Disturbance Effects of Oil Sands Exploration Practices on Coarse-textured Soils and *Populus tremuloides* Michx. Regeneration

by

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ABSTRACT

Oils sands exploration (OSE) sites associated with in situ oil sands development are required to evaluate and delineate oil resources. Once these sites are cleared and disturbed for exploration, they can result in habitat disturbance and fragmentation, invasion of weed species, changes to surface drainage, and changes to soil properties. As many OSE sites are required for development, the large area that is being disturbed represents an important disturbance in Alberta's northern boreal forest. Timely regeneration of boreal forest species after reclamation is critical to limit the negative impacts of exploration activities.

One of the current challenges for industry is the lack of forest regeneration on coarse-textured OSE sites. This study examined the effects of OSE practices on soil properties that could be associated with the slow regeneration of boreal forest species on coarse-textured soils. We conducted field experiments to investigate the effect of OSE practices on coarse-textured soil properties by comparing disturbed and undisturbed sites. The field experiments examined: 1) the changes in soil properties that may result in poor regeneration; in particular, the changes to particle size distribution to determine if OSE practices were homogenizing the natural heterogeneous bedding of coarse-textured soils (textural layering); 2) the soil warming patterns of wood mulch used commonly during reclamation; and, 3) the differences in nutrient availability with different wood mulch surface amendments (no mulch, 10 cm of mulch, and mulch incorporated with soil). The results indicated that OSE disturbance decreased very coarse sand content, silt content, sodium adsorption ratio, and available ammonium and increased fine sand content, bulk density, pH, electrical conductivity, calcium, potassium, carbon:nitrogen, and available nitrate. OSE practices homogenized the natural bedding of coarse-textured soils, but homogenization did not result in a change to plant available water as both field capacity and wilting point increased. The higher field capacity and wilting point were likely due to the redistribution of finer particles throughout the soil profile as indicated by changes to the D_{10}

value. The use of wood mulch on OSE sites resulted in a two week lag for soils with mulch to reach above 1˚C in the spring (delayed soil warming). In this study, mulch use did not result in lower nutrient availability and there were no differences of nutrient availability if mulch was incorporated or applied as layer. Of the soil properties evaluated in this study, the field experiments indicated that changes to coarse-textured soil properties from OSE disturbance that were most likely to affect regeneration included homogenization, pore size distribution, delayed soil warming, and nutrient availability.

A greenhouse experiment was conducted to further investigate the effects of delayed soil warming and commonly used wood mulch on the growth of *Populus tremuloides* and nutrient availability on coarse-textured soils. In the growth chamber experiment, we compared *Populus tremuloides* seedlings started at 5 and 10˚C (with or without mulch) and warmed to 20˚C. Delayed soil warming, mulch amendment, and their interaction affected *Populus tremuloides* growth performance. Delayed soil warming resulted in lower aboveground and belowground growth. The mulch amendment resulted in lower aboveground growth. The interactive effect between delayed warming and mulch amendment resulted in seedlings started at 10˚C without mulch having the better growth performance of all treatment combinations. Though mulch incorporation resulted in changes to measured soil chemical properties and nutrient availability, this did not translate to differences in *Populus tremuloides* growth. Based on this study, lower disturbance construction methods for OSE drilling pads in Alberta's northern boreal forest should be considered for coarse-textured sites and mulch use should be used sparingly on sites to be revegetated with cold sensitive species such as *Populus tremuloides*.

DEDICATION

This work is dedicated to my mother. The importance you placed on education still sticks with me. If you were here, I know you would be very proud.

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CHAPTER 1. INTRODUCTION

1. BACKGROUND

Oil sands deposits in Alberta are separated in to three areas: Peace River, Athabasca, and Cold Lake. In total, these areas underlie approximately 142 200 km^2 of land in Alberta (Alberta Energy 2017a). Active oil sands deposits (90 000 km^2) cover approximately 24% of Alberta's boreal forest (381 000 km^2; Alberta Energy Regulator 2015). As of February 2017, there are 133 oil sands projects operating or under construction (Alberta Energy 2017b). With an additional 43 projects (Alberta Energy 2017b) that are approved, under application, or announced, the ecological impact of oil sands development on the boreal forest will increase.

Current legislation requires that lands disturbed by oil sands development are returned to equivalent land capability (Government of Alberta 1993a). Guidelines suggest that revegetation of these forested lands should be based on the end land use and reflective of native plant communities in the region (Alberta Environment 2010). For oil sands exploration (OSE) sites associated with oil sands facilities, after exploration is completed, the operator must apply for a reclamation certificate within 3 full growing seasons (Alberta Environment 2005). Slow forest species regeneration on OSE sites after reclamation, especially on coarse-textured soils (>50% sand particles), has prevented operators from meeting legislative requirements.

2. NORTHERN BOREAL FOREST IN ALBERTA

The northern boreal forest occupies approximately 58% or 381 000 km^2 of Alberta's land surface, covering most of northern Alberta (Natural Regions Committee 2006). The climate is characterized by short, warm summers and long, cold winters. Mean annual temperature ranges from 1 °C to -3.5 °C, with an average of 0.5°C, getting colder moving from the southern extents to the northern extents. Annual precipitation is 480 mm on average, with 60% to 70% of precipitation falling between April and August. The growing season is generally considered to be from May to September but from June to August for the more northern extents.

Landforms in the northern boreal forest are predominantly fine-textured lacustrine and morainal plains (Natural Regions Committee 2006). The area is level to undulating with approximately 60% forested uplands with 37% wetlands and 3% water in low-lying areas and depressions. Cretaceous shales dominate the upper bedrock layers. Overlying these shales are parent materials of mostly organic (35%), morainal (30%), glaciolacustrine (20%) and glaciofluvial (10%) origin. Soils generally consist of the following: luvisolic (35%) on upland morainal materials; brunisolic (10%) on upland fluvial or eolian materials; organic (30%) in poorly drained wetland areas; gleysolic (15%) in poorly drained transitional areas; and, cryosolic in the northern extents and high elevations locations. Thick forest litter layers, leaching, and low decomposition rates are characteristic of the climate in the northern boreal forest.

The northern boreal forest is a mixture of forested uplands and bogs and fens in the low-lying areas or depressions (Natural Regions Committee 2006). Upland vegetation is a mix of *Populus tremuloides* Michx. (aspen), *Populus balsamifera* L. (balsam poplar), *Picea glauca* (Moench) Voss (white spruce) forests, and *Pinus banksiana* Lamb. (jack pine) forests. Wetland vegetation is a mix of shrub and sedge dominated marshes and fens and treed bogs and fens. Twenty-five % of Alberta’s rare vascular plants are found in the boreal forest.

The diverse climate and vegetation of the boreal forest provides habitat for a diverse collection of species (Natural Regions Committee 2006). The mix of deciduous, mixedwood, and coniferous forests provide habitat for many types of birds and mammals. *Grus americana* (Whooping Crane) is an endangered migratory bird species that breed in the wetlands of the boreal forest. *Rangifer tarandus caribou* (Woodland Caribou) is a threatened mammalian species that can be found in lichen-rich forested areas and treed wetland areas. *Bison bison athabascae* (Wood Bison) is a threatened mammalian species in limited areas of the region. Interspersed wetland areas provide additional habitat for other species of birds and amphibians. Mixedwood forests adjacent to wetlands and water bodies are the most species rich habitats. Water bodies located in the boreal forest are habitat to at least 17 species of fish.

3. OIL SANDS DEVELOPMENT

Environmental Impact Assessments (EIAs) are required for all oil sands surface mining operations and all commercial oil sands facilities that produce more than 2000 m^3 of bitumen or its derivatives per day (Government of Alberta 1993b) before applying for government approval for the facility (Government of Alberta 2003). The focus of these EIAs is to determine the impacts from the facility's construction, operation, and reclamation activities. Therefore, conservation and reclamation plans for areas disturbed by the project are submitted as part of the EIA. Reclamation activities on these sites aim to return productivity to a level similar to or better than the previously undisturbed site. However, the impacts to soil and vegetation from reclamation activities is not well known (e.g. impacts to vegetation after topsoil replacement, amendment results, etc.). With the current public scrutiny of issues associated with the oil sands, it is becoming increasingly important that reclamation activities accomplish their goal.

The two main types of oil sands operations in Alberta are surface mineable and in situ. Approximately 4800 km^2 of active oil sands deposits occur close enough to the surface to allow for surface mining of the deposit (Alberta Energy Regulator 2015). As of 2013, 895 of the 4800 km^2 has been affected by surface mining methods (Alberta Energy 2017a). Eighty percent of oil sands deposits need to be extracted by in situ methods which disturb 85 to 90% less land than comparable mineable operations with no production of tailings (Government of Alberta 2014). However, many features are associated with in situ facilities like well sites, oil sands exploration (OSE sites), access roads, and three dimensional seismic lines. The most common in situ operations are steam assisted gravity drainage (SAGD) and cyclic steam stimulation (CSS) which both use steam injection to increase the flow of bitumen allowing for extraction (Alberta Energy Regulator 2015). As in situ operations will be responsible for the majority of oil sands extraction, it will continue to be an important disturbance in Alberta's boreal forest.

4. OIL SANDS EXPLORATION (OSE) SITE DISTURBANCE AND RECLAMATION

As part of oil sands development, OSE wells are drilled in order to determine the stratigraphy of the area and evaluate and delineate oil resources. For leases in the Oil Sands Areas, exploration wells are required at a minimum of one exploration well per section (2.6 km^2) in more than 60% of the sections in their lease with seismic data from unexplored section (Government of Alberta 2010). In 2011, Alberta Energy (2011) reduced this requirement to one well per 3 or 9 sections depending if the oil sands zone is Cretaceous or pre-Cretaceous, respectively. However, additional exploration wells may be required as part of the oil sands mining approval. Additionally, one exploration well is required per 350 or 700 m by triangulation for oil resources under mines and processing plants depending on the timing of development (Alberta Energy Regulator 2013).

OSE sites are approximately 1 ha in size but given the legislative requirements discussed above companies must drill many sites per year. Though OSE sites are small in size, together they impact a large portion of Alberta’s boreal forest, either directly or indirectly through forest fragmentation. On surface mineable sites, the majority of OSE sites would be disturbed as part of the surface mining process to extract bitumen. But for in situ sites, the majority of these sites are ready for reclamation following drilling. The current practice on OSE sites is mostly winter drilling. This allows for less compaction issues and easier site access as the area is a mosaic of upland and peatland areas. The sites are sometimes kept for observation or monitoring but many are drilled and ready for reclamation the following spring.

Standard OSE site disturbance includes vegetation removal, topsoil salvage, drilling, and reclamation. Forest vegetation is removed from the area required for drilling purposes. Often the cleared vegetation is mulched in to small wood chips. Topsoil is salvaged according to regulations (Alberta Environment 2005) and stockpiled separately from any salvaged subsoil. Often, the surface litter (LFH) is salvaged with the topsoil in one lift and stockpiled in a mixed stockpile of LFH and topsoil. In some cases, subsoil salvage is required or disturbed in order to make the site level. The site is drilled which usually takes a month or less, then subsoil is replaced, compacted, and recontoured. Topsoil is redistributed over the site and often the wood mulch from cleared vegetation is applied to the surface of the replaced topsoil. These sites are left to naturally regenerate or planted with tree species such as *Picea glauca*, *Picea mariana* (Mill.) BSP (black spruce), *Pinus banksiana*, *Populus balsamifera* L., *Betula nana* L. (bog birch), *Alnus viridis* (green alder), or *Picea mariana*. Establishment of forest species on upland OSE sites has been slow, preventing operators form meeting current legislative requirements.

Site preparation and reclamation activities alone can decrease the natural regeneration of species. In Australian forests, Koch et al. (1996) observed that seed store density compared to undisturbed conditions decreased 26% after clearing and burning, 69% after stockpiling and 87% after topsoil replacement. In North Dakota prairie soils, freshly stockpiled topsoil and a one-year-old stockpile had significantly fewer viable seeds after stockpiling and lower seed diversity (Iverson and Wali 1982). In the boreal forest of Alberta, salvaging and replacement of LFH reduced propagule abundance (Mackenzie and Naeth 2010; MacKenzie 2013) and stockpiling reduced seed viability (MacKenzie 2013). As there is a high abundance and diversity of propagules (MacKenzie and Naeth 2010; MacKenzie 2013) located in the LFH and top of mineral soil (Strong and La Roi 1983), stripping activities can reduce plant establishment through dilution (Tacey and Glossop 1980; Rokich et al. 2000; MacKenzie 2013). Dilution of the seed bank from over-salvaging can reduce seedling emergence (Grant et al. 1996), plant density (Tacey and Glossop 1980; Rokich et al. 2000), and plant species richness (Fair 2011). Reduced seed viability from stockpiling has been attributed to high temperature and water (Rokich et al 2000), in situ germination (Rivera et al 2012; MacKenzie 2013), decay or rotting (MacKenzie 2013), or anaerobic conditions (Dickie et al 1988; MacKenzie 2013).

5. DISTURBANCE OF COARSE-TEXTURED SOIL IN THE NORTHERN BOREAL FOREST

In particular, forested species establishment on OSE sites with coarse-textured (sandy) soils has been slow. In the Alberta Oil Sands Region, coarse-textured soils often support *Pinus* *banksiana*, *Populus tremuloides*, some *Picea glauca*, and *Picea mariana* depending on the nutrient and moisture regime (Beckingham and Archibald 1996). As these soils are low in organic matter and clay content, coarse-textured soils tend to have low cation exchange capacity and water holding capacity (Turchenek and Lindsay 1982; Devon NEC Corporation 2012). The low organic matter and clay content also make coarse-textured soil susceptible to wind and water erosion (Alberta Agriculture 1985; Pedocan Land Evaluation Ltd. 1993). They tend to be nutrient poor and well to rapidly drained (Turchenek and Lindsay 1982; Devon NEC Corporation 2012) resulting in an increased leaching of nutrients from the soil with decreased nutrients for plant growth. As coarse-textured soils have less nutrients and moisture, disturbance can have a critical impact on forest regeneration.

Coarse-textured soils are often deposited by wind or water processes (Turchenek and Lindsay 1982; Bock et al. 2006) resulting in different textural layering or bedding (Zettl et al. 2011). Sites with similar coarse textures but supporting different vegetation (i.e. a, b, and d ecosites as defined in Beckingham and Archibald [1996]) differed in the heterogeneity of their layering (Zettl et al. 2011). Textural variation was the highest in moister d2 ecosites, the lowest in drier a1 ecosites, and b ecosites were in between (Zettl et al. 2011). The layering and textural heterogeneity was related to increased field capacity and water storage (Zettl et al. 2011). Huang et al. (2011) indicated that heterogeneity in the layering resulted in more plant available water (PAW) than homogeneous soils with the same texture throughout. The disturbance of naturally occurring heterogeneous bedding of coarse-textured soils may be one reason for the slow regeneration on coarse-textured sites. As OSE disturbance involves the stripping, stockpiling, and replacement of topsoil and subsoil that could result in homogenization of the soil (i.e. mixing the soil resulting in similar particle size variation with depth), it may be an important factor for soil properties that control PAW.

6. USE OF MULCH IN RECLAMATION

The benefits of using woody material for forest reclamation purposes has been evaluated in the past (Harmon et al. 1986; Brown 2010). The majority of benefits are observed with coarse woody debris as opposed to mulch (Harmon et al. 1986; Kayahara et al. 1996; Laiho and Prescott 2004; Landhäusser et al. 2007; Brown 2010). Mulch has been used because of its possible benefits including: increased moisture for plants (Larsson and Båth 1996; Iles and Dosmann 1999); removal of non-merchantable timber such that operators do not need to dispose of it which is costly (MacKenzie and Renkema 2013); mulching is cheaper than clearing using whole logs; fulfillment of forest fire protection requirements (Alberta Sustainable Resource Development 2008); and decreased soil loss through erosion and addition of carbon to the system for organic matter cycling (MacKenzie and Renkema 2013).

As coarse-textured soils are dry and poor in nutrients, mulch use may provide more benefits for soil moisture and nutrients. Soil water content was approximately 4 to 10% higher under pine and spruce mulches than under bare soil (Larsson and Båth 1996; Iles and Dosmann 1999) due to less evaporation at the soil surface (Himelick and Watson 1990; Maggard et al. 2012). Maggard et al. (2012) also suggests that reduced transpiration from weed suppression could contribute to the increase in soil moisture. When mulch was incorporated in to the soil, the decreased bulk density from incorporating the mulch increased soil porosity which can lead to better infiltration (McConkey et al. 2012). Incorporation of mulch also improved water holding capacity and aeration porosity (McConkey et al. 2012). As the mulch is decomposed, the increase in organic matter can also change soil water properties. Wesseling et al. (2009) showed than an addition of 10% organic matter could decrease saturated hydraulic conductivity by one to two orders of magnitude, increase unsaturated hydraulic conductivity and increase water retention capacity. This could be beneficial because less nutrients would be leached out of the soil; however, the decrease in saturated hydraulic conductivity could lead to ponding and run off (Wesseling et al. 2009).

Legislation on the use of mulch on public lands states that this layer of mulch should be less than 5 cm thick, should not be mixed in to the soil, and should not impede revegetation of the site (Alberta Sustainable Resource Development 2009). On sites where mulch has been used as a reclamation tool, observations have shown a lack of revegetation on many of these sites. This is a legislative issue as the operators must revegetate the site (Alberta Sustainable Resource Development 2009) and reclaim it to equivalent land capability (Government of Alberta 1993a).

7. WOOD MULCH AND LEACHATE PROPERTIES

The effects mulch can have on soil properties and revegetation depends on the properties of mulch and its leachate. Mulches can be highly variable on OSE sites because they are a function of the tree species on site at the time of clearing. The wood mulch is made up of woody materials from on site that are chopped into wood chips. This differs from other woody materials such as chunks, rough mulch (logs with branches removed), and whole logs (Vinge and Pyper 2012). Some recent research has examined the characteristics of different mulches used for soil amendments (Table1-1). Bulk densities can range from 0.2 to 0.6 g/cm^3 (Bulmer 2000; Bulmer et al. 2007) which is low compared to the range of 0.9 to 1.8 g/cm^3 for mineral soils (Naeth et al. 1991). Overall, mulches that would be common to the northern boreal forest have a high water holding capacity, high carbon to nitrogen ratio (C:N), low pH, and high total phenols (Table 1-1).

The properties of wood mulch itself can change when applied to soil and possibly explain changes observed to soil properties. Corns and Maynard (1998) found that total N increased within mulch residues for all 3 years after application. The authors attribute this to the loss of weight from decay but it could also be from N fixation in the chips or by nutrient accumulation into wood mediated by wood-decaying fungi (Boddy and Watkinson 1995; Laiho and Prescott 2004). Landhäusser et al. (2007) studied *Populus tremuloides* regeneration with collected leachate from 4 cm of *Populus tremuloides* mulch based on typical moisture levels for weekly rainfall rates in northern Alberta. After seven weeks, mulch significantly decreased in the concentrations of total soluble sugars (-3.7%), starch (-0.015%) and phenols (-1.9%) and increased in the concentrations of available nitrogen (+0.08%) (Landhäusser et al. 2007). One concern with using mulch is that toxic compounds or chemicals may leach in to the soil thereby impeding regeneration. Landhäusser et al. (2007) found that *Populus tremuloides* leachate consisted of high concentrations of phenols, soluble sugars, total nitrogen and ammonium at first but decreased two to three weeks after application. The leachate's pH significantly increased from 3.8 to 6.8 after seven weeks (Landhäusser et al. 2007). In BC, Venner et al. (2009) found that leachates from *Thuja plicata* Donn ex. D. Don (cedar) mulch did not have significant amounts of ammonium-N or nitrate-N. Furthermore, leachate from *Thuja plicata* mulch and forest floor materials from interior BC contained large amounts of phenols but sort-yard waste (mixture of soil, wood, bark, needles and other debris) had relatively low amounts of phenols (Venner et al. 2009). Forest floor materials, *Thuja plicata* mulch and sort-yard waste had non-detectable amount of tannins in their leachates (Venner et al. 2009).

8. WOOD MULCH IMPACTS ON SOIL PROPERTIES

Wood mulch usually decreased bulk density, even when added on top of soil, associated with the addition of organic matter form the mulch itself or organic matter from decomposition (Himelick and Watson 1990; Bulmer et al. 2007). It often decreased the temperature of soil beneath it (Larsson and Båth 1996; Iles and Dosmann 1999; Bulmer 2000; Bulmer et al 2007; McConkey et al. 2012). This was due to mulch insulating soil from solar radiation (Ashworth and Harrison 1983; Montague et al. 1998; Iles and Dosmann 1999) by delaying heat transfer to the soil from the low thermal conductivity of air pockets in mulch (Wooldridge and Harris 1991; Larsson and Båth 1996). Soil moisture increased under mulch (Larsson and Båth 1996; Iles and

Dosmann 1999) due to reduced evaporation (Himelick and Watson 1990; Maggard et al. 2012) and transpiration (Maggard et al. 2012).

The addition of wood mulch to soil has shown varying and inconsistent effects to soil chemical properties depending on the species of tree the mulch was made from and the soil type. Soil pH increased (Iles and Dosmann 1999; Maggard 2012) or decreased (Himelick and Watson 1990; Landhäusser et al. 2007; Maggard 2012). Some studies found differences to carbon, nitrogen, or C:N but not all (Corns and Maynard 1998; Bulmer 2000; Sandborn et al. 2004; Bulmer et al. 2007; Landhäusser et al. 2007; Maggard et al. 2012; McConkey et al. 2012). Most studies found little to no differences in other nutrients such as phosphorous, sulfur, potassium, calcium (Corns and Maynard 1998; Bulmer et al. 2007; McConkey et al. 2012). Landhäusser et al. (2007) indicates that higher amounts of total phenols have been found in soil under *Populus tremuloides* mulch consistent with high total phenols in leachate. Condensed tannins (a non-hydrolyzable polyphenol) were not detected in detectable amounts in leachates or soil (Venner 2009). Venner (2009) indicates that the low condensed tannin levels are likely due to condensed tannins have low solubility in cold water.

9. RESEARCH OBJECTIVES AND THESIS ORGANIZATION

The main objective of this research was to examine alterations in soil properties that may be associated with slow regeneration of boreal forest species on coarse-textured soils from OSE disturbance. *Populus tremuloides* was used as the indicator boreal forest species as it was the most common trees species on our study sites.

Chapter 2 compares undisturbed and disturbed coarse-textured soils on OSE sites, some at different depths, to determine changes in soil properties. For the purpose of this thesis, OSE disturbance is defined as after sites have been drilled, recontoured, and reclaimed (topsoil replaced, mulch applied, and waiting for natural regeneration or tree planting). Undisturbed is defined as areas not affected by OSE disturbance. Specific research objectives were as follows:

- determine if OSE disturbance affects soil physical, hydrological, and chemical properties that could result in poor forest regeneration; in particular, if it homogenizes the natural heterogeneous bedding in coarse-textured soils resulting in a decrease to plant available water; and,
- determine how the use of wood mulch amendments affect the temperature and nutrient availability of coarse-textured soils after OSE disturbance.

Chapter 3 compares different combinations of soil warming regime and wood mulch surface amendments to determine which combination results in the best *Populus tremuloides* seedling growth on coarse-textured soils. Soil warming regimes are based on spring soil warming trends observed from field studies collected under the wood mulch surface amendments in Chapter 2. Specific research objectives were as follows:

- determine if delayed soil warming affects *Populus tremuloides* seedling growth; and
- determine if a mulch amendment affects nutrient availability in coarse-textured soils and the performance of *Populus tremuloides*.

