DEVELOPMENT OF SOILS FOR REVEGETATION IN NORTHERN DIAMOND MINES

By

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ABSTRACT

Mining in the Canadian north has increased since diamonds were discovered in the 1990s. The large physical disturbances and large amounts of waste from diamond mining, coupled with inherent challenges in northern environments due to the harsh climate, make land reclamation particularly challenging. Building suitable anthroposols, human made or altered soils, is the first step for reclamation and ecosystem development as finding a source of soil in remote northern sites is not possible. Small scale field experiments at a diamond mine in northern Canada and greenhouse experiments using diamond mine materials assessed effectiveness of substrate and amendment combinations to build anthroposols, the role of micro topographic variability and use of short term erosion control methods to develop reclamation strategies.

Amendment and substrate combinations under water limited and non-limited conditions using various amendment rates were assessed in greenhouse experiments to determine effects on vegetation and water retention. Substrates were collected from Diavik Diamond Mine (crushed rock, lakebed sediment, processed kimberlite, combinations). Amendments were collected at Diavik or purchased in Edmonton (biochar, Black Earth, fertilizer, hydrogel, peat, sewage, soil, combinations). Experiments ran from 8 to 12 weeks. Two field experiments explored vegetation response on three mine wastes (crushed rock, lakebed sediment, processed kimberlite) with organic amendments (soil, sewage), micro topography (mounds, boulders, depressions, furrows, flats) and erosion control methods (Soil Lynx, erosion control blankets, treated jute, jute with Soil Lynx) over four years. In all experiments, material properties were assessed and vegetation establishment and growth were monitored.

In greenhouse experiments with non-limited water availability, vegetation response was greatest in crushed rock and lowest in processed kimberlite. Under water limited conditions, crushed rock and processed kimberlite were more effective than lakebed sediment. Processed kimberlite had the greatest water retention relative to other substrates. Organic amendments had limited effect on water retention; hydrogel increased water retention in crushed rock and processed kimberlite. In all experiments, sewage at any rate resulted in the greatest above ground biomass and plant height. Soil and peat were more effective at high rates, although plant density increased under water available conditions relative to sewage. Competition of large plants in sewage likely reduced density. Biochar, Black Earth and hydrogel did not improve vegetation establishment or growth due to lack of nutrients or substrate improvement. Fertilizer had a limited effect, only improving plant growth with specific amendment and substrate combinations where nutrients were lacking.

In field experiments, crushed rock was the most successful substrate and processed kimberlite the least. Crushed rock's success was due to its rough surface creating suitable micro sites for seed germination and plant establishment and growth relative to smoother, sandy processed kimberlite. Sewage resulted in greater cover and species richness with taller plants, as its high nutrient content provided resources limiting in unamended or soil amended treatments. Micro topography had a limited effect in crushed rock due to its natural rough surface. In processed kimberlite, and to a lesser extent lakebed sediment, cover, height and number of plants and species were greater when micro topography included low areas which facilitated seed collection and safe micro site creation. Erosion control materials had a limited effect; jute and erosion control blankets provided some benefit in lakebed sediment and processed kimberlite.

This research has contributed significantly to the knowledge base for building anthroposols, with a focus on northern diamond mines, assisting in developing strategies to select substrates, amendments, micro topography and erosion control methods. Results can be expanded to similar disturbances in the north and other environments due to the large number of comparisons assessed and the focus on properties of materials. Major next steps include approaching reclamation strategies at an industrial scale.

PREFACE

Chapter II of this thesis has been published as Miller, V.S. and M.A. Naeth, “Amendments and substrates to develop anthroposols for northern mine reclamation”, Canadian Journal of Soil Science, vol. 97, 266-277 in 2017 (dx.doi.org/10.1139/cjss-2016-0145). V.S. Miller was responsible for experimental design, data collection and analysis and manuscript development. M.A. Naeth was the supervisory author and was involved with experimental design and manuscript development. Chapter III of this thesis has been published as Miller, V.S. and M.A. Naeth, “Hydrogel and organic amendments to increase water retention in anthroposols for reclamation”, Applied and Environmental Soil Science, as Article ID 4768091, 11 pages (https://doi.org/ 10.1155/2019/4768091) under a Creative Commons Attribution License (CC by 4.0). V.S. Miller was responsible for experimental design, data collection and analysis and manuscript development. M.A. Naeth was the supervisory author and was involved with experimental design and manuscript development. Chapter IV of this thesis is submitted to the Canadian Journal of Soil Science as V.S. Miller and M.A. Naeth, “Amendments to improve plant response under simulated water limited conditions in diamond mine anthroposols.” V.S. Miller was responsible for experimental design, data collection and analysis and manuscript development. M.A. Naeth was the supervisory author and was involved with experimental design and manuscript development.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

I. BACKGROUND

1. INTRODUCTION

Disturbances are increasing worldwide with the rapidly rising population, and so are subsequent resource needs and land use requirements. The exact amount of land impacted by human activity is uncertain. Ellis et al. (2010) estimated that 39 % of ice free land is used for agriculture and urban settlements, with additional land used for forestry, mining and other disturbances; Vitousek et al. (1997) estimated that one third to one half of land has been transformed by humans. Mining in the Canadian north (arctic and subarctic regions with a cold climate, underlying permafrost and short growing season) increased dramatically in the last three decades since diamonds were discovered in 1991 in the Northwest Territories (Baker et al. 2001, Bryan and Bonner 2003). Diamond mining produces expansive disturbances and large amounts of waste materials, commonly associated with soil and vegetation removal and infrastructure, such as roads, pads, stockpiles and buildings (BHP Diamonds Inc. 1995, Drozdowski et al. 2012).

Arctic and subarctic climate and site conditions (BHP Diamonds Inc. 1995, Kidd and Rossow 1998, ABR 2001, Deshaies et al. 2009) can be challenging, making disturbances long lasting and difficult to reclaim. The growing season is short with few warm days, frequent cold temperatures and frost. Soils are thin with little nutrients. Decomposition is slow, which slows nutrient cycling and plant establishment, growth and development. Plants produce little viable seed on irregular schedules, reproduce vegetatively and have limited propagule dispersal (Bishop and Chapin III 1989b, Kidd and Rossow 1998). Natural recovery of disturbed sites can take decades (Jorgenson and Joyce 1994, Naeth and Wilkinson 2011).

Despite increased development and mining in the north rapidly creating disturbances that require reclamation, current knowledge of reclamation techniques is limited. Disturbances in the arctic and subarctic require development of suitable soils for revegetation (Johnson 1987). In the late 1980s, reclamation research in the north began, with a focus on use of amendments to build anthroposols to support revegetation (Johnson 1987, Bishop and Chapin III 1989b, Densmore 1994, Jorgenson and Joyce 1994, Kidd and Rossow 1998, Reid and Naeth 2005a, Reid and Naeth 2005b, Stevens 2006, Rausch and Kershaw 2007, Deshaies et al. 2009, Naeth and Wilkinson 2010, Martens 2011, Drozdowski et al. 2012). Researchers noted the importance of topographic variability in supporting plant reestablishment (Bell and Bliss 1980, Beatty 1984, Sohlberg and Bliss 1984, Cargill and Chapin III 1987, Smith and Capelle 1992, Jumpponen et al.

1999), although quantification of impact and use in reclamation continues to be limited (Naeth and Wilkinson 2011).

With decades of mining forecasted for current diamond mines, other mines in development and similar current and historical disturbances across the north and other environments, development of effective reclamation practices in a timely manner is essential. Reclamation of disturbed sites in the north depends on two main components: building a suitable soil for revegetation and development of plant materials and revegetation methods for these challenging conditions. This research program focused on soil development using amendments and substrates, micro topography and erosion control methods at Diavik Diamond Mine.

2. LITERATURE REVIEW

2.1 Diamond Mining

Diamonds are mined in at least 15 regions worldwide, mostly in England, Russia, India, Africa and Canada (Hart 2001). The primary source of diamonds is in former volcanoes in kimberlite pipes. Kimberlites are complex and variable rocks that tend to be basic and intrusive and contain metals (Baker et al. 2001). Kimberlite pipes are carrot shaped and extend hundreds of kilometers below ground, where diamonds are formed as heat and pressure compress layers of carbon atoms (Hart 2001). The pipes act as conveyor belts carrying diamonds close to the surface, and tend to be found in clusters where earth's crust is over 2.5 billion years old.

Diamonds have been mined globally for thousands of years, with India producing diamonds before 800 BCE (Hart 2001). Exploration in North America began prior to 1960, with deposits too small for mining found around the Great Lakes, in northern Ontario, Michigan, Wisconsin, Kentucky and Arkansas. Exploration in Canada's territories began in the late 1970s and early 1980s. In the late 1980s and early 1990s, exploration focused on Slave Craton in the Northwest Territories (Baker et al. 2001, Hart 2001, Bryan and Bonner 2003). Slave Craton consists of 932,400 km^2 of 2.6 billion year old archean rock, located approximately 300 km northeast of Yellowknife, north of Lac de Gras. In 1991, a kimberlite pipe was discovered under Point Lake.

Following this discovery, companies rushed to stake claims in the area (Hart 2001, Bryan and Bonner 2003). One of these claims was Lac de Gras, destined to be Diavik Diamond Mine (Appendix 1). In 2017, there were five diamond mines in Canada; Diavik, Ekati and Gahcho Kué in Northwest Territories, Stornoway’s Renard Diamond Project in Quebec and Victor in Ontario;

Snap Lake in Northwest Territories (2015) and Jericho in Nunavut (2008) are closed (Natural Resources Canada 2011, Canadian Press 2016, Marshall 2016). This region, the Canadian Barrens, produces 10 to 15 % of global diamonds (Baker et al. 2001, Hart 2001). Diamond mining usually begins with pit excavation, using drilling and explosives to expose the kimberlite pipe (Kwiatkowski 2007). It can be done entirely underground or shift to underground mining when pit extraction is no longer economically feasible. Diamonds are separated from ore using non-chemical, gravity based methods (Rio Tinto 2013). As diamonds are economic to mine at 200 mg per tonne of kimberlite ore, large amounts of waste and by-products are created, mainly processed kimberlite from the pipe and glacial till, lake sediment and rock from development of the pit (Kwiatkowski 2007, Baker et al. 2001, Drozdowski et al. 2012, Rio Tinto 2013). Other types of waste are produced in the mining camps, including sewage and sludge from water treatment, and stockpiling of removed surface material, like soil, in some cases.

2.2 Reclamation In The North

2.2.1 Arctic environment

Globally, 5.5 % of the earth's surface is arctic (Crawford 1989). The Northwest Territories has seven ecozones, including the Southern Arctic which is divided into Tundra Plains and Tundra Shield with Diavik in the latter. The Tundra Shield comprises 43 % of the Ecozone and is located between the Northwest Territories and Nunavut borders and the treeline. The climate is characterized by short, cool summers and long, cold winters (Diavik Diamond Mine Inc. 2010b, Ecosystem Classification Group 2012). Frost occurs throughout the year.

Regional topography is expressed in elevation changes of approximately 50 m in rolling hills and depressions (Diavik Diamond Mine Inc. 2010b). Repeated glaciations formed the area; the last one occurring 9,500 years ago, creating eskers, till, boulder fields and rocky outcrops (Ecosystem Classification Group 2012). Bedrock is primarily precambrian granite and sedimentary shaped by frost. Permafrost is continuous, creating landscape features through frost activity and freeze-thaw cycles (Peterson and Billings 1980, Sohlberg and Bliss 1984, Walker 1996, Martens 2006, Kwiatkowski 2007, Slaymaker 2009, Ecosystem Classification Group 2012). Soil freezing and frost heaving force substrates upwards, creating raised domes; forming ice wedge polygons when substrates shrink and crack. Patterned ground, earth hummocks, desiccation cracks, mud boils, broken bedrock and thermokarst features develop with permafrost melting.

Soil development is limited by low temperatures. Cryosols are most common, with occurrences of some regosols and brunisols (Johnson 1987, Deshaies et al. 2009, Diavik Diamond Mine Inc. 2010b, Ecosystem Classification Group 2012). Cryosols are permafrost affected soils (Matheus and Omtzigt 2012). Turbic cryosols are mineral soils affected by frost churning which creates patterned ground; static cryosols have no frost churning; organic cryosols are found in peatlands with permafrost below.

The arctic climate limits nutrient inputs (Crawford 1989). Permafrost restricts chemical weathering, already limited by temperature, and nutrient accumulation cannot occur. Primary nutrient sources are precipitation and biological, with precipitation limited by a high pressure zone. Nutrient cycling is limited, with most nutrients in plant biomass and the upper soil, which has slow decomposition due to low microbial activity (Bliss 1962, Johnson 1987, Deshaies et al. 2009). Little nitrogen is provided in precipitation and nitrogen fixation is limited by low temperatures, making it the limiting nutrient (ABR 2001, Martens 2003, Drozdowski et al. 2012). Phosphorus is very low in arctic soils with precipitation the primary source (Crawford 1989, ABR 2001, Drozdowski et al. 2012). Nutrient accumulation is slow, requiring 10,000 and 70,000 years to replenish nitrogen and phosphorus, respectively, in Barrow, Alaska.

In the arctic, soil water and vegetation are strongly related (Peterson and Billings 1980, Ostendorf and Reynolds 1998). In arid environments, low water availability stresses plants and reduces availability of nutrients (Jorgenson and Joyce 1994, Ostendorf and Reynolds 1998). In contrast, tundra soils are often waterlogged or frozen as permafrost limits percolation of water (Jorgenson and Joyce 1994, Kwiatkowski 2007, Diavik Diamond Mine Inc. 2010b). Drought may be the main cause of seedling loss, with increased germination after snow melt or rain (Bell and Bliss 1980, Jumpponen et al. 1999, Drozdowski et al. 2012). Micro topography leads to small scale hydrologic changes and vegetation patterns (Peterson and Billings 1980).

The arctic has a relatively small flora (Bliss 1962), with over 1,000 vascular species above the tree line, less than 0.4 % of the global total (Billings 1987). The low arctic is characterized by shrub and graminoid communities and the high arctic by sparse vegetation and evergreen shrubs (Crawford 1989). The Southern Arctic Ecozone is mostly treeless (Ecosystem Classification Group 2012). Vegetation communities include erect dwarf shrub tundra, low shrub tundra to non tussock - dwarf shrub - moss tundra, with the first two most common. Erect dwarf shrub tundra is dominated by *Betula glandulosa* Michx. (resin or dwarf birch), *Vaccinium uliginosum* L. (bog blueberry or bog bilberry), *Vaccinium vitis idaea* L. (mountain cranberry or lingonberry), *Ledum palustre* L. (marsh Labrador tea), *Salix glauca* L. (grayleaf willow), *Empetrum nigrum* L. (black crowberry), mosses and lichens, with 80 to 100 % cover in moist areas to little cover in dry areas. Low shrub tundra has many of the same shrub species, dominated by *Salix* sp. L. (willow) and *Alnus* sp. Mill. (alder) with thick moss. Non tussock - dwarf shrub - moss tundra cover is 50 to 100 % with extensive moss, peat and some shrubs.

To survive in the arctic, plants must be adapted to low temperatures and frequent frosts (Crawford 1989). Permafrost limits trees and deep rooting species through restricted rooting depths of soil. Depth of the active layer is 30 to 40 cm in organic soils and over 2 m in coarse soils (Martens 2000). Arctic plants must complete necessary metabolic activities during the short growing season and in low temperatures to have a positive net carbon gain for the year (Billings 1987, Crawford 1989, Kidd and Rossow 1998). Arctic plants follow a C3 photosynthetic pathway with high photosynthesis rates at low temperatures. Due to the short growing season, low temperatures and variable climate, arctic plants must allocate carbon resources for growth and maintenance in poor years. Large root systems and carbohydrate reserves allow plants to survive with little photosynthetic input. Arctic plants have high root to shoot ratios, allowing more water and nutrient uptake at low temperatures (Densmore et al. 2000).

Arctic plants must tolerate low soil nutrients. Deciduous forbs, graminoids and shrubs have low nitrogen and phosphorus use efficiency relative to evergreen shrubs (Chapin III and Shaver 1989). High efficiency in infertile soils allows plants to maximize biomass created and dominate resource use whereas low efficiency allows high rates of photosynthesis and metabolic activities. Nutrient additions can reduce nutrient use efficiency of evergreens and reduce their abundance in fertile areas. Arctic plants tend to have relatively small niches with a high degree of habitat specificity between species.

Low temperatures reduce seed production and colonization (Kidd and Rossow 1998, ABR 2001). Sexual reproduction requires more energy than vegetative (Crawford 1989). To adapt to the climate, sexual reproduction can occur over multiple seasons, with few years where viable seeds are produced (Bliss 1962, Crawford 1989, Forbes and Jefferies 1999).

Limiting factors for plants in the arctic are influenced by wind exposure which reduces snow cover, soil water and temperature during the growing season (Crawford 1989, Anderson and Bliss 1998, Zhelezona et al. 2005). Wind can remove litter, impacting soil nutrients, and be abrasive to plants, reducing ambient temperature. Thus micro topographic differences, like those from permafrost and freeze-thaw activity, play a major role in plant community distribution. Arctic plants tend to grow low to the ground avoiding wind, improving drought resistance (Kwiatkowski 2007) and taking advantage of warmer temperatures (Bliss 1962).

2.2.2 Succession on disturbed sites

The physical environment is important for revegetation on disturbed areas (Mori et al. 2006). During early stages of primary succession, plant communities are controlled by abiotic conditions in a harsh environment with limited soil, nutrients or organic matter (Jumpponen et al. 1999, Mori et al. 2008). Early successional sites have greater risk for desiccation due to intense radiation of the surface from lack of cover. As plants modify their environment, biotic relationships become more important. Development of vegetation communities in primary succession begins with the appearance of plants, followed by increasing numbers and species of plants until a structured community is formed. Succession begins with sites dominated by rocks and bare ground and plant cover increasing with time. Due to harsh conditions in arctic environments, establishment of pioneer species can assist colonization of later successional species by improving site conditions such as fixing nitrogen and creating organic matter (Cargill and Chapin III 1987). Organic matter is essential in developing self-sustaining plant communities as it increases water and nutrient holding capacity, cation exchange capacity and is an energy source for soil microorganisms (Martens 2003, Reid and Naeth 2005a).

Natural recovery in the north can be slow due to the harsh climate and limited plant colonization and reproduction (Kidd and Rossow 1997, Densmore et al. 2000, Rausch and Kershaw 2007, Deshaies et al. 2009). The seed bank and seed rain are significant for natural recolonization, especially in species rich areas (Chapin III and Chapin 1980, Rausch and Kershaw 2007). Proximity to suitable native vegetation is important (Oasis Environmental, Inc. 2004). At mesic sites, natural recovery is relatively rapid as nutrients and water are suitable for native species (Cargill and Chapin III 1987). When disturbed, these sites are subjected to secondary succession if the organic layer is not removed. Seeds tend to be the limiting factor. At xeric sites, like roads, gravel pits and gravel pads, there is little organic soil and few seeds in the substrate. Here primary succession occurs and tends to be dependent on seeds transported via wind, water or biological vectors. Micro sites can improve plant germination and establishment through shading and reduced evaporation as xeric sites lose water rapidly. Micro topography is most important in the early stages of succession (Sterling et al. 1984).

2.2.3 Challenges reclaiming mining disturbances

Mining disturbances introduce major challenges through removal of vegetation and shallow soil, soil compaction, alterations to nutrient and hydrologic cycling, changes in soil temperature and creation of waste piles (Sheoran et al. 2010, Drozdowski et al. 2012). Disturbance type influences its reclamation. Removal of the seed bank drastically slows ecosystem recovery (Vavrek et al. 1999). For example, in tussock tundra, burned sites recovered to near pre disturbance conditions in 20 years, whereas bulldozed sites with the top layer of soil removed required decades to recover. Mine substrates can resemble those exposed during glacial retreat and revegetation of gravel pads resembles primary succession (Kwiatkowski 2007).

Gravel disturbances are common in the arctic, including pads, pits and roads (Johnson 1987, Rausch and Kershaw 2007). Gravel pads are built to protect permafrost (Johnson 1987, Walker 1996). Gravel pits and pads are difficult to revegetate due to slow and reduced seed germination, restricted dispersal of native seeds, low nutrients and low water content. They have limited nutrient and water holding capacity due to low organic matter, often exacerbated by competition from seeded non-native species (Johnson 1987, Bishop and Chapin III 1989b, Jorgenson and Joyce 1994, BHP Diamonds Inc. 1995, Forbes and Jefferies 1999, ABR 2001, Kidd et al. 2006, Kwiatkowski 2007). Seed banks are limited in gravel sites (Kwiatkowski 2007, Rausch and Kershaw 2007) and xeric conditions can negatively affect microbial populations and their activities (Kidd and Max 2000b). Gravel pads tend to be elevated, reducing access to ground water and changing natural flow patterns (Walker 1996) and are compacted, with decompaction disturbing underlying permafrost (Kwiatkowski 2007).

Water is the primary limiting factor to revegetation on disturbed mine sites (BHP Diamonds Inc. 1995), with revegetation of gravel pads more likely when water is available (Walker 1996). However, gravel pads commonly block natural drainage, are disconnected from the hydrologic system and alter snow drift, resulting in water stress (Walker 1996, ABR 2001, Naeth and Wilkinson 2004). Germination is limited by water and tends to be low on gravel pads unless precipitation is high (Bishop and Chapin III 1989a). Berms can be built to trap drifting snow and increase soil water at melt, although much is lost (Jorgenson and Joyce 1994). Plant cover can increase with water or decrease if excess water leaches nutrients.

In the arctic, most plant available nutrients are in organic matter (Johnson 1987). Organic matter removal during disturbance results in loss of nutrients; reduced cation exchange capacity lowers water and nutrient holding capacities and nutrients introduced with fertilizer are lost by leaching. Fertilizer can stimulate germination on gravel pads, but low cover results in leaching of nutrients as plants are not taking them up from all areas (Jorgenson and Joyce 1994). As vegetation grows and decomposes, it can trap water and nutrients and contribute to organic matter.

Depth of gravel plays an important role in revegetation. Plant cover on gravel pads is inversely related to gravel depth as it influences ground water uptake (Walker 1996, Oasis Environmental, Inc. 2004). Thick gravel pads tend to be restricted to plant species adapted to xeric conditions (Jorgenson and Joyce 1994). Thin layers of gravel can result in permafrost thawing and increased depth of the active layer (Kidd et al. 2006). A deeper active layer can increase the rooting zone and nutrient pool. Plant growth and species diversity tend to be higher on thin gravel, likely due to access to ground water (Jorgenson and Joyce 1994, Oasis Environmental, Inc. 2004). With greater than 80 cm of gravel, natural revegetation is extremely limited (BHP Diamonds Inc. 1995). Removal of gravel can damage permafrost, resulting in flooding.

Natural revegetation in the north is slow, lengthening with harsh conditions from human disturbances. Naturally revegetated gravel pits tend to have more bare ground and lower species diversity than surrounding areas. Natural recovery can thus increase erosion risk. Rausch and Kershaw (2007) found that seeded gravel pits had significantly higher plant densities than unseeded ones, especially in species poor areas. Natural recolonization can be limited on gravel areas even after 20 years (Jorgenson et al. 1990). Eight years after abandonment of gravel pads in Alaska, native species cover was 2.7 % and species richness was 4.6 (Bishop and Chapin III 1989b). Naturally colonizing species were primarily legumes (five of nine important species) and all were riparian species, as riparian gravel bars have similar properties to gravel pads. Pads close to a river had greater cover and more species, especially legumes. Dominance of legumes as early colonizers indicates lack of nitrogen limits other species on gravel pads (Kidd and Rossow 1997, Kidd and Max 2000a, Kwiatkowski 2007).

2.3 Building Anthroposols

Development of a suitable substrate, or soil, is the most important step in reclamation of drastic disturbances. Arctic soils have many inherent limitations and disturbances introduce more. Suitable soils are essential for plant growth and are the foundation of ecosystem development, but finding a source of soil is a major reclamation challenge especially in the north where sites are remote and native soil is limited. Common sources include soil removed prior to a disturbance or soil taken from another area. Often there is not enough soil due to thin soil layers and surface bedrock making removal unfeasible (Sheoran et al. 2010), additional disturbances are created where soil is scavenged and transportation costs are high (Larney and Angers 2012). In reclamation, amendments and substrate materials can be used to improve soil properties for revegetation (ABR 2001, Reid and Naeth 2005b, Rausch and Kershaw 2007, Sheoran et al. 2010) or to build soils, called anthroposols, where native soil is limited or not available (Johnson 1987, Naeth et al. 2012).

With increasing disturbances, soils are becoming more influenced and altered by human activity (Lehmann and Stahr 2007, Naeth et al. 2012). Due to this, development of a classification system that allowed for inclusion of human altered soils was essential in Canada as they did not fit in any of the orders in the Canadian System of Soil Classification (Naeth et al. 2012). Australia, United Kingdom, France, Germany, Slovakia, Russia and the International Union of Soil Science (World Reference Base classification system) all have soil classification systems that include human influenced soils and were used to inform development of the Canadian order in 2012 (Naeth et al. 2012). Anthroposols are soils that have been altered by human activity or constructed by humans (Naeth et al. 2012). This can include soils that have had layers (of at least 10 cm depth) removed or modified by human activity or where manufactured materials have been added to soil; overall human activity has altered the soil forming factors and a new pedogenic trajectory may have been introduced (Naeth et al. 2012). Anthroposols are classified at the great group level based on the material composition of the layers, specifically the organic carbon content and the presence of anthropogenic artefacts (materials made by humans like plastic, glass, garbage, concrete) (Naeth et al. 2012).

Land reclamation represents an important area where soils are altered or built (anthroposols). Use of waste materials, especially local materials, to build anthroposols is increasingly common when a local soil source is lacking (Séré et al. 2008, Sheoran et al. 2010, Larney and Angers 2012). Waste materials reduce use of other resources, such as topsoil which is limited, provide a low cost material and are a strategy for recycling waste (Séré et al. 2008, Larney and Angers 2012). As waste is being used to build soil, it eliminates the need for continued management, reclamation or disposal in overcrowded landfills. Various waste materials are produced from different industries and human activities. Industrial materials are materials have been processed or extracted and include crushed ore and waste rock (mining), pulp and paper sludge (paper milling), and sawdust and wood chips (lumber milling). Other materials like lake sediment, rock, LFH, peat, topsoil, subsoil, glacial till and overburden are often removed during site development and stockpiled on sites. Sewage, biosolids and compost can be sourced from urban or industrial sites and manure from agricultural sources. These waste materials can be used alone or in combination to build anthroposols or they can be amended with other materials, such as fertilizer.

Materials used to build soils are mineral (waste rock, overburden, till) and organic (sewage, biosolids, manure, compost, manure). Mineral materials are highly variable due to differences in industrial practices (extraction, processing) and source (parent material, location). They tend to present many challenges for soil building due to their limiting factors. Generally, they have low organic matter and nutrient content and poor water holding capacity (Cooke and Johnson 2002, Sheoran et al. 2010). Texture is variable due to industrial practices and source material, but plays an important role on water and nutrient holding capacity and plant establishment, and can often be poor, such as high rock content (Sheoran et al. 2010). Mineral materials can have elevated metals and cause acid mine drainage (sulphur rich rock) (Dudka and Adriano 1997, Wong 2003, Drozdowski et al 2012). Organic materials are high in organic matter which is essential for self-sustaining plant communities as it increases soil water, nutrients, water and nutrient holding capacities and cation exchange capacity; improves soil texture and structure, pH and electrical conductivity; and provides energy sources for microorganisms (Johnson 1987, ABR 2001, Wong 2003, Reid and Naeth 2005a, Nason et al. 2007, Naeth and Wilkinson 2010, Drozdowski et al. 2012, Larney and Angers 2012). Organic materials can also, depending on their source, have elevated metals, poor pH and presence of chemicals or bacteria, such as sewage, biosolids, water treatment sludge (Edmonds 1976, Kwiatkowski 2007, Nason et al 2007). Inorganic additions can also be added to address specific limitations, such as lime to increase pH (Sheoran et al. 2010) and inorganic fertilizer to increase nutrient availability.

Use of various materials to build anthroposols allows soils to be tailored to address specific needs or functions. For example, if vegetation growth is the primary goal then chemical and physical limitations must be addressed (Séré et al. 2008) compared to if stability and reduced erosion is the primary goal. Many chemical, physical and biological soil properties must be considered when building anthroposols as they are commonly limiting factors especially when using waste materials. Chemical properties such as pH, fertility, cation exchange capacity and electrical conductivity have important impacts on plant response. An ideal pH for plants is neutral, with under 5.5 resulting in reduced growth and soil microorganisms and increased metal availability (Dudka and Adriano 1997, Sheoran et al. 2010). Waste rock containing pyrites can especially cause acidity problems as weathering produces sulphuric acid (Cooke and Johnson 2002). Adequate fertility, especially macro nutrients like nitrogen, phosphorus and potassium and important micro nutrients, is essential for successful growth and tends to be provided through fertilization or addition of organic matter as most mine waste is low in fertility (Cooke and Johnson 2002, Sheoran et al. 2010). Cation exchange capacity influences nutrient and water holding capacity, with organic matter and increasing the proportion of fine particles improving cation exchange capacity (Rouble 2011, Larney and Angers 2012). Soil salinity can influence plant growth and soil structure, with electrical conductivity greater than 4 to 5 dS m^{-1} considered poor and greater than 8 to 10 dS m^{-1} considered unsuitable (Soil Quality Criteria Working Group 1987, Alberta Environment and Parks 2016).

Physical properties like texture, structure, aggregation and bulk density are important in anthroposol building, especially when using waste materials. Fine grained materials with clay and silt size particles are most suitable for plants as they have good water and nutrient holding capacities and support greater plant emergence (Densmore 1994, Densmore et al. 2000, Mori et al. 2006); however when the fine fraction is high, they can have high compaction and low infiltration (Cooke and Johnson 2002, Sheoran et al 2010). Coarse textured materials, such as sand, have low water and nutrient retention and cation exchange capacity and tend to be prone to erosion (Sheoran et al. 2010, Drozdowski et al. 2012). Loamy soils are best for plant establishment and growth, combining benefits of all size fractions (Sheoran et al. 2010). Materials, like waste rock, can have a large component of very coarse fragments which can have major impacts as particles under 2 mm are mainly responsible for water and nutrient holding capacity, (Cooke and Johnson 2002, Saxton and Rawls 2006, Keller et al. 2010, Sheoran et al. 2010). Structure and aggregation, the way soil particles are held together, influence water holding capacity, porosity, aeration and soil stability and are negatively affected by compaction and soil removal (Sheoran et al. 2010). Aggregates can be formed through interaction of clay particles, addition of organic matter and microbial activity (Larney and Angers 2012). Materials with high bulk density can negatively impact root growth which impacts plant growth (Sheoran et al. 2010). Natural soils have a bulk density between 1.1 and 1.5 g cm^{-3}, which can increase with mining activity (Sheoran et al. 2010). Organic matter can reduce bulk density through aggregation and adding lower bulk density material (Larney and Angers 2012).

Soil microorganisms, bacteria and fungi play an important role in soil health. They are key players in decomposition, transform nutrient form and availability, alter soil structure and can form symbiotic relationships with plants (Dudka and Adriano 1997, Sheoran et al. 2010). Disturbances negatively affect populations through physical disruption of the soil and stockpiling resulting in changes in soil conditions (Sheoran et al. 2010). Return of these communities is essential for long term successful of reclamation through reestablishment of necessary cycles.

2.3.1 Amendments and substrates

Substrate materials are generally found or produced in large amounts and form the basic matrix of an anthroposol. They tend to compose the mineral component of the anthroposol. Amendments are materials available in small quantities or requiring small quantities to improve soil or substrate properties (Naeth 2013). They are generally used to address specific limitations of a soil or substrate, such as nutrient content or alter pH. Soil amendments are generally categorized as structure improving (e.g. peat, soil) and nutrient providing (e.g. fertilizer, gypsum) (Reid and Naeth

2005a, 2005b). Some materials, like sewage, fall into both categories as they provide significant nutrients, like nitrogen and phosphorus, and improve soil structure. Initial nutrient additions facilitate plant response and nutrient cycling. Improvement of structure increases water holding capacity and nutrient availability, often by providing organic carbon to hold water and nutrients and alter texture.

Soil building requires working with amendment and substrate combinations. Research at Ekati Diamond Mine focused on use of peat moss, lake sediment, sewage sludge, fertilizer, rock phosphate, calcium carbonate and gypsum to amend processed kimberlite (Reid 2002, Reid and Naeth 2002, 2005a, 2005b, Stevens 2006). Ameliorating both nutritional and structural limitations resulted in the best results. Sewage and peat moss were most effective, with highest ground cover on a sewage, peat, gypsum and rock phosphate combination. Sewage provided available nitrate and peat provided organic carbon to retain nutrients over multiple years.

At Diavik Diamond Mine, revegetation experiments on a gravel pad assessed combinations of substrate materials, including processed kimberlite, glacial till (lakebed sediment in the current research), mixes of kimberlite and till (50:50 and 25:75) and gravel and amendments including topsoil, sewage, fertilizer and wastewater treatment sludge (Drozdowski et al. 2012). After two growing seasons, plant density and health was highest on 25:75 with sludge, gravel, kimberlite and topsoil, till and fertilizer and till and topsoil. After five growing seasons, sewage treatments had significantly greatest plant cover, followed by till and fertilizer and unamended 50:50 (Naeth and Wilkinson 2010). Species richness was highest in gravel fertilizer, gravel topsoil, till topsoil and 50:50 topsoil. Growth and species richness was lowest in kimberlite and sludge treatments.

Selection of appropriate amendments and substrates or combinations is based on physical and chemical properties, cost and availability of materials (Larney and Angers 2012). Disturbances at Diavik often leave substrates or materials that can be used in reclamation, such as gravel or processed kimberlite (ABR 2001). Materials on site that could be used as amendments include soil and sewage. Amendments such as fertilizer or biochar must be brought on site.

2.3.1.1 Processed kimberlite

Separating diamonds from kimberlite ore produces large volumes of processed kimberlite (Baker et al. 2001, Drozdowski et al. 2012, Rio Tinto 2013). Processed kimberlite must either be used for reclamation or reclaimed. It can be coarse or fine textured. During diamond extraction, ore is crushed, screened repeatedly and mixed with water and magnetic ferro silicon sand (to enhance gravity drainage and diamond extraction) (Diavik Diamond Mine Inc 2010a). Coarse rejects are removed and transported to a containment facility; fine processed kimberlite is pumped as slurry to a containment facility. Fine processed kimberlite particles are $\leq$ 1 mm and coarse processed kimberlite is > 1 mm, with a typical maximum size of 2 mm. Kimberlite is primarily composed of silicon, magnesium and iron with trace elements of various metals such as nickel, chromium and zinc and is high in sulphur (Baker et al. 2001, Drozdowski et al. 2012). Processed kimberlite has no organic matter, few available nutrients, basic pH and serpentine chemistry (Kidd and Max 2000a, Martens 2000, Baker et al. 2001, Reid 2002, Reid and Naeth 2005a, Reid and Naeth 2005b, Kwiatkowski 2007, Naeth and Wilkinson 2010, Drozdowski et al. 2012). Serpentine soils tend to be unproductive and have elevated magnesium and metal concentrations. Processed kimberlite can have high soil water content due to its medium texture, resulting in more water filled pores (Naeth and Wilkinson 2011). The dark colour can increase soil temperature, which can improve plant growth and increase temperature sensitive processes, but can increase evaporation and reduce soil water (Martens 2001, Naeth and Wilkinson 2010, Naeth and Wilkinson 2011, Drozdowski et al. 2012).

Processed kimberlite requires amendments to address its structural and nutritional limitations. Reid and Naeth (2005b), Stevens (2006) and Drozdowski et al. (2012) found that unamended kimberlite had little plant cover. After 5 years, unamended kimberlite and kimberlite with fertilizer or sludge had lowest plant densities and richness and cover had declined (Naeth and Wilkinson 2010). Plants at Ekati Diamond Mine grew in kimberlite, but had small biomass with evidence of metal toxicity (Kidd and Max 2000a, Martens 2001). Reid and Naeth (2005b) found good growth in processed kimberlite using high rates of amendments and combinations. Peat amendment improved plant response (Martens 2002).

2.3.1.2 Glacial till

Glacial till is overburden material removed prior to mining; large amounts are available (Kidd and Max 2001, Rio Tinto 2013). Till must be used for reclamation or reclaimed. Glacial till is deposited by movement of glaciers and contains clay, sand, gravel and boulders in various proportions (Martens 2003). At Ekati Diamond Mine, till stockpiles were composed of glacial till, lake sediment and processed kimberlite (Kidd and Max 2001), with high proportions of silt and clay (lake sediment has more fines than glacial till) and rough and hummocky surfaces (Kidd and Max 2002, Martens 2005, 2007). Till has acidic pH, low organic matter and nutrient concentrations, low electrical conductivity and acceptable metal concentrations (Martens 2007). Calcium is higher in till than in lake sediment.

At Ekati Diamond Mine, stockpiles with sandy gravel texture (glacial till) had more vegetation than sandy silt substrate (lake sediment) (Martens 2005, 2007, 2012). The high plant growth on till stockpiles with colonization to nearby areas was attributed to micro sites and reduced compaction created from rocks. Native grass cultivars provided most vascular plant cover with smaller amounts of forbs and no shrubs; mosses and plant litter provided substantial cover.

2.3.1.3 Gravel and crushed rock

Gravel and crushed rock are used interchangeably in the diamond mine industry. At some sites, overburden is used to make gravel (Wells 2013). Gravel has coarse texture, low water and nutrient holding capacities and high leachability (Kidd and Max 2002, Naeth and Wilkinson 2010, Drozdowski et al. 2012). Naeth and Wilkinson (2010) found gravel was efficient at collecting and retaining water. The coarse texture results in large pores that fill with air; as air is a poor heat conductor gravel can have relatively low temperatures. The coarse texture may provide micro sites for germination and establishment, sheltering plants from erosion.

Drozdowski et al. (2012) found unamended gravel was one of the best substrates for revegetation after 2 years. After 5 years, gravel was more effective than processed kimberlite or 25 % kimberlite and 75 % till (Naeth and Wilkinson 2010), although cover and number of plants declined over time (Naeth and Wilkinson 2014). Species richness was highest on gravel sites. Bishop and Chapin III (1989a) found *Salix alaxensis* (Andersson) Coville (felt leaf willow) seedlings survived on unamended gravel. Thus gravel appears to have water and nutrients, provides important micro sites and has low metals. While gravel can be effective for germination and establishment, plants remain small and it is unlikely that growth will be sustainable in the long term due to its poor structure (Naeth and Wilkinson 2010).

2.3.1.4 Lake sediment

During diamond mining, lake sediment is often removed and stockpiled. These stockpiles must be used in reclamation or reclaimed. At some mines lake sediment is mixed with other potential substrate materials such as glacial till, complicating interpretation of its use for reclamation. Texture varies widely from clay, silt and sand to large boulders (Drozdowski et al. 2012). A high proportion of fine particles can result in poor structure, creating a hard, smooth surface with reduced water infiltration and seedling penetration (Kidd and Max 2001, Naeth and Wilkinson 2010, Drozdowski et al. 2012, Martens 2012). Materials with more clay and silt have higher water and nutrient holding capacities and can improve coarse textured substrates (Densmore 1994, Densmore et al. 2000, Reid and Naeth 2005a, 2005b, Naeth and Wilkinson 2010). Diavik and Ekati lake sediment is fine textured with a high silt fraction, low cation exchange capacity, organic carbon and water content and neutral pH (Reid and Naeth 2005a, 2005b, Naeth and Wilkinson 2010). Lake sediment decreased cation exchange capacity in the field (Reid and Naeth 2005b) and nutrients and cation exchange capacity in the greenhouse (Reid 2002, Reid and Naeth 2005a). Naeth and Wilkinson (2010) found it collected and retained water.

Naeth and Wilkinson (2010, 2014) found lake sediment amended with fertilizer or sewage had high plant density and cover after 5 years; unamended it had poor plant growth. Lake sediment with processed kimberlite combines benefits of fine texture with coarse texture, increasing cation exchange capacity and diluting metals in kimberlite and improving structure of lake sediment. Mixes of 25:75 kimberlite and lake sediment amended with sludge had highest plant cover after 2 years (Drozdowski et al. 2012); unamended it was not successful after 5 years (Naeth and Wilkinson 2010). Mixes of 50:50 lake sediment and kimberlite had good plant cover when unamended or amended with sewage; unamended it was more effective than unamended lake sediment or 25:75 kimberlite and lake sediment. In the greenhouse, processed kimberlite with lake sediment was ineffective for plants (Reid and Naeth 2005a). In the field at Ekati Diamond Mine when mixed with processed kimberlite, it supported plants in the first year, but to a lesser degree in the second year (Reid and Naeth 2005b). Kidd and Max (2001) found low germination and survival on lake sediment. Inconsistent results indicates that lake sediment may be effective for plant growth, but lack of nutrients and organic carbon limits success and requires ameliorating.

2.3.1.5 Peat

Peat is commonly used as an amendment in reclamation. It can increase cation exchange capacity, water and nutrient holding capacities, organic carbon, phosphorus and other nutrients (Martens 2002, Reid and Naeth 2005a, 2005b, Stevens 2006). High carbon to nitrogen ratios may initially limit nitrogen, which will increase with decomposition (Reid and Naeth 2005b). Organic amendments with high carbon to nitrogen ratios are more effective when combined with a nutrient source to produce a suitable ratio. Using peat in reclamation requires its removal from another site, increasing the disturbance area unless the site is already being disturbed. Peat is slow to regenerate with long term impacts on the secondary disturbance site (Price et al. 1998).

Reid (2002) and Reid and Naeth (2005b) found combinations of amendments with peat had significantly greater cover and growth than those without. Stevens (2006) found greater growth and health of plants in substrates amended with peat in the greenhouse and field. Mackenzie and Naeth (2010) found peat mineral soil mix had significantly lower species richness, abundance and soil nutrients than LFH mineral soil mix.

2.3.1.6 Topsoil

Topsoil (surface soil) can increase organic matter, nutrients, cation exchange capacity and water and nutrient holding capacities alone or with substrates (Johnson 1987, ABR 2001, Deshaies et al. 2009, Naeth and Wilkinson 2010, Drozdowski et al. 2012). Densmore (1994) found topsoil had high organic matter, nitrogen and field capacity and less sand than clay and silt. It contains plant propagules making it a potential source of native species (Chapin III and Chapin 1980, Johnson 1987, ABR 2001, Mackenzie and Naeth 2010). The top 10 cm of arctic soil can contain hundreds of seeds per m^2 (Archibold 1984). It can contain soil microorganisms involved in nutrient adsorption, decomposition and nutrient cycling, including mycorrhizal fungi important for plant health and growth (Kidd 1996, ABR 2001, Martens 2002). Organic soil has significantly higher bacterial biomass than lake sediment or esker material (Kidd 1996).

Densmore (1994) found succession on placer mine spoil in Alaska was rapid with topsoil, associated with greatest species richness, height and cover. Mackenzie and Naeth (2010) found LFH mineral soil mix, similar to topsoil, had significantly higher species richness, density, cover and soil nutrients than peat mineral soil mix in the oil sands. At Ekati Diamond Mine, organic soil was better for plants than lake sediment or esker material, increasing cover and productivity relative to controls in short and long terms (BHP Diamonds Inc. 1995, Kidd 1996, Kidd and Rossow 1997, Kidd and Max 2000b). On gravel pads at Diavik Diamond Mine, it consistently increased plant density and with various substrates was among the top ten treatments (Drozdowski et al. 2012). Naeth and Wilkinson (2010) found topsoil had highest species richness after 5 years. It is an ideal reclamation material, but limited due to its scarcity in the arctic and subarctic (Johnson 1987, Kidd and Rossow 1997). Removal from undisturbed areas results in greater disturbances, thus stockpiling topsoil during mining is essential.

2.3.1.7 Sewage

Sewage is available from waste treatment facilities at most mines. At Diavik, it is biologically treated and phosphorus removed by an alum and filtration system (Rio Tinto 2013). Texture can vary; at Diavik it was loam texture and neutral pH (Drozdowski et al. 2012). Sewage can provide significant nitrogen, phosphorus, potassium and sulphur (Reid 2002, Reid and Naeth 2005a, 2005b, Naeth et al. 2006). Kwiatkowski (2007) found sewage treated substrates had a carbon to nitrogen ratio approaching an ideal 10:1 for respiration and decomposition. Sewage releases nutrients more slowly than fertilizers (Bishop et al. 2000). Fertilizer may provide short term nutrients before sewage begins to decompose (Naeth and Wilkinson 2010). Sewage increases cation exchange capacity and organic matter, reducing nutrient and water loss (Reid and Naeth 2005a, 2005b, Naeth et al. 2006, Naeth and Wilkinson 2010, Drozdowski et al. 2012).

In the greenhouse, Reid and Naeth (2005a) found amendment combinations with sewage increased ground cover, root and shoot biomass and plant height. Reid and Naeth (2005b) found combinations with sewage increased plant cover, height and shoot biomass more than lake sediment or peat on kimberlite tailings at Ekati Diamond Mine. On gravel pads, sewage resulted in low plant densities in the first 2 years due to high metals (Drozdowski et al. 2012). After 5 years plant density and cover were greatest with sewage (Naeth and Wilkinson 2010).

Regulations at various levels and public concerns play an important role in the use of sewage for reclamation (Sheoran et al. 2010). Concerns with sewage use are based on presence of bacteria and metals (Edmonds 1976, Reid and Naeth 2005b, Drozdowski et al. 2012). Edmonds (1976) found fecal coliform counts in sewage applied to a clearcut forest in summer dropped from 1.08 x 10^5 / g to 358 / g in 204 days and to 0 over winter after 267 days. Counts in sewage applied in winter dropped from 1.2 x 10^5 / g to 20 / g in 162 days. Slight increases occurred in spring and summer, but never approached initial levels and were similar to sites without sewage. Drozdowski et al. (2012) found *Salmonella* in one sewage sample and 511 / g fecal coliforms at 0 to 10 cm and 448 / g at 20 to 30 cm. Fecal coliforms in sewage stored over winter were significantly lower than in directly applied sewage. Studies indicate cold temperatures reduce fecal coliform bacteria rapidly. Guidelines do not exist for fecal coliforms in sewage, but concentrations > 1,000 / g in compost are considered unsuitable (Drozdowski et al. 2012).

Sewage can contain high concentrations of metals (Kwiatkowski 2007, Naeth and Wilkinson 2010, Drozdowski et al. 2012). Chromium, cobalt, copper, molybdenum, nickel and zinc were elevated in soil with sewage at Diavik Diamond Mine. Metals must be mobile and available to be a risk for plants and toxicities tend to occur with copper, nickel and zinc (Naeth and Wilkinson 2010, Foy et al. 1978). Most metals in soils are bound to organic matter, form hydrolysis species, adsorb to clay or iron hydroxides and complex with inorganic ligands, reducing mobility. Dissolved organic matter can bind to metals and is highly mobile. Ashworth and Alloway (2004) found sewage increased nickel and copper leaching, whereas zinc was adsorbed. Weng et al. (2002) found higher copper and lead bound to dissolved organic matter than cadmium, nickel or zinc. Tadesse et al. (1991) found *Triticum aestivum* L. (common wheat) yield increased when sewage with metals was applied relative to inorganic metal salts. Sewage and inorganic salts increased metal concentrations in plant tissue, particularly at low pH. Zinc increased less when applied through sewage and was higher in *Triticum aestivum* in sandy than silty clay loam soils.

