Challenges of utilizing municipal compost as an amendment in boreal forest reclamation subsoil material

by

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Abstract

Forest reclamation sites are often located in areas not suited for agriculture and therefore have poor soil conditions. To assist in the rehabilitation of forests on these types of sites, organic amendments can be used. Close to large urban centers, compost derived from municipal organic waste can be utilized to enhance soil suitability for plant growth by increasing organic matter and nutrient availability. When organic amendments are incorporated into the soil surface, however, improved subsoil conditions are often accompanied by an increase in cover of disturbance adapted ruderal species that compete with planted tree seedlings. The primary objective of this thesis was to examine a novel site preparation technique that explores the impact of inverting a 25 cm organic layer (here compost) beneath a 20 cm mineral soil cap. We hypothesized that the buried compost layer would provide a deep, nutrient rich rooting environment for tree seedlings while the cover of mineral soil would limit interspecific competition from weedy species during the vulnerable initial years following planting. This method was compared to the more conventional treatment of applying materials at the soil surface including salvaged topsoil material and compost.

All soil treatments containing compost had poor seedling survival after the first growing season, with no seedling survival in the surface applied compost. Soil treatments with a mineral soil cap over compost initially had high mortality (70%); however, growth for the remaining tree seedlings was better in the second growing season relative to other soil treatments. This poor survival was clearly influenced by the chemical composition of the compost and our failure to incorporate the material deep enough into the mineral subsoil. During the composting process at the waste plant, biosolids had been added, which significantly increased the salinity of the material and most likely led to the low tree seedling survival. Furthermore, a salt tolerant, aggressive annual weed (*Kochia scoparia*) established across the research site in the first growing season and established as a thriving monoculture in the soil treatments containing compost, further negatively influencing tree seedling survival. A mineral soil cap using fine textured soil was more effective in limiting *Kochia scoparia* than a coarse textured soil; however, a greater cap thickness would have been advantageous. The fine and coarse mineral soil cap insulated the underlying compost layer, creating conditions of higher soil temperature, greater moisture availability, but also limited oxygen availability compared to the surface applied compost. After the second growing season, the salinity of the compost was significantly reduced and surviving tree seedlings in soil treatments with a mineral soil cap over compost grew better. Likely their root systems accessed microsites with favorable soil conditions, most probable at the interface between the fine or coarse mineral soil cap and the compost.

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Chapter 1: Introduction

1.1 Disturbance and forest ecosystems

Natural disturbances such as wildfire, insect outbreaks, and strong winds are essential drivers of forest ecosystem structure and function throughout the world (Franklin et al. 2002). The severity and temporal variation of a natural disturbance influences the spatial distribution of soil nutrients belowground (i.e. soil heterogeneity) and the composition of plant communities forming aboveground (Vinton & Burke 1995; Schlesinger et al. 1996; Stoyan et al. 2000). Thus, native forest species are adapted to reestablishing after locally common disturbance regimes (Gutschick & BassiriRad 2003) and forest ecosystems have a strong capacity to recover structure and compositional function following a natural disturbance equivalent to pre-disturbance states, a quality referred to as resilience (Holling 1996). However, as our societies are advancing technologically, economically, and industrially, our reliance on renewable and non-renewable resources is increasing to match the growth in those sectors. Forest ecosystems are increasingly subjected to anthropogenic disturbances because they contain renewable resources such as timber and nonrenewable mineral and energy resources. Forest ecosystems may not readily adapt to recovering from such a severe disturbance, as some of these anthropogenic disturbances are outside the range of variability for a natural disturbance (Angel et al. 2005; Burton & Macdonald 2011). Surface mining to extract non-renewable resources is such a disturbance. It involves the removal of overlying vegetation and deeper soil layers, drastically disrupting the hydrological, physical, and nutritional processes in forest soils (MacKenzie & Naeth 2010; Alberta Environment & Water 2011; Franklin et al. 2012; Macdonald et al. 2012). To restore basic ecological forest function, significant effort in reclamation is required and often aims to return these areas back to equivalent land capability as the pre-disturbance condition (Powter et al. 2012).

The boreal forest is a circumpolar biome that extends across the northern hemisphere with roughly one third of its area existing in Canada. In Alberta, the boreal forest natural region covers 58% of the province and contains the most area affected by surface mining (Natural Regions Committee 2006). Long cold winters and short warm summers characterize the boreal forest as well as a mosaic of understory vegetation and low number of tree species that are able to tolerate these conditions (Bonan & Shugart 1989). The landscape ranges from level to undulating with highlands and hills occurring in the upland areas and fens and bogs interspersed in the lowland regions. Upland soils are dominated by Luvisols and Brunisols with vegetation consisting primarily of deciduous, mixedwood, and coniferous trees (Natural Regions Committee 2006). The most common upland tree species are trembling aspen (*Populus tremuloides* Michx.), balsam poplar (*Populus balsamifera* L.), white spruce (*Picea glauca* (Moench) Voss), lodgepole pine (*Pinus contorta* var. latifolia) and jack pine (*Pinus banksiana* Lamb.). Lowland soils are usually Greysols and Organic soils dominated with scattered stands of black spruce (*Picea mariana* (Mill.) Britton, Sterns and Poggenb.) and shrubby or sedge fens and marshes (Natural Regions Committee 2006).

Following a natural disturbance, early successional tree species such as trembling aspen and lodgepole pine begin forest regeneration in the boreal (Chen & Papadiouk 2002). These species are typically the first to close the forest canopy, determining the composition of herbaceous, shade-tolerant understory species. After canopy closure, shade tolerant tree species such as white spruce that are slow growing and long lived remain in the community, eventually becoming one of the dominant species (Macdonald & Fenniak 2007; van Oijen et al. 2005). A forest canopy regulates resources such as light, water, and nutrients for understory community species (Macdonald & Fenniak 2007) while initiating nutrient and carbon cycling (van Oijen et al. 2005). This creates a strong relationship between the forest canopy, the mosaic of herbaceous species that make up the understory, and the forest floor surface soil layers that is the basis of a functioning forest ecosystem (Bashkin 2003; Merilä et al. 2010; Quideau et al. 2013b).

1.2 Surface mining and soil reconstruction

Mineral resource extraction through surface mining has been prevalent in Alberta since the opening of the first coal mine in the late 1800's and since then 2,000 mines are known to have operated in Alberta (Alberta Energy Regulator 2018). In 2014, nine active coal mines in Alberta generated 30.8 million tons of marketable coal, supplying 55% of the province's electricity (Government of Alberta 2018). More recently, the oil sands just north of Fort

McMurray are quickly and extensively impacting the natural landscape. 4,800 km^2 (480,000 ha) of surface mineable land is designated for oil sands mining and 895 km^2 (89,500 ha) has already been cleared and disturbed (Government of Alberta 2018). With the amount of land in Alberta facing the anthropogenic disturbance of surface mining, reclamation has become an integral part of the mining process.

The construction of a reclamation site begins with a landscape and cover soil design that will influence early forest ecosystem development and its future trajectory. Although undisturbed forests are characterized by a range of soil horizons and landforms that are operationally unfeasible in forest reclamation, establishing belowground complexity should be attempted (Macdonald et al. 2012). Open pit surface mining begins by clearing all vegetation and harvesting merchantable timber before soil salvage and stockpiling occurs in three stages. Although the direct transfer and placement of soil material on active reclamation sites has been shown to lead to faster ecosystem restoration with greater native vegetation establishment (Bradshaw 2000), it is often operationally unfeasible due to space availability and logistical challenges. In Alberta, the forest floor material, or topsoil, is generally salvaged to a depth of 30 cm and includes the organic forest floor layers (L-F-H/A horizons) and mineral B horizon. The subsoil material beneath the forest floor material is salvaged to an approximate depth of 3 m and includes the C horizon. The remaining overburden material is removed up to 75 m (TransAlta 2015; Alberta Environment & Water 2011). Overburden is often hauled to other locations and deposited as dumps instead of using it as infill for the mine pit. These deposits are then contoured, forming large-scale closure landforms that provide the base for forest reclamation.

Intending to mimic a forest soil profile, the overburden is then covered with a subsoil layer serving as the lower mineral horizon and a coversoil material serving as the surface organic and mineral soil layer. Forest floor material is often capped over subsoil, although other coversoil materials (e.g. organic amendments) can also be used. Forest floor material is considered a valuable resource, as it provides native soil organic matter that increases nutrient availability (McMillan et al. 2007), houses a rich propagule bank that promotes the establishment of boreal forest understory species (Mackenzie & Naeth 2010; Macdonald et al.

2012), and increases microbial activity (McMillan et al. 2007). Finally, tree seedlings are planted to assist in the rehabilitation of the reclamation site and develop the forest structure.

1.3 Challenges associated with forest reclamation

The process of soil salvage, stockpiling, and placement results in reconstructed soils that are highly modified and arranged with different physical, chemical, and biological properties compared to undisturbed soils (Abdul-Kareem & McRae 1984; Ghose & Kundu 2004; Mackenzie & Naeth 2010; Shrestha & Lal 2011; Anderson et al. 2008; Boyer et al. 2011; Macdonald et al. 2015a). Handling and stockpiling of reclamation soil material reduces its structure and quality, leading to low organic matter and nutrient levels (McMillan et al. 2007), disrupted microbial communities (Macdonald et al. 2012), and decreased propagule bank viability, lowering the number of native species that establish on reclamation sites (Mackenzie & Naeth 2010). Furthermore, the use of heavy machinery to reconstruct the soil profile can lead to reconstructed soils with high bulk densities (Sheoran et al. 2010) that can physically impede tree seedling root elongation (Kozlowski 1999; Sinnett et al. 2008).

Following soil placement, native tree seedlings are typically planted on forest reclamation sites. The purpose of planting trees is to establish a continuous tree canopy as quickly as possible; a closed canopy will contribute to the buildup of litter, initiating the development of the forest floor surface soil layers (Klinka et al. 1990) while fostering the establishment of a forest understory community (Maundrell & Hawkins 2004; Strong 2000). However, there is often little herbaceous cover following soil placement and tree planting leading to the establishment of disturbance adapted, shade-intolerant, annual species (Lee 2004). These early to mid-successional forb and graminoid species can compete with tree seedlings for nutrients, moisture, and light (Landhäusser & Lieffers 1998; Maundrell & Hawkins 2004; Casselman et al. 2006; Franklin et al. 2012; Johansson et al. 2013) while suppressing the development of a diverse native understory community (Macdonald et al. 2012). Low light conditions created by these undesired species especially affect shade intolerant, early successional tree species whose survival hinges on their ability to outgrow aboveground competition (e.g Chapman 1945). To increase their chance of survival, tree seedlings are able to selectively placing fine roots and leaves in areas with high resource availability as they rapidly grow above and below-ground organs (Adams et al. 2013; Pierik et al. 2013). Therefore, tree seedling root system development and biomass allocation can vary on the same coversoil material based on the presence or absence of competition as well as the species composition of competing ground cover (Eviner & Hawkes 2008; Coll et al. 2003; Morris et al. 1993).

1.4 Alternative coversoil materials and nutrient amendments

Although forest floor material capped over subsoil is considered one of the most effective arrangements of reclamation soils to re-establish boreal forest structure and function, there is often a deficit in forest floor material to cover the entire overburden landform in addition to the soil limitations that result from handling and stockpiling. However, soil limitations also associated with the subsoil material necessitate alternative coversoil materials or nutrient amendments to increase subsoil surface suitability for plant growth.

To promote tree seedling establishment on reclamation sites, synthetic fertilizers (immediately available and controlled release) have been applied where nutrient deficiencies appear to limit tree growth (Sloan & Jacobs 2013; Rowland et al. 2009; Schott et al. 2015) and organic amendments (e.g. wood chips, peat, compost) have been used as alternatives to forest floor material (Fung & Macyk 2000; Larney & Angers 2012; Olsen & Jones 1989). Synthetic fertilizer may promote tree seedling establishment and recovery of ecosystem function (Rowland et al. 2009); however, broadcast fertilization generally results in low rates of fertilizer recovery by outplanted tree seedlings (Sloan & Jacobs 2013; Hangs et al. 2003). Synthetic fertilizer may often be lost through leaching (Sloan & Jacobs 2013), immobilized by microbes in the soil (Fisher & Binkley 2000), or taken up by competing herbaceous vegetation (Sloan & Jacobs 2013; Hangs et al. 2003). Instead of salvaged forest floor material, organic amendments have also been incorporated into subsoils to increase organic matter levels and total nutrient stocks (Quideau 2013a; Larney & Angers 2012), to improve soil structure and water holding capacity (Fierro et al. 1999; Gardner et al. 2012), and to increase soil microbial biodiversity (Hahn & Quideau 2013; Mabuhay et al. 2006; Ros et al. 2003). Nevertheless, organic amendments can have negative effects on reclamation site development because they may not provide the same advantages as native organic matter in the forest floor material (Vetterlein & Hüttl 1999). Wood chips and mulch, for example, can serve as an insulator, reducing soil temperatures and impeding forest vegetation establishment (Vinge & Pyper 2012; Landhäusser et al. 2007; Ramnarine unpublished). Similarly, peat material, which is commonly used in the oil sands region of northern Alberta due to its abundance in lowland forests, is structurally and functionally different from organic matter found in non-disturbed upland forests (Turcotte 2008; Rowland et al. 2009).

Using organic amendments that are the by-product of the agriculture or forest industry as well as urban and human waste has become more widespread, as they also divert organic material from landfills (Olsen & Jones 1989; Larney & Angers 2012; Larney et al. 2003). These organic amendments span a wide range of materials and can be split into six categories: animal manure; municipal biosolids and septage; green manure and crop residue; food residue and waste; waste from manufacturing; and compost (Goss et al. 2013). However, the effectiveness of these organic amendments can be contingent on the interplay between the type of organic amendment, the application rate, the degree of incorporation, and its placement method on site. Municipal compost blended with biosolids, for example, may be high in salts from the residual salts in the biosolids that are concentrated during the composting process (Stofella & Kahn 2001). Therefore, excessive application rates of municipal compost blended with biosolids may lead to elevated salt levels contributing to possible phytotoxicity in plants (Gouin 1977, 1993; Chong & Purvis 2004; Gouin & Walker 1977; Vogtmann & Fricke 1992) and increased nutrient leaching in the first year following application (Dere et al. 2011; Scotti et al. 2015).

In the literature, organic amendments have primarily been applied at the surface and this has shown increased competition performance leading to reduced seedling survival and growth (Berry 1979; Bay et al. 2012; Chang et al. 1996; Smith et al. 1979; Staples et al. 1999). To reduce the establishment of competitive species and create artificial soil heterogeneity, a novel technique is to place, arrange, and layer organic amendments beneath a mineral soil cap. Organic matter and nutrients have been placed at the root zone of tree seedlings in forestry site preparation techniques such as soil inversion and mounding (Landlife 2008; Örlander et al. 1991, 1998). When the forest floor is not diminished, these techniques invert the forest floor beneath mineral subsoil (Landlife 2008; McMinn & Grismer 1984; Örlander et al. 1991, 1998). The buried forest floor provides a deep, well aerated, rooting environment with a reliable supply of water and nutrients (Örlander et al. 1998) while the cover of mineral subsoil limits interspecific competition during the vulnerable initial years following tree seedling planting (Landlife 2008; McMinn & Grismer 1984; Örlander et al. 1991).

Although the layering of soils with different textures can increase soil moisture availability for plant growth (Huang et al. 2013), the sharp boundaries between soil layers of different textures and densities can affect soil hydrology and aeration (Chong & Cowsert 1997; Guebert & Gardner 2001; Jin et al. 2013). Organic amendments have a high water holding capacity that can reduce soil aeration if proper drainage is not ensured (Bunt 1988), creating anaerobic conditions that may influence root placement and distribution in the reconstructed soil profile (Jung et al. 2014; Neira et al. 2015; Veijalainen et al. 2008). Moreover, the composition of an organic amendment could influence soil nutrient and microbial environments that determine greenhouse gas (CO_2, N_2O, and CH_4) emissions, which are further reflective of soil oxygen availability (Conrad 1996; Brady & Weil 2002; Linn & Doran 1984; Yoshida et al. 2015; Ginting et al. 2003). Therefore, the texture of a mineral soil cap that overlays an organic amendment layer may affect the physical and chemical characteristics of the organic amendment by influencing gas and water exchange between the organic amendment layer and the overlying surface soil layer. Reconstructing the landform on a forest reclamation site provides a platform to explore placing an organic amendment layer at the root zone of planted tree seedlings and covering this with nutrient poor mineral subsoils of different textures.

1.5 Objectives

Overall, the research in this thesis addresses two major challenges in forest restoration and reclamation: (1) limiting interspecific competition in the vulnerable initial years following tree seedling planting and (2) increasing subsoil surface suitability to improve early tree seedling survival and growth. The objective of this thesis was to examine a novel site preparation (layered) technique applied for forest reclamation that utilized the inversion of a compost (co-composted municipal compost and biosolids) layer beneath a nutrient poor mineral soil cap.

In Chapter 2, the compost layer covered with a fine or coarse textured subsoil was evaluated for its effectiveness in promoting out-planting performance of three boreal tree species while limiting the competing vegetation response over two growing seasons. This method was compared to more conventional, surface applied coversoil material treatments. Tree seedling performance was assessed in terms of survival, height, and root collar diameter as well as biomass allocation and root system development. The vegetation response was assessed by estimating percent cover based on the growth form of each individual species. Furthermore, the height in relationship to mineral soil capping depth over compost of a particularly pervasive species (*Kochia scoparia* (L.) Schrad) and its rooting depth in fine mineral subsoil were also assessed to determine future capping depth applications.

In Chapter 3, the physical and chemical characteristics of compost when surface applied or when covered with a fine or coarse mineral soil cap were investigated and compared. Edaphic conditions between compost layers were assessed in terms of soil nutrient and physical characteristics, soil moisture and temperature, and soil oxygen availability and gas exchange.

Chapter 4 provides a synthesis of the research followed by management strategies and applications. This chapter also identifies study limitations and areas for future research.

Chapter 2: Evaluating early tree seedling growth and competition in response to municipal compost placement on a reclamation site

2.1 Introduction

The organic litter and upper mineral soil layer is one of the most important structural and functional components of a forest ecosystem (Osman 2013; Bonan & Shugart 1989). Collectively defined as the forest floor, these layers serve as a storehouse for nutrients and organic matter (Persson 2012; Goodale et al. 2002; Harden et al. 1997; Prescott et al. 2000), contain soil microbes that decompose plant litter, positively influencing soil structure (Frouz 2013; Berg & McClaugherty 2014), and enhance water infiltration and retention (Fisher & Binkley 2000). Vegetation type influences forest floor composition by contributing to plant litter accumulation that will regulate soil nutrient accrual (Kishchuk et al. 2014; Vogt et al. 1995) and determining the legacy propagule bank of viable seeds that influence future plant communities (Greene et al. 1999). Thus, the forest floor in conjunction with soil microbes and the overlying plant community forms a tightly regulated biogeochemical cycle that is the basis of a functioning forest ecosystem (Bashkin 2003; Merilä et al. 2010; Quideau et al. 2013b).

Disturbance is an integral part of forest ecosystems throughout the world (Franklin et al. 2002). Natural disturbances such as wildfire, insect outbreaks, and strong winds influence the aboveground vegetation composition and organic matter in the forest floor (Brais et al. 2000; Grenon et al. 2004; Norris et al. 2009; Thiffault et al. 2008). However, forested regions are also subject to anthropogenic disturbances because they contain economically important renewable resources such as timber and non-renewable mineral and energy resources. Some of these disturbances are outside the range of variability for natural disturbances and therefore forest ecosystems may not readily adapt to recovering from such a severe disturbance (Angel et al. 2005; Burton & Macdonald 2011). Surface mining to extract non-renewable resources is such a disturbance, as it involves the removal of overlying vegetation and deeper soil layers drastically disrupting the hydrological, physical, and nutritional processes in forest soils (Alberta Environment & Water 2011; MacKenzie & Naeth 2010; Franklin et al. 2012; Macdonald et al.

2012). Thus, significant effort in the reclamation of these areas is required and the restoration of basic ecological forest function is of the utmost importance.

The surface mining process begins by removing the overlying vegetation, soil layers suitable for plant growth (forest floor material and subsoil), and remaining overburden to access the resource below. Overburden is often hauled to other locations and deposited as dumps instead of using it as infill for the mine pit. These deposits are then contoured, forming large-scale closure landforms that provide the base for forest reclamation. Forest floor material and subsoil are salvaged, sometimes stockpiled, and used as capping material for the overburden landforms (Macdonald et al. 2012). Direct placement without stockpiling of these capping materials on active reclamation areas has become more prevalent, as it preserves more of the soil propagules contained in these materials (Mackenzie & Naeth 2010; Macdonald et al. 2015a). Finally, tree seedlings are planted to assist in the rehabilitation of these sites to develop the forest structure. The establishment of a continuous tree canopy contributes to the buildup of litter initiating the development of the forest floor (Klinka et al. 1990), while inhibiting the establishment of shade-intolerant, disturbance-adapted vegetation that can compete with tree seedlings (Landhäusser & Lieffers 1998; Franklin et al. 2012) and suppress the development of a diverse understory community (Macdonald et al. 2012).

The placement of a suitable rooting medium for plants to access resources is the foundation of a forest ecosystem (Zipper et al. 2013). Forest floor material capped over subsoil is the desired arrangement of reconstructed reclamation soils, as forest floor material provides native soil organic matter that increases nutrient availability and plant propagules that promote the rapid establishment of native forest vegetation (Mackenzie & Naeth 2010; Macdonald et al. 2012). Nevertheless there is often a deficit in forest floor material to cover the entire overburden landform and the chemical, physical, and biological quality of forest floor material decreases substantially during stockpiling (Abdul-Kareem & McRae 1984; Ghose & Kundu 2004; Mackenzie & Naeth 2010; Shrestha & Lal 2011; Anderson et al. 2008; Boyer et al. 2011). Therefore, alternative coversoil materials or amendments are often used to increase the subsoil surface suitability for plant growth. Subsoils are characterized by low organic matter and nutrient levels (McMillan et al. 2007), reduced soil structure from handling and stockpiling

(Bussler et al. 1984), and increased soil compaction from heavy machinery during placement (Sheoran et al. 2010).

To promote tree seedling establishment on reclamation sites, synthetic fertilizers (immediately available and controlled release) have been applied where nutrient deficiencies appear to limit tree growth (Sloan & Jacobs 2013; Rowland et al. 2009; Schott et al. 2015) and organic amendments (e.g. wood chips, peat, compost) have also been used as alternatives to forest floor material (Fung & Macyk 2000; Larney et al. 2003; Olsen & Jones 1989). Synthetic fertilizer may promote seedling establishment and recovery of ecosystem function (Rowland et al. 2009); however, broadcast fertilization generally results in low rates of fertilizer recovery by outplanted tree seedlings (Sloan & Jacobs 2013; Hangs et al. 2003) and increases competition on the reclamation site (Schott et al. 2015). Instead of salvaged forest floor material, organic amendments have also been incorporated into subsoils to increase organic matter levels and total nutrient stocks (Quideau 2013a; Larney & Angers 2012), to improve soil structure and water holding capacity (Fierro et al. 1999; Gardner et al. 2012), and to increase soil microbial biodiversity (Hahn & Quideau; Mabuhay et al. 2006; Ros et al. 2003). However, organic amendments may not provide the same advantages as native organic matter in the forest floor (Vetterlein & Hüttl 1999) and the source and application rate of organic amendments can have negative effects on reclamation. For example, wood chips and mulch can serve as an insulator, reducing soil temperatures and impeding vegetation establishment (Vinge & Pyper 2012; Landhäusser et al. 2007; Ramnarine unpublished). Furthermore, peat material is structurally and functionally different from organic material found in the forest floor (Turcotte 2008; Rowland et al. 2009). Similarly, excessive application rates of municipal compost blended with biosolids has shown elevated salt levels contributing to possible phytotoxicity in plants (Gouin 1977, 1993; Chong and Purvis 2004; Gouin and Walker 1977; Vogtmann and Fricke 1992).