Table 1-1. Physical and chemical characteristics of mulch from previous studies

Wood chip amendment	WHC[d]	C:N	pH	Total C (g/kg)	Total N (g/kg)	Total P(g/kg)	Total K (g/kg)	Tannins (g/kg)	Total Phenols (g/kg)
Sort-yard waste[a]	-	160	5.7	213	1.3	-	-	0.6	4.2
Aspen[b]	262	410	4.9	481	1.3	0.23	1.4	0	5.1
Birch[b]	255	524	3.4	474	1	0.12	0.5	0.2	4.7
Cedar[c]	-	607	2.9	516	0.85	-	-	0	12
Douglas fir[b]	206	1226	3.7	470	0.4	0.15	0.3	0.1	6.3
Spruce[b]	239	1305	3.5	473	0.4	0.08	0.3	0	6.6

[a] mixture of soil, wood, bark, needles and other debris (Bulmer et al. 2007; Venner 2009)

[b] denotes average for all chip sizes in Venner et al. (2011)

[c] Venner et al. (2009)

[d] water-holding capacity

CHAPTER 2. EFFECTS OF OIL SANDS EXPLORATION DISTURBANCE ON COARSE-TEXTURED SOIL PROPERTIES

1. INTRODUCTION

Most of Alberta's oil sands resources (80%) in the boreal forest will be developed by in situ extraction methods (Government of Alberta 2014). As part of the development of these resources, approved projects will require many Oil Sands Exploration (OSE) sites to be drilled in order to evaluate those oil resources. OSE sites are most often less than 1 ha in size, prepared and drilled over the course of a month in the winter, and ready for reclamation the following spring. Forested sites are prepared for drilling by removing the vegetation on site by mulching, stripping off the organic and topsoil layers, and stockpiling the mulch and topsoil separately on site. Once drilling is complete, the site is reclaimed. Reclamation generally consists of recontouring the subsoil, replacing salvaged topsoil and applying wood mulch to the topsoil surface. These sites are left then to either naturally regenerate or are planted with native boreal tree species.

Forest regeneration on these sites has been slow, particularly on coarse-textured (sandy) soils, even when planted. Studies have shown that salvaging, stockpiling, or replacement practices alone can reduce seed density (Koch et al. 1996; Iverson and Wali 1982), seed viability (MacKenzie 2013), seed diversity (Iverson and Wali 1982), and propagule abundance (Mackenzie and Naeth 2010) in the salvaged topsoil material reducing plant species richness (Fair 2011) and density (Tacey and Glossop 1980; Rokich et al. 2000). Further, the soil texture type (fine or coarse) can produce differing severity of effects on plant regeneration after soil salvaging and replacement activities (Benvenuti 2003 and MacKenzie 2013). Coarse-textured soils in the Alberta Oil Sands Region are known to be low in organic matter, nutrient poor, and well to rapidly drained with a low water holding capacity (Turchenek and Lindsay 1982; Devon NEC Corporation [Devon] 2012). With low organic matter and low clay content, coarse-textured soils tend to have low cation exchange capacity and water holding capacity. This results in an increased leaching of nutrients from the soil and less available nutrients for plant growth. The low organic matter and clay content also makes coarse-textured soil susceptible to wind and water erosion (Alberta Agriculture 1985; Pedocan Land Evaluation Ltd. 1993). On xeric, nutrient poor, coarse-textured soils, *Pinus banksiana* Lamb. (jack pine) is most common with *Populus tremuloides* Michx. (aspen) being more common on mesic, nutrient medium, coarse-textured soils (Beckingham and Archibald 1996). As coarse-textured soils are already limiting in nutrient and water availability, changes to soil properties resulting from disturbances could have a significant impact on successful regeneration.

Coarse-textured soils are often deposited in layers by wind or moving water. This heterogeneous bedding or layering of sands can influence other soil properties. Sites with a similar coarse texture supported different plant communities and forest types (Zettl et al. 2011). Their study showed that though the average texture of the sites were the same, the textural variations in these layers throughout the depth of the soil profile was different. The presence of layering and textural heterogeneity was observed to increase field capacity and water storage. The disturbance of the bedding of these coarse-textured soils may be one of the reasons for the slow regeneration on coarse-textured sites and the ability to establish the species that were present before disturbance. As OSE construction involves the stripping, stockpiling, and replacement of topsoil and subsoil, homogenization of the soil occurs (i.e. mixing the soil resulting in similar particle size across the soil depth) potentially impacting plant available water (PAW).

The use of wood mulch during reclamation activities on OSE sites could also impact soil physical and chemical properties and soil conditions such as soil temperature, resulting in differences that may impact seedling establishment. In the presence of pine mulch, conifer-dominated forests in Iowa on sandy loam soils, soil temperatures were around 6˚C lower compared to bare soil (Iles and Dosmann 1999). In another example, spruce mulch significantly decreased weekly soil temperatures by 6˚C compared to bare soil at a site in Sweden (Larsson and Båth 1996). Further, in the boreal region of British Columbia, McConkey et al. (2012) found a decrease in soil temperature in June and July under mulch but results were variable when mulch was incorporated in to the soil. Wood mulch amendments are also composed of more recalcitrant, high lignin, compounds that can result in small but longer lasting soil effects (Larney and Angers 2012). In previous studies, different types of wood mulch have been shown to have effects on soil: pH (Himelick and Watson 1990, Iles and Dosmann 1999, Landhäusser et al. 2007); carbon and nitrogen concentrations (Corns and Maynard 1998, Sanborn et al. 2004, Landhäusser et al. 2007); and phenols (Landhäusser et al. 2007).

This research examines the changes to coarse-textured soil properties on OSE sites that may contribute to slow forest regeneration. In this study, coarse-textured soil properties at sites disturbed by OSE drilling in the Athabasca Oil Sands Region were compared to similar undisturbed sites. We compared these undisturbed and disturbed sites to address the following questions: 1) Does OSE disturbance affect coarse-textured soil physical, hydrological, and chemical properties that could result in poor forest regeneration? In particular, does disturbance homogenize the natural heterogeneous bedding in coarse-textured soils resulting in a decrease of plant available water? 2) Does the use of wood mulch on coarse-textured soils after OSE disturbance result in lower soil temperatures in the spring and lower nutrient availability for plants?

2. METHODS

2.1. STUDY AREA

This research was conducted on leases at Devon's Pike SAGD facility, 25 km southeast of Conklin, Alberta (55.6314˚ N, -111.0839˚ W). The area is located in the Central Mixedwood Natural Subregion of the Boreal Forest Natural Region of Alberta. The general climate in this region is characterized by very cold long winters and short warm summers (Natural Regions

Committee 2006). Conklin is located between Fort McMurray, Alberta and Cold Lake, Alberta. Fort McMurray has a mean annual temperature of 1.0°C with an average of 418 mm of precipitation (134 mm snowfall and 316.3 mm rainfall) and 97 frost free days (Government of Canada 2014). Cold Lake has an annual temperature of 2.1°C with an average of 421 mm of precipitation (129 mm snowfall and 319.2 mm rainfall) and 116 frost free days (Government of Canada 2014).

The Central Mixedwood Subregion is the largest natural subregion (44%) of the Boreal Forest Natural Region of Alberta (Natural Regions Committee 2006). Upland vegetation is a mix of *Populus tremuloides* deciduous, *Populus tremuloides-Picea glauca* (Moench) Voss (white spruce) mixedwood, and *Picea glauca* and *Pinus banksiana* coniferous forests. Sites with average moisture and nutrient regimes commonly consist of *Populus tremuloides* or *Populus tremuloides* - *Picea glauca* stands with *Viburnum edule* (Michx.) Raf. (low bush cranberry), *Rosa spp.* (rose), and *Alnus crispa* (Vill.) Lam.&DC. (green alder) understories. The area lies within the Mostoos Hills Upland physiographic region of the Eastern Alberta Plains (Pettapiece 1986). Topography of the area is level to hummocky (Wynnyk et al. 1963; Pettapiece1986). Parent materials in the area are generally morainal, coarse-textured morainal, and glaciofluvial veneer over morainal materials (Pettapiece 1986; Andriashek 2003). Sandy morainal deposits in the Mostoos Hills Uplands can contain up to 50% sand (Andriashek 2003). Organic deposits in this area are thin (<1 m) and discontinuous (Andriashek 2003). Luvisolic, brunisolic, and organic soils are common on morainal upland, coarse-textured upland, and poorly drained lowland material, respectively (Natural Regions Committee 2006).

2.2. INITIAL SITE SELECTON AND CHARACTERIZATION

Universal Transverse Mercator (UTM) coordinates for sites that were part of Devon's Pike OSE program were overlaid on surficial materials maps for the area (Andriashek 2002a, Andriashek 2002b). These sites were disturbed by OSE activities and 'OSE disturbance' is herein defined as OSE sites that have been drilled, recontoured, and reclaimed (topsoil replaced, wood mulch applied, and waiting for natural regeneration or tree planting). OSE sites that were located in upland morainal, sandy morainal, and glaciofluvial map units were selected for further review. Light detection and ranging (LiDAR) surficial maps for the selected sites were reviewed to further refine sites to locations that occurred on upland areas. May 27 to 29, 2013, locations were ground-truthed for sites occurring on coarse-textured soils (sand to sandy loam) and the overstory vegetation was characterized. A total of six sites occurred on coarse-textured soils and displayed similar *Populus tremuloides–Picea glauca* mixedwood overstory vegetation. These six sites were selected for further soil assessment and sampling.

2.3. SOIL ASSESSMENT AND SAMPLING

Soil was sampled on July 16 to 25, 2013 at each of the six sites. Sites were stratified into three sections based on different slope position that occurred on each site (crest, upper, mid, lower, or toe) to capture site variability. One pit was excavated in each stratification resulting in three soil pits (used as subsamples for each site) on each of the disturbed and undisturbed portions of the sites (a total of 6 pits per site). Areas where soil and vegetation were affected by OSE activities, i.e. vegetation clearing, soil disturbance, drilling, or reclamation, were considered to be “disturbed”. Areas adjacent to the disturbed sites that were not disturbed by OSE activities were considered “undisturbed”. Soil pit coordinates were recorded using a Garmin 62s hand held global positioning system (GPS). Soil pits were excavated using a shovel from surface to 50 cm (1 x 1 m) and a dutch auger from 50 to 100 cm. Soil pits were described according to the Canadian System of Soil Classification (Soil Classification Working Group 1998; Appendix A). Soil Series were assigned according to the Alberta Soil Names File for soil correlation area 20 (Bock et al. 2006).

Disturbed soil samples (approximately 500 to 1000 g) were collected from each pit face at depths of 0 to 15 cm (with no mixing of topsoil and subsoil), 15 to 30 cm, and 30 to 45 cm using a soil knife. If there was a change in parent geological material below 45 cm, additional soil samples were collected. Soil samples were placed in labelled plastic bags.

At all six sites, soil cores were collected from within each sampling interval at 5, 20, and 35 cm. A ledge on the side of the soil pit was excavated to facilitate the extraction of an undisturbed soil sample. PVC cores, 2 inch in diameter and 5 cm in length, were slowly pushed into the soil using a mallet. The force was dispersed as equally as possible by placing a wooden block on top of the core before using the mallet. The core was dug out of the soil using a flat putty knife large enough to cover the bottom of the core. Cores were lined and taped to limit disturbance to the core and loss of soil. Cores were refrigerated at 4°C prior to laboratory analysis.

Field assessments of soil repellency and unsaturated hydraulic conductivity (K_{unsat}), using Decagon's Mini Disk Infiltrometer were completed according to Robichaud et al. (2008) at a 1 cm depth (soil surface). Previous work has shown that the Mini Disk Infiltrometer was an effective method of measuring soil water repellency (Hunter 2011). One measurement was taken at each of the three soil pits, as well as two additional points on each of the undisturbed and disturbed portions of the site, for a total of five measurement points (subsamples) in each of the disturbed and undisturbed areas of each site. The amount of water, in millilitres, infiltrating in one minute was taken as the repellency value for each point. The amount of water infiltrating over two minutes (measured at 10 second intervals) was used to calculate K_{unsat}. Measurements were entered into an Excel spreadsheet with a calculation macro provided by Decagon (Decagon Devices Inc. 2013). The macro uses the cumulative infiltration measurements over time, default van Genuchten parameters of a given soil texture, to provide an estimate of K_{unsat} (Decagon Devices Inc. 2012).

2.4. LABORATORY ANALYSES

Field moisture content of the disturbed soil samples was assessed on a ~50 g subsample by the gravimetric method with oven-drying for 24 hours (Carter and Gregorich 2008). Bulk density was calculated using the method for mineral soils in Carter and Gregorich (2008) with an adaption for using the volume of the core (calculated using the length and diameter of the PVC core).

Particle size analysis (PSA) was completed on air-dried soil samples using a combination of sieves (sand fraction) and the hydrometer method (Carter and Gregorich 2008), allowing estimation of percentages of sand, silt, and clay as well as a detailed cumulative particle size distribution (PSD) curve. The proportion of particles less than diameters (% particles<d) of 2.0, 1.0, 0.5, 0.25, 0.105, 0.053, 0.02, 0.006, and 0.002 mm and its standard deviation were calculated for the undisturbed and disturbed portions of the sites. From the PSD curves, particle diameter of the 10th and 60th percentiles (D_{10} and D_{60}) were estimated using linear interpolation.

Air-dried soil samples were sent to Exova laboratory in Edmonton, Alberta for analyses of chemical parameters. Available ammonium (NH_4^+) and available nitrate (NO_3^-) were determined by extraction with 2.0 M KCl (Carter and Gregorich 2008). Hydrogen ion concentration (pH), electrical conductivity (EC), sodium adsorption ration (SAR), and soluble ions (calcium, magnesium, sodium, and potassium) were determined by extractions from saturated paste (Carter and Gregorich 2008). Total organic carbon (TOC), total nitrogen (TN), and carbon to nitrogen ratio (C:N) were determined using a modified Leco combustion (Sparks 1996). Laboratory values that were above detection for C:N were substituted for the limit value (e.g. >12.8 = 12.8). Laboratory values that were below detection for NO_3^-, TN, SAR, sodium, and potassium were substituted for the mid-point value between zero and the nominal detection limit (e.g. <0.5 = 0.025).

Moisture retention curves (desorption from saturation) were measured using pressure extraction method on the soil cores (Carter and Gregorich 2008). Saturated cores were equilibrated for 7 days at pressures of 2, 15, 50, and 100 kPa (0.2, 1.5, 50, 10.2 m of water). After each 7-day equilibration period, cores were removed and weighed. After equilibration at 100 kPa, the PVC, nylon cloth, and elastics were weighed. Soil cores were transferred to smaller ring cores and the procedures were repeated for pressures of 100 kPa (10.2 m), 300 kPa (30.6 m), 500 kPa (51.0 m), and 1500 kPa (153.0 m). Volumetric water content was determined for the core at each pressure to construct a moisture retention curve. Curves were fitted to the Van Genuchten model (1980) to obtain estimates of saturated water content (θ_s), residual water content (θ_r), alpha, and the slope of the curve (n). Field capacity (FC) of the soil was calculated at a pressure of 15 kPa and the wilting point (WP) of the soil was calculated at 1500 kPa. Plant available water (PAW) was calculated as the difference in volumetric water content between FC and WP.

2.5. SELECTION AND PREPARATION OF SITES FOR FIELD MEAUSREMENT OF SOIL TEMPERATURE AND NUTRIENT AVAILABILITY

Following PSA in the laboratory, three of the six sites with the most similar soil textures, profiles, and drainage classes were revisited. At each site, measurement plots were located near an undisturbed and disturbed soil pit location, where soil samples were taken previously, with similar texture, slope, and aspect.

On September 7 and 8, 2013, 2 x 2 m plots were established with the following soil treatments: 1) undisturbed, no mulch; 2) disturbed, no mulch; 3) disturbed, 10 cm of mulch as a layer on top of the soil surface; and 4) disturbed, 10 cm of mulch that was incorporated into the top 10 cm of the soil surface. Plots on each of the three sites were considered to be replicates (n=3). On each of the sites, soil pits were excavated in the centre of each of the treatment plots by shovel to a total depth of 40 cm. Decagon 5TM soil temperature and moisture probes were installed into the pit face at depths of 5 cm, 20 cm, and 35 cm below the soil surface in each pit.

Soil was replaced into the excavated pit subsoil first then topsoil. For the undisturbed, no mulch treatment, the LFH layer was kept intact and replaced on top of the topsoil. For the disturbed, no mulch treatment, the 2 x 2 m plot was cleared of any mulch (if mulch was present). For the disturbed, 10 cm of mulch as surface layer treatment, mulch from the site was collected and placed over the 2 x 2 m plot and evened out to a layer 10 cm thick by shovel. For the disturbed, 10 cm of incorporated mulch treatment, mulch from the site was collected and placed over the 2 x 2 m plot and evened out to a layer 10 cm thick by shovel. Mulch was incorporated into the top 10 cm of the soil by mixing with a shovel. Probes were attached to Em50 series data loggers that were attached to wooden posts approximately 20 cm above the ground surface. Data loggers were programmed to take hourly soil temperature (°C) readings. Data was collected from September 7, 2013 to September 26, 2014. Data was downloaded by laptop using ECH_2O Utility program.

The summer after plot establishment Plant Root Simulator (PRS™) probes supplied by Western Ag Innovation Inc. (Western Ag) of Saskatoon, Saskatchewan were installed in plots to estimate nutrient availability in soil between the different treatment plots. On July 3, 2014, two pairs of cationic and anionic probes were installed in opposite corners of each plot. Probes were installed, removed, cleaned and stored according to the laboratory provided procedures (Western Ag Innovations Inc. 2012). Probes were buried for a total of 34 days and removed August 6, 2014. Probes were shipped in the laboratory supplied styrofoam lined box with ice packs to Western Ag for desorption of ions off the resin membranes using 0.5 M hydrochloric acid and laboratory analysis. Both pairs of cationic and anionic probes were pooled to give one sample per plot. The eluate was colorimetrically quantified using a flow injection analyzer to determine ammonium ($prsNH_4^+$), nitrate ($prsNO_3^-$), and phosphate ($prsPO_4^{3-}$) supply rates. Total nitrogen (prsTN) was a calculated parameter from adding $prsNO_3^-$ and $prsNH_4^+$. Calcium (prsCa), magnesium (prsMg), potassium (prsK), iron (prsFe), manganese (prsMn), copper (prsCu), zinc (prsZn), boron (prsB), sulphur (prsS), lead (prsPb), aluminum (prsAl), and cadmium (prsCd) from the probes were quantified by coupled plasma spectroscopy. Supply rates are presented in (µg/10cm^2) for the 34 day period.

2.6. STUDY DESIGN AND DATA ANALYSES

Soil data collected from each of the three soil pits (disturbed and undisturbed) were considered to be subsamples for each of the six sites (n=6). The particle size distribution was compared to determine if OSE disturbance homogenizes the natural heterogeneous bedding of coarse-textured soil. Shapiro-Wilk's test was used to determine normality and a Folded F-test was used to determine the equality of variances. A t-test was performed on the % particles<d and its standard deviation to determine the effect of OSE disturbance on particle size distribution of coarse-textured soils at intervals of 0 to 15, 15 to 30, and 30 to 45 cm. Statistical analyses were performed using SAS 9.3 (SAS Institute Inc. 2012). Data for the following did not meet the assumption of normality: % of particles <d, for d=1.0, 0.5, and 0.25 mm (15 to 30 cm); standard deviation for d=0.25 and 0.105 mm (15 to 30 cm); and % of particles <d for d=0.105, 0.053, and 0.02 mm (30 to 45 cm). T-tests for the above parameters were completed on the untransformed data because the values were part of the particle size distribution curve at each depth. In order to confirm conclusions of significance were still valid for these parameters, Wilcoxon-Mann-Whitney two sample t-tests were completed with a two-sided t approximation to evaluate if the distribution of these parameters were drawn from the same populations.

The soil repellency and K_{unsat} field measurements were compared to determine if OSE disturbance affects other coarse-textured soil properties that may result in poor forest regeneration. Average soil repellency and K_{unsat} were calculated from the five subsamples for the undisturbed and disturbed portions for each of the six sites. Shapiro-Wilk's test was used to determine normality and a Folded F-test was used to determine the equality of variances. Soil repellency and K_{unsat} met the assumptions of normality and equality of variances. A t-test was performed on soil repellency values and K_{unsat} values to compare the effect of OSE disturbance on coarse-textured soils. Statistical analyses were performed using SAS 9.3 (SAS Institute Inc. 2012).

Soil hydrological and chemical parameters were compared to determine if OSE disturbance affects other coarse-textured soil properties that may result in poor forest regeneration. For each remaining soil hydrological parameters and all soil chemical parameters, data were analyzed using a 2 x 3 factorial (two disturbance regimes x three depths) block design. Each site was considered to be a random blocking factor. Soil subsamples from each site (n=6) were pooled at each depth for each soil parameter. Only a subsample (5 of the 6 sites) were analyzed for hydrological parameters so for soil hydrological parameters n=5. Shapiro-Wilk's test was used to determine normality and Levene's test was used to determine the equality of variances. The effects of OSE disturbance on coarse-textured soils at three depths (5, 15, and 25 cm) were tested using a two-way analysis of variance (ANOVA) when assumptions were met (sand, silt, very coarse sand, medium sand, θ_r, FC, PAW, pH, and C:N). For parameters (D_{60}, bulk density, clay, and n) that had a borderline significant Shapiro-Wilk's or Levene's tests ($0.05 \geq p \geq 0.03$), the residuals were examined to determine if an ANOVA, transformation, or permutation ANOVA was required. Two-way ANOVAs were completed for all four parameters. When assumptions of normality were not met, data were log-transformed and ANOVAs were completed on the transformed data (D_{10}, fine sand, WP, EC, and SAR). When multiple transformations failed for normality but variances were equal, a permutation ANOVA (pANOVA; Wheeler 2010) was completed (coarse sand , very fine sand, moisture content, θ_s, α, calcium, magnesium, sodium, potassium, TOC, TN, NH_4^+, and NO_3^-). Statistical analyses were performed using R version 2.15.3 (R Core Team 2013). Least square means were used to compare the effects on soil hydrological parameters as the data were unbalanced. When there were significant effects of disturbance, depth or disturbance x depth interaction, post hoc tests for difference between least square means was completed with a Tukey adjustment for multiple means.

Soil nutrient availability was compared to determine the difference in nutrient availability with wood mulch surface amendments. Chemistry data collected from the resin analysis of the PRS™ probes were analyzed using a complete block design (four treatments). Each site was considered to be a random blocking factor (n=3). Shapiro-Wilk's test was used to determine normality and Levene's test was used to determine the equality of variances. The effects of different soil treatments (undisturbed, disturbed with no mulch, 10 cm of mulch as a layer on top of the soil surface, and 10 cm of mulch that was incorporated into the top 10 cm of the soil surface) were tested using an one-way analysis of variance (ANOVA) when assumptions were met (prsNH_4^+, prsCa, prsMg, prsK, prsPO_4^{3-}, prsFe, prsMn, prsZn, prsS, and prsAl). When assumptions of normality were not met, and multiple transformations failed, a pANOVA (Wheeler 2010) was completed (prsTN, prsNO^{3-}, prsCu, and prsB). Parameters prsPb and prsCd were not compared statistically as supply rates for all treatments were 0 (µg/10cm^2) for the 34 day burial length.

An α-value of ≤0.05 was used to determine significance for all statistical tests. Results for all statistical analyses are presented in Appendix B. Significant effects discussed in the results are in reference to statistical significance (α ≤0.05). Any effects discussed in the results that are not statistically significant but could have some biological significance are designated by "notably but not significantly" and the associated p-value is presented.

To determine soil temperature patterns with wood mulch surface amendments, temperature measurements were collected from the soil treatment plots of the three sites described in Section 2.5 (undisturbed not included). Hourly measurements were averaged to provide daily values for each site and treatment combination. These values were pooled across sites to provide one weekly value for each treatment at 5 cm, 20 cm, and 35 cm depths. Data collected from September 7 to 20, 2013 were not included to allow for the sensors to equilibrate with current soil conditions. As plots were established to identify soil warming patterns, statistical analyses were not performed on the weekly temperatures; data were compared qualitatively.