2.3.1.8 Fertilizer

Fertilizers provide nutrients, commonly low in northern soils (Johnson 1987, ABR 2001, Deshaies et al. 2009, Drozdowski et al. 2012). Nutrient addition is often required to start nutrient cycling that will be supported through decomposition in future (Reid and Naeth 2005b). Growth of established seedlings is often restricted by low nutrients (Bishop and Chapin III 1989a). Effects of fertilizer are often short term as disturbed substrates tend to have low organic matter and cation exchange capacity which fertilizer has no effect on (Johnson 1987, Reid and Naeth 2005a). When nutrients are added without organic matter to ameliorate structural limitations, plant growth often does not respond (Reid and Naeth 2005b). Nutrients will leach deep into the soil or be lost from the site (Johnson 1987, Reid and Naeth 2005b). Fertilizer increased plant growth during a warm summer, but had little effect in a cool summer (Bell and Bliss 1980).

Slow release and time release fertilizers tend to be most effective, allowing plants to develop the root system required for nutrient uptake (Densmore 1994, Houle and Babeux 1994). Arctic plants are adapted to low nutrients and are often unable to use high amounts (Martens 2006). Seedlings in the first growing season tend to be too small to use much fertilizer (Densmore et al. 2000, Adams and Lamoureux 2005). Fertilizer tends to cause a low root to shoot ratio and once nutrients leach, above ground growth slows to allow root growth to catch up as arctic plants tend to have high root to shoot ratios (Bishop and Chapin III 1989a, Densmore et al. 2000, Adams and Lamoureux 2005). Fast release fertilizers or large amounts can negatively affect plant growth (Houle and Babeux 1994, Deshaies et al. 2009).

Fertilizer can increase or decrease seed germination and seedling growth and survival. Densmore (1994) found time release fertilizer increased vascular and non vascular plant cover and *Salix* L. (willow) growth; Naeth and Wilkinson (2010) found fertilizer increased plant growth. Fertilizer effects can occur over multiple years. Shaver and Chapin III (1995) found fertilizer increased nitrogen and phosphorus in leaves in the first year, with increased growth and tillering in the second year and increased flowering in the third year. Nitrogen was elevated in the first year, whereas phosphorus was elevated for 3 to 4 years after application. Stevens (2006) found fertilized greenhouse plants were taller and healthier than unfertilized. Bishop and Chapin III (1989a) found fertilizer reduced germination of *Salix alaxensis*, but increased leaf and stem biomass. Fertilizer can facilitate rapid establishment of plants, although it provides nutrients for a short time and often multiple applications are required (ABR 2001). At Ekati Diamond Mine, Martens (2011) found health of grass cultivars declined as they were unable to survive without repeated nutrient additions. Fertilizers usually increase grass cover initially and at later stages, shrub cover, as grasses and forbs prefer high nutrients and shrubs prefer low (BHP Diamonds Inc. 1995, Forbes and Jefferies 1999, Martens 2006). Nutrients can become immobilized in grasses that decompose slowly, limiting availability to other plants (Bishop and Chapin III 1989a). Fertilizers may be important initially, but long term dependence should be avoided.

2.3.1.9 Other amendments

Other amendments including calcium sources, paper mill waste, sludge, biochar and commercial products can be used in reclamation. Calcium sources like rock phosphate, gypsum or calcium carbonate have been used to improve calcium magnesium ratio that can be limiting for plants, especially in kimberlite substrates (Reid 2002, Reid and Naeth 2005a, 2005b). Calcium sources had no effect on cation exchange capacity and did not alter calcium magnesium ratio (Reid and Naeth 2005b), although gypsum increased available calcium in the greenhouse (Reid and Naeth 2005a). Calcium sources did not affect plant growth or alter substrate properties in the greenhouse (Reid and Naeth 2005a) or over 2 years in the field (Reid and Naeth 2005b). Low precipitation and climate may slow dissolution of calcium sources requiring over 2 years for effects. Schuman et al. (1994) found no plant response on mine spoil sites with gypsum applied until the second or third year. Calcium amendments may be beneficial in the long term; however, climatic conditions limit effectiveness in the short term.

Paper mill waste is the sediment in waste water produced during pulping, composed of cellulose fibres, clay, calcium carbonate and small amounts of chemicals (Reid 2002). It can increase water and nutrient holding capacity and organic matter and improve texture of coarse substrates (Reid and Naeth 2005a). It has low water content, high cation exchange capacity and neutral pH. Reid and Naeth (2005a) found paper mill sludge significantly increased plant cover and biomass in the greenhouse. Paper mill waste is often free, but requires transportation to the site.

Sludge at Diavik Diamond Mine is particulate matter (ground rock, lake sediment, till, runoff water) from a water treatment plant (Drozdowski et al. 2012). Sludge has elevated metals (arsenic, barium, chromium, copper, nickel) although risk is low due to dilution upon application (Kwiatkowski 2007). It has low organic carbon, high ammonium and water content and high sand fraction. Sludge treated substrates had a carbon to nitrogen ratio approaching ideal. Drozdowski et al. (2012) found it increased soil water content, but had variable short term effects on plant growth. After 2 years, it had highest plant growth with processed kimberlite and glacial till (25:75) substrate likely due to high nitrogen and water. After 5 years plant density declined and sludge had no effect on plant growth (Naeth and Wilkinson 2010).

Biochar is the charcoal from biological residues combusted under low oxygen (Chan et al. 2007, Sohi et al. 2009, Major et al. 2010, Beesley et al. 2011, Fellet et al. 2011, Belyaeva and Haynes 2012, Denyes et al. 2012, Houben 2013). It is porous and high in carbon with neutral to alkaline pH. It can increase cation exchange capacity and water and nutrient holding capacities, reduce tensile strength in soil and increase nutrient uptake in plants. It can bind with organic and inorganic contaminants reducing availability (Beesley et al. 2011, Belyaeva and Haynes 2012, Houben 2013). It can increase field and greenhouse plant growth and microbial activity, especially combined with fertilizer (Chan et al. 2007, Major et al. 2010, Beesley et al. 2011, Fellet et al. 2011, Denyes et al. 2012, Jones et al. 2012, Houben 2013).

Commercial products can improve soil properties. Agri-Boost is dehydrated alfalfa with 84 % organic matter and high water holding capacity (Reid 2002, Reid and Naeth 2005a). It provided high available nitrate, significantly increasing ground cover and shoot biomass in a greenhouse, although less than sewage or peat. Black Earth is naturally weathered sub-bituminous coal high in humic substances and humified organic matter (Liem et al. 2003, Black Earth 2009a, 2009b, Liem 2010). It can increase cation exchange capacity and water and nutrient holding capacities, increasing plant emergence, growth and survival and microbial activity. Starch based polymers, polyacrylamide or gel crystals can be added to substrates to retain water (BHP Diamonds Inc. 1995, Yangyuoru et al. 2006, Zohuriaan-Mehr and Kabiri 2008). At Ekati Diamond Mine, although shrub survival was too low to examine hydrogel effects, most surviving shrubs were in pockets with hydrogel (Kidd and Rossow 1998). Sarvaš et al. (2007) found hydrogel increased survival and growth (height, root collar diameter) of *Pinus sylvesris* L. (Scots pine). Use and research on effectiveness of commercial products in northern reclamation is currently limited.

2.4 Micro Topography

Topographic variability, the shape of and features on a landscape, can play an important role in determining plant communities, as can the scale of these features. Plants are distributed at different nested scales; macro scale is considered regional, meso scale is local (10^6 to 10^{10} m^2) and micro scale is small patches within the local area (Peterson and Billings 1980, Sohlberg and Bliss 1984, Billings 1987, Forbes and Jefferies 1999). Micro scale patch size varies with individual researchers, for example, 10 m^2 (Jumpponen et al. 1999), 3 to 30 cm (Sohlberg and Bliss 1984) or 1 to 10 m^2 (Forbes and Jefferies 1999). While macro scale and meso scale variability is important for general determination of plant communities, micro scale variability plays an important role in establishment and survival of plants (Bliss 1962, Sohlberg and Bliss 1984, Anderson and Bliss 1998, Kuntz and Larson 2006).

Plant establishment and development depend on seed germination and plant growth. A micro site is the environment around a seed (Forbes and Jefferies 1999). It must have conditions for germination and establishment, such as water, nutrients and protection from predation and grazing (Smith and Capelle 1992, Forbes and Jefferies 1999, Jumpponen et al. 1999, Mori et al.

2008). Micro topographic variability creates a heterogeneous environment and can influence species distribution (Beatty 1984, Sohlberg and Bliss 1984, Eldridge et al. 1991, Smith and Capelle 1992, Elmarsdottir et al. 2003, Bruland and Richardson 2005, Kuntz and Larson 2006).

2.4.1 Properties of micro topographic variability and micro sites

Biological micro sites include plants, litter, moss mats and lichen crusts. Anderson and Bliss (1998) found vascular plant density and size in a polar desert were greater on moss mats and cryptogamic crusts. Plants, mosses and lichens can be considered nurse plants, providing micro sites for seeds by protecting them, reducing evaporation, increasing soil water, increasing snow cover, stabilizing soil, reducing temperature fluctuations, reducing exposure to harsh sunlight and providing mycorrhizae necessary for seedling establishment (Carlsson and Callaghan 1991, Eldridge et al. 1991, Forbes and Jefferies 1999, Maher and Germino 2006, Stevens 2006). Sohlberg and Bliss (1984) found the environment directly around moss mats had higher temperatures, less wind, more water and more nitrate than bare soil or lichen crusts.

Moss and vascular plant micro sites tend to have high soil water due to reduced evaporation and movement of water from the melting active layer (Sohlberg and Bliss 1984). Ground settling can eject seeds and seedlings that are unprotected by moss or lichen mats and plants, as these can stabilize the soil (Anderson and Bliss 1998, Elmarsdottir et al. 2003). While moss mats may be beneficial for vascular plants, they can be competition and in some cases may dry out fast, resulting in removal of safe sites (Densmore 1992, Anderson and Bliss 1998). Vegetation development can create areas of greater organic matter from litter (Mori et al. 2008). Litter can increase survival by reducing soil temperatures and increasing soil water, but could reduce germination by trapping seeds and preventing soil contact (Eldridge et al. 1991).

Physical micro sites include bare soil, mounds, depressions, rocks, boulders, coarse textured substrates and cracks (Sohlberg and Bliss 1984, Densmore et al. 2000, Mori et al. 2006). Sheltered sites can reduce mortality and increase seed germination and plant growth (Bell and Bliss 1980, Carlsson and Callaghan 1991, Naeth and Wilkinson 2011). Micro sites can traps seeds and provide shelter from wind and areas with increased soil water (Whitehead 1959, Carlsson and Callaghan 1991, Densmore et al. 2000, Rausch and Kershaw 2007).

To germinate, seeds must remain in a location long enough for processes such as respiration and synthesis of nucleic acids to occur (Chambers et al. 1991, Johnson and Fryer 1992). Seeds are often moved by wind, water and animals. Soil surface, topography and seed size and shape can influence seed movement. On rough surfaces and those with large particle size, movement can be slow and seeds remain stationary for long periods. Seeds on rough surfaces are more likely to have time to germinate if conditions like soil water are met (Johnson and Fryer 1992). Coarse substrates may trap seeds between particles, allowing partial burial, increasing seed soil contact, protecting seeds from wind and water erosion and increasing germination and seedling establishment (Harper et al. 1965, Chambers et al. 1991, Jumpponen et al. 1999, Naeth and Wilkinson 2010). Coarse substrates trap more seeds at greater depths (Chambers et al. 1991). Partial burial exposes seeds to soil water as it surrounds the seed and protects it from predation and desiccation (Jumpponen et al. 1999, Elmarsdottir et al. 2003). Humidity may increase in sheltered sites, facilitating root penetration and reducing desiccation (Smith and Capelle 1992). Coarse substrates may provide opportunities for germinating seed penetration, prevented by smooth and compacted surfaces like dry silt (Jumpponen et al. 1999).

Depressions, cracks and barriers like rocks and boulders can trap seed (Sohlberg and Bliss 1984, Johnson and Fryer 1992, Chambers et al. 1991, Densmore et al. 2000, Elmarsdottir et al. 2003). Depressions can trap seeds dispersed in wind or water as wind speed is lower and water gathers in depressions, allowing seeds to accumulate and providing more water (Eldridge et al. 1991, Jumpponen et al. 1999, Martens 2005, Naeth and Wilkinson 2011). Soil water is important for germination and seedling survival as desiccation is a risk in the arctic, especially at sites without vegetation cover (Jumpponen et al. 1999). In depressions, soil temperatures are reduced (Naeth and Wilkinson 2011) and plants are protected from wind (Walker 1996). Lower wind speeds reduce transpiration and can increase seed and seedling survival (Sohlberg and Bliss 1984). Cracks have reduced wind speeds and exposure with water for longer periods than other micro sites (Bell and Bliss 1980).

Rocks and boulders can increase soil water through reduced evaporation from shading soil, reducing wind, creating areas where water flows and enhancing snow trapping (Cargill and Chapin III 1987, Jumpponen et al. 1999, Kidd and Max 2002, Martens 2002, Elmarsdottir et al. 2003, Naeth and Wilkinson 2011) relative to flat areas. Snow can melt earlier near large rocks resulting in a longer growing season (Jumpponen et al. 1999). Rocks can provide shelter from wind and reduce desiccation, with overhanging edges protecting seeds and seedlings (Sohlberg and Bliss 1984, Kidd and Max 2002). Boulders and rocks fit visually in the landscape providing integration of the reclaimed site (Kidd and Max 2002).

Mounds and furrows are less studied than depressions and rocks. Mounds tend to be drier, have fewer nutrients, organic matter, cation exchange capacity, litter and snow cover and greater seasonal temperature fluctuations than depressions (Beatty 1984, Price et al. 1998). Mounds can have high temperatures, increasing decomposition rates and nutrient availability (Walker 1996, Bruland and Richardson 2005). Bruland and Richardson (2005) found wetland hummocks had greater nitrate and ammonium than flats and hollows and were drier. Furrows are a combination of depressions and mounds with ridges and troughs and have characteristics of both. Species diversity tends to be higher in troughs relative to ridges (Sterling et al. 1984).

2.4.2 Importance in natural ecosystems

Micro topographic variability plays an important role in determining plant distribution in all environments. At the alpine tree line, seedling survival was greater when tree or herbaceous cover reduced exposure (Maher and Germino 2006). Beatty (1984) examined naturally created pits, mounds and flat sites on distribution of forest understory plants in areas with and without *Tsuga canadensis* (L.) Carrière (eastern hemlock). In areas without hemlock, micro sites had different vegetation based on species ability to survive in saturated conditions and penetrate thick litter in pits. Competition may result in segregation of species among types of micro sites, as there was little competition in sites with hemlock and little species difference among micro sites. Smith and Capelle (1992) found *Cichorium intybus* L. (chicory) in the greenhouse had higher germination, biomass and survival with rocks and soil clods, relative to smooth surfaces.

Arctic tundra environments are micro topographically diverse, with boulders, hummocks, soil boils, stony areas, desiccation cracks, depressions, polygons and patterned ground (Peterson and Billings 1980, Sohlberg and Bliss 1984, Anderson and Bliss 1998, Naeth and Wilkinson 2011). Anderson and Bliss (1998) found vascular plants in a polar desert had greater density on moss mats and cryptogamic crusts; plants were larger on crusts and a high proportion were growing near stones. In high arctic meadows, species richness and survival were greater in moss turfs than bare soil or lichen crusts; in high arctic barrens, they were higher in desiccation cracks (Sohlberg and Bliss 1984). Mosses, lichens and desiccation cracks provide sites for germination and establishment with water for longer than other micro sites (Bell and Bliss 1980, Sohlberg and Bliss 1984). On recently deglaciated areas, Jumpponen et al. (1999) found pioneer species more likely to establish with concave surfaces, coarse substrates and rocks. Walker (1996) found *Salix* was taller in depressions and gullies from thawing ice, due to warm soils, snow cover protection from wind, deep thaw, fast decomposition and more nutrients.

2.4.3 Importance in reclamation

During reclamation and natural recovery, micro topographic variability has been associated with revegetation; however, creating variability has been restricted and results varied. Disturbance and reclamation activities can remove natural micro topographic variability through compaction, substrate movement, poor soil structure and removal of hydrologic connections (Forbes and Jefferies 1999, Naeth and Wilkinson 2011).

Mackenzie and Naeth (2010) found LFH mineral soil mix had more vegetation than peat, partially due to greater micro topographic variability in the LFH with micro sites created from woody debris and soil clods. Rough surfaces can act as a seed trap, as many seedlings were found in cracks, depressions and adjacent to plants. Elmarsdottir et al. (2003) found more seedlings adjacent to small rocks and in biological crusts in reclamation sites in Iceland. Naeth and Wilkinson (2010) found in the first year following reclamation, plants more likely to germinate and establish near shelter, even at the micro topographic scale. Substrates creating surface variability had greater germination and establishment (Kwiatkowski 2007). The success of gravel treatments may result from surface roughness sheltering plants from wind and water erosion (Naeth and Wilkinson 2010). Plant cover and density at reclamation sites tend to be higher in depressions, crevices and adjacent to large rocks (Naeth and Wilkinson 2011).

Rausch and Kershaw (2007) built furrows on raised gravel pads near Churchill, Manitoba and found fewer seedlings with micro topographic variability. Furrows can bury the seed bank, reducing number of germinating seeds and emerging seedlings. In northern mixed prairie, species richness and diversity were lower on earthen mounds than off (Umbanhower 1992). Naeth and Wilkinson (2011) assessed plant survival in depressions, mounds, boulder and flat micro sites on gravel pads at Diavik Diamond Mine and found it negatively influenced by erosion in depressions. Despite high losses, survival of *Vaccinium vitis-idaea* L. (mountain cranberry), *Empetrum nigrum* L. (black crowberry) and *Arctostaphylos rubra* (Rehder & Wilson) Fernald (arctic bearberry) was highest or individuals were only alive in depressions. At Ekati Diamond Mine, transplant survival and seedling height were greater in ripped sites as troughs can collect water and provide shelter from wind; grass cover was higher in rock pile areas and depressions than in uplands (Martens 2002, 2005, 2007, 2011, 2012). Bishop and Chapin III (1989a) found high germination of *Salix alaxensis* on gravel pads in Alaska near stones with shadier, wetter micro sites. On scarified sites, germination and density were high in furrows with concentrated nutrients and water (BHP Diamonds Inc. 1995, Kidd and Rossow 1997, Martens 2007).

Micro sites can improve plant germination and establishment, especially at xeric sites like gravel pads, that lose water rapidly (Cargill and Chapin III 1987). By identifying the types of micro sites that improve germination, establishment and growth, ability to reclaim degraded sites can be enhanced (Elmarsdottir et al. 2003).

2.5 Erosion Control

Erosion is a problem at many disturbed sites in the north. Lack of vegetation exposes the soil surface to wind and water erosion (Naeth and Wilkinson 2010, 2011). Many factors can increase soil erodibility. Soils with low organic matter and substantial fine particles are especially at risk (Kidd and Rossow 1998, Naeth and Wilkinson 2010, 2011). Flat areas are susceptible as surfaces do not slow wind speeds (Kidd and Max 2002).

Erosion can inhibit vegetation establishment (Matheus and Omtzigt 2012). Seeds applied to the surface are vulnerable to dislocation through wind and water erosion (Martens 2001). Blowing substrate and soil can smother emerging seedlings (Martens 2005). Naeth and Wilkinson (2011) found loss of shrub cuttings in depressions due to infilling from wind and water erosion. Lack of vegetation cover in areas surrounding reclamation sites makes both areas vulnerable to erosion and its effects (Martens 2005). Loss of amendments applied to the surface through erosion reduces their revegetation benefits (Naeth and Wilkinson 2011). For example, topsoil applied in patches disappeared by the second growing season due to erosion.

2.5.1 Erosion control methods

Erosion can be reduced on reclamation sites with contouring, amendments, amendment and seed incorporation, erosion control blankets and mulch. Vegetation can reduce erosion (Adams and Lamoureux 2005, Kidd and Max 2001, Matheus and Omtzigt 2012, Oasis Environmental, Inc. 2004). Rapidly growing species such as *Hordeum vulgare* L. (common barley) and *Lolium multiflorum* Lam. (annual rye grass) can be used (Matheus and Omtzigt 2012). These robust species can inhibit native species, although a low seeding rate can reduce the effects.

Altering soils can reduce erosion potential and negative effects of erosion. Contouring the surface and creating roughness can reduce wind speeds and decrease erosion (Kidd and Max 2002, Martens 2005). Increasing organic matter, through amendments like sewage sludge, can increase water holding capacity and reduce erosion potential (Reid and Naeth 2005b). Incorporation of seeds broadcast on the surface and amendments can reduce loss from wind and water erosion (Reid and Naeth 2005b, Naeth and Wilkinson 2011).

Erosion control blankets are flexible organic or synthetic materials that can be placed on surfaces with high erosion potential and anchored into soil (Matheus and Omtzigt 2012). Synthetic materials are best for long term use and organic materials are best for short term as they readily decompose. Examples of effective erosion control blankets include the Soil Saver (Martens 2003,

2005) and Curlex (Martens 2000, Reid 2002, Reid and Naeth 2005b). They can stabilize the surface, provide organic matter, increase water and nutrient holding capacity, protect establishing seedlings and reduce evaporation and loss of soil water (Martens 2000, 2001, Reid 2002).

Mulch is coarse or fibrous organic material, such as wood chips or straw, used to reduce erosion and improve conditions for plants (Matheus and Omtzigt 2012). Mulch can increase soil temperature, humidity, water holding capacity and nutrient availability (Houle and Babeux 1994). Price et al. (1998) used straw mulch to regenerate *Sphagnum* peat and found that it decreased water interception and decreased evaporation, resulting in greater soil water than with bare soil. Bare soil had greater net radiation and heat flux, whereas the mulch kept temperatures higher at night and cooler during the day. Mulch protected *Sphagnum* L. (sphagnum) diaspores and improved conditions for their establishment and growth. Jorgenson and Cater (1991) found similar greater vascular plant cover under mulch in Alaska, despite intercepted precipitation, likely due to reduced desiccation of the plants. Houle and Babeux (1994) found organic mulch, such as wood chips, increased survival of some woody plant species, but did not affect growth, and generally had little overall impact.

Mulch and erosion control blankets can have negative effects on revegetation. Seeds dispersed onto them can have poor establishment (Densmore et al. 2000, Adams and Lamoureux 2005); seeds dispersed under them can have reduced germination and growth, with seedlings having difficulty penetrating the layer of materials (Densmore et al. 2000, Martens 2005, Matheus and Omtzigt 2012). Mulch or an erosion control blanket can impede assessment of revegetation progress especially in the first year when seedlings are unable to penetrate (Martens 2000). Mulch and erosion control blankets can accumulate blowing materials, negatively affecting seedling establishment (Martens 2005). Lack of assessment of effects of erosion control methods, especially erosion control blankets (Reid 2002), makes selection of their use difficult.

3. RESEARCH PROGRAM OBJECTIVES

The objective of this research program was to build suitable soils for plant establishment and community development after diamond mining in the Canadian north. Small scale field experiments at a diamond mine in northern Canada and greenhouse experiments using waste materials from the diamond mine were conducted to assess what materials were effective to build soil, how much of each to use, and how to place these materials to mimic surface variability of natural environments to successfully support plants (Figure 1.1). The large number of materials and placement methods means that this research can be used in many different environments with different conditions. The general research objectives are to:

- Evaluate effectiveness of substrates, organic and inorganic amendments and various combinations.
- Evaluate influences of micro topographic variability on revegetation.
- Evaluate short term erosion control options on revegetation.
- Develop a process to select appropriate reclamation strategies depending on site conditions and material availability.

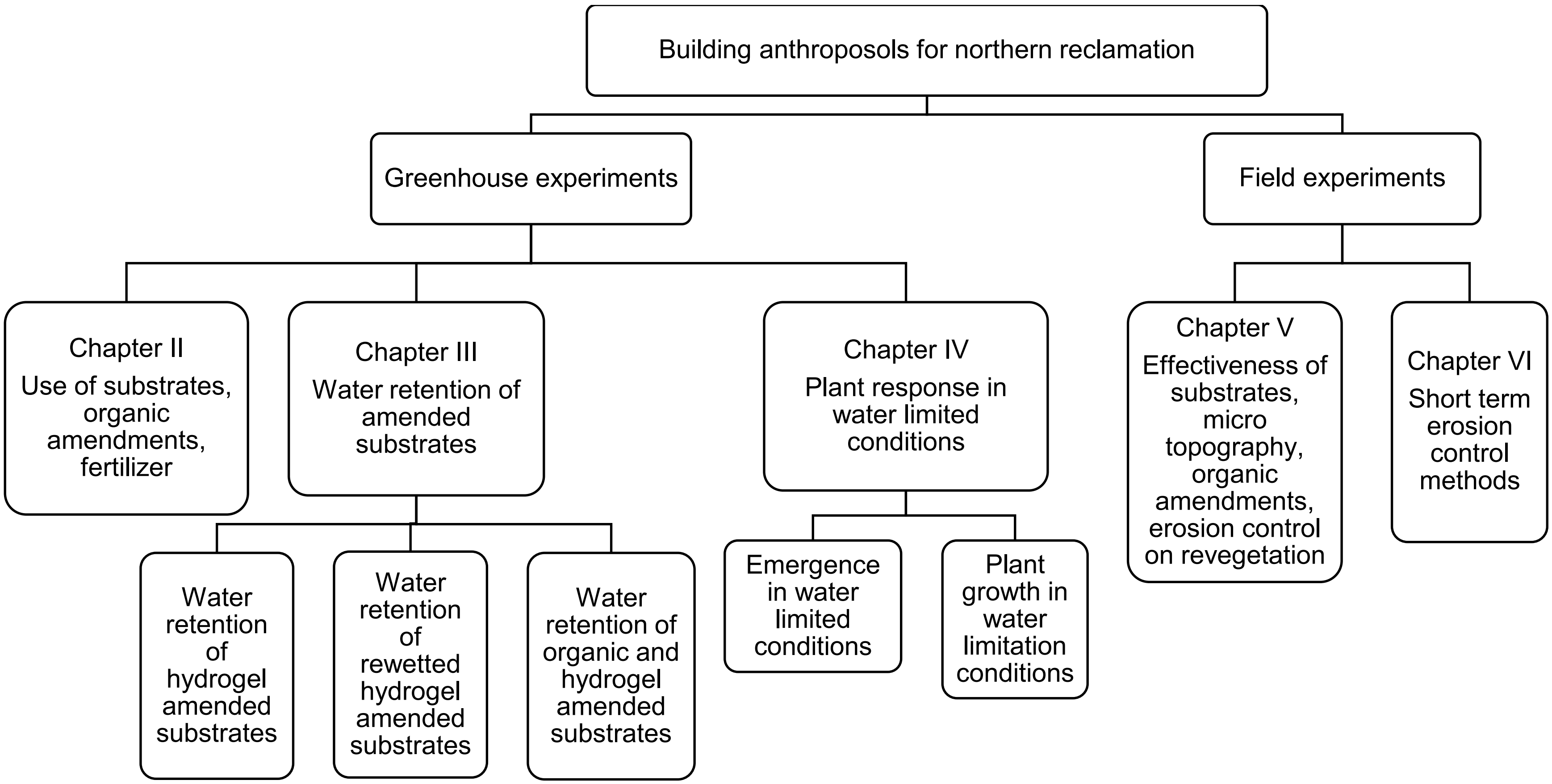

Figure 1.1. Schematic diagram of greenhouse and field experiments.

II. AMENDMENTS AND SUBSTRATES TO DEVELOP ANTHROPOSOLS FOR NORTHERN MINE RECLAMATION

1. INTRODUCTION

Mining in the Canadian arctic and subarctic has increased since diamonds were discovered in 1991, with Canada becoming the third largest diamond producer in 2011 (Baker et al. 2001, Rhéaume and Caron-Vuotari 2013). Mining in the Canadian north is expected to continue to increase, with a 91 % increase in metal and non-metallic mineral outputs from 2011 to 2020 (Rhéaume and Caron-Vuotari 2013). Mining produces large amounts of waste and expansive disturbances, associated with soil and vegetation removal and infrastructure construction. These disturbances require reclamation to meet regulatory requirements and community expectations. Reclamation of disturbances in the arctic and subarctic (hereafter the north) requires development of suitable soils due to limited soil availability (Johnson 1987). Soils are mostly shallow with low organic matter and (or) nutrient concentrations due to cold temperatures resulting in slow decomposition and nutrient cycling (Reid and Naeth 2005a, Deshaies et al. 2009). Soil salvage during mining is not required at northern mines and is rarely conducted due to difficulty in salvaging small amounts from thin soils. In the late 1980s, reclamation research in the north began, with a main focus on revegetation success (Johnson 1987, Bishop and Chapin 1989b, Densmore 1994, Jorgenson and Joyce 1994, Reid and Naeth 2005a, 2005b, Rausch and Kershaw 2007, Deshaies et al. 2009, Drozdowski et al. 2012, Naeth and Wilkinson 2014). Research at diamond mines began soon after the first mine opened in the 1990s.

Processed kimberlite (kimberlite rock that was mined and crushed to remove diamonds) and crushed waste rock are the main waste materials from diamond mining and must be reclaimed or used for reclamation; lakebed sediment is a waste material when mines are located on water bodies. A few studies have been conducted to use these waste materials to build soils, also known as anthroposols, for reclamation. Anthroposols are soils that have been altered by human activity; they include soils that are built for reclamation using various materials such as organic wastes (Naeth et al. 2012). Research found that waste materials mixed with organic and inorganic amendments differed in their effects on vegetation, and those effects changed over time (Reid and Naeth 2005a, 2005b, Drozdowski et al. 2012, Naeth and Wilkinson 2014). Ameliorating both nutritional and structural limitations was most successful. Research is needed to assess combinations of substrates and amendments that will sustainably support revegetation while minimizing or eliminating environmental impacts. Mine waste materials or easy-to-transport materials must be used due to distance to the site and costs associated with transporting materials. Much of the previous research focused on capping waste materials with amendments. To reduce the volume of amendment required, thereby reducing materials transported to site and potential off site disturbance for harvesting of materials, this research focused on incorporation of amendments into substrates. Work to date has not assessed these anthroposols in detail to determine the appropriate combinations of substrate and amendment materials. With decades of mining forecasted for current diamond mines in Canada and other regions of the world, other types of mines in development in the north, and similar current and historical disturbances across the north, effective and timely reclamation practices are essential.

This experiment was designed to quantitatively develop and assess suitable anthroposols for plant establishment and growth after diamond mining in the Canadian north. To be sustainable, materials needed to be waste by-products from mining or materials easily transported to the north. Research objectives were to (i) evaluate suitability of mining waste materials as reclamation substrates, (ii) evaluate suitability of organic and nutrient amendments, and (iii) evaluate combinations of materials for anthroposol building. Results from this research will provide recommendations for enhanced reclamation protocols to be used by industry and regulators in disturbed northern sites and in other areas of the world with diamond mining. Results are not meant to be prescriptive by determining a single successful combination of substrate and amendment but to provide practitioners with the knowledge to select suitable combinations based on dominant materials at their site. Because field research in the north is expensive and limited, this detailed greenhouse study was first needed to determine the best combinations of materials under controlled conditions prior to use in the field.

2. MATERIALS AND METHODS

2.1 Greenhouse Procedures

The greenhouse experiment was conducted using a randomized block design to investigate three factors: substrate, organic amendment and nutrient addition. The experimental layout was 6 substrates x 7 organic amendments and a control x 2 nutrient (fertilizer) additions, replicated 7 times. Each replicate was blocked to address potential small-scale differences in greenhouse conditions. Controls were substrates that received no fertilizer or amendments. The large number of treatments was essential to assess interactions among substrates, organic amendments and nutrient additions to make effective recommendations for reclamation.

Substrates were sourced from Diavik Diamond Mine, located approximately 320 km northeast of Yellowknife, Northwest Territories, Canada, on East Island in Lac de Gras (latitude 64°30′41″, longitude 110°17′23″). One-year-old fine-processed kimberlite was collected from the containment facility, where it was placed as slurry to dry. Lakebed sediment was removed during pit excavation after diking and drainage and stored in stockpiles. Crushed rock was removed as waste rock during pit excavation and crushed for using on site; it is granite, containing <0.04 wt % sulfur and generally <20 mm in size. Three volumetric combinations of processed kimberlite and lakebed sediment were assessed: 25 % processed kimberlite and 75 % lakebed sediment (25:75), 50 % processed kimberlite and 50 % lakebed sediment (50:50), and 75 % processed kimberlite and 25 % lakebed sediment (75:25).

Seven organic amendments were assessed. Treated sewage sludge (hereafter sewage) was from an on site stockpile, dewatered by compressing it between belts. Soil was from a stockpile salvaged from areas around the mine; its age and source were unknown, but the material was targeted for reclamation use. Sphagnum peat moss was purchased from a commercial supplier (Premier Horticulture, Inc.). Fine mini granule Black Earth was provided by Black Earth Humic LP and is naturally weathered subbituminous coal high in humic substances, humified organic matter, and humic acids. Biochar was provided by Alterna Biocarbon, produced by slow pyrolysis of a wood (spruce, pine, and fir) biomass feedstock. Due to its limited availability in the field, soil was assessed as a mix with sewage (sewage-soil) and peat (peat-soil), each material contributing half the targeted organic carbon.

Application rates for organic amendments were based on a 2 % achievable organic carbon target, approximately a quarter of organic carbon in undisturbed soil of the area (8.7 %) (Kwiatkowski 2007). The target was used for all amendment substrate combinations except soil alone due to its low organic carbon (therefore using a 1 % target for soil). Amendments were mixed with substrates to simulate incorporation in the field. To calculate mix ratios for the pots, organic carbon (by gravimetric method for loss of carbon dioxide) and water content of each amendment and substrate were determined (Carter and Gregorich 2008) (Table 2.1).

Substrate and amendment combinations were evaluated with and without fertilizer, as it is an easy to apply reclamation procedure if it enhances reclamation success. Fertilizer application rates were 25 kg ha^{-1} nitrogen and 100 kg ha^{-1} phosphorus, applied at a one to four ratio, approximating natural soil (1.8 mg kg^{-1} nitrogen and 7.0 mg kg^{-1} phosphorus). Phosphorus was monoammonium phosphate (11-52-0), and nitrogen was provided in monoammonium phosphate and urea (46-0-0). Fertilizer was mixed with water and applied in the third week after seedlings emerged.

Pots, 12 cm high and 11 cm diameter, were bottom lined with two layers of landscape fabric and drainage holes partially covered to reduce loss of fine materials but allow drainage. Each pot was filled with approximately 700 cm^3 of treatment material. Pots were seeded with three plant species selected for tolerance of site soil conditions, growth form, competitiveness and previous reclamation research (Reid and Naeth 2005a, Drozdowski et al. 2012). Seed number was based on germination (in brackets) and recommended seeding rates: 8 seeds of slender wheat grass (*Elymus trachycaulus* (Link) Gould ex Shinners ssp. *trachycaulus* 'Adanac') (64 %), 5 seeds of Rocky Mountain fescue (*Festuca saximontana* Rydb. var. *saximontana*) (88 %), and 8 seeds of glaucous blue grass (*Poa glauca* Vahl 'Tundra') (64 %). The experiment ran for 12 weeks, the approximate length of the growing season (June to September), and greenhouse temperatures were set to 20 °C with 18 hours of daylight. During the growing season, Diavik has variable temperatures (minimum to maximum range of -9.7 to 27.3 °C) and long periods of daylight. During germination and emergence, pot surfaces were kept damp to reduce water stress. After germination, pots were watered to maintain approximate field capacity.

2.2 Substrates And Amendments Measurements

To characterize organic amendments and substrates, 3 500 g samples of each were analyzed. Analyses were according to Carter and Gregorich (2008) unless otherwise noted. All samples were analyzed for pH and electrical conductivity by saturated paste method and cation exchange capacity by ammonium acetate extraction. The 6 substrates and the soil amendment were analyzed for particle size by hydrometer method. These 7 materials were assessed for percent coarse fragments by sieving approximately 100 g of material at 2 mm for 5 replicates. Processed kimberlite, 25:75, 50:50, 75:25, sewage, and sewage-soil were analyzed for Canadian Council of Ministers of the Environment (CCME) metals by inductively coupled plasma mass spectrometry (Environmental Protection Agency 2007). Residential/parkland guidelines were used due to the potential use of the site for traditional activities. Sewage was analyzed for fecal coliform by most probable number (American Public Health Association 1992) and salmonella by conventional plate count (Health Canada 2009). Data were assessed in the context of generally accepted reclamation values (Soil Quality Criteria Working Group 1987) and baseline values for the region.

2.3 Vegetation Measurements

Emergence was recorded daily for 2 weeks, every 2 to 3 days from weeks 2 to 4, then weekly thereafter. At weeks 6 and 9, plant density, height, health, physiological development stage, and number of leaves were assessed. At 12 weeks, plant density, height, health, physiological development stage, number of leaves, above ground biomass and below ground biomass were determined. Plant height was measured to the nearest millimetre using a ruler for the tallest living leaf of each individual. Plant health was visually assessed and scored using a five point scale with 1 being healthy and 5 being dead. Physiological development was assessed for each plant, using condensed Zadoks stages (Zadoks et al. 1974). The number of leaves was categorized into <5, 5 to 20, and >20. Above ground biomass was determined by clipping plants of each species at ground level. Below ground biomass was determined for each pot by separating all roots from the substrate and washing with gentle rubbing under running water in a soil sieve to reduce root loss. Biomass was oven dried for 48 hours at 80 °C then weighed.

2.4 Data Analyses

Data were assessed for normality and homogeneity of variance. Data were analyzed using permutational analysis of variance (PERMANOVA) for continuous data, assessing interactions among substrates, amendments, and fertilizer, and assessing block. Tukey's HSD tests were conducted for post hoc analysis, and simple main effects were examined by holding one variable constant and examining comparisons between the other variables. A significance level of 0.05 was used for all statistics. Categorical data were assessed for patterns. Statistical analyses were performed using RStudio Version 3.2.0 (RStudio 2015).

3. RESULTS

3.1 Substrate And Amendment Characterization

Chemical properties of substrates varied, although all were low in organic carbon (<1 %) and slightly alkaline with the exception of lakebed sediment (Table 2.1). Amendments were all acidic, similar to suggested guidelines, except for biochar that was neutral. Organic carbon content and cation exchange capacity were higher than that of substrates. Electrical conductivity was above the guidelines in all materials, except biochar, peat, and peat-soil. It was greater than 4 dS m^{-1} suggested appropriate for reclamation soils (Soil Quality Criteria Working Group 1987) in lakebed sediment, processed kimberlite with lakebed sediment, Black Earth and sewage. The substrates and soil amendment were sandy loam to sand loamy sand texture (Table 2.2). Crushed rock had a high proportion of coarse fragments, and processed kimberlite had little. Antimony, arsenic, beryllium, cadmium, lead, mercury, silver, thallium, tin, uranium, and vanadium met CCME (2013) guidelines. Barium, chromium, cobalt, and nickel were elevated in processed kimberlite and some or all of its combinations; chromium, copper, molybdenum, nickel, selenium, and zinc were elevated in one or both of sewage or sewage-soil (Table 2.3). In sewage, salmonella was not isolated and fecal coliforms were <2.0 MPN g^{-1}.

3.2 Plant Response

Plants emerged and grew in all treatments. Slender wheat grass was most successful, present in 99.9 % of pots in week 12, followed by Rocky Mountain fescue in 84.7 % of pots, and glaucous blue grass in 53.6 % of pots. Above ground biomass was significantly affected by substrate, amendment and fertilizer, with interactions between substrate and amendment ($P = 0.000$), substrate and fertilizer ($P = 0.025$), and amendment and fertilizer ($P = 0.000$). Above ground biomass, plant height, number of leaves, and physiological stage were similar in their response to anthroposols; thus, above ground biomass is used as the focus for discussion. Below ground biomass was significantly affected by substrate, amendment, and fertilizer, with interactions between substrate, amendment, and fertilizer ($P = 0.020$). Plant density was significantly affected by substrate and amendment, with interactions between substrate and amendment ($P = 0.000$). Block was statistically significant in all comparisons ($P = 0.000$); differences were not biologically meaningful and were accounted for in the analyses.

The effects of substrates were relatively consistent for plant growth and density with crushed rock being most effective, followed by lakebed sediment and 25:75; processed kimberlite, 50:50, and 75:25 were less effective. Overall, above ground biomass was less affected by substrate and most strongly affected by organic amendment (Figure 2.1). Below ground biomass was strongly affected by substrate and organic amendments (Figure 2.2). Plant density varied with substrate and organic amendment, and was not affected by fertilizer (Figure 2.3).

3.3 Substrate Effectiveness

Substrates varied significantly in their ability to produce above ground biomass when organic amendments were Black Earth, sewage and sewage-soil ($P < 0.001$ to 0.044), and with or without fertilizer ($P < 0.001$ to 0.039), being greatest on crushed rock, 25:75 and lakebed sediment (Figure

2.1). Biomass was greater on crushed rock than processed kimberlite, 50:50, and 75:25 with all above amendments, except 50:50 and 75:25 with sewage-soil, and greater on crushed rock than 25:75 and lakebed sediment with Black Earth. Biomass was greater in 25:75 than processed kimberlite, 50:50 and 75:25 with sewage, fertilizer and no fertilizer; than lakebed sediment, processed kimberlite and 50:50 with sewage-soil; and than lakebed sediment with no fertilizer. Biomass was greater in lakebed sediment than processed kimberlite, 50:50, and 75:25 with sewage and fertilizer, and than 50:50 with no fertilizer. As crushed rock was surprisingly successful in supporting above ground biomass, unamended crushed rock was compared with other unamended substrates. Above ground biomass did not differ in crushed rock and the other substrates without organic amendment; however, without fertilizer, crushed rock had greater biomass than processed kimberlite, 50:50 and 75:25 ($P < 0.001$).

Substrates varied significantly in their ability to develop below ground biomass. Biomass varied in fertilized substrates when amended with peat, soil, or with no amendment; it varied in unfertilized substrates when amended with Black Earth, peat, peat-soil and soil (Figure 2.4). Biomass was greatest in crushed rock, even without organic amendment.

Plant density differed in substrates with all amendments except Black Earth or peat-soil. Crushed rock tended to have the most plants, with biochar (relative to 50:50, 75:25 and lakebed sediment), peat, sewage and soil (relative to 50:50 and 75:25), and sewage-soil (relative to 50:50) ($P < 0.001$ to 0.047). Without amendment, crushed rock had more plants than any other substrate ($P < 0.002$). When amended with sewage, 25:75, lakebed sediment and processed kimberlite had more plants than 50:50 and 75:25 ($P < 0.001$).

3.4 Amendment Effectiveness

Organic amendment impacted above ground biomass in all substrates, with peat, peat-soil, sewage, sewage-soil and soil significantly increasing above ground biomass relative to no amendment ($P < 0.001$ to 0.039). Biomass was greater with peat-soil and sewage-soil than no amendment in all substrates, sewage in all but 75:25, soil in all but 75:25 and 25:75, and in peat relative to 25:75. Sewage-based amendments resulted in greater biomass than peat or soil amendments ($P < 0.001$ to 0.008). Biomass was greater in all substrates with sewage-soil than peat, soil and peat-soil; greater with sewage in 25:75, crushed rock, processed kimberlite and lakebed sediment, and compared with peat in 50:50. The seed production occurred in pots with sewage. Fertilizer increased above ground biomass in crushed rock ($P < 0.001$) and lakebed sediment ($P < 0.001$) substrates, and biochar ($P = 0.024$) and peat ($P < 0.001$) amendments compared with no fertilizer. Biochar or Black Earth did not significantly affect plant density and growth relative to no organic amendment ($P > 0.05$).

Below ground biomass was greater in substrates amended with peat, soil, peat-soil, sewage, and sewage-soil relative to no organic amendment, with peat more successful (Figure 2.5). Sewage-based amendments relative to peat or soil amendments had few significant differences. Biomass was greater with soil than sewage or sewage-soil in unfertilized crushed rock, greater with peat-soil than sewage in fertilized 75:25, greater with peat than sewage in fertilized lakebed sediment, and greater with peat than sewage and sewage-soil and soil relative to sewage in fertilized crushed rock ($P < 0.001$ to 0.039). Biomass in peat-amended substrates was only greater than sewage or sewage-soil when fertilized. When organic amendment and fertilizer were used, below ground biomass was greatest, especially with peat or peat-soil amendment. Fertilizer relative to no fertilizer was only significantly different with peat in crushed rock and lakebed sediment ($P < 0.001$), indicating that organic amendment played a greater role than fertilizer in biomass production. Without organic amendment, fertilizer only increased below ground biomass in crushed rock substrate ($P = 0.006$).

Amending substrates with peat or peat-soil increased plant density relative to no amendment, whereas sewage had variable results (Figure 2.3). No amendment in crushed rock was more successful than some organic amendments. Substrates with peat, peat-soil and soil had greater plant density than with sewage or sewage-soil ($P < 0.001$ to 0.035). Peat had more plants than sewage in 25:75, 50:50, 75:25 and crushed rock and sewage-soil in 50:50, crushed rock and lakebed sediment; peat-soil had more plants than sewage in 50:50 and 75:25, and sewage-soil in lakebed sediment; and soil had more plants than sewage in 50:50 and 75:25. Processed kimberlite showed no differences between organic amendments ($P > 0.05$).

Plant health ranged from 1 (very healthy) to 5 (all dead) (data not shown). Plants in pots amended with peat, peat-soil or soil were slightly healthier (1.93 ± 0.03, 1.91 ± 0.03, and 1.94 ± 0.04, respectively) and pots with sewage (2.45 ± 0.09) were slightly less healthy. Plants in crushed rock were slightly less healthy (2.31 ± 0.06) than plants in lakebed sediment (2.02 ± 0.04), 25:75 (2.01 ± 0.03), and 50:50 (2.06 ± 0.05). Plant health was not affected by fertilizer.

4. DISCUSSION

The positive response of plants to crushed rock substrate can be explained by the high proportion of coarse fragments that can trap seeds in favourable micro sites, relative to smooth and compacted surfaces, such as lakebed sediment, allowing time for germination (Chambers et al. 1991, Johnson and Fryer 1992, Jumpponen et al. 1999, Naeth and Wilkinson 2014). Large pores from variable particle sizes and the high proportion of coarse fragments facilitate growth of a larger root system. This is especially important in northern ecosystems in which root development and below ground biomass are critical for plants to survive harsh winter conditions by storing carbohydrates in roots (Billings 1987, Densmore et al. 2000). However, in the longer term, crushed rock may not be a suitable substrate unless amended due to its low organic carbon and cation exchange capacity. Crushed rock may have low water retention, which will be restrictive in the environments where precipitation is limited (Naeth and Wilkinson 2014).

Lakebed sediment and 25:75 will be suitable substrates for reclamation. Lakebed sediment pH is similar to native soils (Drozdowski et al. 2012) and has a large proportion of fine particles that can improve water and nutrient holding capacity (Densmore 1994, Densmore et al. 2000, Mori et al. 2006). Lakebed sediment may be too fine textured, as it had little aggregation, and when dry was compact, restricting seed germination and plant growth, and reducing root biomass, which can influence long term effectiveness in the field. Lakebed sediment with a small proportion of processed kimberlite (25:75) combined benefits of the materials, increasing cation exchange capacity, diluting metals in kimberlite and reducing the compact nature of lakebed sediment, also observed by Naeth and Wilkinson (2014).

