Evaluation of substrate and amendment materials for soil reclamation at a diamond mine in the Northwest Territories, Canada

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Drozdowski, B. L., Naeth, M. A. and Wilkinson, S. R. 2012. **Evaluation of substrate and amendment materials for soil reclamation at a diamond mine in the Northwest Territories, Canada**. Can. J. Soil Sci. **92**: 77–88. Mine waste materials with potential for use in soil construction at a diamond mine in the Northwest Territories were evaluated to address physical and chemical limitations for plant establishment, growth and development. Substrates were glacial till, gravel, processed kimberlite, and 50:50 and 25:75 mixes of processed kimberlite and till. Amendments were salvaged topsoil, sewage sludge, inorganic fertilizer and sludge from a water treatment facility. Reclamation soils constructed with these materials were adequate for revegetation. Mixes of processed kimberlite and glacial till enhanced soil structure and diluted adverse concentrations of elements. The original gravel pad, alone or amended, was a suitable substrate for plants. Addition of organic amendments topsoil and sludge, to any substrate, increased organic matter, nutrients and surface water retention. Of amendments evaluated, salvaged topsoil provided the most consistent increase in plant density among substrates. Inorganic fertilizer applied to gravel or till provided results similar to those with topsoil. Sludge had potential to amend mixes of processed kimberlite and till, although results were variable. Sewage was a good source of organic matter, increasing soil water content and macro nutrients. Vegetation response was poor in sewage-amended treatments likely due to combined effects of high copper, molybdenum, phosphorus, selenium, sulphate and zinc.

Key words: Reclamation, soil amendments, native species, diamond mine, reclamation substrate, revegetation

Drozdowski, B. L., Naeth, M. A. et Wilkinson, S. R. 2012. **Évaluation de substrats et d'amendements pour la restauration des sols dans une mine diamantifère des Territoires du Nord-Ouest, au Canada**. Can. J. Soil Sci. **92**: 77–88. Les auteurs ont évalué les déchets miniers qui pourraient servir à la construction de sols artificiels dans une mine diamantifère des Territoires du Nord-Ouest, en vue d'en établir les limites physiques et chimiques pour l'établissement, la croissance et l'épanouissement des plantes. Les substrats consistaient en till glaciaire, en gravier, en kimberlite conditionnée et en mélanges 50:50 et 25:75 de kimberlite conditionnée et de till. Comme amendements, les auteurs ont utilisé la couche de surface du sol récupérée, des boues usées, des engrais minéraux et la boue d'une usine d'épuration de l'eau. Les sols artificiellement restaurés avec ces matériaux conviennent au reverdissement. Les mélanges de kimberlite conditionnée et de till glaciaire rehaussent la texture du sol et diluent la concentration des éléments nocifs. Employé tel quel ou bonifié, le lit de gravier d'origine constitue un substrat convenable pour les plantes. L'addition de sol de surface et de boue à un substrat quelconque accroît la rétention de la matière organique, des éléments nutritifs et de l'eau de surface. Parmi les amendements évalués, le sol de surface engendre la hausse la plus constante de la densité de la végétation sur les différents substrats. L'application d'engrais minéraux au gravier ou au till donne des résultats similaires à ceux obtenus avec le sol de surface. La boue pourrait bonifier les mélanges de kimberlite conditionnée et de till, mais les résultats varient. Les boues constituent une bonne source de matière organique, car elles augmentent la teneur en eau et en macro éléments nutritifs du sol. La végétation réagit mal aux boues usées, sans doute à cause des effets combinés d'une concentration élevée de cuivre, de molybdène, de sélénium, de phosphore, de sulfates et de zinc.

Mots clés: Restauration, amendements du sol, espèces indigènes, mine diamantifère, substrat de restauration, reverdissement

INTRODUCTION

Diamond mining in the Canadian north has intensified since the discovery of diamonds in the Northwest Territories in 1991 (Baker et al. 2001). Diamondiferous kimberlite can be mined economically at <1 carat (200 mg) of diamonds per tonne of ore; therefore, diamond mining involves processing and disposal of large quantities of rock and tailings wastes. Concerns over mining impacts on wildlife, human health and the environment have prompted government agencies to require reclamation of mining disturbances to viable and sustainable ecosystems to protect resource function and integrity (Department of Indian Affairs and Northern Development 2002; Indian and Northern Affairs Canada 2007).

Even in undisturbed conditions, plants and soils in arctic and subarctic landscapes are subjected to

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unique development constraints due to low air and soil temperatures, shallow depth to thaw, nutrient deficiencies and short growing seasons (Haag and Bliss 1974; Chapin and Shaver 1981; Chapin 1983; Billings 1987; Forbes and Jefferies 1999). Diamond mining results in additional constraints for reclamation and revegetation. Shallow soil is removed and/or compacted by heavy equipment; contaminants such as heavy metals are introduced; and changes occur in soil temperature, water and nutrient regimes (Johnson 1987; McKendrick 1991; Truett and Kertell 1992; Walker 1996).

The land surface associated with diamond mining is typically waste rock or tailings waste. Reclamation involves soil construction and re-establishment of soil processes and native plant communities on gravel roads and pads, waste rock and till stockpiles and processed kimberlite containment ponds. There is often little soil material, particularly topsoil, available for land reclamation. Although waste materials from mining processes are available, they are often low in organic matter and nutrients, coarse textured and relatively inhospitable to plants.

Little research has been conducted on diamond mine reclamation in the arctic, particularly using native plant species with specific soil requirements. Due to physical and chemical properties of diamond mine waste materials, limited dispersal of native propagules, low precipitation and no ground water input, mine disturbances can remain barren for years (Clark 1995; Walker 1996). Addition of topsoil (Johnson 1987; Densmore 1994; Mackenzie and Naeth 2010), sewage sludge (Reid and Naeth 2005a, b), peat (Reid and Naeth 2005a, b; Stevens 2006) and inorganic fertilizer (Shaver and Chapin III 1995; Reid and Naeth 2005a, b; Kidd et al. 2006) has significantly enhanced vegetation cover and plant productivity on mine waste materials in the arctic.

The purpose of this research was to evaluate available mining waste materials with potential for use in soil construction for diamond mine reclamation. Treatments were designed to address physical and chemical limitations of individual materials and environmental conditions that constrain plant establishment, growth and development.