3. RESULTS

3.1. SOIL PHYSICAL PROPERTIES

At all three soil depths, there was no significant effect of disturbance on mean proportions of soil particles in each size class, but the across-site variability in many size classes was smaller in the disturbed soil compared to the undisturbed soil (Figure 2-1). At 0 to 15 cm, there was no significant effect of disturbance on the mean % particles with diameters ≤ 1.0, 0.5, 0.25, 0.105, 0.053, 0.02, 0.006, and 0.002 mm. Disturbed soils, however, had lower standard deviations for % particles with diameters ≤ 0.5 (P=0.009), 0.25 (P=0.002), 0.105 (P=0.009), and 0.053 mm (P=0.006) and notably but not significantly smaller at 0.02 mm (P=0.084) than undisturbed soils. There was no significant effect of disturbance on the standard deviations of % particles with diameters ≤ 1.0, 0.006, and 0.002 mm. At 15 to 30 cm, there was no significant effect of disturbance on the mean % particles with diameters ≤ 1.0, 0.5, 0.25, 0.105, 0.053, 0.02, 0.006, and 0.002 mm. Again, however, disturbed soils had lower standard deviations of % particles with diameters ≤ 1.0 (P=0.005), 0.5 (P=0.039), 0.105 (P=0.002), 0.053 (P=0.004), 0.02 (P=0.004), 0.006 (P=0.017), and 0.002 (P=0.031) and notably but not significantly smaller at 0.25 mm (P=0.076). At 30 to 45 cm, there was no significant effect of OSE disturbance on the mean % particles with diameters ≤ 1.0, 0.5, 0.25, 0.105, 0.053, 0.02, 0.006, and 0.002 mm. Disturbed soils had lower standard deviations of % particles ≤ 0.105 (P=0.006), 0.053 (P=0.002), and 0.02 mm (P=0.010) and notably but not significantly at 0.25 (P=0.054) and 0.006 mm (P=0.061). There was no significant effect of disturbance on the standard deviations of % particles ≤ 1.0, 0.5, and 0.002 mm.

Though, there was no significant effect of disturbance on overall sand content, there was a significant effect of disturbance on very coarse sand (P=0.015) and fine sand fractions averaged over all depths (P=0.022). The very coarse sand fraction decreased 0.31% with disturbance and fine sand increased 2.45% with disturbance (Table 2-1). There was no significant effect of disturbance or depth on any other sand fractions. Disturbed soil had 2.6% less silt than undisturbed soil (P=0.043; Table 2-1). There was no significant effect of disturbance on clay content but there was a significant effect of depth on clay content. Clay content increased with increasing depth (Table 2-2). There was a notable but not significant interaction between depth and disturbance on clay content (P=0.052).

There was a significant effect of disturbance on the D_{10} or effective particle diameter associated with the 10th percentile of the PSD (P=0.001). Disturbed soil was three times smaller (Table 2-1) than undisturbed soil. There was no significant effect of disturbance or depth on the D_{60} or typical size. The mean D_{10} size for undisturbed soil was 0.017 mm or very fine sand compared to the D_{10} of 0.0051 mm or silt for disturbed soil.

Disturbance (P<0.001), depth (P<0.001), and their interaction (P=0.014) significantly affected bulk density of the soil. Disturbed soil had generally higher bulk densities than undisturbed soil which also increased with increasing depth below the ground surface (Figure 2-2). Disturbed soil had an average bulk density 0.17 g/cm^3 (14 to 15%) higher than undisturbed soil at 15 to 30 cm and 30 to 45 cm.

3.2. SOIL HYDROLOGICAL PROPERTIES

There was no significant effect of disturbance on soil repellency or K_{unsat}. There was a significant effect of depth (P<0.001) but not disturbance (P=0.129) on the Van Genuchten parameter θ_s. θ_s was 0.09 and 0.11 cm^3/cm^3 higher at 0 to 15 cm than at 15 to 30 cm and 30 to 45 cm, respectively (Table 2-2). There was no significant effect of disturbance or depth on moisture content or the other Van Genuchten parameters (alpha, n, or θ_r). The FC (P=0.007) and WP (P=0.002) increased 5.13% and 3.90%, respectively, with disturbance (Figure 2-3) but there was no significant effect of depth. There was no significant effect of disturbance or depth on PAW (Figure 2-3).

3.3. SOIL CHEMICAL PROPERTIES

There was a significant effect of disturbance ($P<0.001$) on pH. Disturbed soil was higher than undisturbed soil by 1.42 pH units. There was a significant effect of disturbance ($P<0.001$) and depth ($P=0.004$) on EC but not their interaction ($P=0.881$). The EC of disturbed soil was 2.3 times higher than undisturbed soil (Table 2-1). EC values decreased with increasing depth below ground surface (Table 2-2).

There was a significant effect of disturbance ($P<0.001$) and depth ($P<0.001$) on SAR but not their interaction ($P=0.695$). The SAR of disturbed soil was 0.6 times smaller than undisturbed soil (Table 2-1). As there was no significant effect of disturbance on sodium or magnesium, the decrease in SAR can be generally attributed to the 2.0 times higher concentration of calcium ($P=0.039$; Table 2-1). SAR values increased with increasing depth below ground surface (Table 2-2). As there was no significant effect of depth on sodium, this can be generally attributed to the decreases in calcium ($P=0.049$) and magnesium ($P=0.032$) with increasing depth below ground surface (Table 2-2).

There was a significant effect of disturbance ($P=0.009$) and depth ($P<0.001$) on potassium but not their interaction ($P=0.708$). The potassium concentration in disturbed soil was 1.5 times higher than undisturbed soil (Table 2-1). The potassium concentration decreased by 2.5 times and 1.4 times with each respective 15 cm increase in depth below ground surface (Table 2-2).

There was a significant effect of disturbance ($P=0.001$) and depth ($P<0.001$) on C:N but not their interaction ($P=0.981$). The C:N of disturbed soil was 3.0 units higher than undisturbed soil. Though the increase of C:N with disturbance was significant, differences in TOC, TN, and NH_4^+ were not. There was a significant effect of disturbance on NO_3^- ($P=0.040$). The NO_3^-

concentration of disturbed soil was 2.5 times higher than undisturbed soil (Table 2-1). C:N decreased with increasing depth below ground surface (Table 2-2). This was attributed to decreases in TOC ($P<0.001$) and TN ($P=0.014$) with increasing depth below ground surface (Table 2-2). There was no significant effect of depth on NH_4^+ or NO_3^+.

3.4. SOIL TREATMENT PLOTS

There was a significant effect of soil treatments on the plant nutrient availability of ammonium, manganese, magnesium and calcium from the PRS™ probes. The availability of ammonium ($P<0.001$) in undisturbed soil was at least 3.4 times higher than disturbed (Figure 2-4a). There was no difference in ammonium availability between disturbed soil treatments (no mulch, 10 cm of mulch, or 10 cm of mulch incorporated; Figure 2-4a). The availability of manganese ($P=0.046$) in undisturbed soil was at least 2 .0 times higher than disturbed (Figure 2-4b). The manganese availability of disturbed soil with no mulch was notably but not significantly lower ($P=0.095$) than the undisturbed soil and there was no difference between disturbed soil treatments (Figure 2-4b). The availability of magnesium ($P<0.001$) in undisturbed soil was at least 2.9 times lower than disturbed (Figure 2-4c). The magnesium availability of the 10 cm mulch treatment was the highest and there was no difference between the two mulch treatments (Figure 2-4c). The magnesium availability of the disturbed soil with no mulch was 1.4 times lower than the 10 cm mulch treatment (Figure 2-4c). The availability of calcium ($P=0.043$) in undisturbed soil was at least 4.6 lower than disturbed (Figure 2-4d). There was no difference in calcium availability between disturbed soil treatments (Figure 2-4d). There was no significant effect of soil treatments on the plant nutrient availability of all other chemical parameters analysed.

Average weekly soil temperatures showed similar patterns at 5, 20, and 35 cm (Figure 2-5). At 5 cm, soil temperatures in both mulch treatments were approximately 1°C warmer than the no mulch treatment from September until January. All three treatments were around the same soil temperature from January until mid-April. There was a two-week lag observed between the no mulch treatment and both mulching treatments with respect to the date where soil temperature warmed above 1°C. From frozen conditions, the no mulch treatment took approximately 6 weeks (mid-May) to warm to a soil temperature of 12°C or above. Both mulch treatments took approximately 10 weeks (mid-June) to warm to a soil temperature of 12°C or above. From May to mid-August, the no mulch treatment had a soil temperature 2 to 3°C higher than both mulch treatments. The mulch treatments had soil temperatures that were similar with mulch incorporated having a slightly (0.2 to 0.5°C) higher soil temperature from June to August. The soil temperatures at 20 and 35 cm showed a similar pattern but the magnitudes of the differences were smaller.

4. DISCUSSION

4.1. SOIL PHYSICAL PROPERTIES

OSE disturbance homogenized the natural heterogeneous bedding of coarse-textured soils. The lower variability of the particle size distribution in disturbed soils suggests that the natural layering of the soil has been homogenized by OSE disturbance mixing the soil. This homogenization of the soil may have the ability to impact OSE forest regeneration and productivity, similar to the observed homogeneous soil profiles associated with lower productivity ecosites in Zettl et al. (2011).

Slightly more silt and clay, but not significant amounts, were observed in the 30 to 45 cm depths of undisturbed soil compared to disturbed. OSE disturbance is likely redistributing the finer soil at 30 to 45 cm from 0 to 45 cm in disturbed soil resulting in the smaller D_{10} value. Decreased D_{10} value may indicate possible impacts to OSE forest regeneration and productivity as it could indicate a decrease in permeability or hydraulic conductivity of the soil (Hazen 1892).

Compaction can reduce air-filled porosity, macropores, and soil aeration (Herbauts et al. 1996; Startsev and McNabb 2001; Teepe et al 2004; Startsev and McNabb 2009; Ampoorter

2007), increase soil strength (Ampoorter et al. 2007), and promote runoff and soil erosion by reducing saturated hydraulic conductivity and infiltration (De Vries 1983 as cited in Standish et al. 1988). However, with a maximum observed bulk density of 1.48 g/cm^3 soil aeration would be greater than the 10% considered to be limiting (Ampoorter et al. 2007) and below the 1.8 g/cm^3 bulk density value considered limiting for root growth of a sandy soil (Jones 1983; United States Department of Agriculture 2001). Further, unsaturated hydraulic conductivity was not affected by disturbance indicating that compaction did not affect macropores.

4.2. SOIL HYDROLOGICAL PROPERTIES

An increasing amount of studies are observing water repellency effects due to disturbance of not only coarse-textured soils but finer textured soils as well (Debano 2000; Dekker et al. 2005). This study showed no disturbance effects on water repellency or hydraulic conductivity measurements of surface soil. This was consistent with water repellency findings from reclaimed sites in surface mining areas of the Alberta Oil Sands Region (Hunter 2011). However, only the surface of the soil was measured in this study. Oostindie et al. (2008) observed areas where a thin layer at the surface was not repellant but lower layers varied from not repellant to extremely repellant.

Contrary to the hypothesis, the homogenization of the soil increased field capacity and wilting point in similar magnitudes resulting in no change to PAW. Zettl et al. (2011), however, found that increased heterogeneity in particle size distributions were associated with higher field capacity and water storage and Huang et al. (2011) indicated that homogenization could decrease PAW and forest productivity. The difference in results possibly came from two sources. First, Zettl et al. (2011) concluded that the wilting point would not be critical for calculations of PAW in the undisturbed sites they compared because it would be the same reference point. This study observed an increase of almost 4 % to the wilting point value following disturbance. Second, the smaller D_{10} value with disturbance observed in this study (representing an increase in smaller particles following disturbance) could indicate reduced pore sizes and possibly explain the observed increases in field capacity and wilting point. The D_{10} value is often called the effective diameter as the smaller particles have a greater influence on pore sizes (Mahmoodlu et al. 2016). Mahmoodlu et al. (2016) determined that pore size distribution was affected more by mixing of the sand compared to compaction. This may be important for forest regeneration on Alberta's OSE sites as both mixing and compaction of the soil was observed during this study.

4.3. SOIL CHEMICAL PROPERTIES

The increase in pH after disturbance has also been observed in other studies comparing disturbances for forestry or oil and gas reclamation to undisturbed sites (Archibold et al. 2000; Belleau et al. 2006; McConkey et al 2012). Many studies show varying effects of disturbance on soil pH when compared to bare soil that has also been disturbed (Himelick and Watson 1990; Iles and Dosmann 1999; Landhäusser et al. 2007; Maggard et al. 2012). As mulch, largely consisting of *Populous tremuloides* (4.80 to 5.07; Venner et al. [2011]) with some *Picea glauca* (pH of 4.6 to 6.1; Venner et al. [2011]) is present over the sites in this study, it is likely that pH would decrease over time. The effects on soil pH will likely vary depending on pH of the mulch and the initial pH of the soil (Maggard et al. 2012). The changes in pH could affect forest regeneration by changing nutrient availability (Marschner 1986). The low clay content of coarse-textured soils indicate that these sites would have reduced buffering capacity (Howat 2000) and could be subject to large fluctuations in soil pH conditions and nutrient availability. However, the disturbed soil pH value of 6.80 is within the optimal range (6 to 8.5) in Alberta (Alberta Environment and Parks 2016) or (6 to 8) in Canada (Canadian Council of Ministers of the Environment 1991) as not to impact vegetation growth and other receptors

The increase in EC is not expected to limit regeneration as the observed EC of 0.30 dS/m from disturbance is below the 2.0 dS/m considered limiting for salt sensitive species

(Alberta Environment 2001). Similar to EC, the disturbed SAR value of 0.11 is within the optimal values of 4 for soil structure (Alberta Environment 2001). The decreased SAR value at in disturbed sites is a result of the observed increase in soluble calcium on disturbed sites. Belleau et al. (2006) also found an increase in extractable calcium after harvesting which was linked to the amount of slash left on the ground. Increased calcium concentrations were observed during the decomposition of coarse woody debris (Laiho and Prescott 2004; Belleau et al. 2006) and calcium lost from decaying logs (Krankina et al 1999). Mulch on the disturbed sites for this study could be providing similar conditions as the slash left on the ground and decaying wood. The increased soluble calcium with disturbance is not expected to contribute to poor regeneration. In *Populus tremuloides*, growth is better with increased calcium concentrations and would be a growth limiting deficiency if too low (Lu and Sucoff 2001; Frey et al. 2003). Similar to calcium, the increased potassium with disturbance is not expected to limit OSE forest regeneration. Leachate from mulch was likely the source of the increased potassium observed in disturbed sites similar to observations in Kuehne et al. (2008) and Brown (2010).

The C:N ratio value of 15 with disturbance is below the common value of around 20 (Brady and Weil 2008) and 25 where there is competition between microbes and roots for nitrogen (Bollen and Glennie 1961) causing ammonium and nitrate immobilization (Land Resources Network 1993). Therefore, the increase in C:N and available nitrate is unlikely to result in poor forest regeneration on OSE sites. However, other studies have observed lower available or total nitrogen concentrations in soil with mulch (Corns and Maynard 1998; Sandborn et al. 2004; Landhäusser et al. 2007). It is possible that the C:N ratio could increase over time to the limiting value and cause a nitrogen immobilization in the future.

4.4. SOIL TREATMENT PLOTS

An effect of disturbance was observed when measured by PRS™ probes but not when measured from the disturbed soil samples. The difference could be from using different methods of soil extraction versus PRS probes to measure available ammonium. The lower plant available manganese with disturbance could be due to an interaction with soil pH. Sims and Patrick (1978) and Sims (1986) observed that as pH increased, concentrations of soluble or exchangeable manganese decreased and concentrations of less available manganese oxides increased. The higher plant available magnesium with disturbance was likely from the decomposition of woody debris (Laiho and Prescott 2004; Belleau et al. 2006) even though the no mulch treatment had increased magnesium in the plots. This could be due to the site being covered with mulch prior to the plots being established. The higher plant available calcium with disturbance was consistent with the findings in Section 4.3. Higher calcium concentrations after disturbance was likely from the decomposition of woody debris (Laiho and Prescott 2004; Belleau et al. 2006) even though the no mulch treatment had increased calcium in the plots. This could possibly be due to the site being covered with mulch prior to the plots being established.

The mulch treatments took 2 weeks longer to reach 1˚C and 4 weeks longer in the spring to reach a soil temperature of above 12˚C, a critical temperature for *Populus tremuloides* sucker initiation (Fraser et al. 2002; Frey et al. 2003), compared to bare soil. Through the growing season, bare soil was 2 to 3˚C warmer than the mulch treatments, consistent with other studies where bare soil was up to 6˚C warmer (Larsson and Båth 1996; Iles and Dosmann 1999; Bulmer 2000; Maggard et al. 2012). Mulch has more air pockets than soil and because air has a lower thermal conductivity when compared to water, it results in decreased heat transfer to mineral soil (Wooldridge and Harris 1991; Larsson and Båth 1996). In this study, mulch treatments were warmer than bare soil from September to January, consistent with Larsson and Båth (1996). These weekly soil temperature patterns are resulting from mulch acting insulation and absorbing solar radiation (Ashworth and Harrison 1983; Montague et al. 1998; Iles and Dosmann 1999).

The decrease of soil temperature associated with mulch can affect forest regeneration on Alberta's OSE sites. In Corns and Maynard (1998), cooler soil temperatures with 10 cm of mulch have been shown to decrease forb cover and *Populus tremuloides* density; however, the decreased in *Populus tremuloides* density did not last after the first year after harvest. In contrast to Corns and Maynard (1998), Landhäusser et al. (2007) found that a 4 cm layer of *Populus tremuloides* mulch decreased *Populus tremuloides* sucker emergence and delayed emergence of suckers by one week compared to bare soil or leachate treated. Since there was no difference in emergence between leachate treated and bare soil, this implies that the decrease in emergence is due to a physical barrier and not due to toxic compounds (Landhäusser et al. 2007). Delong et al. (1997) also found reduced *Picea glauca* establishment possibly due to physical barriers from litter or decreased temperature. This physical barrier is likely a combination of cool temperatures below 9 to 12˚C needed for *Populus tremuloides* sucker initiation and growth (Fraser et al. 2002; Frey et al. 2003; Landhäusser et al. 2006), the dark environment formed by the mulch not allowing suckers to photosynthesize (Renkema et al. 2009) and that *Populus tremuloides* suckers do not bend easily around the structure of the mulch (Landhäusser et al. 2007). It has been suggested that the cooler temperatures would result in frozen soils in the spring (Vinge and Pyper 2012) causing problems with regeneration. However, Larsson and Båth (1996) showed that the soil would be warmer into the fall and Bulmer et al. (2007) indicates that growing season days would be the same with or without mulch because the "lost" days in the spring from cooler temperatures would be offset by the "added" days from warmer temperatures in the fall. Studies to date have shown varying impacts of mulch on growth performance with different species (Bulmer et al. 2007; McConkey et al. 2012).

5. CONCLUSIONS

Comparing undisturbed and disturbed sites indicated that OSE disturbance affected soil physical, hydrological and chemical properties. OSE disturbance homogenized the natural heterogeneous bedding in coarse-textured soils. Though OSE disturbance homogenized the soil, this did not result in reduced PAW. Field capacity and wilting point both increased in magnitude such that PAW was the same. Of the soil properties evaluated in this study, soil homogenization, pore size distribution as indicated by the changes to D_{10}, and soil temperature are most likely to result in poor forest regeneration on coarse-textured OSE sites. The use of wood mulch on coarse-textured soils after OSE disturbance did result in cooler soil temperatures in the spring (delayed warming) and decreased the availability ammonium to plants and should be investigated further. On an operational scale, options to reduce soil homogenization on coarse-textured OSE sites in Alberta’s boreal forest should be evaluated.

Table 2-1. Mean and standard error (SE) of soil physical (n=6), hydrological (n=5), and chemical (n=6) properties for the effect of OSE disturbance. Different letters indicate statistical significance (α=0.05) between undisturbed and disturbed soil.

	Undisturbed				Disturbed			
Soil Property	Mean		+ SE	-SE	Mean		+ SE	-SE
Very coarse sand (%)	1.83	**a**	0.16	0.16	1.52	**b**	0.16	0.16
Coarse sand (%)	7.99	**a**	0.68	0.68	7.78	**a**	0.68	0.68
Medium sand (%)	25.71	**a**	2.28	2.28	26.38	**a**	2.28	2.28
Fine sand (%)	29.97	**b**	1.10	1.06	32.42	**a**	1.19	1.14
Very fine sand (%)	8.31	**a**	1.27	1.27	8.12	**a**	1.27	1.27
Sand (%)	75.02	**a**	2.31	2.31	77.78	**a**	2.31	2.31
Silt (%)	16.16	**a**	1.24	1.24	13.50	**b**	1.24	1.24
Clay (%)	8.64	**a**	1.28	1.28	8.73	**a**	1.28	1.28
D_{10} (mm)	1.7E^{-02}	**a**	5.06E^{-03}	3.92E^{-03}	5.1E^{-03}	**b**	1.63E^{-03}	1.27E^{-03}
D_{60} (mm)	0.23	**a**	0.02	0.02	0.23	**a**	0.02	0.02
Repellency (mL/min)	7.42	**a**	0.80	0.80	6.50	**a**	1.14	1.14
K_{unsat} (cm/s)	1.70E^{-03}	**a**	2.10E^{-04}	2.10E^{-04}	1.17E^{-03}	**a**	3.50E^{-04}	3.50E^{-04}
θ_s (cm^3/cm^3)	0.44	**a**	0.02	0.02	0.41	**a**	0.02	0.02
θ_r (cm^3/cm^3)	0.02	**a**	0.01	0.01	0.04	**a**	0.01	0.01
alpha (cm^{-1})	0.18	**a**	0.05	0.05	0.20	**a**	0.05	0.05
n (-)	1.45	**a**	0.05	0.05	1.36	**a**	0.05	0.05
Moisture content (%)	15.28	**a**	3.55	3.55	14.93	**a**	3.55	3.55
pH (-)	5.38	**b**	0.14	0.14	6.80	**a**	0.14	0.14
EC (dS/m)	0.13	**b**	0.01	0.01	0.30	**a**	0.03	0.03
SAR (-)	0.20	**a**	0.03	0.03	0.11	**b**	0.02	0.02
Ca (mg/kg)	10.71	**b**	3.93	3.93	21.17	**a**	3.93	3.93
Mg (mg/kg)	3.39	**a**	1.14	1.14	5.13	**a**	1.14	1.14
Na (mg/kg)	1.31	**a**	0.36	0.36	1.21	**a**	0.36	0.36
K (mg/kg)	1.85	**b**	0.35	0.35	2.82	**a**	0.35	0.35
TOC (%)	0.68	**a**	0.16	0.16	0.83	**a**	0.16	0.16
TN (%)	0.05	**a**	0.01	0.01	0.05	**a**	0.01	0.01
C:N (-)	12.21	**b**	0.64	0.64	15.17	**a**	0.64	0.64
Available NO_3^- (ug/g)	0.26	**b**	0.15	0.15	0.64	**a**	0.15	0.15
Available NH_4^+ (ug/g)	2.00	**a**	0.44	0.44	2.26	**a**	0.44	0.44

Table 2-2. Mean and standard error (SE) of soil physical (n=6), hydrological (n=5), and chemical (n=6) properties for the effect of depth. Different letters indicate statistical significance (α=0.05) between the depths of 0 to 15, 15 to 30, and 30 to 45 cm.