Additionally, the surface application of organic amendments or synthetic fertilizer can proliferate the establishment of early to mid-successional forb and graminoid species (Berry 1979; Chang & Preston 2000; Sloan & Jacobs 2013; Bay et al. 2012; Chang et al. 1996; Schott et al. 2015; Smith et al. 1979; Staples et al. 1999) that can compete with tree seedlings for nutrients, moisture, and light (Landhäusser & Lieffers 1998; Maundrell & Hawkins 2004;

Casselman et al. 2006; Franklin et al. 2012; Johansson et al. 2013). Shade intolerant, early successional tree species are especially affected by the low light conditions created by these undesired species and tree seedling survival is dependent on their ability to outgrow aboveground competition (e.g Chapman 1945). This is usually done by rapidly growing above and below-ground organs, selectively placing fine roots and leaves in areas with high resource availability (Adams et al. 2013; Pierik et al. 2013). Tree seedling root system development and biomass allocation may therefore vary on the same coversoil material depending on the presence or absence of competition and the species composition of competing ground cover (Eviner & Hawkes 2008; Coll et al. 2003; Morris et al. 1993). To improve tree seedling growth without promoting interspecific competition, controlled-release synthetic fertilizer or organic amendments have been applied at the root zone of planted tree seedlings (Sloan & Jacobs 2013; Hangs et al. 2003; Jacobs et al. 2005). This leads to a sustained but short-lived nutrient release that efficiently targets tree seedlings without stimulating competing vegetation (Berry 1979; Sloan & Jacobs 2013; Barberá et al. 2005; Hangs et al. 2003; Jacobs et al. 2005).

The application of organic matter and nutrients at the root zone of tree seedlings has been used in forestry site preparation techniques such as soil inversion and mounding (Landlife 2008; Örlander et al. 1991, 1998). On these sites where the forest floor is not diminished, it is inverted beneath mineral subsoil leading to improved tree seedling establishment and growth with reduced colonization by competitive vegetation (Landlife 2008; McMinn & Grismer 1984; Örlander et al. 1991, 1998). The buried forest floor provides a deep, well aerated rooting environment with a reliable supply of water and nutrients (Örlander et al. 1998) while the cover of mineral subsoil limits interspecific competition during the vulnerable initial years following tree seedling planting (Landlife 2008; McMinn & Grismer 1984; Örlander et al. 1991). On forest reclamation sites where forest floor material is unavailable, reconstructing the landform provides a platform to explore placing an organic amendment layer at the rooting zone of planted tree seedlings and covering this with nutrient poor mineral subsoil.

This research investigated a novel site preparation (layered) technique applied for forest reclamation that utilized the inversion of a compost (co-composted municipal compost and biosolids) layer beneath a nutrient poor mineral soil cap. The compost layer covered with a fine or coarse textured subsoil was evaluated for its effectiveness in promoting the early survival and growth of *Populus tremuloides* Michx. (aspen), *Pinus contorta* Douglas ex Loudon (lodgepole pine), and *Picea glauca* (Moench) Voss (white spruce) while suppressing competitive herbaceous vegetation. This method was compared to more conventional coversoil material treatments including salvaged topsoil material, surface-applied compost, and a fine mineral subsoil. It was hypothesized that the subsoil cap over compost would effectively limit herbaceous vegetation colonization while providing greater resources to tree seedlings compared to the other coversoil material treatments.

2.2 Methods

2.2.1 Study area

Research was conducted at the Highvale coal mine, 80 km west of the city of Edmonton, Alberta, Canada (53°26′ N, 114°25′ W). The study area is located in the boreal forest natural region within the Dry Mixedwood forest subregion (Natural Regions Committee 2006). Historically, the landscape is characterized by gently undulating morainal glacial till or lacustrine plains and hummocky upland areas. Forests within this subregion are dominated by trembling aspen (*Populus tremuloides* Michx.), mixed aspen-white spruce stands (*Picea glauca* (Moench) Voss), and some jack pine (*Pinus banksiana* Lamb.) stands (Natural Regions Committee 2006). The dominant soil type in upland forests in this region are Gray Luvisols (Orthic Gray to Dark Gray) that developed over a glacial till parent material.

Anthropogenic disturbances such as forest harvesting and energy resource extraction including surface mining are common throughout this region. Furthermore, approximately 40-70% of the central area in this region has been cultivated for agriculture and planted with cereal and forage crops (Natural Regions Committee 2006). At the beginning of mining operations at the Highvale coal mine in 1970, soil conservation was not a requirement under provincial law and it was not until 1983 when amendments to the Land Surface Conservation and Reclamation Act were added that the salvage of topsoil (i.e. forest floor material) and organic matter became a requirement (Sinton 2011). As a result, there is often a deficit in topsoil material available for reclamation. The Highvale coal mine lease requires previously mined areas to be returned to arable and forested land. Most of the salvaged topsoil is usually allocated to areas reclaimed for agricultural use while areas reclaimed to forest often rely on mineral subsoils of unconsolidated geological material (D. Kuchmak 2015, personal communication).

The Dry Mixedwood subregion has milder winters and the warmest summers compared to most other subregions within the boreal forest natural region (Natural Regions Committee 2006). The mean annual temperature is 3.1°C with daily historical averages ranging from -12.4°C in January to 16.4°C in July. The historical average precipitation is 517 mm, with an average of 389 mm of rain (most of which falls between May and September) and 128 mm of snow. Climate information is based on a 24-year average (1966 to 1990) (Environment Canada 2017). During the first growing season (May – September 2016) at the Highvale coal mine, the average daily temperature was 15.3°C and precipitation totaled 450.8 mm. The dormant period (October 2016 – April 2017) received 157 mm of precipitation, mostly in the form of snow, and the average temperature was -4.4°C. During the second growing season (May – September 2017), the average daily temperature was 15.2°C and precipitation totaled 304.4 mm (Appendix A-1). Climate data was gathered from a weather station approximately 35 km northeast of the Highvale coal mine in the town of Stony Plain, Alberta (53°32' N, 114°06' W) (Environment Canada 2017).

2.2.2 Site construction and soil placement

The study area was located on a large recontoured landform made of unconsolidated geological subsoil material with a clay loam texture (D. Kuchmak 2015, personal communication). The research site occupied approximately six hectares and was located on a slight east-facing slope (6 - 15%). The field experiment was designed as a randomized complete block design with six replicate blocks (100 m × 100 m) each with five randomly assigned soil treatments (Appendix A-2). The five soil treatments were: (1) an uncapped clay loam mineral subsoil (SS); (2) a 20 cm cap of salvaged topsoil (T); (3) a 20 cm layer of compost incorporated into the clay loam mineral subsoil to a depth of 25 cm (4:1 ratio) (C); (4) the same 25 cm layer of clay loam mineral subsoil and compost mixture capped with a 20 cm layer of clay loam mineral subsoil (SSC); (5) the same 25 cm layer of compost and clay loam mineral subsoil mixture capped with a 20 cm layer of a sandy mineral subsoil (SAC) (Appendix A-3). The SAC and SSC soil treatment areas within each block were 25 m by 50 m in size while the other three soil treatment (C, T, and SS) areas were 50 m by 50 m each.

In October 2015, Agricultural Grade Compost was delivered from the Edmonton Composting Facility (53°60' N, 113°34' W) to the research site (approximately 90 km away) and incorporated into the clay loam subsoil using a large breaking disk. To create compost, the Edmonton Composting Facility co-composts municipal compost and biosolids together from gardens and households in Edmonton utilizing naturally occurring microorganisms.

Conventional semi trucks averaging 26 tons of compost per load traveled onto the research site emptying compost directly onto half of each experimental block via a hydraulic-driven moving floor. 144 loads in total were delivered to the site. After half of each block received 625 tons (1,250 tons ha^{-1}) of compost, a Deere 750 K crawler bulldozer evenly distributed compost piles to a 20 cm thickness. A Case IH Steiger 600 tractor pulling a disc harrow and subsequent chisel plow travelled over half of each block with compost, mixing the compost into the clay loam subsoil to a depth of 25 cm (4:1 ratio). The original intent was to incorporate compost to a depth of 40 cm (1:1 ratio); however, operational constraints limited the depth of incorporation to the top 25 cm. The other half of each block not receiving compost was also site prepared to reduce surface compaction and disrupt the existing seedbank in the clay loam subsoil.

In April 2016, stockpiled topsoil and subsoil (sandy and clay loam material) was used to complete construction of the SAC, SSC, and T soil treatments. A 20 cm layer of sandy or clay loam subsoil was layered over the compost subsoil mixture in areas designated for the SSC and SAC soil treatments while areas selected for the T soil treatment received a 20 cm layer of topsoil over clay loam subsoil. A Deere 750 K crawler bulldozer pushed soil onto each soil treatment area ("padding in") to avoid trafficking on the C and SS soil treatments or mixing of the surface soil layer with lower soil layers.

2.2.3 Tree planting and measurements

One-year-old containerized seedlings of commercially grown *Populus tremuloides* (aspen), *Picea glauca* (white spruce), and *Pinus contorta* (lodgepole pine) were obtained from open pollinated seed sources. Aspen seedlings were grown in 6-15 cavities (6 cm × 15 cm; 336 ml) using styroblocks (Beaver Plastic, Edmonton, AB) while white spruce and lodgepole pine seedlings were grown in 4-12 A cavities (4 cm × 12 cm; 125 ml). Tree seedlings were free planted in May 2016 in a random mixture of 54% coniferous (27% white spruce and 27% lodgepole pine) and 46% deciduous (aspen) or a 4:4:7 planting mixture at an approximate spacing of 1.4 m leading to a final density of 5,000 stems ha^{-1}. The final planting composition across six hectares consisted of 13,860 aspen and 8,100 white spruce and lodgepole pine, each.

At the time of planting, average height of seedlings was 26.5 cm for aspen, 27.3 cm for white spruce, and 21.0 cm for lodgepole pine.

Prior to planting, 30 seedlings of each species were randomly selected to assess initial seedling characteristics (Appendix B-1). Height and root collar diameter (RCD) of each seedling was measured and the soil surrounding each root system was gently washed off with cold water. Stems were separated from roots and root volume was determined using the water displacement method (Harrington et al. 1994); roots and stems were then dried to a constant weight at 70°C. Dry mass of roots and stems were determined and root-to-shoot ratio (RSR) was calculated.

To assess early tree seedling survival, height, and RCD, four plots (50 m^2) were established in the first growing season (2016) and two additional plots (50 m^2) were added in the second growing season (2017). Height of each seedling was measured to the nearest 0.5 cm from the soil surface to the terminal bud and RCD was measured at the soil surface to the nearest 0.1 mm. After the first growing season, a second treatment (competition control) was added to each soil treatment that explored the impact of competition removal on tree seedling survival, height, and RCD. Since competition from agronomic and weedy species had been severe in the first growing season, all aboveground vegetation other than seedlings was removed by hand in the original four plots and these competition-free conditions were maintained weed-free throughout the second growing season (No Comp). In the two additional plots, the aboveground vegetation was left (Comp). Seedling survival was determined by counting the number of trees that survived in each plot following the second growing season and a percentage was calculated based on the initial planting density (5,000 stems ha^{-1}). Each plot (50 m^2) initially contained approximately 25 tree seedlings following planting of which 27% were each white spruce and lodgepole pine (about 7 seedlings each) and 46% where aspen (about 12 seedlings).

To determine biomass allocation and root system development of only aspen seedlings in the conventional topsoil soil treatment (T) and the two mineral soil cap over compost soil treatments (SAC and SSC), four aspen seedlings were destructively sampled at the end of the second growing season (August 2017) in each of the T, SSC, and SAC soil treatments. Further within each block and soil treatment, two aspen were excavated each from the No Comp and Comp plots. We chose aspen seedlings that were within one standard deviation of the mean in seedling height and RCD of all measured aspen seedlings in each of the Comp or No Comp plots of the SSC, SAC, and T soil treatments. Seedlings were carefully excavated to include as much of the root system as possible using pitchforks and hand-held trowels. During excavation, roots and stems (main stem, branches, and leaves) were labeled and bagged. Samples were placed in coolers and transported to the University of Alberta laboratory where they remained in the freezer (-18°C) until further processing. In September 2017, samples were thawed and separated into roots, stems (main stem and branches), and leaves. Roots and stems were processed the same as those assessed for initial seedling characteristics (see above).

Colonizing vegetation assessments took place in August 2016 and 2017. Four quadrants in 2016 (2 m^2) and 2017 (1 m^2) were established in each soil treatment in every block. In 2016, quadrants were randomly established in each soil treatment while in 2017, quadrants were randomly established in each of the two Comp plots in every soil treatment. Within each quadrant, species were identified to life-form functional group (graminiod, forb, or shrub) and percent cover was estimated (including bare ground). In 2016, percent cover of a particularly aggressive, invasive forb (*Kochia scoparia* (L.) Schrad) was also measured. Percent cover was measured to the nearest 1% if less than 10% and to the nearest 5% if greater than 10% cover.

2.2.4 Kochia scoparia measurements

In 2016, a very aggressive, invasive species (*Kochia scoparia* (L.) Schrad) established across the entire research site. Its success compared to other species in soil treatments with a mineral soil cap over compost (SAC and SSC) led us to assess the relationship between the height of *K. scoparia* and soil cap thickness in September 2016. In every SAC and SSC soil treatment plot, areas with tall and short *K. scoparia* individuals were identified. To identify these areas, transects were established at 5 m spacing along the width of each soil treatment and *K. scoparia* height was taken every 7 m along each transect, totaling a grid of 28 measurements per soil treatment plot. Based on this data, areas with the shortest and tallest *K. scoparia* individuals were delineated. In each soil treatment plot, three areas with the shortest and three areas with the tallest individuals were located and a small soil pit was dug next to the plants to determine the actual thickness of the sand or subsoil cap in this particular area.

To determine the potential rooting depth of *K. scoparia* when growing only on a fine mineral subsoil (without compost), three *K. scoparia* plants were randomly located in each SS soil treatment plot. A small soil pit approximately 4 cm from the plant stem was excavated to a depth of 55 cm. Soil samples (approximately 500 cm^3) were taken with a soil knife in 10 cm layer increments beneath the plant's stalk, totaling 5 soil samples per plant. In addition, two foliage samples from all plant species growing in the vicinity of the soil pit were taken for DNA marker analysis. These species included the target species (*K. scoparia*) and *Taraxacum officinale, Trifolium repens, Sonchus arvensis, Chenopodium album, Medicago lupulina, Medicago sativa, Agropyron trachycaulum, Cirsium arvense, Melilotus officinalis, Brassica rapa, Equisetum arvense, Matricaria perforata, Vicia cracca,* and *Crepis tectorum*. All soil and foliage samples were placed in separate bags, put into coolers, and brought back to the University of Alberta where they remained in a freezer (-18°C) until the end of September 2016.

In the laboratory, collected foliage samples were used to establish a DNA reference that allowed us to isolate *K. scoparia* roots from the roots of other species in the soil samples. All foliage samples were cleaned with deionized water to remove excess soil or pollen and freeze-dried for 72 hours. Dried samples were then ground using a ball mill (TissueLyser II, Qiagen Inc, Mississauga, ON, Canada). About 20 mg of each ground foliage sample was extracted with 5% Cetyl trimethylammonium bromide (Griffiths et al. 2000). The DNA signature of *K. scoparia* was established at a non-coding chloroplast region, the trnL-trnF intergenic spacer. Using the extracted genomic DNA material, a segment within this region was amplified by a polymerase chain reaction using a universal reverse primer (Taberlet et al. 1991) and species-specific reverse primer developed in this study; these were visualized by gel electrophoresis. A detailed description of *K. scoparia* DNA isolation is provided in Appendix C-1.

In October and November of 2016, all roots within soil samples were separated from the soil in a washing process over fine-mesh sieves involving hand manipulation. Soil samples were washed under a stream of cold water over three stacked sieves with mesh sizes 1, 0.5, 0.3 mm^2 stacked largest to smallest. Roots were picked out of each mesh using forceps, cleaned with deionized water, and then freeze-dried for 72 hours. Dried root samples were ground using a ball mill (TissueLyser II, Qiagen Inc, Mississauga, ON, Canada). Genomic DNA of root samples was extracted in the same way as foliage samples. Using the extracted genomic DNA material, separate polymerase chain reactions using the universal and species-specific reverse primers were run on all root DNA samples within a soil core and visualized using gel electrophoresis to determine the presence or absence of *K. scoparia* roots (Appendix C-1).

2.2.5 Statistical analyses

All analyses were done using R-studio (Boston, MA, USA). The data from 2016 was analyzed as a randomized complete block design to determine the effect of soil treatment (C, T, SS, SAC, and SSC) on the establishment of *Populus tremuloides*, *Pinus contorta*, and *Picea glauca* seedlings. For these results, soil treatment was the main plot (fixed effect) and block was included as the random term. In 2017, the data from this study was analyzed as a blocked split-plot design to determine the impact of soil treatment and competition (Comp and No Comp) on *Populus tremuloides*, *Pinus contorta*, and *Picea glauca* tree seedling survival and growth. For these results, soil treatment was the main plot (fixed effect), competition was the split-plot (fixed effect), and block was included as the random term. For all analyses, residuals were assessed using the Shapiro-Wilk and Levene's test to determine conformation to the assumptions of normality and heterogeneity of variance. If residuals were found to violate the assumptions, a non-parametric test was performed or data was transformed; the untransformed least squared means and standard errors are presented. Significant main effects ($p < 0.05$) were followed by a Fisher's least squared difference (LSD test) to examine differences among soil treatments, while a Holm adjustment $\alpha=0.05$ with pairwise comparisons was used to examine interactions using the lsmeans and cld function from the lsmeans package (Lenth 2016). Analyses were completed using the lme function from the nlme package (Pinheiro et al. 2018).

Seedling survival in 2017 was analyzed using a three-way ANOVA with soil treatment, competition, and species as the independent variables; survival was square root transformed. Seedling height and RCD in 2016 for aspen, lodgepole pine, and white spruce were analyzed individually for each species using a one-way ANOVA with soil treatment as the independent variable; aspen seedling height and RCD were log-transformed. Similarly, seedling height and RCD in 2017 for aspen, lodgepole pine, and white spruce were analyzed individually for each species using a two-way ANOVA with soil treatment and competition as the independent variables; aspen RCD was log-transformed. Seedling characteristics (height, RCD, stem mass, root mass, leaf mass, total mass, root volume, and root-to-shoot ratio) of destructively sampled aspen in 2017 were analyzed using a two-way ANOVA with soil treatment and competition as the independent variables. All variables except height and root-to-shoot ratio (RSR) were log-transformed.

The vegetation response on soil treatments measured as percent cover and analyzed as proportional cover by functional group in 2016 (bare ground, forb, *Kochia scoparia*, and graminoid) and 2017 (bare ground, forb, and graminoid) were analyzed separately in each year using a one-way ANOVA with soil treatment as the independent variable. A simple linear regression was used to determine the effect of mineral soil cap thickness in the SAC and SSC soil treatments on the average height of the tallest and shortest *K. scoparia* individuals in 2016.

2.3 Results

2.3.1 Survival

After two growing seasons with competition removal in the second growing season, survival across all species was highest in the SS (78%) followed by the T (44%), SAC (30%), SSC (17%), and C (0.21%) soil treatments (p<0.001). Survival of all species in the C soil treatment was close to zero and therefore was excluded from further analyses (see below). Survival of white spruce was overall higher (42%) compared to lodgepole pine and aspen (30%) (p=0.002). Survival patterns across all soil treatments were also dependent on the individual species (soil treatment by species interaction, p=0.001; Figure 2-1). White spruce had a similar survival in the SS and T soil treatments while lodgepole pine and aspen had a higher survival in the SS than in the T soil treatment. Aspen had a greater survival in the SAC compared to the SSC soil treatment, while white spruce and lodgepole pine had a similar survival between these two soil treatments. Tree seedling survival was also influenced by the presence of competition (p<0.001). Although all three species showed a trend of increased survival with competition removal, only white spruce and lodgepole pine had a significant increase in survival in the absence of competition (competition by species interaction, p=0.005; Figure 2-2). Furthermore, this response occurred in all soil treatments except the C soil treatment where survival was negligible regardless of competition control (soil treatment by competition interaction, p=0.001; Figure 2-3).

2.3.2 Height

Aspen seedlings in 2016 grew tallest in the SAC, SSC, and T compared to the SS soil treatment (p=0.002; Figure 2-4 A). Lodgepole pine had a small but significant difference in height in seedlings growing in the T and SSC soil treatments (24 cm) compared to seedlings in the SAC soil treatment (21 cm) (p=0.003; Figure 2-4 B). White spruce seedling height was not significantly different among the four soil treatments (p=0.663; Figure 2-4 C). In 2017 after the removal of competition in the second growing season, both soil treatments with a mineral soil cap over compost (SAC and SSC) had shorter aspen seedlings in areas with competition removal compared to areas without removal; however, there was no effect of competition control on aspen seedling height in the other soil treatments (soil treatment by competition interaction, p=0.016; Figure 2-4 D). Overall aspen were tallest in the SAC (79 cm) followed by the SSC and T soil treatments (63 cm), which was double the height in the SS soil treatment (36 cm) (p<0.001). Similar to aspen, lodgepole pine seedlings were shorter when competition was removed in soil treatments capped with mineral soil over compost (SAC and SSC), while there was no response in the T and SS soil treatments (soil treatment by competition interaction, p=0.002; Figure 2-4 E). Overall, lodgepole pine had a small but significant height difference in seedlings growing in the T, SAC, and SSC soil treatments (29 cm) compared to the SS soil treatment (25 cm) (p=0.002). White spruce seedling height was not influenced by the removal of competition, but after two growing seasons, white spruce seedlings in the SS soil treatment were shorter than seedlings growing in the T soil treatment (p=0.012; Figure 2-4 F).

2.3.3 Root collar diameter

In 2016 aspen seedling root collar diameter (RCD) was not significantly different among the four soil treatments (p=0.238; Figure 2-5 A). Lodgepole pine had a small but significant difference in RCD in seedlings growing in the SS and T soil treatments (5.4 mm) compared to the SSC soil treatment (4.7 mm) (p=0.008; Figure 2-5 B). There was also a small but significant difference in RCD among white spruce seedlings growing in the SS and SAC soil treatments (5.3 mm) compared to the SSC soil treatment (4.7 mm) (p=0.014; Figure 2-5 C). After the removal of competition in the second growing season, only aspen seedlings in the coarse mineral soil cap over compost (SAC) had a smaller RCD in areas with competition removal than in areas with competition, this response was not detected in the other soil treatments (soil treatment by competition interaction, p=0.016; Figure 2-5 D). Overall aspen had the largest RCD in the SAC (10.0 mm), which was significantly greater than in the SSC and T soil treatments (7.0 mm) and double that of the SS soil treatment (5.1 mm) (p<0.001). Similar to aspen, lodgepole pine seedling RCD responded to competition control with a smaller RCD in the absence of competition compared to the presence in the coarse mineral soil cap over compost (SAC) while seedling RCD was similar among the T, SS, and SSC soil treatments (soil treatment by competition interaction, p=0.003; Figure 2-5 E). Overall lodgepole pine had a small but significant difference in RCD in seedlings growing in the SAC soil treatment (6.1 mm) compared to the SS soil treatment (5.5 mm) ($p=0.045$). White spruce seedling RCD was not influenced by the removal of competition; however, after two growing seasons, white spruce seedlings in the SSC had a smaller RCD than seedlings growing in the SAC soil treatment ($p=0.003$; Figure 2-5 F).

2.3.4 Aspen seedling biomass allocation

Aspen seedlings in 2017 were destructively sampled to compare biomass allocation and root system development in the conventional topsoil soil treatment (T) compared to the mineral soil cap over compost soil treatments (SAC and SSC). Seedlings in the presence or absence of competition were also compared. It was observed that the roots of all aspen seedlings growing in the SAC and SSC soil treatments remained in the mineral soil cap and did not expand into the underlying compost layer. Aspen seedlings in the presence of competition in the SAC had a larger RCD than aspen seedlings in the other soil treatments (soil treatment by competition interaction, $p=0.004$; Table 2-1); however, aspen seedling height was not significantly different between competition and soil treatments (soil treatment by competition interaction, $p=0.460$; Table 2-1, 2-2). Although leaf mass, stem mass, root mass, and total mass were also unaffected by competition removal, aspen seedlings in the SAC soil treatment had a larger leaf mass, stem mass, root mass, and total mass than seedlings growing in the SSC and T soil treatments (all $p<0.005$; Table 2-1; Figure 2-6 A). Aspen seedlings in the SAC soil treatment had a larger root volume in the presence of competition, while there was no impact of competition in the other soil treatments (soil treatment by competition interaction, $p=0.023$; Figure 2-6 B; Table 2-1). Overall aspen seedlings had the largest root volume in the SAC (78 ml), which was significantly greater than in the SSC soil treatment (48 ml) and more than double in the T soil treatment (31 ml) ($p<0.001$; Table 2-2). Finally, root-to-shoot ratio (RSR) was not significantly different in the presence or absence of competition among all soil treatments (soil treatment by competition interaction, $p=0.338$); however, competition control had an effect on RSR where overall aspen seedling RSR was lower in the presence of competition (0.90) than the absence (1.12) in the T, SSC, and SAC soil treatments ($p=0.006$; Table 2-2).