MATERIALS AND METHODS

Site Description

Diavik Diamond Mine is located approximately 320 km northeast of Yellowknife, Northwest Territories, Canada, in the sub-arctic tundra on the Precambrian shield (lat. 64°30′41″, long. 110°17′23″), 416 m above sea level. The area is characterized by short, cool summers, long, cold winters, and continuous permafrost. From 2000 to 2009, mean annual temperature was −9.3°C and mean annual precipitation was 133 mm. The mine site is considerably drier than many other subarctic locations. The area mainly consists of massive archean rock outcrops and glacial deposits of boulders, glacial till and eskers. Uplands consist of turbic and static cryosolic soils, and heath tundra dominated by dwarf shrubs including bog birch (*Betula glandulosa* Michx.) and willow (*Salix*) species and ericaceous shrub communities of bog cranberry (*Vaccinium vitis idaea* L.), bog bilberry (*Vaccinium uliginosum* L.), northern Labrador tea (*Ledum decumbens* (Ait.) Lodd. ex Steud.), crowberry (*Empetrum nigrum* L.) and arctic bearberry (*Arctostaphylos rubra* Rehd. and Wilson, Fernald.). Lowlands are dominantly wet tussock tundra with organic cryosolic soils vegetated with sedges and mosses.

Reclamation Treatments and Experimental Design

The research site was established in September 2004 on a raised gravel pad constructed to prevent thawing of the underlying permafrost and to provide a stable surface for development (Jorgenson and Joyce 1994). The gravel pad was previously used for ammonium nitrate storage and consisted of a layer of boulders over tundra, followed by a layer of small to mid-sized rocks, topped with 50 cm of gravel.

Plants and macro and micro soil organisms require a suitable material, or substrate, to establish and grow on. Gravel, the existing substrate at the study site, is generally not hospitable to plants and alternative substrates were required. Along with gravel, four alternative substrates composed of mine waste materials, alone and in combination, were evaluated. They were 100% glacial till over gravel, 100% fine processed kimberlite over gravel and two mixes of till and processed kimberlite (by volume 50:50 and 25:75) over gravel. Glacial till is overburden material from the pit and ranges from clay size particles to boulders >1 m in diameter. The till used is 68% sand and 27% silt. Diavik kimberlite materials are predominantly composed of silicon, magnesium and iron (>95% sand); the most abundant trace elements are nickel, chromium, cobalt, strontium and zinc. These substrates were applied at a depth of 30 to 40 cm over the gravel pad with a front end loader. The gravel pad was considered a control substrate. An undisturbed soil close to the mine site was used as a reference for what properties the ideal reclamation soil might have.

Amendments consisting of materials on site or easily transported were added to substrates to further enhance physical and chemical properties. They were topsoil, sewage sludge, inorganic fertilizer, sludge from the mine water treatment facility and no amendment. Topsoil from a wet tundra environment was stripped (O, A and B horizons) and applied at an average thickness of 10 cm. Untreated sewage was taken directly from the mine containment facility and applied at an average thickness of 4 cm. Sewage was a sandy loam texture with a pH of 7.3, electrical conductivity of 7.5 dS m^{-1}, saturation of 71%, and total carbon content of 6.1%. Chromium, copper, nickel and zinc were at concentrations greater than Canadian Council of Ministers of the Environment guidelines (CCME 2007). Due to shortage of material, sewage was only applied to three substrate treatments, to 50:50 fall seeded plots and to till and 50:50 spring seeded plots. Sludge from the water treatment plant consisted of particulate matter from ground rock, old lake bed sediment, till collected at the bottom of the open pit and water from seepage and runoff (de Rosemond and Liber 2005). It was applied at an average thickness of 4 cm only to processed kimberlite and 25:75 spring seeded plots due to shortage of material. Soils were already high in potassium and sulphur and low in phosphorus and nitrogen; therefore an 11-52-0 (ammonium, phosphate) fertilizer was hand broadcast at a rate of 144 kg ha^{-1} in summers 2005 and 2006 when vegetation was actively growing.

Revegetation treatments included five seed mixes of native tundra grasses and forbs based on water requirements and competitive abilities and a natural recovery control with no revegetation. Plant response was averaged for each substrate-amendment treatment, since responses of native seed mixes were not significant in the period of this research (Naeth and Wilkinson, in preparation), and plant response was only of interest to evaluate the effect of physical and chemical properties of substrate and amendment combinations on plant establishment. Native species evaluated were red fescue (*Festuca rubra* L., Arctared), glaucous blue grass (*Poa glauca* Vahl; Tundra), alpine blue grass (*Poa alpina* L., Gruening), nuttall's alkali grass (*Puccinellia nuttalliana* Schult), blue joint (*Calamagrostis canadensis* Michx., Beauv.), polar grass (*Arctagrostis latifolia* R. Br., Alyeska), rocky mountain fescue (*Festuca saximontana* Rydb.), tickle grass (*Agrostis scabra* Wild.), slender wheat grass (*Agropyron pauciflorum* Schwein, Hitchc.), alpine wheat grass (*Agropyron violaceum* Hornem.), tufted hair grass (*Deschampsia caespitosa* L., Beauv.), alpine sweet broom (*Hedysarum alpinum* L.), northern sweet broom (*Hedysarum mackenzii* Rich.), reflexed locoweed (*Oxytropis deflexa* Pall.), showy locoweed (*Oxytropis splendens* Dougl. ex Hook.), northern yellow locoweed (*Oxytropis campestris* L.) and broad leaved willow herb (*Epilobium latifolium* L.). The seed mixes were broadcast by hand to obtain a total density of 50 plants m^{-2} with equal representation of species. Revegetation treatments were applied in spring (June) and fall (September) 2005.

Research plots were established using an incomplete randomized design with replication. Five substrates, five soil amendments, six seed mixes and two seasons of seeding or planting were applied to each of three blocks. Five substrate plots (each 300 m^2 in blocks one and three and 150 m^2 in block two) were randomly established in each of the three blocks. Each substrate plot was divided into four strips of equal size for amendments. Each amendment strip was divided in half for season of seeding treatments (fall and spring), which were further divided into subplots (approximately 3 m^2) for seeding revegetation mixes.

Field and Laboratory Measurements

Soil samples were collected from three random locations in each amendment plot at the time of construction and amendment application at depth increments of 0–10 cm and 20–30 cm. Reference soil samples were collected at 0–10 cm from turbic and static cryosols in heath and shrub tundra communities on East Island away from direct mining activity.

Each soil sample was analyzed for available phosphorus and potassium by a modified Kelowna extraction technique (Qian et al. 1994), available nitrogen and sulphur using calcium chloride extraction (Carter 1993), total cations (calcium, potassium, magnesium, sodium) and pH using a saturated soil paste method (McKeague 1978), cation exchange capacity and extractable cations by barium chloride extraction (McKeague 1978) and total carbon and total inorganic carbon by Leco furnace combustion (Carter 1993). Total organic carbon was calculated by subtracting inorganic carbon from total carbon. One-third of the samples were analyzed for metals considered important by guidelines of the CCME including silver, arsenic, barium, beryllium, cadmium, cobalt, chromium, copper, mercury, molybdenum, nickel, lead, strontium, selenium, tin, thallium, uranium, vanadium and zinc using inductively coupled plasma optical emission spectroscopy (Environmental Protection Agency 1994) and particle size by hydrometer (Gee and Bauder 1986). Sewage sludge treatment samples were analyzed for fecal coliforms by membrane filtration and *Salmonella* by a multiplex polymerase chain reaction assay (Way et al. 1993).

