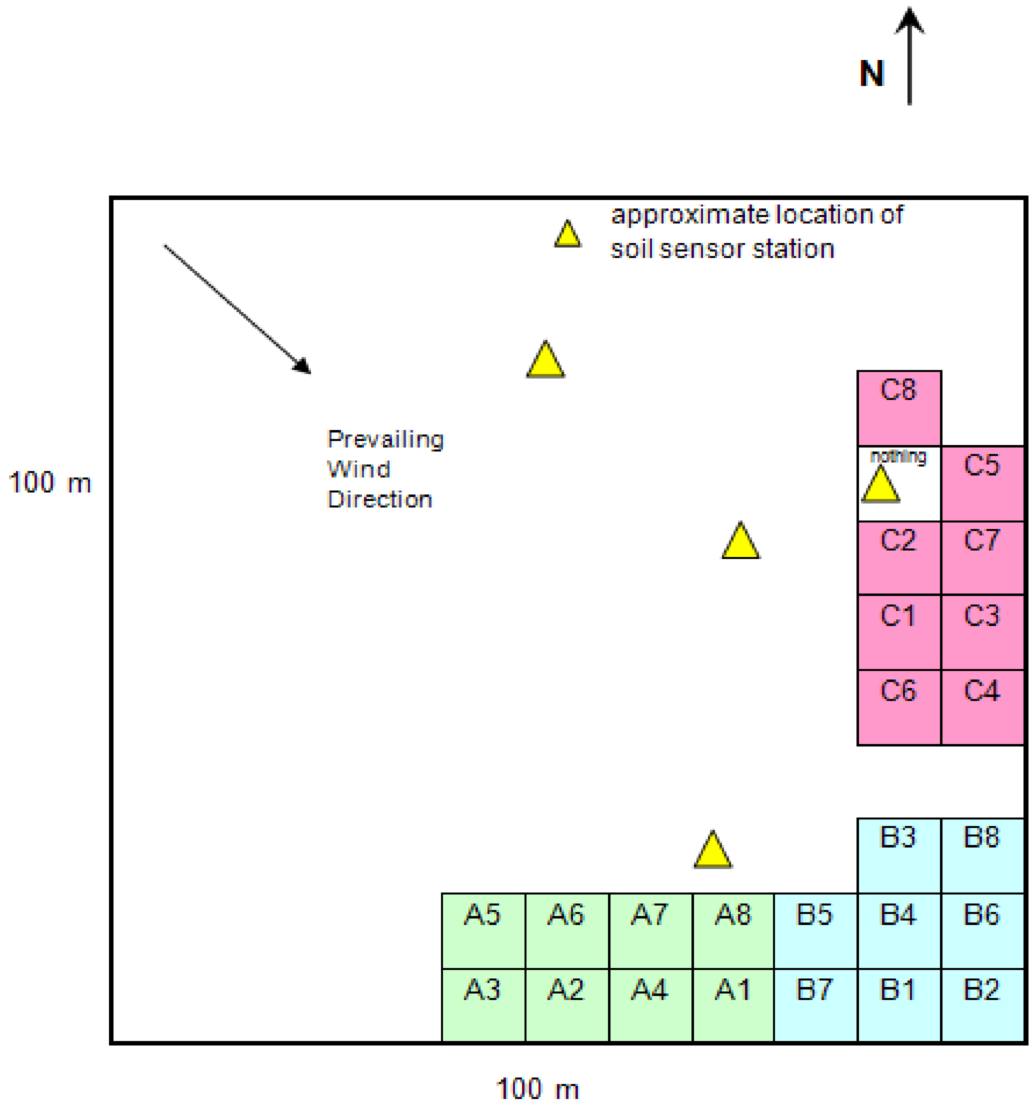

Fig. 2. Schematic layout of soil treatment plots in three replicate blocks denoted as A, B and C. The eight treatment plots comprised: 1 = No amendment (Control); 2 = Commercial peat (Peat); 3 = Lake sediment (Sediment); 4 = Underlying flax straw (Straw); 5 = Mulched LFH and mineral soil (LFH); 6 = Fertilizer (NPK); 7 = Manure pellets (Pellets); and 8 = Demonstration (Demo).