	0 to 15 (cm)				15 to 30 (cm)				30 to 45 (cm)			
Soil Property	Mean		+ SE	-SE	Mean		+ SE	-SE	Mean		+ SE	-SE
Very coarse sand (%)	1.73	**a**	0.17	0.17	1.63	**a**	0.17	0.17	1.66	**a**	0.17	0.17
Coarse sand (%)	8.47	**a**	0.73	0.73	7.72	**a**	0.73	0.73	7.46	**a**	0.73	0.73
Medium sand (%)	27.25	**a**	2.38	2.38	25.86	**a**	2.38	2.38	25.02	**a**	2.38	2.38
Fine sand (%)	31.71	**a**	1.27	1.22	31.26	**a**	1.25	1.21	30.55	**a**	1.23	1.18
Very fine sand (%)	8.78	**a**	1.30	1.30	8.05	**a**	1.30	1.30	7.81	**a**	1.30	1.30
Sand (%)	78.19	**a**	2.57	2.57	76.24	**a**	2.57	2.57	75.02	**a**	2.57	2.57
Silt (%)	15.36	**a**	1.39	1.39	14.74	**a**	1.39	1.39	14.39	**a**	1.39	1.39
Clay (%)	6.45	**b**	1.40	1.40	9.00	**ab**	1.40	1.40	10.50	**a**	1.40	1.40
D10 (mm)	0.01	**a**	4.09E^{-03}	3.06E^{-03}	0.01	**a**	4.29E^{-03}	3.16E^{-03}	0.01	**a**	2.38E^{-03}	1.78E^{-03}
D60 (mm)	0.24	**a**	0.02	0.02	0.23	**a**	0.02	0.02	0.22	**a**	0.02	0.02
θ_s (cm^3/cm^3)	0.49	**a**	0.02	0.02	0.40	**b**	0.02	0.02	0.38	**b**	0.02	0.02
θ_r (cm^3/cm^3)	0.03	**a**	0.01	0.01	0.04	**a**	0.01	0.01	0.03	**a**	0.01	0.01
alpha (cm^{-1})	0.24	**a**	0.05	0.05	0.14	**a**	0.05	0.05	0.19	**a**	0.05	0.05
n (-)	1.35	**a**	0.06	0.06	1.41	**a**	0.06	0.06	1.46	**a**	0.06	0.06
Moisture content (%)	17.21	**a**	3.86	3.86	15.35	**a**	3.86	3.86	12.78	**a**	3.86	3.86
pH (-)	5.98	**a**	0.17	0.17	6.15	**a**	0.17	0.17	6.16	**a**	0.17	0.17
EC (dS/m)	0.29	**a**	0.04	0.03	0.18	**b**	0.02	0.02	0.15	**b**	0.02	0.02
SAR (-)	0.10	**b**	0.02	0.02	0.17	**a**	0.03	0.03	0.20	**a**	0.04	0.03
Ca (mg/kg)	25.49	**a**	4.73	4.73	12.83	**ab**	4.73	4.73	9.50	**b**	4.73	4.73
Mg (mg/kg)	6.92	**a**	1.36	1.36	3.32	**ab**	1.36	1.36	2.54	**b**	1.36	1.36
Na (mg/kg)	1.26	**a**	0.39	0.39	1.28	**a**	0.39	0.39	1.24	**a**	0.39	0.39
K (mg/kg)	4.14	**a**	0.39	0.39	1.68	**b**	0.39	0.39	1.19	**b**	0.39	0.39
TOC	1.28	**a**	0.18	0.18	0.57	**b**	0.18	0.18	0.43	**b**	0.18	0.18
TN	0.07	**a**	0.01	0.01	0.04	**ab**	0.01	0.01	0.03	**b**	0.01	0.01
C:N	17.58	**a**	0.76	0.76	12.39	**b**	0.76	0.76	11.10	**b**	0.76	0.76
Available NO_3^- (ug/g)	0.48	**a**	0.18	0.18	0.37	**a**	0.18	0.18	0.48	**a**	0.18	0.18
Available NH_4^+ (ug/g)	2.15	**a**	0.51	0.51	2.09	**a**	0.51	0.51	2.15	**a**	0.51	0.51

Figure 2-1. Particle size distribution curves at depths of 0 to 15 cm (a), 15 to 30 cm (b), and 30 to 45 cm (c) for undisturbed and disturbed OSE sites. Error bars represent one standard deviation of the mean (n=6) and asterisks indicate statistically significant difference between disturbed and undisturbed sites (α=0.05) of the standard deviation of the size fraction.

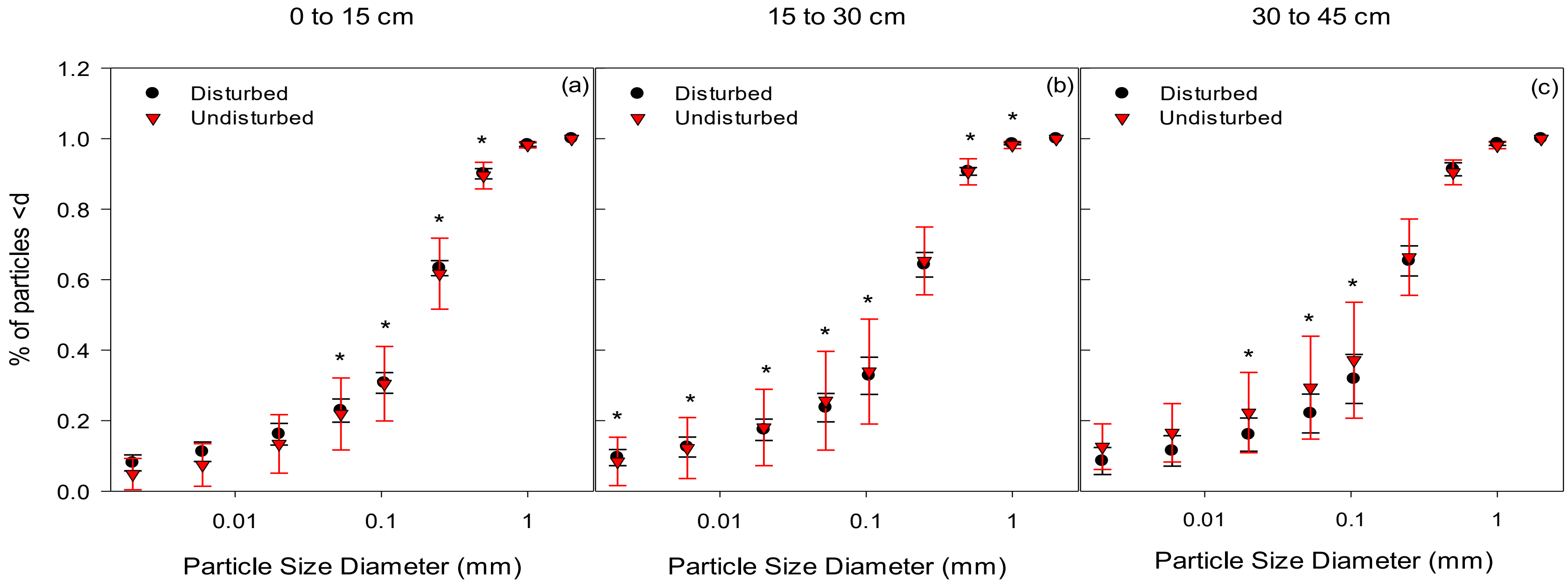


Figure 2-2. Bulk density in soils samples collected from undisturbed and disturbed OSE sites at depth of 0 to 15 cm, 15 to 30 cm, and 30 to 45 cm. Error bars represent one standard error of the mean and different letters indicate statistical significance (α=0.05) between the means (n=6).

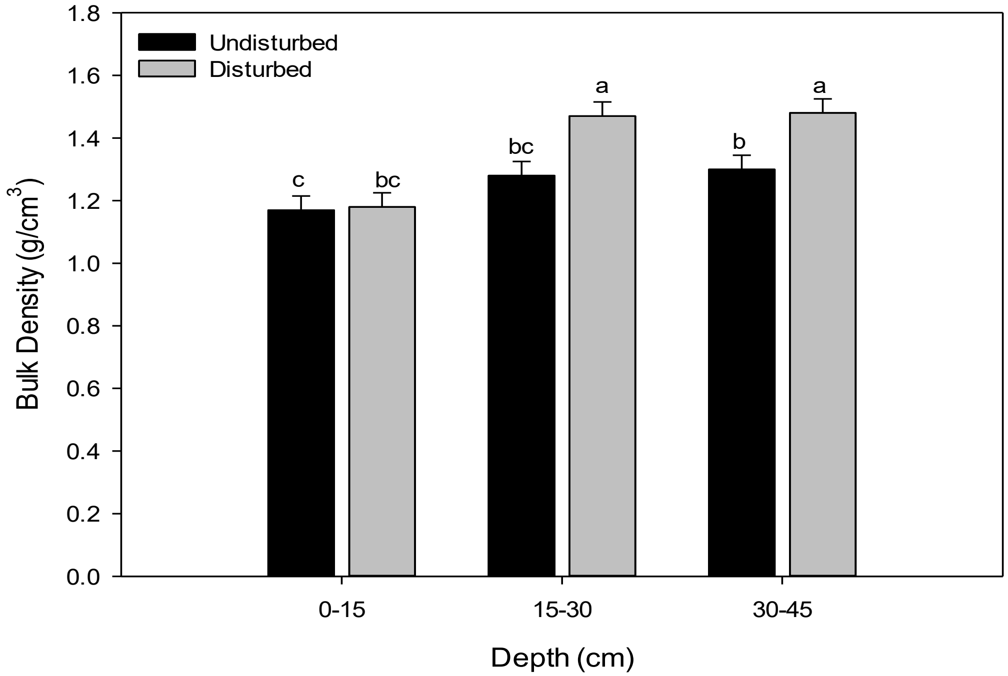


Figure 2-3. Field capacity (a), wilting point (b), and plant available water (c) in soil samples collected from undisturbed and disturbed OSE sites. Error bars represent one standard error of the least square mean and asterisks indicate with statistical significance (α=0.05) of soil properties between disturbed and undisturbed sites (n=5).

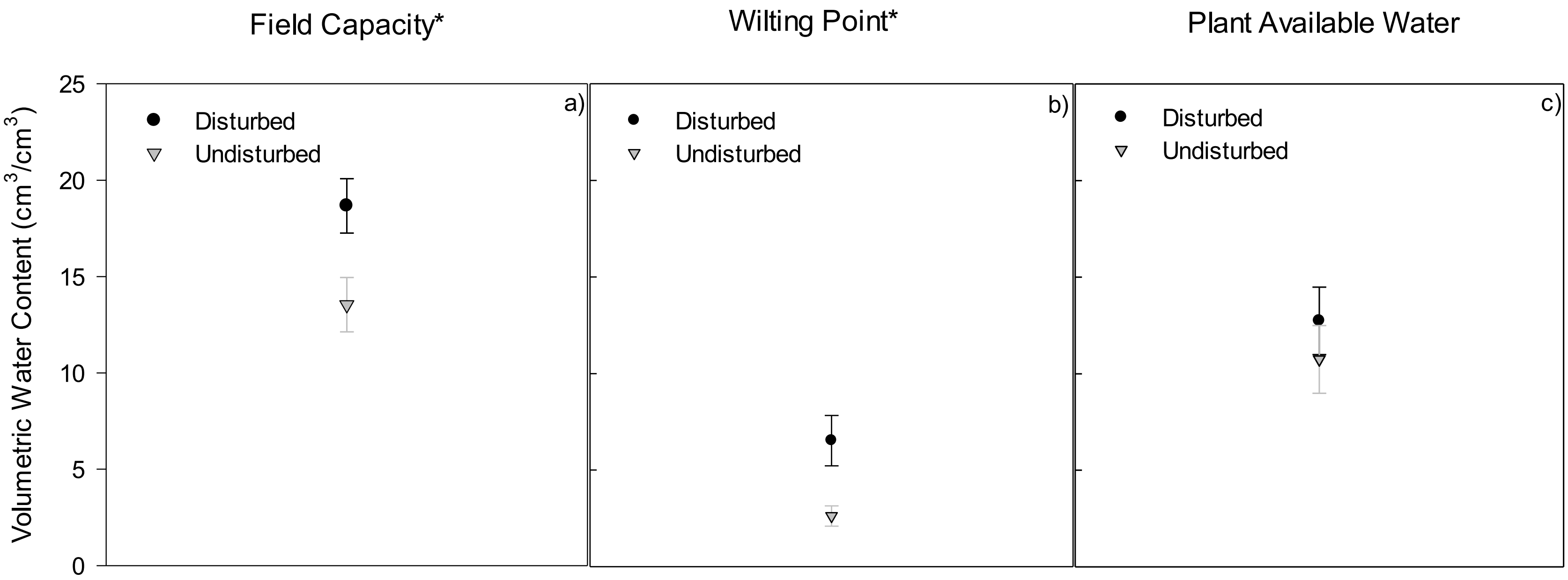


Figure 2-4. Plant available nutrients from resin analysis of PRS probes for ammonium (a), manganese (b), calcium (c), and magnesium (d) supply rates in soil collected from undisturbed, no mulch, 10 cm mulch, and 10 cm mulch incorporated treatments. Error bars represent one standard error of the least square mean and asterisks indicate with statistical significance (α=0.05) treatments (n=3).

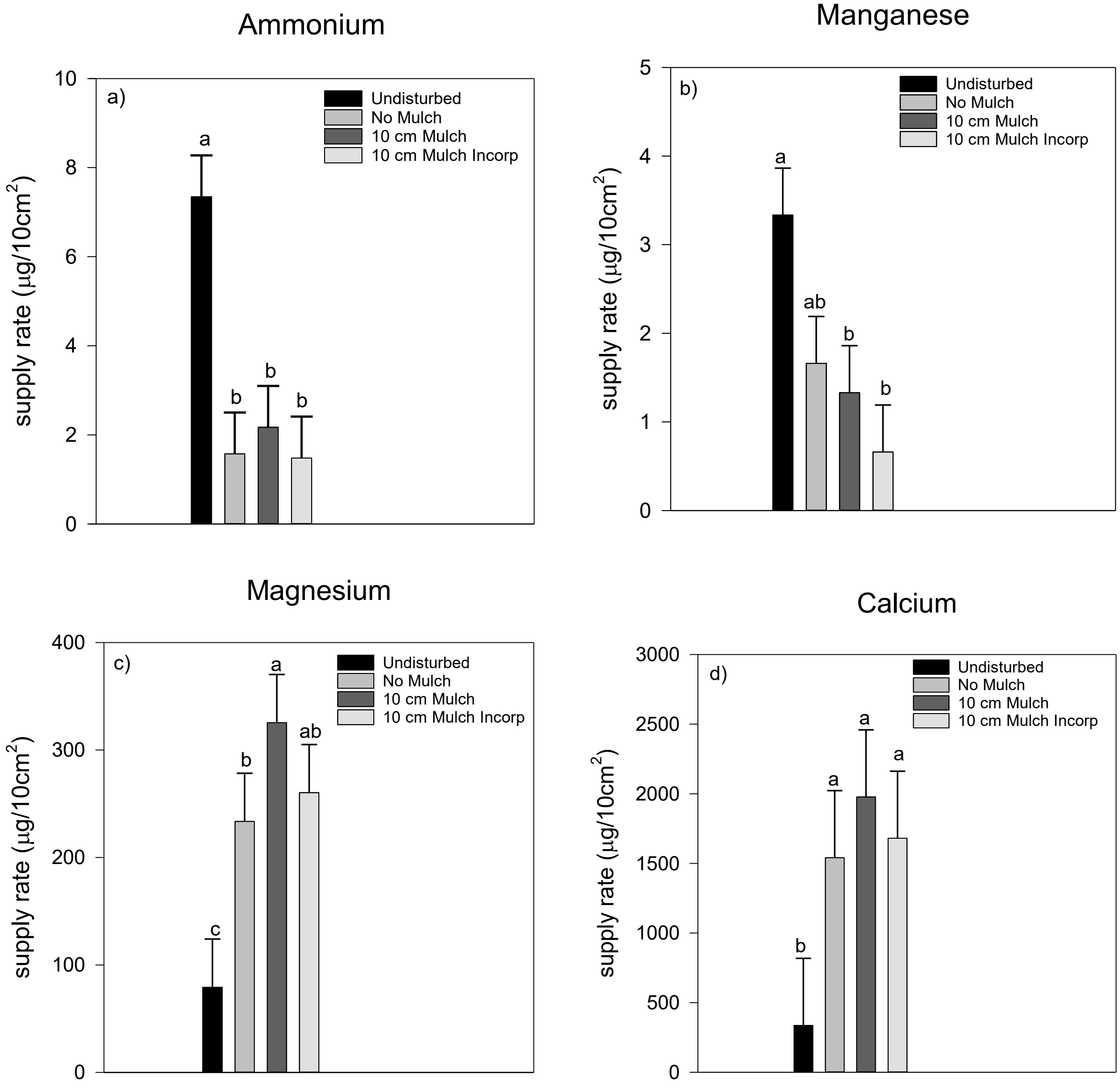
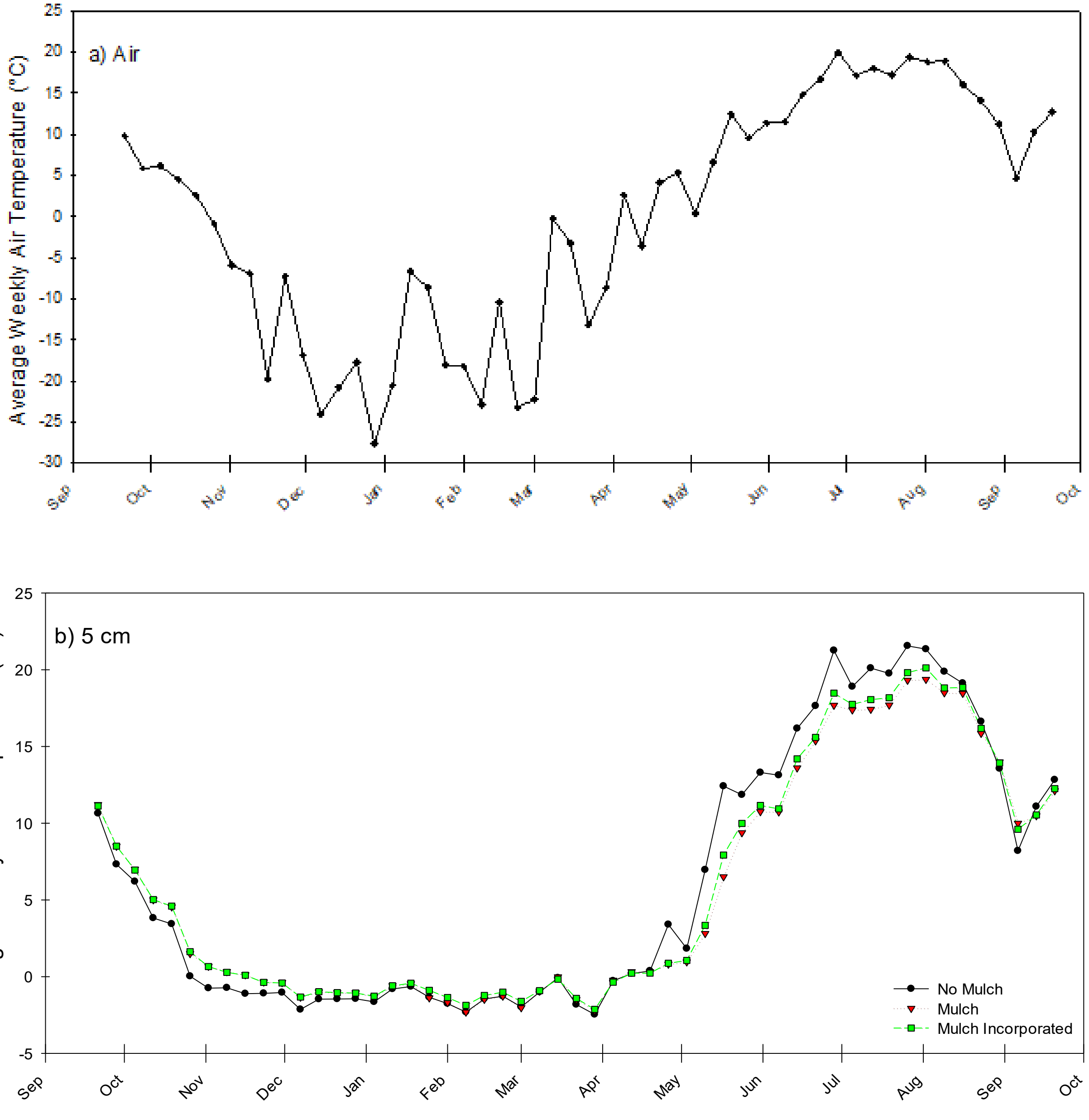
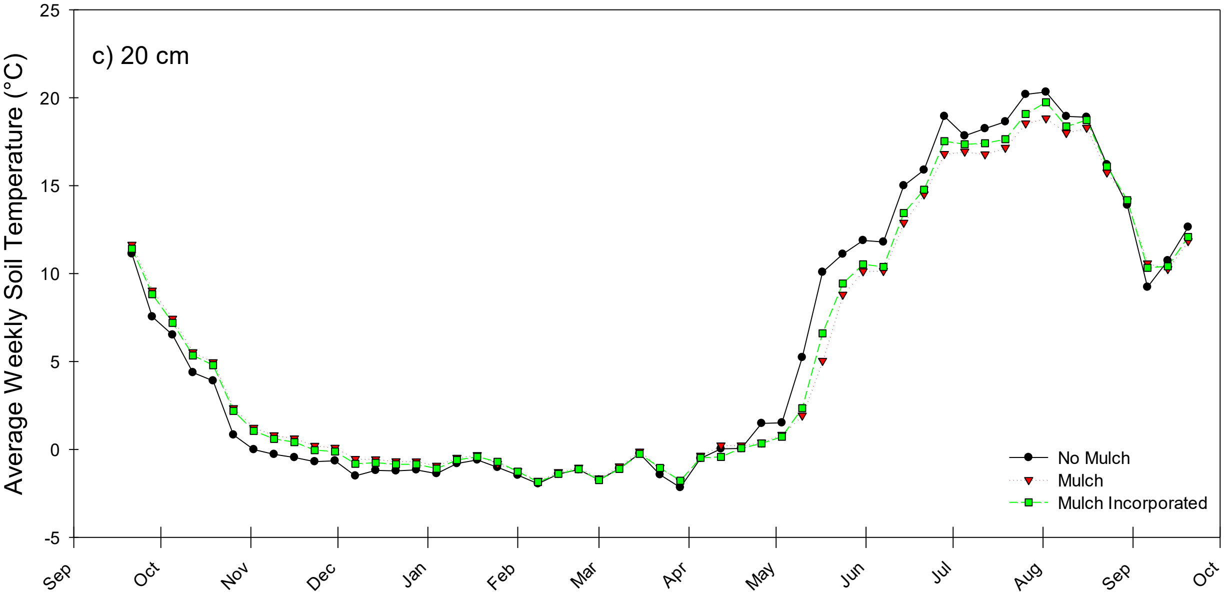
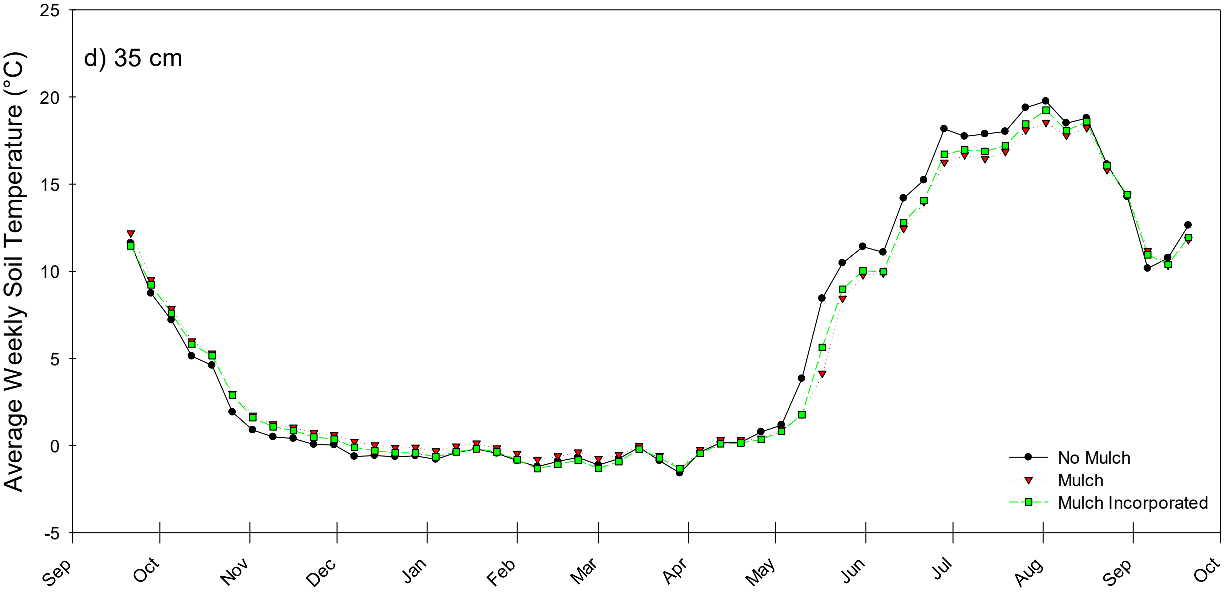


Figure 2-5. Average weekly air temperature (a) measured at the Christina Lake Weather Station (Alberta Agriculture and Forestry 2014), soil temperature (b) at 5 cm soil depth, soil temperature (c) at 20 cm soil depth, and soil temperature (d) at 35 cm soil depth of disturbed soil plots with no mulch, 10 cm of mulch, and 10 cm of mulch incorporated from September 21, 2013 to September 26, 2014 (n=3).




c) 20 cm
Average Weekly Soil Temperature (°C)
25
20
15
10
5
0
-5
Sep
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
No Mulch
Mulch
Mulch Incorporated


d) 35 cm
Average Weekly Soil Temperature (°C)
25
20
15
10
5
0
-5
Sep
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
No Mulch
Mulch
Mulch Incorporated

CHAPTER 3. EFFECTS OF DELAYED SOIL WARMING AND MULCH INCORPORATION ON *POPULUS TREMULOIDES* MICHX. (ASPEN) GROWTH PERFORMANCE

1. INTRODUCTION

Wood mulch is often used as an amendment in forest in reclamation, particularly in areas were organic surface material are lacking. It is well understood that mulch changes the soil temperature regime because woody material absorbs solar radiation (Ashworth and Harrison 1983, Montague et al. 1998, Iles and Dosmann 1999), and delays heat transfer to the soil surface soil due to its insulative properties (Wooldridge and Harris 1991, Larsson and Båth 1996). Cooler soil temperatures can decrease organic matter decomposition, restrict nutrient availability, and affect plant metabolism (Bonan and Shugart 1989). Soil temperature effects on plant growth will vary with species (Landhäusser et al. 2001; Peng and Dang 2003; Dang and Cheng 2004). Reduced establishment (Delong et al. 1997), growth (Landhäusser and Lieffers 1998; Wan et al. 1999; Landhäusser et al. 2001; McConkey et al. 2012), biomass (Peng and Dang 2003), and net photosynthetic and transpiration rate (Ambebe et al. 2010) of various species were observed with decreased temperature; however, the majority of these studies compared consistently low soil temperatures to consistently higher soil temperatures.