Processed kimberlite, as expected, negatively impacted emergence and growth, even when combined with lakebed sediment, except in high amounts. Kimberlite's serpentine chemistry results in unproductive soils with a low calcium to magnesium ratio and elevated metal concentrations (Baker et al. 2001, Reid and Naeth 2005a), particularly affecting plants not native to serpentine soils (Brady et al. 2005). Its high concentrations of barium, cobalt, chromium, and nickel may negatively affect plant establishment and growth. Chromium decreased plant growth and photosynthesis in common sunflower (*Helianthus annuus*) (Davies et al. 2002); nickel reduced growth in mustard (*Brassica*) species (Ma et al. 2009) and root growth in Italian catchfly (*Silene italica*) from nonserpentine soils (Mattioni et al. 1997). Accumulated barium (Nogueira et al. 2010), chromium (Davies et al. 2002), and nickel (Mattioni et al. 1997) in plants is a concern due to wildlife in and around Diavik. Available metals in these substrates should be assessed as in many soils, metals are unavailable in inorganic compounds or bound with organic material, clays and other metals (Foy et al. 1978). The texture and structure of processed kimberlite likely reduce its effectiveness as it has little aggregation and was primarily single-grained particles.

Although the use of this major waste material of diamond mining would be beneficial, the use in high amounts does not benefit plants and would negatively affect reclamation.

Substrate limitations due to poor structure and texture, lack of organic matter (<0.5 %) and low cation exchange capacity resulted in little aggregation and nutrient or water holding ability. Addition of organic amendments was essential to mitigate these limitations in the main material of the anthroposol. Organic matter can improve structure through aggregate formation, increase porosity and reduce bulk density (Haynes and Naidu 1998). Amendments with readily available nutrients were beneficial for plant growth, like sewage, but were less beneficial for plant density relative to less nutrient available amendments, such as peat.

Sewage effectiveness, either alone or combined with soil, was due to large amounts of readily available nutrients (Reid and Naeth 2005a) and soil structure improvement. Its high nutrient concentrations allow plants to grow quickly and large and to develop seed heads during the short experiment, while its slower decomposition provides nutrients over a longer period than fertilizer (Bishop et al. 2000). Sewage was not most effective for increasing plant density and in some cases, decreased it relative to other amendments or no amendment. Rapid growth may reduce establishment of many individuals as a smaller number of large plants may dominate the growing space and nutrients. In the field, this may be less problematic as space would be less limited. Elevated metal concentrations and high electrical conductivity, nearly 6 dS m^{-1}, which is considered poor soil quality (Alberta Environment and Parks 2016), may reduce plant establishment, although it did not appear to impact ability of those that established to grow. Adding soil to sewage reduced elevated metals and electrical conductivity, which in turn reduced negative effects of sewage on plant density while still increasing plant growth, similar to or greater than sewage. Elevated metal concentrations and salinity in sewage will decrease over time in the field while still providing benefits from nutrient addition, water retention and improved soil structure (Naeth and Wilkinson 2014).

Effectiveness of peat for increasing plant density and root growth, either alone or with soil, was seen in previous research. Reid and Naeth (2005b) found peat increased plant cover, growth, and health. Its high water and nutrient holding capacities, low electrical conductivity and high organic matter content can support germination and establishment of plants. Its high carbon to nitrogen ratio may initially limit nutrients that will become more available with decomposition. Nutrients in anthroposols are essential for growth especially in northern ecosystems with limited nutrient availability (Bishop and Chapin 1989b); however, slow nutrient addition from peat may support root development that is essential for arctic species. Rapid release and high nutrient addition, as seen with some fertilizer, can result in a low root to shoot ratio (Bishop and Chapin 1989b), negatively affecting survival. Smaller plants growing in peat and (or) soil may facilitate establishment of a greater number of plants as there may be less competition.

The lack of effect of biochar and Black Earth on plant density and growth may be due to their limited change to substrate structure. Although both have beneficial properties, including high organic carbon and cation exchange capacity, they were unable to improve substrate structure in the same way as peat, sewage and soil, by promoting aggregation and development of larger pores while providing nutrients and organic matter. They decompose slowly, which limit their effect in a 12 week greenhouse experiment; they may be more effective in the field although their use in the north has been limited. Jones et al. (2012) applied biochar to agricultural fields in Wales and found increased crop biomass after 3 years in the field. Biochar and Black Earth may improve emergence and growth in the long term, but without improving substrate structure, they are not effective in the short term, which are most critical for reclamation. Use of biochar in combination with peat, sewage or soil for amending processed kimberlite may reduce metal availability [(Beesley et al. 2011), although increases in some metals or no effect was seen with biochar by Fellet et al. 2011].

Fertilizer only affected plant growth in some substrates and amendments and did not increase plant density. Although fertilizer provided plants with an immediate source of nutrients, addition of organic amendments played a greater role in increasing growth and density in our experiment, due to improvement of both physical and nutrient limitations, also seen in Reid and Naeth (2005b). Fertilizer can increase mortality and reduce germination and root growth (Bishop and Chapin 1989b, Deshaies et al. 2009), with potential vegetation dependency on continued applications. Fertilizer should only be considered with some substrates and organic amendment combinations, such as crushed rock and lakebed sediment substrates, and organic amendments such as peat and biochar. Fertilizer can address short term nutrient limitations in an amendment like peat, which improves substrate structure, but decomposes too slow to provide nutrients within the first few months of plant growth. Regular watering in this experiment may have flushed nutrients faster than in the field where there is limited precipitation, although poor water retention in the substrates and liquid application of the fertilizer may also have resulted in drainage before plants could access nutrients.

The strength of this experiment is in the ability to use the results to select the most suitable combination of available materials. Many mining sites have limited access that makes it expensive to transport large amounts of external products. By adjusting reclamation plans to what is available on site, the amount of material brought in can be limited. For example, if processed kimberlite is the dominant waste material, rather than capping it with crushed rock, which tends to be common practice, addition of other substrates, such as lakebed sediment, can reduce the negative properties and provide for successful plant establishment. Sites with waste treatment facilities have continued access to sewage sludge, and rather than treating it as a waste product, placement directly on reclamation sites, or added with soil, can improve plant establishment and growth. Crushed rock is a common waste product at many mine sites and other types of disturbances. It is commonly used for capping or road construction. However, it shows suitability as a reclamation substrate, especially with organic amendments, such as peat. Selection of reclamation materials must also be based on site challenges and goals. If erosion is an immediate issue on site, the use of sewage will be effective as it supports immediate and rapid plant growth. If establishment of a highly diverse community with area for ingress of plants from the natural environment is the goal, the use of peat or soil will be more effective.

Additional greenhouse experiments should examine combinations of substrates and amendments, like crushed rock and lakebed sediment to combine benefits of coarse and fine materials, and peat and sewage to provide rapidly available nutrients while reducing the negative attributes. Lower application rates of amendments should be examined; although high application rates in this experiment were essential to begin to understand amendment effectiveness, they are not sustainable in the field where limited materials are available. Greenhouse experiments provide an important opportunity to explore large numbers of combinations of materials; however, environmental conditions vary from the field and must be considered when extrapolating greenhouse results to the field. Greenhouse studies to examine effectiveness of substrates under drier conditions are needed to better approximate northern environmental conditions as precipitation in the study area is 242 to 413 mm, mean 306 mm, with approximately 45 % as rainfall. Rainfall peaks in August and September; snowfall peaks in November, resulting in little rain falling during the early part of the growing season when plants require it for germination and establishment. With a better understanding of effective combinations of materials from the greenhouse using conditions to approximate the field, field studies are the next step to examine anthroposols. Highly variable field conditions can be hard to replicate in the greenhouse, such as addition of wind, variable temperatures (minimum to maximum between June and September was -9.7 to 27.3 °C) and inconsistent precipitation and are an important part of subsequent field experiments to understand long term suitability of anthroposols. Greenhouse experiments limit use of larger waste materials that would be used on site for reclamation due to size limitations in pots.

Due to the wide range of materials examined, results from this research can be adapted for different disturbances and locations. Northern disturbances are increasing and many have similar conditions and materials as diamond mining, such as crushed rock or sewage. Diamonds are mined in at least 15 regions worldwide, including England, Russia, Australia, India and Africa (Hart 2001). Many will have similar environmental challenges such as limited water and large amounts of produced waste materials. Building anthroposols for reclamation is essential due to lack of native soil present on many mining or other large disturbance sites. Use of waste materials to build anthroposols represents a leading frontier and an essential step, especially in areas with limited access to bring in external materials. Substrates, organic amendments, and fertilizer played an important role in improving vegetation establishment and growth in diamond mine waste materials.

5. CONCLUSIONS

Effective anthroposol building is influenced by selection of substrates, organic amendments, and fertilizer addition. Organic amendment addition had the greatest effect on plant emergence and growth, through improvement of structure of the substrates; substrates and fertilizer application played a smaller role. Crushed rock, 25:75 and lakebed sediment were the most effective substrates. Sewage-soil and sewage increased above ground biomass the most, whereas peat, soil and peat-soil increased the number of plants and root growth the most. Black Earth and biochar were not effective organic amendments. Fertilizer should only be used in combination with certain substrates and amendments to increase plant growth, such as with peat as it addressed short term nutrient limitations.

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Table 2.1. Chemical properties of substrates and amendments[a].

Material	Cation Exchange Capacity (meq 100 g^{-1})	Electrical Conductivity (dS m^{-1})	Soil Reaction (pH)	Total Organic Carbon (%)
Guidelines[b]	>3	<1[c]	5.0	>1
Substrates				
Crushed Rock	1.0 (0.1)	1.0 (0.0)	7.8 (0.0)	0.1
Processed Kimberlite	9.8 (0.3)	3.8 (0.0)	8.2 (0.0)	0.4
75:25[d]	8.0 (0.2)	4.2 (0.1)	8.1 (0.0)	0.2
50:50	6.1 (0.1)	6.3 (0.1)	7.9 (0.0)	0.2
25:75	4.0 (0.2)	4.8 (0.2)	7.8 (0.0)	0.3
Lakebed Sediment	1.4 (0.1)	4.7 (0.1)	4.6 (0.0)	0.2
Amendments				
Biochar	15.6 (1.4)	0.5 (0.1)	6.9 (0.0)	74.8
Black Earth	136.7 (1.8)	4.1 (0.1)	3.6 (0.0)	45.2
Peat	112.0 (7.0)	0.5 (0.0)	3.9 (0.0)	43.4
Peat-soil	21.6 (1.0)	0.8 (0.0)	4.1 (0.0)	N/A
Sewage	69.8 (4.7)	5.9 (0.4)	6.1 (0.3)	28.6
Sewage-soil	17.5 (0.9)	3.1 (0.2)	5.0 (0.0)	N/A
Soil	13.3 (0.6)	1.9 (0.1)	4.5 (0.0)	2.7

[a]Values are mean with standard error in brackets.
[b]Guidelines are based on generally accepted reclamation values (Soil Quality Criteria Working Group 1987), baseline data and results from research in the area (Reid and Naeth 2005b, Drozdowski et al. 2012, Naeth and Wilkinson 2014).
[c]Electrical conductivity over 4 dS m^{-1} is considered poor in most environments (Soil Quality Criteria Working Group 1987).
[d]Values refer to ratio of processed kimberlite to lakebed sediment.

Table 2.2. Texture of applicable substrates and amendments[a].

Material	Coarse (%)	Sand (%)	Silt (%)	Clay (%)	Texture
Crushed Rock	62.2 (3.2)	87.1 (1.2)	10.0 (0.6)	2.9 (0.9)	Loamy sand
Processed Kimberlite	0.1 (0.0)	88.2 (0.6)	8.2 (0.6)	3.6 (0.0)	Sand/loamy sand
75:25[b]	7.5 (1.9)	81.3 (0.1)	12.4 (0.3)	6.3 (0.4)	Loamy sand
50:50	10.0 (0.5)	79.3 (0.2)	14.9 (0.1)	5.7 (0.1)	Loamy sand
25:75	19.6 (1.8)	70.1 (0.6)	22.4 (0.6)	7.5 (0.5)	Sandy loam
Lakebed Sediment	22.6 (2.8)	66.9 (1.2)	27.7 (0.4)	5.4 (0.8)	Sandy loam
Soil	28.9 (3.6)	74.3 (0.7)	20.7 (0.7)	4.9 (0.7)	Sandy loam

[a]Values are mean with standard error in brackets.
[b]Values refer to ratio of processed kimberlite to lakebed sediment.

Table 2.3. Metal concentrations[a] in processed kimberlite substrates and sewage above CCME guidelines[b].

Metal	CCME Guidelines[c] (mg kg^{-1} Dry Weight)	Processed Kimberlite	75:25[d]	50:50	25:75	Sewage	Sewage-soil
Barium (Ba)	500	685.3 (30.4)	652.0 (14.2)				
Chromium (Cr)	64 (total)	428.7 (2.9)	361.0 (7.8)	272.3 (11.3)	169.0 (2.5)	69.6 (6.6)	
Cobalt (Co)	50	73.5 (2.3)	59.9 (2.4)				
Copper (Cu)	63					997.0 (23.0)	174.3 (13.2)
Molybdenum (Mo)	10					35.9 (0.1)	
Nickel (Ni)	50	1,250.0 (50.0)	1,003.7 (46.0)	784.7 (10.7)	467.3 (3.3)	74.6 (3.0)	
Selenium (Se)	1					4.97 (0.11)	
Zinc (Zn)	200					1,333 (33)	235 (15)

[a]Values are mean with standard error in brackets.
[b]Values not presented were below guidelines.
[c]Canadian Council of Ministers of the Environment (2013) guidelines for residential/parkland were used.
[d]Values refer to ratio of processed kimberlite to lakebed sediment.

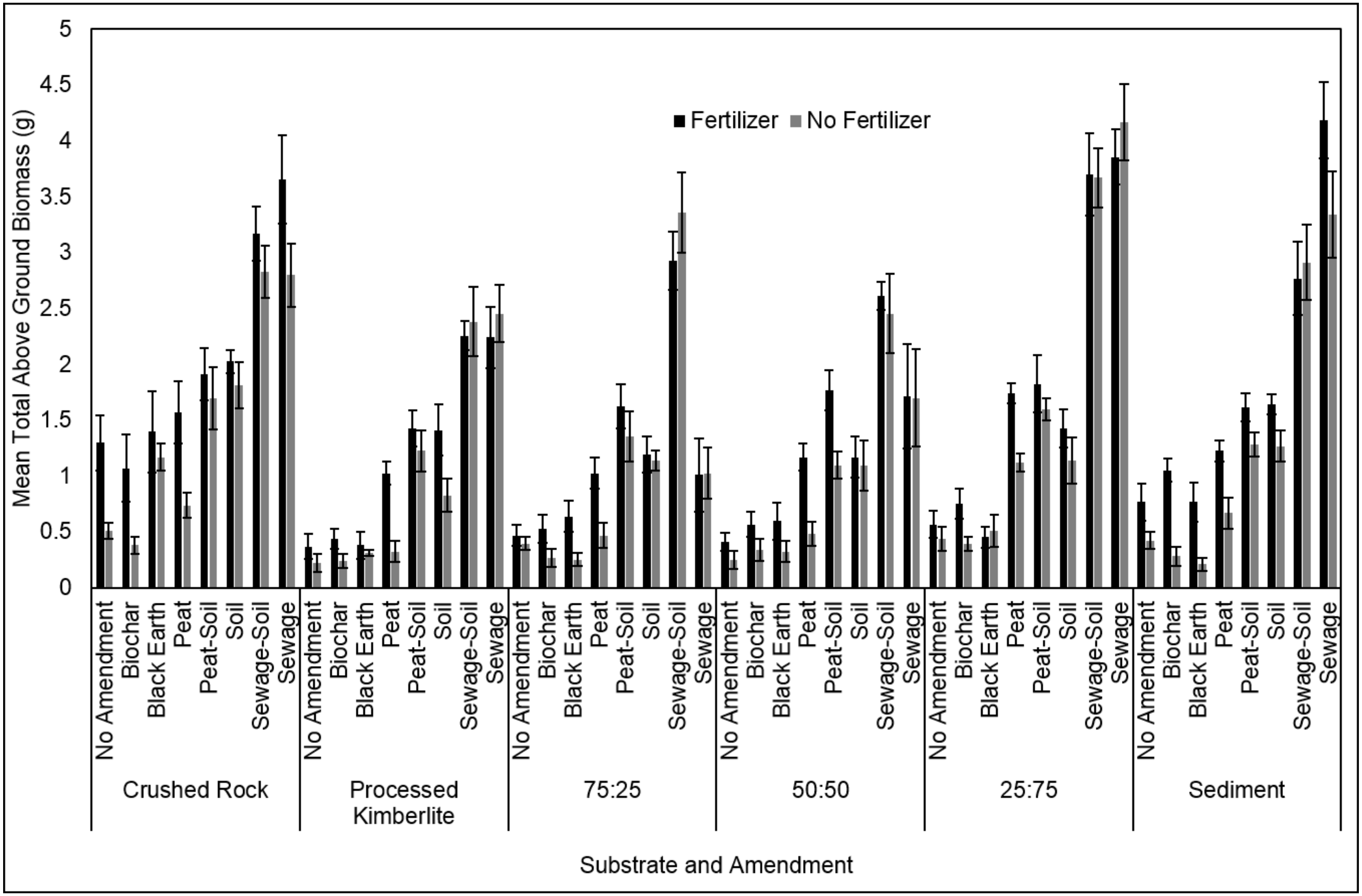

Figure 2.1. Mean above ground biomass in week 12 by treatment (mean ± SE).

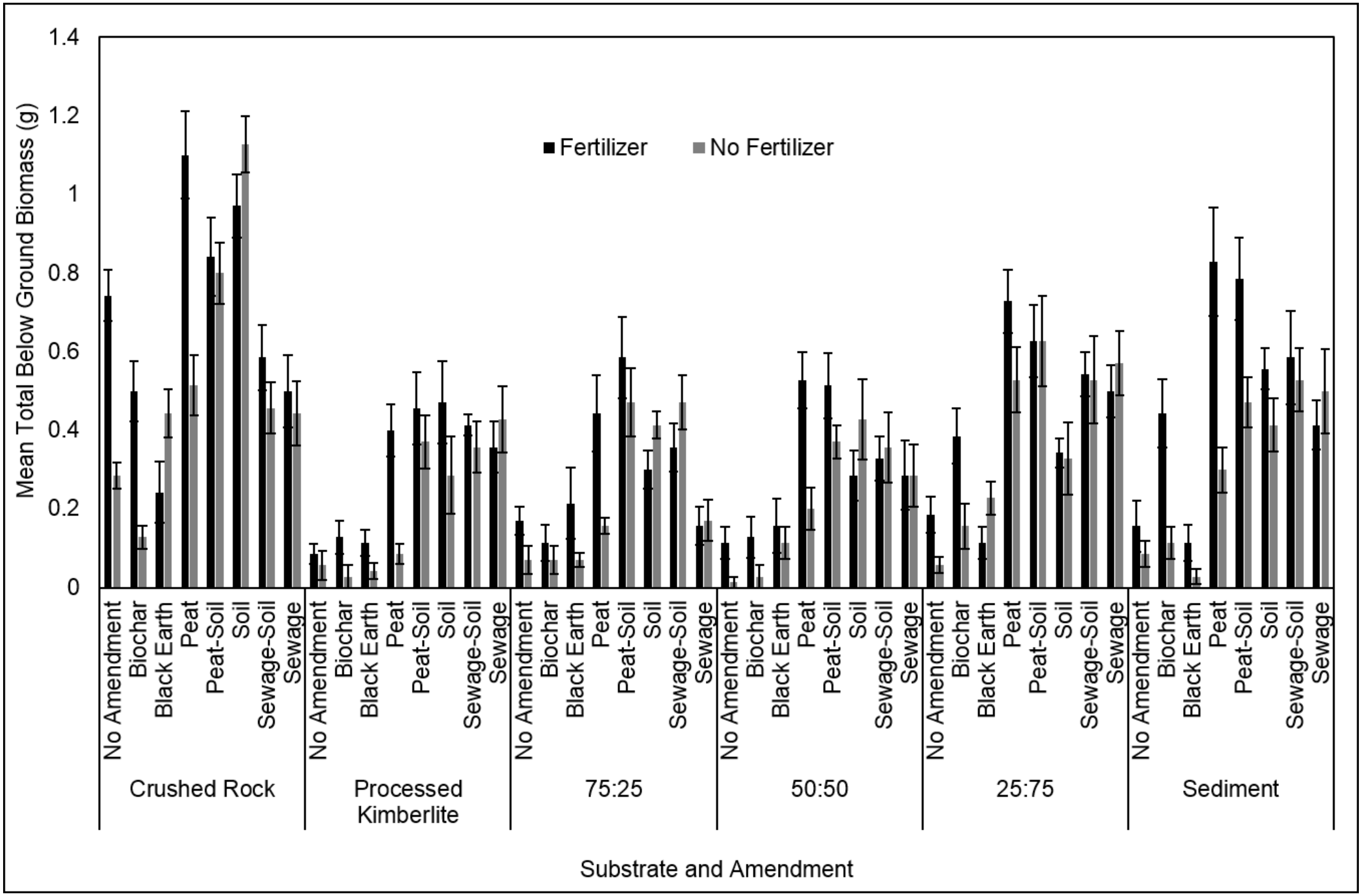

Figure 2.2. Mean below ground biomass in week 12 by treatment (mean ± SE).

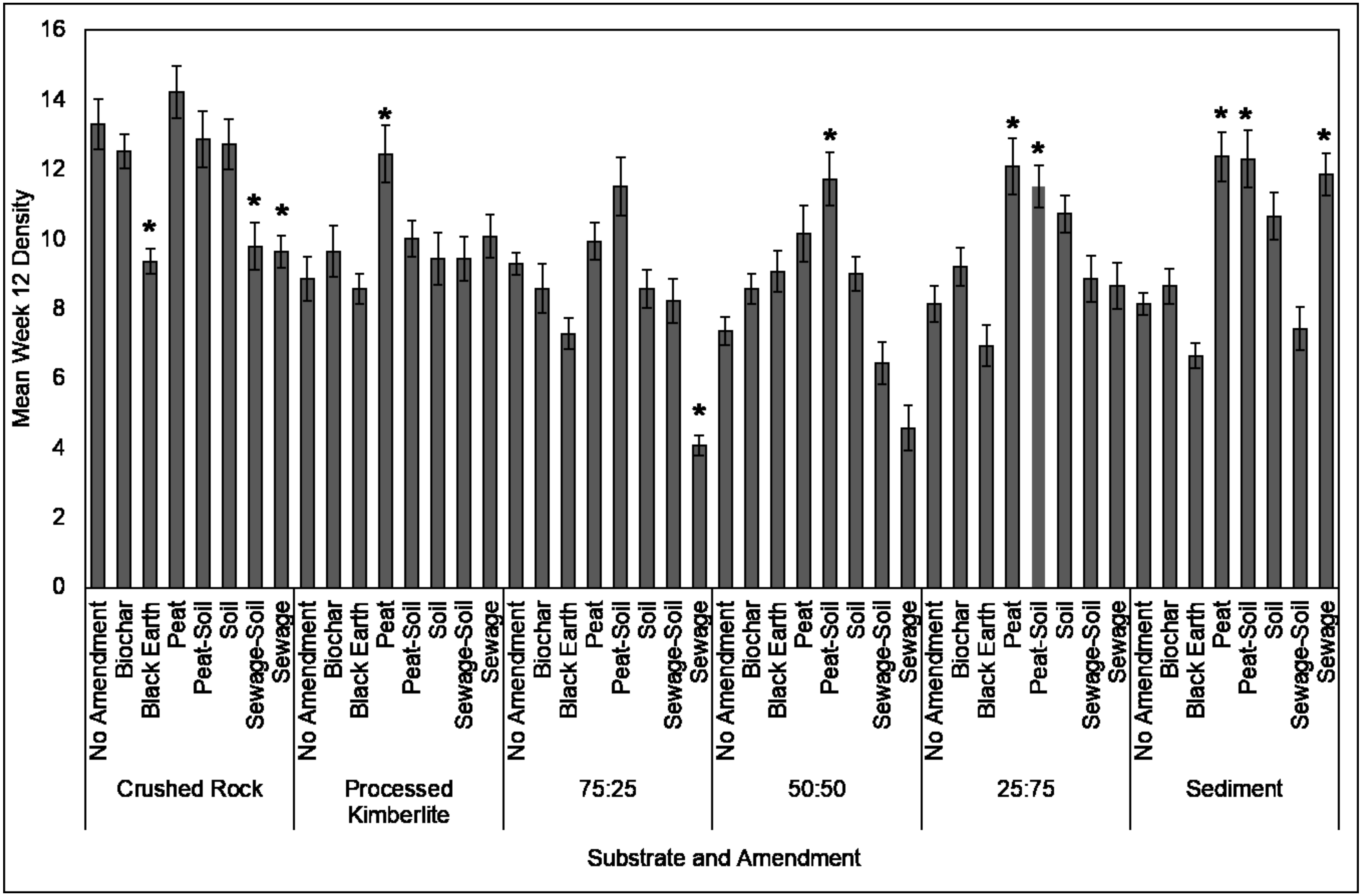

Figure 2.3. Mean density in week 12 by treatment (mean ± SE). * Denotes a significant difference from no amendment.

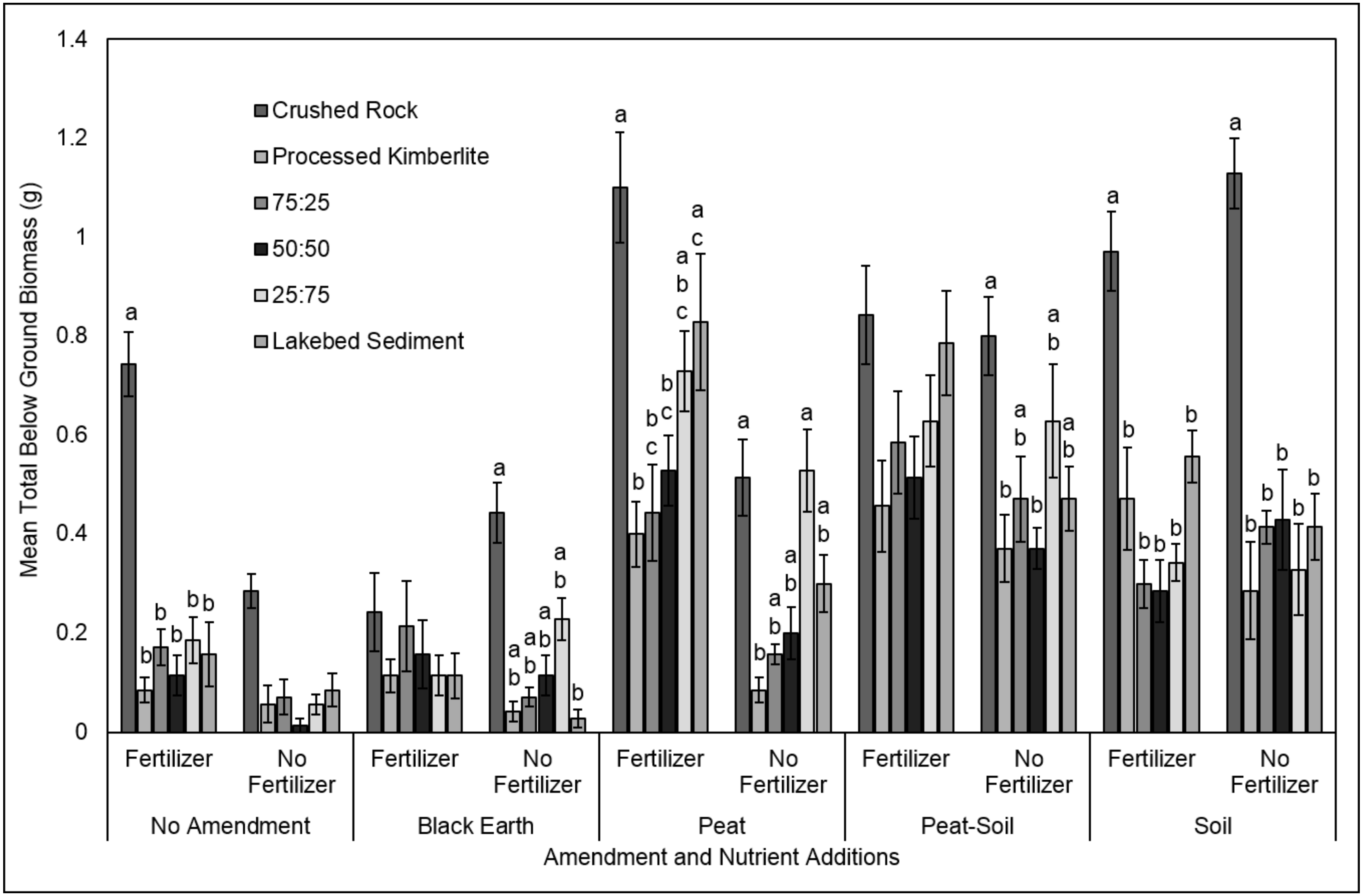

Figure 2.4. Below ground biomass in week 12 compared between substrates with the same amendment and fertilizer treatments (mean ± SE). Only treatments with significant differences are shown and marked by different letters within amendment and fertilizer combinations.

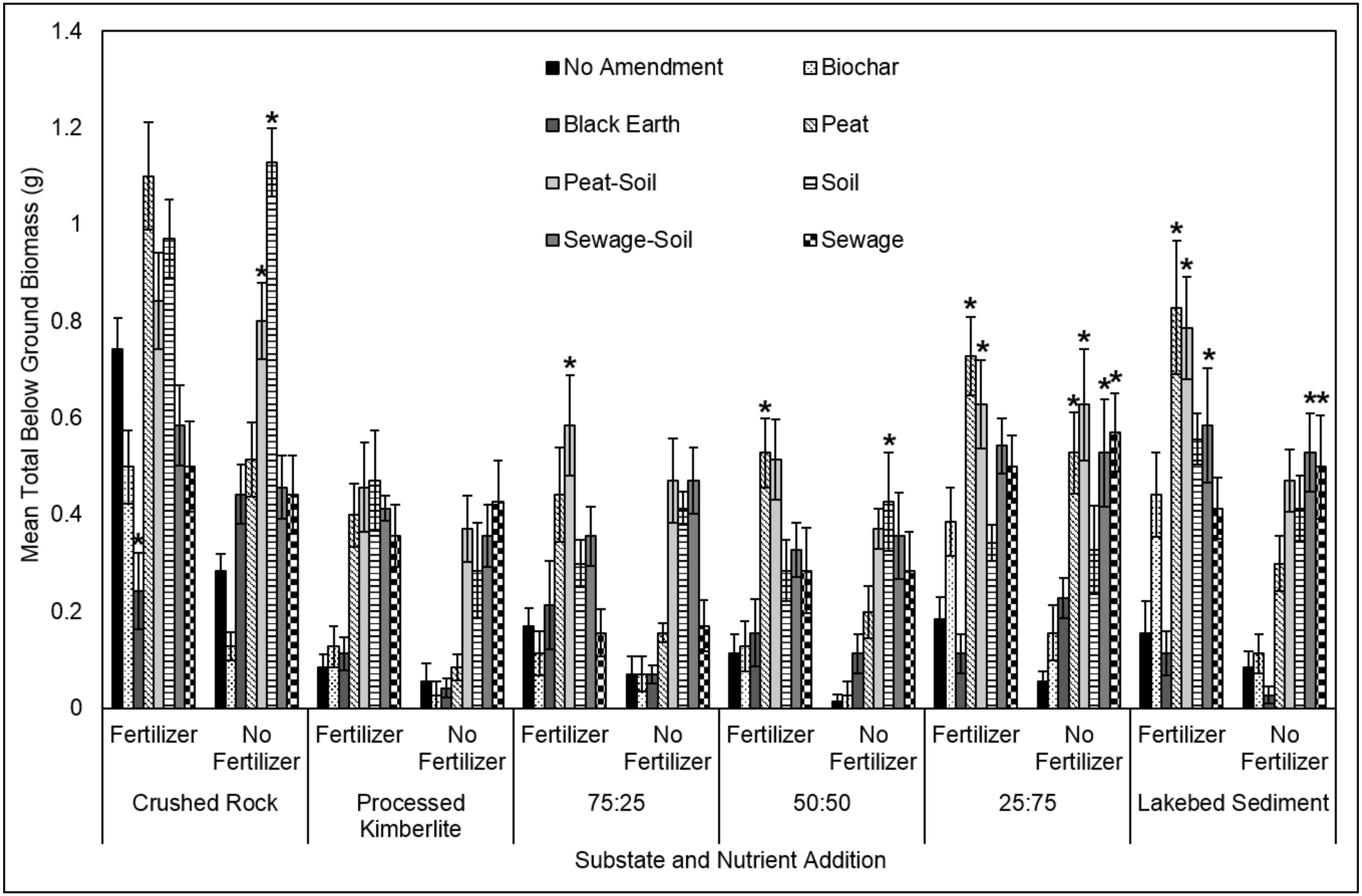

Figure 2.5. Below ground biomass in week 12 compared between organic amendments and no organic amendment in all substrates with and without fertilizer (mean ± SE). * Denotes a significant difference from no amendment.

III. HYDROGEL AND ORGANIC AMENDMENTS TO INCREASE WATER RETENTION IN ANTHROPOSOLS FOR LAND RECLAMATION

1. INTRODUCTION

Mining and other industrial activities produce large amounts of waste and disturb large areas that require land reclamation. Some waste materials must be capped due to their chemical properties; others can be used for reclamation. Soils can be built by combining waste materials and adding amendments to ameliorate the limiting properties required for vegetation establishment and growth (e.g. Drozdowski et al. 2012, McGeehan 2012, Kumar 2013). These anthroposols, human made or human altered soils (Naeth et al. 2012), are important in land reclamation as they use materials that would otherwise need to be handled as waste and may be confined to landfills.

Water holding capacity of soil materials is an important consideration for land reclamation. Suitable soil water content is essential for seed germination, seedling establishment and plant survival as desiccation is a major risk on disturbed sites, especially in arid environments like the arctic (Bishop and Chapin III 1989, Jumpponen et al. 1999, Sarvaš et al. 2007). Water holding capacity of materials varies with properties such as structure, pore size, particle size, proportion of coarse material and organic matter content (Saxton and Rawls 2006, Sheoran et al. 2010). Particle size plays an important role in water holding capacity (Saxton and Rawls 2006, Sheoran et al. 2010). Sand textured materials have large particles resulting in few larger pores relative to clay or silt textured materials, which have smaller particles and numerous smaller pores and result in greater water holding capacity. The proportion of coarse fragments over 2 mm significantly influences water holding capacity as it creates large pores that are unable to hold water (Saxton and Rawls 2006, Sheoran et al. 2010). Organic matter can increase water holding capacity as it alters particle aggregation and pore size distribution (Hudson 1994, Saxton and Rawls 2006).

Unamended mine wastes tend to have low water holding capacity and therefore amendments are essential to reduce water limitation in reclamation soils. Numerous amendments have been proposed to increase water holding capacity, primarily organic amendments. An alternative is hydrogel, an acrylic polymer that absorbs water and releases it over time which can be mixed with soil or other soil materials to increase water retention and reduce water stress on vegetation (Johnson 1984, Akhter et al. 2004, Rowe et al. 2005, Abedi-Koupai et al. 2008). While it is known that hydrogel and organic amendments can increase water retention, studies comparing their effect on water retention of different reclamation soil materials are limited.

The objectives of this research were to determine whether water retention of soil building materials (hereafter substrates) was altered by various amounts and application methods of hydrogel and select organic amendments and whether water retention was altered with rehydration of the materials. We hypothesized that substrates would retain different amounts of water regardless of the amount of amendment and that amendments would alter water retention regardless of substrate depending on amendment and application rate and method.

2. MATERIALS AND METHODS

2.1 Substrates And Amendments

Three primary waste materials from Diavik Diamond Mine, Northwest Territories, Canada (latitude 64˚30’41’’, longitude 110˚17’23’’), processed kimberlite, lakebed sediment and crushed rock, were used for the experiments. Treated sewage sludge (hereafter sewage) and salvaged soil (hereafter soil) were sourced from Diavik Diamond Mine. Peat (Premier Horticulture Inc.) and Soil Moist were purchased from a commercial supplier. Soil Moist is a synthetic acrylic cross linked polyacrylamide (hereafter hydrogel) that absorbs water and releases it slowly as soil dries, potentially reducing watering needs up to 50 % (JRM Chemical Inc. 2011, 2012). It has a slightly acidic to neutral pH and potassium salt base, persists 3 to 5 years in soil and is advertised as non-toxic to plants (JRM Chemical Inc. 2011, 2012). Chemical properties of materials varied considerably (Table 3.1).

2.2 Experimental Procedure

Three greenhouse experiments were conducted using complete randomized designs, all replicated 4 times. The hydrogel experiment and rewetting hydrogel experiment evaluated 3 substrates x 10 hydrogel treatments (3 application rates x 3 application methods and a control of each substrate with no hydrogel). Hydrogel application rates were manufacturer recommended (488 kg ha^{-1}), half recommended and double recommended. Application methods representing potential field methods were dry substrate and dry hydrogel mixed then wetted (dry/dry), dry substrate and wet hydrogel mixed then wetted (dry/wet), and substrate and hydrogel wetted separately then mixed and wetted again (wet/wet). The amendment experiment evaluated 3 substrates x 11 treatments (5 amendments x 2 application rates and a control of each substrate with no amendment). Application rates were manufacturer recommended for hydrogel and 10 %

by volume organic amendments, and double hydrogel and 20 % by volume organic amendments. A 10 % by volume was considered potentially feasible for field application for reclamation. Five amendments were dry substrate and dry hydrogel mixed then wetted (dry/dry), dry substrate and wet hydrogel mixed then wetted (dry/wet), peat, sewage and soil.

For all experiments, 7 cm tall and 8 cm diameter round pots were used. Two layers of landscape fabric were placed in the bottom to reduce loss of material through holes in the pot base. Consistent volumes of dry substrate of known weight were mixed with required amendments to achieve target volume ratios then placed in the pots. For the dry/wet treatment, hydrogel was saturated by placing it in a beaker of water for 24 hours, draining excess water, then mixing with dry substrates. For the wet/wet treatment, hydrogel was saturated as above and the substrate was saturated by placing it in a tray of water for 24 hours then mixing. Weight of filled pots prior to saturation was determined based on the known weight of each component (substrate, amendment, landscape fabric, pot) to facilitate assessment of water retention.

After mixing, all pots were wetted by placing them in a tray of water for 24 hours to approximate saturation. Pots were weighed upon removal from the water, representing the 0 hour or saturation weight. Pots were weighed approximately twice a day for the first two days then daily until constant or near constant weight. For hydrogel rewetting experiment, pots were rewetted using the same method after drying and weighing as above.

Substrate particle size was determined by sieving 5 replicates of each through sieve sizes 19.0, 12.5, 9.5, 6.3, 4.0, 2.0, 1.0, 0.5, 0.25, 0.212, 0.106, 0.053 and less than 0.053 mm. All large rocks, greater than approximately 4 cm, were removed in this experiment due to the size of the pots which could not accommodate that particle size. Sieves were stacked in piles of three based on the order above and material placed on the largest sieve, with a pan at the bottom. The stack was moved smoothly and consistently by hand for 1 minute. The material left in each sieve was weighed and what passed through into the pan was placed on the top of the next stack of three sieves, repeated until all sieves were used.

2.3 Data Analyses

Water retention was determined by subtracting pre-watering weight from the weight at each assessment and calculating the % water by weight. Three time periods were assessed for each experiment: 0 hours, approximating saturation; 48 hours, approximating field capacity; and near dry (77.2 hours for hydrogel experiment, 73.5 hours for rewetting hydrogel experiment, 124.6

hours for amendment experiment). Data were assessed for normality and homogeneity of variance, then analyzed using ANOVA for continuous data. The final time period in the amendment experiment was log 10 transformed to improve homogeneity. Tukey HSD tests were completed for post hoc analysis for a priori comparisons. A significance level of 0.05 was used. Statistical analyses were performed using RStudio Version 3.4.0 (2017).

3. RESULTS

3.1 Substrate Texture

Substrate particle size varied (Table 3.2). Coarse material over 2 mm dominated crushed rock (58.5 %) and lakebed sediment (42.3 %) (keep in mind large sized rock pieces were removed prior to sieving); lakebed sediment and processed kimberlite contained a large proportion of fine material under 212 um, 17.9 % and 16.5 %, respectively.

3.2 Hydrogel Experiment

There was significant interaction between substrate and hydrogel treatment (application method and rate) (saturation $P < 0.001$; field capacity $P < 0.001$; near dry $P < 0.001$).

Substrate influenced water retention, with processed kimberlite holding more water than lakebed sediment and crushed rock at saturation (significant in 100 % of comparisons), field capacity (90 %) and near dry (85 %). At field capacity and near dry, lakebed sediment and processed kimberlite did not differ when no amendment was added. With no amendment addition, lakebed sediment held more water than crushed rock, statistically more at saturation and field capacity. At double application rates, crushed rock held more water than lakebed sediment although the significance of effect decreased over time.

Application method had a limited effect in crushed rock relative to lakebed sediment and processed kimberlite (Figure 3.1). Dry/wet application tended to have the greatest water retention and wet/wet the lowest, particularly in processed kimberlite. In crushed rock and processed kimberlite, higher application rates generally resulted in greater water retention than lower rates or no amendment addition (Figure 3.1). Application rate had little effect in lakebed sediment, between rates or no amendment.

3.3 Rewetting Hydrogel Experiment

There was significant interaction between substrate and hydrogel treatment (application method and rate) (saturation $P < 0.001$; field capacity $P < 0.001$; near dry $P < 0.001$). Water retention was generally less upon rewetting than initial saturation.

Substrate affected water retention when materials were rewetted especially at saturation and field capacity. Processed kimberlite held more water than lakebed sediment and crushed rock at saturation (statistically 100 % of comparisons) and field capacity (95 %). At near dry, the effect declined (70 %) although processed kimberlite continued to have the highest water retention, especially when hydrogel was applied dry/wet and at recommended rates. When applied at high rates at near dry, crushed rock tended to be statistically similar to processed kimberlite; at low rates, lakebed sediment was similar to processed kimberlite. At field capacity and near dry, lakebed sediment and processed kimberlite did not differ when no amendment was added, nor did crushed rock to processed kimberlite at near dry. Crushed rock and lakebed sediment had few significant differences (30 % of comparisons differed at saturation and 10 % at field capacity and near dry). Generally, crushed rock tended to have greater water retention at higher application rates and lakebed sediment at lower or no application.

Upon rewetting, application method had a limited effect except in processed kimberlite where wet/wet tended to have the lowest retention (Figure 3.2). Higher application rates resulted in greater water retention in crushed rock and processed kimberlite (Figure 3.2). Addition of hydrogel at any rate tended to increase water retention relative to no amendment though significance varied. Rate had a limited effect in lakebed sediment.

3.4 Amendment Experiment

There was significant interaction between substrate and treatment (amendment and rate) (saturation $P < 0.001$; field capacity $P < 0.001$; near dry $P < 0.001$).

Substrate affected water retention with processed kimberlite having higher retention than crushed rock and lakebed sediment at saturation (statistically 100 % of comparisons) and field capacity (95 %, no amendment did not differ from lakebed sediment). As substrates approached near dry, differences became less significant between processed kimberlite and lakebed sediment (statistically 36 % of comparisons), whereas processed kimberlite remained greater than crushed rock (82 %). Processed kimberlite held more water than crushed rock with all amendments except dry/dry, whereas it only held more than lakebed sediment in dry/wet and sewage. With hydrogel, crushed rock tended to have greater water retention than lakebed sediment, although statistical significance was reduced over time with only wet/dry double significant across the three time periods. Lakebed sediment tended to have greater retention than crushed rock with organic amendments and no amendment, except sewage, although by near dry only soil and peat recommended and no amendment were significantly greater.

Amendment selection altered water retention differently between substrates (Figure 3.3). Hydrogel generally resulted in greater water retention in crushed rock and processed kimberlite compared to organic amendments (except peat in processed kimberlite). In lakebed sediment, water retention showed little consistent effect of amendment, although peat tended to have the greatest water retention. Application rate was important for hydrogel treatments especially in crushed rock and processed kimberlite, with less variation in organic amendments (Figure 3.3). Generally, addition of amendments at any rate increased water retention in crushed rock and processed kimberlite relative to no amendment, whereas in lakebed sediment addition of amendment rarely increased water retention compared to no amendment.

4. DISCUSSION

Development of methods to increase water retention in anthroposols built from mine waste materials is essential for successful reclamation. Some clear trends emerged from this research showing the importance of substrate, amendment, hydrogel application method and amendment application rate in altering water retention for reclamation anthroposols.

4.1 Substrate

Substrate variability in water retention despite amendment amount, application rate and amendment type clearly shows its importance for anthroposol building. Using results of this research, good choices can be made to use substrate material alone or in mixes, with and without amendments.

Greater water retention in processed kimberlite relative to crushed rock and lakebed sediment is due to its composition of particles under 2 mm. At saturation, unamended processed kimberlite held approximately 25 % water by weight indicating high water retention even without amendments. Large amounts of coarse fragments in mine waste are common due to extraction and blasting, parent material and treatment of waste (Sheoran et al. 2010). Coarse fragments create large pores that cannot hold water, reducing water holding capacity; large rocks take up volume that would have been composed of mineral soil under 2 mm that primarily holds water (Saxton and Rawls 2006, Keller et al. 2010, Sheoran et al. 2010), as seen in crushed rock and lakebed sediment. Lakebed sediment has more fine textured material than crushed rock, resulting in greater pore space and surface area (Khaleel et al. 1981), leading to higher water retention than crushed rock when unamended. However, in the field, the finer texture of lakebed sediment may negatively impact water retention, as a high proportion of fine particles can result in poor structure, creating a hard, smooth surface which can reduce infiltration (Naeth and Wilkinson 2010, Sheoran et al. 2010, Martens 2012).

With hydrogel, water retention in crushed rock can be greater than in lakebed sediment. The hydrogel can fit into the large pores for maximum expansion and more held water. The high proportion of sand and large pores in processed kimberlite also facilitate hydrogel expansion. Expansion is essential for long term success of field applications as hydrogel needs to be rewetted through natural precipitation. Success under field conditions may be reduced in crushed rock as hydrogel crystals may slip into the gaps between rocks that are not accessible to plant roots (Rowe et al. 2005). Fine particles in the lakebed sediment may have restricted expansion of hydrogel, reducing water retention and effectiveness in this substrate. Abedi-Koupai et al. (2008) compared effects of hydrogel application on water retention in sandy loam, loam and clay, finding highest water content increases in sandy loam and least in clay, likely due to reduced expansion of the hydrogel. Saline conditions can reduce water uptake of hydrogel (Akhter et al. 2004) and lakebed sediment had the highest electrical conductivity of all the substrates.

The small increases found in lakebed sediment with amendment addition may be too small to be practical in the field, especially relative to greater increases in water retention in crushed rock and processed kimberlite with amendment addition. A more promising method in anthroposol construction may be to mix lakebed sediment with crushed rock or processed kimberlite to gain the best from each of the substrates.