Soil water and temperature Smart Sensors™ were installed in each treatment just above the gravel pad substrate interface (approximately 30 cm) and 5 to 10 cm below the surface. Data were collected on an hourly basis using HOBO Micro Stations.

Vegetation was assessed in late August 2005 and late July 2006, during peak plant production, in three 20 × 50 cm quadrats located in each 5 m^2 subplot, using a systematic, random method. The margins of each small plot were not sampled to remove edge effects from neighbouring treatments. Plant density by species was determined by counting individual stems rooted in each quadrat. Based on species area curves, three samples provided sufficient information regarding density and richness of each species in the subplot. Overall species health was based on a four point scale allotted to individual plants of each species.

Statistical Analyses

Data were tested for normality and homogeneity of variance prior to analyses. A Type III one way analysis of variance was performed to determine significant differences for soil and vegetation parameters (Zar 1999). Significant treatment effects were further analyzed using LSD post hoc tests. In all statistical analyses, a confidence level of 95% was chosen to distinguish statistically significant variation. A two sample t-test was conducted to determine significant differences between spring and fall seeded plots.

RESULTS AND DISCUSSION

Soil Texture

Soil texture at 0–10 and 20–30 cm depths for all treatments was loamy sand (81% sand, 15% silt, 4% clay) to sandy loam (72% sand, 23% silt, 5% clay), except for one gravel and three processed kimberlite treatments that were sand (90% sand, 6% silt, 4% clay). At 0–10 cm, soil averaged 79% sand, 16% silt, 5% clay; at 20–30 cm, it averaged 81% sand, 15% silt, 4% clay. Undisturbed reference soil was sandy loam texture (64% sand, 31% silt, 5% clay).

Reclamation and reference soils fell into approximately the same area of the textural triangle. However, the higher sand and lower silt in the reclamation treatments than in the reference soil could reduce ability to retain water and nutrients, lower cation exchange and buffer capacities, and increase thermal conductivity.

Soil Temperature and Volumetric Water Content

Mean air temperature in 2005 was similar to the 10 yr average, whereas 2006 was warmer (Table 1). Soil temperatures steadily increased from May 1 with multiple peaks from late June to early August and steadily declined beginning in mid-August (data not shown). Soil surface temperature (5 cm depth) increased earlier in spring, was generally higher, had more extreme ranges, and decreased earlier in fall than temperature at 30 cm. There were no significant temperature differences among reclamation treatments. Mean surface soil temperatures in reclamation treatments during the growing season in 2005 were 12°C (10–14) in June, 13°C (12–14) in July, and 11°C (10–12) in August; in 2006 they were 17°C (15–19) in June, 15°C (13–17) in July, and 14°C (12–15) in August. Processed kimberlite alone or with sludge had the highest mean daily surface temperature in any month except June, when sewage and sludge amendments that had just been applied had slightly higher temperatures.

Table 1. Mean daily average soil temperature (°C) in reclamation treatments at 5 cm depth

	2005			2006		
Treatment	June	July	August	June	July	August
Gravel unamended	10.7	12.0	9.6	15.4	13.3	12.2
Gravel fertilizer	10.1	12.0	10.2	15.6	14.1	13.0
Gravel topsoil	10.3	12.5	10.4	16.1	14.4	13.5
PK unamended	13.0	14.3	11.6	18.6	16.6	15.0
PK fertilizer	12.7	14.1	11.6	15.9	15.7	13.4
PK topsoil	12.4	13.5	11.5	17.3	15.3	13.9
PK sludge	n/a	13.9	11.5	18.4	16.4	15.0
Till unamended	11.1	12.6	10.2	17.0	14.7	13.7
Till fertilizer	11.3	12.8	10.4	16.7	14.7	13.7
Till topsoil	10.7	12.3	10.1	15.7	14.0	13.1
Till sewage	13.7	12.6	10.4	16.1	14.1	13.1
50:50 unamended	11.6	13.3	10.9	16.3	15.0	14.2
50:50 fertilizer	12.3	13.5	10.9	16.6	14.9	13.8
50:50 topsoil	11.6	13.0	10.6	16.7	14.7	13.5
50:50 sewage	10.8	12.7	10.8	15.7	14.8	13.8
25:75 unamended	12.3	13.5	10.9	17.3	15.1	14.0
25:75 fertilizer	12.4	13.6	11.0	17.4	15.0	13.8
25:75 topsoil	12.1	13.4	10.9	17.4	15.1	14.0
25:75 sludge	14.4	13.3	10.7	16.8	14.2	13.6
Average	11.9	13.1	10.7	16.7	14.8	13.7
Standard deviation	1.2	0.7	0.6	0.9	0.8	0.7
Maximum	14.4	14.3	11.6	18.6	16.6	15.0
Minimum	10.1	12.0	9.6	15.4	13.3	12.2

The higher temperatures in processed kimberlite treatments were likely due to the darker colour of the material (similar to black sand) than lighter coloured treatments. Surface temperature in the gravel treatment was lowest throughout the growing season. Its coarse texture was likely associated with high porosity. Soil water was also lower than in other treatments, resulting in surface pores being filled with air, which is a poor heat conductor.

Differences in temperatures among reclamation treatments were not statistically significant. The small differences are unlikely to impact revegetation, since relatively few plant species in this region produce dormant seeds, and they germinate best in temperatures between 12 and 20°C (Bliss 1959; Amen 1966; Haag and Bliss 1974; Bell and Bliss 1980). Apomixis and vegetative reproduction are common (Bliss 1971; Billings 1974), but these processes and root growth, would also not be impacted by such small temperature differences (Billings et al. 1978).

Precipitation in 2005 (132.5 mm) at the mine site was similar to the 10-yr average, whereas 2006 was wetter (167.9 mm). Most precipitation occurred in August or September. Surface soil water (5 cm depth) was generally higher and had more extreme ranges than at 30 cm. Volumetric water content among reclamation treatments ranged from 0 to over 20% at both 5 and 30 cm depths (Figs. 1 and 2). The majority of reclamation treatments had volumetric water contents between 5 and 10% throughout the growing seasons. Although magnitudes varied, all treatments showed similar response patterns to precipitation, with water content peaking after precipitation events.