Soil temperature data observed on coarse-textured OSE sites in Chapter 2 (Figure 2-5; Section 3.4) showed a lag of up to two weeks in spring where soil temperature remained cooler (delayed soil warming), in areas covered with mulch compared to bare areas, consistent with other studies (Larsson and Båth 1996; Bulmer et al. 2007). This shift in temperature regime can have a significant effect on plants where spring phenology is synchronized with warming air and soil temperatures. Given the short growing season in the boreal region (Rumney 1968), lower spring soil temperatures caused by mulch may limit tree growth (Vinge and Pyper 2012). Landhäusser and Lieffers (1998) first observed that *Populus tremuloides* is sensitive to low soil temperatures. Warmer soil temperatures may be more important for *Populus tremuloides* which have deeper roots on coarse-textured soils (Strong and La Roi 1983). Thus, the effects of delayed soil warming observed when mulch is used as an amendment on *Populus tremuloides* grown on coarse-textured soils should be investigated.

The incorporation of wood mulch during reclamation activities could also affect nutrient availability. Depending on mulch type, variable changes have been observed on measured soil pH (Himelick and Watson 1990; Iles and Dosmann 1999; Landhäusser et al. 2007; Maggard et al. 2012), nitrogen (Landhäusser et al. 2007; McConkey et al. 2012), carbon (Landhäusser et al. 2007; McConkey et al. 2012), potassium (Krankina et al. 1999; Bulmer 2000; Kuehne et al. 2008; Brown 2010; Maggard et al. 2012) and phosphorus (Carlyle et al. 1998; Bulmer 2000; Laiho and Prescott 1999). Further, by adding so much carbon to the system from mulch, this may result in a nitrogen sink. With microbes competing for nitrogen with plant roots (Bollen and Glennie 1961) causing ammonium and nitrate immobilization (Land Resources Network 1993), nitrogen can be even more limiting in the soil. With the impact of mulch on nutrient availability being so variable, the effect of mulch incorporation on nutrient availability specifically on *Populus tremuloides* grown in coarse-textured soil should be explored further.

Current vegetation regeneration on upland sites has been slow on OSE sites using mulch as a reclamation amendment. Given that the low temperatures on OSE sites are caused by wood mulch used as a reclamation technique to enhance forest regeneration, the effect of delayed soil warming and mulch warrants further investigation. A growth chamber experiment was executed to investigate the effect of delayed soil warming and mulch amendment on the growth performance (i.e. height, number of leaves and branches, leaf area, dry mass, root volume, and seedling NPK) of *Populus tremuloides* seedlings and nutrient availability in coarse-textured soils. Two soil warming temperature regimes (started at 5 and 10˚C) following the patterns observed in Chapter 2 and two substrate treatments (with and without mulch) were used in the experiment. I predicted that delayed soil warming (started at 5˚C) in combination with the mulch treatment would result in greatest reduction of growth in *Populus tremuloides* seedlings, as mulch incorporation would result in decreased nutrient availability, mainly by immobilizing nitrogen.

2. METHODS

2.1. EXPERIMENTAL DESIGN

Soil and mulch were collected from OSE sites at Devon Canada Corporation's Pike Steam Assisted Gravity Drainage facility on September 7, 2013. OSE sites were the same three sites that were used as part of the soil treatment plots established in Chapter 2. Six 25 L plastic pails of soil were collected from each site (0 to 10 cm depth) by shovel. One 25 L pail of mulch was collected by shovel from the surface of each site. Collected soils were kept at 0°C and mulch at 4°C for approximately 15 months before they were used in this experiment. Soil samples from all three sites were combined and homogenized for use in the experiment. Mulch from all three sites were combined and homogenized for use in the experiment. Three soil samples were taken from the combined soil for analysis of initial physical and chemical properties (see below in Section 2.3). Nursery grown dormant *Populus tremuloides* seedlings were obtained from Woodmere Nursery Ltd. (Peace River, Alberta). Seedlings were container grown in cavities of 5 cm in diameter and 12 cm depth. Seedlings had been stored frozen and were slowly thawed at 5°C prior to planting.

Seedlings were sorted by height and care was taken that the same height distributions of seedlings were assigned to one of the following soil warming and mulch treatment combinations: started at 5˚C with or without mulch or started at 10˚C with or without mulch. Twenty seedlings with the same height distribution as the seedlings used in the study were selected for initial morphological and nutrient measurements described below in Section 2.2.

The two soil warming regimes tested were observed at OSE sites over the previous year (Chapter 2, Figure 2-5). The soil warming regime started at 5°C kept the soil temperature at 5°C for 2 weeks after budflush, increased temperature at a rate of 0.6°C day^{-1} until it reached 20°C during the warming period, and was held constant at 20°C for the remainder of the experiment (Figure 3-1). The soil warming regime started at 5°C was designed to simulate the cooler soil temperature during the 2-week lag in spring with a slower rate of warming similar to the conditions where mulch is applied as a layer on top of the soil. The soil warming regime started at 10°C kept soil temperature at 10°C for 2 weeks after budflush, increased soil temperature at a rate of 1°C day^{-1} until it reached 20°C during the warming period and was held constant at 20°C for the remainder of the 70 day experiment (Figure 3-1). The soil warming regime started at 10°C was designed to simulate the warmer soil temperature during the spring (no lag) with a faster rate of warming similar to conditions with no mulch or bare soil. Starting temperatures of 5 and 10ºC were chosen as they have physiological relevance for aspen. At a soil temperature of 5ºC root growth is inhibited and water uptake significantly reduced while at 10ºC aspen can start to grow roots (Landhäusser and Lieffers 1998; Wan et al. 1999).

The experimental setup was adapted from the soil temperature experiment in Hankin (2015). Briefly, seedlings were placed with soil or soil and mulch mixture in water-tight polyvinyl chloride (PVC) pots (20 cm height x 10 cm diameter) with a false bottom that allowed for water drainage. Pots were placed in a cooling water bath system that allowed for the control of soil temperature (Model A419, Johnson Controls Inc., Milwaukee, WI). Pots and water bath system are described in more detail in Hankin (2015), but see Figure 3-2. Each water bath was assigned to a soil warming regime started at 5 or 10˚C. Styrofoam peanuts were placed on top of the soil in each pot and water surface in the water bath to increase insulation and reduce soil warming. Soil temperatures in the pots were monitored daily using soil temperature and moisture probes (Decagon 5TM) in pots for each treatment combination.

Once each water bath container was assigned to a soil warming regime, the system was started at the either 5°C or at 10°C for the first 25 days until all seedlings had flushed. Budflush was considered Day 1 of the experiment and the experiment ran for a total of 70 days. N^{15}-

labelled ammonium nitrate ($^{15}NH_4{}^{15}NO_3$) fertilizer was added to all pots at a rate of 10 kg N/ha, two weeks after budflush and before the start of the warming period. Pots were moved and rotated every 5 days to reduce the impact of potential spatial variation within the growth chamber. Air temperature was kept at 18°C for the first 30 days and then was increased to 21°C for the remainder of the experiment. Relative humidity was kept between 35 and 40% throughout the experiment. Light levels in the growth chamber were about 350 µmol m^{-2} s^{-1} (photosynthetically active radiation PAR), measured using a hand-held light meter (Decagon Sunfleck Ceptometer. Day length was 17 hours during the budflush period which increased to 20 hours for the remainder of the experiment. Seedlings were kept just below field capacity at a volumetric water content of approximately 0.2 m^3/m^3, measured daily using soil moisture probes (Decagon 5TM).

2.2. SEEDLING SAMPLING AND MEASUREMENTS

A subsample of seedlings (n=20) was selected for initial morphological and nutrient measurements, 25 days prior to budflush or Day 1 (Table 3-1). Nine seedlings from each of the four treatments were randomly selected after the budflush period (Day 17) for measurements of growth (height, number of branches, leaf area, and root volume) and dry mass (stem, root, and leaf). Of those nine seedlings, five were randomly selected for measurement of nutrient (NPK) and N^{15} tissue concentrations. Leaves were randomly selected from five seedlings of each treatment after the warming period (Day 44) for measurement of NPK and N^{15} tissue concentrations. Nine seedlings from each treatment were randomly sampled at the conclusion of the experiment (Day 70) for measurements of growth and dry mass.

Seedlings were separated into leaves, stems, and roots, all samples were dried at 70°C for three days. After dry mass measurements, dry stems, roots, and leaves, were ground to pass #40 mesh (0.4 mm) using a Wiley Mini-Mill (Thomas Scientific, New Jersey, USA). Stems, roots, and leaves were combined in proportion to their dry mass and sent to the Natural

Resources Analytical Laboratory (NRAL) in Edmonton, Alberta for analysis of nutrient (NPK) and N^{15} tissue concentrations for the whole seedling. Total nitrogen concentrations were determined using the Dumas Combustion Method (Bremner 1996) and Costech Analytical's Model 4010 Elemental Analyzer System (Valencia, California). Total phosphate and potassium were measured using the United States Environmental Protection Agency (US EPA) microwave assisted acid digestion method (US EPA 2007) and a Themo Fisher Scientific's iCAP 6000 series Inductively Coupled Plasma-Optical Emission Spectrometer (Cambridge, UK). N^{15} concentration in tissue was determined by dry combustion and continuous flow stable isotope analysis (Bremner 1996; Horwitz 2000) using ThermoFinnigan's Delta+ Advantage Continuous Flow Isotope Ratio Mass Spectrometer (Bremen, Germany).

2.3. SOIL SAMPLING AND MEASUREMENTS

The three soil samples collected prior to the experiment (Section 2.1) were analysed for initial physical and chemical parameters (Table 3-2). Soil samples were placed in a clean 30.5 by 30.5 by 7.5 cm plastic drying pan. Samples were air-dried for six days, turning once after 3 days. After air-drying, samples were ground using a 2 mm sieve to extract all fragments greater than 2 mm in diameter. Air-dried and ground samples were sent to NRAL in Edmonton, AB for analysis. Samples were analysed for total organic carbon (TOC), total nitrogen (TN), particle size analysis (PSA), available nitrogen, available phosphorus, available potassium, hydrogen ion concentration (pH), electrical conductivity (EC) and N^{15} in soil. TOC and TN concentrations were determined by Dumas Combustion Method (Bremner 1996) using Costech Analytical's Model 4010 Elemental Analyzer System (Valencia, California). PSA was completed using the hydrometer method (Carter and Gregorich 2008). Available ammonium (NH_4^+) and available nitrate (NO_3^-) were determined by extraction with 2.0 M KCl (Carter and Gregorich 2008) and measured colorimetrically using Westco's Model 2000 SmartChem Discrete Wet Chemistry Analyzer (Connecticut, USA). Available phosphorus (PO_4^{3-}) and available potassium (K^+)

extracted using modified Kelowna extraction (Alberta Agriculture 1995). The pHs of samples were determined using a 1M $CaCl_2$ solution (McLean 1982) and EC concentrations were determined using a standard 0.010 M KCl solution (Miller and Curtin 2008). N^{15} concentration in soil was determined by dry combustion and continuous flow stable isotope analysis (Bremner 1996; Horwitz 2000) using ThermoFinnigan's Delta+ Advantage Continuous Flow Isotope Ratio Mass Spectrometer (Bremen, Germany).

At the end of the experiment, soil samples were taken from randomly selecting 5 of the 9 pots for each treatment combination. Soil samples were air-dried for six days, and ground using a 2 mm sieve to extract all fragments greater than 2 mm in diameter. Samples were analysed for available NPK, pH, and N^{15} concentrations using the same methods described above.

2.4. DATA ANALYSES

The data were analyzed as a 2 x 2 factorial design with two soil warming regimes (started at 5 an 10˚C) and two mulch amendments (no mulch and mulch). Shapiro-Wilk's test was used to determine normality and Levene's test was used to determine the equality of variances. For parameters that had a borderline significant Shapiro-Wilk's or Levene's tests ($0.05 \geq p \geq 0.03$), the residuals were examined in order to determine if an analysis of variance (ANOVA), transformation, or permutation ANOVA (pANOVA; Wheeler 2010) was required. The effects of delayed soil warming and mulch amendment were tested using a two-way ANOVA when assumptions were met. Statistical analyses were performed using SAS 9.4 (SAS Institute Inc. 2013). When assumptions of normality or equality of variance were not met, the data were transformed. Multiple transformations failed for normality but variances where equal, so a pANOVA was completed using R version 2.15.3 (R Core Team 2013). Least square means were used to compare effects of warming, mulch, or warming x mulch interaction. When there were significant effects, post hoc tests for differences between least square means were completed with a Tukey adjustment for multiple means. An α-value of ≤0.05 was used to determine significance for all statistical tests. Results for all statistical analyses are presented in Appendix C. Significant effects discussed in the results are in reference to statistical significance ($\alpha \leq 0.05$). Any effects discussed in the results that are not statistically significant but could have biological significance are designated by “the effect was not significant” and the associated p-value is presented.

3. RESULTS

3.1. EFFECTS OF DELAYED SOIL WARMING AND MULCH AMENDMENT ON SELECTED GROWTH PARAMETERS OF *POPULUS TREMULOIDES* SEEDLINGS

Following budflush (Figure 3-1), there was a significant effect of delayed soil warming on leaf area development (P=0.024) but not on any other measured variables (i.e. height growth, number of branches and leaves, stem mass, root mass, root volume, seedling NPK, or N^{15}; Table 3-3). Seedlings started at 10˚C had a 25% greater leaf area than seedlings started at 5˚C (Table 3-3). Leaf mass was also 25% greater for seedlings started at 10˚C but the effect was not significant (P=0.051; Table 3-3). There was a significant effect of mulch amendment on seedling N (P=0.012), K (P=0.013), and seedling N^{15} (P=0.003) but not on any other measured variables (Table 3-4). Seedling N and K were respectively 20% and 10% greater for seedlings grown with mulch compared to without mulch. Seedling P was also 10% greater for seedlings grown with mulch but the effect was not significant (P=0.056; Table 3-4). Seedling N^{15} was 2.5 times higher in seedlings grown without mulch compared to with mulch (Table 3-4). Seedling N^{15} also showed a significant interaction (P=0.012) between delayed soil warming and mulch amendment (Figure 3-3). The seedlings with the cold regime and no mulch had 2.4 to 4.0 times higher seedling N^{15} than all other treatment combinations. The number of branches (P=0.015) and leaves (P=0.039) showed a significant interaction between delayed soil warming and mulch amendment (Figure 3-4); however, there were no significant differences between the means of the treatment combinations when post-hoc tests were adjusted for multiple comparisons.

Following the warming period (Figure 3-1), there was a significant effect of delayed soil warming on seedling P (P=0.007) but not on any other measured variables (i.e. seedling NPK or N^{15}). Seedling P was 13% greater for seedlings started at 5˚C than seedlings started at 10˚C (Table 3-5). The significant effects of the mulch amendment after the budflush period were no longer observed on seedling N (P=0.062), P (P=0.320), K (P=0.430), and N^{15} (P=0.990; Table 3-6). The significant interaction between delayed soil warming and mulch amendment after budflush on seedling N^{15} also disappeared (P=0.885).

At the conclusion of the experiment (Figure 3-1), there was a significant effect of delayed soil warming on number of leaves (P=0.019), leaf area (P<0.001), leaf mass (P=<0.001), stem mass (P=0.013), and root mass (P=0.038) but not height, number of branches, and root volume (Table 3-7). There were 21% more leaves, 53% greater leaf area development, 45% greater leaf mass, 14% greater stem mass, and 13% greater root mass for seedlings started at 10˚C compared to seedlings started at 5˚C (Table 3-7). There was a significant effect of mulch amendment on number of branches (P=0.047), leaf mass (P=0.006), and stem mass (P=0.041). There were 23% more branches, 19% greater leaf mass, and 12% greater stem mass for seedlings grown without mulch compared to with mulch (Table 3-8). Root mass (P=0.053) and root volume (P=0.083) for seedlings without mulch were also lower but the effect was not significant. Leaf area development (P=0.007), leaf mass (P=0.005), and stem mass (P=0.023) showed a significant interaction between delayed soil warming and mulch amendment. In seedlings grown with or without mulch, leaf area development was lower for seedlings started at 5˚C than seedlings started at 10˚C (Figure 3-5). A significant interaction was observed for leaf and stem mass (Figure 3-6). Seedlings started at 10˚C and without mulch treatment combination had 26 to 79% greater leaf area development, 34 to 65% greater leaf mass, and 24 to 26% greater stem mass than the other treatment combinations.

Interestingly many of the seedlings started to set bud during the warming period regardless of treatment. After the warming period (Day 44), approximately 45% of the seedlings sampled had set bud and 100% of sampled seedlings set bud by the conclusion of the experiment.

3.2. EFFECTS OF DELAYED SOIL WARMING AND MULCH AMENDMENT ON SELECT SOIL PROPERTIES

At the conclusion of the growth chamber experiment (Figure 3-1), soil properties were analysed from soil used to grow the seedlings. There was a significant effect of delayed soil warming on nitrate (P=0.024) and phosphate (P=0.005) but not any other measured properties (i.e. pH, ammonium, potassium, total organic carbon, and total nitrogen). Nitrate and phosphate concentrations were 12% and 19% lower, respectively, for seedlings started at 10˚C than seedlings started at 5˚C (Table 3-9). There was a significant effect of mulch amendment on pH (P<0.001), phosphate (P<0.001), potassium (P<0.001), total organic carbon (P<0.001), and total nitrogen (P<0.001) but not the other measured properties. Soils without mulch had a 2% higher pH than soils with mulch. Soils with mulch had a 30% lower phosphate concentration than soils without mulch (Table 3-10). Soils without mulch had a 22% lower potassium concentration than soil with mulch. Soil with mulch had 59% higher total organic carbon and 34% higher total nitrogen compared to soils without mulch. There were no significant interactions between delayed soil warming and mulch amendment for soil properties.

4. DISCUSSION

Delayed soil warming (started at 5°C compared to 10°C and warming to 20°C), mulch amendment, and their interaction affected *Populus tremuloides* seedling growth. Effects were primarily observed in aboveground growth performance. Belowground growth performance (root mass only) of seedlings was affected by delayed soil warming. Seedlings started at 5˚C with no mulch treatment combination had better aboveground growth performance than all other treatment combinations. The mulch amendment and delayed soil warming did not decrease nutrient availability in soil, as predicted, with the exception of available phosphate. Main findings are discussed in greater detail below.

As discussed in Section 3.1, seedlings started to set bud during the warming period. As this study had a different temperature regime than the majority of the other studies in order to closely resemble temperature results seen in the field, the lasting effects of low soil temperature on growth could be masked. Belowground growth performance (root mass and root volume) showed marginal significance ($P<0.08$) for mulch incorporation that could have been affected by the seedlings setting bud. Seedling quality could have been a factor resulting in budset. Seedlings used in Hankin (2015) also set bud and low initial non-structural carbohydrates were observed in seedlings. As well, the same growth chamber was used for this experiment as in Hankin (2015). Potentially, growth chamber conditions such as low light could have also been a factor resulting in budset.

4.1. EFFECTS OF DELAYED SOIL WARMING AND MULCH AMENDMENT ON SELECTED GROWTH PARAMETERS OF *POPULUS TREMULOIDES* SEEDLINGS

Initially, seedlings started at 10°C during budflush showed around 25% greater aboveground growth in seedlings started at 5°C. This was primarily observed in early leaf area development. Combined with detectable increases in leaf mass, this indicates that seedlings in the cold conditions produced smaller leaves. By the end of the experiment, the effect of delayed warming increased with larger differences to aboveground growth (more and larger leaves and higher stem mass) and the development of an effect on belowground growth (root mass). Also by the end of the experiment, seedlings grown without mulch had better aboveground growth (number of branches, leaf mass, and stem mass). Cold limitations to growth performance in this experiment were not related to the availability of nutrients measured during this experiment, as soil nutrient availability was the same or greater for soil started at 5˚C. The greater aboveground growth observed in seedlings without mulch is also not likely due to the availability of nutrients measured during this experiment. Available phosphate was the only measured soil property that had higher availability in soil for seedlings grown without mulch but was not reflected by higher uptake of P in seedlings grown without mulch.

The greater seedling P for seedlings started at 5˚C was likely due to the higher concentration of available phosphate in soil associated with soil at 5˚C. Higher Seedling N and K with mulch compared to without could be due to an initial growth response to soil with mulch having higher soil concentrations of total nitrogen and potassium. The initial response likely disappeared as seedlings grown without mulch performed better (indicated by leaf area, leaf mass, and stem mass) than with mulch, decreasing the initial effects of increased soil availability. Higher nitrate concentrations in soil at 5˚C could partially contribute to the higher seedling N^{15} concentrations observed for seedlings started at 5˚C without mulch than any other treatment combinations.