4.2 Hydrogel Application Method

While substrates differ intrinsically in water holding capacity, methods to increase water retention are essential as use of waste materials is influenced by many factors beyond water holding capacity, including nutrient content, presence of metals and salts, availability and regulatory requirements. Hydrogel application research had previously focused on dry application (Johnson 1984, Akhter et al. 2004, Abedi-Koupai et al. 2008) whereas this research tested three strategies.

With initial wetting, dry/wet application was most successful since wetting hydrogel in advance allowed the crystals to expand to their maximum size without being impeded by the substrate.

Wet/wet application was less successful likely from loss of material due to challenges with mixing and hydrogel migration to the surface of the pots, especially in lakebed sediment, reducing crystal expansion with water when there is a lack of contact with the substrate. The rough and irregularly shaped pieces in crushed rock may have impeded hydrogel migration. Wet/wet application is difficult to scale up to an industrial level, limiting its effectiveness for large disturbances; dry/wet may have similar challenges. The reduced success of dry/dry application relative to dry/wet application may be due to the hydrogel expanding within the substrate, potentially limiting full expansion.

Rewetting hydrogel demonstrated there would likely be a limited effect of application method in the field. Although dry/wet still tended to be the most successful method, differences were smaller than with initial wetting. As pots were allowed to dry before rewetting, all of the treatments started the same. Small differences, especially with wet/wet having lower water retention, may be due to how the hydrogel originally settled in the pots, limiting its effectiveness. Overall, the limited effect of application method of hydrogel means method can be determined by what is industrially feasible, likely dry/dry application.

4.3 Amendment Selection

Effects on water retention of adding organic amendments relative to hydrogel is important for reclamation, especially knowing that the effectiveness varied with substrates. The greater increases in water retention with hydrogel, especially dry/wet, in crushed rock and processed kimberlite than lakebed sediment is likely due to the coarser textured substrates potentially allowing hydrogel to expand more, holding more water (Abedi-Koupai et al. 2008). Hydrogel can hold 40 to 500 times its weight in water, depending on type, size and chemical makeup (Johnson 1984, Akhter et al. 2004, Abedi-Koupai et al. 2008), with the primary goal of increasing available water and acting as a reservoir.

Organic amendments are commonly added to soil or substrates to address physical, chemical and biological limitations, rather than the single problem of low water holding capacity. Organic matter increases soil water and nutrient content, water and nutrient holding capacities and cation exchange capacity; improves soil texture and pH; and provides energy sources for microorganisms (Smith et al. 1987, Reid and Naeth 2005a, Drozdowski et al. 2012, Larney and

Angers 2012). Organic amendments, like peat, take up physical space, whereas hydrogel has to expand, which may result in greater water retention in lakebed sediment, although peat showed limited statistical differences from hydrogel indicating that all amendments had poor success in lakebed sediment. Peat has increased water holding capacity in many experiments (Smith et al. 1987, Martens 2002, Reid and Naeth 2005a, 2005b) and resulted in the greatest increase relative to other organic amendments in this research. The limited increase in water retention with sewage may have resulted from its form. The sewage was collected after being dewatered, which involved pressing between two belts to remove excess water. The sewage remained very wet and therefore may have had a reduced ability to take up large amounts of additional water. The limited increase in water retention with addition of soil may due to its low organic carbon content, relative to peat and sewage and the high proportion of sand (coarse fragments 28.9 %; sand 74.3 %, silt 20.7 % and clay 4.9 %).

While organic amendments hold water, their greatest influence on water holding capacity of the substrates will result from their effect on structure and aggregation (Smith et al. 1987). As microorganisms decompose the organic matter, products help form aggregates, which increase water holding capacity and improve infiltration and percolation (Smith et al. 1987, Sheoran et al. 2010). Therefore, organic amendments are likely to have a greater effect in the long term than hydrogel. While hydrogel showed a large increase in water retention in the short term of the experiments, its long term effectiveness is less. Hydrogel decreased in effectiveness over time in other studies due to degradation from environmental exposure (Akhter et al. 2004, Rowe et al. 2005). Rowe et al. (2005) found an 85 % reduction in water held after 42 months. In this research, all treatments held slightly less water between the initial wetting of the hydrogel and subsequent rewetting. However, increased water retention over the first few critical growing seasons may result in greater plant growth, which over time will increase organic matter content as plants die and decompose, improving soil structure.

4.4 Application Rate

The more important effect of application rate than application method for hydrogel, especially in crushed rock and processed kimberlite, is important for anthroposol building in reclamation. In other research, increasing the amount of hydrogel also increased the amount of water held (Akhter et al. 2004, Abedi-Koupai et al. 2008) as seen with crushed rock and processed kimberlite. The relationship was less clear in lakebed sediment as water retention was high even when no amendment was applied, although generally higher application rates slightly increased water retention. The reason for the low water retention of dry/wet hydrogel applied at a double rate in lakebed sediment compared to other treatments in lakebed sediment for the amendment experiment is unknown, however it demonstrates the uncertainty related to using hydrogel in lakebed sediment where the patterns are not as clear.

Determination of the appropriate application rate is influenced by several factors, including cost of material, amount available, depth of mixing and substrate. Many reclamation sites are remote, creating challenges for economically transporting large amounts of material to sites. Use of on site materials, such as sewage, topsoil or manure (depending on the site), reduces transportation costs, but supply may be limited for reclamation. Hydrogel represents an option for remote sites as it is easy to transport, small in volume and weight, though it may have a higher cost depending on the source of the organic materials.

4.5 Outstanding Questions And Recommendations

This research begins to address the challenge of increasing water retention in mine waste materials used for soil building in reclamation. Additional research to focus on outstanding questions will further the knowledge required for successful reclamation implementation. As these experiments were completed in the greenhouse, they had limited exposure to natural environmental conditions, such as temperature and precipitation. Hydrogel is estimated to last 3 to 5 years in soil (JRM Chemical Inc. 2012); however, mine waste materials may have chemical and physical properties that result in faster hydrogel breakdown and degradation. Harsh environmental conditions, including short summers, cold winters, frequent freeze-thaw cycles and extended periods of light in summer, may negatively affect both hydrogel (reduced ability to hold water as it breaks down) and organic amendments (slow decomposition limiting the positive effect on soil structure). In the field, substrates may not be saturated often due to short rainfall events, which could influence effectiveness of the amendments. Rowe et al. (2005) found that their hydrogel went from anhydrous to full capacity in 30 minutes when exposed to saturation by water. However, amendments, especially hydrogel, may not expand to their full capacity in partially saturated conditions common on mine sites. Increased water retention also only represents one factor required to build successful anthroposols for revegetation. Research is needed to compare the plant response for various plant species to both hydrogel and to the organic amendments in these substrates.

5. CONCLUSIONS

The addition of hydrogel and organic amendments has potential for building anthroposols for reclamation simply by its effects on water retention. Water retention was increased with use of amendments and varied with substrate materials. Processed kimberlite generally held the most water with and without amendments. A double application rate for both hydrogel and organic amendments resulted in greatest increases in water retention. Applying wet hydrogel to dry substrates resulted in the greatest initial increase in the amount of water held, but over time, there were only small differences. Dry hydrogel would be easiest to apply at an industrial scale. Differences among substrates showed that hydrogel resulted in the greatest increases in water retention in crushed rock and processed kimberlite, whereas lakebed sediment showed little increase with amendment addition, especially hydrogel, and was only slightly greater with peat.

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Table 3.1. Chemical properties of substrates and amendments.

Material	Cation Exchange Capacity (meq 100 g^{-1})	Electrical Conductivity (dS m^{-1})	Soil Reaction (pH)	Total Organic Carbon (%)
Crushed Rock	1.0 (0.1)	1.0 (0.0)	7.8 (0.0)	0.1
Lakebed Sediment	1.4 (0.1)	4.7 (0.1)	4.6 (0.0)	0.2
Processed Kimberlite	9.8 (0.3)	3.8 (0.0)	8.2 (0.0)	0.4
Peat	112.0 (7.0)	0.5 (0.0)	3.9 (0.0)	43.4
Sewage	69.8 (4.7)	5.9 (0.4)	6.1 (0.3)	28.6
Soil	13.3 (0.6)	1.9 (0.1)	4.5 (0.0)	2.7

Data are presented as means with standard errors in brackets.
Adapted from: Miller and Naeth 2017.

Table 3.2. Particle size of substrates.

Sieve Size	Crushed Rock (%)	Lakebed Sediment (%)	Processed Kimberlite (%)
19.0 mm	4.3 (1.4)	7.0 (1.8)	0.0 (0.0)
12.5 mm	14.3 (1.7)	6.0 (1.1)	0.0 (0.0)
9.5 mm	10.7 (0.9)	4.1 (0.4)	0.0 (0.0)
6.3 mm	8.8 (0.7)	5.9 (0.3)	0.0 (0.0)
4.0 mm	9.3 (0.4)	7.8 (0.5)	0.0 (0.0)
2.0 mm	11.1 (0.2)	11.5 (0.3)	0.5 (0.0)
1.0 mm	9.6 (0.2)	11.8 (0.2)	13.0 (0.7)
500 um	9.2 (0.2)	12.1 (0.3)	42.3 (1.2)
250 um	8.7 (0.2)	12.1 (0.4)	23.0 (0.7)
212 um	2.1 (0.2)	3.7 (0.1)	4.7 (0.2)
106 um	5.6 (0.2)	8.4 (0.3)	8.6 (0.5)
53 um	5.0 (0.3)	9.2 (0.5)	5.4 (0.4)
Pan	1.1 (0.1)	0.3 (0.1)	2.5 (0.2)

Data are presented as means with standard errors in brackets (n = 5).
Amounts for each sieve size represent the percentage by weight of material caught in that sieve.

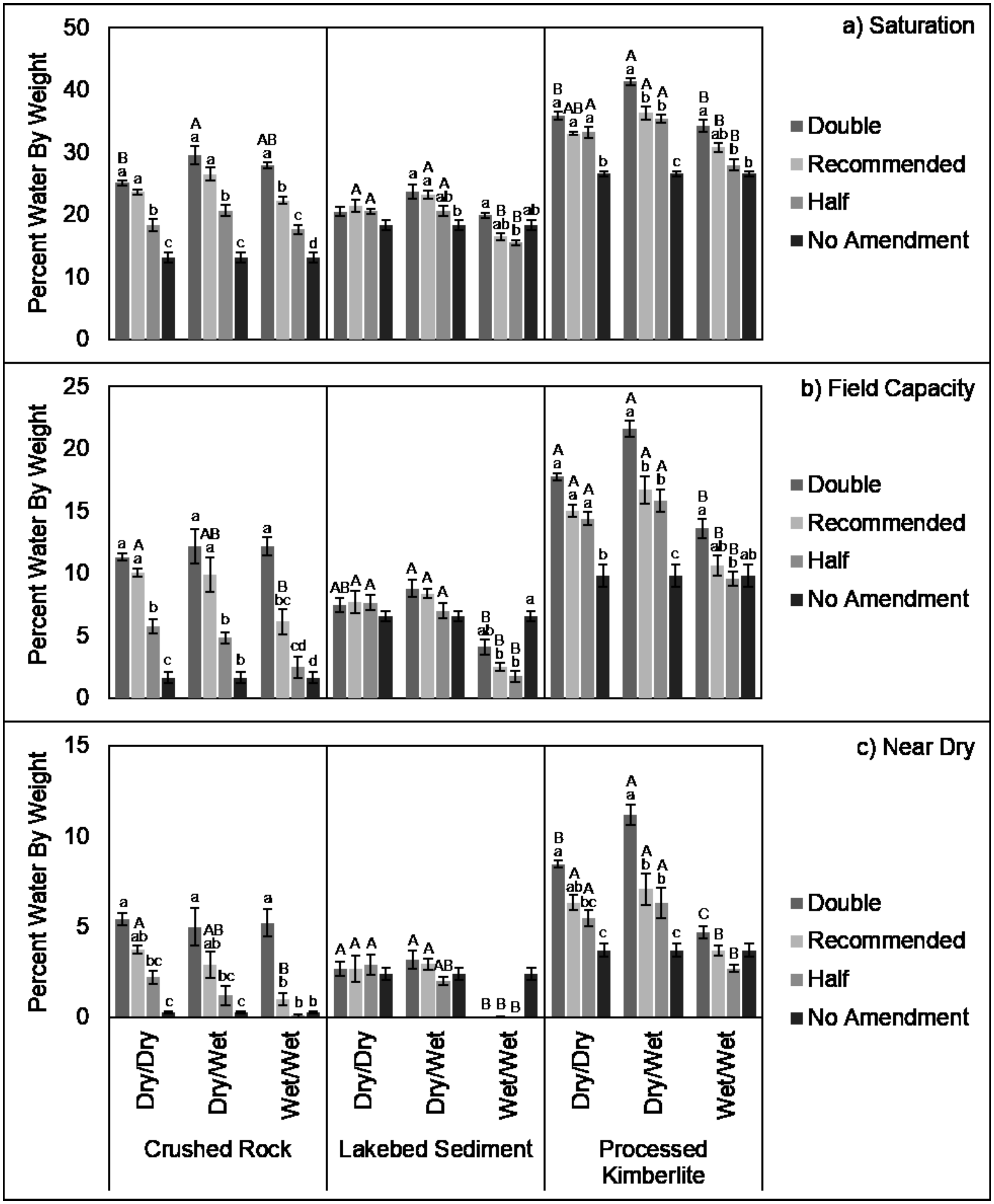

Figure 3.1. Mean percent water by weight for hydrogel experiment 1 (± standard error, n = 4). Lower case letters represent significantly different rates within a substrate and application method. Upper case letters represent significantly different application methods within a substrate and rate.

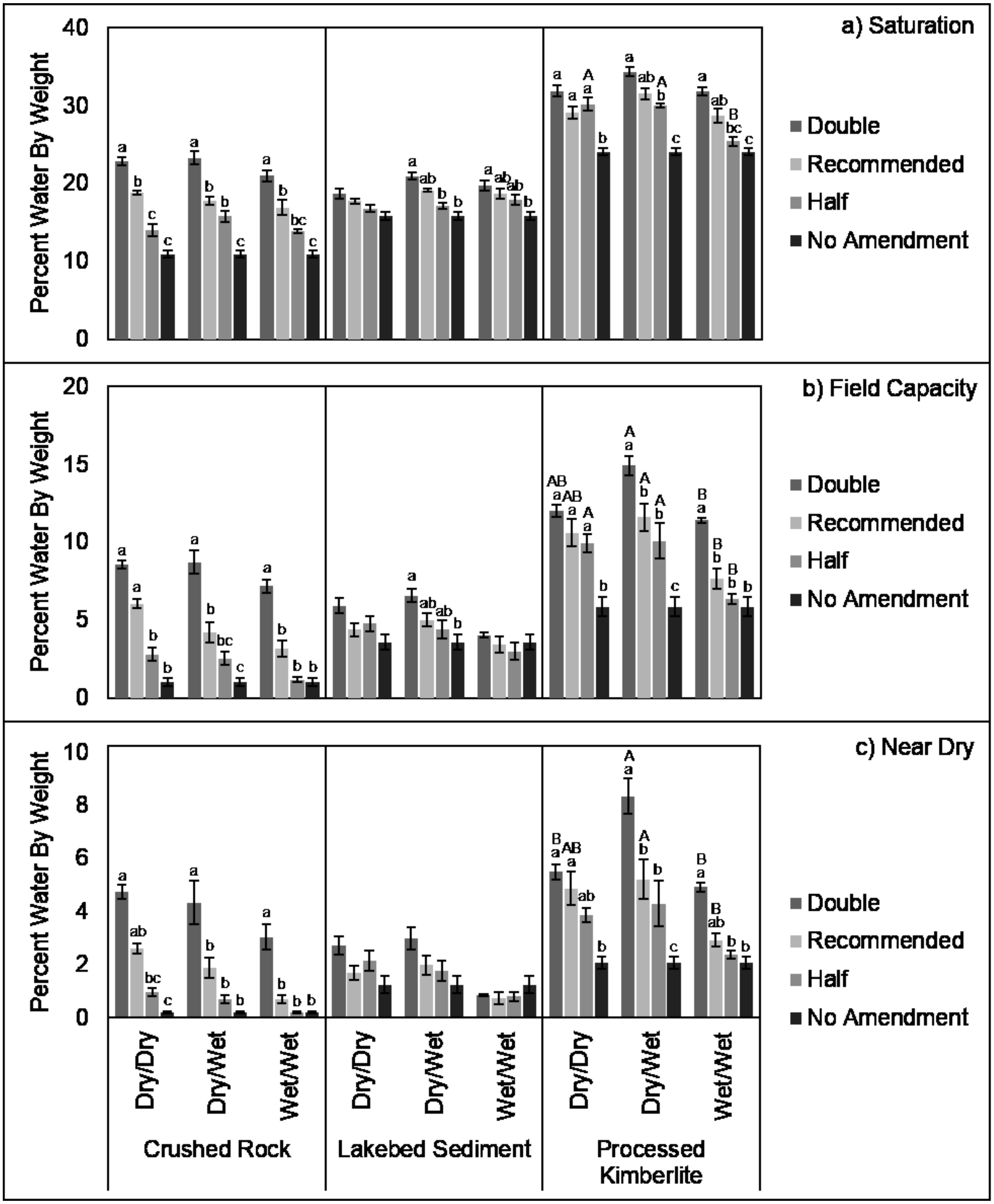

Figure 3.2. Mean percent water by weight for rewetting hydrogel experiment 2 (± standard error, n = 4). Lower case letters represent significantly different rates within a substrate and application method. Upper case letters represent significantly different application methods within a substrate and rate.

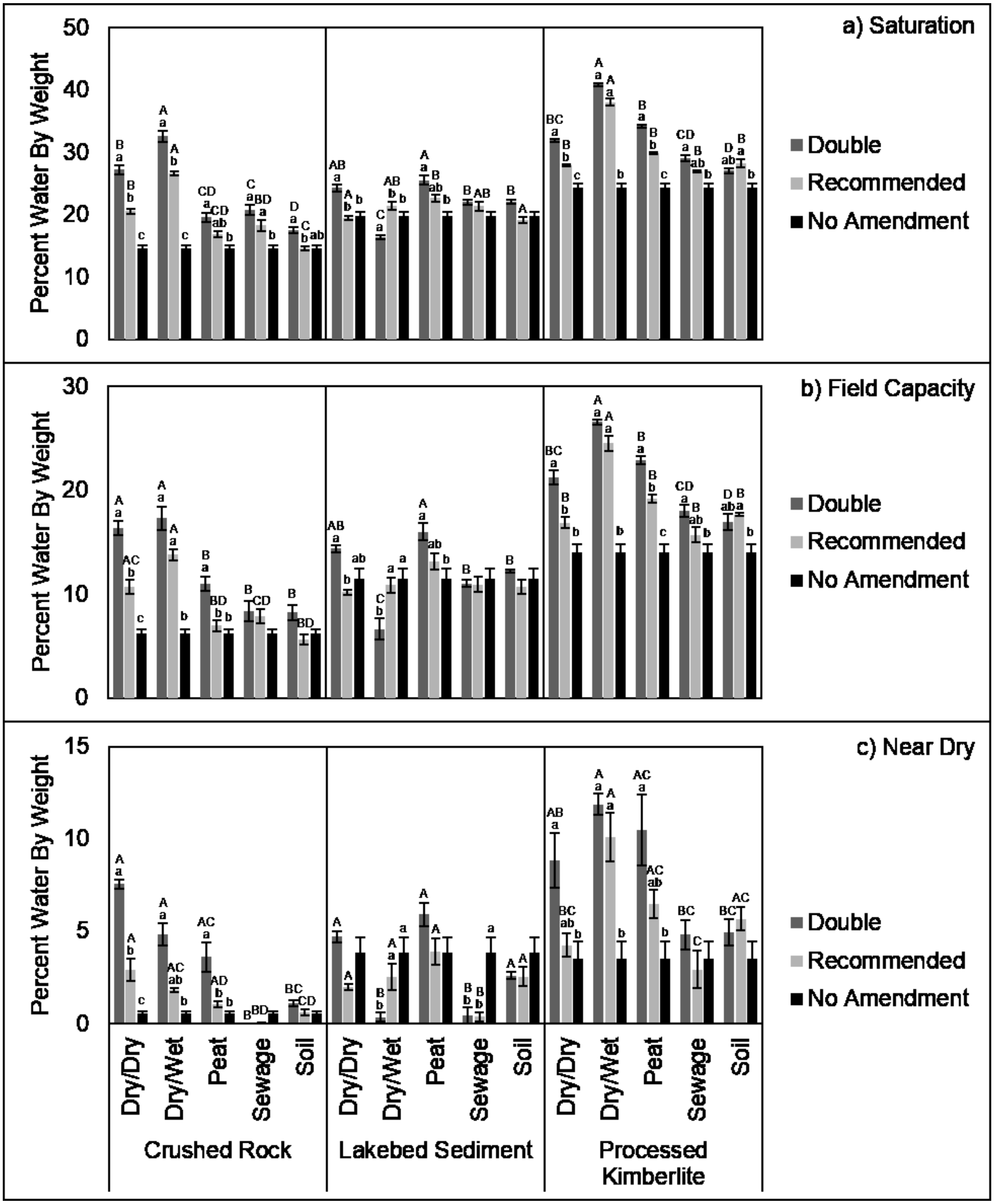

Figure 3.3. Mean percent water by weight for amendment experiment 3 (± standard error, n = 4). Lower case letters represent significantly different rates within a substrate and amendment. Upper case letters represent significantly different amendments within a substrate and rate.

IV. AMENDMENTS TO IMPROVE PLANT RESPONSE UNDER SIMULATED WATER LIMITED CONDITIONS IN DIAMOND MINE ANTHROPOSOLS

1. INTRODUCTION

Successful revegetation is essential for recovery of disturbed sites. However, limited soil availability for reclamation highlights the need for anthroposol building in most large scale disturbances. Building suitable anthroposols, soils altered by human activity or built for reclamation (Naeth et al. 2012), requires consideration of many factors, including water holding capacity, nutrients and structure. Industrial waste materials, such as crushed rock and overburden, can be used to build anthroposols when organic amendments are added to improve soil conditions (Sydnor and Redente 2002, Drozdowski et al. 2012, McGeehan 2012, Miller and Naeth 2017). Organic amendments commonly include waste materials such as manure and sewage; peat and topsoil which may be removed during disturbances such as mining; and crop by-products such as straw.

Water limitation is a common challenge for revegetation in disturbed areas (Bell and Bliss 1978, 1980, Jorgenson and Joyce 1994, Akhter et al. 2004). Removal or burial of soil and organic layers can expose subsoil or parent materials with limited water holding capacity due to poor structure and low organic matter content. Waste materials produced in mining or other disturbances, such as crushed rock, tend to have low water holding capacity due to large amounts of coarse fragments and low organic matter (Cooke and Johnson 2002, Saxton and Rawls 2006, Sheoran et al. 2010). For example, Drozdowski et al. (2012) found gravel never held more than 5 % volumetric water throughout the growing season regardless of the amendment. Disturbances in the north have additional water limitation challenges as precipitation tends to be low during the growing season, except for snow melt in spring.

Addressing water limitation during anthroposol building must be balanced with meeting other plant and site needs. Suitable soil structure, considering texture and bulk density, increases water holding capacity and is important for plant establishment and root development. Organic matter provides nutrients, improves soil structure and infiltration, increases water and nutrient holding capacity and may introduce important microorganisms for decomposition to barren materials (Johnson et al. 1994, Sheoran et al. 2010, Larney and Angers 2012). Nutrients, such as nitrogen and phosphorus, are essential for plant growth and decomposition and nutrient cycling in the north is slow (Billings 1987, Johnson 1987, Forbes and Jefferies 1999).

Additional challenges are related to remote location which can limit transportation of materials not available on site (Larney and Angers 2012) and sourcing materials which can create additional disturbances. Use of polyacrylamide gels, or hydrogel, is becoming more common in agriculture and reclamation to improve plant water supply in a growth medium as they can hold 40 to 500 times their weight in water (Johnson 1984, Holliman et al. 2005). Although it is an easily transported material for remote locations relative to organic amendments such as manure or peat, plant response is inconsistent (Akhter at al. 2004, Rowe et al. 2005). Factors that may be effective for plant growth and establishment may not be for seed germination. Thus the objective of this research was to assess effectiveness of inorganic and organic amendments to mine waste materials, or substrates, to increase plant emergence and growth under water limited conditions as commonly experienced in disturbed sites.

2. MATERIALS AND METHODS

2.1 Substrates And Amendments

Substrates were collected from Diavik Diamond Mine, Northwest Territories, Canada, (latitude 64˚30’41’’, longitude 110˚17’23’’). Processed kimberlite, lakebed sediment (or till) and crushed rock are the primary waste materials produced during mining and were used as base materials or substrates for anthroposols. Amendments were selected based on effectiveness in previous experiments, availability in remote northern sites and ease of transport, application methods and scalability. Amendments were sourced from Edmonton or Diavik Diamond Mine. Soil Moist is a synthetic acrylic cross linked polyacrylamide with a potassium salt base (hereafter hydrogel) that absorbs water and releases it as soils dry (JRM Chemical Inc. 2011, 2012). Treated sewage sludge (hereafter sewage) and soil were sourced from Diavik Diamond Mine and peat was purchased in Edmonton from a commercial supplier (Premier Horticulture Inc.). Basic material properties (Table 4.1) were described in detail in Miller and Naeth (2017).

2.2 Greenhouse Procedures

The experiments evaluated 3 substrates x 16 treatments (3 application rates x 5 amendments and a control of unamended substrate), replicated 4 times for the emergence experiment and 5 times for the plant growth experiment. Emergence and plant growth were evaluated separately as they may respond differently to amendments. As germination cannot be monitored within pots, emergence of seedlings was assessed. Pots for the emergence experiment were randomly placed in a tray in the greenhouse using a complete randomized design. For the plant growth experiment, 1 replicate of pots was placed per tray to account for variation in the greenhouse using a complete randomized block design.

Three application rates were used: the recommended rate at 0.35 kg m^{-3} for hydrogel and 10 % by volume for organic amendments, then half and double the recommended rates. The recommended rate for hydrogel was based on volume of material in the pots (determined using the application rate from JRM Chemical Inc. (2012) and a reasonable field application depth). The 10 % of volume application rate of organic amendments was considered feasible for field application for reclamation. Five amendments were dry substrate and dry hydrogel mixed (hydrogel/dry), dry substrate and wet hydrogel mixed (hydrogel/wet), peat, sewage and soil. Wet or dry hydrogel will impact application feasibility and may impact plant and seed response, so both were assessed.

For the emergence experiment, 7 cm tall and 8 cm diameter round pots were used. For the plant growth experiment, 12 cm tall and 11 cm diameter round pots were used. Two layers of landscape fabric were placed in the bottom to reduce material loss. Amendments were mixed with substrates at appropriate ratios to build anthroposols and placed in pots. For hydrogel/wet, hydrogel was saturated for 24 hours then excess water drained prior to mixing with substrate. Pots were saturated by repeatedly applying water to the surface and allowing 24 hours of drainage prior to planting. For the emergence experiment, pots were planted with 15 slender wheat grass (*Elymus trachycaulus* (Link) Gould ex Shinners ssp. *trachycaulus* Adanac) seeds (germination 76 %); for the plant growth experiment, pots were planted with 12 *Elymus trachycaulus*. Seeds were covered with a thin layer of anthroposol.

For the emergence experiment, water stress was induced by dampening pot surfaces with water every four days, so the pots were dry between waterings. For the plant growth experiment, pot surfaces were dampened with water daily for the first two weeks to ensure successful germination. After two weeks, pots were watered with 100 mL once per week. Based on prior research, 100 mL per week was considered adequate to induce water limitation conditions. There were no represented heavy rainfall events, only minor rainfall events with the watering regime. At Diavik Diamond Mine, annual precipitation averages 306 mm (242 to 413 mm) with approximately 45 % as rainfall (Diavik Diamond Mine Inc. 2012). Rainfall is highest in August and September, with little rain in June and July when plants are germinating and establishing. The plant growth experiment ran for 8 weeks and the emergence experiment ran for approximately 8 weeks until no further emergence was observed. Greenhouse conditions were set to 20 °C with 18 hours of daylight.

2.3 Vegetation Measurements

Pots for the emergence experiment were monitored daily for two and a half weeks, followed by every two to four days. Emerged seedlings were counted then removed. During monitoring, seeds were reburied if they were on the surface.

For the plant growth experiment, number of emerged plants, including dead plants, was assessed daily for 2 weeks, and every 2 to 3 days thereafter. At 4 weeks, emergence and survival were monitored weekly. At 4 weeks, number of plants, height, health and physiological stage were assessed. At 8 weeks, number of plants, height, health, number of leaves and above and below ground biomass were assessed. Height, health, stage and number of leaves were assessed for each plant. Maximum plant height was measured to the nearest millimetre using a ruler. Plant health was visually assessed and scored using a five point scale (1 = healthy; 5 = dead). Physiological development was assessed using condensed Zadoks stages (Zadoks et al. 1974); stage was not assessed at eight weeks as plants were in a narrow developmental range; instead number of leaves were counted. Above ground biomass was collected by clipping plants at ground level. Below ground biomass was determined by separating roots from the anthroposol and washing gently under running water in a soil sieve to reduce root loss. Biomass was oven dried for 48 hours at 80 °C then weighed.

2.4 Data Analyses

Number of plants emerged by 34 days (representing mid peak emergence), 37 days (peak emergence) and 58 days (total emergence) was calculated and assessed. For the plant growth experiment, individual plant height, health, stage and number of leaves was averaged to represent the pot. Variables were statistically assessed at week 8. Data were analyzed with R Studio 3.4.0 (2017). Density (alive vs dead; $\rho = -0.5338$, $P = 0.0000$) and growth variables (height, number of leaves, above and below ground biomass; $\rho > 0.6068$, $P = 0.0000$) were correlated based on Spearman rank correlation with a Holm-Bonferroni correction, therefore select variables (number of live plants, above ground biomass, health) were selected for assessment based on strength of visual trends, quality of data and strong correlations. Below ground biomass and number of dead plants patterns were briefly described as visual trends. Data were evaluated for normality and homogeneity of variance; differences between substrate and treatments (amendment and rate) were assessed using a two way analysis of variance. The growth experiment was assessed using a mixed model with block as a random factor. Above ground biomass was log 10 transformed to improve normality and homogeneity of variance. Tukey post hoc analyses were completed to test a priori comparisons with a p value of 0.05.

3. RESULTS

3.1 Emergence Experiment

Under water limitation, emergence was poor initially then sharply increased between 31 and 37 days, reaching a plateau around 5.5 weeks (Figure 4.1). Crushed rock and processed kimberlite showed emergence prior to this, unlike lakebed sediment (except in a few treatments such as sewage double). Final emergence averaged 43.3 % (Table 4.2). At the three time periods, significant interactions between substrate and treatment (amendment and rate) occurred (34 days, $P = 0.0009$; 37 days, $P = 0.0091$; 58 days, $P = 0.0160$). Despite significant interactions, there were few differences between treatment comparisons of interest.

Emergence was significantly affected by substrate, tending to be higher in crushed rock and processed kimberlite relative to lakebed sediment, especially when amended with hydrogel (Figure 4.2). With organic amendments, differences were less, but emergence still tended to be greater in crushed rock and processed kimberlite. Without amendments, emergence was highest in processed kimberlite and lowest in lakebed sediment. Emergence tended to occur in lakebed sediment after watering events, when the surface was not as compacted as when dry.

Amendment did not significantly impact emergence in most cases and patterns were inconsistent among substrates. Significant differences were limited to processed kimberlite in the early time periods. At 34 days, hydrogel/wet double had greater emergence than soil double and hydrogel/wet half greater than peat half; at 37 days at the double rate, hydrogel/wet and peat had greater emergence than soil. Generally, hydrogel was among the treatments with greater emergence in processed kimberlite and lower emergence in lakebed sediment, whereas organic amendments varied. Crushed rock showed inconsistent patterns and tended to have small differences at lower application rates.

Amendment rate had a limited significant effect on emergence. Significant differences were limited to crushed rock amended with hydrogel/dry where double had greater emergence than no amendment at all time periods and recommended rate at 34 days. Emergence tended to be higher with double application rate, especially in crushed rock, though not significantly (Figure 4.2). Unamended crushed rock and lakebed sediment were visually the least effective treatments, with addition of amendments resulting in increased emergence in most cases; unamended processed kimberlite was more variable.

3.2 Plant Growth Experiment

Most emergence occurred after 5 to 13 days when pots were dampened daily, with a sharp increase in crushed rock and processed kimberlite (Figure 4.3). Emergence was slow in lakebed sediment, peaking at 29 days (Figure 4.3). No clear differences in emergence timing occurred with treatments, except in lakebed sediment where emergence was fastest in sewage double. Final emergence averaged 71.8 %, higher than that under water limitation (Table 4.2). A significant interaction occurred with substrate and treatment (amendment and rate) for number of live plants ($P = 0.0212$) and above ground biomass ($P < 0.0001$). Plant health was significantly affected by substrate ($P = 0.0000$) and treatment ($P = 0.0000$), declining between weeks 4 and 8.

Number of live plants was highest in processed kimberlite and lowest in lakebed sediment, though only in certain treatments (Figure 4.4). Few dead plants occurred in processed kimberlite (15.0 % of pots had dead plants, 13 dead plants overall), with more in crushed rock (41.3 % of pots, 118 overall) and lakebed sediment (63.8 % of pots, 92 overall). Crushed rock had individual treatments with the highest number of dead plants relative to processed kimberlite and lakebed sediment (data not shown).

Above ground biomass was greatest in crushed rock and processed kimberlite, especially with organic amendments (Figure 4.5). Below ground biomass was not statistically assessed due to small masses, although it was highest in crushed rock and processed kimberlite with 58.9 % and 76.3 % of pots having measurable biomass, respectively; it was lowest in lakebed sediment with 16.3 % of pots having measurable biomass (data not shown). Overall below ground biomass was less than 0.11 g, with most substrate and treatment combinations less than 0.05 g.

Plants were significantly healthier in lakebed sediment than crushed rock and processed kimberlite which did not differ, although differences were small (Figure 4.6). No plants reached seed production stage.

Amendment had a limited effect on number of live plants, with significant differences only at double application rates. In crushed rock, there were more plants with sewage than hydrogel (wet or dry) and more in peat and soil than hydrogel/wet double (statistically 40 % of comparisons at double). In lakebed sediment, sewage only had more plants than hydrogel/dry double (10 % at double) and there were no significant differences in processed kimberlite. Amendment rate had no effect in lakebed sediment or processed kimberlite between rates or no amendment. In crushed rock with hydrogel/wet, only double had significantly fewer plants than recommended or no amendment. Processed kimberlite had the highest number of dead plants in no amendment, although overall there were few. In crushed rock and lakebed sediment, hydrogel treatments tended to have the most dead plants, and no amendment in crushed rock.

Above ground biomass increased with organic amendments, especially sewage and in crushed rock. In all substrates, biomass was greater with sewage than other amendments at all rates (statistically 100 % of comparisons). At double rate, biomass was greater with peat and soil than hydrogel wet or dry in crushed rock, and greater with soil than hydrogel in processed kimberlite. In crushed rock, biomass was greater with peat than hydrogel wet or dry at the recommended rate and hydrogel/wet at half rate. Rate significantly affected biomass for organic amendments, especially sewage, with higher rates resulting in greater biomass. In all substrates, biomass increased with sewage at all rates relative to no amendment and was greater with double than half. In lakebed sediment and processed kimberlite, biomass was greater in sewage double than recommended; in crushed rock it was higher with sewage recommended than half. Significant differences with other amendments were limited to crushed rock and processed kimberlite. In crushed rock, biomass was greater with peat at all rates and soil double than no amendment. In processed kimberlite, biomass was greater with soil double than no amendment or half. With hydrogel, biomass did not differ with rate or no amendment. Sewage had a similar effect on below ground biomass, which was lowest with no amendment and hydrogel.

Amendment had limited significant effects on plant health (Figure 4.6). At double rate, plants were healthier with all organic amendments than hydrogel. There were no significant differences at lower rates, although plants were in poorest health with hydrogel and healthiest with sewage. Rate had no significant effect on health, although adding double soil and sewage resulted in significantly healthier plants than no amendment (Figure 4.6). While differences were small and not significant, all rates of hydrogel had similar or less healthy plants than no amendment, whereas organic amendments at any rate improved health relative to no amendment.

4. DISCUSSION

Although water limitation is a major challenge in revegetation of disturbed sites where anthroposols are built, solely focusing on it may not improve vegetation response. This research highlights the importance of substrate and amendment selection for emergence and plant growth. Emergence was strongly influenced by substrate selection with limited effects of amendment, whereas growth and survival were impacted by both substrate and amendment, especially sewage.

4.1 Substrate

Emergence success of processed kimberlite may be due to greater water retention with or without amendments relative to crushed rock and lakebed sediment (Miller and Naeth 2019), improving conditions for emergence. While unamended crushed rock tends to have low water content (Miller and Naeth 2019), larger particles create crevices and gaps where seeds can fall and water can collect, providing small safe sites for germination and emergence (Jumpponen et al. 1999). Bishop and Chapin III (1989a) found unamended gravel pads had sufficient water and nutrients for germination and survival. Drozdowski et al. (2012) found successful establishment and initial growth on unamended gravel, although Naeth and Wilkinson (2014) found reduced establishment and low cover over time. More dead plants in unamended crushed rock relative to other substrates and organically amended crushed rock raises concerns about long term suitability of this reclamation material and the importance of organic amendments.

Lakebed sediment holds more water than crushed rock when unamended due to finer texture (Larney and Angers 2012, Miller and Naeth 2019). However, this results in a hard material when dry (Sheoran et al. 2010), slowing germination and reducing seedling emergence and number of seedlings (Jumpponen et al. 1999). Drozdowski et al. (2012) found poor plant establishment after 2 years on unamended lakebed sediment and Naeth and Wilkinson (2014) found the same after 5 years, likely due to the fine texture. The tendency of lakebed sediment to have the fewest and smallest plants regardless of treatment indicates amendments may not address all challenges, and even with amendments, water retention may not be improved (Miller and Naeth 2019). Combining lakebed sediment with crushed rock or processed kimberlite may improve substrate structure through reduction of fine materials causing compaction.

Where water limitation was not introduced until after emergence, quicker germination, emergence and initial preferable growing conditions, including greater water availability and/or less compaction, resulted in larger plants in crushed rock and processed kimberlite. Even with frequent watering during germination and emergence, the hardness of lakebed sediment may reduce growth as roots are slower to establish and access water and nutrients (Sheoran et al. 2010) relative to the more coarsely textured crushed rock and processed kimberlite, resulting in smaller plants. Over time, as plants establish and grow in lakebed sediment, it may become more suitable as fine texture materials can have higher water content (not seen in Miller and Naeth 2019, although it may be due to the coarse fraction) and nutrient holding capacity. Williamson et al. (2011) found adding a layer of fine glacial till over waste rock improved plant growth. However, with a short growing season, delays in germination, emergence and growth can present challenges as water from snow melt will become less available and time for growth, especially of roots, will be reduced. In the arctic, root development is essential as plants depend on carbohydrate storage in a large root network for winter survival; root growth improves access to water and nutrients through greater surface area exploration (Curtis and Claassen 2005, Sheoran et al. 2010). Low root development in all substrates, especially lakebed sediment, represents a challenge for successful reclamation. No plants reached seed production, creating another issue; in the north, seed production can take multiple seasons due to limited resources (Billings 1987).

Declining plant health may be due to water or nutrient limitation becoming a greater challenge as plants grew larger, requiring more resources. In the north, the growing season is two to three months, therefore survival over that time is essential. Although differences were small, healthier plants in lakebed sediment may be due to delayed germination and emergence resulting in plants being younger and smaller, with less water and nutrient requirements, and not as stressed as older plants in crushed rock and processed kimberlite.

The success of processed kimberlite as a growth medium was unexpected due to previous poor performance (Drozdowski et al. 2012, Miller and Naeth 2017) and observations of growth at field sites at Diavik Diamond Mine. Water limitation created improved conditions for processed kimberlite as it retains more water than crushed rock and lakebed sediment due to its lack of coarse material (Keller et al. 2010, Sheoran et al. 2010, Miller and Naeth 2019). Long term vegetation response at field sites may not reflect greenhouse results; while lakebed sediment and crushed rock have large coarse components, there will be more material available for plants to draw water from. The dark colour of kimberlite may result in greater evaporation of water than in the greenhouse due to direct sun exposure, long days and erosion prone material constantly shifting. Processed kimberlite's serpentine chemistry and elevated metals (barium, chromium, cobalt and nickel, Miller and Naeth 2017) may also represent challenges long term.

4.2 Amendment And Rate

The lack of impact of amendments on emergence under water limited conditions relative to that of substrate implies substrates provide most limiting factors (water, resources, suitable conditions) for germination and emergence regardless of amendment. Number of live plants over time was similar to emergence, although increased with organic amendments, especially in crushed rock. Organic amendments can improve soil structure and take up physical space for water holding (Zabinski and Cole 2000) relative to hydrogel. High rates of sewage increased plant number; sewage may provide immediate improvement of substrate structure and nutrient availability, resulting in greater plant survival. Lack of impact of rate on emergence and number of plants indicates a limited impact of amendment. However, in crushed rock and lakebed sediment, poor success of no amendment implies that while differences were rarely significant, amendments at any rate improved establishment and survival.

Plant growth was strongly influenced by amendment selection. Growth tends to be limited by nutrient availability, whereas germination, and subsequently emergence, is more strongly affected by water availability (Bishop and Chapin III 1989a). Larger and healthier plants with organic amendments, especially sewage, shows addressing both nutrient and structural limitations are essential for successful vegetation response (Reid and Naeth 2005b); organic amendments address many of these limitations, whereas materials such as hydrogel only address water limitation. On quarry waste rock, treatments that only addressed water holding capacity or nutrient supply were not successful relative to addition of organic wastes which improved both, resulting in greater growth (Williamson et al. 2011). Sydnor and Redente (2002) found improved root establishment in acidic mine waste when amended with organic amendments relative to unamended waste.

Sewage tends to have a low carbon to nitrogen ratio resulting in readily available nutrients which plants can use for short term growth (Sort and Alcañiz 1999, Larney and Angers 2012). Due to limited nutrient availability in northern ecosystems, amendments with available nutrients, such as sewage or fertilizer, result in increased growth (Forbes and Jefferies 1999, Reid and Naeth 2005b, Drozdowski et al. 2012, Miller and Naeth 2017) although many northern species are adapted to low nutrient conditions (Billings 1987). High concentrations of nutrients may support weed species, especially grasses, and slow native vegetation response due to competition (Forbes and Jefferies 1999, Sort and Alcañiz 1999, Krautzer et al. 2012, Larney and Angers 2012). Long term sewage tends to be more successful than fertilizer as it adds organic matter leading to improved soil structure and water and nutrient holding capacity, with a reduced risk of rapid nutrient loss on sites with limited vegetation (Reid and Naeth 2005b, Larney and Angers 2012). Depending on treatment, sewage may have elevated metals (Miller and Naeth 2017) and bacteria (Reid and Naeth 2005a), although bacteria tend to decrease rapidly in cold temperatures (Edmonds 1976, Drozdowski et al. 2012), and metals are dependent on adsorption with organic matter and potential uptake by plants.

Peat and soil improved growth as in other research (see Reid and Naeth 2005b, Drozdowski et al. 2012), although less than sewage. Peat contains large amounts of organic matter and nutrients with increased effectiveness long term, as a high carbon to nitrogen ratio can limit short term nutrient availability (Reid and Naeth 2005b). Zabinski and Cole (2000) found peat improved soil structure by creating spaces for water and root growth. Soil is similar as organic matter decomposes slowly; the soil used here had low organic carbon likely due to long term stockpiling. Soil can be a source of seeds and vegetative propagules, although stockpiling can reduce viability (Mackenzie and Naeth 2019). Naeth and Wilkinson (2014) found soil increased species diversity, with limited effects on nutrient availability relative to sewage or fertilizer.

Use of small amounts of sewage to improve plant growth is a benefit as large remote disturbances have limited availability of materials. Many mines lack organic material for reclamation (Sheoran et al. 2010); use of waste materials reduces waste management, storage or disposal (McGeehan 2012) and disturbances to source nonlocal natural materials. Higher applications of peat and soil are required to approach the effect of sewage, although soil and peat are likely to have longer term effects than sewage due to slower decomposition, potentially improving vegetation response over time. Adding fertilizer or high nutrient waste materials, such as sewage, to peat and soil may improve the carbon to nitrogen ratio while addressing soil structure and longer term nutrient availability (Reid and Naeth 2005b). While organic amendments increased growth, plants were overall smaller than Miller and Naeth (2017) found, although it cannot be determined whether smaller plants were due to amendment rates, growth period or water limitation.

Hydrogel did not improve plant growth, indicating that alone it is not a useful material for anthroposol building in sites like Diavik. While hydrogel increased water retention (Miller and Naeth 2019), it does not provide nutrients or improve soil structure and has had variable effects on vegetation response. Akhter et al. (2004) found hydrogel had no effect on the number of seedlings, but increased growth of *Hordeum vulgare* L. (barley) and *Triticum aestivum* L. (wheat) in sandy loam and loam soils, whereas the number of seedlings of *Cicer arietinum* L. (chickpea) improved only at some levels of hydrogel addition and growth differences were not significant. Sarvaš et al. (2007) found increased survival of *Pinus sylvestris* L. (scots pine) seedlings at one site with hydrogel, but not at a second site. Rowe et al. (2005) found that pocket planting trees in blocky quarry waste with hydrogel or slate processing fines improved growth, but only fines increased survival; addition of fertilizer in all treatments may have contributed to higher growth due to better retention of nutrients than if unamended. Hydrogel in planting pockets is becoming common for reclamation (Rowe et al. 2005, Sarvaš et al. 2007, Williamson et al. 2011), but root growth may be limited to the amended area (Rowe et al. 2005). Hydrogel in coarse materials can have reduced effectiveness due to movement of crystals to areas unavailable to plants (Rowe et al. 2005). Water holding capacity of hydrogel degrades rapidly; approximately 85 % reduction in 18 months (Holliman et al. 2005) and 42 months (Rowe et al. 2005). Hydrogel can be degraded through mechanical breakage and UV exposure creating free radicals and breaking bonds, reducing its water holding capacity (Caulfield et al. 2002, Holliman et al. 2005); salinity can reduce the ability of hydrogel to swell (Molloy et al. 2000, Akhter et al. 2004). Assessment of hydrogel combined with other materials such as fertilizer or sewage to address nutrient limitations is an important next step to determine its usefulness for anthroposol building in remote mine sites. In some studies hydrogel moved to the surface (Holliman et al. 2005, Miller and Naeth 2019) which can reduce its effectiveness as exposure can result in breakdown of hydrogel, evaporation of water and reduced access by plants to water. The cause of hydrogel migration is unknown and therefore difficult to assess if it would occur under field conditions.

Limited differences between hydrogel application methods on vegetation response indicates it does not play a major role. Dry application is easiest at an industrial scale, but limited precipitation after placement may impact success (Sarvaš et al. 2007), whereas wet application immediately provides water.