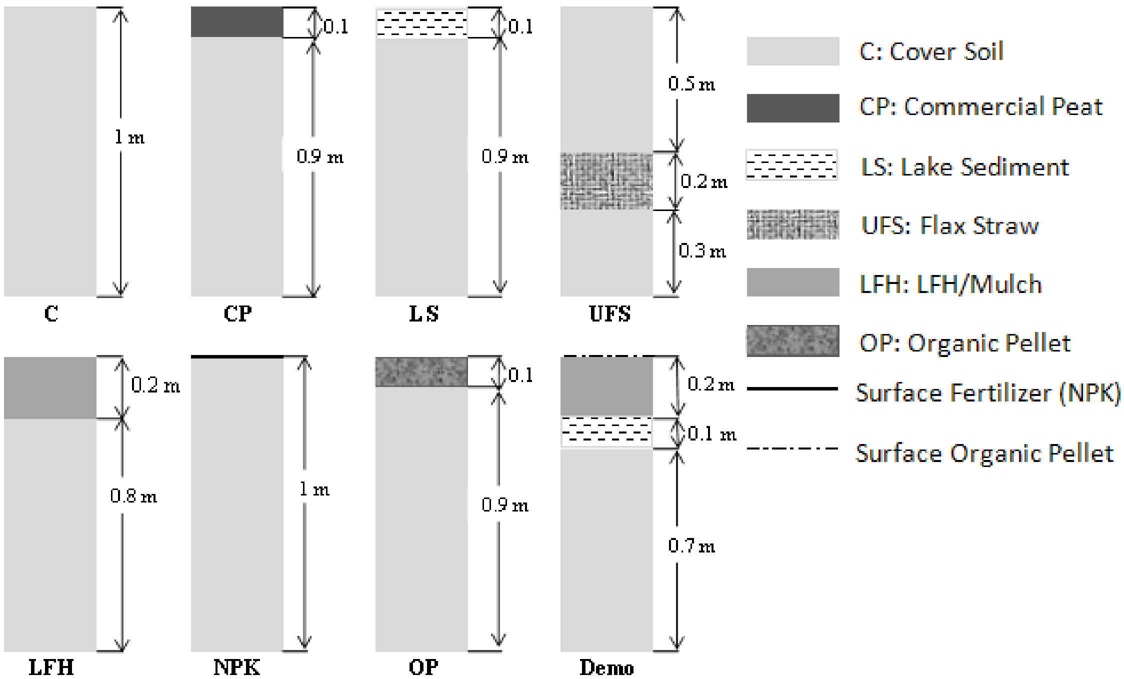

Fig. 3. Schematic illustration of treatment profiles. Treatments include control cover soil (C), commercial peat (CP), lake sediment (LS), underlying flax straw (UFS), mulched LFH material (LFH), fertilizer (NPK), organic manure pellets (OP) and demonstration (Demo).