Cold limitations to growth are well documented but growth did not recover once the soil was warmed from 5 to 20˚C. This suggests that physiological changes to the seedlings could not be overcome after warming and continued to restrict growth for the length of this experiment. It unknown if differences in growth could be overcome if seedlings started at 5 and 10˚C had the same number of days at 20˚C (growing degree days). It is possible that reduced root water flow to leaves of the seedlings during periods where the soil temperature was 5˚C but air temperature was higher could affect growth (Wan et al. 1999). It is also possible that the inability of seedlings to recover could be due to stress from photosynthetic damage or hormone signalling suggested by Hankin (2015). Studies have shown the impact of cold soil temperatures on decreasing carbon assimilation, Rubisco performance, and photosystem efficiency of various species (Zarter et al. 2006; Sage and Kubien 2007; Moyes et al. 2015). Ensminger et al. (2008) showed that Scots pine (*Pinus sylvestris* L.) seedlings with a low soil temperature had a decreased recovery rate during warming in the spring leading to delayed photosynthetic capacity recovery. The photosynthetic recovery rate of cold soils that were warmed in the spring was reduced by decreased photochemical efficiency of photosystem II via reduced electron transport, impaired CO_2 assimilation and deactivation of Rubisco proteins (Ensminger et al. 2008). Changes to hormones that affect plant growth regulation in times of stress, such as abscisic acid (ABA; Davies and Zhang 1991), could result in the cold induced growth differences observed in this experiment. Studies have showed that increases in ABA can result in closure of stomata during times of stress such as cold temperatures and drought (Davies and Zhang 1991; Wan and Zwiazek 2001; Wan et al. 2004). Hankin (2015) suggests from the increased concentrations of signalling elements that after warming from 5˚C stress hormones continued to be synthesized.

Interactions were observed between delayed soil warming and mulch incorporation for leaf area, leaf mass, and stem mass with seedlings started at 10˚C without mulch having the best growth performance of all treatments. Smaller leaves resulting from the combination of cold temperature and mulch incorporation would reduce light-harvesting capacity resulting in decreased carbohydrate production for root, stem, and leaf growth (area and mass; Landhäusser and Lieffers 1998). Because there was an observed difference of leaf development between seedlings started at 10˚C with and without mulch, cold limitations are not solely responsible for reduced growth. The exact cause of smaller leaf development and reduced growth from the interaction of delayed soil warming and mulch amendment is unknown. Possibly, growth effects from the combination of delayed soil warming and mulch incorporation are associated with other factors such as physiological changes to seedlings such as root water flow (Wan et al. 1999) or stress-induced photosynthetic changes and hormone signalling (Hankin 2015) discussed above, mulch causing a dark environment leading to poor photosynthesis (Renekma et al. 2009), other soil properties not measured here such as micronutrients (calcium, magnesium, and iron), aeration (Osko and Glasgow 2010), and bacterial community and activity changes (Tiquia et al. 2002), or combinations of these.

4.2. EFFECTS OF DELAYED SOIL WARMING AND MULCH AMENDMENT ON SELECT SOIL PROPERTIES

Only available nitrate and available phosphate in soil were affected by delayed soil warming. The lower available nitrate in soil started at 10˚C compared to 5˚C could be partially due the higher use of nitrate by seedlings started at 10˚C but this was not reflected in higher seedling N of seedlings started at 10˚C. Lower available nitrate could also be due to increased denitrification by soil denitrifiers in soil started at 10˚C (Snider et al. 2009; Risk et al. 2013). The lower available phosphate concentration in soils started at 10˚C is likely due to warmer temperatures increasing the rate of immobilization and chemical fixation there by reducing solubility (Mack and Barber 1960a; Mack and Barber 1960b; Hinman et al. 1962; Beaton and Read 1963; Power et al. 1963).

Soil pH was lower with mulch than without despite higher concentrations of potassium, a basic cation. Studies have shown that effects on soil pH can vary (Himelick and Watson 1990; Iles and Dosmann 1999; Landhäusser et al. 2007; Maggard et al. 2012) depending on the pH of the mulch and the initial pH of the soil (Maggard et al. 2012). Mulch from the sites used for this study would have largely consisted of *Populus tremuloides* mulch with some component of white spruce mulch (*Picea glauca*) (see Chapter 2, Section 2.2). Venner et al. (2011) characterized *Populus tremuloides* mulch, which has a pH of 4.80 to 5.07 while *Picea glauca* mulch had a pH of 4.6 to 6.1. The lower pH value in the mulch treatment is likely due to leaching of acidic compounds from mulch into the soil demonstrated by Landhäusser et al. (2007) where leachate collected from *Populus tremuloides* mulch had low pH values initially with the effects tapering off over the duration of the 7 week experiment.

The concentration of available phosphate remained near the starting soil concentration without mulch but was lower with mulch. As there was no lasting difference of mulch amendment for seedling P, the effect is not likely due to differences in plant uptake. Though the availability of phosphate to plants has been shown to be pH-dependent (Devau et al. 2010), it is unlikely that the lower soil pH with mulch resulted in the lower available phosphate. Soil at the start and soil with mulch at the conclusion of the experiment had the same soil pH (7.8) but the concentration of available phosphate for the starting soil (14.9 mg/kg) was well above soil with mulch (9.78 mg/kg). The lower available phosphate in soil with mulch is likely due to immobilization. Carlyle et al. (1998) found that woody fragments, when buried and incorporated with sandy soil could reduce phosphate leaching through phosphate accumulation in the woody fragments. Laiho and Prescott (1999) found that decomposing coarse woody debris with low initial phosphate concentrations gained phosphate in the woody material and could immobilize phosphate up to four times the initial concentration.

The concentration of available potassium remained near the starting soil concentration with mulch but was lower in soils with no mulch. As there was no lasting difference of mulch amendment for seedling K, the effect is not likely due to differences in plant uptake. The higher soil concentration of available potassium with mulch could be due to leaching of potassium from mulch into to the soil. In Krankina et al. (1999) and Kuehne et al. (2008), different tree species showed potassium concentrations increasing in coarse woody debris and in leachate from coarse woody debris, respectively. Brown (2010) also observed that available potassium was higher in soil with coarse woody debris similar to the species mix used in this study, *Populus tremuloides* and *Picea glauca*.

The total organic carbon and nitrogen concentration with mulch was above the starting soil concentration. The increase in total carbon concentration is likely due to carbon added to the soil from the mulch. In a greenhouse study, soils treated with *Populus tremuloides* mulch or *Populus tremuloides* mulch leachate contained higher water soluble carbon than without mulch (Landhäusser et al. 2007). Though total nitrogen was higher in soils with mulch than without, this did not translate to higher ammonium or nitrate concentrations in soil. This contradicts the hypothesis that mulch as a higher carbon soil substrate would have acted to immobilize nitrogen (nitrogen sink). However, several other studies have observed nitrogen (available or total) concentrations in soil that were lower for treatments with mulch (Corns and Maynard 1998; Sandborn et al. 2004; Landhäusser et al. 2007). It is possible that the differences in total nitrogen between this study and other studies may be due to differences in the length of the experiments and rates of decomposition, soil temperature interactions (as seen in Hankin 2015; interaction P=0.094 in this experiment), or nitrogen being leached from the mulch in to the soil (Corns and Maynard 1998; Landhäusser et al. 2007).

5. CONCLUSIONS

Delayed soil warming, mulch amendment, and their combination reduced the growth performance of *Populus tremuloides* seedlings on coarse-textured soils from OSE sites. Cold limitations decreased aboveground and belowground growth whereas mulch incorporation decreased aboveground growth. Though delayed warming and mulch amendment independently changed soil nutrient availability, changes observed to soil nutrient availability did not appear to limit growth performance of *Populus tremuloides* seedlings on coarse-textured soils. As the combination of seedlings started at 10˚C grown with no mulch had the best growth performance (leaf area, leaf mass, stem mass), the use of mulch may be undesirable on coarse-textured OSE sites being revegetated with *Populus tremuloides* in the northern boreal forest. Using mulch in patches or woody debris of different sizes (mulch to coarse woody debris) may alleviate some of the undesirable effects observed in this study. In the northern boreal forest, seedlings used on reclaimed OSE sites that use a mulch amendment will be subject to delayed soil warming and mulch growth limitations continually each year in the spring. Seedlings could possibly recover from growth limitations in the fall or growth limitations could compound yearly leading to poor survival and overall poor revegetation of the site.

Table 3-1. Mean and standard error (SE) of initial morphological and nutrient measurements of *Populus tremuloides* seedlings (n=20) 25 days prior to experiment.

Seedling measurements	Mean	SE
Height (cm)	37.3	0.99
Stem mass (g)	1.2	0.06
Root volume (cm^3)	6.9	0.46
Root mass (g)	2.0	0.12
Nitrogen (%)	1.3	0.11
Phosphorus (%)	0.2	0.01
Potassium (%)	0.6	0.03
N^{15} (%)	0.5	0.10

Table 3-2. Mean and standard error (SE) of initial soil properties (n=3) 25 days prior to experiment.

Soil Properties	Mean	SE
Moisture (%)	8.8	0.22
Clay (%)	8.4	0.67
Silt (%)	11.9	0.59
Sand (%)	79.7	0.81
EC (µs/cm)	164.3	8.11
pH (-)	7.8	0.06
Available NH_4^+ (mg/kg)	2.9	0.16
Available NO_3^- (mg/kg)	3.0	0.18
Available PO_4^{3-} (mg/kg)	14.9	0.29
Available K^+ (mg/kg)	60.3	3.33
TOC (%)	0.9	0.08
TN (%)	0.04	0.003
N^{15} (%)	2.9	0.24

Table 3-3. Mean and standard error (SE) of measured growth parameters on *Populus tremuloides* seedlings (n=9 or 5) after the budflush period (Day 17 of 70) in response to soil warming regime. Seedlings were started at a soil temperature of 5 or 10˚C and warmed to 20˚C. Different letters indicate statistical significance (α=0.05) between means of each growth parameter.

Seedling Measurements	n	10˚C Mean		10˚C SE	5˚C Mean		5˚C SE
Height (cm)	9	42.57	**a**	1.22	41.50	**a**	1.22
# of Branches	9	8.61	**a**	0.60	8.16	**a**	0.60
# of Leaves	9	60.56	**a**	4.16	56.56	**a**	4.16
Leaf area (cm^2)	9	96.33	**a**	5.78	77.01	**b**	5.78
Leaf mass (g)	9	0.66	**a**	0.05	0.53	**a**	0.05
Stem mass (g)	9	1.46	**a**	0.07	1.39	**a**	0.07
Root volume (cm^3)	9	10.39	**a**	0.64	9.34	**a**	0.62
Root mass (g)	9	1.75	**a**	0.07	1.70	**a**	0.07
Nitrogen (%)	5	1.10	**a**	0.05	1.17	**a**	0.05
Phosphorus (%)	5	0.18	**a**	0.01	0.19	**a**	0.01
Potassium (%)	5	0.61	**a**	0.02	0.59	**a**	0.02
N^{15} (%)	5	9.47	**a**	2.11	15.62	**a**	2.11

Table 3-4. Mean and standard error (SE) of measured growth parameters on *Populus tremuloides* seedlings (n=9 or 5) after the budflush period (Day 17 of 70) in response to mulch amendment. Seedlings were grown in soil with or without mulch. Different letters indicate statistical significance (α=0.05) between means of each growth parameter.

Seedling Measurements	n	No Mulch			Mulch		
		Mean		SE	Mean		SE
Height (cm)	9	42.65	**a**	1.22	41.42	**a**	1.22
# of Branches	9	8.33	**a**	0.60	8.44	**a**	0.60
# of Leaves	9	55.67	**a**	4.16	61.44	**a**	4.16
Leaf area (cm^2)	9	80.21	**a**	5.78	93.13	**a**	5.78
Leaf mass (g)	9	0.56	**a**	0.05	0.63	**a**	0.05
Stem mass (g)	9	1.39	**a**	0.07	1.45	**a**	0.07
Root volume (cm^3)	9	9.40	**a**	0.64	10.33	**a**	0.62
Root mass (g)	9	1.71	**a**	0.07	1.73	**a**	0.07
Nitrogen (%)	5	1.03	**b**	0.05	1.24	**a**	0.05
Phosphorus (%)	5	0.18	**a**	0.01	0.19	**a**	0.01
Potassium (%)	5	0.57	**b**	0.02	0.63	**a**	0.02
N^{15} (%)	5	17.71	**a**	2.11	7.38	**b**	2.11

Table 3-5. Mean and standard error (SE) of measured seedling nutrients on *Populus tremuloides* seedlings (n=5) after the warming period (Day 44 of 70) in response to soil warming regime. Seedlings were started a soil temperature of 5 or 10˚Cand warmed to 20˚C. Different letters indicate statistical significance (α=0.05) between means of each growth parameter.

Seedling Measurements	n	10˚C			5˚C		
		Mean		SE	Mean		SE
Nitrogen (%)	5	0.79	**a**	0.29	0.83	**a**	0.03
Phosphorus (%)	5	0.121	**b**	0.004	0.137	**a**	0.004
Potassium (%)	5	0.49	**a**	0.02	0.48	**a**	0.02

Table 3-6. Mean and standard error (SE) of measured seedling nutrients on *Populus tremuloides* seedlings (n=5) after the warming period (Day 44 of 70) in response to mulch amendment. Seedlings were grown in soil with or without mulch. Different letters indicate statistical significance (α=0.05) between means of each growth parameter.

Seedling Measurements	n	No Mulch			Mulch		
		Mean		SE	Mean		SE
Nitrogen (%)	5	0.77	**a**	0.03	0.85	**a**	0.03
Phosphorus (%)	5	0.131	**a**	0.004	0.126	**a**	0.004
Potassium (%)	5	0.48	**a**	0.02	0.50	**a**	0.02

Table 3-7. Mean and standard error (SE) of measured growth parameters on *Populus tremuloides* seedlings (n=9) after the growth period (Day 70) in response to soil warming regime. Seedlings were started at a soil temperature of 5 or 10˚C and warmed to 20˚C. Different letters indicate statistical significance (α=0.05) between means of each growth parameter.

Seedling Measurements	n	10˚C			5˚C		
		Mean		SE	Mean		SE
Height (cm)	9	43.71	**a**	1.25	42.66	**a**	1.25
# of Branches	9	9.33	**a**	0.63	8.39	**a**	0.63
# of Leaves	9	73.50	**a**	3.66	60.66	**b**	3.66
Leaf area (cm^2)	9	134.54	**a**	4.68	87.66	**b**	4.68
Leaf mass (g)	9	1.49	**a**	0.05	1.03	**a**	0.05
Stem mass (g)	9	2.30	**a**	0.08	2.01	**b**	0.08
Root volume (cm^3)	9	13.30	**a**	0.57	13.86	**a**	0.57
Root mass (g)	9	3.69	**a**	0.14	3.27	**b**	0.14

Table 3-8. Mean and standard error (SE) of measured growth parameters on *Populus tremuloides* seedlings (n=9) after the growth period (Day 70) in response to mulch amendment. Seedlings were grown in soil with or without mulch. Different letters indicate statistical significance (α=0.05) between means of each growth parameter.

Seedling Measurements	n	No Mulch			Mulch		
		Mean		SE	Mean		SE
Height (cm)	9	43.30	**a**	1.25	43.05	**a**	1.25
# of Branches	9	9.77	**a**	0.63	7.94	**b**	0.63
# of Leaves	9	70.67	**a**	3.66	63.50	**a**	3.65
Leaf area (cm^2)	9	116.88	**a**	4.68	105.31	**a**	4.68
Leaf mass (g)	9	1.36	**a**	0.05	1.15	**b**	0.05
Stem mass (g)	9	2.27	**a**	0.08	2.04	**b**	0.08
Root volume (cm^3)	9	14.30	**a**	0.57	12.86	**a**	0.57
Root mass (g)	9	3.67	**a**	0.14	3.29	**a**	0.14

Table 3-9. Mean and standard error (SE) of measured soil properties (n=5) at the conclusion of a growth chamber experiment (Day 70) in response to soil warming regime. *Populus tremuloides* seedlings were started at a soil temperature of 5 or 10˚C and warmed to 20˚C. Different letters indicate statistical significance (α=0.05) between means of each soil property.

Soil Property	10˚C			5˚C		
	Mean		SE	Mean		SE
pH (-)	7.92	**a**	0.02	7.91	**a**	0.02
Available NH_4^+ (mg/kg)	2.50	**a**	0.06	2.57	**a**	0.06
Available NO_3^- (mg/kg)	2.77	**b**	0.10	3.14	**a**	0.10
Available PO_4^{3-} (mg/kg)	10.63	**b**	0.54	13.10	**a**	0.54
Available K^+ (mg/kg)	51.06	**a**	2.11	50.35	**a**	2.11
TOC (%)	1.03	**a**	0.05	1.11	**a**	0.05
TN (%)	0.044	**a**	0.002	0.045	**a**	0.002
N^{15} (%)	1204.61	**a**	179.10	1393.86	**a**	179.10

Table 3-10. Mean and standard error (SE) of measured soil properties (n=5) at the conclusion of a growth chamber experiment (Day 70) in response to mulch amendment. *Populus tremuloides* seedlings were grown in soil with or without mulch. Different letters indicate statistical significance (α=0.05) between means of each soil property.

	No Mulch			Mulch		
Soil Property	Mean		SE	Mean		SE
pH (-)	7.99	**a**	0.02	7.83	**b**	0.02
Available NH_4^+ (mg/kg)	2.49	**a**	0.06	2.58	**a**	0.06
Available NO_3^- (mg/kg)	2.97	**a**	0.10	2.94	**a**	0.10
Available PO_4^{3-} (mg/kg)	13.95	**a**	0.54	9.78	**b**	0.54
Available K^+ (mg/kg)	44.52	**b**	2.11	56.88	**a**	2.11
TOC (%)	0.83	**b**	0.05	1.32	**a**	0.05
TN (%)	0.038	**b**	0.002	0.051	**a**	0.002
N^{15} (%)	1359.55	**a**	179.10	1238.90	**a**	179.10

Figure 3-1. Growth chamber experiment simulating two soil warming treatments (started at 5 or 10˚C and warmed to 20˚C) during the budflush period (a), warming period (b), and growth period (c) of *Populus tremuloides* seedlings over a 70 day period.

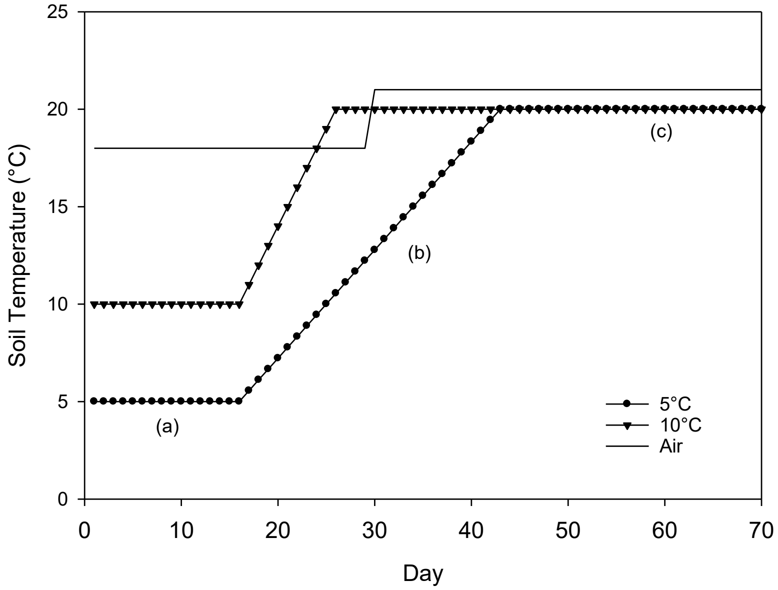


Figure 3-2. Design of water-tight pots (a) and water bath system (b) used to control the soil temperature of *Populus tremuloides* seedlings (Hankin 2015).

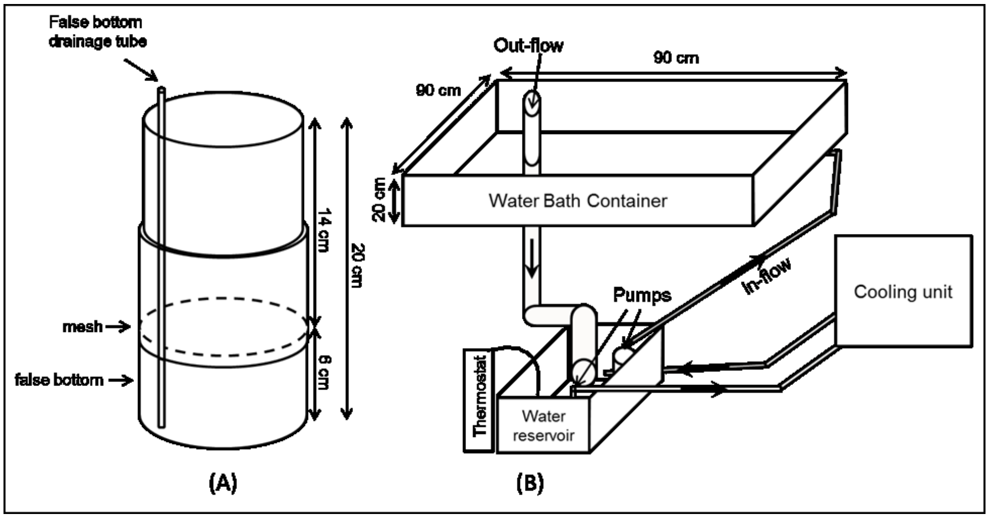


Figure 3-3. N^{15} of *Populus tremuloides* seedlings (n=5) measured after the budflush period (Day 17) and warming period (Day 44) of a 70 day growth chamber experiment. Seedlings were started at 5 or 10˚C, with mulch (M) or without mulch (NM), and warmed to 20˚C. Different letters indicate statistical significance (α=0.05) between the means of treatment combinations after each period.

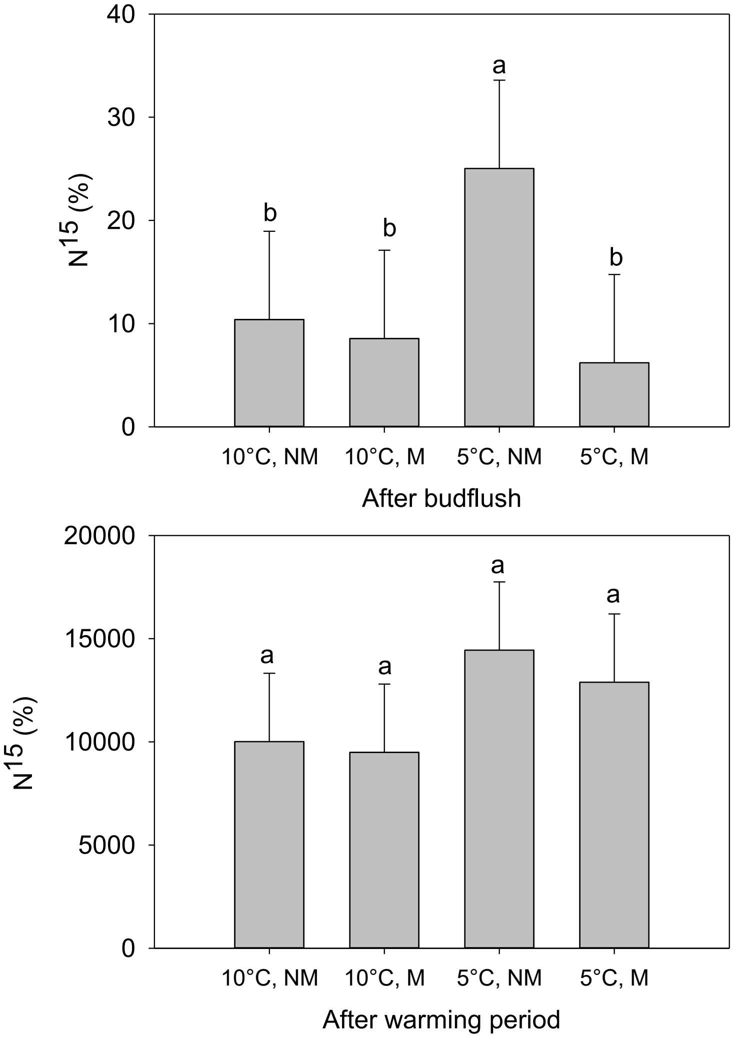


Figure 3-4. Number of branches and leaves of *Populus tremuloides* seedlings (n=9) measured after the budflush period (Day 17) of a 70 day growth chamber experiment. Seedlings were started at 5 or 10˚C, with mulch (M) or without mulch (NM) and warmed to 20˚C. Different letters indicate statistical significance (α=0.05) between the means of treatment combinations.

