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The effects of subsoil ripping on soil physical properties and soil water dynamics on reconstructed soils at Genesee Prairie Mine, Alberta.

by

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Abstract

Surface mining activities have significantly depleted natural tree cover, especially trembling aspen (*Populus tremuloides*), in the Boreal Forest and Aspen Parkland Natural Regions of Alberta. The natural soil profile is usually destroyed during these mining activities and soil and landscape reconstruction is typically the first step in the reclamation process. However, the mine tailings and overburden materials used for these new soils often become compacted during the reconstruction process because they are subjected to high amounts of traffic with heavy equipment. Compacted soils generally have low porosity and low penetrability through increased soil strength, making it difficult for roots to elongate and explore the soil. Compaction also reduces infiltration capacity and drainage, which can cause excessive runoff and soil erosion. To improve the pore size distribution and water transmission, subsoil ripping was carried out in a test plot at Genesee Prairie Mine, Alberta. Within the site, six replicates with two treatments each, unripped (compacted) and ripped (decompacted), were established with 20-m buffers between them. The main objective of this research was to characterize the effects of subsoil ripping on soil physical properties as well as soil water dynamics during spring snowmelt. Results showed improved bulk density, pore size distribution and water infiltration in the soil as a result of the deep ripping. The ripping treatment likely improved the soil physical properties with respect to aspen revegetation.

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1. Chapter 1 – General Introduction

1.1 Background

Mining activities have significantly depleted natural tree cover, especially dominant tree species trembling aspen (*Populus tremuloides*), in the Boreal Forest and Aspen Parkland Natural Regions of Alberta (Peltzer et al. 2000; McCartney 1993). Soil reconstructed with mine tailings and overburden is commonly seeded to agricultural cover crops. Reclamation to agricultural land use may be a viable reclamation endpoint depending on regulations (i.e., the White Zone of Alberta), but agricultural cover crops may also be used to initially improve soil conditions for later introduction of native species. Cover crops increase organic matter, moisture retention properties and decrease the risk of soil erosion (Pollster 2000). Common species used include barley, legumes, agronomic grasses and alfalfa because of their economic importance and their ability to rapidly establish in a variety of soil conditions. These species however do not accurately represent the natural biodiversity of the landscape and do not meet long term reclamation goals. Therefore, native species are being used more frequently to restore natural vegetation cover which has become an increasingly important objective in ecosystem reconstruction in the White Zone of Alberta (AESRD 2014).

Revegetation with trees may be unsuccessful on reclaimed mine soils due to poor soil quality after disturbance (Mukhopadhyay et al. 2013). Subsoil compaction is a common problem in areas with heavy site traffic such as cultivated land and mined areas or areas undergoing soil reconstruction and is likely the cause of poor tree establishment and growth. Compaction can occur naturally such as through the formation of a fragipan horizon however, it most commonly occurs from the weight of heavy machinery on the land surface compressing the soil and reconstruction activities (Khan et al. 2012). According to Hamza and Anderson (2005), compaction is defined as "the process by which soil grains are rearranged to decrease void space and bring them into closer contact with one another, thereby increasing the bulk density". Vegetation growth is reduced in compaction-affected environments as the result of reduced plant-available water through increased bulk density and soil strength (Banjita and Rao 2012) and reduced infiltration (van Dijck and van Asch 2002). Heavy compaction alters the soil pore size distribution, reduces plant available water, and aeration, and, as a result, may alter the soil water balance via reduced infiltration and drainage. This is due to the reduction in large pore spaces (macropores) because macoaggregates are rearranged so that they are closer together.

A method of alleviating subsoil compaction is through subsoil ripping. Subsoil ripping involves decompacting heavily compacted subsoil by “ripping” up the hard pans to break up soil aggregates and increase large pore spaces (macropores). Subsoil ripping has been shown to be beneficial for improving soil physical and water balance properties in studies by Chapman and Allbrook 1987; Harrison et al. 1994; Sojka et al. 1997; Sojka et al. 1993. This in turn has led to better conditions for vegetation establishment and growth. Research on the influence of subsoil ripping to improve soil physical conditions, soil-pore size distribution and soil water dynamics is important for ecosystem reconstruction in Alberta.