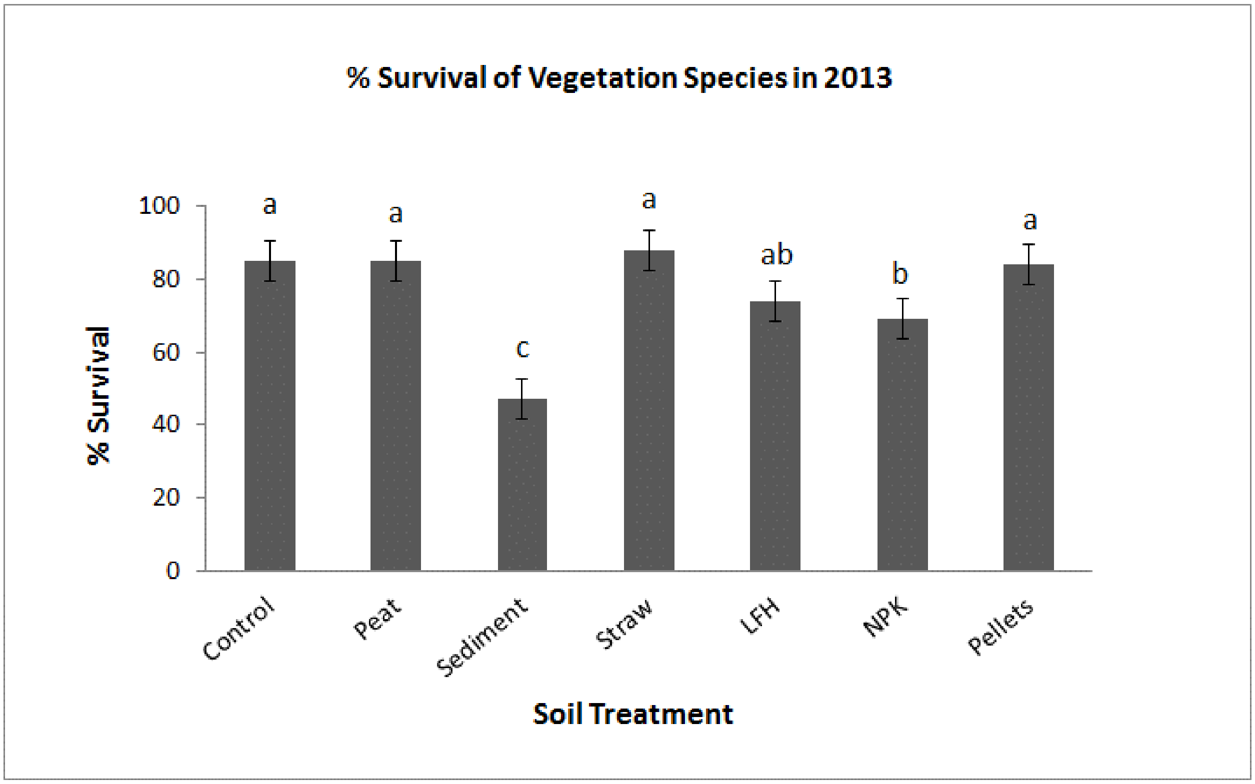

Fig. 4. Average percent survival of vegetation species across treatment plots in August 2013. Letters indicate significant differences among treatments. Bars represent standard errors of means.

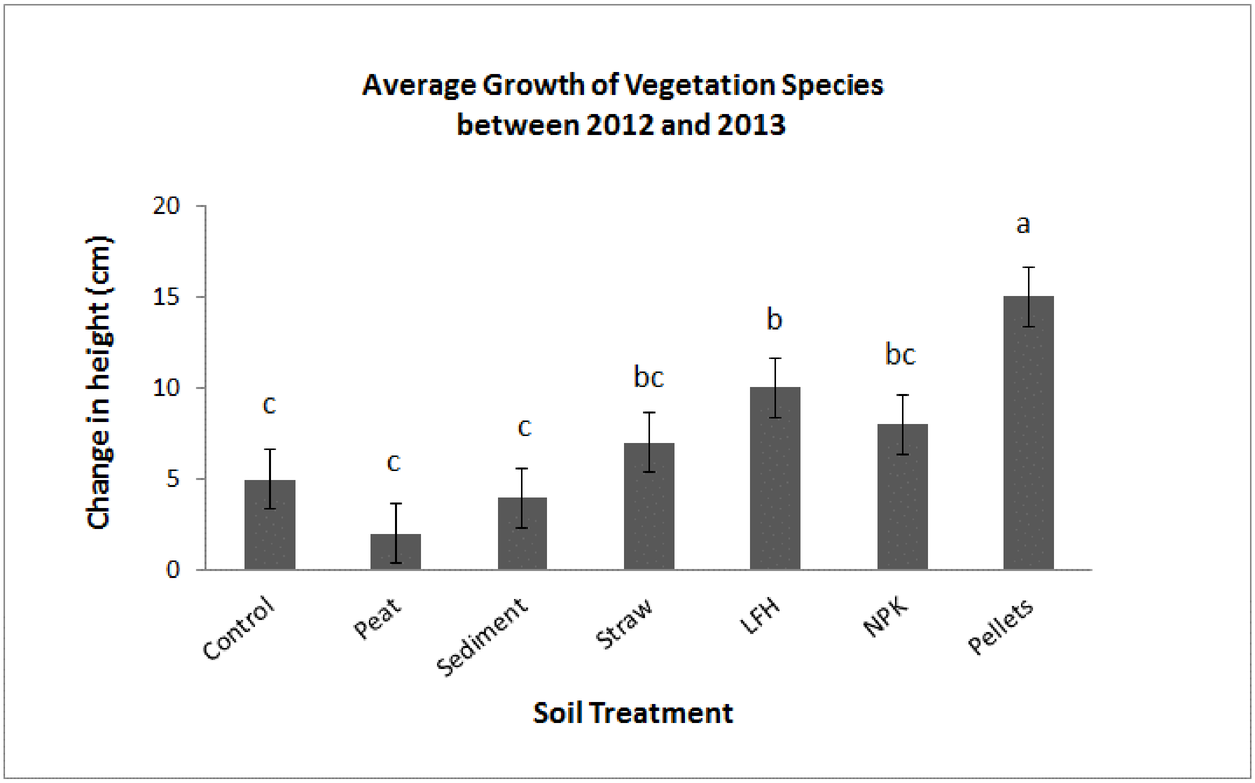

Fig. 5. Average growth (based on geometric means) of vegetation species across treatment plots. The growth data were derived as the differences in above ground heights between August 2012 and August 2013. Letters indicate significant differences among treatments. Bars represent standard errors of means.