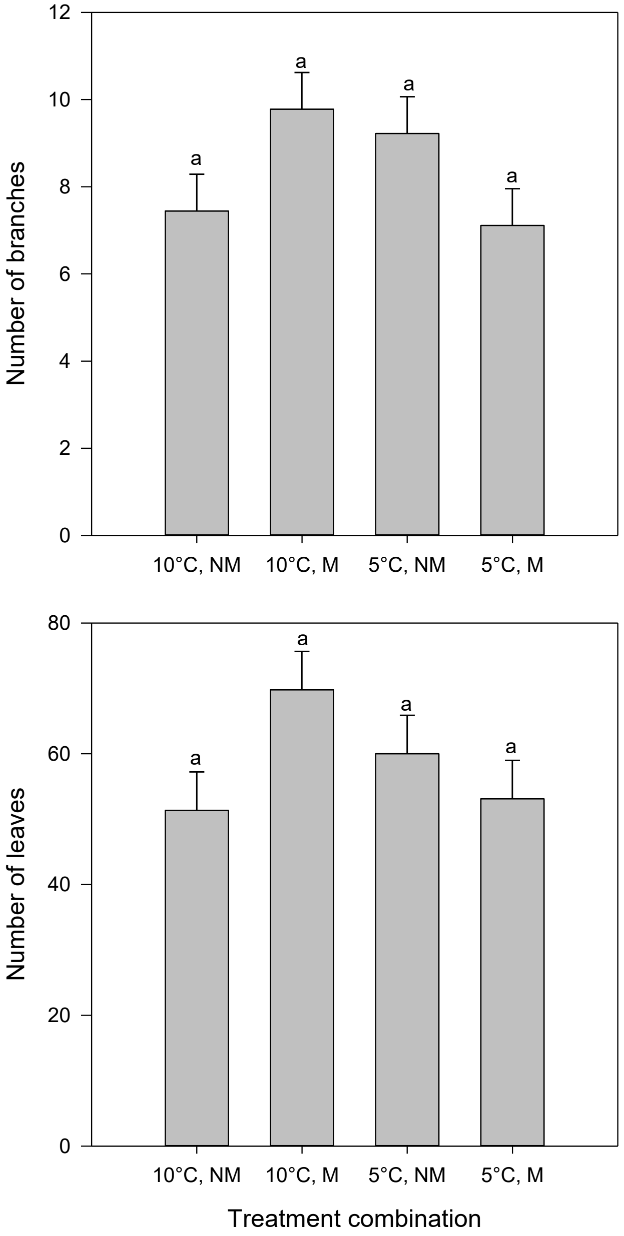


Figure 3-5. Leaf area development of *Populus tremuloides* seedlings (n=9) measured at the conclusion of a 70 day growth chamber experiment. Seedlings were started at 5 or 10˚C, with mulch (M) or without mulch (NM) and warmed to 20˚C. Different letters indicate statistical significance (α=0.05) between the means of treatment combinations.

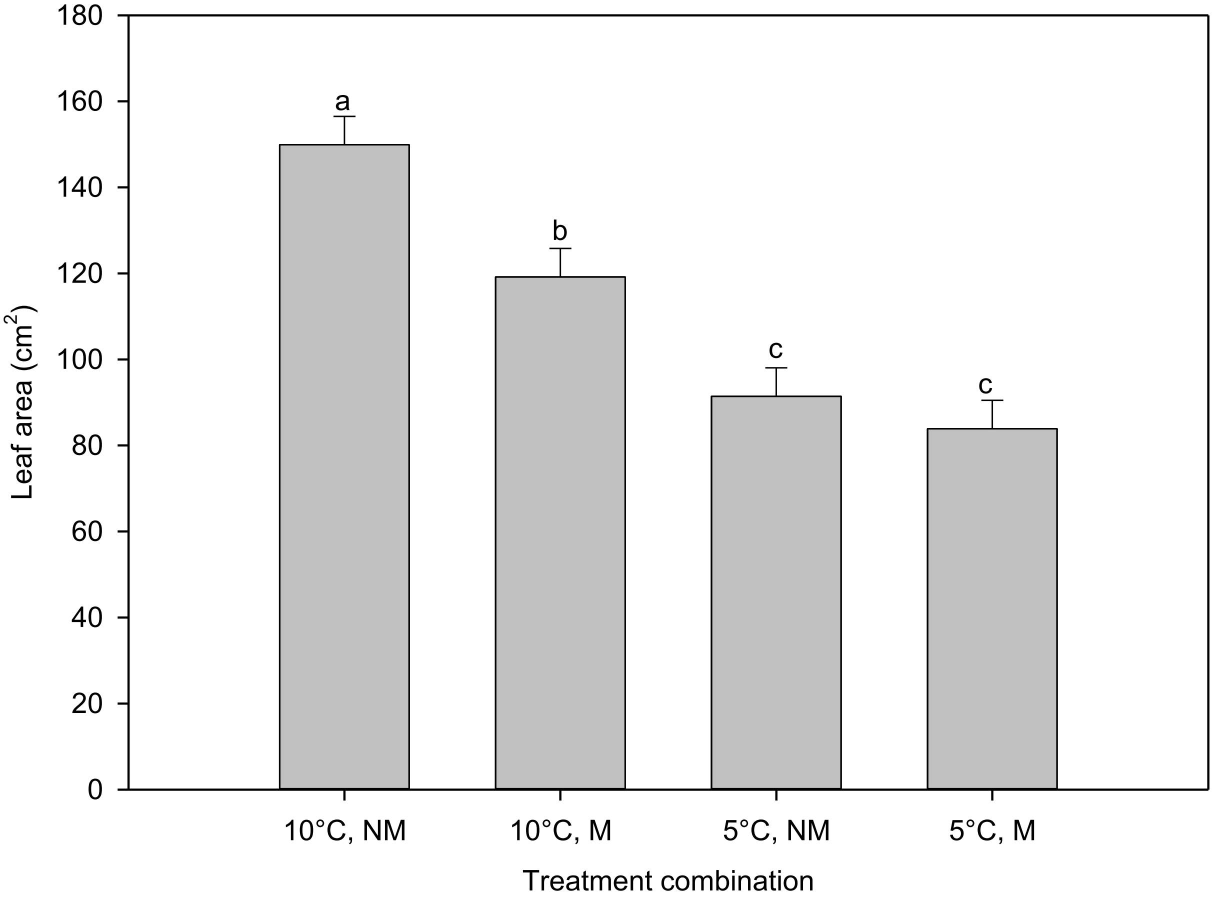
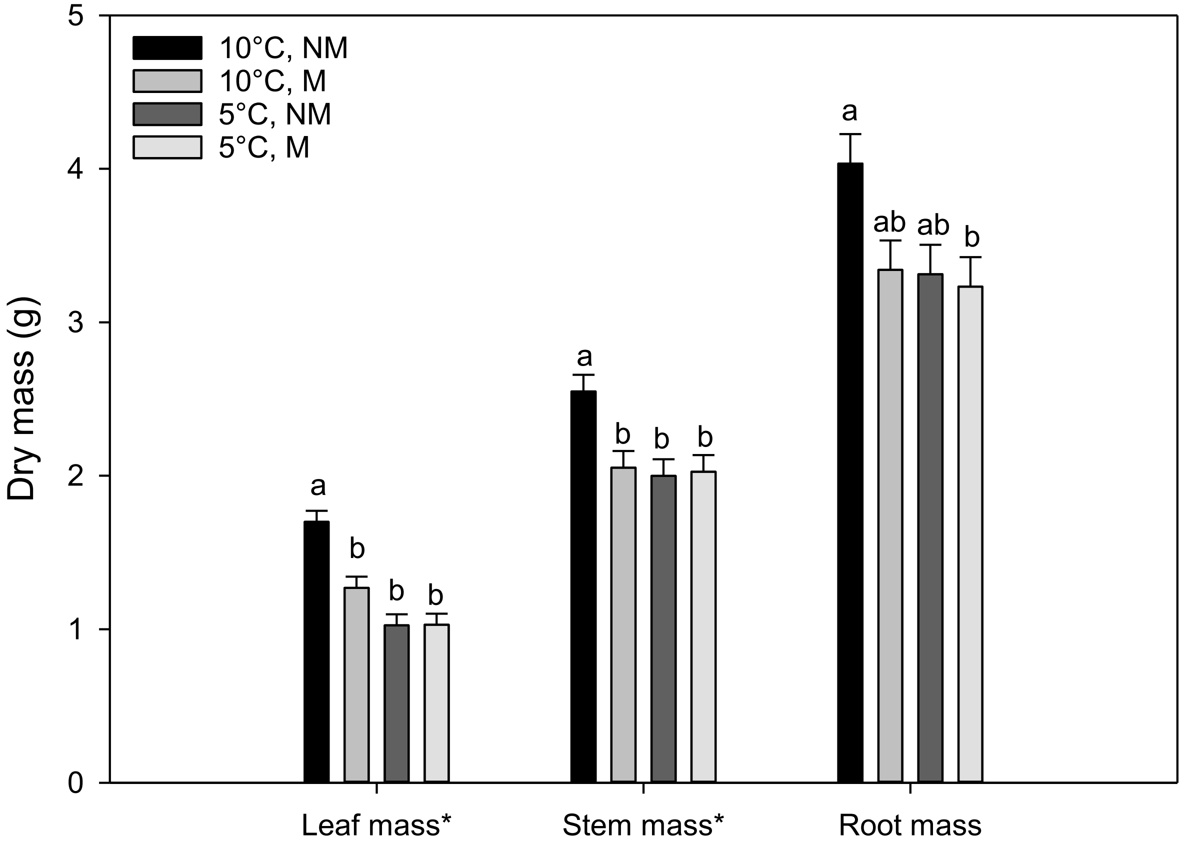


Figure 3-6. Leaf, stem, and root dry mass of *Populus tremuloides* seedlings (n=9) measured at the conclusion of a 70 day growth chamber experiment. Seedlings were started at 5 or 10˚C, with mulch (M) or without mulch (NM) and warmed to 20˚C. Different letters indicate statistical significance (α=0.05) between the means of treatment combinations. Asterisks indicate significant interaction between treatments.



CHAPTER 4. SYNTHESIS AND FUTURE RESEARCH

1. RESEARCH SUMMARY

Oil Sands Exploration (OSE) wells have to be drilled to evaluate and delineate oil resources needed for oil sands development. As 80% of the oil sands deposits have not been accessed and will be extracted using in situ methods (Government of Alberta 2014), OSE disturbance will continue to be an important disturbance in the northern boreal forest. The objective of this research was to examine the effects of OSE disturbance on coarse-textured soils that may affect *Populus tremuloides* Michx. (aspen) seedling regeneration. Disturbed and undisturbed coarse-textured soils at OSE sites were compared at different depths to determine changes in soil physical, hydrological, and chemical properties. In particular, this was also analyzed to determine if OSE disturbance homogenized the natural heterogeneous bedding of coarse-textured soils resulting in a decrease of plant available water (PAW).

OSE disturbance did homogenize the natural heterogeneous bedding of coarse-textured soils at all three depths analyzed (0 to 15 cm, 15 to 30 cm, and 30 to 45 cm). The mean % of particles did not change for any measured diameters; however, the standard deviation of soil particles at most measured diameters for disturbed soils was reduced. This suggests that OSE disturbance made the soil profile more homogeneous which could affect forest productivity (Huang et al. 2011; Zettl et al. 2011). In this study, the homogenization of soil did not translate to a decrease to PAW similar to Huang et al. (2011). Field capacity and wilting point increased in similar magnitudes so that PAW remained the same. This was likely due to the redistribution of small amounts of finer particles represented by the increased D_{10} value of disturbed soil. The D_{10} can be indicative of pore size as smaller particles have a greater influence on pore sizes (Mahmoodlu et al. 2016). Homogenization of the disturbed coarse-textured soil in this study likely decreased pore sizes resulting in the increases to field capacity and wilting point.

Bulk density increased by 14 to 15% with disturbance at 15 to 30 cm and 30 to 45 cm depths. Considering the majority of OSE activities are done in the winter, a 14 to 15% increase to coarse-textured soils is somewhat surprising. The observed increase to bulk density is likely from machinery traffic (Corns and Maynard 1998; Stone and Elioff 1998) when during soil replacement and recontouring activities. However, the highest observed density value of 1.5 g/cm^3 is not likely to limit root growth (Jones 1983; United States Department of Agriculture 2001). OSE disturbance decreased very coarse sand content, silt content, sodium adsorption ratio, and available ammonium and increased fine sand content, pH, electrical conductivity, calcium, potassium, carbon:nitrogen, and available nitrate. However, these parameters were at levels that were unlikely to result in poor forest regeneration on OSE sites on their own. Though mulch used during OSE reclamation did alter nutrient availability, changes were unlikely to affect forest regeneration during the length of this study with the exception of available ammonium.

Other than soil homogenization and available ammonium, soil properties affected by OSE disturbance that most likely result in poor forest regeneration included soil temperature. Similar patterns of soil temperature were observed at 5, 20, and 35 cm depths of coarse-textured OSE sites. The differences observed between treatments decreased with depth. Two observations of delayed soil warming could result in effects to forest regeneration especially *Populus tremuloides*, a cold sensitive species (Dang and Cheng 2004). One, there was a 2 week lag period in the spring where soil under mulch treatments remained below 1˚C but the bare soil treatment was above 1˚C. Two, in the surface depth, soil under mulch treatments took almost 4 weeks longer to warm to the 12˚C needed for sucker initiation (Fraser et al. 2002; Frey et al. 2003). In the fall, mulch treatments remained warmer than bare soil through to the end of the year. Temperature patterns were consistent with other studies (Larsson and Båth 1996; Iles and Dosmann 1999; Bulmer 2000; Maggard et al. 2012) and can result in impacts to *Populus tremuloides* growth (Corns and Maynard 1998; Landhäusser et al. 2007).

A growth chamber study was completed to further investigate the possible effects of delayed soil warming and mulch incorporation, identified from the first experiments, on the growth performance of Populus tremuloides and nutrient availability in coarse-textured soils. Two soil warming regimes and two substrate treatments were compared. Soil warming regimes were established to model temperature patterns observed in field plots. One started at 5˚C and warmed to 20˚C to simulate delayed soil warming associated with mulch use. The other started at 10˚C and warmed to 20˚C to simulate warming on sites when no mulch is used. The two substrate treatments used in the experiment were with and without mulch.

Delayed soil warming, mulch amendment, and their interaction affected *Populus tremuloides* seedling growth and soil nutrient availability. Effects of delayed soil warming were observed to both aboveground and belowground growth performance. Effects of mulch amendment were observed to aboveground growth performance. Delayed warming and mulch amendment interacted such that the seedlings started at 10˚C with no mulch treatment combination had greater aboveground growth performance than all other treatment combinations. The mulch amendment and delayed soil warming did not decrease nutrient availability in soil, as predicted, with the exception of available phosphorus. The lower available phosphorus was not reflected in changes to seedling phosphorus. Thus, it was unlikely that soil nutrient availability of measured parameters were responsible for changes to growth performance of seedlings. Because the seedlings started to set bud during the warming period, effects on additional parameters such as belowground growth could have been masked.

2. MANAGEMENT IMPLICATIONS

OSE disturbance homogenized the natural bedding of coarse-textured soils which altered the hydrological properties. As homogenization does not provide benefits for PAW and often can decrease PAW (Huang et al. 2011), efforts should be made to reduce soil homogenization on coarse-textured soils. Methods of drilling pad construction where the forest floor is protected could be used. Bachmann et al. (2015) demonstrated that *Populus tremuloides* growth was best when the forest floor was protected. This same method where the LFH and topsoil is not stripped but the forest floor is protected (Bachmann et al. 2015) would also protect the heterogeneity of the natural bedding in coarse-textured soils.

Many of the disturbed sites for this study had mulch depth above the 5 cm (Appendix A) allowed in legislation for public lands (Alberta Sustainable Resource Development 2009). Legislation also requires that the mulch not be incorporated in to the soil (Alberta Sustainable Resource Development 2009). The availability of nutrients in soil with mulch as a layer or incorporated were both greater than or equal to nutrient availability in soil with no mulch. Thus, the restriction of mulch as a layer and not to incorporate it on OSE sites in Alberta's boreal forest, may not be required.

As this study observed better growth performance of *Populus tremuloides* with seedlings were flushed at 10˚C without mulch, the use of mulch on OSE sites being revegetated to *Populus tremuloides* may not be beneficial. The delayed warming observed with mulch use may be important for sites that are being re-established to cold sensitive species like *Populus tremuloides* (Dang and Cheng 2004). On coarse-textured OSE sites, where *Populus tremuloides* and *Pinus banksiana* L. (jack pine) are common, mulch use may be unfavourable for their growth. The optimum temperature for total biomass was 22.4˚C for *Pinus banksiana* and 19.4˚C for *Populus tremuloides* compared to 16˚C for *Picea mariana* (Mill.) BSP (black spruce), and 13.7˚C for *Picea glauca* (Moench) Voss (white spruce; Peng and Dang 2003). The use of mulch could be limited to OSE sites being revegetated to species that can handle lower optimum soil temperature such as *Picea mariana* or *Picea glauca*. If mulch is used for reclamation on OSE sites, efforts should be made to reduce the effects of delayed warming and mulch presence. This could be done by using mulch in patches on the site and using woody debris of various sizes (mulch up to coarse woody debris). This would decrease effects with delayed warming and mulch because of the patches without mulch allowing soil warming and light. Different sized woody debris would also allow the same by allowing more solar radiation to reach the soil when larger pieces are used instead of just fine pieces. As an alternative to mulching, some of the cleared vegetation could be converted into biochar. It is possible that using the cleared vegetation in the form of a biochar could reduce some of the *Populus tremuloides* growth performance effects observed with delayed warming and mulch presence. The use of biochar as a soil amendment has shown positive effects for seedling productivity or soil nutrients in other applications such as coal and oil sands mining (Liu 2015; Dietrich et al. 2017). However, this alternative would require future research prior to application.

3. STUDY LIMITATIONS AND FUTURE RESEARCH

In Chapter 2, the original experiment was intended to be conducted on coarse-textured *Pinus banksiana* sites. After visiting the sites, the six sites selected were the closest in texture, vegetation, and age since disturbance (Appendix A). Though we found that coarse-textured soil was homogenized, this resulted in an increase to field capacity and wilting point and no change to PAW. The parent material textures, classified according to Bock et al. (2006), were a combination of L2 or C2. L2 has coarse-textured over fine-textured till where the change occurs between 30 and 100 cm (Bock et al. 2006). C2 has very coarse-textured soil through the 1 m profile (Bock et al. 2006). It is possible that sites that have L2 parent material textures could be homogenized but increase in field capacity, similar to this study, because of presence of the lower layer of fine-textured material. Whereas, a fully coarse-textured site might be homogenized decreasing field capacity similar to homogeneous sites in Zettl et al. (2011) and Huang et al. (2011). A comparison between layered and full coarse-textured material could be completed to evaluate this effect. We used three wide depths in this study (0 to 15 cm, 15 to 30 cm, and 30 to 45 cm). More granularity in depths would be helpful to explain changes in the heterogeneity.

Chapter 2 also investigates other changes to soil physical, hydrological, and chemical properties. Analysis of biological properties such as microbial activity and community structure, similar to Tiquia et al. (2002), on coarse-textured OSE sites in the northern boreal forest could be assessed. An evaluation of the properties over time and different textures would also be interesting to see which effects were short term versus long term.

In the mulch treatment plots, plots were established a few years after reclamation. It is possible that no mulch treatments, in terms of soil chemistry were already affected by mulch that was on the site previous to plot establishment. Completing this experiment right after soil reclamation but before any mulch was added or for a longer length of time would provide more clarity. Collecting data from these treatments over a longer length of time would also help determine if effects are short term or long term.

In Chapter 3, there were a few limitations and improvements that could be made. Based on Hankin (2015) soil temperatures during budflush were increased to 5 and 10˚C to hopefully observe bigger, more pronounced differences in growth. Soil temperatures of 5 and 10ºC were chosen for this study because at 5˚C root growth is inhibited and water uptake is significantly reduced while at 10ºC aspen can start to grow roots (Landhäusser and Lieffers 1998; Wan et al. 1999). An even greater difference between temperatures could be used if this experiment is repeated. Soil temperature treatments of 5˚C and 12˚C or greater could be used. Using a temperature of 10˚C, could still be affecting growth of *Populus tremuloides* (Fraser et al. 2002; Frey et al. 2003). Since the seedlings set bud during this experiment, seedling quality was considered to be a factor interfering with the observed growth results in this experiment. This could be similar to the low initial non-structural carbohydrates observed in seedling as discussed in Hankin (2015) possibly resulting in differences to growth response and budflushing. Non-structural carbohydrates were not measured as part of this study. As well, the same growth chamber was used for this experiment as in Hankin (2015). Potentially, growth chamber conditions such as low light could have also been a factor resulting in budset. The experiment should be repeated with seedlings from a different source or from seed and a different growth chamber to determine if the seedling source or growth chamber was a factor resulting in budset during this experiment.

As there were significant interactions of delayed warming and mulch incorporation on seedling performance, this should be explored further. Growth performance effects were observed with delayed soil warming, mulch, and their interaction. It is unknown if these effects would continue in to the fall when soil temperature with mulch would be warmer than soil with no mulch. It is possible that the differences in growth would disappear if the seedling had the same number of growing degree days. The experiment should be completed so that there is delayed warming at the start and delayed cooling at the end to allow the assessment of this possibility. The experiment could also be completed over two growing season. This would determine if seedlings would possibly recover from growth limitations in the fall or if growth limitations would compound yearly leading to poor survival. The mechanisms how of cold temperature and mulch incorporation reduces growth require further study. This could include examination of stress induced photosynthetic damage or hormone signaling, reduced light for photosynthesis, soil biological changes, and soil properties not measured as part of this study such as aeration and micronutrients.

Further research is required to determine if biochar would be a good alternative to mulch on coarse-textured OSE sites being revegetated to *Populus tremuloides*. This should include research on different species compositions, pyrolysis temperatures, and coarse-textured soil types and their effects on soil properties and growth performance in the short and long term.

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APPENDIX A. STUDY SITE SOIL INFORMATION SUMMARY

Table A-1. Study site soil information summary classified according to (Bock et al. 2006).