Gravel treatments, regardless of amendment, had the lowest volumetric water content throughout the growing season, never $>5\%$ (Figs. 1 and 2). Other substrates and amendments had significantly higher water contents at any measured time, indicating a major restriction to using gravel as a sole reclamation substrate. Highest water contents were usually found in a ratio of 25:75 with sludge. Adding sludge and sewage increased water content. Sludge was composed of 95% water, while sewage had high organic matter which would increase water holding capacity. The positive effect of sludge and sewage on soil water was reduced with time since application. The effect of sludge was not as great in processed kimberlite as in 25:75 treatments. The coarse

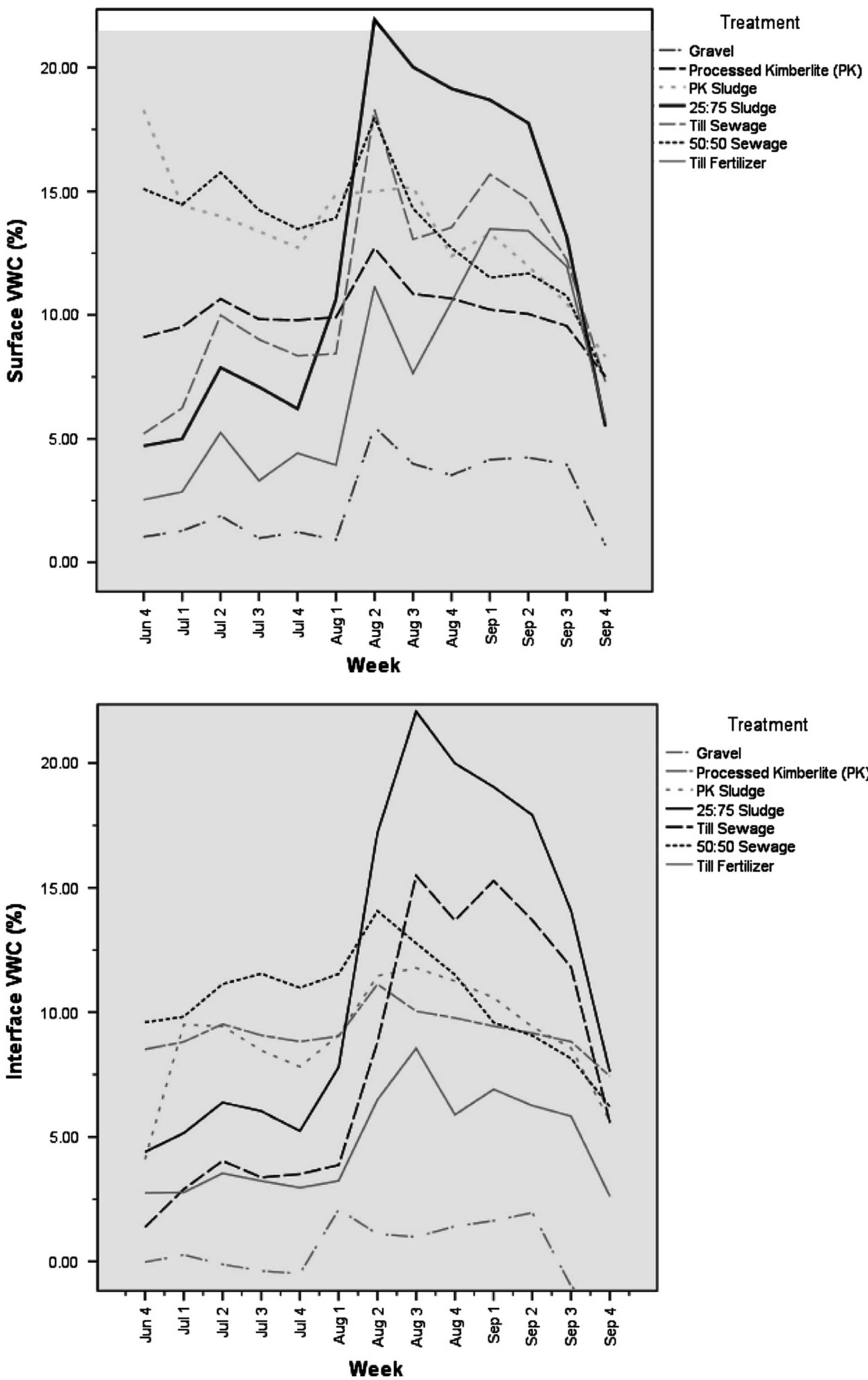

Fig. 1. Mean volumetric water content at 5 cm and 30 cm depth in selected reclamation treatments in 2005.

sand texture of processed kimberlite may have resulted in more rapid drainage. The higher clay content in the till with fertilizer treatment may have enhanced water retention.

In the harsh environment of the study site, these differences in water content among treatments could have significant impacts on revegetation. Similar to our study, Bell and Bliss (1980) found that seeds germinated