2.3.5 Vegetation response

In 2016, the total vegetation cover was low and a significant portion was bare ground in the SS soil treatment (61%) while there was less than 5% bare ground in the T soil treatment and close to no bare ground in the C, SSC, and SAC soil treatments ($p<0.001$; Figure 2-7 A). Forbs dominated the T, C, SSC, and SAC soil treatments although the proportion of forbs relative to total cover was almost 100% in the C, SAC, and SSC soil treatments and lower in the T soil treatment at 85% ($p<0.001$). *Kochia scoparia* dominated the forb cover in all soil treatments that included compost, but in the C soil treatment its cover was 97%, which was significantly higher than in the SSC and SAC soil treatments (90%). In the T and SS soil treatments other forbs dominated and *K. scoparia* made up only 7% of forb cover ($p<0.001$; Figure 2-7 A). After the first growing season, graminoids made up a relatively small proportion of total cover in the T soil treatment (16%) but it was greater than the SS soil treatment (8%) and the C, SSC, and SAC soil treatments (1%) ($p=0.001$).

There was a negative relationship between soil cap thickness and the height of *K. scoparia* individuals on a fine mineral soil cap over compost (SSC: $y=205.05-3.85x$, $p=0.024$, $R^2=0.413$; Figure 2-8). However, no relationship was found for the coarse mineral soil cap over compost (SAC: $p=0.808$; data not shown). All excavated *K. scoparia* plants in the SS soil treatment rooted to a depth of at least 30 cm and approximately 72% of the plants reached a depth of at least 50 cm (Table 2-3).

In 2017, bare ground decreased in the SS soil treatment to 47% although it continued to make up the largest proportion of total cover in this soil treatment. Comparatively, bare ground increased slightly in the SSC and SAC soil treatments but remained less than 10% and similar to the T and C soil treatments ($p<0.001$; Figure 2-7 B). Forb cover was lower in the second growing season, but forbs continued to dominate the SSC and SAC soil treatments (75%) compared to the other soil treatments ($p=0.023$). Graminoid cover increased significantly in all soil treatments; the proportion of graminoids relative to total cover was highest in the C soil treatment (55%), followed by the T soil treatment (32%) and the SAC and SSC soil treatments (18%), and was least in the SS soil treatment (4%) ($p<0.001$; Figure 2-7 B). Although *K. scoparia* cover was not separately measured in 2017, it was observed that *K. scoparia* abundance decreased significantly in 2017; particularly in the C, SSC, and SAC soil treatments, other forbs and graminoid species increased in these soil treatments.

2.4 Discussion

Covering a rich compost layer with a (20 cm) mineral soil cap (SAC and SSC) did not reduce competition as we had initially hypothesized. This negative result was driven by one aggressive colonizing species (*Kochia scoparia*) that was contained in the original seedbank for the salvaged clay loam subsoil material and had established across the entire research site. The roots of this species were able to penetrate the mineral soil cap in the SSC and SAC, accessing the buried compost layer and dominating the vegetation in these soil treatments. The excavation and DNA identification showed clearly that even under nutrient poor conditions in the fine mineral subsoil (SS), *K. scoparia* can extend its root down to at least 50 cm. Other potentially competitive species were not as abundant in these soil treatments, but it is unclear if this was due to competition with *K. scoparia* or the inability of these species to penetrate the mineral soil cap. The coarse mineral soil cap in the SAC soil treatment was not as effective in limiting *K. scoparia* establishment as the fine mineral soil cap in the SSC soil treatment and cap thickness played a significant role; shorter *K. scoparia* individuals established in areas where the fine mineral soil cap was thicker. Another factor that may have rendered the fine mineral soil cap in the SSC less effective was the higher than average precipitation during the first growing, which can reduce soil penetration resistance (Whalley et al. 2005) and may have allowed the quick growing *K. scoparia* root system to penetrate through the mineral soil cap and into the compost layer (2016: 450.8 mm; Appendix A-1). This suggests that a thicker fine mineral soil cap could have been more effective in suppressing *K. scoparia* establishment in the SSC soil treatment.

K. scoparia was present in all soil treatments in 2016; however, the vegetation on soil treatments with compost (C, SSC, and SAC) were clearly dominated by large *K. scoparia* individuals, indicating that substrate conditions were driving the growth of this species. *K. scoparia* is a highly competitive C_4 species that can rapidly establish on recently disturbed mining landscapes because of its ability to germinate at low soil temperatures and emerge early in the growing season (Wali & Freeman 1973). As a facultative alkali halophyte (Khan et al. 2001), *K. scoparia* has high water-use efficiency and salt tolerance (Low 2016; Bilski & Foy 1988), requiring sodium as a micronutrient (Brownell & Crossland 1972; Friesen et al. 2009).

However, in 2017 the vegetation response in soil treatments with compost shifted. The proportion of graminoids, primarily *Agropyron trachycaulum*, made up more than 50% of the total cover in the C soil treatment, while graminoids and forbs other than *K. scoparia* (*Matricaria perforata* and *Chenopodium album*) established in the SSC and SAC soil treatments. *K. scoparia* abundance has been found to decrease over time and is attributed to allelopathic chemicals produced by the decaying leaves and roots of dead *K. scoparia* individuals suppressing the growth of the next generation of individuals establishing in subsequent growing seasons (Wali 1999). Based on personal observations in the field, the C, SSC, and SAC soil treatments were covered with a thick mat of dead *K. scoparia* material following the first growing season. Although graminoid and forb species other than *K. scoparia* began to colonize soil treatments with compost in 2017, bare ground in the SSC soil treatment also increased in 2017. This might be an indication that if *K. scoparia* had not been so prolific during the first growing season, the fine mineral soil cap may have worked as intended. Furthermore, the C soil treatment had similar competition levels as the SSC and SAC soil treatments during the first growing season, though tree seedling survival in this soil treatment was significantly lower. This suggests that substrate conditions in the compost not only influenced the vegetation response on soil treatments with compost, but may have also influenced low tree seedling survival in the C soil treatment.

The relatively low survival of all three tree species in soil treatments with compost (C, SSC, SAC) after two growing seasons could have been a result of the magnitude of herbaceous competition; however, the compost itself could have played a significant role in this response. The compost application rate (1250 tons ha^{-1}) at the research site was much higher and much more concentrated (4:1 ratio) than was originally planned. These application rates are also much higher than has been reported previously in the literature. Several of these studies indicate that low compost application rates resulted in tree seedling survival and growth that was equal to (Martinez et al. 2003; Thompson et al. 2001) or better than their highest application rates (Newton & Whitehead 1998; Spargo & Doley 2016; Topper & Sabey 1986; Smith et al. 1979). For example, Smith et al. (1979) applied 0, 112, 224, and 448 tons of compost ha^{-1} (co-composted municipal compost and biosolids) in furrows (at the root zone) and broadcast incorporated. *Pinus ellioti* seedlings after six years in the 112 and 225 tons ha^{-1} overall grew taller than those in the 448 tons ha-^{1}; this was attributed to intense competition from herbaceous vegetation with the higher application rate despite compost also being applied in furrows. In forest reclamation, a single application of compost may be justified as a kick-start soil treatment to promote early tree seedling establishment (Fuentes et al. 2010). However, the very high compost application rate and concentration in our study clearly had a negative effect on early tree seedling survival and growth.

In addition to the high application rate, the source of compost may have contributed to low early tree seedling survival particularly in the C soil treatment. Compost was sourced from the Edmonton Composting Facility where municipal compost and biosolids from households in Edmonton are co-composted together. Co-composting municipal compost and biosolids has shown enhanced quality and effectiveness (Willson 1991; Tognetti et al. 2007; Vallini et al. 1992; Young et al. 2000) by increasing organic matter levels (Tognetti et al. 2007) and nutrient content (particularly N and P concentrations) (Kashmanian et al. 2000; Young et al. 2000). However, excessive application rates of compost blended with biosolids have shown elevated nutrient and salt levels contributing to phytotoxicity in plants (Gouin 1977, 1993; Chong & Purvis 2004; Gouin & Walker 1977; Vogtmann & Fricke 1992) and disproportionate leaching (Dere et al. 2011; Scotti et al. 2015). *Kochia scoparia* is a salinity tolerant species (Bilski & Foy 1988) and following tree seedling planting in 2016, symptoms of salt stress and phytotoxicity, including wilting, leaf loss, and tip burning of leaves (USDA NRCS 2002; Soil Improvement Committee 1995; Barbour et al. 1998; Hanson et al. 1999), were observed on aspen in the C soil treatment (E. Marenholtz, personal communication). Therefore, the high application rate of co-composted municipal compost and biosolids at the research site may have contributed to low early tree seedling survival in the C soil treatment as well as the proliferation of *K. scoparia* in the C, SSC, and SAC soil treatments. Moreover, it was observed that the roots of excavated aspen seedlings in the SSC and SAC soil treatments in 2017 remained in the mineral soil cap and did not expand into the underlying compost suggesting their avoidance of the compost layer. More detail on compost physical and chemical characteristics are provided in Chapter 3.

Although competitive herbaceous vegetation established across all soil treatments, the SS had the highest proportion of bare ground relative to total cover among soil treatments in 2016 and 2017. A higher proportion of bare ground relative to total cover decreased light interception for tree seedlings, which may have driven higher seedling survival in the SS relative to other soil treatments in 2017. Low survival for aspen and lodgepole in the T, C, SSC, and SAC relative to the SS soil treatment in 2017 can be explained by their shade intolerance, often leading to reduced survival in an understory setting (Landhäusser & Lieffers 2001). Although white spruce is considered a shade tolerant understory species, competition with herbaceous species that severely limit light availability during the early years following planting can also hinder its establishment (Lieffers & Stadt 1994). Therefore, reduced survival for all tree species in the T, C, SSC, and SAC soil treatments relative to the SS appears to be partly influenced by intense interspecific competition creating an environment of low light availability for tree seedlings. However, aspen were shorter in the SS relative to the T, SSC, and SAC soil treatments and this could be driven by low soil organic matter and nutrient levels belowground limiting tree seedling growth (see Chapter 3).

Though the presence of competition in all soil treatments limited seedling survival, once the seedlings were established it did not appear to limit seedling height and RCD growth in the SSC and SAC soil treatments. Interestingly, aspen seedlings that survived into the second growing season were tallest and had the largest RCD in the SSC and SAC soil treatments regardless of competition. This suggests that the layered technique in the SSC and SAC soil treatments may provide additional resources belowground, allowing aspen to outgrow the competition. Furthermore, aspen and lodgepole pine seedlings in the SSC and SAC were taller in the presence of competition, likely a response that can be attributed to a shade avoidance survival strategy that has been described for shade intolerant species (Smith 1981, 1982; Claveau et al. 2002; Gilbert et al. 2001). As shade intolerant, early successional species, the survival of aspen and lodgepole pine seedlings is dependent on their ability to outgrow aboveground competition (e.g. Chapman 1945). This indicates that seedlings attempted to gain a competitive advantaged by enhancing light quality and availability for themselves and worked best in an environment where resources other than light (i.e. water, nutrients, and growing space) were not limiting (Bockstette et al. 2017, 2018).

Seedling characteristics of destructively sampled aspen indicated that overall, aspen seedlings in the SAC had larger biomass characteristics belowground and aboveground than those in the T and SSC soil treatments. This appears to be driven by aspen seedlings in the presence of competition in the SAC soil treatment, which had a larger RCD than all other seedlings. However, the average RCD of destructively sampled aspen seedlings in the presence of competition in the SAC soil treatment (13.4 mm) was higher than the average RCD of all measured aspen seedlings in the presence of competition in the SAC soil treatment (11.3 mm). It is therefore unclear if this effect is unanimous across all aspen in the presence of competition in the SAC soil treatment or just those destructively sampled. Still, destructively sampled aspen seedlings in the presence of competition in the SAC soil treatment were not taller than other destructively sampled seedlings. Aspen seedlings in the SAC were competing mostly with forb species, which compete most effectively aboveground limiting light availability (Eviner & Hawkes 2008; Coll et al. 2003; Morris et al. 1993). As aspen reached the top of the herbaceous canopy in the second growing season, light may not have been a limiting resource and aspen's indeterminate growth may have allowed seedlings in the presence of competition to increase their overall biomass. Furthermore, competition had an overall effect on aspen seedling RSR where destructively sampled aspen in the presence of competition had a lower RSR than seedlings in the absence of competition in the T, SSC, and SAC soil treatments. With light as a limiting resource in the presence of competition in these soil treatments, aspen seedlings may have allocated more resources aboveground. To outgrow competition, aspen usually grow rapidly aboveground and belowground, selectively placing fine roots and leaves in areas with high resource availability (Adams et al. 2013; Pierik et al. 2013). With light as an abundant resource in the absence of competition in the SAC, SSC, and T soil treatments, aspen seedlings may have allocated more resources belowground.

Overall, the use of compost in forest reclamation to improve tree seedling establishment where nutrient deficiencies appear to limit tree growth is likely dependent on the compost source, application rate, and degree of incorporation in the subsoil as well as the placement method. Although compost capped with 20 cm of mineral soil (SSC and SAC) allowed the establishment of an aggressive species (*Kochia scoparia*), aspen grew tallest and largest in these soil treatments. The fine mineral soil cap appears to be more effective in limiting the growth of *K. scoparia* and other competition; tree seedling survival in the SSC soil treatment may have been higher if wet conditions had not encouraged *K. scoparia* root penetration in the first growing season. Furthermore, the high compost application rate relative to other studies (e.g. Spargo & Doley 2016; Bay et al. 2012; Smith et al. 1979) clearly also impacted tree seedling survival and *K. scoparia* colonization. It is likely that a reduced compost application rate with a deeper incorporation into the subsoil in the C, SSC, and SAC soil treatments would have led to higher seedling survival, while a thicker fine mineral soil cap (greater than 50 cm) in the SSC soil treatment could have limited *K. scoparia* competitiveness.

Tables

Table 2-1. Seedling measurements (average ± standard error of the mean) in 2017 for destructively sampled aspen grown in the topsoil cap (T), fine mineral soil cap over compost (SSC), and coarse mineral soil cap over compost (SAC) soil treatments with competition removal (No Comp) and without competition removal (Comp) in the second growing season (n=6). Different letters indicate significantly different means (α = 0.05). Note: 'RCD' refers to root collar diameter and 'RSR' refers to root-to-shoot ratio.

	Soil Treatment					
Seedling Characteristics	**T**		**SSC**		**SAC**	
	Comp	No Comp	Comp	No Comp	Comp	No Comp
Height (cm)	72.00 **a** (± 3.96)	71.04 **a** (± 3.52)	77.88 **a** (± 8.39)	65.29 **a** (± 4.14)	85.75 **a** (± 7.57)	75.58 **a** (± 1.55)
RCD (mm)	7.60 **b** (± 0.35)	8.31 **b** (± 0.48)	8.81 **b** (± 0.47)	7.83 **b** (± 0.25)	13.40 **a** (± 1.35)	9.24 **b** (± 0.29)
Leaf mass (g)	3.18 **b** (± 0.35)	4.70 **ab** (± 0.97)	3.65 **ab** (± 1.02)	3.18 **b** (± 0.68)	12.87 **a** (± 3.46)	7.03 **ab** (± 1.02)
Stem mass (g)	11.50 **b** (± 1.26)	13.40 **b** (± 1.92)	15.10 **ab** (± 2.72)	10.33 **b** (± 1.06)	44.26 **a** (± 16.07)	17.90 **ab** (± 1.86)
Root mass (g)	8.26 **c** (± 0.70)	11.13 **c** (± 1.74)	13.48 **ab** (± 2.59)	15.06 **ab** (± 3.94)	38.30 **a** (± 12.67)	19.45 **ab** (± 2.49)
Total mass (g)	22.93 **b** (± 1.95)	29.23 **b** (± 4.27)	32.23 **ab** (± 5.14)	28.57 **b** (± 5.44)	95.43 **a** (± 31.93)	44.38 **ab** (± 5.13)
Root volume (ml)	26.95 **c** (± 1.64)	36.04 **bc** (± 6.20)	45.38 **bc** (± 5.74)	49.01 **bc** (± 8.89)	108.08 **a** (± 28.49)	54.38 **b** (± 6.24)
RSR ($g\ g^{-1}$)	0.78 **a** (± 0.09)	0.88 **a** (± 0.09)	1.09 **a** (± 0.38)	1.41 **a** (± 0.19)	0.89 **a** (± 0.07)	1.09 **a** (± 0.08)

Table 2-2. Results of a two-way ANOVA in 2017 examining seedling measurements for destructively sampled aspen grown in the topsoil cap (T), fine mineral soil cap over compost (SSC), and coarse mineral soil cap over compost (SAC) soil treatments with competition removal (No Comp) and without competition removal (Comp) in the second growing season (n=6). P-values are given and bolded when significant (α = 0.05). Note: 'RCD' refers to root collar diameter and 'RSR' refers to root-to-shoot ratio.

	Soil Treatment	**Competition**	**Interaction**
Height (cm)	0.132	0.082	0.460
RCD (mm)	**<0.001**	**0.015**	**0.004**
Leaf mass (g)	**0.005**	0.405	*0.057*
Stem mass (g)	**0.002**	**0.048**	*0.065*
Root mass (g)	**<0.001**	0.632	0.098
Total mass (g)	**<0.001**	0.182	*0.062*
Root volume (ml)	**<0.001**	0.256	**0.023**
RSR (g g^{-1})	*0.076*	**0.006**	0.338

Table 2-3. The average proportion of soil samples that contained *Kochia scoparia* roots in the fine mineral subsoil (SS) soil treatment in 2016 (average ± standard error of the mean). Soil samples were taken in 10 cm increments to a depth of 50 cm beneath three plants in each SS soil treatment (n=6). The presence or absence of *K. scoparia* in each soil samples was determined using DNA references from foliage samples isolating *K. scoparia* roots from the roots of other community species.

Soil Treatment	Depth (cm)	*Kochia scoparia* detected (%)
SS	0-10	100 (± 0.00)
	10-20	100 (± 0.00)
	20-30	100 (± 0.00)
	30-40	94.44 (± 5.56)
	40-50	72.22 (± 10.24)

Figures

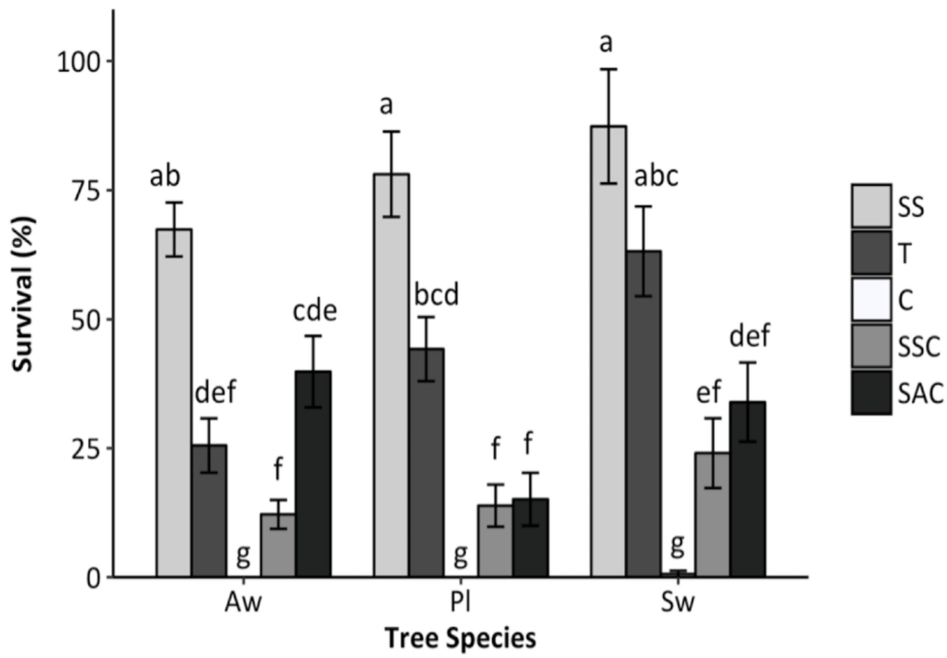

Figure 2-1. The average percent survival after two growing seasons for aspen (Aw), lodgepole pine (Pl), and white spruce (Sw) grown in the fine mineral subsoil (SS), topsoil cap (T), compost cap (C), fine mineral soil cap over compost (SSC), and coarse mineral soil cap over compost (SAC) soil treatments. Error bars are standard error of the mean (n=6) and different letters indicate significantly different means (α = 0.05).

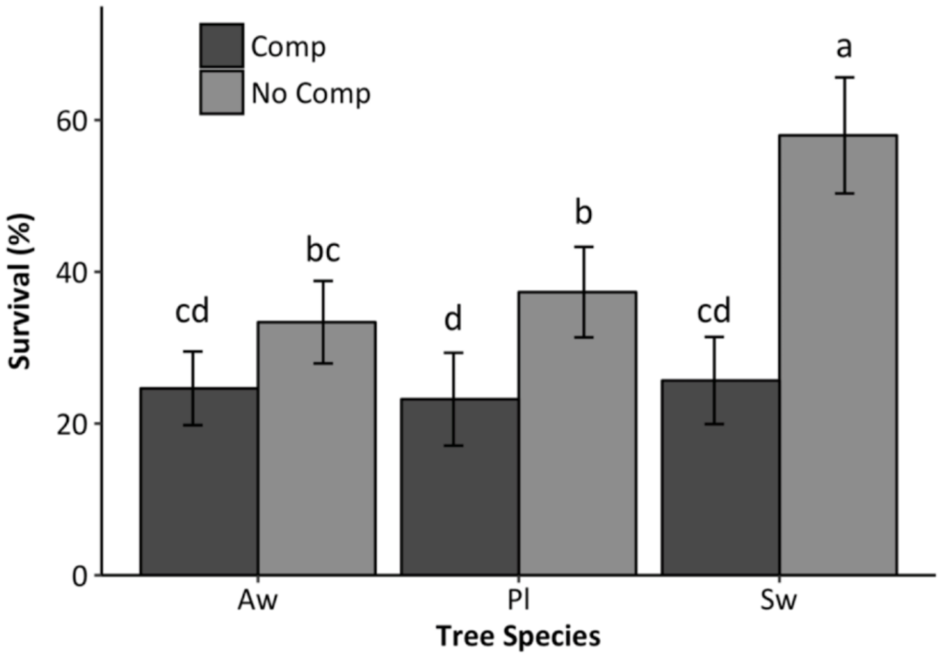

Figure 2-2. The average percent survival after two growing seasons for aspen (Aw), lodgepole pine (Pl), and white spruce (Sw) seedlings with competition removal (No Comp) and without competition removal (Comp) in the second growing season. Error bars are standard error of the mean (n=6) and different letters indicate significantly different means (α = 0.05).

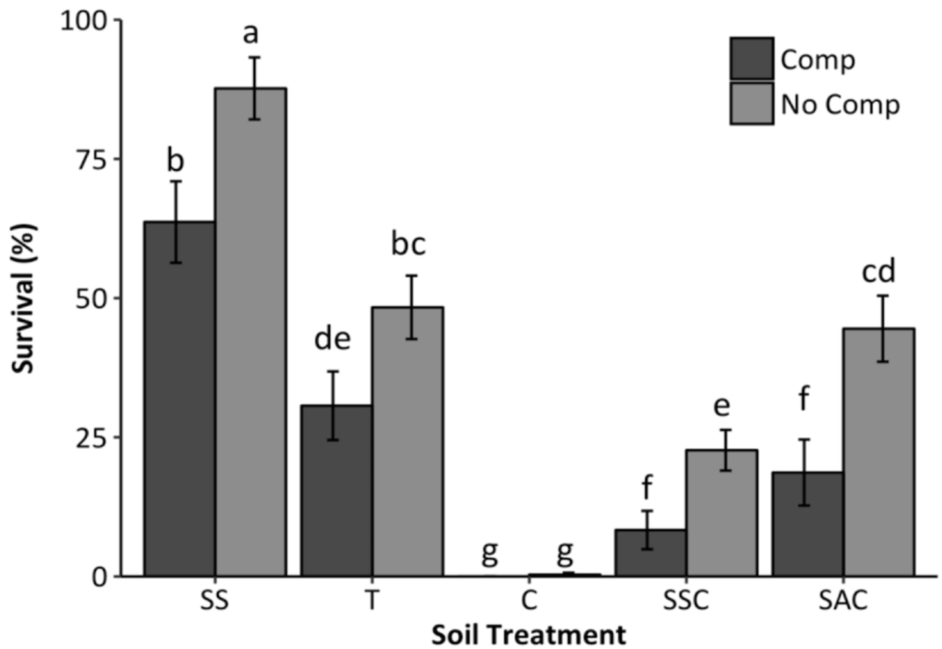

Figure 2-3. The average percent survival after two growing seasons for tree seedlings grown in the fine mineral subsoil (SS), topsoil cap (T), compost cap (C), fine mineral soil cap over compost (SSC), and coarse mineral soil cap over compost (SAC) soil treatments with competition removal (No Comp) and without competition removal (Comp) in the second growing season. Error bars are standard error of the mean (n=6) and different letters indicate significantly different means ($\alpha = 0.05$).