1.2. Natural Regions of Alberta – Boreal and Parkland

The site where the research described in this thesis was carried out straddles the Central Parkland and Dry Mixedwood subregions in Alberta. The Boreal Forest Natural Region occupies most of Northern Alberta, extending to south-central Alberta. This region makes up approximately 58% of the province and covers a total area of 381,046 km^2 of land (Natural Regions Committee 2006). The Boreal forest has many sub-regions; the sub-region of interest in this project is the Dry Mixedwood Natural sub-region, located in the north-west and central areas of Alberta. Other sub-regions include the Central Mixedwood, Upper Boreal Highlands, Athabasca Plain, Peace-Athabasca Delta, Northern Mixedwood, and the Boreal Subarctic Natural Subregions. The Dry Mixedwood covers an estimated 22% of the Boreal Forest area and is characterized by warmer summers and milder winters than most other Boreal sub-regions (Natural Regions Committee 2006). Climate in the Boreal is predominantly characterized by short, warm, moist summers and long, severely cold, dry winters (Bonan and Shugart 1989). Precipitation ranges between 400-500 mm annually, peaking in the months of June and July (Natural Regions Committee 2006).

The Boreal is vegetated by deciduous, mixedwood and coniferous forest. Dominant deciduous vegetation includes trembling aspen (*Populus tremuloides*) and balsam poplar (*Populus balsamifera*). The dominant terrain of the Dry Mixedwood varies from level to gently undulating glacial till or lacustrine plains to hummocky uplands (Natural Regions Committee 2006). Soils in these areas are dominantly Orthic Gray Luvisols on moderately-well to well-drained forested sites. Dry areas include steep, south and west facing slopes and make up a small percent of the land. Common vegetation in these areas includes porcupine grass (*Stipa spartea*), june grass (*Koeletia macrantha*) and sedge species, commonly found on Chernozems.

The majority (~90%) of the Boreal forest area is crown land and is regulated under the Alberta Forest Service Division. This is known as the “Green Zone” of the province, although some areas of “White Zone” (privately owned) land are interspersed. Common disturbances in the Boreal include cultivation and tree harvesting as well as mining. Over 50% of the Dry Mixedwood sub-region has been cultivated for forage crops while the pulp and paper industry has had an effect on aspen forests due to aspen harvesting from timber industries (Natural Regions Committee 2006). The most arguably severe disturbances in the Boreal however are from oil and gas and coal mining activity. The majority of oil deposits in Canada are found in Northern Alberta and large scale mining has occurred since 1967 (Deming 2000).

The Parkland Natural Region or Aspen Parkland Region is adjacent to the Boreal Forest Natural Region and is located within the western Canadian provinces, extending south into the United States. In Alberta, the Parkland Region includes three sub-regions located in geographically different areas; the Foothills Parkland, Peace River Parkland and the Central Parkland sub-region. Characteristics of the Parkland make it exclusive to the prairies, particularly the climatic transition between the cooler, northern boreal and warmer, southern grassland eco-regions (Natural Regions Committee 2006).

Approximately 9% of the province is Parkland and covers an estimated 60,747 km^2 of land (Natural Regions Committee 2006). Seasonal climate is extreme between short, hot summers and long, cold, snow-covered winters. The Parkland is warmer and drier than the Boreal, with a mean annual temperature of approximately 2^{o}C (Natural Regions Committee 2006). Topography is mostly level to gently undulating and composed mainly of glacial sediments such as glacial till (Natural Regions Committee 2006).

Parkland soil characteristics allow the support of woody vegetation in forested areas and healthy grass stands in grassland areas (Natural Regions Committee 2006). Dominant soil types include Black Chernozems in grassland areas (Groveland) and Dark Gray Chernozems in forested areas (Northern). Dominant woody vegetation includes trembling aspen (*Populus tremuloides*) and balsam poplar (*Populus balsamifera*). Dominant grasses include plains rough fescue (*Festuca hallii*) and foothills rough fescue (*Festuca campestris*). Willows are dominant in shrubland areas. Weather and land characteristics of the Parkland make it favorable for cultivation, especially the dark, nutrient rich Chernozemic soils. These soil types tend to be well-aerated and have high water holding capacities due to soil structure characteristics.