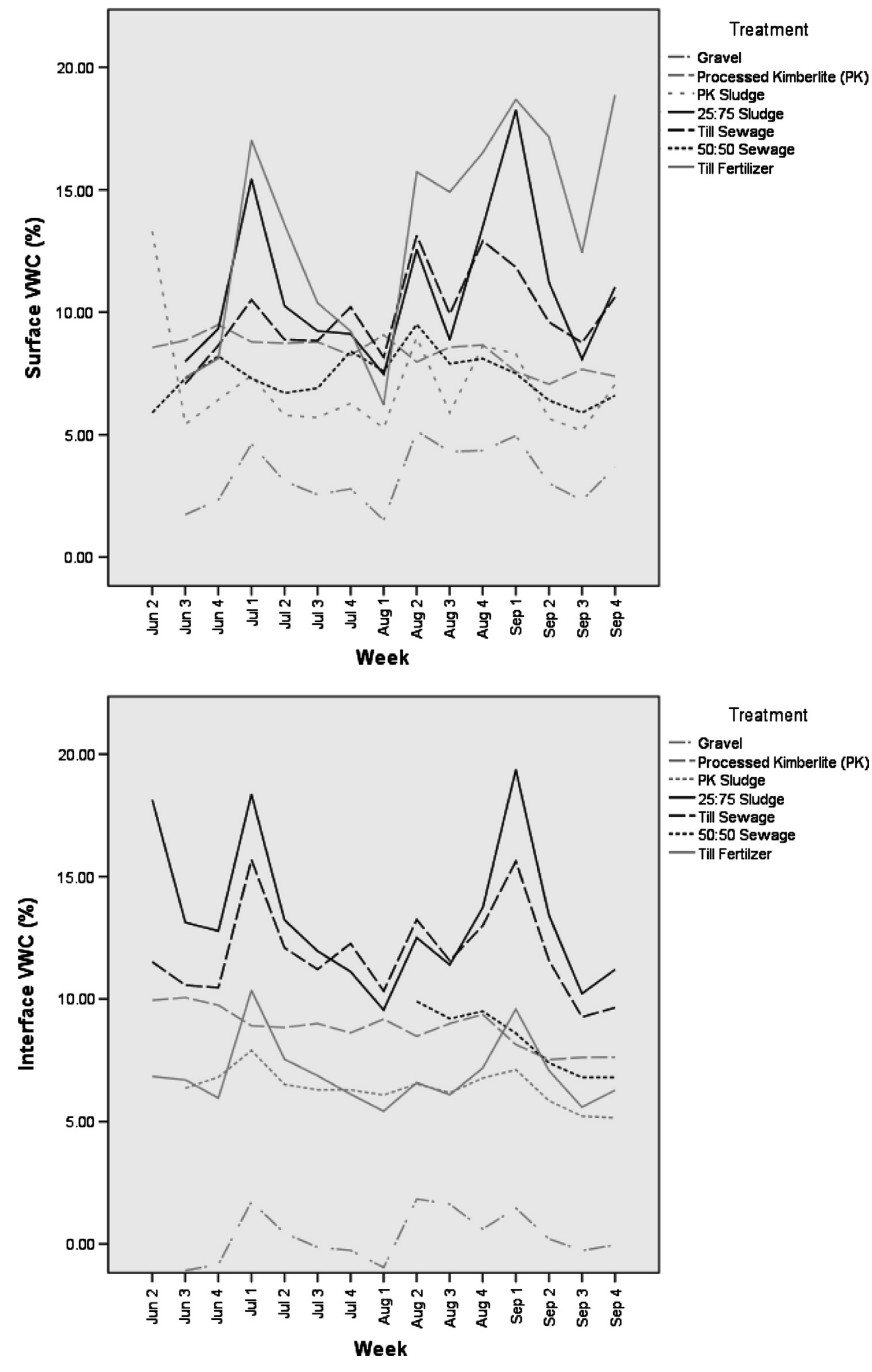

Fig. 2. Mean volumetric water content at 5 cm and 30 cm depth in selected reclamation treatments in 2006.

and established best in microsites, such as soil cracks where soil water would likely be highest over the longest periods in summer. Seedling deaths generally resulted from summer drought and most seeds germinated following periods of snow melt or after infrequent summer rains.

Soil Chemical Properties

The reference soil had significantly lower pH (4.5) than all treatments (average 7.4) at 0–10 cm (Table 2). Soil pH was highest in processed kimberlite (8.2), and only in topsoil amended or till based treatments did it drop below 7. Soils in the arctic are generally slightly acidic (Schimel et al. 1996; Smyth 1997). However, Chapin and Shaver (1981) found plants adapted to the arctic are capable of surviving within a pH range of slightly acidic to slightly alkaline.

Electrical conductivity was generally higher in all treatments than the reference soil, being highest in till with sewage (Table 2). Although little research has been conducted in the arctic on effects of increased electrical conductivity on native plant species, it is generally accepted that an electrical conductivity <4 dS m^{-1} will not reduce plant growth. Electrical conductivity only surpassed this value in till with sewage and was only >2 dS m^{-1} in processed kimberlite, processed kimberlite with fertilizer, 50:50 with sewage and 25:75 with sludge.

Sodium adsorption ratio was generally higher in all treatments than the reference soil, being highest in till with sewage (Table 2). A sodium adsorption ratio <4 is generally considered non limiting to plant growth and no values were above that. Most treatments had significantly higher calcium than reference soil; there were no statistically significant differences among treatments (data not shown). Of the substrates, processed kimberlite had highest calcium (83.2 mg L^{-1}) with similar concentrations among the rest (65.7 mg L^{-1}). Magnesium varied extensively among treatments and was significantly highest in processed kimberlite (346.1 mg L^{-1}) and lowest in reference soil (6.0 mg L^{-1}) and treatments amended with topsoil (data not shown). Sodium ranged from 6.8 mg L^{-1} in the reference soil to 149.9 mg L^{-1} in till with sewage.

All reclamation treatments had significantly less total carbon than the reference soil (Table 2). Till with sewage and all topsoil amended treatments had significantly greater total carbon than unamended or fertilizer amended substrates. Organic carbon increases available nutrients in a rehabilitating system by increasing cation exchange capacity and can improve soil physical (texture, increase water holding capacity, decrease bulk density) and chemical (pH, electrical conductivity) conditions (Sort and Alcaniz 1999; Adriano 2001; Rate et al. 2003). Reid and Naeth (2005a, b) found sewage sludge significantly increased cation exchange capacity and organic carbon of kimberlite tailings, which lead to greater shoot and root biomass. Cation exchange capacity at 0–10 cm was lower in all treatments relative to the reference soil (Table 2). It was lowest in gravel and highest in processed kimberlite alone and with fertilizer. Results were similar at 20–30 cm.

Regardless of the substrate or amendment used, nitrogen and sulphur generally increased relative to the reference soil (Table 2). Fertilizer and sewage resulted in higher nitrogen compared to unamended substrates, significant only for till and 25:75 substrates due to high variability among samples. Processed kimberlite had significantly greater sulphur than most treatments except those amended with sewage or sludge. Available phosphorus was lower in most reclamation treatments than in reference soil with the exception of topsoil and sewage-amended treatments. Phosphorus in sewage-amended treatments was significantly higher than all other treatments. In processed kimberlite, processed kimberlite with fertilizer and with sludge, till with sewage and 50:50 with sewage, potassium was significantly elevated above the reference soil and other reclamation treatments.

Nitrogen is considered the most common limiting nutrient in tundra communities due to low decomposition and mineralization rates (Atkin 1996; Schimel et al. 1996). A widespread source of phosphorus in the arctic is from snowfall and precipitation, which is limited; therefore soil phosphorus is extremely low (Crawford 1989). Although native arctic plants are adapted to low soil phosphorus, they grow better when phosphorus is readily available (Crawford 1989). Thus higher amounts of nitrogen and phosphorus in some treatments may present an advantage for vegetation. Potassium is naturally high in arctic soils from potassium rich minerals such as orthoclase, biotite and muscovite. The higher potassium in processed kimberlite results from break down of the phyllosilicate mineral mica, of which it is composed.

Metals

Heavy metal concentrations for 11 (antimony, beryllium, cadmium, lead, mercury, molybdenum, selenium, gold, thallium, tin, uranium) of the 19 metals analyzed were below detection limits at both depths and therefore pose little environmental concern. Arsenic, barium, chromium, cobalt, copper, nickel, vanadium and zinc were present in the reference soil and reclamation treatments. No environmental quality guidelines for metals have been developed for arctic soils, therefore they were compared to the earth's Precambrian crust, reference soil from the area, and the CCME (2007) agricultural soil quality guidelines. The crustal abundance of metals serves as a guide for soil that has developed from a granite parent geological material (Taylor 1964). The reference soil provides insight into natural metal concentrations in the area, and CCME guidelines give approximate concentrations that may be considered hazardous to the environment.