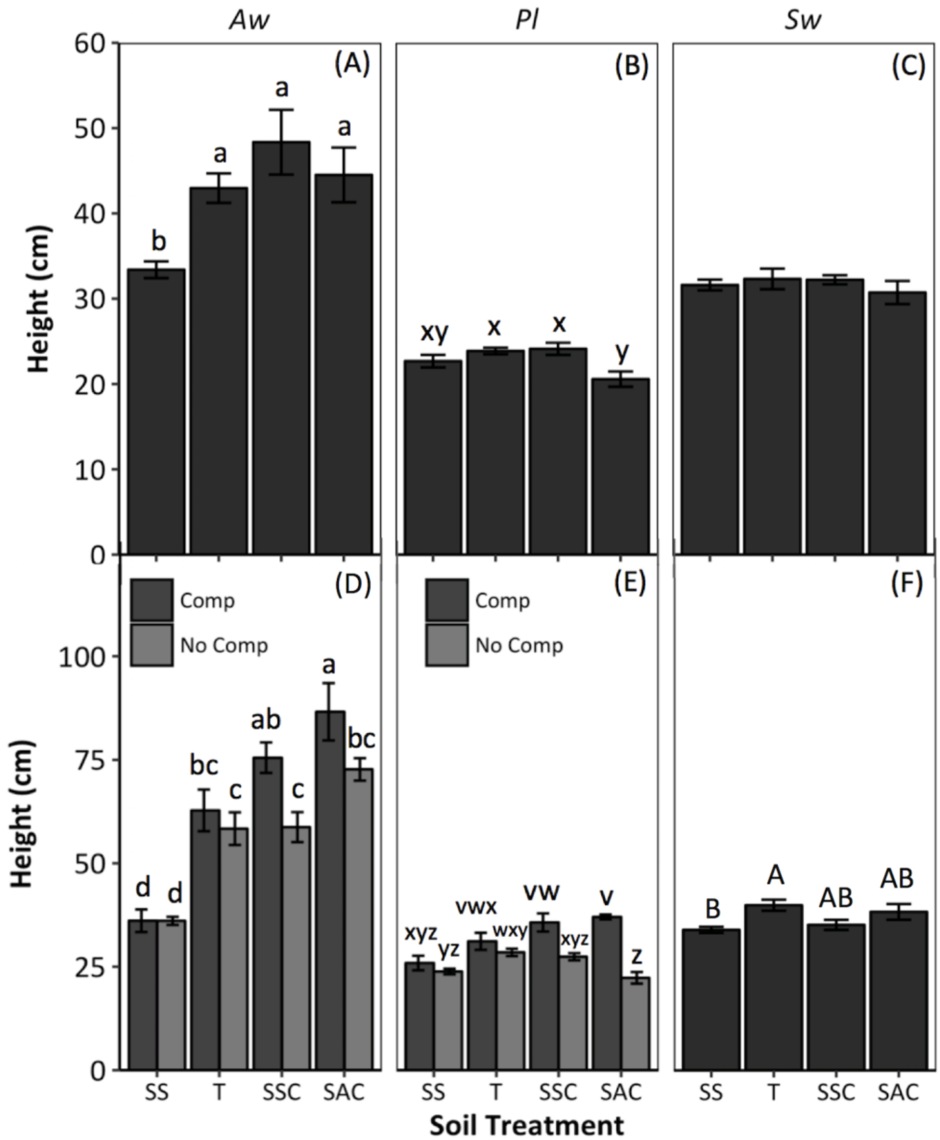

Figure 2-4. Average tree seedling height in 2016 (A, B, C) and 2017 (D, E, F) for aspen (Aw), lodgepole pine (Pl), and white spruce (Sw) grown in the fine mineral subsoil (SS), topsoil cap (T), fine mineral soil cap over compost (SSC), and coarse mineral soil cap over compost (SAC) soil treatments. Competition removal in the second growing season, presence of competition (Comp) and absence of competition (No Comp), had an effect on aspen and lodgepole pine seedling height. Error bars are standard error of the mean (n=6) and different letters indicate significantly different means (α = 0.05). The compost cap (C) soil treatment was not included in seedling height comparisons because of very low seedling survival.

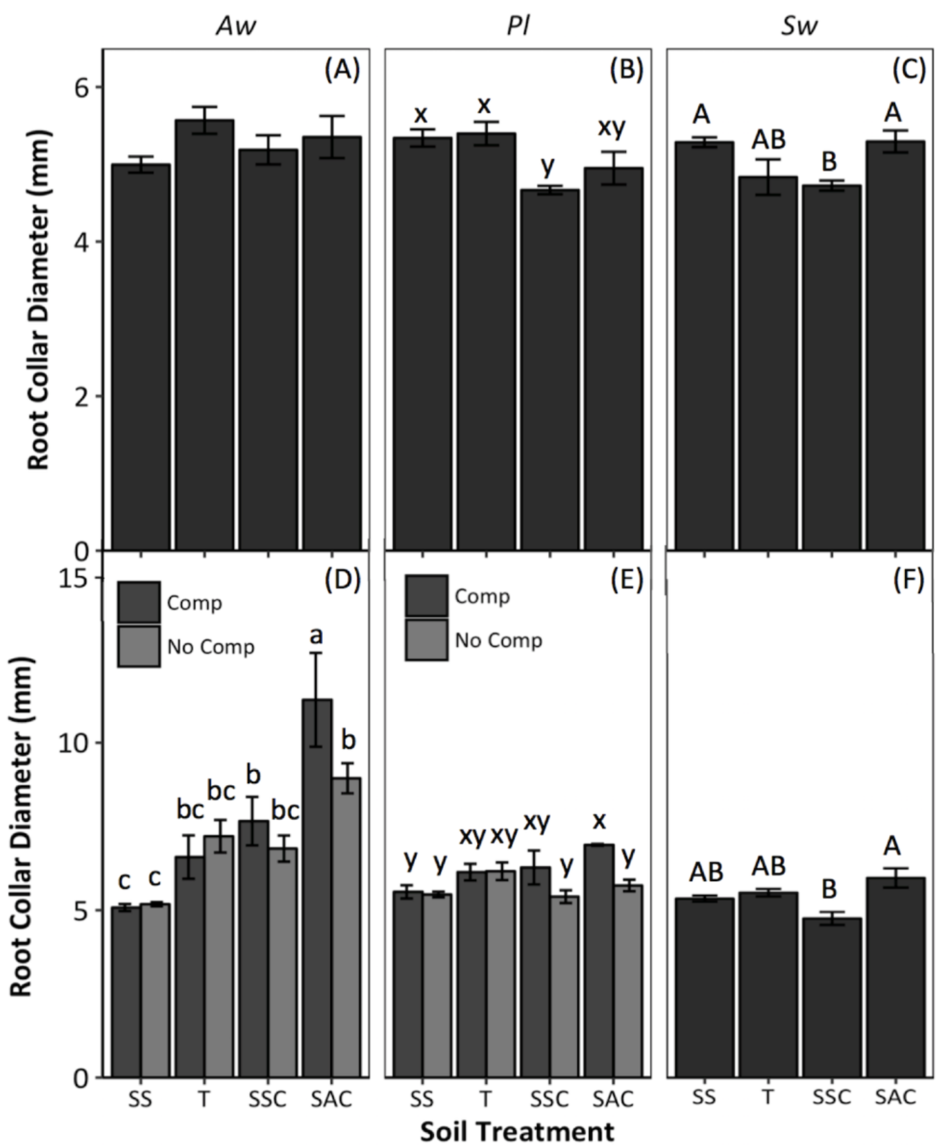

Figure 2-5. Average tree seedling root collar diameter (RCD) in 2016 (A, B, C) and 2017 (D, E, F) for aspen (Aw), lodgepole pine (Pl), and white spruce (Sw) grown in the fine mineral subsoil (SS), topsoil cap (T), fine mineral soil cap over compost (SSC), and coarse mineral soil cap over compost (SAC) soil treatments. Competition removal in the second growing season, presence of competition (Comp) and absence of competition (No Comp), had an effect on aspen and lodgepole pine seedling RCD. Error bars are standard error of the mean (n=6) and different letters indicate significantly different means (α = 0.05). The compost cap (C) soil treatment was not included in seedling RCD comparisons because of very low seedling survival.

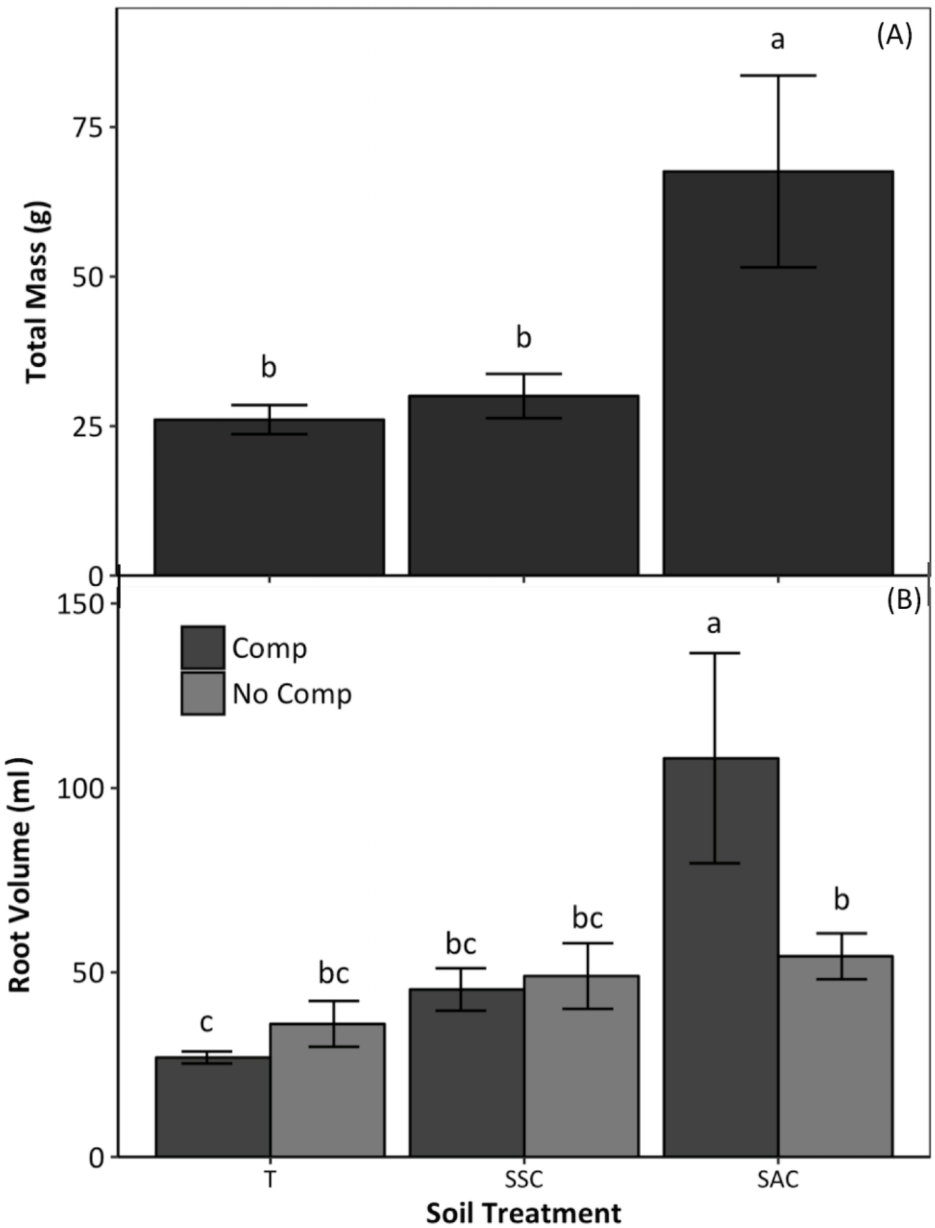

Figure 2-6. Average total mass (A) and root volume (B) in 2017 of destructively sampled aspen grown in the topsoil cap (T), fine mineral soil cap over compost (SSC), and coarse mineral soil cap over compost (SAC) soil treatments. Competition removal in the second growing season, presence of competition (Comp) and absence of competition (No Comp), had an effect on aspen seedling root volume. Error bars are standard error of the mean (n=6) and different letters above bars indicate significantly different means ($\alpha = 0.05$).

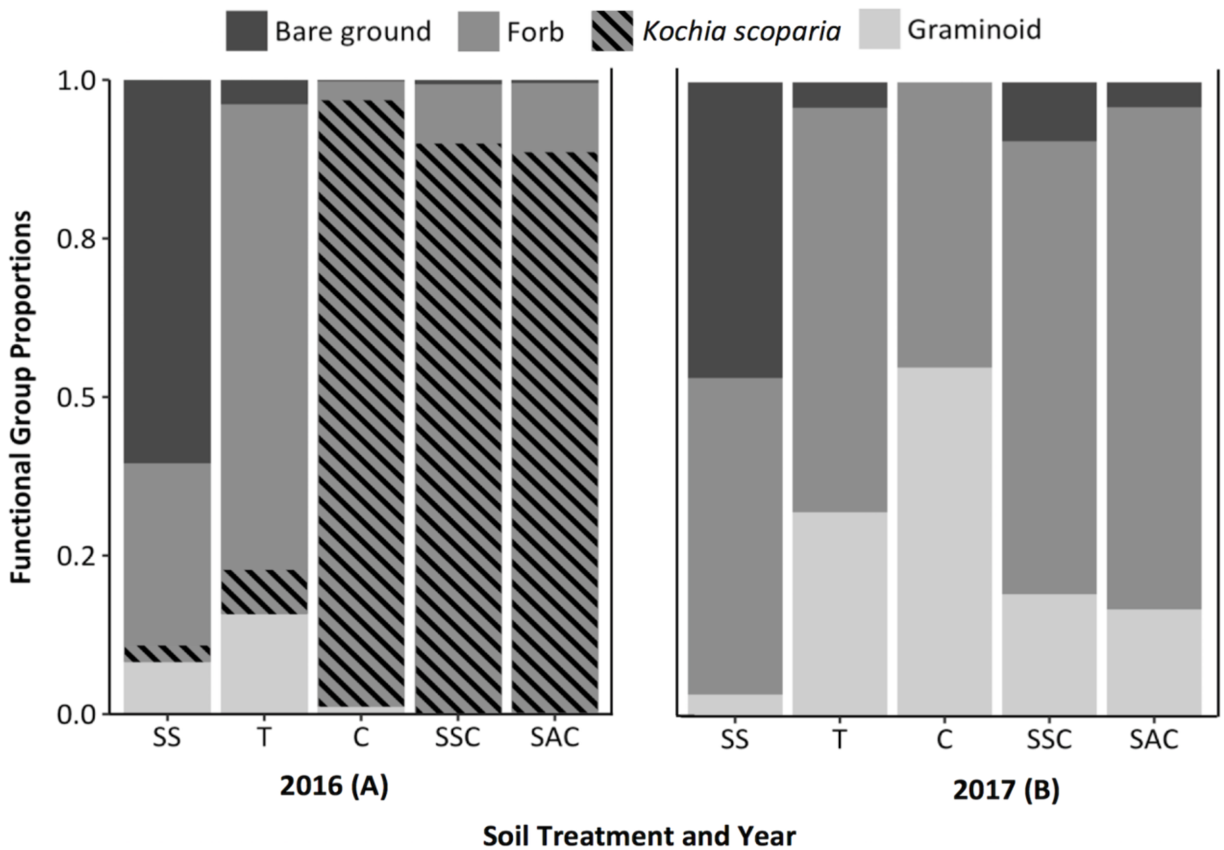

Figure 2-7. Functional group cover as a proportion of total cover in 2016 (A) and 2017 (B) in the fine mineral subsoil (SS), topsoil cap (T), compost cap (C), fine mineral soil cap over compost (SSC), and coarse mineral soil cap over compost (SAC) soil treatments (n=6). *Kochia scoparia* cover was only measured in 2016.

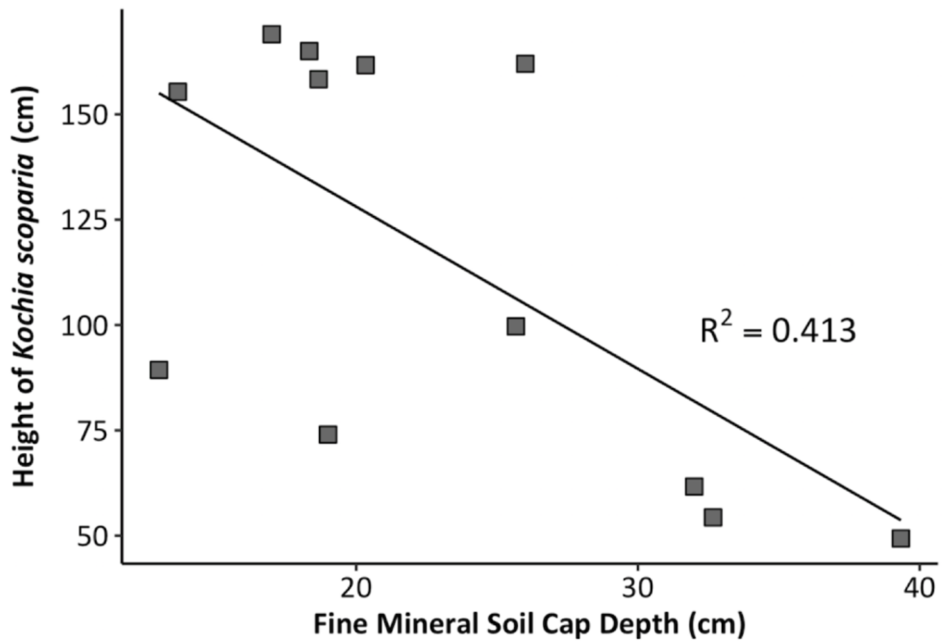

Figure 2-8. Relationship between fine mineral subsoil cap depth and the average height of the tallest and shortest *Kochia scoparia* individuals in the fine mineral soil cap over compost (SSC) soil treatment in 2016 (y=205.05-3.85x; p=0.024).

Chapter 3: Physical and chemical characteristics of municipal compost in response to placement methods

3.1 Introduction

Organic amendments have been extensively used as organic fertilizers and soil conditioners that improve soil physical, chemical, and biological characteristics enhancing plant growth (Larney & Angers 2012). As they occur in many forms (e.g. wood chips, peat, compost), organic amendments are widely available and their incorporation in soil contributes a substantial amount of organic matter that can improve soil productivity (Akala & Lal 2000; Larney & Angers 2012). The addition of organic amendments can increase total nutrient stocks (Larney & Angers 2012; Quideau et al. 2013a), improve soil structure and water holding capacity (Fierro et al. 1999; Gardner et al. 2012), and increase soil microbial biodiversity (Hahn & Quideau 2013; Mabuhay et al. 2006; Ros et al. 2003). Furthermore, utilizing organic amendments that are the by-product of the agriculture or forest industry as well as urban and human waste has become more prevalent because they also divert organic material from landfills (Olsen & Jones 1989; Larney & Angers 2012; Larney et al. 2003). These organic amendments span a wide array of materials and can be split into six major categories: animal manure; municipal biosolids and septage; green manure and crop residue; food residue and waste; waste from manufacturing; and compost (Goss et al. 2013).

As was described in Chapter 2, the effectiveness of organic amendments appears to be contingent on the interplay between the source of organic amendment, application rate, degree of incorporation, and its placement method on site. In this study, I examined a novel site preparation (layered) technique applied for forest reclamation that utilized the inversion of a compost layer beneath a poor mineral soil cap. The compost layer covered with either a fine or coarse textured subsoil was evaluated for its effectiveness in promoting the early survival and growth of planted tree seedlings while suppressing competitive herbaceous vegetation. This method was compared to surface applied, more conventional coversoil material treatments. All soil treatments containing compost had poor seedling performance, with the surface applied compost exhibiting 0.21% survival in all tree species (Chapter 2). Although soil treatments with a mineral soil cap over compost also had an initially low survival (< 30%), the tree seedlings that survived the first growing season started to outperform seedlings in soil treatments without compost in the second growing season, indicating that the mineral soil cap over compost provided favorable conditions for tree seedling growth.

In this study, the compost source, the application rate, and the degree of incorporation likely played a significant role in seedling response. In Chapter 2 we suggested that the incorporation of compost into the subsoil was much lower than originally planned, leading to a much higher compost concentration than what has been reported as suitable in the literature (Newton & Whitehead 1998; Spargo & Doley 2016; Topper & Sabey 1986; Martinez et al. 2003; Smith et al. 1979; Thompson et al. 2001). Further, I suggested in Chapter 2 that the source of compost (co-composted municipal compost and biosolids) resulted in elevated salts levels, contributing to possible phytotoxicity (Gouin 1977, 1993; Chong & Purvis 2004; Gouin & Walker 1977; Vogtmann & Fricke 1992) and resulting in a disproportionate leaching of soil nutrients (Dere et al. 2011; Scotti et al. 2015). This response has been attributed to the residual salts in the biosolids that were concentrated during the composting process (Stofella & Kahn 2001).

The majority of the literature on organic amendments has focused on the surface application of these amendments. Placing organic amendments beneath a mineral soil cap is a novel technique where the placement, arrangement, and layering of organic amendments can create artificial soil heterogeneity that may help ameliorate poor soil conditions and reduce the establishment of herbaceous species that can compete with tree seedlings in the vulnerable initial years following planting (Landhäusser & Lieffers 1998; Maundrell & Hawkins 2004; Casselman et al. 2006; Franklin et al. 2012; Johansson et al. 2013). Although the layering of soils with different textures can increase soil moisture availability for plant growth (Huang et al. 2013), abrupt differences in soil layer texture and density can affect soil hydrology and aeration in the soil profile (Chong & Cowsert 1997; Guebert & Gardner 2001; Jin et al. 2013). The high water holding capacity of organic amendments could lead to reduced aeration if proper drainage is not ensured (Bunt 1988), creating anaerobic conditions that influence root distribution and placement throughout the soil profile (Jung et al. 2014; Neira et al. 2015; Veijalainen et al. 2008). Moreover, the composition of an organic amendment could influence soil nutrient and microbial environments, which are some of the controlling factors in CO_2, N_2O, and CH_4 emissions (Conrad 1996; Ginting et al. 2003). These greenhouse gases are also reflective of soil oxygen availability for plant growth, as CO_2 emissions occur under aerobic conditions (Brady & Weil 2002), while N_2O emissions are proliferated at low oxygen availability (Linn & Doran 1984), and CH_4 emissions occur under strictly anaerobic conditions (Yoshida et al. 2015). The textural composition of the mineral soil cap that is placed over the compost as well as the amount of compost and its degree of incorporation into the underlying subsoil may also affect the physical and chemical characteristics of the compost by influencing gas and water exchange between the compost layer and the surface soil layer.

The objective of this chapter was to investigate and compare the physical and chemical characteristics of compost when surface applied or when covered with mineral soil caps of different soil textures.

3.2 Methods

3.2.1 Study area

Research was conducted at the Highvale coal mine, 80 km west of the city of Edmonton, Alberta, Canada (53°26' N, 114°25' W). The study area is located in the boreal forest natural region within the Dry Mixedwood forest subregion, which has milder winters and the warmest summers compared to other subregions within the boreal forest (Natural Regions Committee 2006). The mean annual temperature is 3.1°C with daily historical averages ranging from -12.4°C in January to 16.4°C in July. The historical average precipitation is 517 mm, with an average of 389 mm of rain (most of which falls between May and September) and 128 mm of snow. Climate information is based on a 24-year average (1966 to 1990) (Environment Canada 2017). Further research site and environmental characteristics coincide with the description in Chapter 2.

3.2.2 Site construction, soil placement, and tree planting

The study area was located on a large recontoured landform made of unconsolidated geological subsoil material with a clay loam texture (D. Kuchmak 2015, personal communication). The field experiment was designed as a randomized complete block design with six replicate blocks (100 m × 100 m) each with five randomly assigned soil treatments. The five soil treatments were: (1) an uncapped clay loam mineral subsoil (SS); (2) a 20 cm cap of salvaged topsoil (T); (3) a 20 cm layer of compost incorporated into the clay loam mineral subsoil to a depth of 25 cm (4:1 ratio) (C); (4) the same 25 cm layer of clay loam mineral subsoil and compost mixture capped with a 20 cm layer of clay loam mineral subsoil (SSC); (5) the same 25 cm layer of compost and clay loam mineral subsoil mixture capped with a 20 cm layer of a sandy mineral subsoil (SAC). To explore soil chemical and physical differences among soil treatments with compost, the compost beneath a fine mineral soil cap (SSC-C) in the SSC soil treatment and the compost beneath a coarse mineral soil cap (SAC-C) in the SAC soil treatment were differentiated from the compost at the surface (C).