4.3 Outstanding Questions And Reclamation Applications

Assessment of lakebed sediment combined with crushed rock or processed kimberlite, combining hydrogel with organic amendments or fertilizer, and combining slower decomposing organic matter with fast decomposing are important next steps to address limitations of materials in this research. Extension of these experiments to the field is necessary as precipitation patterns are variable, natural variation in surface impacts where water collects and larger tests plots are essential to create realistic growth mediums with more space for water and nutrient uptake. Sheoran et al. (2010) estimated that 0.9 to 1.2 m of non-compacted growth medium is needed to meet vegetation water needs in water limited conditions. Limited root growth is of concern for revegetation in northern environments due to the importance of roots for winter survival, so assessments should include additional treatments or longer experimental periods to determine if root growth increases. Experiments spanning multiple years are essential to assess if vegetation is improving soil conditions through organic matter additions from litter and roots (Jorgenson and Joyce 1994, Rowe et al. 2005, Sheoran et al. 2010). Response of alternative vegetation types (shrubs, forbs, mosses) to successful anthroposols will inform northern revegetation strategies due to their importance in these ecosystems.

Under water limitation, crushed rock and processed kimberlite were more successful than lakebed sediment, resulting in faster emergence, higher densities and larger plants. Due to concerns about processed kimberlite, crushed rock is the most suitable substrate although amending is essential. Organic amendments, especially sewage, increased plant growth. Sewage applied at any rate increased growth relative to no amendment, whereas other organic amendments tended to require high rates, which may be a challenge where material availability is limited. Increasing application rate tends to increase growth, although final rate determination may be influenced mainly by material availability. Hydrogel alone does not improve plant response, although combined with fertilizer or available organic materials it may be more successful. Hydrogel does represent a material that can be easily transported to remote sites although there are higher purchase costs than organic amendments available from on site.

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Table 4.1. Chemical and physical properties of substrates and amendments.

Property	Crushed Rock	Lakebed Sediment	Processed Kimberlite	Peat	Sewage	Soil	Guidelines[1]
Cation Exchange Capacity (meq 100 g^{-1})	1.0 (0.1)	1.4 (0.1)	9.8 (0.3)	112.0 (7.0)	69.8 (4.7)	13.3 (0.6)	>3
Electrical Conductivity (dS m^{-1})	1.0 (0.0)	4.7 (0.1)	3.8 (0.0)	0.5 (0.0)	5.9 (0.4)	1.9 (0.1)	<1
Soil Reaction (pH)	7.8 (0.0)	4.6 (0.0)	8.2 (0.0)	3.9 (0.0)	6.1 (0.3)	4.5 (0.0)	5.0
Total Organic Carbon (%)	0.1	0.2	0.4	43.4	28.6	2.7	>1
Particle Size[2,3]							
19.0 mm (%)	4.3 (1.4)	7.0 (1.8)	0.0 (0.0)				
12.5 mm (%)	14.3 (1.7)	6.0 (1.1)	0.0 (0.0)				
9.5 mm (%)	10.7 (0.9)	4.1 (0.4)	0.0 (0.0)				
6.3 mm (%)	8.8 (0.7)	5.9 (0.3)	0.0 (0.0)				
4.0 mm (%)	9.3 (0.4)	7.8 (0.5)	0.0 (0.0)				
2.0 mm (%)	11.1 (0.2)	11.5 (0.3)	0.5 (0.0)				
1.0 mm (%)	9.6 (0.2)	11.8 (0.2)	13.0 (0.7)				
500 um (%)	9.2 (0.2)	12.1 (0.3)	42.3 (1.2)				
250 um (%)	8.7 (0.2)	12.1 (0.4)	23.0 (0.7)				
212 um (%)	2.1 (0.2)	3.7 (0.1)	4.7 (0.2)				
106 um (%)	5.6 (0.2)	8.4 (0.3)	8.6 (0.5)				
53 um (%)	5.0 (0.3)	9.2 (0.5)	5.4 (0.4)				
Pan (%)	1.1 (0.1)	0.3 (0.1)	2.5 (0.2)				

Data are presented as means with standard errors in brackets.
Adapted from: Miller and Naeth 2017, 2019.
[1]Guidelines are based on generally accepted reclamation values (Soil Quality Criteria Working Group 1987), baseline data and results from research in the area (Reid and Naeth 2005b, Drozdowski et al. 2012, Naeth and Wilkinson 2014).
[2]Amounts presented for each sieve size represent the percentage of material caught in that sieve.
[3]Soil was not assessed for all sieve size; previous analysis found coarse fragments 28.9 %; sand 74.3 %, silt 20.7 % and clay 4.9 % (Miller and Naeth 2017).

Table 4.2. Percent emergence between substrates in emergence and growth experiments.

Variable	Emergence (%)[3]		
	Crushed Rock	Lakebed Sediment	Processed Kimberlite
Emergence Experiment[1]			
Minimum	26.7	11.7	33.3
Maximum	71.7	46.7	73.3
Mean	49.3	31.1	52.6
Growth Experiment[2]			
Minimum	65.0	55.0	58.3
Maximum	86.7	81.7	90.0
Mean	75.2	65.0	75.3

[1]Based on a seeding rate of 15 seeds.
[2]Based on a seeding rate of 12 seeds.
[3]Percentages calculated by averaging number of plants emerged and dividing by number of seeds in each treatment then determining minimum, maximum and mean percent emerged.

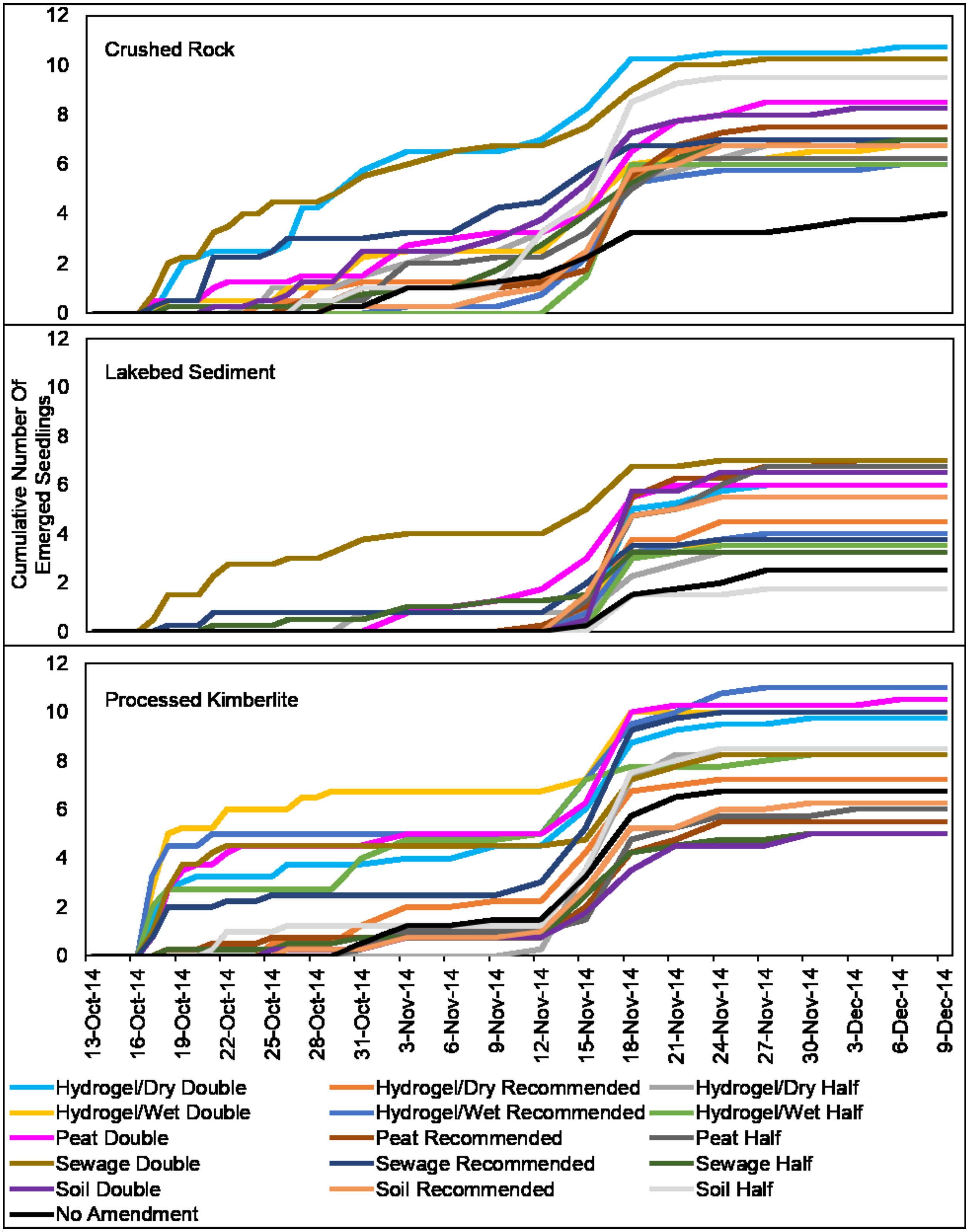

Figure 4.1. Cumulative emergence over the emergence experiment.

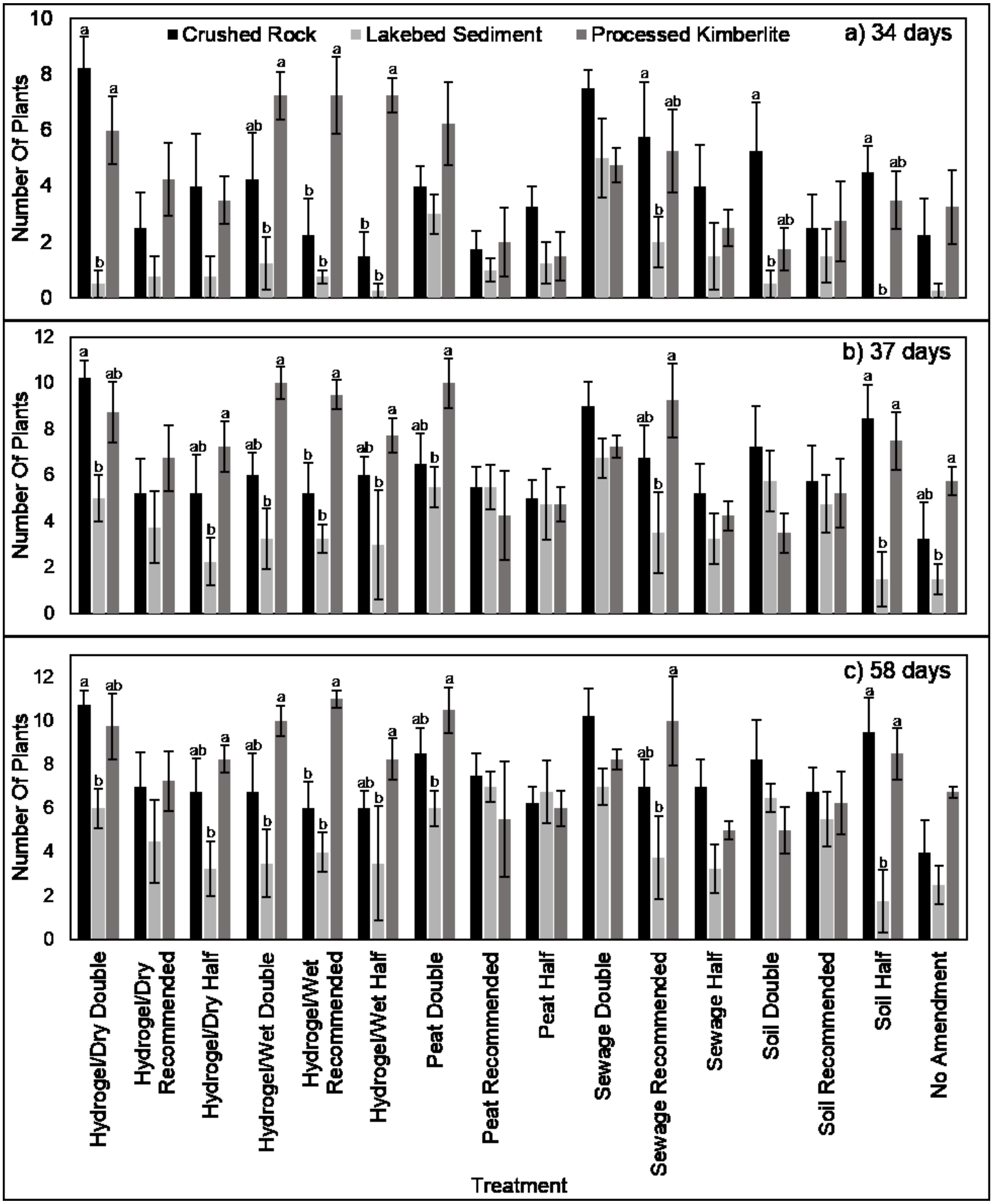

Figure 4.2. Cumulative number of plants over time in the emergence experiment (mean ± SE). Substrates are compared within each treatment with significant differences marked by different letters.

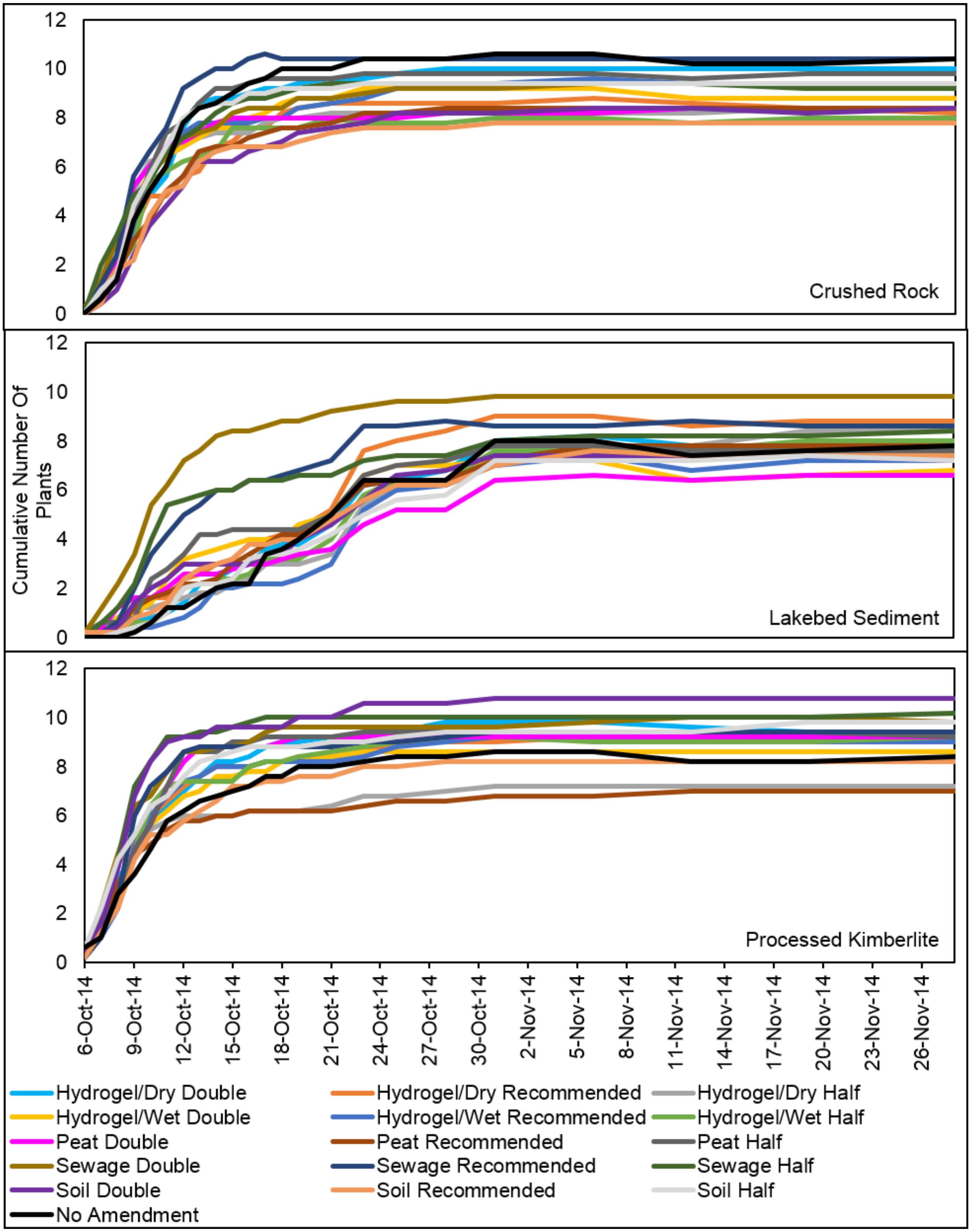

Figure 4.3. Cumulative number of plants over the growth experiment.

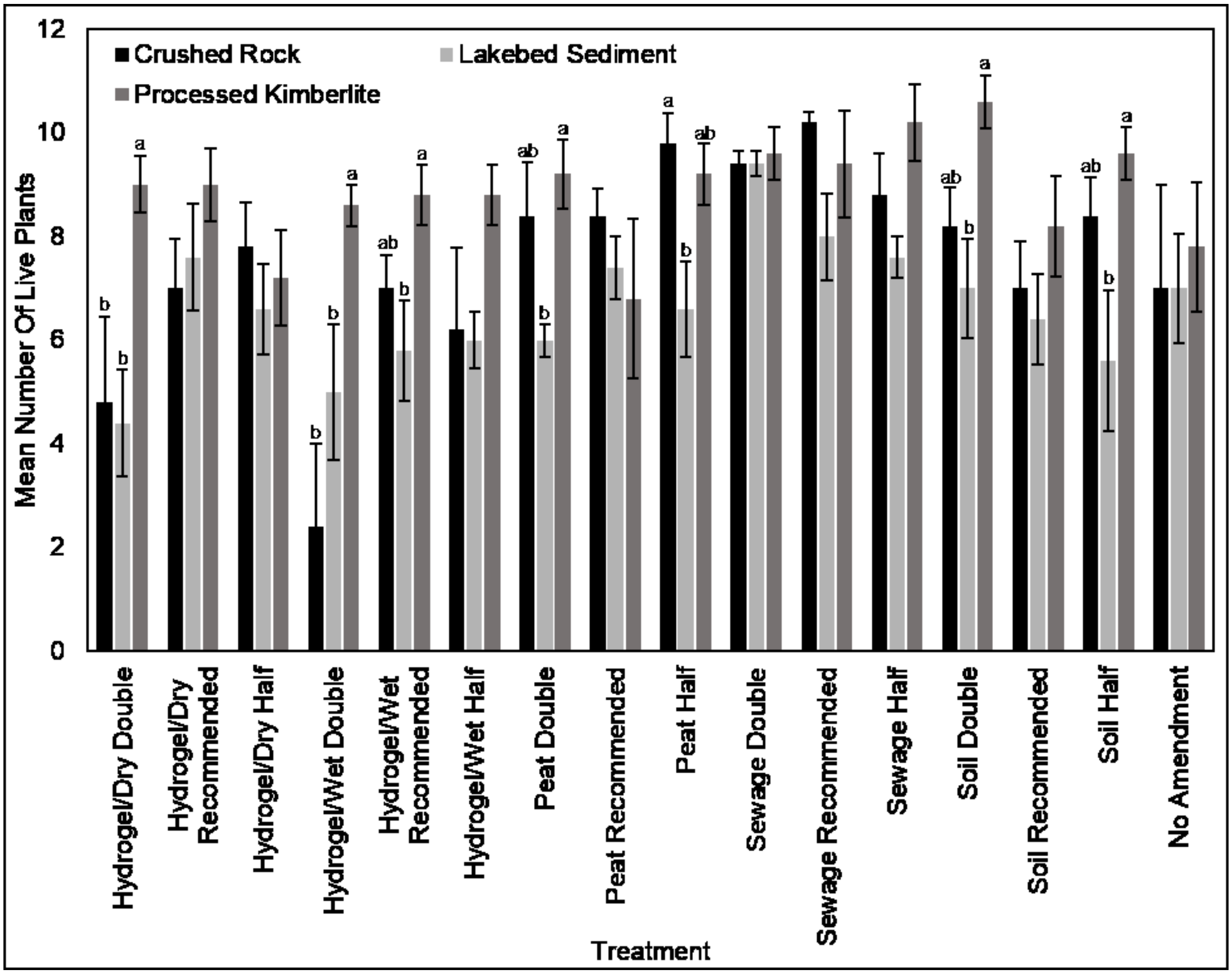

Figure 4.4. Number of live plants at week 8 of the growth experiment (mean ± SE). Substrates are compared within each treatment with significant differences marked by different letters.

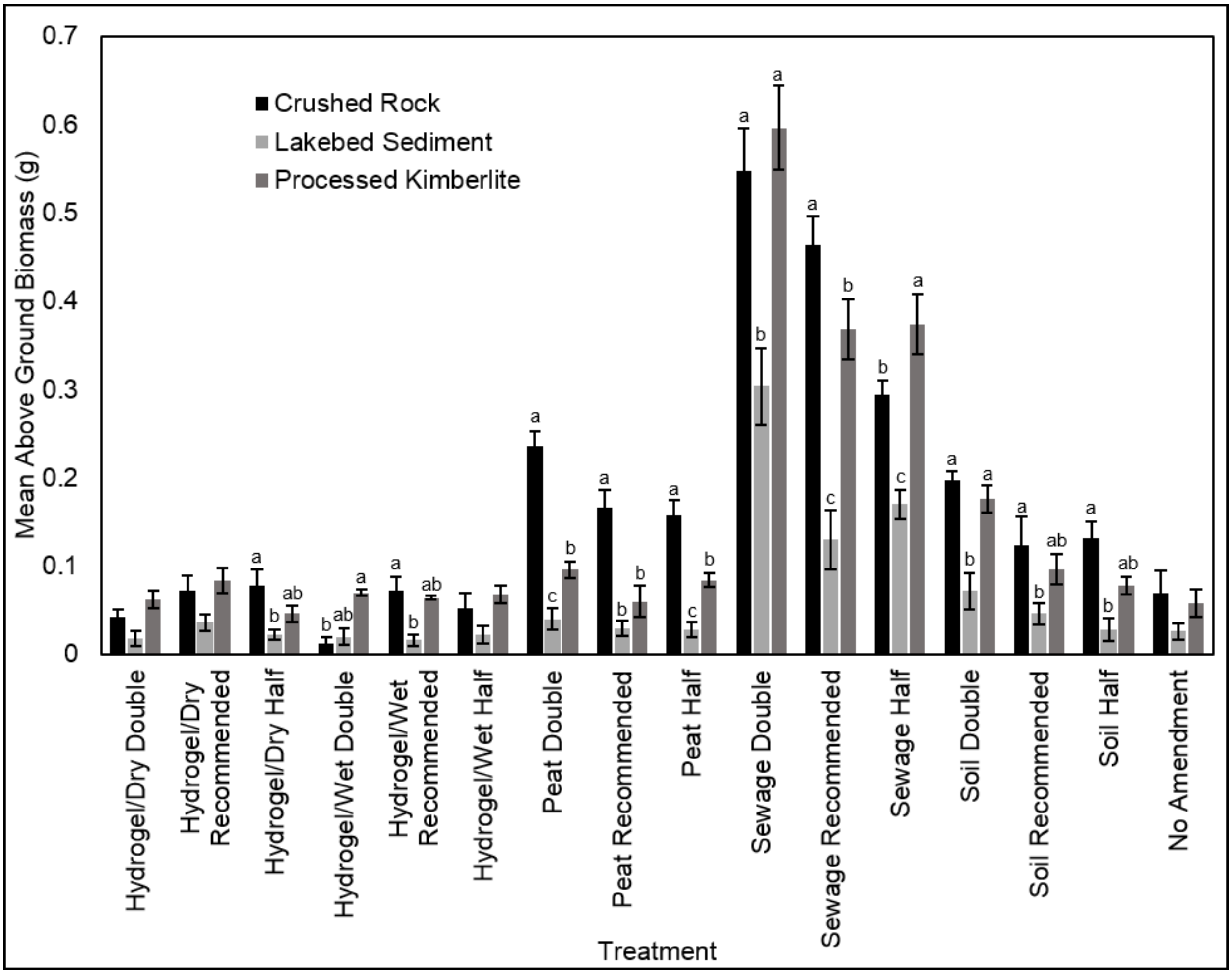

Figure 4.5. Above ground biomass at week 8 (mean ± SE). Substrates are compared within each treatment with significant differences marked by different letters.

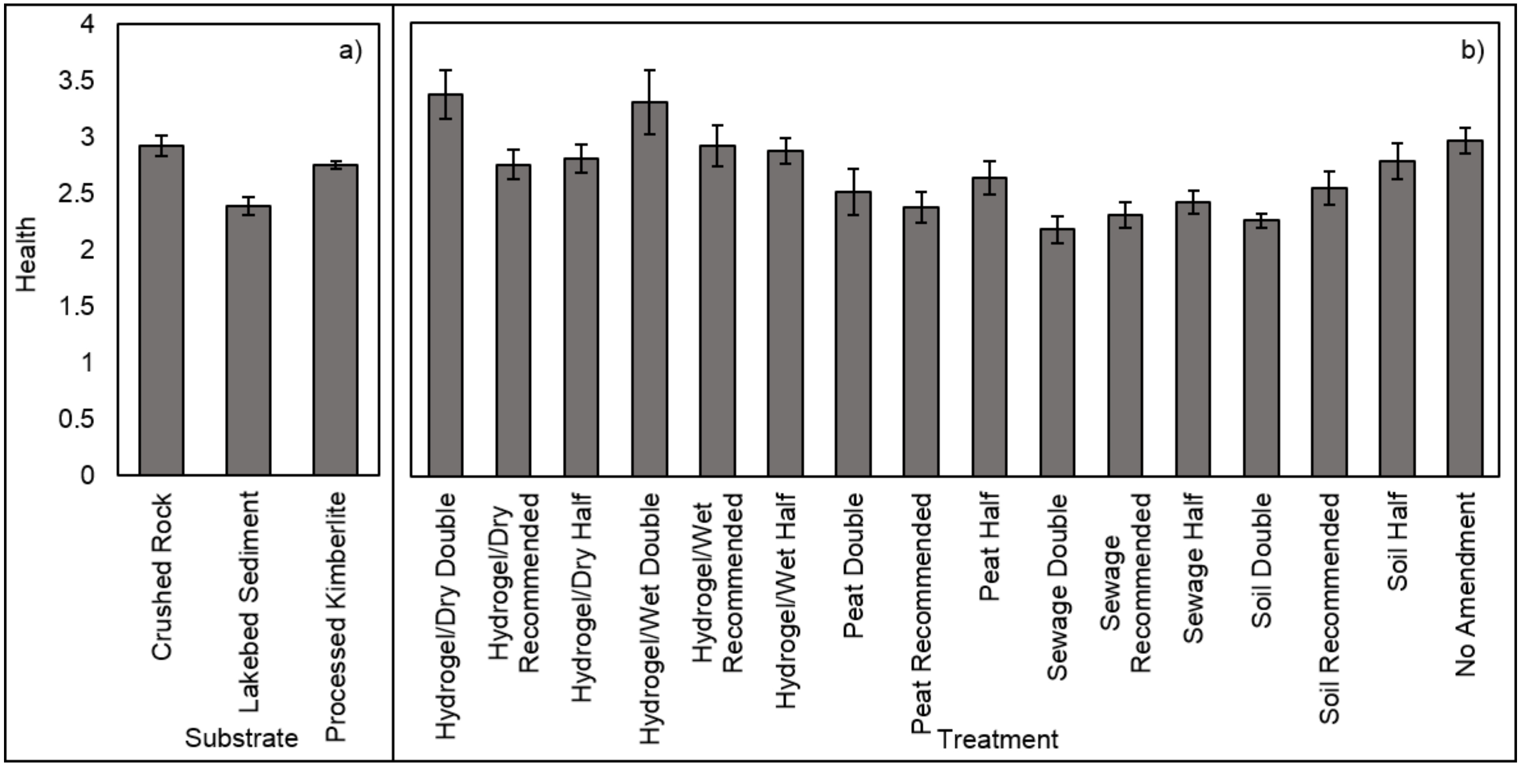

Figure 4.6. Effect of a) substrate and b) treatment on plant health at week 8 of the growth experiment (mean ± SE).

V. ROLE OF MICRO TOPOGRAPHIC VARIABILITY, ORGANIC AMENDMENTS AND EROSION CONTROL IN PLANT ESTABLISHMENT AND GROWTH ON WASTE MATERIALS AT A NORTHERN DIAMOND MINE

1. INTRODUCTION

Improved access to northern Canada and discovery of diamonds in the early 1990s have increased disturbances in these remote regions (Baker et al. 2001, Bryan and Bonner 2003, Drozdowski et al. 2012) which are expected to continue (Rhéaume and Caron-Vuotari 2013). Effective reclamation strategies to establish vegetation are essential as revegetation of arctic soils has inherent limitations, and disturbances introduce more. A short growing season, frequent cold temperatures and limited precipitation create harsh conditions for plants and reduce organic matter decomposition rate and nutrient availability (Crawford 1989, Ostendorf and Reynolds 1998, Bliss and Gold 1999, Jumpponen et al. 1999, Deshaies et al. 2009).

Gravel pads and roads are common disturbances as a layer of gravel is placed on tundra to protect permafrost during development and use. Removal upon site closure is not feasible, requiring gravel to be reclaimed. Gravel disturbances are low in organic matter, nutrients and water holding capacity, with limited seed banks and high compaction (Johnson 1987, Jorgenson and Joyce 1994). They tend to be elevated, altering overland flow, reducing ground water and surface flow, altering snow drift and creating dry areas (Walker 1996).

Limited soil availability due to thin soil layers, lack of stockpiling during site development and long distances to other material sources present challenges for reclamation (Johnson 1987, Sheoran et al. 2010, Larney and Angers 2012), therefore use of on site mining waste materials to build anthroposols is essential. Anthroposols are soils that are altered by human activity, including soils built using waste materials (Naeth et al. 2012). Reclamation research has focused on amendments to improve conditions or build soils using available organic and mineral materials; success varied with materials used. Addressing both structural and nutrient limitations in materials tends to result in the most positive vegetation response (Reid and Naeth 2005a, 2005b, Cohen-Fernández and Naeth 2013, Miller and Naeth 2017).

Building a suitable soil requires consideration of what material to use and how to place it. Arctic tundra environments are micro topographically diverse, with boulders, hummocks, stony areas, desiccation cracks, depressions, polygons and patterned ground (Peterson and Billings 1980, Sohlberg and Bliss 1984). Small scale differences on the landscape create a heterogeneous environment of micro sites and can influence species distribution by altering seed movement, soil water, resources, wind exposure and temperature (Jumpponen et al. 1999, Elmarsdottir et al. 2003, Rausch and Kershaw 2007). Disturbance and reclamation activities can remove natural micro topography through compaction, substrate movement, poor soil structure and removal of hydrologic connections (Allen 1989, Forbes and Jefferies 1999, Naeth and Wilkinson 2011). During reclamation and natural recovery, micro topographic variability has been associated with improved revegetation (Elmarsdottir et al. 2003, Mackenzie and Naeth 2010, Naeth and Wilkinson 2010); however, created variability has been limited and results varied (Umbanhower 1992, Martens 2007, Rausch and Kershaw 2007, Naeth and Wilkinson 2011). By identifying types of micro topography that improve plant germination, establishment and growth, soils can be placed in a way that improves revegetation.

Erosion control research has been sparse in northern disturbances even though erosion is a problem at many disturbed sites, as low organic matter and aggregation make soil vulnerable to erosion and lack of vegetation exposes the surface to wind and water erosion. Erosion can negatively impact vegetation establishment through loss of seeds, displacement and burial of seedlings and formation of a soil crust (Agassi and Ben-Hur 1992, Cerdà and García-Fayos 2002, Moreno-de las Heras et al. 2008, Martens 2005, Naeth and Wilkinson 2011). Eroded materials can negatively impact downstream systems through addition of nutrients and sediment (Faucette et al. 2005, Bhattarai et al. 2011). Erosion can cause loss of nutrients, litter and added amendments (Allen 1989, Edeso et al. 1999), as evidenced by Naeth and Wilkinson (2011) who found that surface applied topsoil disappeared by year 2. Erosion control methods include planting rapidly establishing vegetation, recontouring and creating surface roughness, adding amendments and soil conditioners, incorporating amendments and seeds and placing of erosion control blankets or mulch, although success varies and research is limited (Agassi and Ben-Hur 1992, Loch 2000, Gyasi-Agyei 2004, Cohen-Fernández and Naeth 2013).

During closure of Diavik Diamond Mine, the site must be reclaimed to a stable and safe condition for humans and wildlife with no long term management (Diavik Diamond Mine Inc. 2010b). Building a suitable soil is essential for revegetation and ecosystem development. Diavik produces large amounts of waste materials, primarily crushed rock, processed kimberlite and lakebed sediment, which are important resources for soil building. The objectives of this research are to evaluate the role of organic amendments, micro topographic variability and short term erosion control methods in improving vegetation response for primary waste materials at Diavik Diamond Mine in the field over multiple years. With decades of mining forecasted for current and planned diamond mines, and similar current and historical disturbances across the north, development of effective reclamation practices in a timely manner is essential.

2. MATERIALS AND METHODS

2.1 Research Site

Diavik Diamond Mine is located approximately 300 km northeast of Yellowknife, Northwest Territories, Canada, on East Island; a 20 km^2 area at the east end of Lac de Gras (latitude 64°30′41″, longitude 110°17′23″). Diavik is located in tundra in the low arctic, approximately 100 km north of the treeline (Diavik Diamond Mine Inc. 2010b). It has short, cool summers and long, cold winters. January is generally coldest averaging -27.2 ºC and July warmest averaging 13.2 ºC (Diavik Diamond Mine Inc. 2012). Permafrost ranges from 1 m in wet areas to 5 m in bedrock (Diavik Diamond Mine Inc. 2010b). Average annual precipitation is 305.8 mm; 169.5 mm snow and 136.3 mm rain (Diavik Diamond Mine Inc. 2012). Precipitation peaks in August or September and November; snow melt occurs in early June. Site construction began in 2001 with production in 2003 as an open pit mine, transitioning to an underground mine in 2013 and back to both in 2018. Construction of pits and processing of ore resulted in stockpiling large amounts of waste material including processed kimberlite, lakebed sediment or till (hereafter lakebed sediment) and crushed rock.

2.2 Experimental Design And Treatments

The research site consists of 3 blocks at the former magazine storage facility on raised crushed rock (granite waste rock with < 0.04 wt % sulphur) pads on natural eskers. Each block was divided into 3 equal sized plots with processed kimberlite, lakebed sediment or no substrate added (crushed rock). Fine processed kimberlite, material less than 1 mm, collected from the containment facility where it was placed as a slurry to dry at least a year earlier, was placed in a 50 cm layer. Lake sediment, removed from pits after diking and water pumping, was placed in a 50 cm layer. All materials were tilled in June 2013 with an excavator to loosen the surface, remove sparse vegetation and facilitate manual creation of micro topography.

The experimental design was a complete randomized block. Within each substrate, micro topography, organic amendment and erosion control treatments were combined (3 amendments x 8 micro topography x 2 erosion control = 48 combinations x 3 substrates = 144 combinations).

Blocks 1 and 3 had two replicates and block 2 had one replicate. Amendment treatments were sewage sludge (hereafter sewage), soil and no amendment. Sewage and soil were sourced from site. Sewage is biologically treated on site, dewatered by compressing between two belts and stockpiled. Sewage has cation exchange capacity 69.8 meq 100 g^{-1}, electrical conductivity 5.9 dS m^{-1}, pH 6.1 and total organic carbon 28.6 % (Miller and Naeth 2017). Soil was taken 20 cm below the surface of a stockpile salvaged from patches around the mine, age and exact source unknown. Soil cation exchange capacity was 13.3 meq 100 g^{-1}, electrical conductivity 1.9 dS m^{-1}, pH 4.5 and total organic carbon 2.7 %.

Micro topographic treatments were furrows and flats, and large and small mounds, depressions and boulders. Treatments were based on previous research and natural micro topography in the north. Large treatments were 20 to 30 cm at the tallest or deepest point and 40 to 50 cm wide; small were 10 to 20 cm at the tallest or deepest point and 20 to 30 cm wide. Furrows were 10 to 15 cm high between deepest and tallest points with three furrows per plot. All furrows ran north to south to be perpendicular with the dominant wind direction (east). Flat sites were smoothed to create relatively level surfaces and large rocks removed. Erosion control treatments were with and without Soil Lynx. Soil Lynx is an anionic polymer that when activated with water creates a chemical bond between soil particles reducing erosion (Clearflow Group Inc. 2015).

Plots 1 x 1 m were laid in a grid with 0.75 m buffers. Micro topography was constructed by hand. Approximately 2.4 L of organic amendments were incorporated into the top 5 to 10 cm of substrate; plots with no organic amendment were mixed in the top 5 to 10 cm for consistency. Seeds of 12 grasses and forbs, wild collected in the Northwest Territories, were broadcast in late June 2014 (Table 5.1). Germination was tested in light and dark conditions (Table 5.1). Seeding rates were based on available seed amounts, resulting in approximately 1 g m^{-1} (1,600 seeds) (Table 5.1). Before and after seeding, plots were lightly raked to improve seed-soil contact. Prior to seeding, plots were watered with approximately 1.2 L. Soil Lynx was applied to erosion control plots at 16.7 kg ha^{-1} (Clearflow Group Inc. 2015) after seeding. After seeding and application of Soil Lynx, all plots were water with approximately 1.5 L.

2.3 Vegetation Measurements

Vegetation was assessed during peak plant production (July to August) using 0.75 x 0.75 m quadrats located in the centre of each plot. A walk through was conducted annually to observe erosion and large scale vegetation growth patterns. In year 1 (2014), plants were counted as grass or forb (live and dead separately) due to species identification challenges of young plants.

Evidence of grazing, other animal activity (feces, tracks) and presence of moss were recorded. General comments about plant health, developmental stage and areas of growth were recorded.

In years 2 and 3, live stems by species were counted. Cover was visually assessed to the nearest 0.5 % as vascular vegetation (grass, forbs, shrubs); moss, lichen and algae; litter; anthroposol. Trace was recorded if cover was less than 0.5 %. Average height of live plants was estimated to the nearest 0.5 cm. Plant health was visually assessed for the plot and scored using a six point scale, with 1 being healthy and 6 dead. General comments about developmental stage were recorded, including seedhead presence. Evidence of grazing and other animal activity (feces, tracks) and general observations on plant locations were recorded.

Year 4 assessment focused on cover, visually assessed to the nearest 0.5 % as grass; forbs; shrubs; moss, lichen and algae; litter; anthroposol. Cover less than 0.5 % was recorded as trace. In all plots except flat micro topography, additional cover measurements were taken to understand within plot treatment effects of micro topography. Cover of vascular plants and moss, lichen and algae were separately determined relative to the micro topography feature (in/on depressions, boulder piles, mounds and low furrow areas relative to around depressions, boulder piles, mounds and high furrow areas) to the nearest 0.25 %. Percent of the plot that was the micro topographic feature was estimated to the nearest 1 %. Dominant, healthy and unhealthy species were recorded. Average height of live plants was estimated to the nearest 0.5 cm. Plant health was visually assessed for the plot and scored on the six point scale. Presence of seedheads and plant establishment in small, loose rocks were recorded.

2.4 Soil Measurements

In year 3, soil was sampled in 3 random locations in buffers of each substrate in each block and 3 random locations around the blocks representing tundra. In each location, a 75 cm x 75 cm quadrat was placed, except tundra. Percent cover of surface material was estimated by diameter categories of >20 cm, 10 to 20 cm, 5 to 10 cm and <5 cm. In each quadrat, small samples were taken from 0 to 10 cm using a trowel and sieved in the field for 1 minute through a 2 mm sieve, then placed in bags and refrigerated until analyses. Analyses were according to Carter and Gregorich (2008) unless otherwise noted. Cation exchange capacity was assessed by ammonium acetate extraction (Mckeague 1978); electrical conductivity and pH in saturated paste; total nitrogen by LECO combustion (Sparks et al. 1996); particle size by hydrometer. Total organic carbon was determined from the difference between total carbon by combustion (Sparks et al. 1996) and total inorganic carbon by carbonate reaction with acetic acid.

2.5 Data Analyses

Data were analyzed with RStudio 3.4.0 (2017). Due to scale differences between substrates for most variables, visual and mean differences of substrates were visually compared. Within each substrate, continuous data (vegetation cover, height, number of live plants, species richness and Shannon Weiner H Index) were assessed using a three way ANOVA with block as a random factor followed by Tukey post hoc analysis. Due to extremely poor vegetation performance in processed kimberlite and high proportion of plots with low values, statistical analysis of the continuous data was not conducted. Data were assessed using mean and standard error, with results presented when showing patterns of interest. Replicate treatment plots were averaged within blocks to account for variation. Correlations of variables between years were assessed using Pearson and Spearman rank correlations with a Holm Bonferroni correction. Categorical data were assessed using Chi-square analysis (Fisher Exact when assumptions not met) for each variable (substrate, organic amendment, micro topography, erosion control) followed by testing subsets of the data to determine differences. To account for multiple statistical analyses, p values were corrected with Holm Bonferroni. A p value of 0.05 was used for all analyses.

Data were log 10 transformed when assumptions were not met, including vegetation cover in year 4 and number of live plants in years 1, 2 and 3 (except crushed rock in year 3). Grass, forb, shrub, moss, lichen and algae cover were pooled to represent overall vegetation cover. Moss, lichen and algae and forb cover were visually compared in addition to overall vegetation cover due to importance in the ecosystem. Vegetation cover and mean height in years 2, 3 and 4 showed a strong relationship statistically ($\rho > 0.6$) and visually, therefore only the final year was analyzed. Number of live plants in years 1, 2 and 3 showed variable relationships ($\rho = 0.4$ to 0.8) and visual differences so all years were analyzed. To calculate species richness and diversity (using the Shannon Weiner H Index), unknown species were removed. Shannon Weiner H was calculated using $-\Sigma(P_i \ln P_i)$ where P_i is proportion of species i relative to total number of samples. Species richness and diversity were strongly correlated ($\rho = 0.8$ to 0.9, $r = 0.8$ to 0.9) in years 2 and 3, therefore only richness was analyzed due to better meeting of assumptions; richness relationship was moderate between the two years ($\rho = 0.5$, $r = 0.5$) and showed some visual differences in intensity of effects so both years were analyzed. Health was visually assessed using mean and standard error in all years.

To assess micro topography effects, proportion of micro topography with vegetation cover was calculated as vegetation cover in micro topographic treatment divided by percent area of micro topographic treatment x 100 %. Each substrate was assessed using three way ANOVA with block as a random factor followed by Tukey post hoc analysis, with data log 10 transformed.

3. RESULTS

3.1 Substrate Properties

Crushed rock contained a larger percentage of surface material over 5 cm diameter (approximately 35.4 %) than lakebed sediment (10.8 %) and processed kimberlite (1.4 %) (Table 5.2). Tundra soil, crushed rock and processed kimberlite contained more sand than lakebed sediment and lakebed sediment contained the most silt and clay. All substrates had lower organic carbon and total nitrogen than tundra soil and higher pH, especially processed kimberlite. Cation exchange capacity was highest in processed kimberlite. Electrical conductivity was greater than recommended for reclamation soils (4 dS m^{-1}) (Soil Quality Criteria Working Group 1987) in lakebed sediment.

3.2 Vegetation Response

3.2.1 Substrate

Live plants were more numerous in all years on crushed rock than lakebed sediment and processed kimberlite (Figure 5.1). Number of plants increased each year in all substrates, with changes small between years 2 and 3 in crushed rock. Species richness was greatest in crushed rock and lowest in processed kimberlite (Figure 5.2), increasing between years 2 and 3.

Vegetation cover increased each year in crushed rock and lakebed sediment, being highest in crushed rock in all years and lowest in processed kimberlite (Figure 5.3). Moss, lichen and algae cover was less than 1.1 % in years 2 and 3 in crushed rock and lakebed sediment, and under 0.02 % throughout for processed kimberlite. In year 4, moss, lichen and algae cover increased to 7.7 ± 0.8 % in crushed rock (90.3 % plots with more than trace) and 2.9 ± 0.4 % in lakebed sediment (61.8 % plots with more than trace). Forb cover in year 4 was low (under 0.8 %, 22.7 % of plots with more than trace) and highest in crushed rock and lakebed sediment. Shrubs were only present in six crushed rock plots. Height increased each year in all substrates, with tallest plants generally in crushed rock and shortest in processed kimberlite.

Plant health declined over time in crushed rock, being healthiest of all substrates in year 2 and least in year 4 (1.5 to 3.2). Health improved with time in processed kimberlite, being least in year

2 and moderate in year 4 (2.3 to 3.7). Lakebed sediment had the healthiest plants in years 3 and 4 with little change over time (2.0 to 2.3). There were more plots with seedheads in crushed rock than lakebed sediment and processed kimberlite in year 2; in years 3 and 4, over 95 % of plots in crushed rock and lakebed sediment had seedheads (Table 5.3). Crushed rock had the most plots with evidence of grazing and processed kimberlite the least (Table 5.3).

3.2.2 Treatment

3.2.2.1 Organic amendment

Organic amendment did not significantly affect number of live plants in crushed rock in years 1 and 2, although there were generally more in sewage; in year 3 fewest plants were in sewage (Table 5.4, Figure 5.4). In lakebed sediment, the most plants were in sewage in years 1 and 2, though differences were small, with no difference in year 3 (Table 5.4). Processed kimberlite had little difference in number of live plants between amendments. Species richness was higher in sewage than soil and no amendment in all years and substrates, except year 3 in crushed rock (Table 5.4, Figure 5.5); in year 2 in crushed rock, soil was also greater than no amendment.

Vegetation cover (Figure 5.6) and plant height were greater with sewage than soil and no amendment in all substrates (Table 5.4); moss, lichen and algae and forb cover followed the same pattern. Plants were healthiest with sewage in processed kimberlite in all years and year 2 in crushed rock and lakebed sediment, with little difference in later years. Seedhead presence was greatest with sewage in crushed rock and lakebed sediment in year 2 (Table 5.4) and processed kimberlite in all years (Figure 5.7). Sewage generally had more plots with grazing in all substrates (Table 5.5).

3.2.2.2 Micro topography

Number of live plants was not affected by micro topography in crushed rock (4 % of comparisons differed significantly in year 1) (Table 5.4). In lakebed sediment, 29 % of comparisons differed in year 1 (mounds had fewest plants; flats, furrows, and small boulders and depressions most) with only 7 % in year 2; in year 3, large mounds had fewest plants (Table 5.4, Figure 5.4). In processed kimberlite, plant number was generally highest in furrows and depressions and lowest in flats and mounds in all years (Figure 5.4). Species richness did not differ in year 2 in crushed rock or lakebed sediment; while there was an overall effect in year 3 for crushed rock and lakebed sediment (Table 5.4), there were no significant differences. Visual differences were small in most substrates and years, although the most species were generally in furrows or depressions and the fewest in mounds or flats for lakebed sediment and processed kimberlite.

Micro topography had no effect on vegetation cover in lakebed sediment (0 % of comparisons significantly different) or crushed rock (1 %) (Table 5.4). In processed kimberlite, greatest cover was found in depressions and furrows, especially large depressions, and lowest in flats. Moss, lichen and algae cover was slightly higher in depressions than other treatments, especially with sewage, although overall differences were small. Forbs showed no consistent pattern of micro topography effect between substrates. Note that of six plots with shrubs in crushed rock, four were depressions. Plant height was not affected by micro topography in crushed rock; tallest plants were in furrows and depressions in lakebed sediment and large depressions in processed kimberlite (Table 5.4, Figure 5.8). Micro topography had a limited effect on plant health in crushed rock and lakebed sediment; in processed kimberlite, plants were generally healthiest in large depressions and least healthy on flats and mounds. Seedhead presence was highest in depressions in processed kimberlite in later years (Figure 5.7), with no difference in any substrate in year 2 (Table 5.4). Micro topography had little effect on grazing, with only processed kimberlite in year 3 having significantly more plots with grazing in depressions and furrows (Table 5.5).