The majority of the Parkland is privately owned and is primarily “White Zone” land. Municipal governments are responsible to assure land use modifications are efficiently regulated in these areas. Public land areas (Green Zones) of the Parkland are regulated under the Public Lands Division of Alberta. The Parkland Region is considered to be the most developed region in the province due to human influence from industrial development (Adams et al. 2003). Exact numbers have not been well documented but it is believed that less than 10% of native vegetation cover remains in the Parkland today (Adams et al. 2003).

1.3. Alberta Coal Mining

Boreal and Parkland areas in Alberta are highly affected by mining activities from major oil sands and coal mining operations. The majority of Alberta’s oil sands are located in the Boreal forest (Athabasca region) and much of the land has been disturbed to accommodate mining activities. To date, 530-km^2 of land has been cleared as a result of oil sands mining (Alberta Environment 2011). Many coal mines are also situated in Boreal and Parkland areas. The largest coal mine in the province is the Highvale mine and has been operating since 1970. It is located 80-km west of Edmonton (south of Wabamun) and has recently been taken under management by SunHills Mining Limited in early 2014. This mine produces 12.6 million tonnes of coal annually (AESRD 2012).

Coal mining has had a significant impact on the Canadian economy. The majority (70%) of Canada's total coal reserves are in Alberta, making it the largest producer in the country (Alberta Industry and Economy 2013). Coal in Alberta is primarily bituminous or sub-bituminous, otherwise known as black coal. There is high global demand for this type of coal because of its high energy characteristics. Coal is Canada's most abundant fossil fuel with currently 33 billion tons of coal remaining to be mined in Alberta alone (Alberta Energy 2012).

There are two primary mining techniques that can be used depending on the depth of the resource: surface mining and underground or in-situ mining. Surface mining is most common in Alberta and has two different methods: strip mining and open-pit mining. Strip mining is done by exposing the resource through removal of surface layers in long strips (Oil Sands Developers Group 2009). After the resource has been removed, the overburden or surface layers that were removed in order to extract the resource are replaced and a new (adjacent) strip is created. This process is repeated until all of the resource is extracted. These techniques are only viable if the resource is close to the surface. Over 31,000-ha of land in Alberta have been disturbed as a result of coal mining since the end of 2010 (AESRD 2012).

Surface mining is one of the most destructive forms of human-caused habitat alteration and degradation (Shrestha and Lal 2011). Large areas disturbed from mining can take many years to reclaim. Reconstructing a new ecosystem after disturbance is important for resuming important ecological processes. This is done through reclamation activities.

1.4. Ecosystem Reconstruction and Approaches to Reclamation in Alberta

When disturbance or mining activities are completed, the next steps are to reclaim the disturbed landscape. It is important to reclaim mined land to be safe, stable and productive land and should be well-managed for sustainable use (Maryati 2013). Both agricultural (White Zone) and forestry (Green Zone) techniques are used for reclamation which has resulted in multiple reclamation objectives (Powter 2011). Privately owned areas of the White Zone are commonly used for farming, grazing, agriculture and mining activities. Areas affected by disturbance in the White Zone are commonly reclaimed to agriculture end uses due to high development potential (favorable soil) but may be later reclaimed to native species. Determination of the end use of land reclaimed from mining must be carried out carefully by considering the physical soil properties, topography condition, microclimate, and risk hazard to achieve a sustainable and productive use (Maryati 2013). The areas of the province that occupy the Green Zone consists of crown land which is subject to governing rules (provincial government) with consistent standards with respect to reclamation (Powter 2011). Common land uses include recreation, tourism, timber production, conservation and oil and gas. Disturbed areas are usually not suitable for cultivation and cannot be developed for agriculture as the law states reclaimed land must function comparably to pre-disturbance conditions (reforested). "Development of wildlife habitat and return of commercial forestry are key reclamation objectives in the Green Zone" (Powter 2011).