The SSC and SAC soil treatment areas in each of the six blocks were 25 m by 50 m in size while the other three soil treatment areas (SS, T, and C) were 50 m by 50 m each. Agricultural

Grade Compost (co-composted municipal compost and biosolids; 1,250 tons ha^{-1}) was delivered from the Edmonton Composting Facility (53°60' N, 113°34' W) to the research site in October 2015. In the C, SSC, and SAC soil treatments, compost was incorporated into the clay loam subsoil to a depth of 25 cm using a large breaking disk (1:4 ratio). In April 2016, a 20 cm layer of sandy or clay loam subsoil was layered over the compost subsoil mixture for the SSC and SAC soil treatments while the T soil treatment received a 20 cm layer of topsoil over clay loam subsoil.

One-year-old containerized seedlings of commercially grown *Populus tremuloides* (aspen), *Picea glauca* (white spruce), and *Pinus contorta* (lodgepole pine) were obtained from open pollinated seed sources and free planted in May 2016 across the research site. The final planting density was 5,000 stems ha^{-1} with 54% coniferous (27% white spruce and 27% lodgepole pine) and 46% deciduous (aspen). More detail regarding soil placement and construction of the site as well as tree planting can be found in Chapter 2.

3.2.3 Soil sampling and analysis, soil temperature, and soil water content

Edaphic conditions were compared among coversoil materials (fine mineral subsoil (SS), coarse mineral soil cap (SA) in the SAC soil treatment, topsoil cap (T), and compost cap (C)) to determine physical and chemical differences among soil materials at the research site (Appendix B-9). Furthermore, edaphic conditions of the compost at the surface (C) and compost with a fine and coarse mineral soil cap (SSC-C and SAC-C) were compared to identify the effect of capping material on physical and chemical differences in the compost. Soil samples were taken in June 2016 and 2017 in every soil treatment in blocks 1, 3, and 6. Sampling occurred at 10 cm depth in the coarse mineral soil cap in the SAC soil treatment and at 30 cm depth in the compost underlying a coarse or fine mineral soil cap in the SAC and SSC soil treatments. In the SS, T, and C soil treatments, soil samples were taken at 10 cm depth. In 2016 this was done using soil cores (7.5 cm^3 × 7.5 cm^3; 331.2 cm^3) and in 2017 soil samples were taken at the same depths without using soil cores. In each soil treatment, the soil core was inserted horizontally, a flat piece of wood was placed on its exposed edge, and a rubber mallet was used to pound the soil core into the soil layer. The surrounding soil was then removed and the soil core was excavated; contents were emptied into bags and placed in a cooler. Soil samples were brought back to the University of Alberta and placed in the refrigerator (3°C) until processing. All soil samples in 2016 were measured for wet weight and dry weight to determine dry bulk density (DBD).

For soil nutrient analyses in 2016 and 2017, soil samples were sieved to pass a 4 mm mesh screen and ground with a ball mill (Retsch MM200; Retsch Inc., Newtown, PA, USA). Soil samples were sent to the Natural Resource Analytical Laboratory at the University of Alberta where all soil analyses were conducted. Soils were analyzed for K^+, Na^+, Mg^{2+}, Ca^{2+}, Cu^+, Mn^{2+}, Zn^{2+}, Al^{3+}, and Fe^{2+} concentrations using the 1M NH4OAc method (Hendershot et al. 2008), total organic matter (OM) was determined using the LOI method (Lim & Jackson 1982), and total phosphorous and total nitrogen were analyzed using the Kjeldahl Digestion method (Rutherford et al. 2008; Kjeldahl 1883). NO_3^- and NH_4^+ were determined using the 2M KCl extraction method (Jones 2001) and PO_4^{3-} with the Modified Kelowna extraction method (Rutherford et al. 2008; Soil & Crop Diagnostic Center 1995). Electrical conductivity (EC) and pH were measured using the extract from a water:soil saturation paste and a Fisher AR20 pH/EC meter (USDA 1954). Soil texture was measured using hydrometer readings and percent total clay (< 2 µm), silt (2-50 µm), and sand (> 50 µm) were determined (Bouyoucos 1962). Sodium adsorption ratio (SAR) was calculated (USDA 1954). A summary of soil physical and chemical data for the different soil materials is provided in Appendix B-9.

Soil temperature and soil water content were assessed for all coversoil materials (Appendix A-4), as well as the compost below the fine and coarse mineral soil cap. Soil temperature and volumetric soil water content sensors (5 TM Decagon Devices Inc., Washington, U.S.A.) were installed horizontally in each soil treatment in all six block in May 2017. The soil treatments with a mineral soil cap over compost (SSC and SAC) received two sensors each, one at a depth of 10 cm in the coarse or fine mineral soil cap and one at a depth of 30 cm in the center of the underlying compost. The SS, T, and C soil treatments received one sensor at a depth of 10 cm. Sensors were connected to data loggers (HOBO Em 50, Decagon Devices Inc., Washington, U.S.A.) that recorded readings every hour. Mean soil temperature and volumetric soil water content were averaged by day between May and September 2017.

3.2.4 Soil oxygen availability and gas exchange

Soil oxygen availability by depth was assessed for each soil treatment. To do this, steel rods were inserted in each soil treatment. This technique utilizes the redox qualities of iron in which red/brown rust indicates the oxidized, aerobic Fe^{3+} state while matt grey indicates the reduced, anaerobic Fe^{2+} state (Carnell & Anderson 1986; Bridgham et al. 1991; Hodge et al. 1993). Hot rolled steel round bars (Metal Supermarkets, Toronto, Ontario, Canada) 80 cm in length and 1 cm in diameter were scrubbed with steel wool and fine sand paper to remove any coatings that may prevent oxidation. One rod was pushed to a depth of 50 cm in four areas in every soil treatment and in all blocks on 6 June 2017 (total of 120 rods). Small soil pits were dug one meter from the location of each rod to determine the depth of each coversoil material and compost in that area. Rods were removed on 31 July 2017 after a 55-day incubation period. At the end of the incubation period, the soil surface was marked on each rod and rods were extracted. The presence of aerobic, anaerobic, and an interface between the two reactions (intermediate) were measured by depth on each rod. Rod assessment was as follows: (1) orange/brown rust indicated the aerobic zone; (2) a combination of raised black and orange/brown rust indicated an intermediate aerobic/anaerobic zone; and (3) matt grey and shiny smooth black indicated the anaerobic zone (Carnell & Anderson 1986; Bridgham et al. 1991; Hodge et al. 1993).

The effect of capping material on oxygen availability in the compost layer was also explored in the compost at the surface and the compost layer under either a fine or coarse mineral soil cap, by assessing the production of carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4) emissions from the compost. CO_2 emissions are indicative of aerobic conditions (Brady & Weil 2002), while N_2O emissions occur under low soil oxygen conditions (Linn & Doran 1984), and CH_4 emissions are indicative of strictly anaerobic conditions (Yoshida et al. 2015). Non-steady state static chambers were used in the C, SSC, and SAC soil treatments to measure CO_2, N_2O, and CH_4 soil gas exchange rates (Holland et al. 1999). Two Acrylonitrile-Butadiene-Styrene (ABS) collars (5 cm diameter) were installed in random locations in each of the soil treatments that contained compost in every block two weeks prior to sampling to diminish the impact of soil disturbance on measured gas exchange rates. The collars in the SSC and SAC soil treatments were installed to a depth of 30 cm (700 cm^3) to characterize the gasses emitted from the compost underlying the fine or coarse mineral soil cap, while the collars in the C soil treatment were installed to a depth of 10 cm (300 cm^3) to characterize the compost at the surface. Sampling occurred on 23 June, 27 July, and 17 August 2017 and the sampling period at each chamber lasted 60 minutes with four samples taken at 0, 20, 40, and 60-minutes. At the beginning of the sampling period, a one-holed rubber stopper with a plastic tube (0.60 cm diameter) extending from the outside to the middle of the chamber was sealed onto each collar. The plastic tube outside the chamber was fitted with a metal clamp to allow gas accumulation during the sampling period (Holland et al. 1999). For each sample, a syringe (50 ml) was attached to the tube, the metal clamp on the tube was loosened, and the syringe was pumped 7 times to thoroughly mix gas inside the chamber. 25 ml of gas was extracted into the syringe, the metal clamp on the tube was tightened, and 20 ml of gas was compressed into a 12 ml evacuated vial. Vials were brought back to the University of Alberta and stored at room temperature for less than three weeks when CO_2, N_2O, and CH_4 concentrations could be analyzed simultaneously in a gas chromatograph (Varian CP-3800; Varian Canada, Mississauga, ON, Canada). Following the method of Holland et al. 1999, gas concentrations were converted to mass and corrected for field conditions. A gas exchange rate for each individual gas was calculated based on the change in concentration over the sampling period, relative to the chamber volumes and surface area of the collar. Exact equations used for calculating gas exchange rates can be found in Appendix C-2.

3.2.5 Statistical analyses

All analyses were done using R-studio (Boston, MA, USA) using the lm or lme function from the nlme package (Pinheiro et al. 2018). Residuals were assessed using the Shapiro-Wilk and Levene's test to determine conformation to the assumptions of normality and heterogeneity of variance for all analyses. If residuals were found to violate the assumptions, the data was log transformed (see below); the untransformed least squared means and standard errors are presented. Significant main effects and interactions were then evaluated using the lsmeans and cld function from the lsmeans package (Lenth 2016).

Edaphic conditions in the compost at the surface (C), in the compost with a fine mineral soil cap in the SSC soil treatment, and in the compost with a coarse mineral soil cap in the SAC soil treatment were compared to determine the effect of capping material on compost physical and chemical characteristics. A one-way ANOVA was used to analyze soil physical properties in 2016 with compost treatment as the independent variable and block was included as the random term. To determine differences in soil nutrients over two growing seasons (2016, 2017), a two-way repeated measures ANOVA was used with compost treatment and year as the independent variables and block was included as the random term. Cu and Zn were log-transformed. For both analyses, significant main effects ($p < 0.10$) were followed by a Fisher's least squared difference (LSD test) to examine differences among compost treatments, while a Holm adjustment $\alpha=0.10$ with pairwise comparisons was used to examine interactions.

Soil water content and temperature in the compost at the surface (C), compost with a fine mineral soil cap in the SSC soil treatment, and compost with a coarse mineral soil cap in the SAC soil treatment in 2017 were analyzed separately using a two-way repeated measures ANOVA with compost treatment and day as the independent variables and block was included as the random term. An LSD test was used to examine significant differences ($\alpha=0.05$) among compost treatments.

To explore soil oxygen availability in 2017, the depth of aerobic, intermediate, or anaerobic reactions on steel rods were measured to a depth of 50 cm in each soil treatment (SS, T, C, SSC, SAC) and analyzed separately for each reaction using a one-way ANOVA with soil treatment as the independent variable and block was included as the random term. The depth of each aerobic, anaerobic, and intermediate reaction was log-transformed. Significant differences in reaction depth among compost treatments were followed by an LSD test ($\alpha=0.05$).

Soil gas exchange rates for CO_2, CH_4, and N_2O in 2017 in the compost at the surface (C), compost with a fine mineral soil cap in the SSC soil treatment, and compost with a coarse mineral soil cap in the SAC soil treatment were analyzed separately for each gas using a two-way repeated measures ANOVA with compost treatment and sampling day as the independent variables and block was included as the random term. Significant main effects ($p < 0.05$) were followed by an LSD test to examine differences among compost treatments, while a Holm adjustment $\alpha=0.05$ with pairwise comparisons was used to examine interactions. A simple linear regression was used to determine the potential effect of soil temperature on CO_2 gas exchange rates and soil water content on N_2O gas exchange rates in each compost treatment.

3.3 Results

3.3.1 Chemical and physical changes

Compost at the surface (C), compost with a fine mineral soil cap (SSC-C), and compost with a coarse mineral soil cap (SAC-C) were compared for differences in soil physical properties in 2016 and soil chemical properties over two growing seasons (2016, 2017) (Table 3-1). The dry bulk density (DBD) was highest in the SSC-C compost treatment (1.07 g cm^{-3}), which was similar to the SAC-C (0.92 g cm^{-3}) but significantly greater than the C compost treatment (0.84 g cm^{-3}) ($p=0.011$).

Chemical properties varied among the three compost treatments between the 2016 and 2017 growing season. pH increased between 2016 and 2017 in all compost treatments and this was significant for SAC-C compost treatment ($p=0.003$; Table 3-1). Electrical conductivity (EC) decreased in the surface compost (C) and the compost with a coarse mineral soil cap (SAC-C) between 2016 and 2017, while EC remained similar between the two growing seasons in the compost with a fine mineral soil cap (SSC-C) becoming elevated in 2017 compared to the C and SAC-C compost treatments (compost treatment by year interaction, $p=0.024$; Figure 3-1 A; Table 3-2). Sodium adsorption ratio (SAR) was overall significantly higher in the SAC-C compared to the C compost treatment ($p=0.040$) and decreased in these compost treatments between the two growing seasons while it remained similar in the SSC-C compost treatment ($p=0.001$; Table 3-2). Although total N remained similar between 2016 and 2017 in all compost treatments, total N was overall higher in the C and SAC-C compared to the SSC-C compost treatment ($p=0.028$; Table 3-2). NH_4 concentrations were similar among compost treatments in 2016 and remained similar in the C and SAC-C compost treatments in 2017, but increased in the SSC-C becoming higher than compost in the C and SAC-C compost treatments (compost treatment by year interaction, $p=0.034$; Figure 3-1 B; Table 3-1). NO_3 levels were similar among all compost treatments in 2016 and 2017 but overall decreased between the two growing seasons ($p=0.002$; Table 3-2). Similarly, Cu levels significantly decreased in all compost treatments between the two growing seasons ($p<0.001$) while Al levels increased in all compost soil treatments ($p<0.001$; Table 3-2). K and Mg concentrations were overall higher in compost with a coarse mineral soil cap (SAC-C) compared to compost with a fine mineral soil cap (SSC-C) (both $p<0.045$) and decreased overall between 2016 and 2017 ($p<0.010$; Table 3-2). The SAC-C compost treatment had higher levels of Mn and Na overall compared to the C soil treatment ($p<0.065$). Furthermore, Mn and Na levels decreased overall between the two growing seasons ($p<0.002$); this was significant for Mn levels in all compost treatments and Na levels in the SAC-C compost treatment (Table 3-1). Finally, OM, total P, PO_4, Ca, Fe, and Zn concentrations were similar from 2016 and 2017 in compost treatments and did not change between the two growing seasons (Table 3-1).

3.3.2 Soil water and oxygen availability, soil temperature, and gas exchange

Compost at the surface (C), compost beneath a fine mineral soil cap (SSC-C), and compost with a coarse mineral soil cap (SAC-C) were compared for differences in soil water content and temperature over the second growing season (2017). Overall, soil water content and temperature were highest in the SAC-C compost treatment (0.23 m^3 m^{-3}; 15.5°C), followed by the SSC-C compost treatment (0.22 m^3 m^{-3}; 15.0°C), and lowest in the C compost treatment (0.19 m^3 m^{-3}; 14.2 °C) (Figure 3-2 A, B). Soil water content and temperature in compost treatments varied by day following a pattern that depended on daily weather conditions (both compost treatment by day interaction, $p<0.001$). Between the SSC-C and SAC-C compost treatments, the soil water content in the SSC-C increased above the SAC-C at the beginning of June and remained similar to the SAC-C until the end of June when soil water content in the SAC-C increased above the SSC-C for the remainder of the growing season (Figure 3-2 A). Soil temperature in the SSC-C increased briefly above the SAC-C at the end of May, but remained slightly lower or similar to the SAC-C throughout the remainder of the second growing season (Figure 3-2 B).

In 2017, soil oxygen availability was determined by measuring the depth of aerobic, intermediate, and anaerobic zones along steel rods in the fine mineral subsoil (SS), topsoil cap (T), compost cap (C), fine mineral soil cap over compost (SSC), and coarse mineral soil cap over compost (SAC) soil treatments. Aerobic reactions were marginally different among soil treatments ($p=0.024$), although they were concentrated in the top 25 cm of the soil (Figure 3-3). The aerobic zone extended deeper in the T and SAC soil treatments (24 cm) than the SS and

SSC soil treatments (18 cm). Intermediate and anaerobic reactions were not significantly different among the soil treatments (both, $p>0.400$; Figure 3-3). The intermediate zone was located at a depth of 25 to 35 cm while the anaerobic zone extended from 35 to 50 cm. However, the 25 cm of compost that extended beneath a 20 cm mineral soil cap in the SSC and SAC soil treatments were located in the intermediate and anaerobic zones (Figure 3-3). This is in contrast to the compost at the surface in C soil treatment, which was located in the aerobic zone (Figure 3-3).

Soil gas exchange was measured in the second growing season (2017) at the compost surface level in the compost cap (C), compost with a fine mineral soil cap (SSC-C) and compost with a coarse mineral soil cap (SAC-C). CO_2 and N_2O gas exchange rates were overall higher in compost capped with mineral soil (SSC-C and SAC-C) compared to compost at the surface (C) throughout the second growing season (both $p<0.001$; Figure 3-4 A, C). Although CO_2 and N_2O gas exchange rates in the SSC-C and SAC-C compost treatments were elevated above the C compost treatment regardless of sampling date, CO_2 emissions were overall higher on 27 July than 23 June and 17 August while N_2O emissions were higher on 23 June than 27 July and 17 August (both $p<0.005$; Figure 3-4 B, D). This is likely dependent on soil temperature and soil water content, as there was a positive relationship between soil temperature and CO_2 gas exchange rates in the SAC-C compost treatment ($y=-4.14+0.42x$, $p=0.032$, $R^2=0.257$; Figure 3-5) as well as between soil water content and N_2O gas exchange rates in the SSC-C compost treatment ($y=-0.0008+0.01x$, $p=0.021$, $R^2=0.29$; Figure 3-6). Overall, CH_4 gas exchange rates for the C, SSC-C, and SAC-C compost treatments were close to zero across all sampling dates (data not shown). CH_4 gas exchange rates were not significantly different among the C, SSC-C, and SAC-C compost treatments ($p=0.106$) and not affected by sampling date ($p=0.097$).

3.4 Discussion

Covering compost with a mineral soil cap did not affect many soil chemical and physical properties of the compost at the research site, particularly in the first growing season. The compost with a fine mineral soil cap over compost (SSC-C), compost with a coarse mineral soil cap (SAC-C), and compost at the surface (C) had similar electrical conductivity (EC) and sodium adsorption ratio (SAR) levels in 2016. The EC was above 4 and SAR was below 13 suggesting that the compost application rate (1,250 tons ha^{-1}) and concentration in the subsoil (1:4 ratio) yielded a saline growing medium (Horneck et al. 2007). This most likely led to the low survival of tree seedlings in the soil treatments containing compost in 2016, as upland boreal forest understory species and trees are generally considered intolerant of saline soils (Howat 2000; Purdy et al. 2005). Furthermore, *Kochia scoparia* (L.) Schrad is a salinity tolerant (Bilski & Foy 1988) invasive forb species that requires Na as a micronutrient (Brownell & Crossland 1972; Friesen et al. 2009) and dominated compost soil treatments in 2016. The establishment of *K. scoparia* in the soil treatments containing compost during the first growing season may have been driven by saline conditions in the compost leading to its competition with tree seedlings for light, further influencing low tree seedling survival (see Chapter 2).

Some compost characteristics changed between the 2016 and 2017 growing seasons and it appears that the texture of the mineral soil cap affected many of these changes. Between 2016 and 2017, EC remained elevated in the compost capped with fine mineral soil (SSC-C), while EC in the compost with a coarse mineral soil cap (SAC-C) and the compost at the surface (C) decreased. This may be explained by the high water holding capacity of the fine textured mineral soil cap limiting water infiltration into the underlying compost layer, thereby limiting the leaching of ions into deeper soil layers (Osman 2013). This is reflected in the soil water content of the SSC-C and SAC-C compost treatments, as the SSC-C had an overall lower soil water content compared to the SAC-C compost treatment. The leaching of ions is also reflected in measured soil nutrients, as more soil nutrients (Cu, Mg, Mn, and Na) decreased in concentration between the two growing seasons in the SAC-C compared to the SSC-C compost treatment (Cu and Mn). SAR, NO_3, Cu, K, Mg, Mn, and Na levels decreased overall in compost treatments between 2016 and 2017, as losses of highly soluble nutrients in organic amendments often occurs following the first year of application (Bugbee 2002; Chong 1999, 2005; Heiskanen 2013; Coleman et al. 1987). The lower nutrient concentrations in the compost in the second growing season may have created a more conducive growing medium for tree seedlings, although these levels continued to be higher than what has been reported in the literature (Chong 2005; Spargo & Doley 2016; Jokela et al. 1990; Smith et al. 1979).

Between 2016 and 2017, NH_4 increased in the compost beneath a fine mineral soil cap (SSC-C) while it remained similar between the two growing seasons in the compost beneath a coarse mineral soil cap (SAC-C) and compost at the surface (C). This indicates that aerobic decomposition of organic matter in all compost treatments was occurring, as organic N needs to be mineralized to NH_4 before being converted to NO_2 and through nitrification, to NO_3. In soil treatments with a mineral soil cap over compost, the mineral soil cap most likely insulated the heat generated from decomposition in the underlying compost, increasing soil temperatures in the compost and thereby increasing CO_2 gas exchange rates relative to the compost at the surface. CO_2 emissions are indicative of aerobic soil conditions (Brady & Weil 2002). This response is further supported by the positive relationship between soil temperature and CO_2 release in the SAC-C compost treatment. Thus, the fine and coarse mineral soil cap may have allowed soil temperature and CO_2 gas exchange rates to increase in the underlying compost as a result of decomposition. Increased CO_2 emissions suggest that oxygen was not limiting in the compost with a mineral soil cap.

However, NO_3 levels decreased overall in all three compost treatments between 2016 and 2017 indicating that nitrifier activity, oxidizing NH_4 to NO_2 and NO_3 during nitrification, may have been inhibited. In the compost beneath a mineral soil cap, the mineral soil cap most likely increased the soil water content of compost, which already had a high water holding capacity. The increased soil water content may have influenced the conversion of NH_4 to NO_2 and through denitrification, to N_2O gas instead of NO_3, increasing N_2O gas exchange rates in the SSC-C and SAC-C relative to the C compost treatment. NO_2 emissions occur under low soil oxygen conditions when water filled pore space exceeds 60% (Bremner & Blackmer 1980; Linn & Doran 1984; Kool et al. 2010) and there was a positive relationship between soil water content and N_2O release in the SSC-C compost treatment. Thus, it seems likely that the fine and coarse mineral soil cap increased soil water content in the underlying compost, initiating denitrification leading to increased N_2O soil gas exchange rates. Although the increased CO_2 emissions suggested that soil oxygen was available in the SSC-C and SAC-C, increased N_2O emissions indicate that soil oxygen conditions were at an interface between aerobic and anaerobic conditions. Since the compost layer was relatively thick (i.e. 25 cm), it is not clear whether the deeper parts of the compost layer were more oxygenated than the shallower parts.

Methane (CH_4) gas exchange rates in all three compost treatments (SSC-C, SAC-C, and C) were negligible, indicating that the fine and coarse mineral soil cap in the SSC and SAC soil treatments did not create strictly anaerobic conditions in the underlying compost (Yoshida et al. 2015). Furthermore, reactions on steel rods in 2017 confirmed what CO_2 and N_2O gas exchange rates indicated, that soil oxygen availability was low (intermediate and anaerobic zones) in the compost with a fine and coarse mineral soil cap (SSC-C and SAC-C), while the compost at the surface (C) was located in aerobic zones. However, this appears to be strictly related to soil depth, as the bands of aerobic, intermediate, and anaerobic reactions did not change excessively among soil treatments. Consequently, tree seedling roots expanding into the compost beneath a mineral soil cap in the SSC and SAC soil treatments may have been inhibited by the lower soil oxygen availability. Based on personal observations in the field during aspen seedling excavation (Chapter 2), aspen seedling roots in the SSC and SAC soil treatments remained in the overlying fine or coarse mineral soil cap without expanding into the underlying compost suggesting their avoidance of this oxygen deficient layer.