Arsenic, barium and vanadium concentrations in all treatments were less than CCME guidelines at 0–10 (Table 3) and 20–30 cm (data not shown). Zinc and copper were also less than CCME guidelines except in till with sewage, where they were higher. Nickel and chromium exceeded CCME guidelines in all reclamation treatments. Crustal abundance values were exceeded in almost all cases for arsenic, chromium, cobalt and nickel, but rarely for barium, copper, vanadium and

Table 2. Soil properties of reclamation treatments and reference soil at 0–10 cm

Reclamation treatment	Hydrogen ion concentration (pH)	Electrical conductivity (dS m^{-1})	Sodium adsorption ratio	Cation exchange capacity (meq 100 g^{-1})	Total carbon (%)	Available nitrogen (mg kg^{-1})	Available phosphorus (mg kg^{-1})	Available potassium (mg kg^{-1})	Available sulphur (mg kg^{-1})
Gravel unamended	7.3 (0.6)	0.7 (0.3)	1.2 (0.4)	2.3 (1.5)	0.2 (0.1)	9.1 (6.3)	3.2 (0.01)	41.6 (18.4)	5.8 (1.3)
Gravel fertilizer	7.4 (0.4)	0.9 (0.3)	0.7 (0.1)	3.6 (2.1)	0.2 (0.1)	29.6 (43.3)	21.0 (14.5)	68.8 (34.7)	9.8 (3.5)
Gravel topsoil	7.0 (0.5)	1.1 (0.2)	0.7 (0.3)	7.1 (1.3)	2.2 (1.1)	3.9 (1.7)	7.6 (0.5)	108.3 (56.2)	36.3 (1.2)
PK none	8.2 (0.1)	3.0 (1.0)	1.2 (0.2)	11.8 (1.1)	0.7 (0.04)	3.6 (0.9)	1.7 (0.7)	662.8 (44.6)	99.8 (25.7)
PK fertilizer	8.1 (0.0)	2.7 (0.4)	1.2 (0.2)	12.3 (1.7)	0.7 (0.1)	6.4 (3.2)	28.0 (16.1)	330.3 (22.4)	80.7 (12.1)
PK topsoil	6.1 (0.7)	0.6 (0.3)	0.9 (0.7)	8.0 (2.5)	2.0 (1.2)	3.1 (1.5)	7.2 (1.8)	60.9 (17.5)	33.9 (41.2)
PK sludge	8.2 (0.1)	2.0 (0.1)	1.7 (0.4)	7.5 (1.1)	1.3 (0.8)	1.9 (0.5)	3.3 (0.9)	356.0 (29.1)	51.7 (20.0)
Till unamended	6.5 (0.4)	0.9 (0.3)	0.9 (0.3)	3.0 (1.1)	0.1 (0.01)	8.6 (8.0)	7.3 (0.0)	61.3 (11.6)	19.4 (6.1)
Till fertilizer	7.0 (0.0)	1.3 (0.5)	0.8 (0.1)	2.6 (0.5)	0.1 (0.01)	54.1 (40.0)	13.7 (2.9)	72.8 (8.5)	21.4 (5.0)
Till topsoil	6.1 (0.3)	1.1 (0.2)	1.2 (0.7)	6.5 (1.3)	1.8 (0.5)	10.1 (9.3)	9.4 (3.7)	73.6 (13.2)	32.6 (9.3)
Till sewage	7.2 (0.1)	7.1 (2.0)	3.7 (1.5)	9.0 (2.7)	3.5 (0.8)	34.0 (34.2)	487.5 (98.7)	272.9 (163.7)	133.0 (21.8)
50/50 unamended	8.1 (0.1)	2.1 (0.1)	1.1 (0.3)	7.8 (3.0)	0.4 (0.04)	6.2 (2.7)	3.9 (0.8)	194.0 (21.8)	52.0 (6.4)
50/50 fertilizer	8.1 (0.2)	1.7 (0.5)	1.0 (0.2)	7.6 (2.2)	0.4 (0.1)	14.9 (19.7)	13.7 (0.6)	188.9 (39.0)	42.1 (12.6)
50/50 topsoil	6.9 (0.5)	0.9 (0.5)	0.7 (0.2)	7.9 (0.6)	1.9 (0.4)	3.3 (2.6)	7.3 (2.2)	80.9 (22.6)	22.2 (18.6)
50/50 sewage	7.6 (0.1)	3.6 (1.5)	1.7 (0.4)	8.8 (1.7)	1.7 (0.3)	12.7 (7.2)	250.5 (74.8)	307.5 (139.7)	62.1 (14.7)
25/75 unamended	8.0 (0.2)	1.4 (0.2)	0.9 (0.1)	4.7 (0.8)	0.3 (0.1)	6.4 (0.8)	4.7 (1.2)	148.2 (37.5)	35.9 (10.8)
25/75 fertilizer	8.0 (0.1)	2.1 (0.5)	1.1 (0.1)	5.6 (2.0)	0.3 (0.1)	38.6 (39.6)	15.0 (7.5)	183.4 (22.2)	50.3 (3.0)
25/75 topsoil	6.5 (0.6)	0.6 (0.0)	0.6 (0.2)	8.9 (1.0)	2.3 (1.0)	2.8 (0.7)	9.0 (0.7)	70.4 (17.0)	1701 (3.0)
25/75 sludge	7.9 (0.1)	2.6 (0.7)	1.6 (0.3)	4.0 (0.2)	0.7 (0.3)	16.1 (10.8)	5.8 (1.1)	198.7 (50.9)	72.4 (35.4)
Reference soil	4.5 (0.5)	0.2 (0.1)	0.5 (0.4)	18.5 (6.5)	9.3 (6.5)	1.8 (1.2)	7.0 (5.6)	117.2 (78.0)	9.8 (5.4)

Standard deviations are in parentheses.