Mining industries in the province are regulated by the *Environmental Protection and Enhancement Act* (EPEA) under the Alberta Government. The EPEA has set guidelines that industries must follow that promote restoration of the disturbed land. Land must be capable of supporting a wide range of uses that are comparable to pre-disturbance uses (Alberta Environment 2011). When a site is ready to be reclaimed, there are 3 Environmental Site Assessment Phases that must be completed before certification can be granted. Phase I involves site visits, operator interviews, aerial photos and development of site history. This phase also involves identifying the presence or absence of contaminants and their distribution in the environment (air, ground water, etc.). Phase II consists of collecting soil and groundwater samples and in-depth testing for contaminants and risk assessments. Phase III involves soil contaminant removal (remediation) and future confirmatory sampling for the lowest possible allowable contaminant concentrations outlined under the Alberta Tier 1 and 2 guidelines. After successful remediation, topsoil is placed on the site and vegetation is reestablished. Land needs to be monitored for many years to assure healthy growth of vegetation and that any contaminants stay at or below criteria. Operators can apply for reclamation certification after the final stages are met and when the reclaimed portion performs equivalent to the surrounding areas or to predisturbance consitions. It can take many years to reach certification because of difficulty in achieving a full self-sustaining ecosystem after disturbance. “Reclamation certificates are issued when monitoring over time demonstrates the land is at least as ecologically productive as it was before the area was mined” (AESRD 2009).

It is difficult to initially reclaim disturbed areas to native tree species due to disturbed soil conditions. Different trees have varying degrees of ameliorative effects on reconstructed soils on mine sites and therefore the survival and performance of the planted species varies in coal mining areas (Mukhopadhyay et al. 2013). Cover crops including oats, legumes and barley help improve soil conditions by adding organic matter to the soil, improving water infiltration capabilities, reducing erosion and providing protection for seedlings (Pollster 2000; AESRD 2014). It is common for annual cover crops to be initially seeded prior to native tree and shrub planting (Pollster 2000; AESRD 2014). These species tend to meet short-term reclamation goals and acceptable land use needs and help conserve the soil for future reclamation. However, the promotion of native species for reclamation is important to restore ecosystem functioning in disturbed areas of the White Zone. Of the 31,000-ha of disturbed land due to coal mining activities, over 15,500-ha or 49% has been either permanently or temporarily reclaimed since the end of 2010 (AESRD 2012).

Considering the importance of ecosystem health and long-term sustainable functioning, reclaimed soil must be capable of performing a wide range of processes, including the support of vegetation. One of the functions of soil is to store and supply water and nutrients for plant growth. Without healthy soil, vegetation cannot flourish. Achieving proper soil conditions is very difficult once disturbance has been mitigated. Mining negatively impacts physical, chemical and biological properties of mine soils (Shrestha and Lal 2011). However once proper soil conditions are met, the establishment of vegetation can further increase soil quality and fertility. Establishment of tree cover in mine degraded soil helps to improve soil quality through the buildup of organic matter, reduced erosion, develop microbial communities, initiate nutrient cycling and enhance overall aesthetics of the area (Mukhopadhyay et al. 2013).

1.5. Soil Physical Properties

1.5.1 Soil Structure and the Pore System

Soil is highly complex and constantly evolving in the environment therefore, its structure is difficult to define (Hillel 1980). There are 4 main components that make up soil: particles, water, organic matter and air. Structure is dependent on the amounts of each of these constituents and their orientation in the soil, along with other environmental factors such as salinity and pH (McCauley et al. 2005). According to Hillel (1980), a soil's ability to respond to environmental stressors such as tillage, traffic and rain impact are all dependent on soil structure. Most importantly, however, soil structure is defined by the arrangement of aggregates and pores and the interactions between particles (Hillel 1980). Porosity, which is defined as the amount of pores or voids in the soil for water, nutrient and gas transport are very dynamic in time and space and highly variable in soil. A soil's ability to retain water and nutrients and keep them readily available for vegetation determines the quality of soil and its function in the environment.

Aggregates are the building blocks of soil that make up the soil skeleton. Aggregates are classified as microaggregates or macroaggregates. Microaggregates are the smaller building blocks or individual peds that make up the soil matrix. Many microaggregates bind together to form macroaggregates, which are the larger structural units that determine the soils stability. Spaces between macroaggregates (macropores) are responsible for water and air movement in the soil (Hoorman et al. 2009; Hillel 1980). Different levels of aggregation exist and determine the level of resistance to environmental processes. The arrangement of aggregates in the soil affects total porosity and pore size distribution.