Tree seedlings that survived into the second growing season (2017) were tallest and largest in the fine and coarse mineral soil cap over compost (SSC and SAC) soil treatments compared to the topsoil cap (T) and fine mineral subsoil (SS) soil treatments (see Chapter 2). This suggests that soil nutrients, moisture, space, and oxygen availability belowground were not limiting (or became less so) to tree seedlings. Although greenhouse gas (CO_2, N_2O, and CH_4) emissions and reactions on steel rods indicated that soil oxygen availability was still low in the compost beneath a fine and coarse mineral soil cap in the SSC and SAC soil treatments, tree seedlings may have had the ability to selectively place their roots depending on microsites of more favorable soil nutrient and soil oxygen availability conditions (Barlow 2010; Hodge 2004; Hutchings & De Kroon 1994; McNickle et al. 2009; Neatrour et al. 2007).

Overall, the use of compost on forest reclamation sites to improve tree seedling establishment where nutrient deficiencies appear to limit tree growth is dependent on the placement method as well as the source of compost, the application rate, and the degree of incorporation in the subsoil. If a coarse or fine mineral soil cap is applied over compost, it will play a significant role in the decomposition and water storage of the compost layer. This may lead to oxygen depletion in the compost that influences tree seedling establishment, as the decomposition consumes the available oxygen and the increased water content initiates denitrification.

Tables

Table 3-1. Summary of compost chemical characteristics in 2016 and 2017 for the compost cap (C), compost with a fine mineral soil cap (SSC-C), and compost with a coarse mineral soil cap (SAC-C). Values represent averages and standard error of the mean (n=3). Different letters indicate significantly different means (α = 0.10). Note: 'EC' refers to electrical conductivity, 'SAR' refers to sodium adsorption ratio, and 'OM' refers to organic matter.

		C		SSC-C		SAC-C	
		2016	**2017**	**2016**	**2017**	**2016**	**2017**
pH		7.43 **ab** (± 0.07)	7.67 **ab** (± 0.03)	7.49 **ab** (± 0.16)	7.61 **ab** (± 0.04)	7.38 **b** (± 0.03)	7.76 **a** (± 0.07)
EC (dS m^{-1})		18.03 **a** (± 3.78)	8.26 **b** (± 2.81)	12.87 **ab** (± 1.95)	19.27 **a** (± 2.15)	19.30 **a** (± 4.35)	9.17 **b** (± 1.82)
SAR		4.43 **ab** (± 0.51)	1.35 **c** (± 0.14)	4.68 **ab** (± 0.31)	2.77 **bc** (± 1.03)	6.47 **a** (± 1.10)	3.27 **bc** (± 0.56)
OM (%)		22.02 **a** (± 1.08)	23.19 **a** (± 2.10)	15.36 **a** (± 3.23)	25.46 **a** (± 2.19)	24.55 **a** (± 4.36)	22.81 **a** (± 2.06)
Total N (%)		1.31 **a** (± 0.04)	1.08 **a** (± 0.08)	0.78 **a** (± 0.18)	0.80 **a** (± 0.10)	1.27 **a** (± 0.23)	0.97 **a** (± 0.07)
Total P (%)		0.56 **a** (± 0.02)	0.64 **a** (± 0.01)	0.43 **a** (± 0.10)	0.54 **a** (± 0.06)	0.62 **a** (± 0.05)	0.54 **a** (± 0.01)
Nutrients (mg kg^{-1})	NH_4	79.67 **b** (± 49.43)	215.38 **b** (± 193.13)	230.55 **b** (± 182.55)	961.41 **a** (± 42.59)	342.71 **b** (± 198.49)	238.14 **b** (± 214.46)
	NO_3	977.97 **a** (± 290.05)	105.30 **a** (± 33.11)	423.78 **a** (± 227.65)	49.76 **a** (± 14.20)	996.14 **a** (± 346.19)	126.12 **a** (± 64.60)
	PO_4	572.28 **a** (± 261.64)	774.28 **a** (± 61.98)	490.73 **a** (± 255.31)	752.41 **a** (± 49.31)	572.10 **a** (± 263.18)	690.83 **a** (± 99.37)
	Al	0.22 **b** (± 0.08)	0.48 **a** (± 0.02)	0.17 **b** (± 0.04)	0.46 **a** (± 0.05)	0.20 **b** (± 0.04)	0.42 **a** (± 0.02)
	Ca	12690.67 **a** (± 1664.43)	13241.00 **a** (± 1312.38)	10756.33 **a** (± 1525.14)	10044.33 **a** (± 1770.28)	15289.33 **a** (± 2345.90)	11812.67 **a** (± 1956.14)

Nutrients (mg kg^{-1})	Cu	1.91 **a** (± 0.24)	0.78 **b** (± 0.10)	1.96 **a** (± 0.05)	0.73 **b** (± 0.06)	2.83 **a** (± 0.56)	0.83 **b** (± 0.13)
	Fe	1.85 **a** (± 0.44)	1.26 **a** (± 0.17)	1.31 **a** (± 0.20)	1.26 **a** (± 0.12)	2.23 **a** (± 0.48)	1.61 **a** (± 0.80)
	K	3275.33 **ab** (± 268.69)	2214.67 **ab** (± 87.27)	2468.00 **ab** (± 340.62)	1686.00 **b** (± 301.60)	4008.67 **a** (± 794.86)	2490.67 **ab** (± 48.03)
	Mg	1136.33 **ab** (± 54.57)	860.33 **b** (± 78.24)	1049.00 **ab** (± 114.15)	697.67 **b** (± 54.27)	1474.33 **a** (± 220.35)	936.33 **b** (± 45.12)
	Mn	10.97 **ab** (± 1.57)	1.63 **c** (± 0.46)	11.16 **ab** (± 1.24)	3.48 **c** (± 1.94)	13.63 **a** (± 1.47)	6.05 **bc** (± 0.65)
	Na	1166.00 **ab** (± 180.41)	361.33 **b** (± 52.74)	1131.00 **ab** (± 102.63)	613.67 **b** (± 202.51)	1907.67 **a** (± 475.09)	798.33 **b** (± 86.52)
	Zn	30.46 **a** (± 24.85)	7.24 **a** (± 0.58)	4.67 **a** (± 0.48)	5.83 **a** (± 0.60)	7.27 **a** (± 1.06)	8.33 **a** (± 3.56)

Table 3-2. Results of a two-way repeated measures ANOVA examining changes in compost chemical characteristics over two growing seasons (2016, 2017) for the compost cap (C), compost with a fine mineral soil cap (SSC-C), and compost with a coarse mineral soil cap (SAC-C) (n=3). P-values are given and bolded when significant (α = 0.10). Note: 'EC' refers to electrical conductivity, 'SAR' refers to sodium adsorption ratio, and 'OM' refers to organic matter.

	Unit	Compost Treatment	Year	Interaction
pH	-	0.970	**0.003**	0.287
EC	dS m^{-1}	0.598	**0.081**	**0.024**
SAR	-	**0.040**	**0.001**	0.578
OM	%	0.495	0.182	0.124
Total N	%	**0.028**	0.139	0.459
Total P	%	0.133	0.394	0.202
NH_4	mg/kg	**0.024**	**0.048**	**0.034**
NO_3	mg/kg	0.265	**0.002**	0.420
PO_4	mg/kg	0.960	0.242	0.933
Al	mg/kg	0.628	**<0.001**	0.752
Ca	mg/kg	0.153	0.367	0.452
Cu	mg/kg	0.250	**<0.001**	0.533
Fe	mg/kg	0.302	0.215	0.719
K	mg/kg	**0.040**	**0.006**	0.650
Mg	mg/kg	**0.041**	**0.002**	0.510
Mn	mg/kg	**0.061**	**<0.001**	0.763
Na	mg/kg	**0.063**	**0.002**	0.467
Zn	mg/kg	0.245	0.644	0.495

Figures

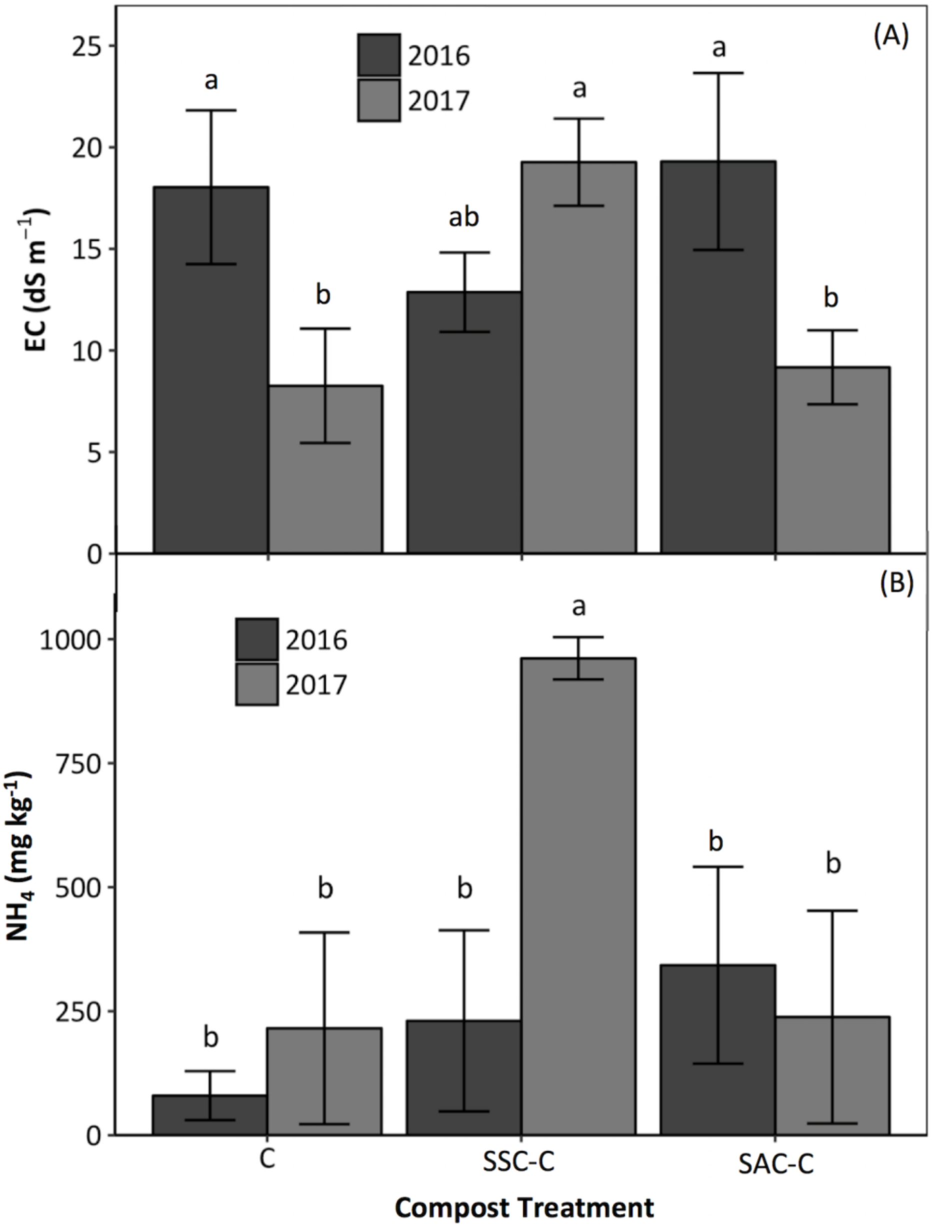

Figure 3-1. Average electrical conductivity (EC) (A) and NH_4 (B) in 2016 and 2017 for the compost cap (C), compost with a fine mineral soil cap (SSC-C), and compost with a coarse mineral soil cap (SAC-C). Error bars are standard error of the mean (n=3) and different letters above bars indicate significantly different means (α = 0.10).

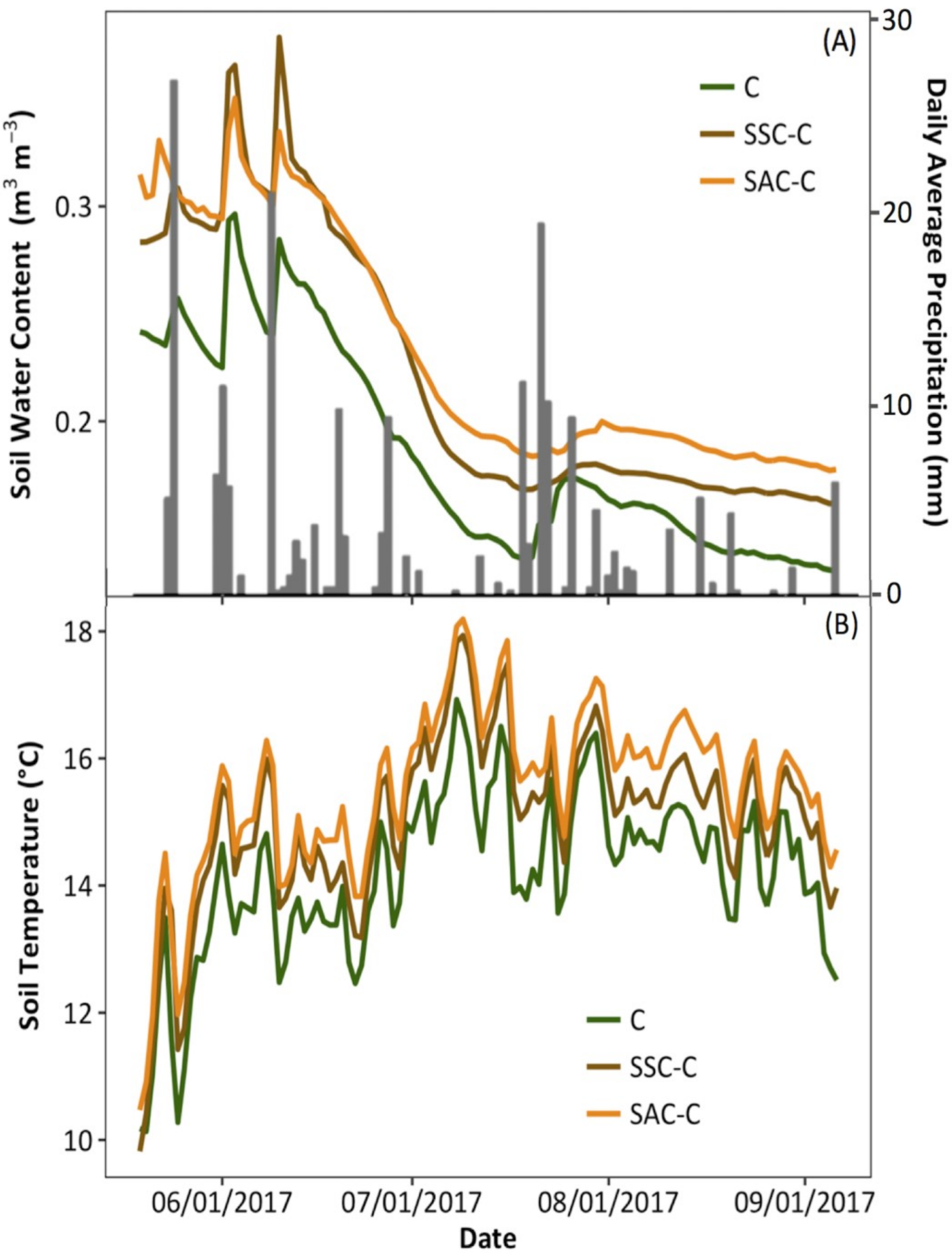

Figure 3-2. Average daily soil water content (A) and soil temperature (B) over the 2017 growing season (19 May - 9 September) for the compost cap (C), compost with a fine mineral soil cap (SSC-C), and compost with a coarse mineral soil cap (SAC-C) (n=6). Gray bars represent the daily precipitation from a weather station located 30 km northeast of the research site. Sensors were located at a depth of 10 cm in the compost cap (C) while they were located at a depth of 30 cm in the compost underlying a fine or coarse mineral soil cap (SSC-C and SAC-C). Precipitation data was accessed from Environment Canada (2017).

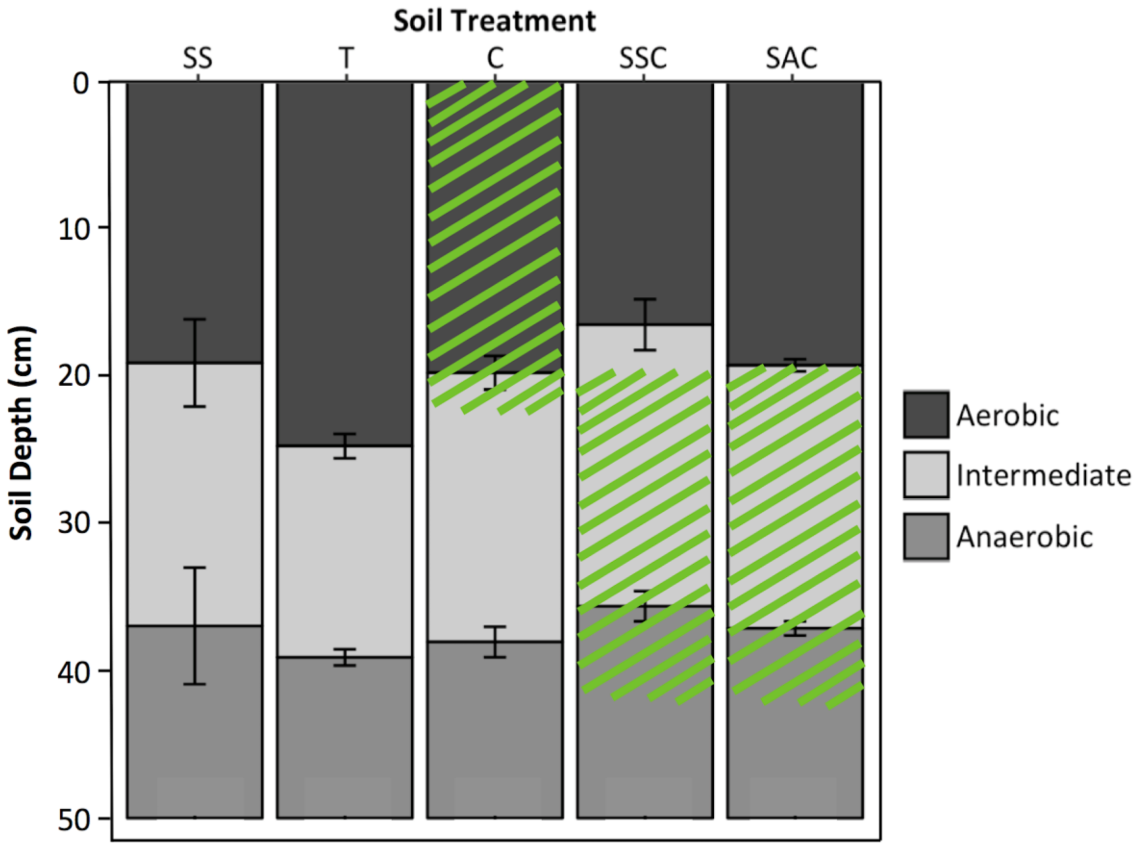

Figure 3-3. Aerobic, intermediate, and anaerobic reactions on steel rods based on soil depth in 2017 for the fine mineral subsoil (SS), topsoil cap (T), compost cap (C), fine mineral soil cap over compost (SSC), and coarse mineral soil cap over compost (SAC) soil treatments. Error bars are standard error of the mean (n=6). The green shaded area indicates the location of compost in the C, SSC, and SAC soil treatments.

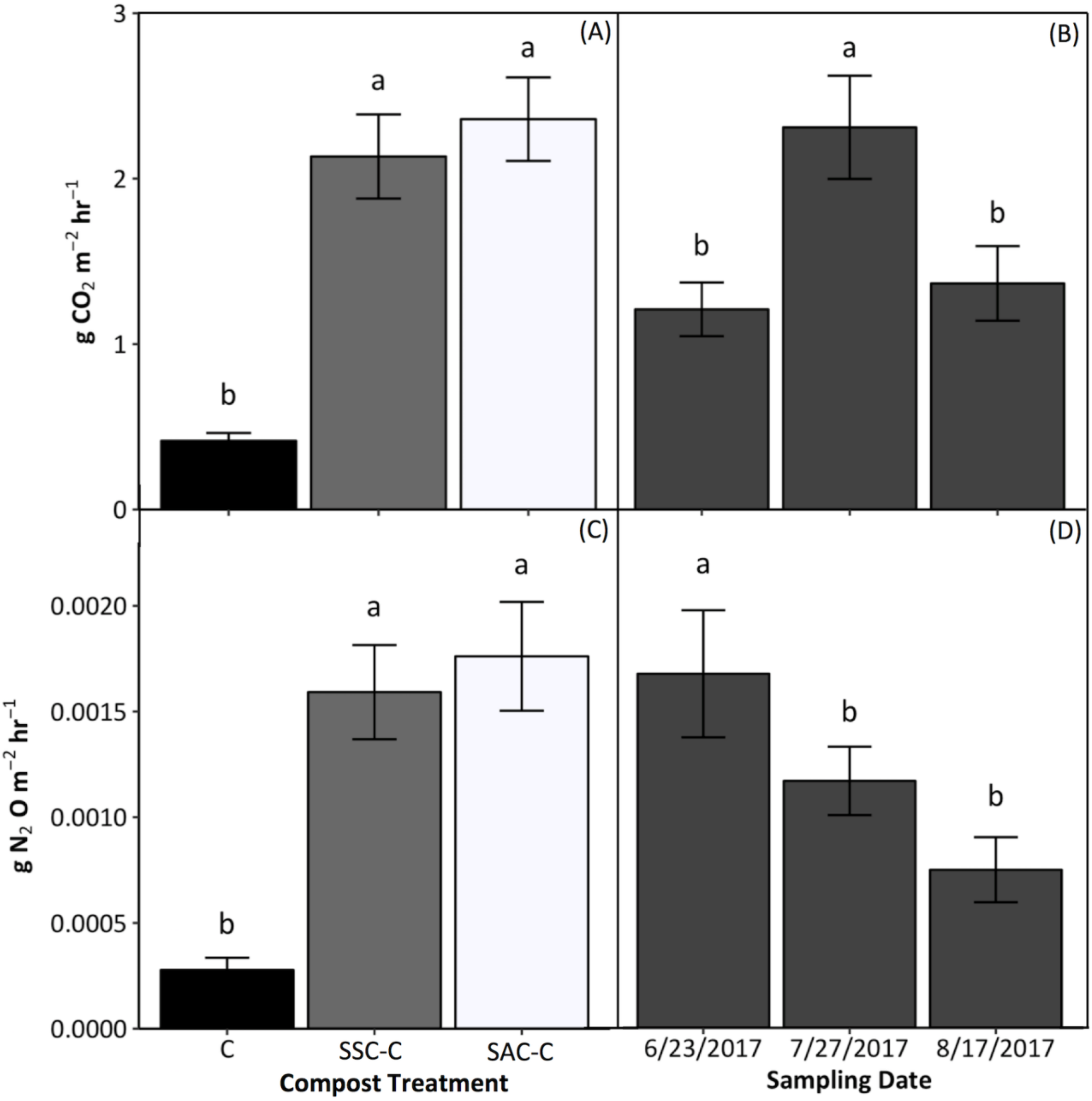

Figure 3-4. Average soil gas exchange rates for CO_2 (A) and N_2O (C) for the compost cap (C), compost with a fine mineral soil cap (SSC-C), and compost with a coarse mineral soil cap (SAC-C) over the 2017 growing season and on each sampling date (23 June, 27 July, and 18 August 2017) (B, D). Error bars are standard error of the mean (n=6) and different letters above bars indicate significantly different means ($\alpha = 0.05$). Chambers in the compost cap (C) were installed to a depth of 10 cm while they were installed to a depth of 30 cm in the compost underlying a fine or coarse mineral soil cap (SSC-C and SAC-C).