Table 3. Mean heavy metal concentrations in reclamation treatments at 0–10 cm

Reclamation treatment	Arsenic	Barium	Chromium	Cobalt	Copper	Nickel	Vanadium	Zinc
Gravel unamended	2.5 (1.4)	86.3 (101.9)	79.8 (88.3)	17.3 (22.3)	10.3 (9.2)	268.3 (371.3)	16.6 (16.8)	40.0 (17.3)
Gravel fertilizer	1.8 (0.3)	61.3 (54.4)	48.7 (57.4)	13.7 (17.6)	7.3 (2.1)	221.7 (338.9)	10.7 (2.1)	36.7 (5.8)
Gravel topsoil	3.8 (0.9)	136.0 (62.2)	108.1 (55.0)	25.7 (20.1)	14.7 (1.5)	419.3 (373.6)	24.0 (3.5)	36.7 (5.8)
PK unamended	1.8 (0.6)	281.3 (59.6)	333.3 (21.8)	71.3 (12.1)	17.0 (2.6)	1296.6 (172.1)	25.3 (3.1)	46.7 (5.8)
PK fertilizer	1.9 (0.6)	277.0 (45.4)	305.7 (20.1)	82.7 (6.7)	16.3 (2.5)	1493.3 (106.9)	24.0 (1.0)	46.7 (5.8)
PK topsoil	5.3 (1.3)	78.0 (15.6)	53.7 (23.7)	8.3 (2.5)	16.0 (7.5)	68.7 (67.0)	26.0 (6.1)	30.0 (10.0)
PK sludge	2.2 (0.7)	335.3 (101.8)	410.3 (71.1)	76.7 (10.7)	17.3 (1.5)	1360.0 (191.6)	28.3 (4.5)	46.7 (5.8)
Till unamended	4.9 (0.9)	117.0 (43.5)	67.1 (40.7)	14.0 (11.3)	19.7 (2.5)	143.3 (205.0)	33.0 (4.4)	70.0 (52.0)
Till fertilizer	4.1 (0.6)	122.0 (53.4)	93.8 (74.4)	16.7 (11.6)	18.7 (4.0)	205.3 (226.6)	30.7 (5.0)	43.3 (5.8)
Till topsoil	4.3 (0.5)	94.0 (7.1)	73.4 (22.7)	12.0 (2.8)	14.5 (0.7)	140.5 (48.8)	26.5 (0.7)	30.0 (0.0)
Till sewage	3.5 (0.5)	164.7 (75.5)	151.0 (93.7)	26.3 (20.2)	90.0 (56.2)	410.0 (399.6)	27.7 (4.2)	250.0 (158.7)
50:50 unamended	3.5 (2.0)	205.0 (89.4)	179.5 (109.4)	41.0 (26.2)	18.3 (1.2)	673.3 (509.4)	29.7 (3.1)	43.3 (5.8)
50:50 fertilizer	2.5 (0.2)	258.3 (37.4)	256.0 (20.7)	61.7 (6.4)	22.0 (6.2)	1080.0 (113.6)	27.3 (2.5)	50.0 (0.0)
50:50 topsoil	4.3 (0.5)	106.7 (24.7)	116.4 (53.1)	18.0 (7.5)	13.3 (2.1)	275.3 (146.8)	22.3 (0.6)	30.0 (0.0)
50:50 sewage	3.8 (2.0)	178.0 (47.1)	182.0 (56.9)	45.5 (17.1)	22.0 (52.6)	769.0 (296.9)	23.0 (2.2)	157.0 (146.4)
25:75 unamended	4.4 (1.2)	181.0 (12.5)	151.7 (35.1)	39.0 (12.1)	20.3 (4.7)	616.7 (262.8)	31.3 (7.6)	46.7 (5.8)
25:75 fertilizer	3.5 (1.1)	195.3 (32.6)	215.3 (63.1)	52.7 (15.2)	18.7 (2.3)	903.7 (320.4)	29.0 (3.6)	46.7 (5.8)
25:75 topsoil	4.0 (0.8)	61.0 (5.3)	36.9 (9.5)	7.0 (2.0)	11.3 (2.3)	68.0 (33.6)	18.7 (0.6)	20.0 (0.0)
25:75 sludge	3.2 (0.7)	256.7 (92.1)	249.0 (52.4)	55.7 (16.1)	17.0 (2.6)	967.7 (289.1)	28.7 (4.0)	46.7 (5.8)
Reference soil	3.7 (1.6)	61.6 (7.6)	27.2 (7.0)	4.6 (1.1)	21.2 (29.0)	15.8 (3.6)	21.4 (6.6)	32.0 (4.5)
CCME guidelines	12	750	64	40	63	50	130	200
Crustal abundance	1.8	425	100	25	55	75	135	70

CCME, Canadian Council of Ministers of the Environment.
Crustal abundance values from Taylor (1964).
Values are in mg kg^{-1}; standard deviations are in parentheses.

zinc. Treatments exceeded reference soil values mostly for barium, chromium, cobalt, nickel, vanadium and zinc; often for arsenic, and rarely for copper.

Molybdenum and selenium concentrations were highest in sewage and sludge amended treatments. Molybdenum and selenium were above or close to CCME guidelines in sewage-amended treatments. Mean molybdenum content was 12.3 ($\pm$9.3) mg kg^{-1} in 50:50 sewage and 15.0 ($\pm$12.1) mg kg^{-1} in till sewage. Mean selenium content was 0.9 ($\pm$0.6) mg kg^{-1} and 0.8 ($\pm$0.6) mg kg^{-1} in the same treatments. Selenium was also present in gravel and processed kimberlites treatments although in concentrations well below CCME guidelines.

Concentrations above CCME guidelines varied with metals. Highest exceedances from CCME, reference soil and crustal abundance occurred in till, till mixes and topsoil for arsenic; processed kimberlite with sludge for barium; gravel, till and till mixes for chromium; processed kimberlite or mixes for cobalt; sewage for copper; processed kimberlite for nickel, till and sewage for zinc. Adding topsoil diluted the concentration of chromium, and vanadium was lowest in gravel treatments. Thus, no one substrate or amendment was notable for increasing metals. Most results were not significant due to the high variability in samples.

Soils developed from ultrabasic rocks are usually enriched in chromium, cobalt, nickel and zinc (Anderson et al. 1973; Adriano 2001); therefore, reclamation treatments derived from kimberlite will have higher concentrations of these elements. Although chromium, cobalt, nickel and zinc are considered essential micronutrients in low concentrations, at high concentrations they can be toxic to plants, animals and humans. Chromium has been found in kimberlite material at other mine sites and was not taken up by plants or leached (Stevens 2006). In soils, most heavy metals occurred as inorganic compounds or were bound to organic matter, clays or hydrous oxides of iron, manganese and aluminum (Foy et al. 1978).

With precipitation and sorption of most metals by soil, the only metals to be concerned with are zinc and nickel, because plant toxicities frequently occur. Toxicologically, zinc is relatively inconsequential since there is a wide range between usual environmental and toxic concentrations (Adriano 2001). Although nickel was above CCME guidelines it is likely complexed with various organic and inorganic ligands (Ni-II form), which is stable over a wide range of pH and redox conditions and unavailable to plants. For a metal to be assimilated, it must be mobile, transported and bioavailable to plants. Zinc and nickel are likely incorporated in soil organic material, and are not dissolved in soil solution, sorbed onto exchange sites, or in the free ionic or complexed form and are thus not bioavailable. Cobalt toxicities only occur under very unusual conditions and chromium is not phytotoxic in soils even at high concentrations (Foy et al. 1978). As long as soil pH remains relatively high chromium will remain in trivalent form, which is less toxic to plants and less mobile in surface and subsurface environments than the hexavalent form. There has been no research conducted on effects of these metals on plant species growing in the arctic, therefore it is difficult to determine how they will affect long-term revegetation success.

Microbial Properties

Salmonella was isolated in one sample from 50:50 sewage in fall 2004, but not from any 2005 samples. Fecal coliforms were in all sewage-amended treatments at 0–10 and 20–30 cm (data not shown), averaging 511 g^{-1} at 0–10 cm and 448 g^{-1} at 20–30 cm. Research on surface-applied sewage has shown coliform survival rates decrease with time, especially with decreasing temperatures (Edmonds 1976; Estrada et al. 2006; Rufete et al. 2006). Fecal coliform bacteria decreased significantly in sewage stockpiled over winter at the research site and were higher in sewage brought to the site and subsequently applied. While there are no specific guidelines for raw sewage sludge, CCME considers values >1000 g^{-1} unacceptable in composts.