3.2.2.3 Erosion control

There were slightly more live plants without Soil Lynx than with it in crushed rock in all years with no effect in lakebed sediment (Table 5.4). Species richness, vegetation cover, height, health, seedhead presence and grazing were not affected by Soil Lynx (Table 5.4). Moss, lichen and algae showed no difference; forb cover was slightly higher with Soil Lynx than without in all substrates. Erosion control had no effect on processed kimberlite, except in year 1, with slightly more plants without Soil Lynx than with it (3.7 vs 2.3) and year 4 where Soil Lynx had slightly greater cover in combination with sewage.

3.2.3 Proportion of micro topography with vegetation cover

Proportion of micro topography with vegetation cover was greater in crushed rock (19.2 ± 1.9 %) than lakebed sediment (13.9 ± 1.6 %) and processed kimberlite (2.4 ± 0.4 %), and significantly impacted by organic amendment and micro topography (Table 5.4). Sewage resulted in greater proportion of micro topography with cover than soil or no amendment in crushed rock and lakebed sediment; soil resulted in greater cover than no amendment in crushed rock. Proportions were generally greater in furrows and depressions and lowest in mounds and boulders in crushed rock and lakebed sediment (Figure 5.9). In processed kimberlite proportions were highest with sewage and furrows and depressions. Moss, lichen and algae cover patterns were the same as total vegetation cover.

3.2.4 Species differences

Across all substrates, the most successful seeded species were slender wheat grass and blue grass species, which had highest seeding rates; nodding locoweed was the most successful forb (Table 5.6). Since forbs were seeded at a low rate due to limited availability, they were all relatively successful. Species with an average of more than 1 plant per plot were most common in crushed rock and least in processed kimberlite. *Epilobium angustifolium* L. (fireweed) was most successful unseeded species in crushed rock (year 2, 10.8 ± 2.0; year 3, 7.3 ± 1.4) and lakebed sediment (year 2, 1.2 ± 0.3; year 3, 1.6 ± 0.3). In crushed rock, 9 sewage amended plots in year 2 had over 100 fireweed individuals and a soil plot had 252; in year 3 a no amendment plot had 342 plants. Unknown grasses, too small to be identified, were common in crushed rock (year 2, 3.2 ± 0.5; year 3, 4.6 ± 0.3), lakebed sediment (year 2, 3.9 ± 0.9; year 3, 2.2 ± 0.2) and processed kimberlite (year 2, 1.0 ± 0.1; year 3, 1.8 ± 0.2).

4. DISCUSSION

4.1 Substrate

Success of crushed rock is due to its rough surface creating seed traps and favourable micro sites for seed germination and plant growth (Peterson and Billings 1980, Johnson and Fryer 1992, Jumpponen et al. 1999, Gyasi-Agyei 2004, Naeth and Wilkinson 2014) and structure suitable for root development (Miller and Naeth 2017). Even under water limited conditions (Chapter IV), crushed rock was among the most successful treatments indicating it had sufficient water and resources for plants, at least initially (also seen in Bishop and Chapin III 1989a). Crushed rock can increase infiltration by slowing water movement over the surface (Gyasi-Agyei 2004, Bhattarai et al. 2011). Naeth and Wilkinson (2014) found crushed rock was one of the most successful substrates in the first 2 years, with reduced success by year 5, indicating it may not meet plant requirements long term. While we saw slower change of some variables in crushed rock between years 3 and 4 relative to lakebed sediment, plant establishment and especially growth continued to increase and remain higher than other materials. While rapidly growing vegetation may compete with slower growing species for resources, it may improve conditions for other species to establish. Potential reduction of seeded species over time may facilitate establishment of slow growing native species, such as shrubs. Crushed rock had higher proportion of moss, lichen and algae, as seen in Naeth and Wilkinson (2014), and these vegetation types are a key component of arctic environments and established without direct human action. Reduced plant health in crushed rock is likely due to plants being more advanced during monitoring as most had released seed and begun to senesce with greater previous year growth relative to plants in lakebed sediment, which reduced the health score.

Lakebed sediment may be a suitable substrate for anthroposol building. Miller and Naeth (2017) found lakebed sediment among the better combinations for plant response although addition of 25 % processed kimberlite improved it; under water limited conditions it was least successful (Chapter IV). After 5 years, Naeth and Wilkinson (2014) found unamended lakebed sediment had poor plant establishment and growth; however with amendments it was among some of the most successful treatments. Benefits of lakebed sediment result from its fine texture which can increase water and nutrient holding capacity (Reid and Naeth 2005a, 2005b), although this is not always seen (Miller and Naeth 2019). This fine fraction can negatively affect its success as it can become very hard when dry, restricting seedling emergence (Jumpponen et al. 1999), root growth (Tsuyuzaki et al. 1997) and plant growth, reducing water infiltration and increasing runoff. Loss of seeds through erosion (Cerdà and García-Fayos 2002) may be higher in lakebed sediment due to a smoother surface relative to crushed rock. It is difficult to determine whether a crust formed on lakebed sediment from raindrop impact (Agassi et al. 1981), as the material is dense throughout, and generally crusts do not form on soils with less than 10 % clay (Ben-Hur 1994). Vegetation may improve lakebed sediment over time by increasing infiltration, soil aeration and organic matter directly and by acting as a trap (Nicolau 1996, Puigdefabregas et al. 1999), making it a more effective substrate as seen in the greater increase in vegetation cover between years 3 and 4 relative to crushed rock.

Combining crushed rock and lakebed sediment may create a suitable substrate. Nicolau (2002) found cracks, stones and plants can break down soil crusts and increase infiltration; while lakebed sediment may be compact throughout, adding crushed rock with its higher coarse fraction may increase infiltration, reduce hardness and improve plant establishment. The fine fraction of lakebed sediment may increase water and nutrient holding capacity supporting vegetation long term, although cation exchange capacity of both materials is low. Reid and Naeth (2005a, 2005b) found adding lake sediment to processed kimberlite resulted in less successful vegetation than other amendments and declined over time, reducing nutrients and cation exchange capacity; therefore combinations should be tested.

Processed kimberlite was an unsuitable substrate with or without amendments relative to crushed rock and lakebed sediment. Poor chemical and physical attributes reduce its success (Elmarsdottir et al. 2003, Reid and Naeth 2005b, Naeth and Wilkinson 2014, Miller and Naeth

2017). Processed kimberlite was among successful materials for plant establishment and growth under simulated water limitation in the greenhouse, indicating potential initial success (Chapter IV); however, poor results in the field negate this. Greater water retention in the greenhouse relative to crushed rock and lakebed sediment (Miller and Naeth 2019) likely does not help in the field; plants are not restricted to accessing water in small pots where coarse fragments negatively impact water retention. Naeth and Wilkinson (2014) similarly found poor success of processed kimberlite over time as capped amendments eroded and benefits were lost. Reid and Naeth (2005b) found good growth on processed kimberlite, when structure and nutrient improving amendments were added at higher rates and in combination. Erosion is a major challenge in processed kimberlite; burial and displacement of plants and seeds results in poor establishment and cover. There is concern about uptake of metals by plants in processed kimberlite, although Naeth et al. (2018b) found metals of concern were below detection limit or had low concentrations in plant tissue from processed kimberlite and lakebed sediment. While processed kimberlite would be beneficial for use of waste material, success seems limited.

4.2 Organic Amendment

Amendment had a limited impact on number of plants, as seen in Chapter IV where substrate played the key role. Elmarsdottir et al. (2003) found limited differences in seedling density in reclamation sites from 0 to 11 years since reclamation, while cover varied widely. At Diavik, Naeth and Wilkinson (2014) found treatment had no effect on plant density in 4 years, although topsoil was successful; in year 5 sewage capped substrates had more plants. Sewage and soil had a limited effect increasing water retention (Miller and Naeth 2019). As water has a major impact on germination, the limited effect of organic amendments on plant establishment is expected. Naeth et al. (2018a) similarly found limited impact of amendments on water content, other than hydrogel, and an inconsistent impact on emergence.

The slight increase in plant establishment in lakebed sediment with sewage in early years may be due to micro sites where sewage was exposed at the surface. As lakebed sediment tends to have a smoother surface than crushed rock, sewage may create areas where seeds collect, facilitating germination. As sewage decomposes and vegetation provides sites for collection, the effect declines. The reduced number of plants in crushed rock with sewage in year 3 may be due to fewer larger plants outcompeting many small plants (Elmarsdottir et al. 2003), especially fireweed. Sewage increased richness in most cases as higher nutrient content in sewage supported a greater variety of species than poorer quality soil or no amendment.

Greater cover and height with sewage in all substrates is due to provision of essential nutrients absent in substrates, which in turn initiates nutrient cycling and improves substrate structure (Reid and Naeth 2005a, 2005b, Drozdowski et al. 2012). Reid and Naeth (2005b) found kimberlite amended with sewage had increased nitrogen, phosphorus and organic carbon, resulting in greatest plant cover, height and above ground biomass. They combined sewage with peat, gypsum and rock phosphate (which when used without sewage were much less successful) at a higher application rate. After 5 years, Naeth and Wilkinson (2014) found substrates capped with sewage had greatest cover. Sewage is available on site while the mine is in operation and could be stockpiled for reclamation, reducing needs for disposal and transportation of off site materials. Use in low quantities and incorporation with substrates reduces concern of metal uptake in plants and runoff of nutrients in the oligotrophic Lac de Gras. Faucette et al. (2005) found high initial loss of nutrients from surface applied organic mulches, although sites with no mulch had greater loss due to lack of vegetation.

Rapid establishment of herbaceous cover, especially grasses, may compete with slow growing native species (Bishop and Chapin III 1989b, Elmarsdottir et al. 2003, Macdonald et al. 2015). Grass is a small component of the ecosystem, which is dominated by shrubs, lichen, sedges and cotton grass (Ecosystem Classification Group 2012). However, its rapid growth can facilitate establishment of other species by reducing wind and erosion, stabilizing the substrate, increasing organic matter and nutrients through decomposition of plant material, creating safe micro sites and increasing infiltration and water holding capacity (Loch 2000, Elmarsdottir et al. 2003, Reid and Naeth 2005a, Moreno-de las Heras et al. 2009, Cohen-Fernández et al. 2013, Macdonald et al. 2015). Martínez-Ruiz et al. (2007) found seeding commercial grasses and legumes did not inhibit establishment of species from the surrounding community on uranium mine wastes. There is limited native seed available and propagation techniques for many northern species are uncertain thus use of grasses is often required. To reduce potential competition and encourage establishment of native species, seeding rates may be lowered or herbaceous vegetation cut back after a few years of growth. Long term monitoring is needed to determine if natural ingress occurs in combination with seeded species.

Soil had little effect on plant response relative to sewage. Generally soil provides propagules and seeds, organic matter and nutrients and improves structure, resulting in greater plant emergence, growth and survival (Holmes 2001, Drozdowski et al. 2012, Cohen-Fernández et al. 2013). Cohen-Fernández et al. (2013) found establishment and growth responded positively to 5 cm of soil and Holmes (2001) to 10 and 30 cm. At low applications, soil may be less effective, especially if stockpiled rather than direct placed (Hargis and Redente 1984, Holmes 2001). Stockpiling can negatively impact microbial activity, nutrients, organic matter, structure, leaching, volatilization and erosion (Abdul-Kareem and McRae 1984, Visser et al. 1984, Williamson and Johnson 1990, Mackenzie et al. 2019). Stockpiling can negatively affect propagule and seed survival and subsequent germination even in the short term (Naeth and Wilkinson 2014, Mackenzie et al. 2019), and reduce surface area for seed rain collection (Holmes 2001). Mackenzie et al. (2019) found significant declines in seed viability for 24 of 27 boreal species after stockpiling 8 and 16 months. Even in high arctic polar deserts, seedbanks contain significant viable seed (Bliss and Gold 1999). Fireweed was one of the only plants established on the stockpile, although it was expected to establish in plots with or without soil due to its proximity to the site. Our soil texture was similar to the substrates so soil addition likely did not improve it.

Incorporation of amendments may dilute benefits. Mixing with poor quality substrates may not support vegetation as well as placing a layer of amendment on the surface (Hargis and Redente 1984, Cohen-Fernández et al. 2013). Incorporating may bury seeds in amendments. However due to its remote location, there are restrictions on how much material can be brought to site, thus use of limited on site material is essential. Incorporation reduces the amount of amendment needed as a thick layer is not needed to support vegetation alone as a greater part of the substrate profile is improved (Hargis and Redente 1984). Incorporation reduces loss of material from erosion (Allen 1989). Gilley and Eghball (1998) found incorporating manure or compost in agricultural fields conserved nutrients and improved soil physical properties relative to capping. At Diavik, after 5 years Naeth and Wilkinson (2014) found lakebed sediment capped with 4 cm of sewage had approximately 15 % vegetation cover, whereas we incorporated less than 1 cm of sewage and had approximately 24 % cover in year 4.

4.3 Micro Topography

In processed kimberlite, depressions and furrows increased vegetation response. Lack of rocks creates smooth sites with few barriers to collect seed or slow seed movement (Elmarsdottir et al. 2003). Built micro topography creates low areas which collect seeds that are displaced and protect from wind and water erosion (Jumpponen et al. 1999, Naeth and Wilkinson 2011) and may collect organic matter and nutrients, which increase as plants grow. Seeds must remain in a site to germinate there (Johnson and Fryer 1992) and low areas may provide this shelter. Jumpponen et al. (1999) found greater establishment in depressions than mounds or flat surfaces. Low areas may have improved growth conditions, as they tend to be wetter and cooler than high areas (Price et al. 1998, Jumpponen et al. 1999). The dark colour of processed kimberlite results in slightly higher temperatures than other substrates (Drozdowski et al. 2012); reduced temperature may improve establishment. Naeth et al. (2018a) found built depressions had lower temperatures than flats or mounds and slightly greater water content, whereas Naeth and Wilkinson (2011) found lower water content in depressions, potentially due to erosion burying sensors. In processed kimberlite, micro topography eroded over time therefore effects may be short term. Naeth et al. (2018a) found poorer establishment in depressions than around them, potentially due to burial of seeds under eroded materials, reducing emergence.

Existing small scale micro topography in crushed rock, and to a lesser extent lakebed sediment, such as small rocks and surface variability, means built micro topography may not have provided additional benefits. Mackenzie and Naeth (2010) thought LFH’s rougher surface, from woody debris and soil clods under 10 cm, improved plant establishment relative to smoother peat, with vegetation establishing near plant bases, woody debris and in pits and cracks. Jumpponen et al. (1999) found greater recruitment on substrates with coarse surfaces. Seeds are trapped and held for germination and water may collect in rocks and crevices, providing necessary resources for success (Johnson and Fryer 1992, Jumpponen et al. 1999, Elmarsdottir et al. 2003, Mackenzie and Naeth 2010, Macdonald et al. 2015). Paschke et al. (2000) found no effect of pits at one roadcut site on plant establishment and transplant survival; Rausch and Kershaw (2007) found little effect of micro topography on gravel disturbances in Churchill, Manitoba. Naeth et al. (2018a) found better plant survival in pits than mounds at one site and reduced survival in pits at another, with limited impact on vegetation cover. As seeds were mixed in substrate surfaces, the hard lakebed sediment may have limited seed movement by wind and water, reducing need for larger micro topography. Where micro topography did positively impact lakebed sediment, depressions and furrows were generally more successful than flats and mounds; rationale for these improvements are similar to processed kimberlite.

While micro topography had a limited effect on plots overall except in processed kimberlite and establishment in lakebed sediment, there was consistently greater plant cover in low areas than mounds or boulders. Price et al. (1998) found *Sphagnum* establishment greater in negative relief areas even when overall sites showed no micro topography effect. Poor establishment on raised areas likely had a limited effect on the whole plot due to benefits they provide. Boulders may shade the surface, provide wind protection, collect snow, insulate seeds and plants, reduce evaporation and increase water content, creating effective micro sites around them (Cargill and Chapin III 1987, Jumpponen et al. 1999, Rausch and Kershaw 2007, Naeth et al. 2018a) and collect seeds. Jumpponen et al. (1999) found greater recruitment near boulders decreasing with distance. Mounds may act similarly, with greater plant establishment around than on them (Naeth et al. 2018a).

Understanding long term impacts of micro topography on colonization of native species is essential despite short term effects being limited. After 4 years, seeded species remain the majority of cover with ingress beginning. Other species may have different requirements and micro topography may play an important role creating different niches. For example, 4 of the 6 plots with shrubs in crushed rock were depressions. Hough-Snee et al. (2011) found mounding on a former landfill created ecosystem heterogeneity and niches for species with wetland species between mounds and xeric on mounds 10 years after reclamation, although the effect on overall species composition was uncertain.

4.4 Erosion Control

Addition of Soil Lynx had a limited impact on vegetation. Processed kimberlite is at highest risk of erosion due to its sand texture (He et al. 2008), smooth surface and lack of rocks slowing wind and water speed (Gyasi-Agyei 2004, Chen et al. 2011) and poor vegetation establishment (Agassi and Ben-Hur 1992, Edeso et al. 1999, Loch 2000, Gyasi-Agyei 2004, Macdonald et al. 2015). Erosion of micro topography was less in crushed rock and lakebed sediment than processed kimberlite, with many depressions and furrows filling in and mounds shrinking. Soil Lynx provided little protection due to the high proportion of sand in processed kimberlite. Anionic polyacrylamides work by forming bonds with soil particles through cation bridging, Van der Waals interaction and hydrogel bonds (Theng 1982, Ben-Hur 1994, Hanna 2018); however, sand lacks charge resulting in weaker bonds that are easily broken by movement of sand by wind and water. Polyacrylamides are temporary, breaking down over time (He et al. 2008), and as vegetation establishes slowly on processed kimberlite, reapplication may be required. Experimental set up may have played a role as Soil Lynx was applied to individual plots and therefore erosion occurred in adjacent plots and buffers and moved into erosion control plots. Testing of additional erosion control methods, like mats, is an important next step for areas where erosion is high.

5. CONCLUSIONS

Use of on site waste materials to build anthroposols provides potential solutions to remote sites. Crushed rock was the most suitable substrate for vegetation establishment and growth; however, lakebed sediment became increasingly successful over time. Future research should assess the suitability of crushed rock and lakebed sediment combined in various ratios to address their respective limitations. Processed kimberlite showed poor vegetation response and is likely of limited use for reclamation even when combined with amendments.

For all substrates, small amounts of sewage incorporated in the top 5 to 10 cm improved vegetation cover and height. Sewage is likely not available in sufficient quantities to reclaim an entire site, but could be used in islands to support natural egress into unamended areas. Although stockpiled soil provided few benefits, as the site is repeatedly disturbed it should be collected and direct placed for progressive reclamation. Micro topography had a limited effect when materials with a rough surface were used, such as crushed rock, although plant cover was greater in low areas than high in all substrates. With lakebed sediment, low areas may increase plant establishment with little effect on cover, therefore building low areas would provide only small improvements. For these materials, reclamation strategies may not need to actively build micro topography, but should avoid removing it and creating smooth sites. If processed kimberlite is selected, practitioners should ensure low areas are created as they improved establishment and growth. Soil Lynx did not improve vegetation response in any substrate.

Table 5.1. Seeded species on research plots.

Species	Common Name	Collection Location[1]	Collection Habitat	Seed Mix %[2]	Light Germination (%)	Dark Germination (%)
Agrostis scabra Willd.	Rough bentgrass	Tulita	Seismic line, wet	10.7	84	98
Arctagrostis latifolia (R. Br.) Griseb.	Wideleaf polargrass	Mackenzie Delta uplands, Liard, Edzo	Thaw slump, exposed, old burn, wet meadow	7.6	38[3] 28	46 14
Calamagrostis purpurascens R. Br.	Purple reedgrass	Mackenzie Delta uplands, Hay Rover, Rae Edzo, Inuvik	Thaw slump, gravel, off winter road access, gravel slope	5.5	30 16	24 12
Deschampsia caespitosa (L.) P. Beauv.	Tufted hairgrass	Hay River	Gravel area	12.2	86	52
Elymus trachycaulus (Link) Gould ex Shinners	Slender wheat grass	Edzo, Yellowknife	Gravel pit, Canadian shield	14.5	76	22
Festuca saximontana Rydb.	Rocky mountain fescue	Fort Resolution	Dry, grassy clearing	7.1	96	84
Hedysarum alpinum L.	Alpine sweetvetch	Inuvik	No information	0.1	64	74
Oxytropis campestris (L.) DC.	Field locoweed	Inuvik	Gravel slope	0.2	46 34	60 18
Oxytropis deflexa (Pall.) DC.	Nodding locoweed	Inuvik	No information	0.7	78	80
Poa alpina L.	Alpine blue grass	Inuvik, Fort Good Hope	Wet roadside depression, off winter road access	10.3	58	66
Poa glauca Vahl	Glaucous blue grass	Inuvik	Gravel hilltop	24.2	36	36
Trisetum spicatum (L.) K. Richt.	Spike trisetum	Mackenzie Delta uplands	Thaw slump	6.8	66	74

[1]All collection locations are in Northwest Territories and collected between 2005 and 2007.
[2]Percent of seed mix is based on the total number of seeds applied; amount of seed is based on amounts available.
[3]Where there were multiple seed sources of species, germination of each was tested before pooling.

Table 5.2. Mean physical and chemical properties (± SE) of reclamation substrates and tundra soil.

Soil Property	Crushed Rock	Lakebed Sediment	Processed Kimberlite	Tundra Soil
Content > 20 cm (%)	6.6 (2.7)	3.0 (1.3)	0.0 (0.0)	N/a
Content 10-20 cm (%)	14.4 (5.9)	3.2 (0.7)	0.7 (0.3)	N/a
Content 5-10 cm (%)	14.4 (3.9)	4.6 (0.6)	0.7 (0.3)	N/a
Content < 5 cm (%)	64.6 (10.0)	89.2 (1.5)	98.6 (0.4)	N/a
Sand (%)	76.4 (2.0)	62.6 (0.7)	79.6 (1.0)	80.9 (9.7)
Silt (%)	19.7 (1.7)	29.9 (0.7)	15.3 (0.8)	15.4 (9.1)
Clay (%)	4.0 (0.4)	7.5 (0.3)	5.1 (0.4)	3.7 (0.7)
Cation Exchange Capacity (meq 100 g^{-1})	4.14 (0.95)	2.56 (0.19)	15.34 (0.23)	3.82 (0.72)
Total Nitrogen (%)	0.033 (0.002)	0.040 (0.004)	0.029 (0.002)	0.061 (0.018)
Electrical Conductivity (dS m^{-1})	0.57 (0.12)	6.64 (1.26)	2.98 (0.77)	0.20 (0.10)
Soil pH	7.9 (0.2)	7.1 (0.1)	8.7 (0.1)	5.0 (0.0)
Total Organic Carbon (%)	0.19 (0.05)	0.10 (0.03)	0.11 (0.00)	1.02 (0.34)

Table 5.3. Percentage of plots with seed heads and evidence of grazing in each substrate.

Growing Season	Presence Of Seedheads (%)			Grazing Evidence (%)		
	Crushed Rock	Lakebed Sediment	Processed Kimberlite	Crushed Rock	Lakebed Sediment	Processed Kimberlite
Year 2	82.9a	28.2b	9.2c	32.5a	25.6a	13.3b
Year 3	99.6a	95.8b	42.6c	88.8a	75.4b	35.0c
Year 4	100.0a	99.6a	60.1b			

Significant differences between substrates are denoted by different letters within each year.

Table 5.4. Significant relationships for vegetation response variables in crushed rock and lakebed sediment.

Variable	Crushed Rock	Lakebed Sediment
Number Of Live Plants Year 1	Erosion control (F = 6.18, P = 0.015) Micro topography (F = 2.22, P = 0.040)	Organic amendment (F = 4.37, P = 0.015) Micro topography (F = 5.84, P < 0.000)
Number Of Live Plants Year 2	Erosion control (F = 8.28, P = 0.005)	Organic amendment (F = 6.36, P = 0.003) Micro topography (F = 3.29, P = 0.004)
Number Of Live Plants Year 3	Erosion control (F = 4.33, P = 0.040) Organic amendment (F = 7.01, P = 0.002)	Micro topography (F = 3.65, P = 0.002)
Species Richness Year 2	Organic amendment (F = 22.85, P < 0.000)	Organic amendment (F = 64.15, P < 0.000)
Species Richness Year 3	Micro topography (F = 2.12, P = 0.049)	Micro topography (F = 2.30, P = 0.033) Organic amendment (F = 8.12, P = 0.001)
Vegetation Cover Year 4	Organic amendment * micro topography (F = 1.84, P = 0.044)	Organic amendment (F = 110.10, P < 0.000)
Mean Height Year 4	Organic amendment (F = 78.71, P < 0.000)	Organic amendment (F = 71.46, P < 0.000) Micro topography (F = 3.90, P = 0.001)
Seedheads Presence Year 2	Organic amendment (X^2 = 30.06, P < 0.000)	Organic amendment (X^2 = 167.10, P < 0.000)
Proportion Of Micro Topography With Vegetation Coverage	Organic amendment (F = 101.03, P < 0.000) Micro topography (F = 18.25, P < 0.000)	Organic amendment (F = 49.80, P < 0.000) Micro topography (F = 26.90, P < 0.000)

Table 5.5. Proportion of plots showing evidence of grazing in years 2 and 3.

Treatment	Year 2			Year 3		
	Crushed Rock	Lakebed Sediment	Processed Kimberlite	Crushed Rock	Lakebed Sediment	Processed Kimberlite
Organic Amendment						
No Organic Matter	12.5c	10.3b	2.5b	87.5	66.3b	22.5b
Sewage	60.0a	62.5a	35.0a	87.5	95.0a	62.0a
Soil	25.0b	3.8b	2.5b	91.3	65.0b	20.5b
Micro Topography						
Flat	46.7	27.6	6.7	83.3	73.3	17.9d
Furrow	16.7	30.0	16.7	93.3	73.3	46.7bd
Large Boulder	26.7	20.0	3.3	83.3	80.0	16.7d
Large Depression	43.3	26.7	23.3	100.0	80.0	60.0abc
Large Mound	43.3	23.3	6.7	100.0	73.3	13.3d
Small Boulder	36.7	30.0	6.7	76.7	76.7	24.1ad
Small Depression	33.3	23.3	33.3	93.3	83.3	66.7bc
Small Mound	13.3	24.1	10.0	80.0	63.3	33.3bd

Significant differences in each substrate are denoted by different letters within each year.

Table 5.6. Mean (± SE) number of individuals of seeded species in each substrate in years 2 and 3.

Species	Year 2			Year 3		
	Crushed Rock	Lakebed Sediment	Processed Kimberlite	Crushed Rock	Lakebed Sediment	Processed Kimberlite
Agrostis scabra	1.5 (0.2)	0.1 (0.0)	0.0 (0.0)	1.0 (0.1)	0.1 (0.0)	0.0 (0.0)
Arctagrostis latifolia	0.1 (0.0)	0.0 (0.0)	0.0 (0.0)	0.1 (0.0)	0.0 (0.0)	0.0 (0.0)
Calamagrostis purpurascens	0.2 (0.1)	0.0 (0.0)	0.0 (0.0)	0.2 (0.0)	0.1 (0.0)	0.0 (0.0)
Deschampsia caespitosa	2.9 (0.2)	0.3 (0.1)	0.0 (0.0)	1.5 (0.1)	0.7 (0.1)	0.2 (0.1)
Elymus trachycaulus	22.6 (0.7)	12.1 (0.6)	5.4 (0.4)	22.9 (0.7)	12.1 (0.4)	4.2(0.3)
Festuca saximontana	10.5 (0.5)	1.4 (0.2)	0.0 (0.0)	12.7 (0.5)	2.9 (0.2)	0.2 (0.0)
Hedysarum alpinum	0.1 (0.0)	0.0 (0.0)	0.0 (0.0)	0.1 (0.0)	0.0 (0.0)	0.0 (0.0)
Oxytropis campestris	0.2 (0.0)	0.0 (0.0)	0.0 (0.0)	0.2 (0.0)	0.0 (0.0)	0.0 (0.0)
Oxytropis deflexa	1.0 (0.1)	0.1(0.0)	0.1 (0.0)	1.1 (0.1)	0.2 (0.0)	0.2 (0.0)
Poa alpina	8.1 (0.4)	1.0 (0.2)	0.0 (0.0)	11.2 (0.4)	2.8 (0.2)	0.1 (0.0)
*Poa glauca**	22.2 (0.6)	5.6 (0.6)	0.6 (0.1)	18.1 (0.5)	12.7 (0.6)	2.8 (0.2)
Trisetum spicatum	2.8 (0.2)	0.1 (0.0)	0.0 (0.0)	5.6 (0.3)	1.0 (0.1)	0.1 (0.0)

*Poa glauca includes *Poa glauca* and unknown *Poa* sp., most unknown *Poa* sp. were expected to be *Poa glauca*.

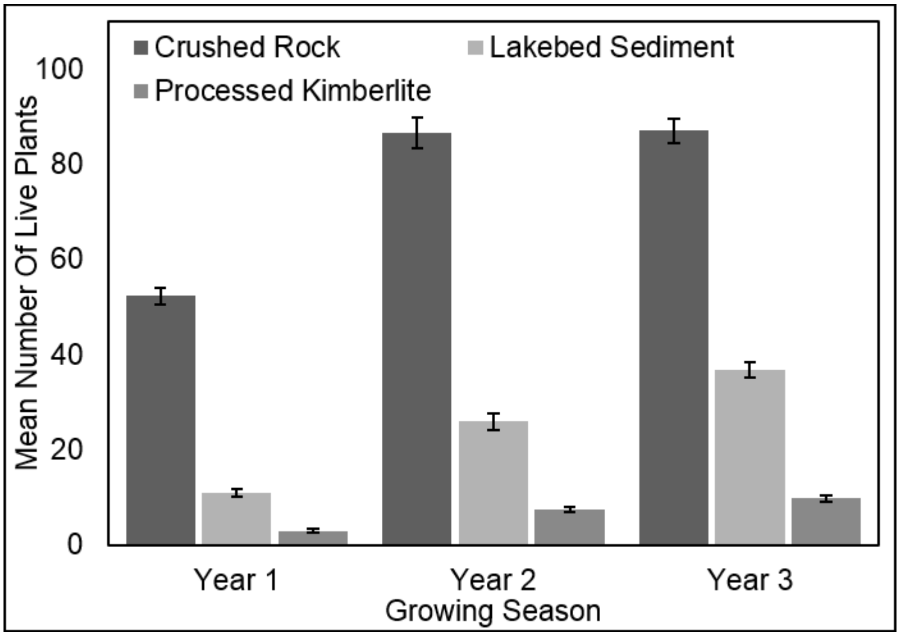

Figure 5.1. Mean number of live plants (± SE) on substrates.

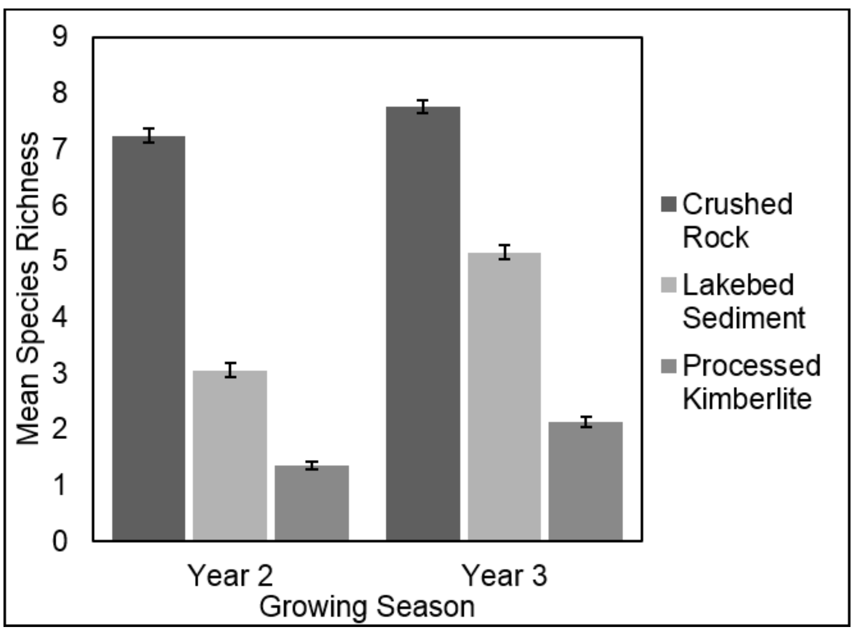

Figure 5.2. Mean species richness (± SE) on substrates.

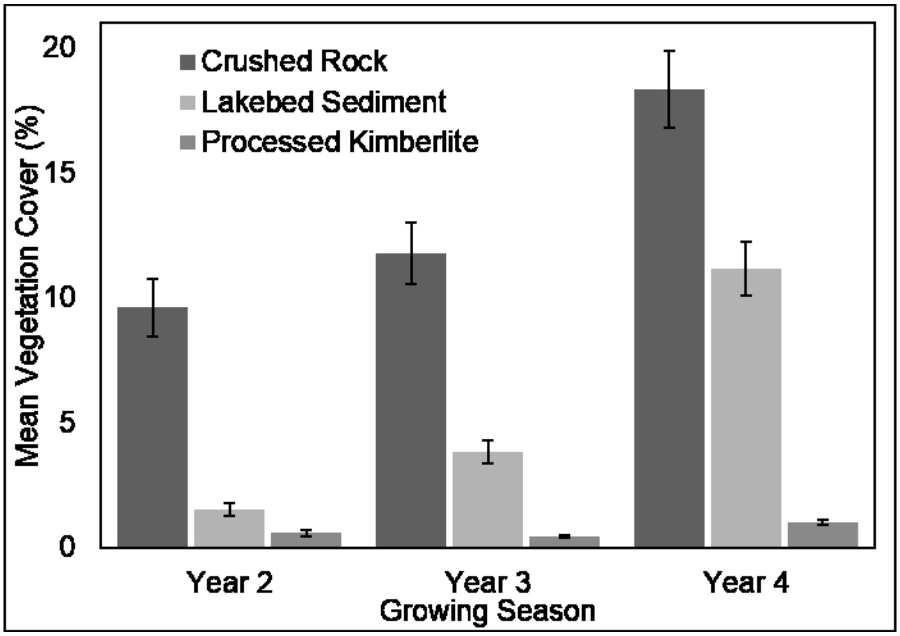

Figure 5.3. Mean vegetation cover (± SE) including grass, forbs, shrubs, moss, lichen and algae on substrates.

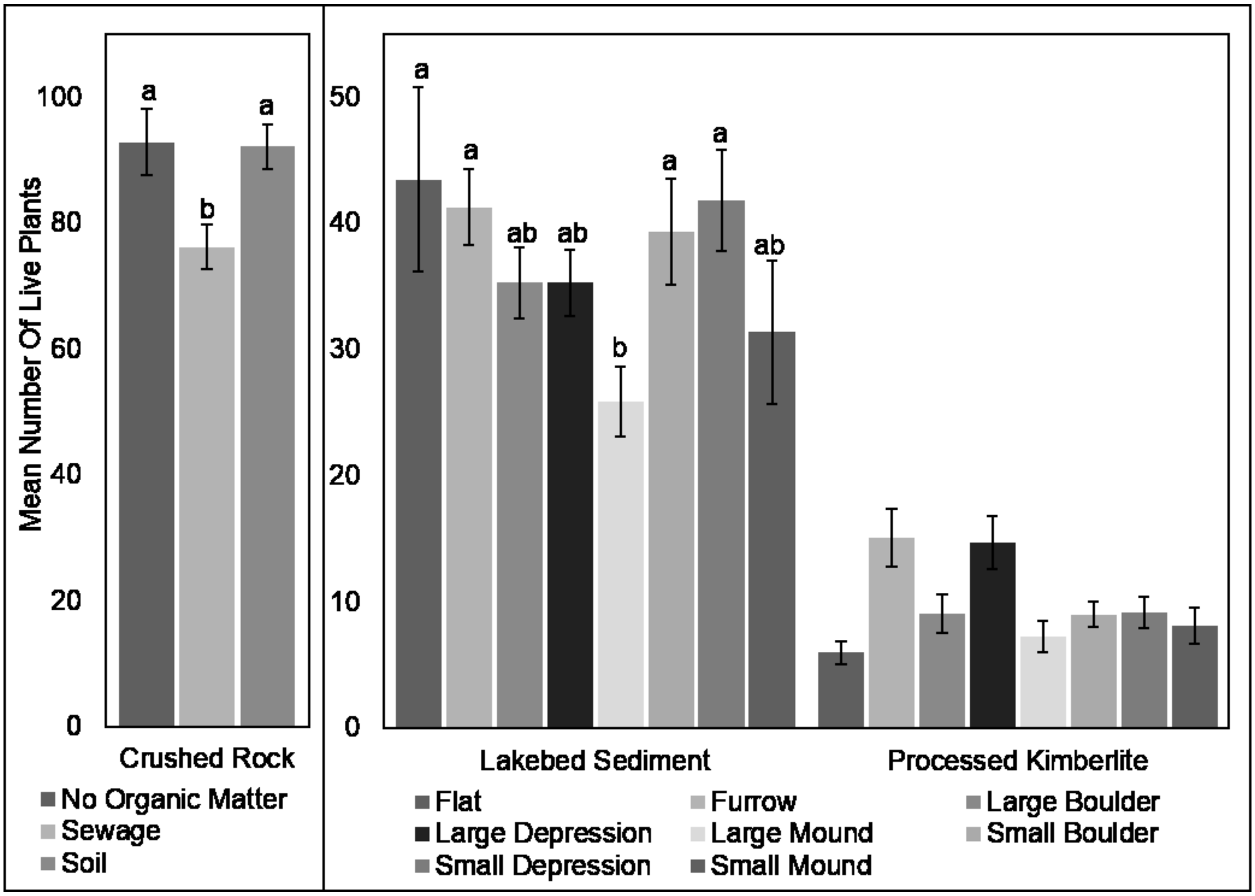

Figure 5.4. Mean number of live plants (± SE) in year 3. Significant differences between micro topography or organic amendment treatments are denoted by letters within each substrate (scales are different and processed kimberlite was not statistically compared).

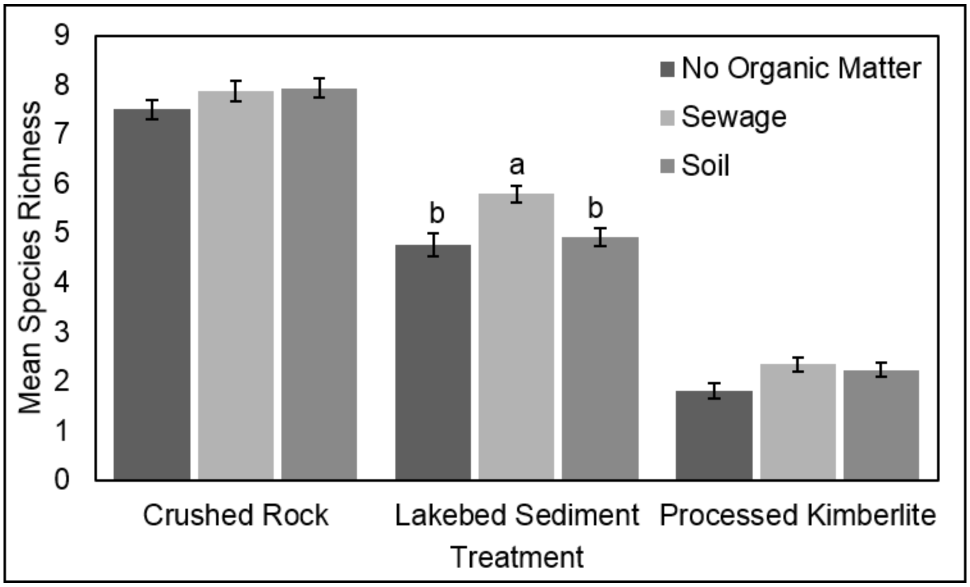

Figure 5.5. Mean species richness (± SE) in year 3. Significant differences between organic treatments are denoted by letters within each substrate and variable (processed kimberlite was not statistically compared).

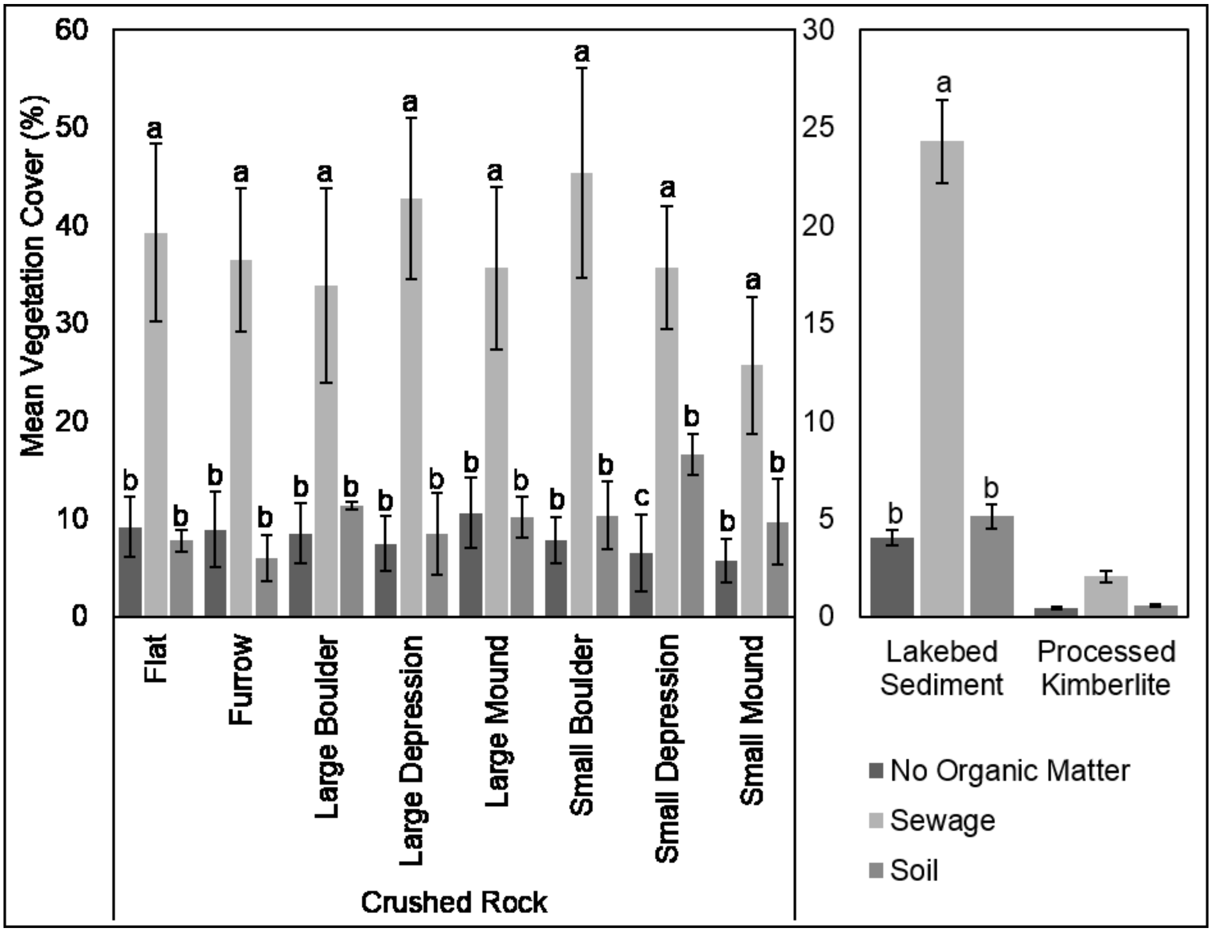

Figure 5.6. Mean vegetation cover (± SE) including grass, forbs, shrubs, moss, lichen and algae in year 4. Significant differences between organic treatments are denoted by letters within each substrate (processed kimberlite was not statistically compared).

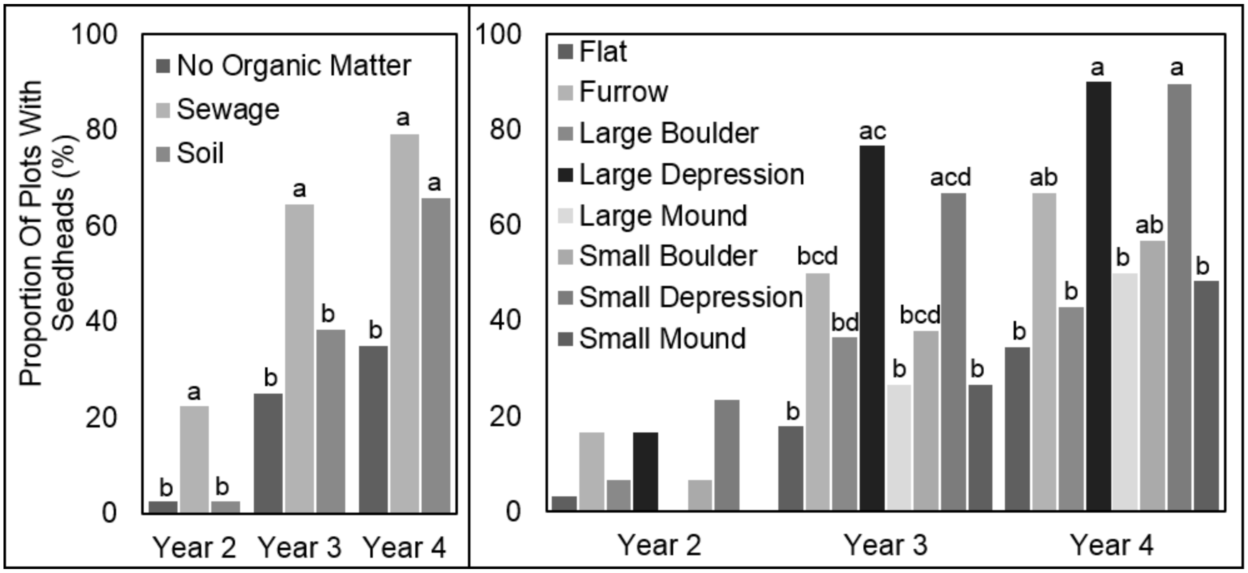

Figure 5.7. Proportion of processed kimberlite plots with seedheads in years 2, 3 and 4. Significant differences are denoted by different letters within each year.