Site	Pit	Treatment	PM	Slope (%)	A	P	LFH (cm)	Mulch (cm)	TS (cm)	Sub-group	Soil Series
1	1	Undisturbed	L2	5-9	E	Mid	6	-	9	BR.GL	WNFzb
1	2	Undisturbed	C2	5-9	NW	Upper	13	-	13	E.DYB	MIL
1	3	Undisturbed	C2	5-9	W	Toe	7	-	10	O.GL	MILzl
1	1	Disturbed	C2	5-9	N	Mid	-	9	7	E.EB	MIL
1	2	Disturbed	C2	5-9	-	Crest	-	4	6	E.EB	MIL
1	3	Disturbed	C2	5-9	S	Upper	-	4	5	E.EB	MIL
2	1	Undisturbed	C2	9-15	N	Toe	4	-	10	O.GL	MILzl
2	2	Undisturbed	L2	2-5	S	Upper	5	-	12	O.GL	WNF
2	3	Undisturbed	C2	2-5	W	Toe	4	-	13	O.GL	MILzl
2	1	Disturbed	C2	9-15	N	Mid	-	20	0	DIS	-
2	2	Disturbed	L2	9-15	N	Mid	-	20	0	DIS	-
2	3	Disturbed	C2	9-15	N	Lower	-	30	0	E.DYB	MIL
3	1	Undisturbed	C2	5-9	W	Mid	5	-	30	E.DYB	MIL
3	2	Undisturbed	L2	2-5	NW	Upper	13	-	7	O.GL	WNF
3	3	Undisturbed	C2	9-15	S	Upper	8	-	18	E.DYB	MIL
3	1	Disturbed	C2	5-9	E	Upper	-	0	13	DIS	-
3	2	Disturbed	L2	5-9	E	Mid	-	0	19	GL.GL	WNFgl
3	3	Disturbed	C2	9-15	E	Upper	-	0	15	DIS	-
4	1	Undisturbed	L2	2-5	S	Lower	12	-	13	O.GL	WNF
4	2	Undisturbed	C2	5-9	N	Mid	9	-	25	E.DYB	MIL
4	3	Undisturbed	L2	5-9	N	Lower	5	-	8	E.EB	SUT
4	1	Disturbed	L2	5-9	N	Upper	-	4	15	DIS	-
4	2	Disturbed	C2	5-9	N	Crest	-	1	13	DIS	-
4	3	Disturbed	L2	5-9	N	Toe	-	1	15	DIS	-
5	1	Undisturbed	L2	5-9	N	Lower	9	-	9	O.GL	WNF
5	2	Undisturbed	C2	2-5	-	Mid	11	-	17	E.DYB	MIL
5	3	Undisturbed	C2	5-9	-	Crest	8	-	18	O.GL	MILzl
5	1	Disturbed	C2	2-5	-	Crest	-	1	9	DIS	-
5	2	Disturbed	L2	5-9	N	Mid	-	0	1	DIS	-
5	3	Disturbed	C2	5-9	N	Lower	-	0	15	DIS	-
6	1	Undisturbed	C2	2-5	-	Upper	17	-	15	O.G	BMT
6	2	Undisturbed	L2	-	N	Mid	17	-	9	GL.GL	WNFgl
6	3	Undisturbed	L2	5-9	N	Upper	10	-	15	E.DYB	SUT
6	1	Disturbed	C2	2-5	N	Toe	-	25	25	E.DYB	MIL
6	2	Disturbed	C2	2-5	N	Lower	-	9	0	DIS	-
6	3	Disturbed	L2	5-9	N	Mid	-	6	6	DIS	-

PM = parent material, A = aspect, P = Position, TS = topsoil depth

APPENDIX B. P-VALUES FOR STATISTICAL ANALYSES FROM CHAPTER 2

Table B-1. T-test results for the effect (α=0.05) of OSE disturbance on coarse-textured soil particle size distribution mean and standard deviation at a depth of 0 to 15 cm (n=6).

	t-test		
Soil property	Df	t Value	P>t
mean % particles < 1.0 mm	10	0.23	0.824
mean % particles < 0.5 mm	10	0.36	0.730
mean % particles < 0.25 mm	10	0.30	0.773
mean % particles < 0.105 mm	10	0.04	0.969
mean % particles < 0.053 mm	10	0.22	0.832
mean % particles < 0.02 mm	10	0.87	0.402
mean % particles < 0.006 mm	10	1.62	0.136
mean % particles < 0.002 mm	10	1.79	0.104
standard deviation % particles < 1.0 mm	10	-1.11	0.294
standard deviation % particles < 0.5 mm	10	-3.22	**0.009**
standard deviation % particles < 0.25 mm	10	-4.11	**0.002**
standard deviation % particles < 0.105 mm	10	-3.26	**0.009**
standard deviation % particles < 0.053 mm	10	-3.50	**0.006**
standard deviation % particles < 0.02 mm	10	-2.09	0.084
standard deviation % particles < 0.006 mm	10	-1.46	0.196
standard deviation % particles < 0.002 mm	10	-1.16	0.288

Table B-2. T-test results for the effect (α=0.05) of OSE disturbance on coarse-textured soil particle size distribution mean and standard deviation at a depth of 15 to 30 cm (n=6). Wilcoxon-Mann-Witney t-test results are presented for comparison purposes where means or standard deviations were not normally distributed.

	t-test			Wilcoxon-Mann-Whitney t-test (rank sums)	
Soil property	Df	t Value	P>t	Z	P>Z
mean % particles < 1.0 mm	10	1.35	0.206	-1.361	0.201
mean % particles < 0.5 mm	10	0.12	0.907	-0.080	0.938
mean % particles < 0.25 mm	10	-0.26	0.803	0.240	0.815
mean % particles < 0.105 mm	10	-0.22	0.829	n/a	n/a
mean % particles < 0.053 mm	10	-0.46	0.658	n/a	n/a
mean % particles < 0.02 mm	10	-0.18	0.862	n/a	n/a
mean % particles < 0.006 mm	10	0.09	0.931	n/a	n/a
mean % particles < 0.002 mm	10	0.42	0.687	n/a	n/a
standard deviation % particles < 1.0 mm	10	-4.25	**0.005**	n/a	n/a
standard deviation % particles < 0.5 mm	10	-2.67	**0.040**	n/a	n/a
standard deviation % particles < 0.25 mm	10	-2.02	0.076	1.842	0.093
standard deviation % particles < 0.105 mm	10	-4.04	**0.002**	2.642	0.023
standard deviation % particles < 0.053 mm	10	-3.79	**0.004**	n/a	n/a
standard deviation % particles < 0.02 mm	10	-3.78	**0.004**	n/a	n/a
standard deviation % particles < 0.006 mm	10	-2.85	**0.017**	n/a	n/a
standard deviation % particles < 0.002 mm	10	-2.77	**0.031**	n/a	n/a

Table B-3. T-test results for the effect (α=0.05) of OSE disturbance on coarse-textured soil particle size distribution mean and standard deviation at a depth of 30 to 45 cm (n=6). Wilcoxon-Mann-Witney t-test results are presented for comparison purposes where means or standard deviations were not normally distributed.

	t-test			Wilcoxon-Mann-Whitney t-test (rank sums)	
Soil property	Df	t Value	P>t	Z	P>Z
mean % particles < 1.0 mm	10	1.53	0.156	n/a	n/a
mean % particles < 0.5 mm	10	0.54	0.604	n/a	n/a
mean % particles < 0.25 mm	10	-0.21	0.841	n/a	n/a
mean % particles < 0.105mm	10	-0.83	0.429	0.400	0.697
mean % particles < 0.053mm	10	-1.32	0.218	1.201	0.255
mean % particles < 0.02mm	10	-1.41	0.189	1.201	0.255
mean % particles < 0.006 mm	10	-1.47	0.264	n/a	n/a
mean % particles < 0.002 mm	10	-1.45	0.177	n/a	n/a
standard deviation % particles < 1.0 mm	10	-1.33	0.213	n/a	n/a
standard deviation % particles < 0.5 mm	10	-1.37	0.201	n/a	n/a
standard deviation % particles < 0.25 mm	10	-2.47	0.054	n/a	n/a
standard deviation % particles < 0.105 mm	10	-3.53	**0.006**	n/a	n/a
standard deviation % particles < 0.053 mm	10	-4.14	**0.002**	n/a	n/a
standard deviation % particles < 0.02 mm	10	-3.17	**0.010**	n/a	n/a
standard deviation % particles < 0.006 mm	10	-2.11	0.061	n/a	n/a
standard deviation % particles < 0.002 mm	10	-1.58	0.145	n/a	n/a

Table B-4. Two-way ANOVA results for the effects (α=0.05) of OSE disturbance and depth on coarse-textured soil properties.

Soil property	Effect	Num Df	Den Df	F	P>F
Log D_{10} (cm) n=6	Disturbance	1	22	13.35	**0.001**
	Depth	2	22	1.45	0.255
	Disturbance*Depth	2	22	0.99	0.386
D_{60} (cm) n=6	Disturbance	1	25	0.10	0.758
	Depth	2	25	1.19	0.322
	Disturbance*Depth	2	25	0.35	0.708
Sand (%) n=6	Disturbance	1	25	1.29	0.267
	Depth	2	25	0.66	0.525
	Disturbance*Depth	2	25	1.09	0.350
Silt (%) n=6	Disturbance	1	25	4.57	**0.043**
	Depth	2	25	0.21	0.815
	Disturbance*Depth	2	25	0.03	0.969
Clay (%) n=6	Disturbance	1	25	0.01	0.943
	Depth	2	25	4.17	**0.028**
	Disturbance*Depth	2	25	3.35	0.052
Very coarse sand (%) n=6	Disturbance	1	25	6.79	**0.015**
	Depth	2	25	0.23	0.794
	Disturbance*Depth	2	25	1.35	0.279
Medium sand (%) n=6	Disturbance	1	25	0.24	0.626
	Depth	2	25	0.92	0.412
	Disturbance*Depth	2	25	7.69	0.633
Log fine sand (%) n=6	Disturbance	1	25	5.97	**0.022**
	Depth	2	25	0.46	0.636
	Disturbance*Depth	2	25	1.02	0.375
Bulk density (g/cm^3) n=6	Disturbance	1	25	22.28	**<0.001**
	Depth	2	25	29.08	**<0.001**
	Disturbance*Depth	2	25	5.14	**0.014**
θr (cm^3/cm^3) n=5	Disturbance	1	20	1.94	0.179
	Depth	2	20	0.36	0.701
	Disturbance*Depth	2	20	0.09	0.911
n (-) n=5	Disturbance	1	20	2.33	0.143
	Depth	2	20	1.04	0.371
	Disturbance*Depth	2	20	0.07	0.929

Df = degrees of freedom

Table B-4 (continued). Two-way ANOVA results for the effects (α=0.05) of OSE disturbance and depth on coarse-textured soil properties.

Field capacity (cm^3/cm^3) n=5	Disturbance	1	20	9.12	**0.007**
	Depth	2	20	2.49	0.108
	Disturbance*Depth	2	20	0.93	0.412
Log Wilting Point (cm^3/cm^3) n=5	Disturbance	1	20	13.51	**0.002**
	Depth	2	20	0.36	0.705
	Disturbance*Depth	2	20	0.33	0.723
Plant Available Water (cm^3/cm^3) n=5	Disturbance	1	20	0.23	0.635
	Depth	2	20	1.71	0.206
	Disturbance*Depth	2	20	0.43	0.654
pH (-) n=6	Disturbance	1	25	50.14	**<0.001**
	Depth	2	25	0.33	0.723
	Disturbance*Depth	2	25	0.48	0.623
Log Electrical Conductivity (dS/m) n=6	Disturbance	1	25	30.80	**<0.001**
	Depth	2	25	7.10	**0.004**
	Disturbance*Depth	2	25	0.13	0.881
Log SAR (-) n=6	Disturbance	1	25	14.71	**<0.001**
	Depth	2	25	9.75	**<0.001**
	Disturbance*Depth	2	25	0.37	0.695
Carbon:Nitrogen Ratio (-) n=6	Disturbance	1	25	12.84	**0.001**
	Depth	2	25	23.04	**<0.001**
	Disturbance*Depth	2	25	0.02	0.981

Df = degrees of freedom

Table B-5. Two-way permutation ANOVA results for the effects (α=0.05) of OSE disturbance and depth on coarse-textured soil properties.

Soil property	Effect	Df	SS	MS	Iterations	p-value
Coarse Sand (%) n=6	Disturbance	1	0.371	0.371	72	0.583
	Depth	2	6.633	3.316	595	0.348
	Disturbance*Depth	2	0.689	0.345	51	0.980
	Residuals	25	57.201	2.280		
Very fine sand (%) n=6	Disturbance	1	0.32	0.32	51	0.784
	Depth	2	6.11	3.05	356	0.354
	Disturbance*Depth	2	3.77	1.89	266	0.489
	Residuals	25	70.17	2.81		
Moisture Content (%) n=6	Disturbance	1	1.08	1.08	51	0.980
	Depth	2	118.79	59.40	237	0.515
	Disturbance*Depth	2	31.15	15.58	126	0.865
	Residuals	25	2086.96	83.48		
θ_S (cm^3/cm^3) n=5	Disturbance	1	0.0054	0.0054	681	0.129
	Depth	2	0.0643	0.0322	5000	**<0.001**
	Disturbance*Depth	2	0.0019	0.0009	170	0.772
	Residuals	20	0.0519	0.0026		
α (cm^{-1}) n=5	Disturbance	1	0.0042	0.0042	51	0.882
	Depth	2	0.0475	0.0237	636	0.274
	Disturbance*Depth	2	0.0264	0.0132	310	0.416
	Residuals	20	0.3100	0.0155		
Soluble Calcium (mg/kg) n=6	Disturbance	1	983.5	983.5	2501	**0.039**
	Depth	2	1709.8	854.9	4846	**0.049**
	Disturbance*Depth	2	48.8	24.4	51	0.941
	Residuals	25	6224.0	249.0		
Soluble Magnesium (mg/kg) n=6	Disturbance	1	27.3	27.3	106	0.491
	Depth	2	131.2	65.6	5000	**0.032**
	Disturbance*Depth	2	1.2	0.6	51	1.000
	Residuals	25	493.1	19.7		
Soluble Sodium (mg/kg) n=6	Disturbance	1	0.085	0.085	51	0.706
	Depth	2	0.010	0.005	51	1.000
	Disturbance*Depth	2	0.670	0.335	189	0.593
	Residuals	25	18.129	0.725		

Df=degrees of freedom, SS = sums of squares, MS = mean square error

Table B-5 (continued). Two-way permutation ANOVA results for the effects (α=0.05) of OSE disturbance (treatment) and depth on coarse-textured soil physical properties (n=5 or 6).

Soluble Potassium (mg/kg) n=6	Disturbance	1	8.5	8.5	5000	**0.009**
	Depth	2	59.7	29.8	5000	**<0.001**
	Disturbance*Depth	2	0.9	0.4	137	0.708
	Residuals	25	30.0	1.2		
Total Organic Carbon (%) n=6	Disturbance	1	0.20	0.20	51	0.706
	Depth	2	4.95	2.47	5000	**0.002**
	Disturbance*Depth	2	0.16	0.08	81	0.803
	Residuals	25	8.16	0.33		
Total Nitrogen (%) n=6	Disturbance	1	0.0001	0.0001	51	0.804
	Depth	2	0.0093	0.0046	5000	**0.014**
	Disturbance*Depth	2	0.0003	0.0001	60	1.000
	Residuals	25	0.0237	0.0009		
Available Ammonium (ug/g) n=6	Disturbance	1	0.62	0.62	56	0.980
	Depth	2	0.03	0.02	51	0.980
	Disturbance*Depth	2	3.33	1.67	331	0.447
	Residuals	25	66.05	2.64		
Available Nitrate (ug/g) n=6	Disturbance	1	1.30	1.30	2458	**0.040**
	Depth	2	0.10	0.05	100	0.720
	Disturbance*Depth	2	0.08	0.04	63	0.778
	Residuals	25	7.38	0.30		

Df=degrees of freedom, SS = sums of squares, MS = mean square error

Table B-6. T-test results for the effect (α=0.05) of OSE disturbance on coarse-textured soil repellency and unsaturated hydraulic conductivity (n=6).

Soil property	Df	t Value	P>t
Repellancy (mL/min)	10	-0.65	0.527
Unsaturated hydraulic conductivity (cm/s)	10	-1.3	0.222

Df = degrees of freedom

Table B-7. ANOVA results for the effects (α=0.05) of soil treatments on coarse-textured soil plant nutrient availability measured by resin analysis on Plant Root Simulator (PRS™) probes for a 34 day burial period (n=3).

Soil property	Effect	Num Df	Den Df	F	P>F
prs Ammonium-N (μg/10cm^2)	Treatment	3	6	9.97	**0.010**
prs Calcium (μg/10cm^2)	Treatment	3	6	5.03	**0.043**
prs Magnesium (μg/10cm^2)	Treatment	3	6	25.80	**<0.001**
prs Potassium (μg/10cm^2)	Treatment	3	6	0.43	0.736
prs Phosphate (μg/10cm^2)	Treatment	3	6	0.80	0.538
prs Iron (μg/10cm^2)	Treatment	3	6	2.33	0.174
prs Manganese (μg/10cm^2)	Treatment	3	6	4.96	**0.046**
prs Zinc (μg/10cm^2)	Treatment	3	6	2.20	0.189
prs Sulphur (μg/10cm^2)	Treatment	3	6	0.47	0.711
prs Aluminum (μg/10cm^2)	Treatment	3	6	0.77	0.552

Df = degrees of freedom

Table B-8. Permutation ANOVA results for the effects (α=0.05) of soil treatments on coarse-textured soil plant nutrient availability measured by resin analysis on Plant Root Simulator (PRS™) probes for a 34 day burial period (n=3).

Soil property	Effect	Df	SS	MS	Iterations	p-value
prs Total Nitrogen (μg/10cm^2)	Treatment	3	2212.50	737.49	398	0.573
	Residuals	6	5062.20	843.70		
prs Nitrate-N (μg/10cm^2)	Treatment	3	2450.60	816.87	299	0.632
	Residuals	6	5059.30	843.21		
prs Copper (μg/10cm^2)	Treatment	3	0.25	0.08	555	0.479
	Residuals	6	0.50	0.08		
prs Boron (μg/10cm^2)	Treatment	3	14.92	4.97	331	0.728
	Residuals	6	38.83	6.47		

Df=degrees of freedom, SS = sums of squares, MS = mean square error

APPENDIX C. P-VALUES FOR STATISTICAL ANALYSES FROM CHAPTER 3

Table C-1. Two-way ANOVA results for the effects (α=0.05) of delayed soil warming and mulch incorporation on measured growth parameters of *Populus tremuloides* seedlings after the budflush period (Day 17).

Seedling Measurement	Effect	Num Df	Den Df	F	P>F
Height (cm)	Warming	1	32	0.37	0.547
	Mulch	1	32	0.50	0.486
	Warming*Mulch	1	32	0.95	0.338
# of Leaves	Warming	1	32	0.46	0.502
	Mulch	1	32	0.96	0.334
	Warming*Mulch	1	32	4.63	**0.039**
Leaf area (cm^2)	Warming	1	32	5.59	**0.024**
	Mulch	1	32	2.50	0.124
	Warming*Mulch	1	32	0.31	0.579
Leaf mass (g)	Warming	1	32	4.13	0.051
	Mulch	1	32	1.11	0.301
	Warming*Mulch	1	32	0.70	0.408
Stem mass (g)	Warming	1	32	0.44	0.513
	Mulch	1	32	0.27	0.605
	Warming*Mulch	1	32	1.17	0.288
Root volume (cm^3)	Warming	1	31	1.40	0.246
	Mulch	1	31	1.10	0.302
	Warming*Mulch	1	31	0.27	0.609
Nitrogen (%)	Warming	1	16	0.96	0.341
	Mulch	1	16	7.97	**0.012**
	Warming*Mulch	1	16	0.19	0.666
Phosphorus (%)	Warming	1	16	0.04	0.836
	Mulch	1	16	4.24	0.056
	Warming*Mulch	1	16	0.90	0.358
Potassium (%)	Warming	1	16	0.86	0.366
	Mulch	1	16	7.80	**0.013**
	Warming*Mulch	1	16	0.27	0.613
N^{15} (%)	Warming	1	16	4.24	0.056
	Mulch	1	16	11.98	**0.003**
	Warming*Mulch	1	16	8.10	**0.012**

Df = degrees of freedom

Table C-2. Permutation ANOVA results for the effects (α=0.05) of delayed soil warming and mulch incorporation on measured growth parameters of *Populus tremuloides* seedlings after the budflush period (Day 17).

Seedling Measurement	Effect	Df	SS	MS	Iterations	p-value
# of Branches	Warming	1	1.78	1.78	103	0.495
	Mulch	1	0.11	0.11	51	0.804
	Warming*Mulch	1	44.44	44.44	5000	**0.015**
	Residuals	32	204.22	6.84		
Root mass (g)	Warming	1	0.021540	0.215360	92	0.522
	Mulch	1	0.005660	0.005658	51	0.902
	Warming*Mulch	1	0.070800	0.070800	90	0.533
	Residuals	32	3.161080	0.908784		

Df = degrees of freedom; SS=sum of squares; MS=mean squares

Table C-3. Two-way ANOVA results for the effects (α=0.05) of delayed soil warming and mulch incorporation on seedling nutrition of *Populus tremuloides* seedlings after the warming period (Day 44).

Seedling Measurement	Effect	Num Df	Den Df	F	P>F
Nitrogen (%)	Warming	1	16	0.80	0.383
	Mulch	1	16	4.03	0.062
	Warming*Mulch	1	16	0.43	0.522
Phosphorus (%)	Warming	1	16	9.49	**0.007**
	Mulch	1	16	1.06	0.320
	Warming*Mulch	1	16	0.58	0.457
Potassium (%)	Warming	1	16	0.02	0.883
	Mulch	1	16	0.65	0.430
	Warming*Mulch	1	16	0.29	0.595
N^{15} (%)	Warming	1	16	2.20	0.157
	Mulch	1	16	<0.01	0.990
	Warming*Mulch	1	16	0.02	0.885

Df = degrees of freedom

Table C-4. Two-way ANOVA results for the effects (α=0.05) of delayed soil warming and mulch incorporation on growth parameters of *Populus tremuloides* seedlings at the conclusion of the experiment (Day 70).

Seedling Measurement	Effect	Num Df	Den Df	F	P>F
Height (cm)	Warming	1	32	0.35	0.558
	Mulch	1	32	0.02	0.884
	Warming*Mulch	1	32	0.60	0.444
# of Branches	Warming	1	32	1.13	0.296
	Mulch	1	32	4.26	**0.047**
	Warming*Mulch	1	32	2.07	0.160
# of Leaves	Warming	1	32	6.16	**0.019**
	Mulch	1	32	1.92	0.176
	Warming*Mulch	1	32	0.32	0.573
Leaf area (cm^2)	Warming	1	32	50.25	**<0.001**
	Mulch	1	32	3.06	0.090
	Warming*Mulch	1	32	8.37	**0.007**
Leaf mass (g)	Warming	1	32	39.99	**<0.001**
	Mulch	1	32	8.65	**0.006**
	Warming*Mulch	1	32	9.01	**0.005**
Stem mass (g)	Warming	1	32	6.85	**0.013**
	Mulch	1	32	4.58	**0.041**
	Warming*Mulch	1	32	5.69	**0.023**
Root mass (g)	Warming	1	32	4.66	**0.038**
	Mulch	1	32	4.06	0.053
	Warming*Mulch	1	32	2.56	0.120
Root volume (cm^3)	Warming	1	32	0.47	0.497
	Mulch	1	32	3.19	0.083
	Warming*Mulch	1	32	0.19	0.663

Df = degrees of freedom

Table C-5. Two-way ANOVA results for the effects (α=0.05) of delayed soil warming and mulch incorporation on soil properties at the conclusion of the growth chamber experiment (Day 70).

Soil property	Effect	Num Df	Den Df	F	P>F
pH (-)	Warming	1	16	0.06	0.817
	Mulch	1	16	19.93	**<0.001**
	Warming*Mulch	1	16	0.06	0.817
Available NH_4^+ (mg/kg)	Warming	1	16	0.55	0.468
	Mulch	1	16	0.85	0.371
	Warming*Mulch	1	16	4.49	0.050
Available NO_3^- (mg/kg)	Warming	1	16	6.23	**0.024**
	Mulch	1	16	0.02	0.886
	Warming*Mulch	1	16	0.06	0.812
Available PO_4^{3-} (mg/kg)	Warming	1	16	10.57	**0.005**
	Mulch	1	16	30.16	**<0.001**
	Warming*Mulch	1	16	3.73	0.071
Available K^+ (mg/kg)	Warming	1	16	0.06	0.815
	Mulch	1	16	17.08	**<0.001**
	Warming*Mulch	1	16	3.73	0.071
TOC (%)	Warming	1	16	1.24	0.281
	Mulch	1	16	40.85	**<0.001**
	Warming*Mulch	1	16	1.69	0.212
N^{15} (%)	Warming	1	16	0.56	0.466
	Mulch	1	16	0.23	0.640
	Warming*Mulch	1	16	0.04	0.836

Df = degrees of freedom

Table C-6. Permutation ANOVA results for the effects (α=0.05) of delayed soil warming and mulch incorporation on soil properties at the conclusion of the growth chamber experiment (Day 70).

Soil property	Effect	Df	SS	MS	Iterations	p-value
TN (%)	Warming	1	0.000005	0.000005	65	0.615
	Mulch	1	0.000845	0.000845	5000	**<0.001**
	Warming*Mulch	1	0.000125	0.000125	969	0.094
	Residuals	16	0.000520	0.000033		

Df = degrees of freedom; SS=sum of squares; MS=mean squares