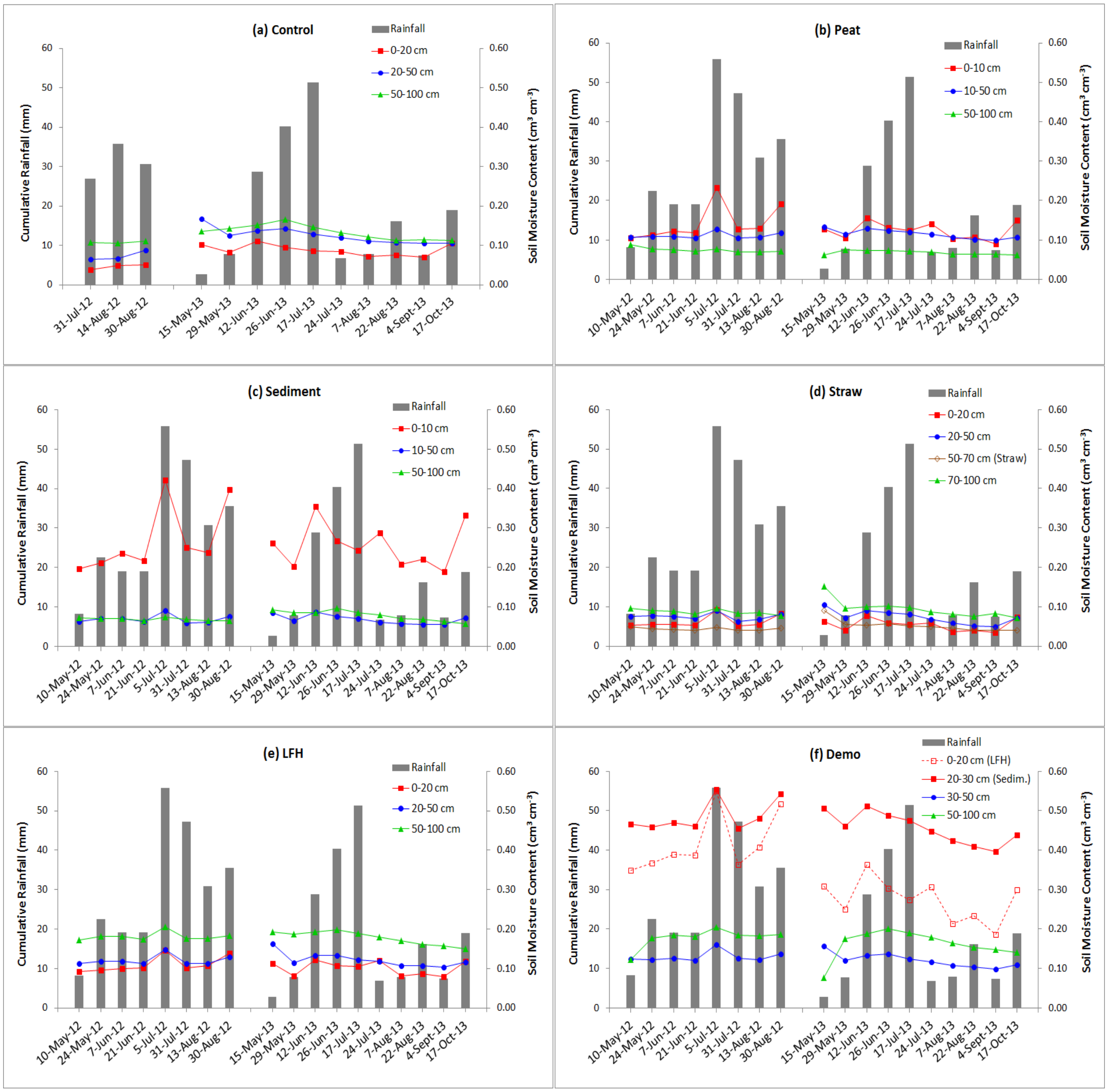

Fig. 6. Cumulative rainfall and temporal distribution of volumetric moisture contents (VMC) in selected treatment plots: (a) Control, (b) Peat, (c) Sediment, (d) Straw, (e) LFH and (f) Demo, for 2012 and 2013 soil moisture monitoring.