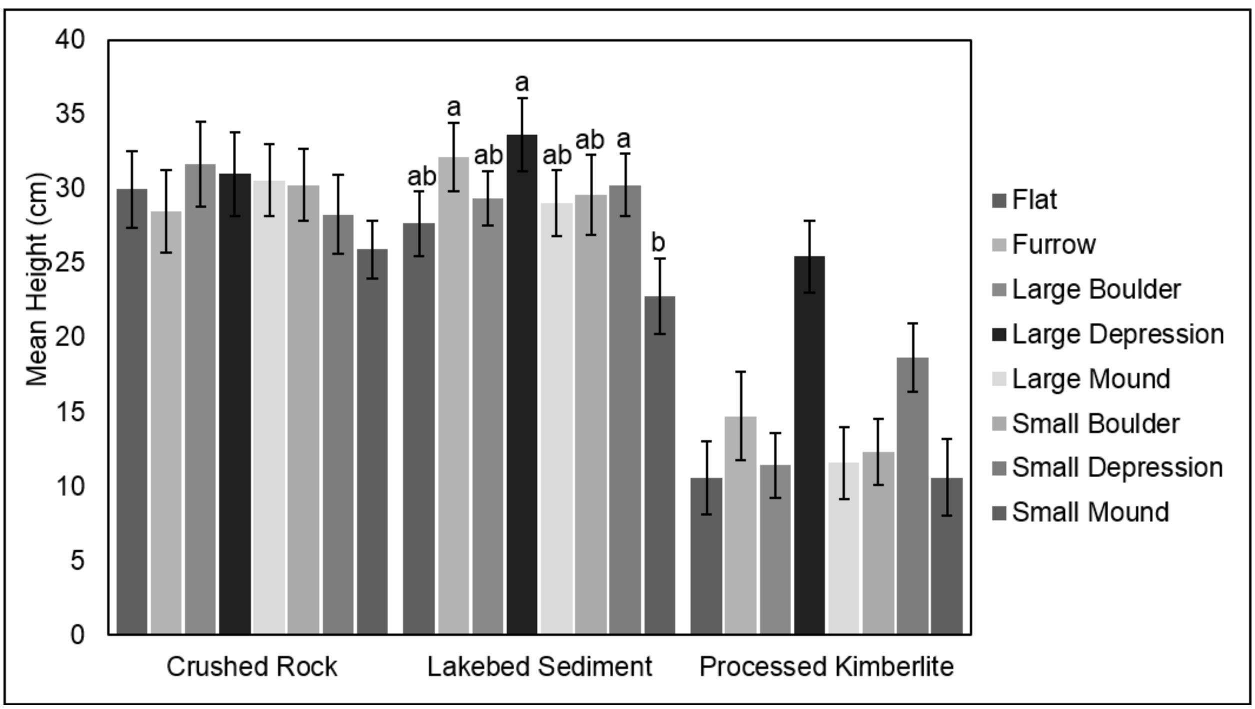

Figure 5.8. Mean height (± SE) in year 4. Significant differences between micro topography treatments are denoted by letters within each substrate (processed kimberlite was not statistically compared).

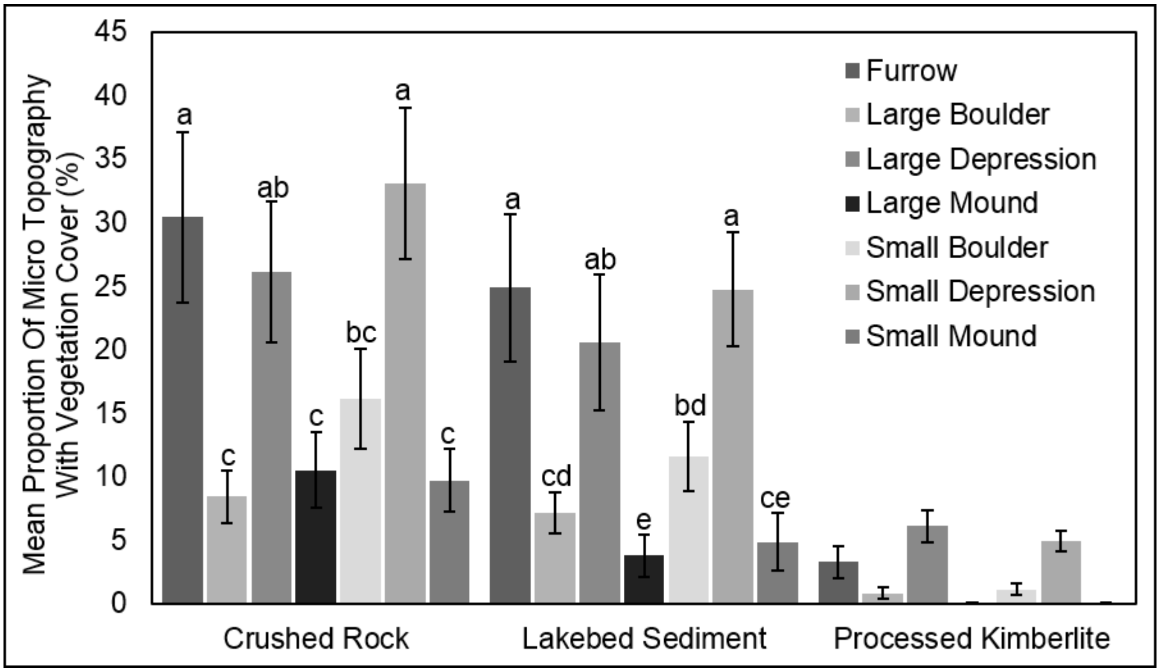

Figure 5.9. Mean proportion of micro topography with vegetation coverage (± SE) in year 4. Significant differences are denoted by different letters within each substrate (processed kimberlite was not statistically compared).

VI. SHORT TERM EROSION CONTROL METHODS TO ENHANCE PLANT ESTABLISHMENT AND GROWTH AT A NORTHERN DIAMOND MINE

1. INTRODUCTION

Erosion is a challenge at many disturbed sites and can negatively impact reclamation. It can cause loss of topsoil, nutrients or amendments (Edeso et al. 1999, Nicolau 2002, Gyasi-Agyei 2004, Rickson 2006, Naeth and Wilkinson 2011, Álvarez-Mozos et al. 2014), reduced availability of water (Nicolau 2002, Rickson 2006), loss of seeds and vegetative propagules (Gyasi-Agyei 2004, Rickson 2006), poor vegetation establishment and growth (Moreno-de las Heras et al. 2008, Naeth and Wilkinson 2011, Álvarez-Mozos et al. 2014) and contamination of downstream systems (Faucette et al. 2005, Rickson 2006, Bhattarai et al. 2011).

Disturbed sites can be prone to erosion when removal or lack of vegetation leaves the surface exposed (Edeso et al. 1999, Loch 2000, Rickson 2006). Changes to topography, such as slope development, can increase runoff velocity and erosion (Rickson 2006, Álvarez-Mozos et al. 2014). Smoothing sites (He et al. 2008) can increase erosion as flat areas do not slow wind or water. Site and reclamation activities can damage soil structure through compaction, breakdown of aggregates, low water content or removal of organic matter and vegetation, leaving a material with greater erosion risk (Edeso et al. 1999, Rickson 2006, He et al. 2008). Materials used to build soils, such as processed kimberlite, may have erosion prone properties, such as a high proportion of sand, lack of organic matter and aggregation and a smooth surface.

Erosion control methods can reduce raindrop impact on soil surface, which causes soil displacement and/or surface sealing (Ben-Hur 1994, Bhattarai et al. 2011, Chen et al. 2011); increase water retention and infiltration (Bhattarai et al. 2011, Chen et al. 2011); reinforce soil against disturbance and increase stability (Ben-Hur 1994, Chen et al. 2011); divert water from sensitive areas; or slow surface velocity of water and wind (Bhattarai et al. 2011, Chen et al. 2011). Methods include vegetation establishment, recontouring, amendments, blankets or mats and geotextiles, mulch and addition of polymers. Long term erosion control is best met through vegetation establishment (Younkin and Martens 1987, Agassi and Ben-Hur 1992, Loch 2000, Nicolau 2002, Gyasi-Agyei 2004, Rickson 2006). Sites are at risk from erosion while vegetation is establishing, therefore immediate methods are often required.

Selection of appropriate methods is generally based on the primary cause of erosion (Chen et al. 2011) and site characteristics. Chen et al. (2011) found a woven mat had high coverage so reduced raindrop impact and slowed runoff initiation as it adsorbed water, but was thin with low roughness which limited soil trapping and deposition or reduction of runoff energy. Faucette et al. (2005) found compost mulches and hydroseeding reduced soil loss, with slightly greater success from mulches as they adsorb more water, increase infiltration and slow runoff. However, nutrients in mulches may be released after initial placement negatively impacting downstream systems (Faucette et al. 2005). A newer technique is polymers or soil conditioners which form bonds between soil particles based on charges of materials, reducing seal formation, increasing soil stability and infiltration and reducing runoff and erosion (Agassi and Ben-Hur 1992, Ben-Hur 1994). Soil texture influences success and polymer lifespan is quite short (He et al. 2008).

Selection of short term erosion control methods requires consideration of vegetation establishment as methods can impact vegetation success; however, research is limited. Price et al. (1998) found straw mulch increased interception of precipitation, but decreased evaporation, resulting in greater soil water and reducing temperature fluxes and creating a more suitable surface for *Sphagnum* revegetation. Houle and Babeux (1994) found limited and variable effects of plastic or organic mulch on survival and growth of woody species in subarctic Quebec. Materials with high surface coverage may be difficult for plants to germinate beneath or emerge through, whether seeding is conducted under or on the material (Densmore et al. 2000, Gyasi-Agyei 2004, Chen et al. 2011). Álvarez-Mozos et al. (2014) found quicker vegetation establishment on slopes with synthetic geotextiles relative to no treatment, but little growth improvement. Cover crops can provide erosion protection, but may reduce native, slow growing species, especially if non-native, mat forming and long lasting (Younkin and Martens 1987, Moreno-de las Heras et al. 2008).

The objective of this experiment was to assess vegetation response to erosion control methods on mine waste at Diavik Diamond Mine in the Northwest Territories, Canada. Mining in the Canadian north increased since the 1990s with the discovery of diamonds (Baker et al. 2001, Bryan and Bonner 2003) and easier access to remote sites, resulting in greater disturbances. Northern sites can be sensitive to erosion due to thin soils that may be disturbed, removed or buried; and slow decomposition and limited seed production, dispersal, plant establishment and growth (Bliss 1962, Johnson 1987, Bishop and Chapin III 1989b, Deshaies et al. 2009) which results in greater bare ground. Waste materials used to build soils, such as crushed rock and processed kimberlite, tend to be prone to erosion with their poor structure and texture and lack of aggregation and organic matter. Assessment of effective erosion control methods for reclamation is essential as disturbances in the north continue to increase.

2. MATERIALS AND METHODS

2.1 Research Site

Diavik Diamond Mine is located approximately 300 km northeast of Yellowknife, Northwest Territories, Canada, on East Island, a 20 km^2 area at the east end of Lac de Gras (latitude 64°30′41″, longitude 110°17′23″). Diavik is in tundra in the low arctic, approximately 100 km north of the treeline (Diavik Diamond Mine Inc. 2010b). It has short, cool summers and long, cold winters. January is coldest, averaging -27.2 ºC, and July warmest, averaging 13.2 ºC (Diavik Diamond Mine Inc. 2012). Permafrost ranges from 1 m in wet areas and 5 m in bedrock (Diavik Diamond Mine Inc. 2010b). Average annual precipitation is 305.8 mm, 169.5 mm snow and 136.3 mm rain (Diavik Diamond Mine Inc. 2012). Precipitation peaks in August or September and November; snow melt occurs in early June. Site construction began in 2001 and production in 2003 as an open pit mine, transitioning to an underground mine in 2013 and back to both in 2018. Construction of pits and processing of ore resulted in stockpiling of waste material including processed kimberlite, lakebed sediment or till (hereafter lakebed sediment) and crushed rock.

2.2 Experimental Design And Treatments

The research site was 3 blocks at the former magazine storage facility, consisting of raised crushed rock (granite waste rock with < 0.04 wt % sulphur) pads on natural eskers. Each block was divided into 3 equal sized plots with processed kimberlite, lakebed sediment or no substrate added (crushed rock). Fine processed kimberlite, material less than 1 mm, collected from the containment facility where it was placed as a slurry to dry at least a year earlier, was placed in a 50 cm layer. Lake sediment, material removed from pits after diking and with water pumped out, was placed in a 50 cm layer. All materials were tilled June 2013 with an excavator to loosen the surface and remove sparse vegetation. Crushed rock had the largest proportion of surface material over 5 cm and processed kimberlite the lowest (Chapter V). Lakebed sediment had the highest silt and clay content and crushed rock and processed kimberlite had more sand. Substrates had low organic carbon and total nitrogen and neutral to slightly basic pH; lakebed sediment and processed kimberlite electrical conductivity was over 2 dS m^{-1} (Chapter V).

Experimental design was a complete randomized block with 5 erosion control treatments x 3 substrates = 15 combinations. Blocks 1 and 3 had two replicates and block 2 one replicate. Erosion control treatments were control, Soil Lynx, treated jute, treated jute with Soil Lynx and erosion control blanket. Soil Lynx is an anionic polymer aimed at reducing erosion that creates a chemical bond between soil particles when activated with water (Clearflow Group Inc. 2015). Treated jute is a natural fiber biodegradable netting embedded with Soil Lynx from Clearflow Group Inc., 55 % ground cover and 4.7 mm thickness. Treated jute with Soil Lynx included application of Soil Lynx before and after placement of treated jute. Erosion control blanket was 100 % biodegradable double net 100 % coconut fiber (C32 BD), 87 % ground cover and 6.6 mm thickness (Cascade Geotechnical Inc.).

Plots 1 x 1 m were laid in a grid, with 0.75 m buffers, and smoothed to create relatively level surfaces. Plots were broadcast seeded in late June 2014 with 6 grasses, wild collected in the Northwest Territories by researchers at Aurora Research Institute. Seeding rates were based on available seed amounts, resulting in approximately 0.7 g m^{-2} (1,300 seeds) (Table 6.1). Before and after seeding, plots were lightly raked for seed-soil contact. Before seeding, plots were watered with approximately 1.2 L.

After seeding, erosion control was applied. For Soil Lynx, approximately 1.7 g of Soil Lynx was applied evenly (16.7 kg ha^{-1} based on Clearflow Group Inc. rate for flat areas). For treated jute and erosion control blanket, shallow trenches were dug on all sides and edges of material secured with staples in the trenches which were filled with substrate. For treated jute with Soil Lynx, Soil Lynx was applied followed by jute and then Soil Lynx again, using methods above. After application of erosion control, 1.5 L of water was applied to plots.

2.3 Vegetation Measurements

Vegetation was assessed during peak plant production (July to August) using 0.75 x 0.75 m quadrats in the centre of each plot. A walk through was conducted annually to observe erosion and large scale growth patterns. Erosion control blankets were not removed, although assessments included vegetation that had not emerged through the blanket when it was visible from above. In year 1 (2014), plants were counted as grass or forb (live and dead separately) due to species identification challenges. Evidence of grazing, other animal activity (feces, tracks) and presence of moss were recorded. General comments about health and stage of development were recorded.

In years 2 and 3, number of live stems by species was counted. Cover was visually assessed from above to 0.5 % as vascular vegetation (grass, forbs, shrubs) and moss, lichen and algae. In the third growing season, litter (including erosion control blanket and jute) and anthroposol were also assessed. Trace was recorded if cover was less than 0.5 %. Average height of live plants was estimated to 0.5 cm. Plant health was visually assessed for the plot and scored using a six point scale, from 1 for healthy plants and 6 for dead. General comments about stage of development were recorded, including presence of seedheads. Evidence of grazing and other animal activity (feces, tracks) were recorded.

In year 4, cover was visually assessed to 0.5 % as grass; forbs; shrubs; moss, lichen and algae; litter (including erosion control blanket and jute); and anthroposol. Trace was recorded if cover was less than 0.5 %. Dominant, healthy and unhealthy species were recorded. Average height of live plants was estimated to 0.5 cm. Plant health was visually assessed for the plot and scored using the six point scale. Presence of seedheads was recorded.

2.4 Data Analyses

Substrates were not compared due to primary interest in techniques to improve vegetation response in each substrate. As processed kimberlite had poor growth (maximum less than 0.6 % cover by year 4), data were visually assessed. For crushed rock and lakebed sediment, only key variables were statistically analyzed (vegetation cover, number of live plants, richness) due to small sample sizes and large variation. Health, mean height and moss, lichen and algae cover were visually assessed using mean and standard error in all years.

Vegetation cover pooled grass, forb, shrub, moss, lichen and algae cover. To calculate species richness and diversity (using Shannon Weiner H Index), unknown species were removed. Shannon Weiner H was calculated using $-\Sigma(P_i \ln P_i)$ where Pi is proportion of species i relative to total number of samples.

Data were analyzed with R Studio 3.4.0 (2017). A p value of 0.05 was used for all analysis. Replicate treatment plots were averaged within blocks to account for variation. Correlation between years was assessed using Pearson and Spearman rank correlations with a Holm Bonferroni correction. Between years, vegetation cover showed moderate to very strong correlation (ρ = 0.4 to 0.9) and number of live plants showed moderate to very strong correlation (ρ = 0.5 to 0.9, r = 0.9); due to some moderate correlations, all years were assessed. Species richness and diversity were very strongly correlated (ρ = 0.8 to 1.0) in years 2 and 3 therefore only richness was analyzed due to better meeting of assumptions. Between years, richness showed strong correlation (ρ = 0.8, r = 0.7) therefore only year 3 was assessed.

One way ANOVA with block as a random factor followed by Tukey post hoc analysis was used when variables met assumptions (crushed rock, year 3 richness, years 2 and 4 vegetation cover;

lakebed sediment with variables log 10 transformed, years 1 and 3 number of live plants, year 4 vegetation cover). Welch's ANOVA followed by pairwise t-tests using non-pooled standard deviation with Holm-Bonferroni correction were used when variables did not meet homogeneity of variance assumptions (crushed rock, years 1 to 3 number of live plants, year 3 vegetation cover; lakebed sediment, year 2 number of live plants, year 3 richness, years 2 and 3 vegetation cover). Categorical data were assessed using Fisher Exact analysis (assumptions for Chi-square not met) within each substrate followed by testing subsets of the data to determine differences. To account for multiple analyses, p values were corrected with Holm Bonferroni.

3. RESULTS

3.1 Vegetation Response

Number of live plants was highest in crushed rock and lowest in processed kimberlite (Figure 6.1). It increased in lakebed sediment each year and in crushed rock between years 1 and 2, with a slight decline in year 3. It varied little over time in processed kimberlite. In crushed rock, number of plants was generally lowest with Soil Lynx and highest with treated jute and treated jute with Soil Lynx, although differences were not significant (Table 6.2). In lakebed sediment, plant number was lowest in control and highest with erosion control blanket and treated jute in all years (Table 6.2); lack of statistical significance in year 2 with Soil Lynx and control was likely due to greater variability with erosion control blankets. In processed kimberlite, plant number was lowest in control and Soil Lynx in all years and highest with treated jute with Soil Lynx in all years and erosion control blanket in year 1. Treated jute and erosion control blanket were also higher than Soil Lynx and control in all years. There were few dead plants in most treatments, except processed kimberlite in year 2 (control, treated jute, treated jute with Soil Lynx) and year 3 (treated jute with Soil Lynx) with over 5 dead.

Species richness was greatest in crushed rock and lowest in processed kimberlite (Figure 6.2). While not statistically different (Table 6.2), richness was highest with treated jute and lowest with erosion control blanket in crushed rock, and highest with erosion control blanket and treated jute and lowest with control in lakebed sediment. In processed kimberlite, species richness was always under 2, but was greater with treated jute, treated jute with Soil Lynx and erosion control blanket than Soil Lynx and control.

Vegetation cover was greatest in crushed rock and lowest in processed kimberlite, increasing annually except in processed kimberlite (Figure 6.3), though low overall. In crushed rock, cover was not significantly affected by treatment (Table 6.2) although in year 4 it was slightly greater with Soil Lynx and treated jute. Elevated Soil Lynx cover was from a large *Hedysarum* sp. (sweetvetch) growing. In lakebed sediment, cover was greatest with erosion control blanket and treated jute and lowest with control, although only statistically different in year 4 (Table 6.2, Figure 6.3). Processed kimberlite cover was low all years; highest with treated jute in year 4 at 0.6 %. Moss, lichen and algae cover was low in years 2 and 3 in crushed rock and lakebed sediment (under 0.5 %), and under 0.1 % in processed kimberlite in all years (Figure 6.4). Cover was greatest in crushed rock in year 4, with treated jute and treated jute with Soil Lynx having greatest cover and control and erosion control blanket least. In lakebed sediment, cover was greatest with erosion control blanket and treated jute and lowest with Soil Lynx. Forb cover was low in all substrates (under 0.5 %) except in crushed rock with Soil Lynx.

Plant height increased each year, being taller in crushed rock and lakebed sediment than processed kimberlite (Figure 6.5). Treatment differences were small with high variability. In crushed rock, treatment with tallest and shortest plants varied each year. In lakebed sediment, plants were generally tallest in erosion control blankets and shortest in control. In processed kimberlite, shortest plants were in control and Soil Lynx.

Plant health decreased in crushed rock over time and increased in lakebed sediment and processed kimberlite (Figure 6.6). Crushed rock and lakebed sediment had small treatment differences, other than year 2 when plants were least healthy in crushed rock with erosion control blankets, and healthiest in lakebed sediment with erosion control blankets and least healthy in control. In processed kimberlite, plants were least healthy in control and Soil Lynx.

There was no significant effect of treatment on seedhead or grazing in any year. In year 3, it approached significance ($P = 0.0842$), with evidence of grazing lowest in control (0 of 5 plots) and greatest with erosion control blanket and treated jute (4 of 5 plots).

3.2 Species Differences

Slender wheat grass was the most abundant seeded species in all substrates (Table 6.3). In crushed rock in both years and lakebed sediment in year 3, alpine blue grass and spike trisetum were common. Unknown grasses due to small size were common in all substrates, as well as unseeded *Epilobium angustifolium* L. (fireweed) and other *Poa* species (likely dominated by *Poa glauca* Vahl (glaucous blue grass) seeded in adjacent plots for the main experiment (Chapter V)) in crushed rock and lakebed sediment.

3.3 Material Loss In Erosion Treatments

Based on visually comparing material loss, there was less with treated jute over 4 years than with erosion control blankets which had begun to decompose, becoming much thinner and patchier. Between years 3 and 4, there was less than 4 % difference in litter cover (included jute and blankets) in treated jute plots; cover in erosion control blanket plots decreased from 85 % to 28 %. This cover includes litter in addition to the blanket or jute, but these numbers and visual observations indicate that erosion control blankets are decomposing quicker than jute.

4. DISCUSSION

The presence of a physical layer, such as jute and erosion control blankets, better supported vegetation establishment and growth than Soil Lynx, especially in lakebed sediment and processed kimberlite. While erosion control treatments increased vegetation establishment and growth in many cases, overall success was low relative to amended plots (Chapter V), indicating erosion control treatments alone are not effective as a reclamation treatment.

Lack of effectiveness of Soil Lynx may be due to sandy texture of substrates and more rapid degradation than other materials (He et al. 2008); a single application (recommended annually He et al. 2008); and lack of physical protection, relative to mats and blankets. Activated by water (Hanna 2018), drier conditions in the growing season may have reduced its effectiveness after initial watering. Lack of cations could reduce effectiveness as they act as bridges between soil particles and Soil Lynx (Theng 1982, Agassi and Ben-Hur 1992, Ben-Hur 1994, Hanna 2018).

Unlike Soil Lynx, jute mats and erosion control blankets created a physical barrier against wind and water erosion, which reduces runoff velocity, raindrop impact, material loss and crust formation and increases water storage and infiltration (Ben-Hur 1994, Gyasi-Agyei 2004, Faucette et al. 2005, Chen et al. 2011). As a physical barrier, they can prevent loss of seeds on site, collect seeds being transported from adjacent areas (Gyasi-Agyei 2004) and provide a stable soil structure for plants to establish relative to exposed surfaces (Chen et al. 2011, Cohen-Fernández and Naeth 2013). As mats and blankets degrade, organic matter will be added to substrates, improving their properties (Rickson 2006, Bhattacharyya et al. 2012). Materials can conserve water and moderate and reduce temperature (Cohen-Fernández and Naeth 2013, Naeth et al. 2018), which may improve germination and emergence; however, reducing soil temperatures in a cold climate may not be beneficial. Cohen-Fernández and Naeth (2013) found erosion control blankets on soil capped slopes in limestone quarries resulted in highest seeded plant cover and lowest non-seeded cover relative to other amendments. Bhattacharyya et al. (2012) found greater biomass of seven crops grown with biological mats.

Selecting jute mats or erosion control blankets is dependent on several factors, including coverage and roughness (Chen et al. 2011, Álvarez-Mozos et al. 2014). Although rough materials increase soil deposition, slow runoff and increase infiltration relative to smooth materials (Rickson 2006, Bhattarai et al. 2011, Chen et al. 2011), coverage may be lower. Materials with high coverage provide greater surface protection from raindrop impact and disperse runoff, but may be smoother and can reduce seedling emergence and slow growth as plants struggle to penetrate (Densmore et al. 2000, Gyasi-Agyei 2004, Chen et al. 2011). In our research, erosion control blankets had greater coverage than jute with its larger gaps, but jute was rougher. Coverage may impact germination by reducing temperature and light at the soil surface. Mollard and Naeth (2014) found greater germination of prairie species under erosion control blankets than in direct sunlight or full darkness, although our seeded species showed inconsistent patterns of light and dark germination.

Desired lifespan of material is important. After 4 years, erosion control blankets showed a high degree of loss whereas jute showed little degradation. In arctic environments with slow vegetation response, a long lasting material may be more successful in the long term. Success of mat and blanket treatments varied between substrates. Jute was more successful in crushed rock, although differences were small, jute and erosion control blankets were most successful in lakebed sediment and jute with Soil Lynx in processed kimberlite. The variation between treated jute and treated jute with Soil Lynx is unexpected due to the limited effect of Soil Lynx alone and requires further assessment.

The inconsistent and small effect across years and variables of erosion control treatments in crushed rock clearly indicates that applying treatments had less of an effect relative to other substrates. Its rough surface reduces erosion risk as it slows wind and water speed, increases water infiltration and decreases material loss (Chambers et al. 1991, Johnson and Fryer 1992, Nicolau 2002, Gyasi-Agyei 2004, Bhattarai et al. 2011). The rough surface collects loose material, nutrients and seeds and provides micro sites for seed germination and plant growth (Elmarsdottir et al. 2003, Gyasi-Agyei 2004, Macdonald et al. 2015, Kokulan et al. 2018). Greater plant establishment reduces erosion risk long term as it reduces raindrop impact and runoff velocity and increases infiltration and substrate stability through root growth (Agassi and Ben-Hur 1992, Edeso et al. 1999, Loch 2000, Gyasi-Agyei 2004, Rickson 2006, Moreno-de las Heras et al. 2009). Nicolau (1996) found runoff was three times less with 100 % vegetation cover than 50 %, and infiltration capacity was four to five times greater over time. Reduced erosion risk did not result from erosion control treatments and therefore use is unwarranted, especially due to high costs. On steep slopes, crushed rock should be assessed for erosion risk.

Processed kimberlite was at greater erosion risk than other substrates due to its sand texture, smooth surface with a lack of rocks and little vegetation (Agassi and Ben-Hur 1992, Edeso et al. 1999, Loch 2000, Arnalds and Kimble 2001, Gyasi-Agyei 2004, He et al. 2008, Naeth and Wilkinson 2011). As processed kimberlite has a relatively smooth surface, naturally lacking micro topographic variability, there is a greater risk of loss of seeds by wind and water (Chambers et al. 1991), reducing vegetation establishment. Plots in processed kimberlite had loose material on top of erosion control blankets, in jute mat openings and on Soil Lynx and control plots. The physical barrier created by jute and erosion control blankets resulted in greater plant establishment and growth in this erosion prone material relative to control and Soil Lynx. Processed kimberlite was unsuccessful regardless of treatment used relative to other substrates with poor establishment and growth after 4 years; therefore erosion strategies alone do not play a large role.

Lakebed sediment's erosion risk is between crushed rock and processed kimberlite. It's fine texture can be erosion prone (Naeth and Wilkinson 2011), although there was little visual loss of material, potentially due to its hardness when dry. Water erosion is likely a greater risk than wind due to softening of the material when wet. The hard surface with less micro topography can result in low infiltration, increasing runoff volume and decreasing plant available water, and water and wind moving across the surface quickly causing loss of seeds and loose material (Chambers et al. 1991, Nicolau 1996, Edeso et al. 1999). Compaction and smoother surfaces can reduce germination as surface lying seeds have poor root anchorage and radicle penetration (Sheldon 1974, Jumpponen et al. 1999) and buried seeds have difficulty emerging. Fine textured materials negatively affect root growth (Tsuyuzaki et al. 1997). Areas where lakebed sediment had a greater presence of rocks would likely be at reduced risk, due to increased roughness as seen in crushed rock. Erosion control blankets and jute mats improved vegetation response relative to Soil Lynx or control as they can address many challenges in this substrate, such as providing a physical barrier to collect seeds, slowing water movement and increasing infiltration.

The study area presented some experimental design challenges. The plots are flat and thus do not represent areas of high erosion risk. Steep slopes lacking vegetation are a major challenge because revegetation is difficult, erosion control methods have reduced effectiveness and loss of sediment to downstream systems can be damaging (Agassi and Ben-Hur 1992, Chen et al. 2011). Spring snow melt can result in large amounts of water moving across the landscape, posing greater risks for erosion (Younkin and Martens 1987); however, these plots are elevated gravel pads and therefore are not impacted by water movement from the rest of the landscape. Assessment of erosion control in areas with slopes and large water collection zones is essential.

Experimental plots were surrounded by areas without erosion control from which materials entered, especially in processed kimberlite. Large plots with greater distance between treatments and buffers with restricted erosion should be assessed to reduce edge effect. More plots are required as the small sample size and high variability in many variables limited ability to determine significant treatment effects. Plant growth was low regardless of treatment, thus erosion control alone may not be effective. Substrate limitations should be addressed with amendments (Drozdowski et al. 2012, Miller and Naeth 2017) combined with erosion control.

5. CONCLUSIONS

Erosion control treatments alone did not have major improvements on plant response. While increases were small, erosion control blankets or jute mats generally improved vegetation response in processed kimberlite and lakebed sediment, which are at greater risk of erosion than crushed rock. Crushed rock, due to its rough surface, is less prone to erosion and treatments generally showed little improvement, and are therefore likely not needed on this material. Soil Lynx was not effective for erosion control. Erosion control treatments should be assessed in combination with amendment addition, which can improve vegetation establishment and growth. As Diavik Diamond Mine is remotely located, effectiveness of erosion control treatments must be confirmed so as not to bring additional materials to site.

Table 6.1. Seeded species at research plots.

Species	Common Name	Collection Location[1]	Collection Habitat	Percent Of Seed Mix[2]	Light Germination (%)	Dark Germination (%)
Arctagrostis latifolia (R. Br.) Griseb.	Wideleaf polargrass	Mackenzie Delta/ uplands, Liard, Edzo	Thaw slump, exposed site, old burn site, wet meadow	9.6	38[3] 28	46 14
Calamagrostis purpurascens R. Br.	Purple reedgrass	Mackenzie Delta/ uplands, Hay Rover, Rae Edzo, Inuvik	Thaw slump, gravel area, off winter road access, gravel slope, thaw slump	6.9	30 16	24 12
Deschampsia caespitosa (L.) P. Beauv.	Tufted hairgrass	Hay River	Gravel area	34.9	86	52
Elymus trachycaulus (Link) Gould ex Shinners	Slender wheat grass	Edzo, Yellowknife	Gravel pit, Canadian Shield	12.1	76	22
Poa alpina L.	Alpine blue grass	Inuvik, Fort Good Hope	Wet roadside depression, off access to winter road	13.0	58	66
Trisetum spicatum (L.) K. Richt.	Spike trisetum	Mackenzie Delta/uplands	Thaw slump	23.5	66	74

[1]All collection locations are in Northwest Territories and collected between 2005 and 2007.
[2]Percent of seed mix is based on the total number of seeds applied. Amount of seed is based on amounts available.
[3]Where there were multiple seed sources of species, germination of each was tested before pooling together.

Table 6.2. Statistical analyses for vegetation response variables in crushed rock and lakebed sediment.

Variable	Crushed Rock	Lakebed Sediment
Number Of Live Plants Year 1	F = 0.229, P = 0.910	F = 8.880, P = 0.005
Number Of Live Plants Year 2	F = 0.980, P = 0.497	F = 15.258, P = 0.006
Number Of Live Plants Year 3	F = 5.514, P = 0.053	F = 6.539, P = 0.012
Species Richness Year 3	F = 3.299, P = 0.071	F = 1.328, P = 0.379
Vegetation Cover Year 2	F = 0.293, P = 0.874	F = 1.519, P = 0.348
Vegetation Cover Year 3	F = 0.147, P = 0.956	F = 11.947, P = 0.012
Vegetation Cover Year 4	F = 0.934, P = 0.491	F = 6.981, P = 0.010

Table 6.3. Mean (± SE) number of live plants in years 2 and 3 of seeded species and other dominant species.

Species	Year 2			Year 3		
	Crushed Rock	Lakebed Sediment	Processed Kimberlite	Crushed Rock	Lakebed Sediment	Processed Kimberlite
Arctagrostis latifolia	0.1 (0.1)	0.0 (0.0)	0.0 (0.0)	0.2 (0.3)	0.0 (0.0)	0.0 (0.0)
Calamagrostis purpurascens	0.2 (0.3)	0.0 (0.1)	0.0 (0.0)	0.1 (0.2)	0.1 (0.2)	0.0 (0.0)
Deschampsia caespitosa	7.0 (2.8)	1.1 (0.7)	0.0 (0.1)	5.8 (2.2)	2.5 (2.1)	0.0 (0.0)
Elymus trachycaulus	30.3 (6.5)	12.9 (5.1)	17.1 (8.9)	22.6 (5.7)	15.3 (5.7)	12.1 (5.7)
Poa alpina	11.2 (2.9)	1.9 (1.5)	0.0 (0.0)	11.6 (3.3)	4.8 (2.7)	0.1 (0.1)
Trisetum spicatum	12.7 (3.4)	1.8 (1.6)	0.0 (0.1)	15.4 (2.8)	5.4 (3.7)	0.3 (0.4)
Epilobium angustifolium	5.4 (5.2)	0.5 (1.1)	0.0 (0.0)	5.0 (6.4)	0.4 (0.5)	0.0 (0.0)
Other *Poa* Sp.	0.8 (0.5)	0.4 (0.4)	0.1 (0.1)	1.6 (1.2)	1.4 (0.7)	0.1 (0.2)
Unknown Grass Sp.	1.3 (0.9)	1.4 (1.3)	0.3 (0.4)	0.6 (0.5)	1.4 (0.9)	0.4 (0.4)

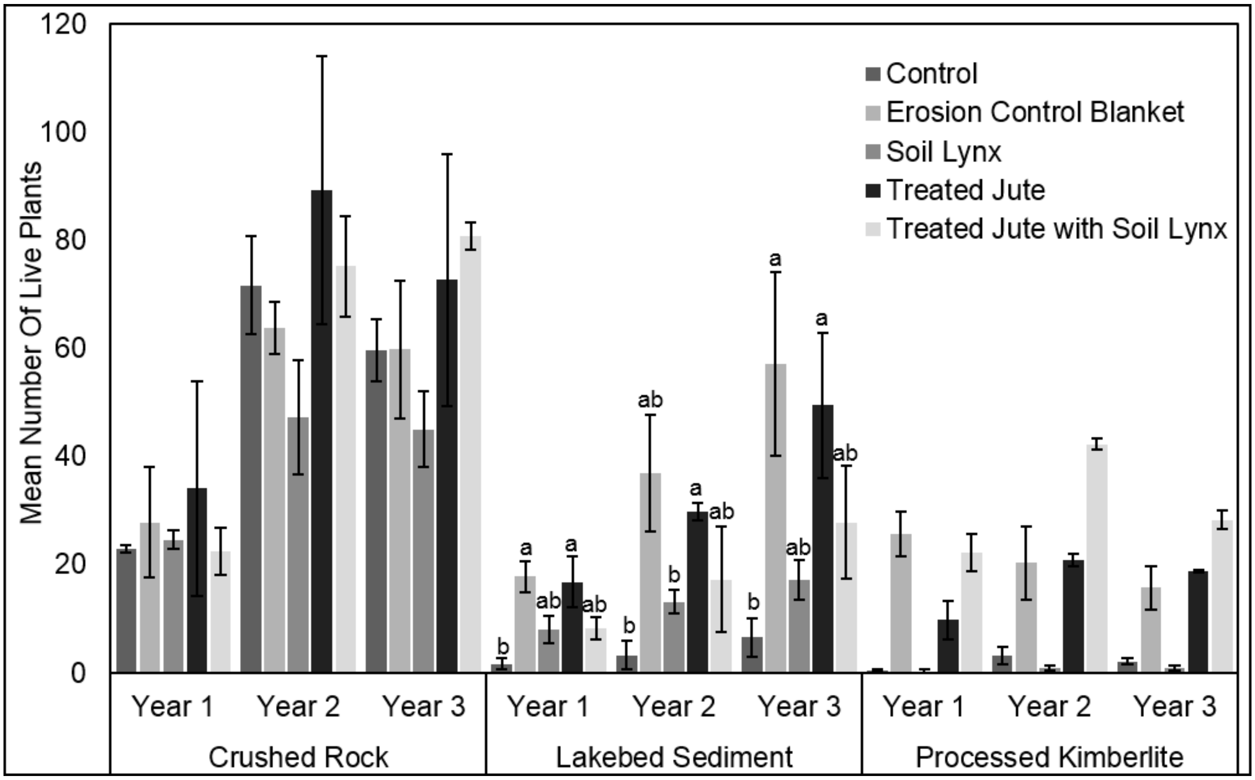

Figure 6.1. Mean number of live plants (± SE) in years 1 to 3. Significant differences between erosion control treatments are denoted by letters within each substrate (note that processed kimberlite was not statistically compared).

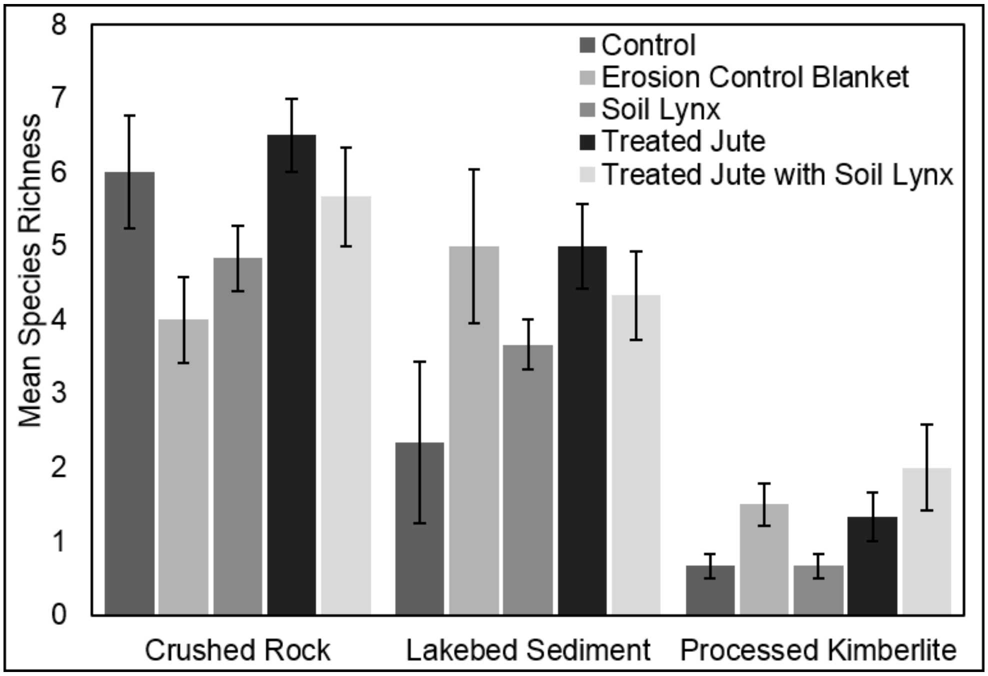

Figure 6.2. Mean species richness (± SE) in year 3. Significant differences between erosion control treatments are denoted by letters within each substrate (note that processed kimberlite was not statistically compared).

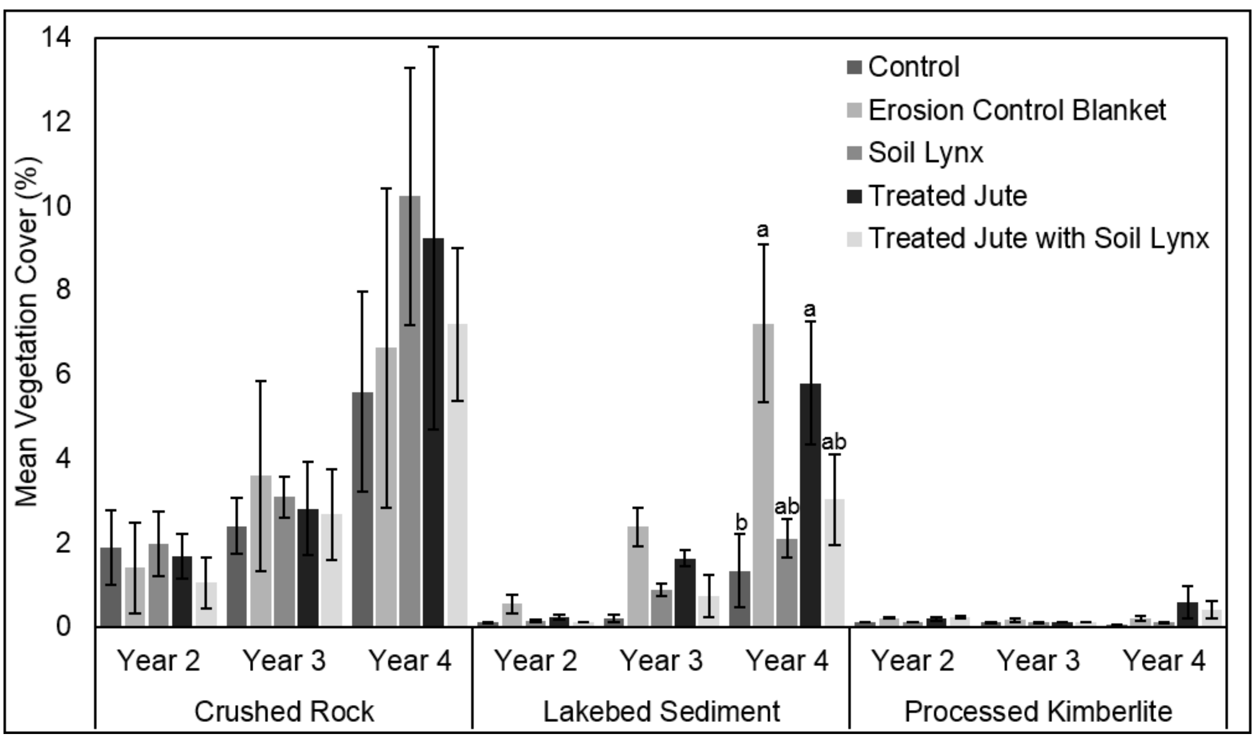

Figure 6.3. Mean vegetation cover (± SE) in years 2 to 4. Significant differences between erosion control treatments are denoted by letters within each substrate (note that processed kimberlite was not statistically compared).

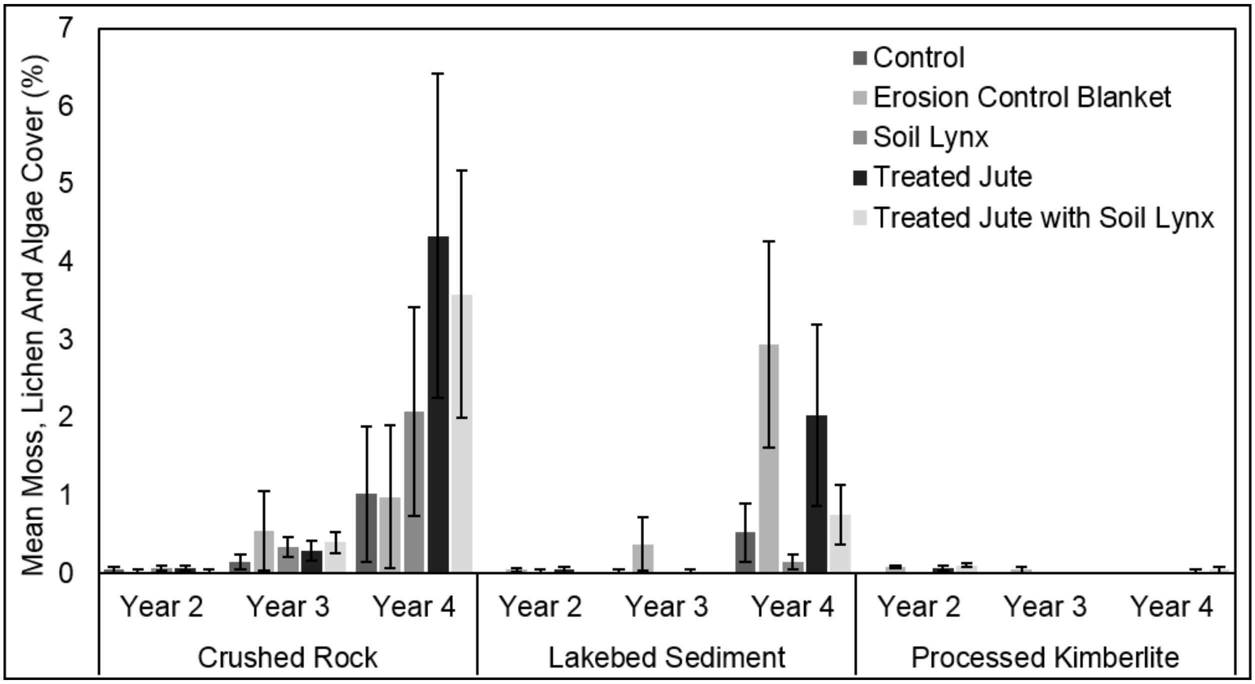

Figure 6.4. Mean moss, lichen and algae cover (± SE) within each substrate in years 2 to 4.