Plant Response

As indicated in the sections above, constructed soils varied considerably in properties deemed to affect plant response. There was no substrate or amendment that consistently led to a lower or higher overall quality of reclamation soil. The ultimate test of an arctic reclamation soil is whether it can support a sustainable and diverse plant community. In the first few years following reclamation on severely disturbed sites, the best measure of success is plant response (density, cover, health). In this study, plants grew and survived on all reclamation treatments. Season of seeding had no effect on plant response ($t = -0.892$, $P = 0.377$), thus data for spring and fall treatments were pooled for further analyses.

A final density of 50 plants m^{-2} was one of the revegetation goals for the reclamation treatments. An initial assessment of plant density was conducted in 2005; however, it was very difficult to identify grass species. In 2006, only 2 yr after seeding, the best performing treatments approached this goal, with mean densities of 29 to 47 plants m^{-2} (Fig. 3).

Plant response was most favourable in 25:75 with sludge, which had significantly higher plant densities than all treatments except gravel, processed kimberlite with topsoil, till with fertilizer, and till with topsoil (Fig. 3). In 25:75 with sludge, plants likely benefitted from nitrogen and water in the sludge, particularly for seed germination. Unamended gravel, the original substrate requiring reclamation, surprisingly, had significantly higher plant densities than unamended processed kimberlite, till or mixes of the two, and was among the best treatments for plant growth. Amendments in general were associated with better plant responses than unamended substrates, except in 50:50 sewage and 25:75 topsoil. Plant densities in treatments amended with topsoil were among the top ten reclamation treatments. Gravel with topsoil had the second highest plant densities and processed kimberlite with topsoil the fourth highest plant densities of all 20 reclamation treatments.

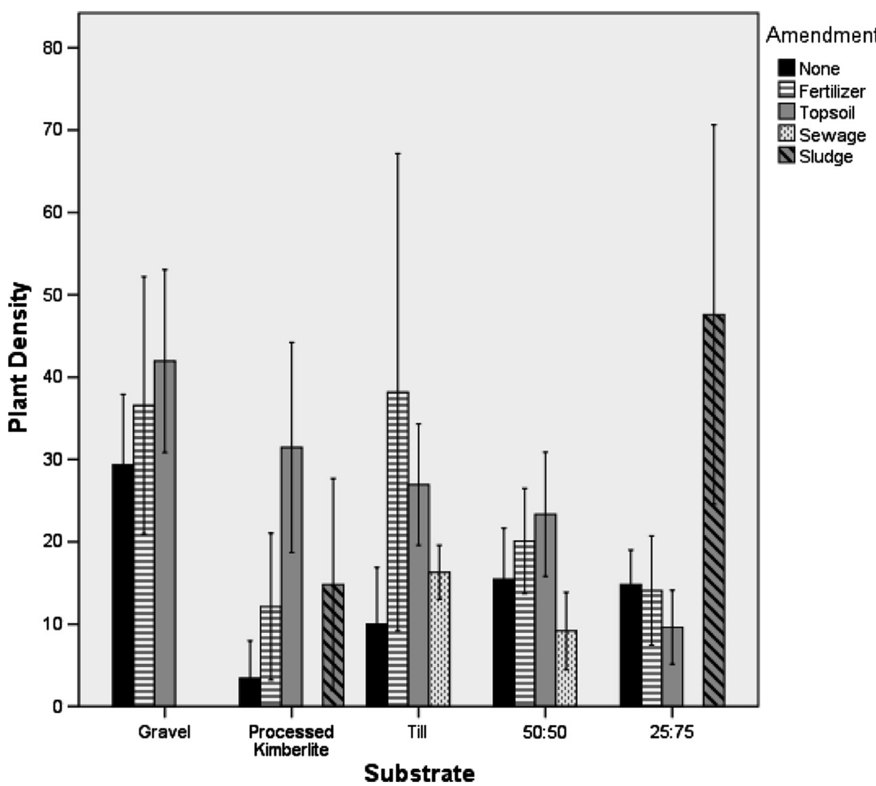

Fig. 3. Mean plant density (per m^2) in reclamation treatments during first growing season. Bars represent ± 2 standard error.

Lowest plant densities occurred in unamended processed kimberlite. Till, 50:50 with sewage and 25:75 with topsoil also had low plant establishment. Poor plant response in unamended processed kimberlite can be explained by physical (sand texture reduces water and nutrient retention, black colour increases surface temperature) and chemical (increased heavy metals, sulphate, pH; low available nutrients) limitations of the material and that in unamended till by poor physical structure (high clay content) (Tables 2 and 3). Addition of topsoil to processed kimberlite and till and fertilizer to till, significantly increased plant establishment. The unexpected low density in 50:50 with sewage can likely be attributed to elevated metal concentrations in sewage and processed kimberlite; the combination proving toxic to plants (Table 3). While plant densities were still relatively low in till with sewage, sewage improved plant establishment compared with unamended till. Nitrogen from the sludge may have leached in processed kimberlite due to its coarse texture and the high water content of sludge.

Plant species did not appear to generally favour any given substrate or amendment. Most reclamation treatments were dominated by glaucous blue grass. Processed kimberlite, processed kimberlite with sludge, till and 50:50 with sewage were dominated by alpine wheat grass; gravel and gravel with fertilizer were dominated by rocky mountain fescue. Northern sweet broom had the highest forb densities although <5 plants m^{-2} in any treatment. All plants were <5 cm in height and most were in good health.

CONCLUSIONS AND APPLICATIONS

Results from this research show a direct relationship between soil reclamation treatments and initial plant establishment. Reclamation soils constructed with various substrates and amendments were adequate for revegetation.

Mixes of processed kimberlite and glacial till enhanced soil structure and diluted potentially adverse concentrations of elements, compared with either substrate alone, thereby facilitating establishment of native plant species. There were no significant differences between 25:75 and 50:50 mixes of processed kimberlite and glacial till in chemical composition or vegetation response; therefore, it would be acceptable to use the one most economical for reclamation. The original gravel substrate, alone or amended, was a suitable substrate. Addition of an organic amendment which increases organic matter, soil nutrients and surface water retention, such as salvaged topsoil or sludge from the water treatment plant, enhanced native plant establishment in any substrate. Topsoil provided the most consistent benefits for substrate enhancement and vegetation success and should be salvaged and used as an amendment whenever possible. Inorganic fertilizer when applied to gravel or glacial till provided results similar to those achieved with topsoil for vegetation success. Sludge had potential as an amendment to mixes of processed kimberlite and glacial till, although results were variable so further research is encouraged. Sewage is a good source of organic matter, which enhances soil water content, and macro nutrients. Initial vegetation response, however, was poor in sewage-amended treatments likely due to the combined effects of high copper, molybdenum, selenium, zinc, sulphate and phosphorus content.

A variety of reclamation landscapes can be created on disturbed sites depending on availability of base substrates and amendments and access. While the results based on the first two growing seasons following application of reclamation and revegetation treatments are promising, further monitoring will determine the long-term success to re-establish tundra communities on these disturbed mine sites.

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