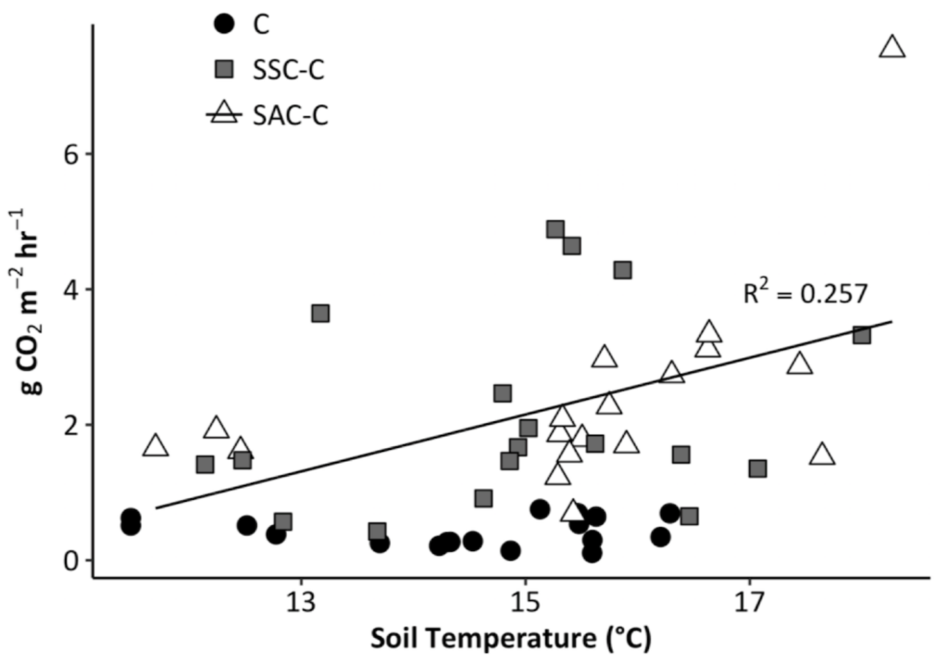

Figure 3-5. Relationship between soil temperature and CO_2 gas exchange rates on 23 June, 27 July, and 18 August 2017 for the compost cap (C), compost with a fine mineral soil cap (SSC-C) in the SSC, and compost with a coarse mineral soil cap (SAC-C) (SAC-C: y=-4.14+0.42x, p=0.032; no significant relationship in the SSC-C and C).

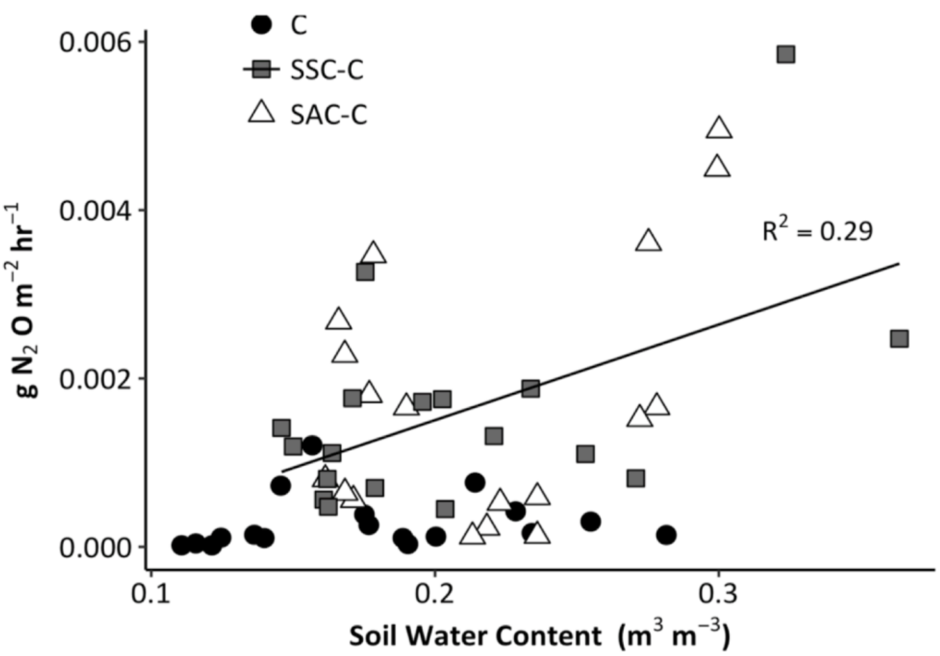

Figure 3-6. Relationship between soil water content and N_2O gas exchange rates on 23 June, 27 July, and 18 August 2017 for the compost cap (C), compost with a fine mineral soil cap (SSC-C), and compost with a coarse mineral soil cap (SAC-C) (SSC-C: y=-0.0008+0.01x, p=0.021; no significant relationship in the SAC-C and C).

Chapter 4: Synthesis and Discussion

4.1 Research summary

Overall, the research in this thesis addressed two major challenges in forest restoration and reclamation: (1) limiting interspecific competition in the vulnerable initial years following tree seedling planting and (2) increasing subsoil surface suitability to improve early tree seedling growth. Investigating an innovative site preparation technique and applying co-composted municipal compost and biosolids from a large urban metropolis addressed both of these challenges. The primary objective of this thesis was to examine a novel site preparation (layered) technique applied for forest reclamation that utilized the inversion of a compost (co-composted municipal compost and biosolids) layer beneath a nutrient poor mineral soil cap. In Chapter 2, the compost layer covered with a fine or coarse mineral subsoil was evaluated for its effectiveness in promoting the early survival and growth of *Populus tremuloides* Michx. (aspen), *Pinus contorta* Douglas ex Loudon (lodgepole pine), and *Picea glauca* (Moench) Voss (white spruce) while suppressing competitive herbaceous vegetation. Although low tree seedling survival in soil treatments with compost was unexpected, further research into edaphic conditions in the compost helped elucidate these results and compare the physical and chemical characteristics of compost beneath the mineral soil cap of fine or coarse material to compost at the surface (Chapter 3).

In Chapter 2, the survival, height, and root collar diameter of aspen, lodgepole pine, and white spruce as well as competition establishment were compared among five soil treatments: fine mineral subsoil (1); topsoil cap (2); compost cap (3); fine mineral soil cap over compost (4); and coarse mineral soil cap over compost (5). Our results showed that all soil treatments containing compost had poor seedling survival following two growing seasons, with the surface applied compost and compost with a mineral soil cap exhibiting 0.21% and < 30% survival in all tree species, respectively. This response was influenced by the source of compost, application rate, and degree of incorporation in the subsoil that created a saline growing medium for tree seedlings in the first growing season and was confirmed in Chapter 3. Our findings also showed that in the first growing season, a salinity tolerant, aggressive annual (*Kochia scoparia*) established across the research site and competed heavily with tree seedlings in soil treatments with compost, further negatively influencing tree seedling survival. We were able to show that the fine mineral soil cap over compost was more effective in limiting the growth of *Kochia scoparia* and a thicker fine mineral soil cap (> 50 cm) may have limited *Kochia scoparia* competitiveness. Although the mineral soil cap over compost allowed the establishment of *Kochia scoparia*, tree seedlings that survived the first growing season grew tallest and largest in soil treatments with a mineral soil cap over compost in the second growing season, suggesting that resources other than light (i.e. water, nutrients, and growing space) were not limiting.

In Chapter 3, our results indicated that the placement method and the textural composition of the mineral soil cap influenced the physical and chemical characteristics of the compost. We provided evidence that the fine and coarse mineral soil cap insulated the underlying compost layer, creating conditions of low oxygen availability in the covered compost compared to the compost at the surface. The mineral soil cap increased soil temperatures from decomposition in the compost, leading to elevated CO_2 emissions while the mineral soil cap also increased the water holding capacity of the underlying compost, initiating denitrification leading to elevated N_2O emissions. Although these results suggest that low oxygen conditions in the compost may have inhibited tree seedling root expansion from the mineral soil cap into the underlying compost, roots of tree seedlings may have accessed microsites with more favorable conditions at the interface between the fine or coarse mineral soil cap and the compost, leading to improved growth compared to soil treatments without compost (Chapter 2).

4.2 Research applications

When considering using organic amendments in future forest reclamation and restoration efforts where nutrient deficiencies appear to limit tree seedling growth, I would advise to initially consider the source of the organic amendment. Other studies in reclamation have used an array of organic amendments such as livestock manure, crop residue, municipal organic waste, peat material, straw, and wood chips that are fresh, composted, or co-composted together to improve soil organic matter and plant growth (e.g Borden & Black 2011; Larney & Angers 2012; Spargo & Doley 2016; Bay et al. 2012; Smith et al. 1979). Compost in this study was sourced from the Edmonton Composting Facility where municipal compost and biosolids from households in Edmonton are co-composted together. However, the City of Edmonton does not require residents to source-separate their household waste (e.g. recyclables, landfill, organics) and instead amassed waste is sorted at the Edmonton Waste Management Centre (City of Edmonton 2018). From personal observations in the field, compost contained small fragments of inorganic material (e.g. glass and plastic). Thus, compost was categorized as a mature and stable Agriculture Grade (Grade B) compost, which had elevated salt levels, concentrated from the biosolids that were co-composted with the organic waste. A thorough understanding of the detailed chemistry and composition of the organic amendment would help ensure its effectiveness.

The compost application rate (1,250 tons ha^{-1}) and degree of incorporation in the subsoil (4:1 ratio) cannot be recommended. Operational constraints limited the incorporation depth, therefore this compost concentration (i.e. application rate and degree of incorporation) was very elevated relative to other studies (e.g. Smith et al. 1979; Bay et al. 2012; Spargo & Doley 2016) leading to high salt levels that appeared to be one of the main factors driving low tree seedling survival in soil treatments with compost in the first growing season. If considering using co-compost municipal compost and biosolids in forest reclamation where salinity intolerant tree species are to be planted, I would recommend using a lower application rate (< 300 tons ha^{-1}) and our intended degree of incorporation (1:1 ratio). This may lead to higher tree seedling survival (e.g. Smith et al. 1979) and increase soil aeration when applied beneath a mineral soil cap.

The novel site preparation (layered) technique is an innovative method that should be implemented and investigated in future forest reclamation and restoration efforts. The establishment and pervasiveness of *Kochia scoparia* in the first growing season across the research site and especially in soil treatments with compost was unexpected and likely a contributing factor to low tree seedling survival in the first growing season. In the second growing season, however, bare ground cover increased in the fine mineral soil cap over compost as *K. scoparia* abundance declined, indicating that the 20 cm fine mineral soil cap over compost may have functioned as intended if *K. scoparia* had not been so prolific in the first growing season. Furthermore, precipitation in the first growing season was higher than average, reducing soil penetration resistance in the fine mineral soil cap and allowing the quick growing *K. scoparia* root system to penetrate through the fine mineral soil cap. Our results indicated that a fine mineral soil cap of at least 50 cm would have been necessary to effectively limit *K. scoparia* establishment in the first growing season. Therefore, fine mineral soil appears to be an effective capping material and future capping depth applications should consider average precipitation.

The fine and coarse mineral soil cap over compost created conditions of low soil oxygen in the compost layer. Although a lower compost concentration (i.e. application rate and degree of incorporation) may have made the textural transition from the mineral soil cap to the compost less abrupt, I would recommend incorporating a coarse material with the compost and applying a coarse soil layer beneath the compost. The high water holding capacity of compost can lead to low aeration if proper drainage is not ensured (Bunt 1988). The addition of a coarse material would ensure water drainage in the compost and increase permeability, regulating N_2O and CO_2 emissions as well as oxygen availability in the compost. Additionally, the use of steel rods to assess soil oxygen availability in soil treatments to a depth of 50 cm was effective and can be recommended. This method is often used to determine fluctuations in water table depth in wetlands (Carnell & Anderson 1986; Bridgham et al. 1991). It was a simple and reliable method that confirmed low soil oxygen availability in the compost beneath a mineral soil cap as suggested by CO_2, N_2O, and CH_4 gas exchange rates.

Finally, although the fine mineral subsoil had the highest survival for all tree species among soil treatments, I would caution the interpretation that this is a suitable material for forest reclamation. The subsoil material had poor chemical and physical characteristics indicated by low nutrient and organic matter levels as well as an elevated dry bulk density. Though these characteristics may have reduced the establishment of herbaceous competition, the absence of a coversoil material in the fine mineral subsoil soil treatment clearly negatively influenced tree seedling growth relative to the other soil treatments. On reclamation sites, the placement of a suitable coversoil material is critical for early tree seedling establishment (Zipper et al. 2013), supporting the development of a continuous tree canopy that will contribute to the formation of the forest floor (Klinka et al. 1990). Moreover, this research site was only monitored for the first two growing seasons and it is presumptuous to draw definitive conclusions regarding the survival and growth of tree seedlings in the fine mineral subsoil as well as other soil treatments without further long term monitoring.

4.3 Study limitations and future research

One of the main limitations in this study was not testing the compost concentration (i.e. application rate and degree of incorporation) on early tree seedling survival and growth in a small-scale preliminary study. The compost application rate was based on information available at the time of the study and with the expectation that we could incorporate the compost much deeper into the subsoil. However, despite the concentration of compost, tree seedlings in compost with a mineral soil cap had better growth compared to soil treatments without compost in the second growing season. This suggests that the 20 cm mineral soil cap over compost may have functioned as intended if *Kochia scoparia* had not colonized the site and the precipitation had not been higher than average in the first growing season.

To determine tree seedling mortality in our study, we had initially tagged individual seedlings in each soil treatment in the first growing season. But in light of the severe competition, it was impossible to locate these individual seedlings at the end of the first growing season. Permanent seedling assessment plots directly following the tree seedling planting in May of 2016 would have been a more effective approach. This would have allowed us to calculate a more accurate representation of seedling survival following the 2016 and 2017 growing seasons based on the density within each seedling assessment plot rather than the planting density across the research site. It would have also allowed us to monitor seedling growth instead of average height over the two growing seasons. This study was not setup to assess vegetation communities in the different soil treatments and as a result, we did not establish permanent vegetation assessment plots following the tree seedling planting in May of 2016. However, the establishment of *Kochia scoparia* made it necessary to measure species specific cover and not establishing permanent plots made it difficult to take the same vegetation measurements each growing season.

Future forest reclamation and restoration projects would benefit from future research investigating the most effective composition of several types of widely accessible organic amendments and their effective concentration (i.e. application rate and degree of incorporation in the subsoil) for application beneath a fine mineral soil cap. Ultimately, reclamation practices could benefit from the development of an organic amendment reclamation standard. Effective concentrations of widely used organic amendments could be recommended based on the subsoil texture and tree species to be planted, while fine mineral soil capping depths could also be recommended based on the average precipitation of different regions. Land practitioners could then choose an organic amendment based on availability in their local area and apply the materials recommended concentration based on the subsoil texture of their reclamation site and target tree species. An effective fine mineral soil cap depth could then be chosen and applied based on the average precipitation in their region. Although organic amendments in the literature appear to be chosen based on availability and proximity to the reclamation site, determining what type of organic amendment to apply on a reclamation site can be difficult when studies are not consistent. This organic amendment reclamation standard may encourage a more widespread use of organic amendments with the novel site preparation (layered) technique in forest reclamation.

Future research could also investigate innovate ways to condense organic amendments so that they can be efficiently applied at the root zone of planted tree seedlings. Other studies have used point source organic amendment and controlled release synthetic fertilizer application directly at the root zone of planted tree seedlings in planting holes (Sloan & Jacobs 2013; Jacobs et al. 2005), as tea bags (Carter & Tobler 2014; Hangs et al. 2003), and as tablets (Berry 1979) showing improved tree seedling growth and minimal uptake by herbaceous vegetation. It has been established in this study and others that the surface application of organic amendments proliferates the establishment of competition (Berry 1979; Bay et al. 2012; Chang et al. 1996; Smith et al. 1979; Staples et al. 1999) and therefore they need to be concealed at the root zone.

Alternatively, future research projects could build upon research into early successional native cover crops and seeding native boreal forest understory species with tree seedlings to suppress the establishment of ruderal species. *Melilotus officinalis* has been used as a cover crop in other studies (Snively 2014; Macdonald et al. 2015b), although mature *M. officinalis* can create a diffuse canopy that increases mortality in shade intolerant species such as lodgepole pine and aspen (Snively 2014). However, overall cover has been shown to remain constant with *M. officinalis* as a cover crop allowing it to serve as a replacement competitor for other herbaceous species, such as grass species, that could more effectively compete with tree seedlings (Snively 2014). Further research that investigates early successional native forbs, their compatibility with native tree seedlings, and their ability to suppress ruderal species establishment potentially in combination with organic amendments would be needed. Although the planting of native forest understory plants is limited due to lack of availability (Macdonald et al. 2012), research could investigate methods to obtain seed and successfully germinate understory species in greenhouses.

Overall, the research in this thesis built upon the current knowledge in forest reclamation and restoration. It is my hope that this thesis will assist researchers and land practitioners interested in using organic amendments to effectively restore disturbed and derelict land back to functioning forest ecosystems.

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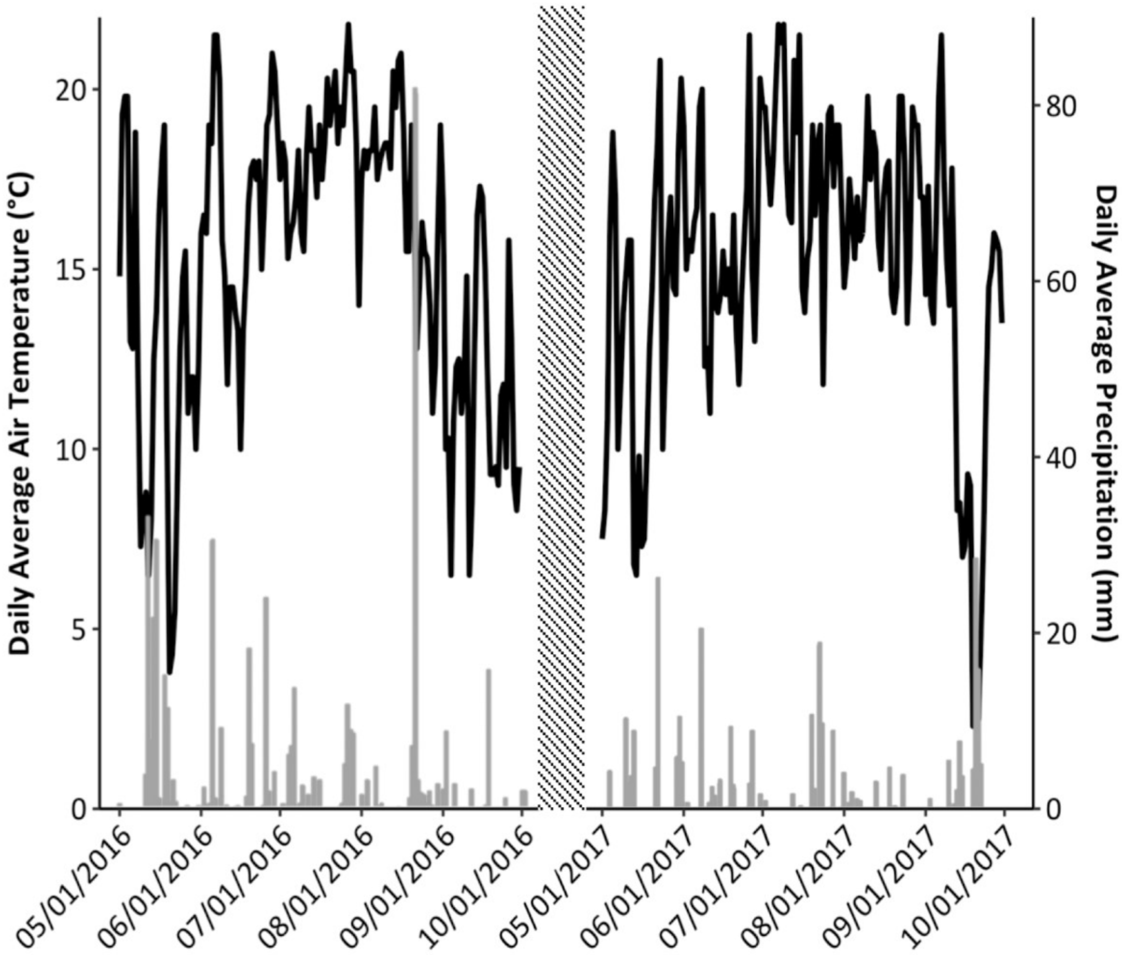
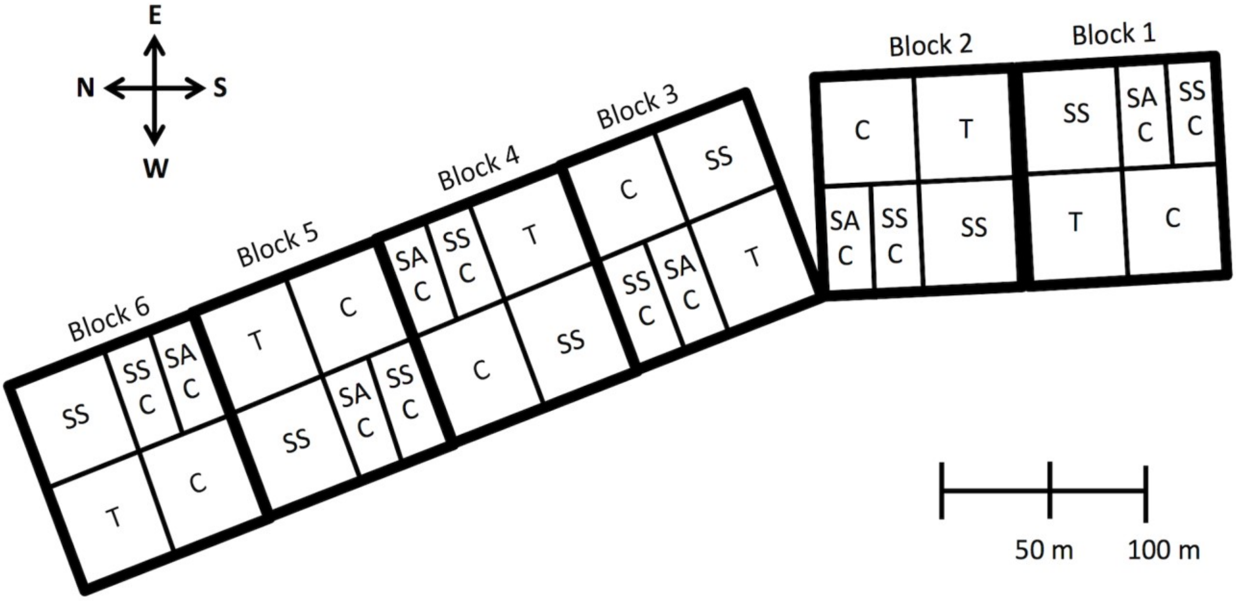
Appendices

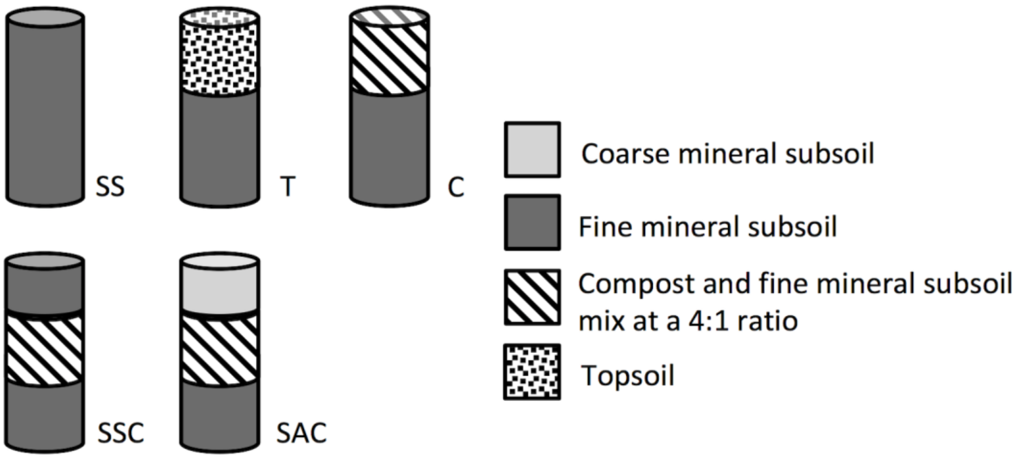
Appendix A Figures



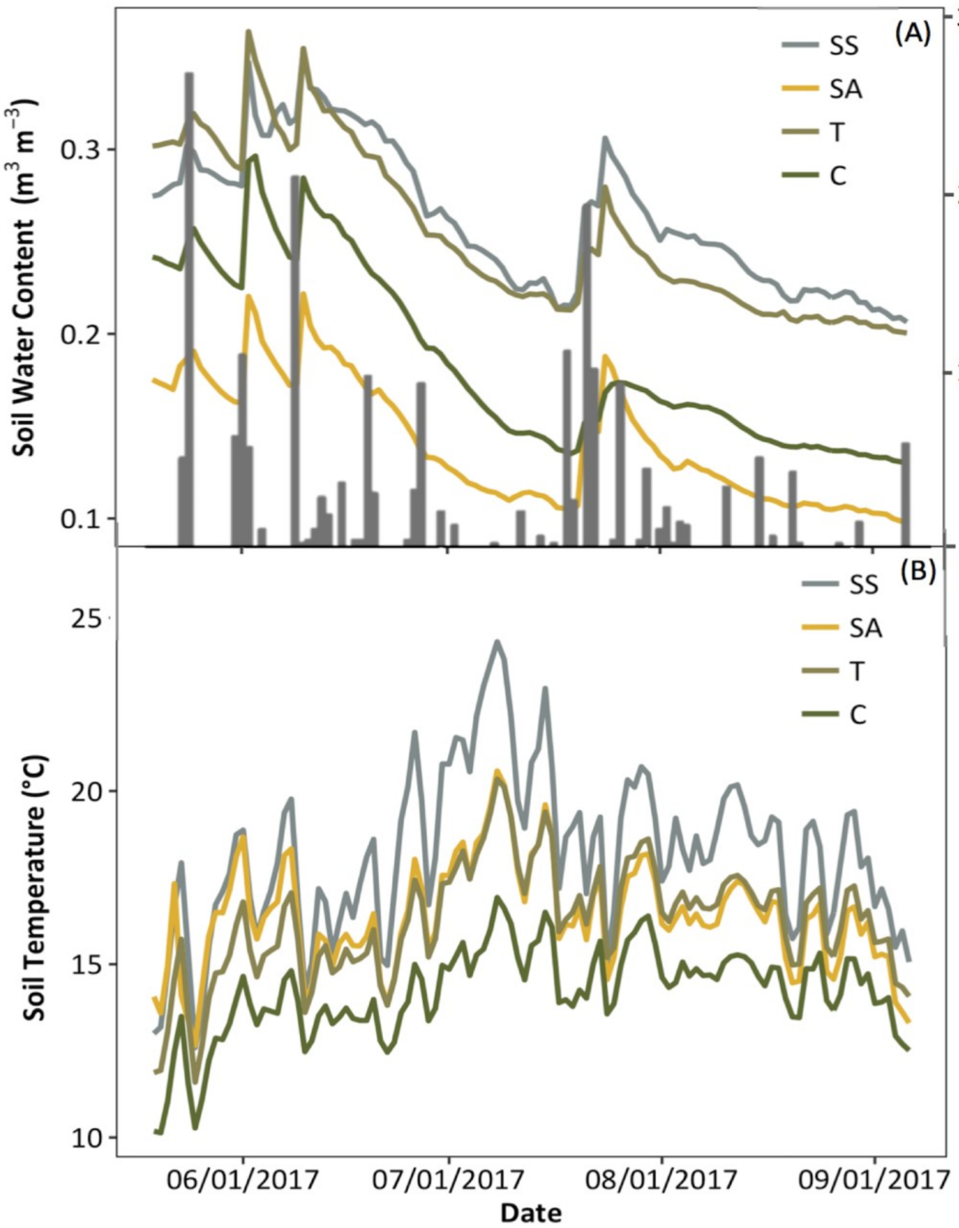
Appendix A-1. Daily average air temperature and precipitation during the 2016 and 2017 growing season (May-September) based on data from a weather station located 30km northeast of the research site at the Highvale coal mine in the town of Stony Plain, Alberta. The black line represents the daily mean temperature and gray bars represent the daily precipitation. Data accessed from Environment Canada (2017).