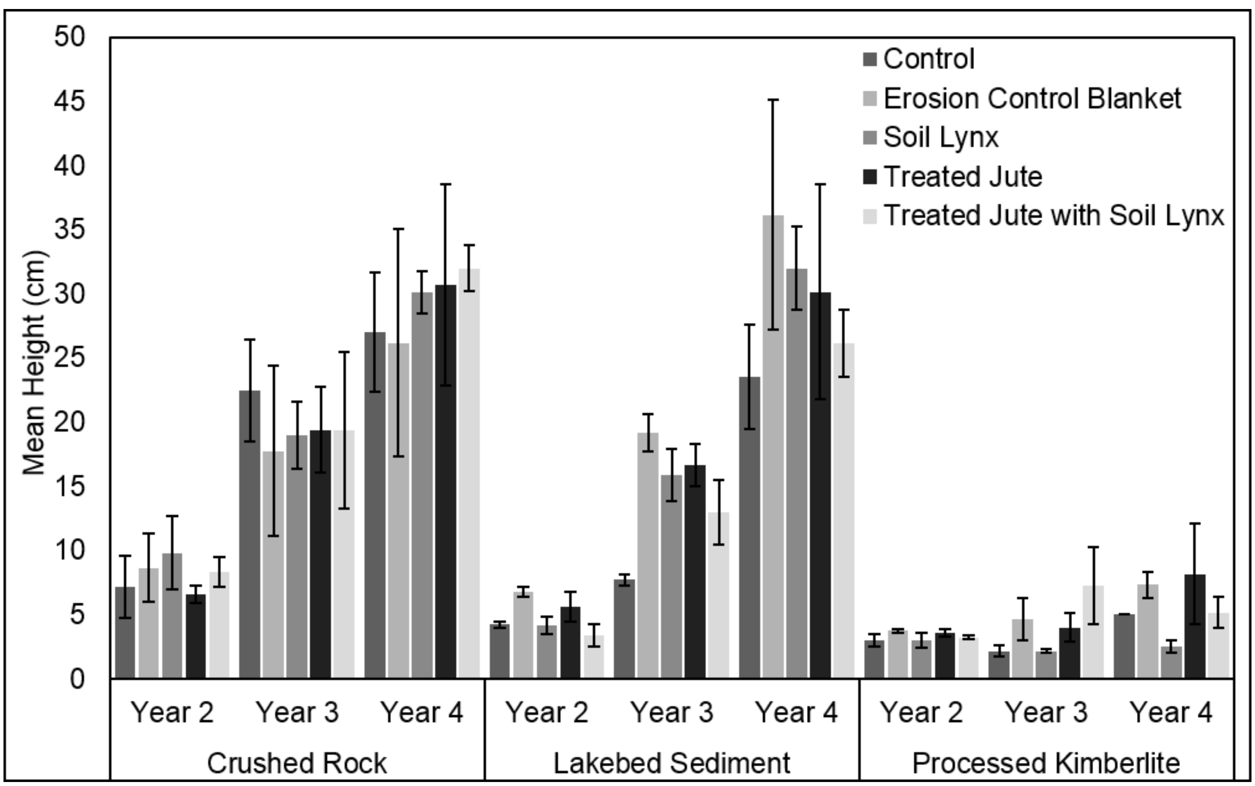

Figure 6.5. Mean height (± SE) within each substrate in years 2 to 4.

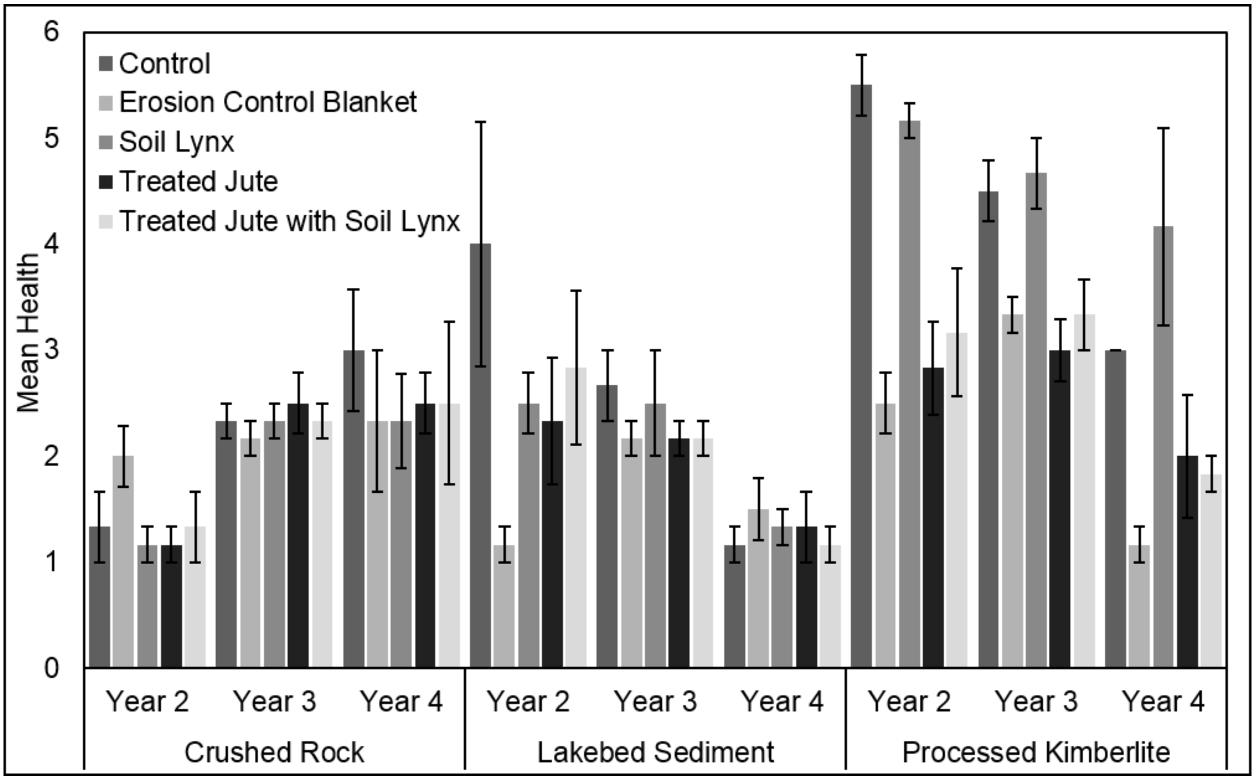

Figure 6.6. Mean health (± SE) within each substrate in years 2 to 4 (note larger numbers are less healthy).

VII. RESEARCH SUMMARY AND RECOMMENDATIONS

1. RESEARCH SUMMARY

The objective of this research program was to build suitable anthroposol soils for revegetation after diamond mining in the Canadian north. Research was conducted in the greenhouse and in the field at Diavik Diamond Mine in Northwest Territories, Canada. A variety of mine waste substrates (crushed rock, lakebed sediment, processed kimberlite) were assessed with various amendments from Diavik (sewage, soil) and other sources (peat, Black Earth, biochar, fertilizer, hydrogel), micro topographic treatments and short term erosion control methods. Plant response to these anthroposols was assessed to determine reclamation suitability.

1.1 Greenhouse Experiments

Under conditions where water was not limited, plant emergence and growth were most affected by organic amendment, which improved substrate structure. Substrates and fertilizer application played a smaller role. Above ground biomass increased the most with sewage-soil and sewage; number of plants was highest with peat, soil and peat-soil, as was root growth in some cases. Black Earth and biochar were not effective amendments, and fertilizer had limited effectiveness except with some substrates and amendments. Crushed rock, 25 % processed kimberlite and 75 % lakebed sediment and lakebed sediment were the most effective substrates.

Experiments to explore techniques to increase water retention showed that processed kimberlite had the highest water retention with or without amendments. Amendments increased water retention in processed kimberlite and crushed rock, especially hydrogel, with double application rates of amendments resulting in greatest increases. Applying wet hydrogel to dry substrates resulted in greatest initial increase of water held, although over time there were only small differences with all hydrogel application methods. Dry hydrogel with dry substrate would have the greatest industrial feasibility. Lakebed sediment showed little increase in water retention with amendments, especially hydrogel, likely due to its inability to fully expand in denser material.

Plant response varied under water limited conditions with substrate and amendment combinations. Crushed rock and processed kimberlite had greater and earlier emergence than lakebed sediment, with substrate having the greatest impact. Number of plants establishing over the experiment were greatest in processed kimberlite and lowest in lakebed sediment. Plants were largest in crushed rock and processed kimberlite. Amendment selection and rate had small and variable effects on emergence. Hydrogel was among the more successful treatments in processed kimberlite and least effective in lakebed sediment; crushed rock varied. Higher rates of application increased emergence although not consistently or significantly. Amendment and rate had a small effect on number of live plants over time, primarily in crushed rock. Plant number was higher with high rates of organic amendments than hydrogel. Above ground biomass in all substrates increased significantly with sewage at any rate, with smaller effects from other organic amendments at high rates in crushed rock. Plants amended with organic amendments were healthier. Hydrogel alone did not improve plant growth.

1.2 Field Experiments

Substrate had a large effect on plant response, with crushed rock being most successful and processed kimberlite least. Plant establishment and growth were best in crushed rock as expressed in number of plants, species richness, cover, seedheads and grazing. Plant response in processed kimberlite was poor overall, with limited vegetation after 4 years. Plant response in lakebed sediment was intermediate between crushed rock and processed kimberlite and became increasingly successful over time, with a large increase in vegetation cover in the final year. Healthiest plants were in lakebed sediment, although health showed inconsistent patterns over years. Overall substrate had the greatest effect on number of plants and species richness.

Organic amendment had a considerable effect on plant response with sewage generally resulting in greater cover, including moss, lichen and algae; taller plants; more seedheads and grazing; and healthier plants and greater species richness although not in all years or substrates. Sewage had a limited effect on plant establishment. No amendment and soil showed limited differences or improvement to vegetation.

Micro topography effects varied with substrate and plant response variable. It had a limited effect on plant establishment in crushed rock; there were generally more plants and species in lakebed sediment and processed kimberlite low areas (furrows, depressions). Vegetation cover was not affected by micro topography in crushed rock and lakebed sediment, whereas in processed kimberlite, plots with low areas had increased cover. There were slight increases in moss, lichen and algae in depressions in crushed rock and lakebed sediment. Depressions and furrows generally resulted in taller plants in lakebed sediment and processed kimberlite. Plant health, seedheads and grazing presence were not impacted consistently by micro topography in crushed rock and lakebed sediment, although in processed kimberlite generally plants were healthier in depressions and there were more plots with seedheads and grazing with depressions and furrows. Vegetation cover was greater in furrows and depressions (low areas) than on mounds (raised areas). The greater impact of micro topography on processed kimberlite may indicate importance of this variability in poorly performing substrates.

Plant establishment and growth remained low in all erosion control treatments relative to sewage amended treatments indicating erosion control alone was insufficient to address site limitations. Erosion control blankets and jute mats were more effective than Soil Lynx or control at increasing plant establishment and growth in lakebed sediment and processed kimberlite. In crushed rock, treatment differences were generally small and most successful treatments varied with year and vegetation parameters. Soil Lynx generally had no positive impact on vegetation. Jute mats showed little loss of material after 4 years relative to erosion control blankets.

Elymus trachycaulus (Link) Gould ex Shinners (slender wheat grass) and *Poa* sp. (primarily *Poa glauca* Vahl (glaucous blue grass)) were the most successful species seeded in the primary field experiment, with *Oxytropis deflexa* (Pall.) DC. (nodding locoweed) the most successful forb. Slender wheat grass, *Poa alpina* L. (alpine blue grass) and *Trisetum spicatum* (L.) K. Richt. (spike trisetum) were the most successful in the erosion control experiment. The unseeded species *Epilobium angustifolium* L. (fireweed) was successful in both experiments. Shrubs established in very few plots and only in crushed rock.

2. APPLICATIONS FOR RECLAMATION

Development of soil building strategies for northern diamond mines in essential as two mines will close in the next 10 years (Diavik and Gahcho Kué) followed by a third (Ekati) soon after. The north is challenging for plant establishment and growth due to harsh climate, limited soil nutrient availability from slow decomposition and limited plant colonization and reproduction. Disturbances add challenges from vegetation removal, soil removal or burial, compaction, changes to nutrient cycling and water movement, waste piles with unnatural materials and seedbank loss. Through this research, recommendations have been developed regarding substrate and amendment selection, construction of micro topography and use of short term erosion control methods, with consideration of how these components integrate.

2.1 Substrates

Substrate strongly influenced germination, emergence and plant growth, therefore selection of appropriate primary materials for anthroposols is essential. Based on field and greenhouse experiments, crushed rock was the most successful substrate. Its key strength is rough texture with many sizes of rocks to trap and reduce seed movement and create safe sites with water and other resources for seeds to germinate, and for plants to establish and grow. Gravel disturbances are common in the north with the practice of laying gravel pads for construction, site use and roads. They lack nutrients, organic matter and seedbanks, have compacted surfaces and xeric conditions and are removed from natural water flow. Although crushed rock has been successful in short term research, its long term success is questionable as evidenced by Naeth and Wilkinson (2014) who found effectiveness declined after 5 years, potentially due to lack of resources as plants grew. However, as vegetation cover continues to increase each year on crushed rock in our research, it may indicate continued success of the material. Greater early plant establishment in crushed rock may provide benefits long term, improving soil properties and aiding in establishment of other species, though competition needs to be considered. Thus crushed rock may be suitable for soil reclamation, particularly if amended to address many of its limitations. Combining with lakebed sediment, with its finer texture, may be a good option.

Lakebed sediment is potentially suitable for plant growth as it is intermediate between crushed rock and processed kimberlite. It has been reasonably successful in other short term research (see Miller and Naeth 2017), and after 5 years, Naeth and Wilkinson (2014) found it among the most successful treatments for plants when amended with fertilizer or sewage. Lakebed sediment is currently strongly considered for revegetation at Diavik Diamond Mine. Its fine texture can improve water and nutrient retention, although it becomes very hard when dry, presenting challenges to seed germination and plant establishment and growth, as seen in our research with poor growth under water limited conditions relative to other substrates. Rocks are less prominent in the material relative to crushed rock and the area between rocks is smoother, especially when dry. Its other challenges as a reclamation material include low cation exchange capacity and water holding capacity, despite its fine texture. Altering the substrate to slow water movement to increase infiltration and create a rougher surface by adding a coarse textured material, such as crushed rock, may improve its structure for reclamation. This was seen with the success of 25 % processed kimberlite and 75 % lakebed sediment in our research (Miller and Naeth 2017). Long term, its fine texture may result in greater nutrient and water holding capacity and established plants may grow better over time in the hard substrate than newly emerging plants and germinating seeds. Amending is essential to address limitations.

Use of processed kimberlite in an anthroposol will be challenging. The containment facility which houses this waste is expected to be approximately 1 km long, 1.3 km wide and 40 m deep at closure, with current plans to cover with waste rock to restrict access and seal it. Using the material in reclamation would reduce the need for long term storage and capping. There is potential risk regarding plant uptake of metals, although preliminary work in the Naeth lab found metals of concern were below detection limit or had low concentrations in plant tissue grown in processed kimberlite and lakebed sediment. In our experiments, processed kimberlite was generally the least successful for plants; Naeth and Wilkinson (2014) found initial increases in establishment and growth with amendment declined rapidly as amendments eroded. Higher water retention of processed kimberlite relative to other substrates (Miller and Naeth 2019), which improved establishment and growth under water limited conditions in the greenhouse, did not correspond with improved vegetation response in the field. Processed kimberlite is also prone to erosion due to its sand texture and lack of structure and organic matter.

If using processed kimberlite is a reclamation goal or a permanent containment facility does not meet reclamation goals, use is possible for anthroposol building. Mixing with other substrates, high amendment rates, micro topography construction focused on creating low areas and erosion control would be essential for use of processed kimberlite as a substrate. Lack of amendments on site and distance to alternative sources limit this option, especially when other substrates show success with low rates of amendment. This strategy would not use all the processed kimberlite available, raising the question of whether to use some to build a moderately successful substrate, reducing amounts left behind; or use none and build a more successful substrate, then deal with the processed kimberlite waste. Consultation with government, First Nations and additional stakeholders would be essential to determine the social acceptability of processed kimberlite use for soil building and the environmental and financial costs of bringing in necessary amendments.

While this research focused on use of these 3 substrates as the primary material of anthroposols, results can be used to inform decisions at other sites by considering key factors of each material. The rough rocky texture of crushed rock provided key micro sites for germination and growth and reduced erosion risk, but had limited organic matter, nutrients and fine material which may impact long term plant growth. The fine texture of lakebed sediment may improve nutrient and water retention, although the hard nature of the material limits the ability of plants to germinate and grow, especially in the first few years. The sandy texture of processed kimberlite is prone to erosion and it has low nutrient concentrations and organic matter, poor structure and elevated metals which limit its effectiveness as a substrate without combination with other substrates and high amendment rates. All substrates have poor structure and low nutrients and organic matter and therefore amending is key.

2.2 Amendments

Amendment selection is key to successful anthroposol building to address both chemical and physical limiting factors in mining waste, such as lack of nutrients and organic matter, poor structure and texture, salinity and pH challenges and elevated metals. Sewage was most successful at improving vegetation growth as it increases cation exchange capacity which reduces nutrient loss; has high nutrient availability, with decomposition resulting in slower release and reduced loss relative to fertilizer; and improves substrate structure. Concerns result from elevated metals and salinity, bacteria and odour, which can be addressed with use of small amounts or mixed with other amendments (with soil in Miller and Naeth (2017)). Bacteria is a limited risk as outdoor storage over winter reduces fecal coliform and *Salmonella* (Drozdowski et al. 2012). Since there are few humans on site, odour is often not an issue and could be controlled with lime if needed in more populated areas. Thus sewage should be considered regardless of substrate selection, especially when it is available on site even at low volumes.

Peat will improve vegetation response by increasing organic matter, providing nutrients, improving substrate structure and increasing water retention. Its high carbon to nitrogen ratio can limit initial nutrient availability resulting in a slower vegetation response than seen with sewage, but this can be mitigated with fertilizer (Miller and Naeth 2017). If peat is available on site it will be an effective amendment, although higher application rates may be required than sewage. Combining with fertilizer or a high nutrient amendment, such as sewage, would address short term nutrient limitations. Use at Diavik is unlikely as peat would have to be transported to site and success was not as great as with sewage which is available on site.

Soil can provide organic matter and nutrients, increase water retention, improve substrate structure, provide seeds and propagules and contains microorganisms. However soil stockpiling can reduce effectiveness. Soil stockpiling and movement can reduce organic matter, nutrient availability, structure, seed viability and microbial populations, thus direct placement should be used whenever possible (Mackenzie and Naeth 2019). Limited field success of soil in this research is likely due to low organic matter and nutrients and similar texture to substrates and may be addressed through direct placement, increased rate of use and combination with high nutrient amendments. Use at Diavik is likely as soil is present on site, although volumes are low.

Organic amendments have greater effectiveness than fertilizer as they can address both physical and chemical limitations, whereas fertilizer only provides nutrients, limiting vegetation response. Miller and Naeth (2017) found fertilizer increased plant biomass in limited situations, but had no effect on other plant properties and Naeth and Wilkinson (2014) found increases to density and cover in only a couple substrates. Added nutrients can leach rapidly if substrates lack nutrient holding capacity and vegetation is too small to use. Fertilizer is easy to transport to remote sites, but should not be used indiscriminately or as a sole amendment since it can impact downstream systems, may support rapidly establishing graminoids which can impact establishment of slower growing species that generally dominate the landscape, and many arctic plants are adapted to low nutrients. Use of fertilizer may be suitable in combination with amendments that have a high carbon to nitrogen ratio, to provide an initial boost of nutrients for plants and start nutrient cycling. Rate of application should be lower than recommended for southern environments and application may be more suitable after plants have germinated when they are able to use nutrients, rather than prior to germination. Monitoring will be important to ensure excess nutrients are not exiting sites as water bodies in the north tend to be oligotrophic and sensitive to nutrient increases.

Some amendments studied were not successful. Biochar and Black Earth, carbon rich amendments, did not improve vegetation response. They did not improve substrate structure and due to the high carbon content may have reduced nutrient availability for plants. Hydrogel was not an effective amendment to improve plant response, although it increased water retention better than organic amendments in crushed rock and processed kimberlite (Miller and Naeth 2019). Hydrogel may increase water retention, but lack of nutrients or organic matter limits benefits it can have on vegetation. Combining hydrogel with organic amendments or nutrients additions could be useful as hydrogel is easy to transport to remote sites.

Organic amendments are essential and require consideration of material placement, application rate and material source. They can be incorporated with substrates or used to cap. Incorporation reduces erosion and loss, increases volume of growth medium and reduces amendment volume required, which is essential in remote sites, but quality may be reduced relative to amendment alone. Capping provides a better growth medium and even a thin layer of soil can improve plant growth. However capped material can be eroded, larger amendment volumes are required and not amending the substrate below can create only a small depth suitable for plant growth. Due to the success of incorporation in this research it is recommended unless the substrate has properties that can negatively affect vegetation (and cannot be alleviated with amendments) and the ecosystem, such as elevated metals that may bioaccumulate in plants and move into the food chain. Rate is determined by amendment characteristics and availability. Sewage is effective at improving plant growth at all rates, including low application, which is essential as there is limited material on site. Use of other amendments, like peat and soil, would require greater volumes to improve vegetation response which is a challenge when limited materials are available on site and transportation of external materials is costly. Remote location plays a role in selection of both amendments and substrates as on site materials eliminate travel and purchase costs, long term management of materials or placement in landfills and disturbance to collect additional material.

2.3 Micro Topography

Micro topography is important in determining plant communities in natural ecosystems as it creates a range of environmental conditions. Active development of micro topographic features in reclamation is getting increased consideration. In our research, the effect of built micro topography varied among substrates. In crushed rock, it had little effect on plants as many of its benefits such as seed trapping, reduced erosion and creation of suitable micro sites were met by the rough surface, micro topography naturally present in crushed rock. In processed kimberlite with its lack of natural variability and sandy texture, micro topographic features that included low areas were important for seed trapping and water collection. One challenge is their loss over time due to erosion. Lakebed sediment has a rocky surface, but areas between rocks are smoother than crushed rock and hard, due to its fine texture. Micro topographic features with low areas can trap seed and collect water collection to improve vegetation response, especially establishment.

Flat sites and mounds tended to be the least successful. Flat sites lack seed trapping, water collection areas and favourable micro sites. Mounds may provide seed trapping and slow water movement around their base, but poor conditions on mounds from harsher wind, water and temperature conditions and changes to nutrient availability limit growth on them. On wet sites or those prone to flooding, mounds may provide areas where species poorly adapted to wet conditions can establish. In all substrates, even when there was no overall micro topography effect, vegetation cover was higher in low areas of depressions and furrows than on high parts of mounds indicating low areas are more suited for plant establishment and growth than high, although mounds may create suitable areas around them.

Disturbances remove micro topographic variability through vegetation and soil removal, compaction and poor soil structure and reclamation practices can do the same. Construction of micro topography with low areas is important with substrates that have little natural topographic variability and a flat surface and should be incorporated into reclamation strategies. For substrates with natural variability, construction less essential; however, in all substrates reclamation should not result in a flat, smooth site.

2.4 Erosion Control

Erosion control is a challenge on most reclamation sites due to the lack of vegetation, exposed soils, changes to topography, damage to soil structure, compaction and removal of organic matter. Erosion control methods using a physical barrier, such as a jute mat or erosion control blanket, were more successful than Soil Lynx. Mats and blankets aid revegetation by increasing seed and material trapping; reducing runoff velocity, raindrop impact and material loss; providing organic matter as they decompose; and having a longer lifespan. Determining whether erosion control methods should be used requires consideration of substrates, various site characteristics and weather patterns.

Crushed rock is at low risk for erosion due to its rough surface. Processed kimberlite is at greater risk as it lacks micro topographic variability naturally, has no rocks and a sandy texture with little organic matter and poor vegetation establishment. Lakebed sediment is at intermediate risk as it is hard when dry and has a smoother surface than crushed rock. Therefore processed kimberlite and lakebed sediment, especially the former, are more at risk for erosion from both wind and water and represent reclamation substrates with a greater need for erosion control. Sites on slopes or areas with a large catchment that feeds into them are at greater risk for erosion due to speed and/or volume of water that is moving through them thus erosion control plays a greater role there.

Remote locations should limit material transported to site, including erosion control materials, requiring careful consideration of success and areas with greater need. Erosion control methods alone had limited improvements on vegetation establishment and growth, and need to be combined with amendments. Specific methods focused on using on site materials could be considered relative to transporting external materials to site, such as building berms or micro topography to direct snow deposition and slow water and wind; and reducing slope length through terracing to reduce water velocity and material loss. Establishment of vegetation is one of the most successful long term strategies to reduce erosion, therefore planting a rapidly establishing cover may be effective. Careful selection of cover species is essential to ensure slower growing native species, like shrubs, are able to establish.

2.5 Building Anthroposols

Combining the knowledge of substrate and amendment selection, micro topography building and erosion control methods is essential to build anthroposols. The first step of anthroposol building is determining the desired end use for a site as this can determine the appropriate materials and techniques to use. For example, if the final goal is to support vegetation growth versus site stability with no vegetation, different decisions will be made.

The next step is selection of an appropriate substrate. Substrate source is the main determining factor, especially in remote sites. Determining what materials are available on site in large enough quantities to act as the primary material for the anthroposol is necessary. Where multiple materials are available, the properties of the materials, both beneficial and negative properties must be considered. For example, at Diavik, processed kimberlite has elevated metals which may be taken up by plants and enter the food chain; this would be challenging to address unless reduced amounts of processed kimberlite were used by mixing with other substrates. As there are other materials available for anthroposol building, this may deter use of processed kimberlite. Part of this step is determination of whether substrates should be used alone or in combination, and whether materials should be layered or mixed. For example, our research shows that lakebed sediment and crushed rock may be effective together.

Once the substrate has been selected, subsequent decisions will be based on addressing limiting factors. Amendment selection will be based on what material is available on site, or material that could be transported to site. For off site materials, weight and size need to be considered if transporting long distances. Building relationships with nearby industries and communities to source waste materials as low cost amendments is valuable. Upon determining what materials are available for amendments, limiting factors of the substrates must be addressed to meet the end land use goals. For example, if the substrate is low in organic matter and nutrients, amendments selected should provide those key resources if vegetation growth is the goal. Building micro topographic variability should be determined based on the nature of the substrate and amendment combination and the natural area. If it is smooth, micro topography should be constructed. If it is naturally rough, building micro topography may not be required. Practitioners should consider the natural micro topography in the surrounding area to determine size and shape of constructed micro topography. The final step is to consider if erosion control is needed based on the erosion risk of the site and material. If the anthroposol naturally has low erosion risk (rough surface, aggregated soil) and the site has a limited risk (flat area, small catchment), erosion control methods would not be required. Erosion control decisions should limit the material required for remote sites and consider use of on site materials to construct alternative erosion control techniques (berms, micro topography, slope terracing).

3. RESEARCH LIMITATIONS AND FUTURE CONSIDERATIONS

3.1 Material Combinations

Due to budget constraints, soil analyses could not be conducted on combinations of materials; therefore expected effects of amendments on substrate properties were based on other research and amendment characteristics. Future research should include detailed soil analyses to better understand causes of vegetation response. Analyses should include nutrient content, organic matter, pH, electrical conductivity, cation exchange capacity, texture, bulk density and penetration resistance. Soil analyses should be completed over multiple years in the field to determine if plant growth is altering soil chemical and physical properties, which is important in ecological succession.

Based on greenhouse and field experiments, combinations of materials were identified as potentially effective, but could not be tested due to limitations in space for plots or pots. Increasing the amount of fine material in crushed rock may improve water and nutrient retention, improving vegetation response long term. This could be completed through removal of large rocks, increased crushing or by combining with lakebed sediment. Lakebed sediment will increase the amount of fine material, benefiting crushed rock, and the greater coarse fraction of crushed rock would increase lakebed sediment's micro topographic variability and reduce its hard nature. Initial greenhouse experiments should combine various ratios of crushed rock and lakebed sediment, in combination with amendments, to determine the most effective combinations before assessing materials in the field. If crushed rock is selected as the most suitable substrate for anthroposol building, it raises the question of whether roads and infrastructure pads will be used as the anthroposol base and mixed with amendments, or if stockpiled crushed rock will be placed on these surfaces. If roads and infrastructure pads are to be amended, the material may be lacking the rocky fraction that was important for micro sites and research will need to determine how much rocky fraction to incorporate. This will require field experimentation due to the size of rocks.

Although hydrogel alone was not an effective amendment, it may be improved by combining with organic amendments such as sewage, or fertilizers. Hydrogel has low weight and small size, facilitating easier transportation to a remote site. If combining a nutrient source with hydrogel improves vegetation response more than either alone, its use may be warranted. However, effectiveness should be assessed in the field due to harsher conditions. Mixing sewage and soil would increase volume of on site amendment available relative to just using sewage, although amendment quality may be reduced. Research would need to determine proportions and application rates of the combined material based on desired vegetation response. Amendments should be combined with erosion control methods and reassessed as alone erosion control only had a small effect on vegetation response.

3.2 Shortage Of Materials

Northern mines have limited on site organic material for reclamation. Soil is rarely stockpiled due to challenges removing it from the rocky landscape, its thin layer and potential risk to permafrost. Gravel pads and roads are usually built directly on soil rather than removing soil. As the majority of these mines were built historically and soil was not stockpiled or direct placed, sites already face shortages that new mines may avoid or reduce. Although sewage is produced on site, it is discarded on top of waste rock piles or stockpiled in waste storage facilities at Diavik which are exposed to the elements and result in material loss. Amounts of sewage and soil are unlikely to meet needs for anthroposol building and revegetation of an entire site; however, use of on site waste material or material removed during disturbances is ideal to reduce cost, waste management and disturbance of additional sites.

Where there is a lack of material on site and limited ability to bring in external material from off site, creating a patchwork of reclamation sites comprised of islands of amended substrates may be an effective reclamation strategy. Reclamation generally places a homogeneous soil layer across an area, which may not be optimal with limited soil material resources. Current island research has been focused on leaving patches of landscape intact during disturbances or creating plant species rich areas using topsoil that provide seeds and propagules native to the area, although research has not assessed northern ecosystems.

Research is needed to assess the ability of plants to establish adjacent to reclaimed areas and the speed at which this occurs in northern sites. Plants had reduced growth on unamended substrates in our research, although they established and survived. Vegetation establishment in buffers between field plots, primarily in crushed rock and lakebed sediment, indicates egress from areas of amended substrate and seeding occurs. Understanding types of vegetation more likely to egress is key, with weedy species more likely to spread than more desired slow growing native species. Spread of weedy species may negatively affect slow growing species or improve conditions for their growth. Research is needed to determine the size of patches to provide necessary seed rain and vegetation propagules to adjacent areas and improve soil quality and the ideal distance between patches.

As sewage resulted in increased plant growth, patches of sewage amended substrate seeded or transplanted with native species could be built in areas of unamended substrate. Unamended substrate should be ripped to reduce compaction and create micro topographic variability, improving conditions despite lack of amending. Soil could be used, which has been the focus of past research, although seeding may be needed if the arctic soil does not provide necessary seed and propagule sources and if it has been stockpiled. Soil and sewage could also be mixed, as discussed above. Species selection for seeding and transplanting would require research as sewage and soil, unless freshly collected, would provide limited seedbanks and plant dispersal methods can have an effect on egress.

Researchers and companies should explore whether processes on site could produce valuable amendments. For example, at sites with camps, excess food and food waste could be composted. Challenges are related to where composting could be completed and potential attraction of native wildlife and would need to be considered carefully.

3.3 Vegetation Response And Material Source

Successful reclamation requires building a suitable growth medium and development of plant material and revegetation methods. This research was focused on the first; in the north, the second remains a major challenge. Seed banks buried beneath gravel pads reduce their effectiveness as a seed source and while adjacent undisturbed seed sources may provide seed and propagules, they have slow and limited effects on large sites where distance between vegetated and bare areas is large. Harsh substrate conditions and lack of seedbank and other vegetation sources limits natural recovery and requires that sites be revegetated.

Revegetation is hindered by a lack of reliable suppliers of native seed or propagules, requiring companies to source themselves or use non-native species. Development of plant material will require individual companies in the north to focus on seed and propagule collection from local sources or work together and with communities to develop an industry to source plant material. Current knowledge of propagation methods and revegetation techniques of northern species is limited and needs to be explored including whether species should be seeded or transplanted, transplant growth techniques and if seed dormancy needs to be broken. If native species limitations are not addressed, non-native species may be used which may not be adapted to the harsh northern climate, limiting effectiveness, or may outcompete slower growing native species, especially when seeded and fertilized, and may inhibit succession of reclaimed sites.

Use of herbaceous vegetation, even when native, can negatively ecosystems. Arctic ecosystems are rarely dominated by herbaceous vegetation, but with shrubs, mosses and lichen. For this research, graminoids and forbs were used due to the limited timeframe of research, slow growing nature of other vegetation types and harsh conditions of substrate. Seed was made available from a research institute, with no option to select species, seeding rates, growth form or type of vegetation due to lack of material available. This does not imply that use of herbaceous vegetation in reclamation does not have value. On disturbed sites, establishment of initial vegetation, including herbaceous, is critical to input organic matter and nutrients, improve soil structure, reduce bulk density and penetration resistance, increase water infiltration, reduce erosion risk, act as a nursery species and provide protected micro sites for other species to establish. Herbaceous vegetation can provide benefits for establishment of slower growing species, with additional research needed to find appropriate seeding rates to ensure benefits of herbaceous cover exceed detriments from competition.

Next steps should include how to incorporate other vegetation types, especially shrubs, into revegetation techniques through seeding or transplanting shrubs when sites are seeded with herbaceous species, seeding or transplanting with shrubs after herbaceous vegetation has established, or growth of herbaceous vegetation for a limited period of time followed by incorporation of vegetation with the substrate and seeding or transplanting of shrubs. Moss and lichen revegetation techniques are currently limited and should be explored in combination with revegetation using herbaceous vegetation. Research being conducted in the Naeth lab to develop revegetation strategies for moss, lichen and shrubs needs to be combined with anthroposol research to ensure effective techniques for herbaceous vegetation meet requirements of other vegetation types.

3.4 Spatial Scale

Spatial scale is a limitation of this research as all experiments were conducted in pots in the greenhouse or on small scale field plots. Future research needs to assess effective treatments in larger field plots and at an industrial scale. Two key areas where this will help address questions is erosion control and micro topography. Erosion control application in small areas surrounded by areas without erosion control may have influenced success of techniques. Future research should assess erosion control on larger plots where surrounding erosion is restricted. With micro topography, features were built by hand due to site access limitations and small plot areas. This would not be feasible for reclamation at an industrial scale, where equipment would be used to create larger features. Larger micro topographic features may be beneficial in processed kimberlite as it may take longer to erode. Research is needed to assess the impact of multiple micro topographic features in combination. For example, while mounds had limited vegetation establishment on them, mounds adjacent to depressions may direct water into them. As plant species have different requirements for germination, emergence and growth, multiple types of micro topography may be more beneficial than a single type. Selected treatments, including substrates, amendments, micro topography and erosion control, should be built at an industrial scale using industrial equipment so patterns seen at the small scale are repeated.

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APPENDIX 1. RESEARCH SITE

1. LOCATION AND HISTORY

Diavik Diamond Mine is located approximately 300 km northeast of Yellowknife, Northwest Territories, Canada, on East Island (latitude 64° 30’ 41” N, longitude 110° 17’ 23” W) (Figure A.1), a 20 km^2 area at the east end of Lac de Gras (Bryan and Bonner 2003). The site was discovered in the early 1990s during the staking rush in the Northwest Territories. In 1991 Dominion Diamond Corporation (formerly Harry Winston Diamond Ltd., prior Aber Resources Ltd.), staked four claims in the region covering 325,000 ha (Hart 2001, Bryan and Bonner 2003, Diavik Diamond Mine Inc. 2010b). One claim was Lac de Gras, the future Diavik Diamond Mine. Aber joined Rio Tinto (formerly Diavik Diamond Mine Inc., prior Kennecott Resources Ltd.) in 1992, and in 1994 found diamonds in Lac de Gras drill cores. Eira Thomas, the chief geologist of Aber, found the highest grade cluster of diamond pipes globally, with a rare 2 carat visible diamond (Hart 2001). The deposit was predicted to contain 138 million carats. Kimberlite pipes under Lac de Gras are 55 million years old, surrounded by 2.7 billion years old precambrian granites and metamorphosed sedimentary rocks (Diavik Diamond Mine Inc. 2010a).

Diavik Diamond Mine began construction in 2001 and production in 2003 (Bryan and Bonner 2003, Diavik Diamond Mine Inc. 2010a, 2010b, Rio Tinto 2013, 2017). It is owed 60 % by Rio Tinto and 40 % by Dominion Diamond Corporation. It is Canada's largest diamond mine, producing over 100 million carats of rough diamonds by 2016. There are four kimberlite pipes associated with Diavik, A154 North and South, A418 and A21, all located under Lac de Gras adjacent to East Island. To access diamonds under the lake, two dikes were built for open pit mining, transitioning to full underground mining in late 2012 for A154 and A418 (Diavik Diamond Mine Inc. 2010a, 2010b, 2018). Development of a dyke for A21 began in 2014 with project approval, and production began in 2018 using open pit mining (Rio Tinto 2015, 2018, Diavik Diamond Mine Inc. 2018). All infrastructure is on East Island, including ore processing facilities, accommodations, administration buildings, plants (power, boiler, water treatment, sewage treatment), fuel tanks, wind farm, air strips, roads, gravel pads and processed kimberlite containment area (Diavik Diamond Mine Inc. 2010a, 2010b). The remote location of the site requires most of the supplies and equipment to be transported on the winter ice road.

Diamonds are present in kimberlite at low quantities, initially estimated at an average of 3.9 carats per tonne at Diavik (estimated at 2.8 carats per tonne in 2016), resulting in large quantities of processed kimberlite waste (Bryan and Bonner 2003, Rio Tinto 2017). Processed kimberlite is placed as a slurry and left to dry in the processed kimberlite containment facility which is expected to be 1.0 x 1.3 km x 40 m high and hold over 45 Mt (Rio Tinto 2015, 2017). As of 2017, 30.2 Mt of processed kimberlite has been produced, with 77.5 % fine (< 1 mm) and 22.5 % coarse (1 to 10 mm) (Diavik Diamond Mine Inc. 2010b, 2018). Other primary waste materials include crushed rock and lakebed sediment. Crushed rock is from waste rock, also known as blasted rock (Diavik Diamond Mine Inc. 2010b). As of 2017, approximately 91.5 Mt of type I rock, 15.3 Mt of type II rock (since 2011, type II has been categorized as type III) and 70.1 Mt of type III rock has been produced (Diavik Diamond Mine Inc. 2018). Type I is granite, contains < 0.04 wt % sulphur, is considered non-acid generating and is stockpiled on site or crushed for use in roads, dikes and construction (Diavik Diamond Mine Inc. 2016, 2018). Type II and III are granite with biotite schist. Type II with 0.04 to 0.08 % sulphur is considered low risk; type III with > 0.08% sulphur is potentially acid generating. Both are stockpiled or used for construction in select locations in the processed kimberlite containment facility dam or underground in cemented rock fill. Lakebed sediment, also referred to as till or overburden, was removed from pits after diking; water was pumped out and it is stockpiled on site for use in reclamation. As of 2017, approximately 12.5 Mt of lakebed sediment has been produced (Diavik Diamond Mine Inc. 2018). The expected overall footprint of the mine is 12.7 km^2 (Diavik Diamond Mine Inc. 2010b).

The expected life span for Diavik Diamond Mine is 16 to 22 years (Diavik Diamond Mine Inc. 2010a, Rio Tinto 2013). Upon completion of mining, the site must be reclaimed. Relevant federal and territorial regulatory documents include the Canadian Environmental Protection Act, Mackenzie Valley Resource Management Act, Fisheries Act, Environmental Protection Act and Environmental Rights Act (Government of Canada 2000, Diavik Diamond Mine Inc. 2010b). Specific reclamation regulatory documents are the 2002 Mine Site Reclamation Policy For The Northwest Territories (Minister of Indian Affairs and Northern Development 2002) and Guidelines for the Closure and Reclamation of Advanced Mineral Exploration and Mine Sites in the Northwest Territories (Mackenzie Valley Land and Water Board and Aboriginal Affairs and Northern Development 2013). Closure goals include reclaiming to stable land and water that is safe for wildlife and humans, a final landscape allowing for traditional use and guided by pre disturbance conditions that does not attract or repel wildlife and a site that does not require long term management (Diavik Diamond Mine Inc. 2010b). The mine’s environmental agreement specifies progressive reclamation during active mining (Government of Canada 2000, Diavik Diamond Mine Inc. 2010a, Rio Tinto 2013).

2. BIOPHYSICAL DESCRIPTION

Diavik Diamond Mine is located approximately 100 km north of the treeline and 200 km south of the Arctic Circle (Diavik Diamond Mine Inc. 2010a). It is in the Tundra Shield of the Southern Arctic Ecozone, in the Point Upland Low Arctic South Ecoregion (Ecosystem Classification Group 2012). Point Upland is the most northern part of the Tundra Shield. Diavik Diamond Mine is 416 m above sea level in Lac de Gras (Bryan and Bonner 2003). Lac de Gras has a surface area of 572 km^2 and a watershed of 3,559 km^2 (Diavik Diamond Mine Inc. 2010b); it is ultra-oligotrophic due to low nutrients and supports few aquatic plants.

Diavik Diamond Mine has short, cool summers and long, cold winters (Diavik Diamond Mine Inc. 2010b, 2012, Ecosystem Classification Group 2012). Based on site data from 2002 to 2012, January is generally the coldest month, averaging -27.2 ºC (-1.4 to -44.0); December was coldest in 2012. July is generally warmest, averaging 13.2 ºC (0.5 to 27.3). Permafrost is present, as the mine is located in the continuous permafrost zone. The active layer ranges from 1 m in areas with poor drainage to 5 m in bedrock. Annual total precipitation from 2002 to 2012 was 242.3 mm (2010) to 413.2 mm (2006), with snow fall 103.1 mm (2011) to 224.6 mm (2006) and rainfall 75.8 mm (2012) to 188.6 mm (2006). Average annual precipitation is 305.8 mm, 169.5 mm snow and 136.3 mm rain. Precipitation generally peaks in August or September and November, although in 2012 it was lower than expected in September and higher in January and March. Snow melt occurs in early June. In 2012, average wind speed ranged from 0 to 17.6 km hr^{-1} and wind direction had a slight prevalence from the southeast, although dominant wind direction varies, shifting from southeast to east to northwest. In summer (June to August), prevailing winds are from the east.

Soil development on East Island is limited due to low temperatures. There is < 0.5 to > 2.0 m of organic matter accumulated in depressions and crevices in the bedrock and till (Diavik Diamond Mine Inc. 2010b, Ecosystem Classification Group 2012). Glacial till is the most common substrate and soils are cryosols, with turbic and static cryosols most common. Point Upland contains extensive areas of exposed bedrock, with approximately 40 % of East Island surface covered in rocky outcrops, dominated by granite.

Diavik Diamond Mine is located in tundra in the low arctic, which transitions between taiga and upper arctic tundra (Diavik Diamond Mine Inc. 2010b, Ecosystem Classification Group 2012). Plant communities are dwarf tree/shrub wetlands and wet sedge meadows, raised hummock grasslands and moss lichen communities with rocky outcrops. Sedge meadows form if water accumulates on organic soil. Vegetation associations include heath tundra, sedge, boulder, esker complexes, bedrock, riparian and lichen veneer. The dominant plant community is heath tundra, covering most dry upland in the region. No rare plant species are present. Common species include *Vaccinium uliginosum* L. (bog blueberry or bog bilberry), *Vaccinium vitis-idaea* L. (mountain cranberry or lingonberry), *Betula nana* L. (dwarf birch), *Arctostaphylos rubra* (Rehder & Wilson) Fernald (arctic or red fruit bearberry), lichens, *Carex* sp. L. (sedges) and *Eriophorum* sp. L. (cotton grasses) (Ecosystem Classification Group 2012). Exposed bedrock and rocky outcrops are dominated by lichens.

Wildlife on East Island include year round residence by denning animals like wolverines (*Gulo gulo*), grizzly bears (*Ursus arctos horribilis*), foxes (*Vulpes* sp.), ground squirrels (*Urocitellus parryii*) and ermine (*Mustela erminea*) (Diavik Diamond Mine Inc. 2010b). Ground squirrels and lemming are widespread. Caribou (*Rangifer tarandus*) migrate through the area during spring, summer and fall. Only ravens (*Corvus* sp.) and ptarmigan (*Lagopus* sp.) are present year round, but over 80 bird species migrate into or travel through the region in summer (Diavik Diamond Mine Inc. 2010a, 2010b).

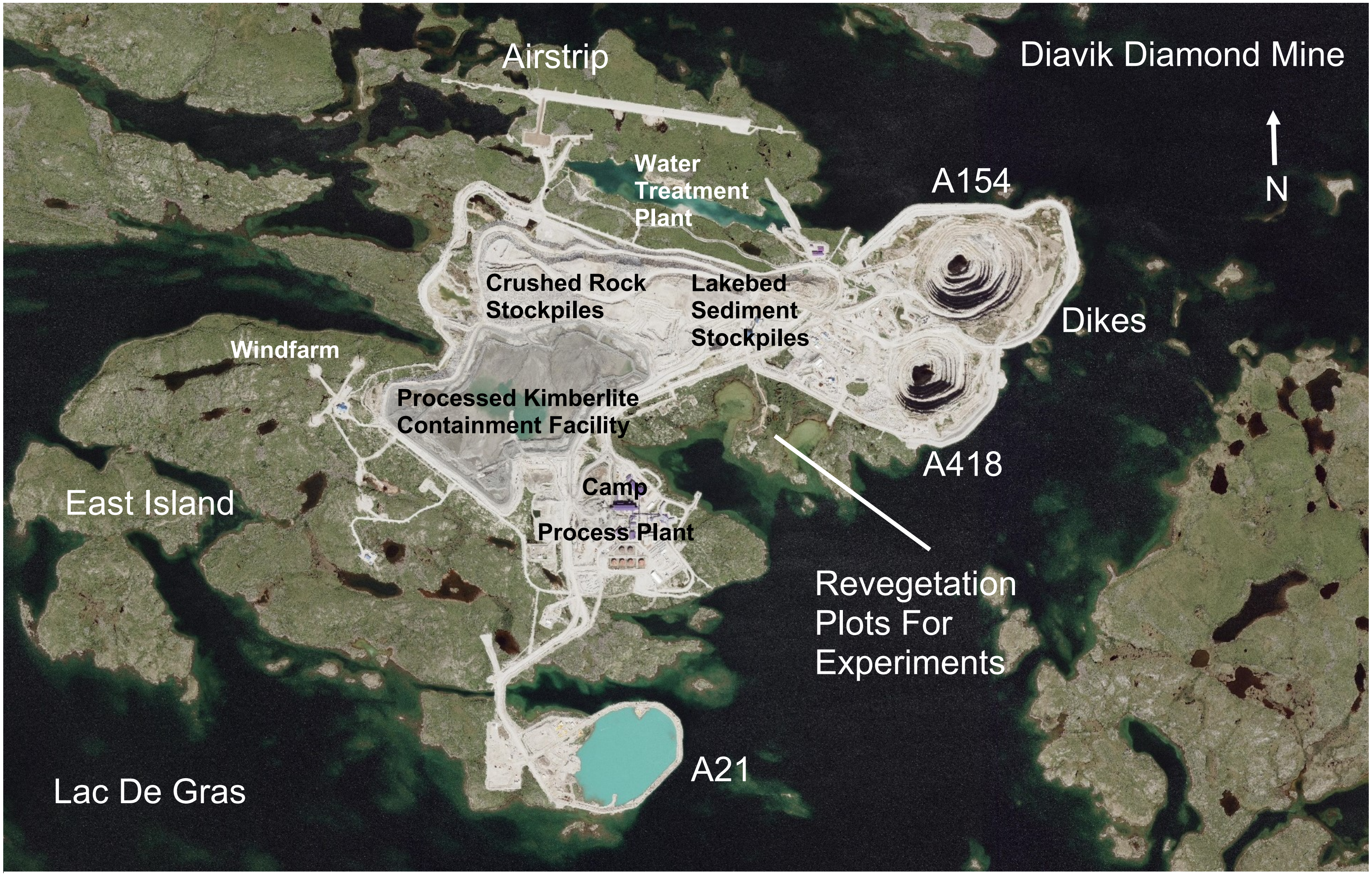

Figure A.1. Layout of Diavik Diamond Mine on East Island, Northwest Territories, and location of research site (Source: Diavik Diamond Mine Inc.).