Appendix A-2. Map of the research site at the Highvale coal mine. The five soil treatments (Appendix A-3) are designated within each block. Each block is 100 m by 100 m; the SSC and SAC soil treatment areas in each of the six blocks were 25 m by 50 m in size while the other three soil treatments (SS, T, and C) were 50 m by 50 m each.



Appendix A-3. The five soil treatments at the research site at the Highvale coal mine: (1) an uncapped clay loam mineral subsoil (SS); (2) a 20 cm cap of salvaged topsoil (T); (3) a 20 cm layer of compost incorporated into the clay loam mineral subsoil to a depth of 25 cm (4:1 ratio) (C); (4) the same 25 cm layer of clay loam mineral subsoil and compost mixture capped with a 20 cm layer of clay loam mineral subsoil (SSC); (5) the same 25 cm layer of compost and clay loam mineral subsoil mixture capped with a 20 cm layer of a sandy mineral subsoil (SAC).



Appendix A-4. Average daily soil water content (A) and soil temperature (B) over the 2017 growing season (19 May - 9 September) for the fine mineral subsoil (SS), coarse mineral soil cap (SA) in the SAC (coarse mineral soil cap over compost) soil treatment, topsoil cap (T), and compost cap (C). Gray bars represent the daily precipitation from a weather station located 30 km northeast of the research site. Sensors were installed at a depth of 10 cm and precipitation data was accessed from Environment Canada (2017).

Appendix B Tables

Appendix B-1. Initial seedling measurements (average ± standard error of the mean) of aspen (Aw), lodgepole pine (Pl), and white spruce (Sw) planted at the Highvale coal mine research site (n=30). Note: 'RCD' refers to root collar diameter and 'RSR' refers to root-to-shoot ratio.

	Species		
	Aw	**Pl**	**Sw**
Height (cm)	26.52 (± 1.07)	21.03 (± 0.63)	27.32 (± 0.74)
RCD (mm)	3.77 (± 8.68)	4.30 (± 0.11)	3.60 (± 0.07)
Stem mass (g)	0.75 (± 0.07)	1.29 (± 0.09)	1.19 (± 0.05)
Root mass (g)	2.26 (± 0.19)	2.16 (± 0.15)	1.42 (± 0.10)
Total mass (g)	3.01 (± 0.24)	5.98 (± 0.36)	4.40 (± 0.16)
Root volume (ml)	20.73 (± 1.61)	18.17 (± 1.18)	11.88 (± 0.72)
RSR (g g^{-1})	3.11 (± 0.19)	1.82 (± 0.13)	1.22 (± 0.09)

Appendix B-2. Results of a three-way ANOVA in 2017 examining the percent survival of aspen (Aw), lodgepole pine (Pl), and white spruce (Sw) with competition removal (No Comp) and without competition removal (Comp) in the second growing season in the fine mineral subsoil (SS), topsoil cap (T), compost cap (C), fine mineral soil cap over compost (SSC), and coarse mineral soil cap over compost (SAC) soil treatments (n=6). P-values are given and bolded when significant (α = 0.05).

Treatment and species effects	**P-value**
Soil Treatment	**<0.001**
Competition	**<0.001**
Species	**0.002**
Soil Treatment × Species	**0.001**
Competition × Species	**0.005**
Soil Treatment × Competition	**0.001**
Soil Treatment × Competition × Species	0.390

Appendix B-3. Results of a one-way ANOVA in 2016 examining seedling height of aspen (Aw), lodgepole pine (Pl), and white spruce (Sw) in the fine mineral subsoil (SS), topsoil cap (T), fine mineral soil cap over compost (SSC), and coarse mineral soil cap over compost (SAC) soil treatments (n=6). P-values are given and bolded when significant (α = 0.05).

	Aw	Pl	Sw
Soil Treatment	**0.002**	**0.003**	0.663

Appendix B-4. Results of a two-way ANOVA in 2017 examining seedling height of aspen (Aw), lodgepole pine (Pl), and white spruce (Sw) with competition removal (No Comp) and without competition removal (Comp) in the second growing season in the fine mineral subsoil (SS), topsoil cap (T), fine mineral soil cap over compost (SSC), and coarse mineral soil cap over compost (SAC) soil treatments (n=6). P-values are given and bolded when significant (α = 0.05).

	Soil Treatment	Competition	Interaction
Aw	**<0.001**	**0.001**	**0.016**
Pl	**0.002**	**<0.001**	**0.002**
Sw	**0.012**	**0.010**	0.733

Appendix B-5. Results of a one-way ANOVA in 2016 examining seedling root collar diameter (RCD) of aspen (Aw), lodgepole pine (Pl), and white spruce (Sw) in the fine mineral subsoil (SS), topsoil cap (T), fine mineral soil cap over compost (SSC), and coarse mineral soil cap over compost (SAC) soil treatments (n=6). P-values are given and bolded when significant (α = 0.05).

	Aw	Pl	Sw
Soil Treatment	0.238	**0.008**	**0.014**

Appendix B-6. Results of a two-way ANOVA in 2017 examining seedling root collar diameter (RCD) of aspen (Aw), lodgepole pine (Pl), and white spruce (Sw) with competition removal (No Comp) and without competition removal (Comp) in the second growing season in the fine mineral subsoil (SS), topsoil cap (T), fine mineral soil cap over compost (SSC), and coarse mineral soil cap over compost (SAC) soil treatments (n=6). P-values are given and bolded when significant (α = 0.05).

	Soil Treatment	Competition	Interaction
Aw	**<0.001**	0.217	**0.016**
Pl	**0.045**	**0.002**	**0.003**
Sw	**0.003**	0.437	0.383

Appendix B-7. Results of a one-way ANOVA in 2016 examining proportional cover by functional group (bare ground, forb, *Kochia scoparia*, and graminoid) in the fine mineral subsoil (SS), topsoil cap (T), compost cap (C), fine mineral soil cap over compost (SSC), and coarse mineral soil cap over compost (SAC) soil treatments (n=6). P-values are given and bolded when significant (α = 0.05).

	Bare ground	Forb	*Kochia scoparia*	Graminoid
Soil Treatment	**<0.001**	**<0.001**	**<0.001**	**0.001**

Appendix B-8. Results of a one-way ANOVA in 2017 examining proportional cover by functional group (bare ground, forb, and graminoid) in the fine mineral subsoil (SS), topsoil cap (T), compost cap (C), fine mineral soil cap over compost (SSC), and coarse mineral soil cap over compost (SAC) soil treatments (n=6). P-values are given and bolded when significant (α = 0.05).

	Bare ground	Forb	Graminoid
Soil Treatment	**<0.001**	**0.023**	**<0.001**

Appendix B-9. Summary of coversoil material soil physical characteristics in 2016 and chemical characteristics in 2016 and 2017 for the fine mineral subsoil (SS), coarse mineral soil cap (SA) in the SAC (coarse mineral soil cap over compost) soil treatment, topsoil cap (T), and compost cap (C). Values represent averages and standard error of the mean (n=3). Different letters indicate significantly different means (α = 0.10). Note: 'DBD' refers to dry bulk density, 'EC' refers to electrical conductivity, 'SAR' refers to sodium adsorption ratio, and 'OM' refers to organic matter.

		SS		SA		T		C	
		2016	**2017**	**2016**	**2017**	**2016**	**2017**	**2016**	**2017**
DBD (g cm^{-3})		1.75 **a** (± 0.02)	--	1.58 **b** (± 0.03)	--	1.32 **c** (± 0.04)	--	0.84 **d** (± 0.03)	--
pH		8.18 **ab** (± 0.04)	8.47 **a** (± 0.08)	7.74 **cde** (± 0.17)	7.77 **cd** (± 0.08)	8.01 **bc** (± 0.09)	8.13 **b** (± 0.17)	7.43 **e** (± 0.07)	7.67 **de** (± 0.03)
EC (dS m^{-1})		2.32 **bc** (± 0.79)	0.90 **c** (± 0.29)	3.95 **bc** (± 1.40)	2.39 **bc** (± 0.65)	1.35 **bc** (± 0.31)	1.37 **bc** (± 0.75)	18.03 **a** (± 3.78)	8.26 **b** (± 2.81)
SAR		1.78 **b** (± 0.14)	1.05 **bc** (± 0.26)	1.11 **bc** (± 0.46)	0.68 **bc** (± 0.09)	0.27 **c** (± 0.04)	0.60 **c** (± 0.12)	4.43 **a** (± 0.51)	1.35 **bc** (± 0.14)
OM (%)		3.75 **b** (± 1.10)	2.73 **b** (± 0.79)	7.82 **b** (± 6.52)	0.81 **b** (± 0.13)	5.83 **b** (± 0.35)	4.89 **b** (± 0.34)	22.02 **a** (± 1.08)	23.19 **a** (± 2.10)
Total N (%)		0.07 **d** (± 0.01)	0.06 **d** (± 0.01)	0.04 **d** (± 0.03)	0.02 **d** (± 0.01)	0.23 **c** (0.04)	0.20 **c** (± 0.03)	1.31 **a** (± 0.04)	1.08 **b** (± 0.08)
Total P (%)		0.04 **c** (± 0.01)	0.05 **bc** (± 0.01)	0.05 **bc** (± 0.01)	0.05 **bc** (± 0.01)	0.05 **bc** (± 0.01)	0.06 **b** (± 0.01)	0.56 **a** (± 0.02)	0.64 **a** (± 0.01)
Nutrients (mg kg^{-1})	NH_4	46.63 **ab** (± 39.19)	1.47 **c** (± 0.71)	29.35 **b** (± 22.82)	44.01 **ab** (± 21.59)	40.24 **ab** (± 28.01)	26.87 **b** (± 18.26)	79.67 **ab** (± 49.43)	215.38 **a** (± 193.13)
	NO_3	1.81 **d** (± 0.31)	3.53 **d** (± 1.30)	60.81 **bc** (± 23.98)	59.54 **bc** (± 11.94)	36.25 **c** (± 20.39)	46.02 **c** (± 27.94)	977.97 **a** (± 290.05)	105.30 **b** (± 33.11)
	PO_4	8.64 **c** (± 1.55)	6.27 **c** (± 1.74)	28.09 **bc** (± 11.91)	316.33 **abc** (± 301.32)	32.34 **bc** (± 5.69)	19.64 **bc** (± 5.03)	572.28 **ab** (± 261.64)	774.28 **a** (± 61.98)

Nutrients (mg kg^{-1})	Al	0.09 **b** (± 0.02)	0.28 **ab** (± 0.06)	0.33 **ab** (± 0.25)	0.18 **ab** (± 0.02)	0.21 **ab** (± 0.03)	0.53 **a** (± 0.22)	0.22 **ab** (± 0.08)	0.48 **a** (± 0.02)
	Ca	4033.67 **b** (± 100.28)	3388.33 **b** (± 667.54)	2170.00 **c** (118.60)	1970.67 **c** (± 163.97)	4761.00 **b** (219.16)	3883.00 **b** (± 226.41)	12690.67 **a** (± 1664.43)	13241.00 **a** (± 1312.38)
	Cu	0.80 **c** (± 0.16)	0.01 **d** (± 0.01)	1.27 **bc** (± 0.30)	0.15 **d** (± 0.11)	1.46 **ab** (± 0.18)	0.05 **d** (± 0.05)	1.91 **a** (± 0.24)	0.78 **c** (± 0.10)
	Fe	0.08 **b** (± 0.03)	0.05 **b** (± 0.02)	0.13 **b** (± 0.01)	0.10 **b** (± 0.02)	0.68 **a** (± 0.09)	0.82 **a** (± 0.16)	1.85 **a** (± 0.44)	1.26 **a** (± 0.17)
	K	233.00 **cd** (± 5.03)	204.33 **cd** (± 25.39)	182.33 **d** (± 61.23)	268.33 **cd** (± 116.97)	445.67 **cd** (± 20.09)	477.33 **c** (± 50.45)	3275.33 **a** (± 268.69)	2214.67 **b** (± 87.27)
	Mg	510.00 **c** (± 42.14)	475.00 **c** (± 24.54)	257.67 **d** (± 0.90)	255.67 **d** (± 9.77)	516.33 **c** (± 36.70)	505.67 **c** (± 33.35)	1136.33 **a** (± 54.57)	860.33 **b** (± 78.24)
	Mn	3.00 **cd** (± 0.51)	2.54 **d** (± 0.96)	6.65 **bc** (± 0.68)	10.08 **ab** (± 1.54)	4.63 **cd** (± 0.16)	1.33 **d** (± 0.43)	10.97 **a** (± 1.57)	1.63 **d** (± 0.46)
	Na	263.33 **bc** (± 19.84)	150.33 **cd** (± 51.87)	124.00 **d** (± 50.86)	72.67 **ef** (± 11.98)	43.33 **f** (± 5.70)	88.33 **d** (± 16.15)	1166.00 **a** (± 180.41)	361.33 **b** (± 52.74)
	Zn	0.15 **c** (± 0.02)	0.36 **bc** (± 0.04)	0.38 **bc** (± 0.13)	0.42 **bc** (± 0.08)	0.25 **bc** (± 0.01)	0.61 **b** (± 0.20)	6.46 **a** (± 0.94)	7.24 **a** (± 0.58)

Appendix B-10. Results of a two-way repeated measures ANOVA examining changes in coversoil material chemical characteristics over two growing seasons (2016, 2017) for the fine mineral subsoil (SS), coarse mineral soil cap (SA) in the SAC (coarse mineral soil cap over compost) soil treatment, topsoil cap (T), and compost cap (C) (n=3). P-values are given and bolded when significant (α = 0.10). Note: 'DBD' refers to dry bulk density, 'EC' refers to electrical conductivity, 'SAR' refers to sodium adsorption ratio, and 'OM' refers to organic matter.

	Unit	Coversoil material	Year	Interaction
pH	-	**<0.001**	**0.007**	0.344
EC	dS m^{-1}	**<0.001**	**0.001**	**0.024**
SAR	-	**<0.001**	**<0.001**	**<0.001**
OM	%	**0.001**	0.289	0.426
Total N	%	**<0.001**	**0.006**	**0.011**
Total P	%	**<0.001**	**0.005**	0.987
NH_4	mg/kg	**0.003**	**0.053**	**0.014**
NO_3	mg/kg	**<0.001**	0.367	**0.031**
PO_4	mg/kg	**<0.001**	0.606	0.531
Al	mg/kg	**0.010**	**0.007**	0.335
Ca	mg/kg	**<0.001**	0.120	0.532
Cu	mg/kg	**<0.001**	**<0.001**	0.277
Fe	mg/kg	**<0.001**	0.211	0.653
K	mg/kg	**<0.001**	**0.008**	**<0.001**
Mg	mg/kg	**<0.001**	**0.012**	**0.011**
Mn	mg/kg	**<0.001**	**0.002**	**0.001**
Na	mg/kg	**<0.001**	**0.099**	**0.025**
Zn	mg/kg	**<0.001**	**0.008**	0.296

Appendix B-11. Results of a two-way ANOVA examining daily average soil water content and soil temperature over the 2017 growing season (19 May - 9 September) for the compost cap (C), compost with a fine mineral soil cap (SSC-C), and compost with a coarse mineral soil cap (SAC-C) (n=6). P-values are given and bolded when significant ($\alpha = 0.05$).

	Compost Treatment	Date	Interaction
Soil water content	**<0.001**	**<0.001**	**<0.001**
Soil temperature	**<0.001**	**<0.001**	**<0.001**

Appendix B-12. Results of a one-way ANOVA in 2017 examining aerobic, intermediate, and anaerobic reactions on steel rods based on soil depth in the fine mineral subsoil (SS), topsoil cap (T), compost cap (C), fine mineral soil cap over compost (SSC), and coarse mineral soil cap over compost (SAC) soil treatments (n=6). P-values are given and bolded when significant (α = 0.05).

	Aerobic	Intermediate	Anaerobic
Soil Treatment	**0.024**	0.405	0.488

Appendix B-13. Results of a two-way repeated measures ANOVA examining gas exchange rates for CO_2, N_2O, and CH_4 for the compost cap (C), compost with a fine mineral soil cap (SSC-C), and compost with a coarse mineral soil cap (SAC-C) over the 2017 growing season and on each sampling date (23 June, 27 July, and 18 August 2017) (n=6). P-values are given and bolded when significant ($\alpha = 0.05$).

	Compost Treatment	Date	Interaction
CO_2	**<0.001**	**<0.001**	0.115
N_2O	**<0.001**	**0.005**	*0.068*
CH_4	0.106	0.097	0.085

Appendix C Supporting Text

Appendix C-1. In the laboratory, collected foliage samples were used to establish DNA references that allowed us to isolate *K. scoparia* roots from the roots of other plants in the soil samples. All foliage samples were cleaned with deionized water to remove excess soil or pollen and freeze-dried for 72 hours. Dried samples were then ground using a ball mill (TissueLyser II, Qiagen Inc, Mississauga, ON, Canada) and saved in 20 ml glass vials at room temperature for up to three months, or in a freezer (-20 °C) for extended periods of time. About 20 mg of each ground tissue sample was extracted with 5% Cetyl trimethylammonium bromide (CTAB) (Griffiths et al. 2000). DNA yield and purity were quantified using a Nanodrop 2000 (Thermo Fisher Scientific, Wilmington, DE, USA) with DNA concentration measured from 2 to 608 ng/µl, 260/230 absorbance ratio of 1.00 to 3.16 and 260/280 absorbance ratio of 1.13 to 2.14. Two of the community species (*Chenopodium album* and *Brassica rapa*) gave poor DNA yield. They were then extracted with 2 % CTAB (Doyle & Doyle 1987; McNickle et al. 2008) followed by cleaning with the 5% CTAB method. DNA yield and purity were 0.5 to 70 ng/µl, 260/230 absorbance ratio of 0.73 to 2.00 and 260/280 absorbance ratio of 1.42 to 12.13. DNA extracts were stored at -20°C for downstream activities. The DNA signature of *K. scoparia* was established at a non-coding chloroplast region, the trnL-trnF intergenic spacer. From the extracted genomic DNA material, a segment within the region was amplified by a polymerase chain reaction (PCR) using a species-specific primer. We used a universal forward primer (E (5'-GGTTCAAGTCCCTCTATCCC-3') (Taberlet et al. 1991)) and a species-specific reverse primer developed in this study, Koch6 (5'-GGGACCGAAATCCTTTAGTTC-3'). The PCR was done in volumes totaling 25 µl: 5.5 µl autoclaved deionized water, 2.5 µl of forward primer E at 10 µM, 2.5 µl of reverse primer Koch6 at 10 µM, 12.5 µl of EconoTaq PLUS 2X Master Mix (Lucigen Corp., Middleton, WI, USA), and 2 µL of 1-10 ng/µl of DNA template. Amplifications were performed using an Eppendorf Mastercycler Pro S gradient thermal cycler (Model 6321; Eppendorf Canada, Mississauga, ON, Canada). Thermal cycler conditions: 94 °C for 5 min, 35 cycles of 94 °C for 60 s, 60 °C for 60 s, 72 °C for 80 s, followed by a final extension of 72 °C for 30 min. PCR products were visualized right away by gel electrophoresis using a Mini-Sub Cell GT Horizontal Electrophoresis System (Bio-Rad Laboratories, Mississauga, ON, Canada) on a 10 cm long × 15 cm wide gel slab, 1.5 % agarose, with SYBR® Safe DNA gel stain, ran in 2-tiers at 100V for 35 min. Amplicon lengths were compared with a 700 base-pair (bp) ladder that was run simultaneously on the gel. *K. scoparia* gave a prominent band at around 350 bp while all other community species gave no bands. In order to verify the negative result of the other community species on the gel, DNA extracts of all species (including *K. scoparia* and the other community species) were run through a PCR as described above, but replacing the species-specific reverse primer with a universal reverse primer (F (5'-ATTTGAACTGGTGACACGAG-3') (Taberlet et al. 1991)). All species gave bands between 150 to 550 bp. DNA extracts and PCR products were saved at 2-8 °C for up to three months, or in a freezer (-20 °C) for extended periods of time.

After roots were picked out of soil samples in a washing process over fine-mesh sieves involving hand manipulation, they were freeze-dried for 72 hours. Dried samples were ground using a ball mill (TissueLyser II, Qiagen Inc, Mississauga, ON, Canada) and saved in 20 ml glass vials at room temperature for up to three months, or in a freezer (-20 °C) for extended periods of time. Genomic DNA of the root tissue samples was extracted in the same way as the foliage samples, except that up to 50 mg of ground material was used for the extractions. DNA yield and quality were 0 to 479 ng/µL, 260/230 absorbance ratio of -6.46 to 40.79 and 260/280 absorbance ratio of -0.07 to 4.04. On all root DNA samples, separate PCRs were performed with the species-specific reverse primer (Koch6) and with the universal reverse primer. Samples that gave bands on the gel with reverse primer Koch6 were identified as *K. scoparia* (+ve). DNA extracts and PCR products were saved at 2-8 °C for up to three months, or at -20 °C for extended periods of time.

Appendix C-2. Gas exchange rates for CO_2, N_2O, and CH_4 for the compost cap (C), compost with a fine mineral soil cap (SSC-C), and compost with a coarse mineral soil cap (SAC-C) were calculated following the method of Holland et al. 1999 using the following equations:

$$C_m = \frac{(C_v \times M \times P)}{(R \times T)}$$

where C_m is the mass/volume concentration of CO_2, N_2O, or CH_4 (mg m^{-3}); C_v is the trace gas concentration (ppm); M is the molecular weight of CH_4, N_2O, or CO_2; P is barometric pressure (e.g. 1); R is the universal gas constant (0.0820575 L atm mol^{-1} K^{-1}); and T is air temperature at the time of sampling (K) (K =°C + 273.15).

$$G = \left(\frac{V \times C_{rate}}{A}\right) \times 60 \times \frac{1}{1000}$$

where G is the soil gas exchange rate of CH_4, N_2O, or CO_2 (g m^{-2} $hour^{-1}$); V is the internal volume of the respiration chamber (m^3); C_{rate} is the change in concentration of gas (C_m) over the sampling period (mg m^{-3} min^{-1}); and A is the area of the base of the collar (m^2).