The pore size distribution of a soil affects many soil functions (Hoorman et al. 2009). The largest and smallest pores are referred to as macropores and micropores, respectively. Micropores are the tiny pores (air or water filled) formed by the tight packing arrangement of individual peds or microaggregates. These pores are smaller than 0.08-mm (Brady and Weil 2002). Micropores hold matrix water via tight capillary bonds and surface adsorption. Soils with many micropores have high water holding capacities and generally have high pore volumes. However, water movement in micropores is slow and the water held in the smallest micropores is not available to plants. High clay soils have many micropores. "Up to half of the water held by clay soils is held so tightly in micropores that it cannot be removed by growing plants" (Brady and Weil 2002). Macropores are the larger pores formed from the loose packing of soil structural units or between macroaggregates (Brady and Weil 2002). These pores are larger than 0.08-mm and are responsible for the transport of structural water, air, gas and nutrients in the soil (Brady and Weil 2002). High amounts of macropores are found in soils with many large particles, such as sandy soils. They are also found in soils with many large cracks and well-structured soils with macroaggregates. Sandy materials have low porosity but high water flow capabilities because of large pore sizes. Water drains quickly in large macropores (gravitational flow) due to weak capillary forces. Pore sizes range widely in soil and depend on the distribution of particle sizes, soil texture, and packing arrangement.

Well-structured soils with different pore sizes and many large macroaggregates are the most desirable soil for most uses (Brady and Weil 2002). Loamy textured, highly aggregated soils have ideal pore size distributions with balanced amounts of both macro- and micropores. Loamy soils provide enough drainage during periods of heavy saturation along with retaining adequate amounts of water during drier periods for use by vegetation. Other environmental factors can impact soil porosity including organism activity through burrowing animals and anthropogenic influences such as tilling processes.

1.5.2 Soil Water Balance

As discussed, one of the most important soil characteristics for vegetation is the ability to retain water and nutrients and readily transmit them to plant roots. The amount of plant-available water is determined by the soil pore size distribution, precipitation patterns and groundwater. Plant-available water is the difference between field capacity and permanent wilting point (Kirkham 2004). Soils with higher amounts of medium to small sized pores tend to have the highest plant-available water, such as loamy soils.

Soil water can either be available or unavailable to plants. During periods of heavy saturation, all the pores are filled with water and gravitational water can drain freely from macropores. This water is unavailable to plants because it drains too quickly for plants take up and use. Once all the gravitational water has gone, field capacity is reached where remaining water in pores, capillary water, is held in medium and small sized pores. Capillary water is easily removed by plant roots or evapotranspiration (McCauley et al. 2005) and is plant-available water. Once all the capillary water is gone, residual water remains in the smallest pores. This water cannot be taken up by plants due to strong adsorptive forces with soil particles. If capillary water is not replaced with precipitation, then permanent wilting point is reached and plant mortality may occur if the soil remains dry.

Water is also lost from the soil through evapotranspiration. This is a term that couples transpiration (water lost from plants) and evaporation (water lost from surface) and refers to water lost to the atmosphere. The pathway through which evapotranspiration occurs is called the Soil-Plant-Atmosphere Continuum (SPAC). SPAC considers how the soil, vegetation and atmosphere are connected by evapotranspiration processes through the loss and gain of water. Precipitation infiltrates into the soil and may be taken up by roots. It is then brought up to the leaves then exits through evaporation to the atmosphere where the cycle repeats. Evapotranspiration in the environment varies with water availability in the atmosphere, abundance of vegetation and the soil's plant available water.

Water as well as nutrients can also be lost from the soil from drainage. Drainage occurs when water moves below the root zone. Drainage rates are highest in sandy soils due to high gravitational flow in larger pores. Drainage is important for soil aeration and removing toxins and excess salts in the soil, however too much drainage can lead to decreased plant-available water and leaching of important nutrients leading to poor soil functionality.

Infiltration is the movement of water from the soil surface into the soil. Water sources for infiltration include snowmelt, rainwater and irrigated water. Infiltration is governed by gravity and capillary forces along with soil texture and pore size distribution. Higher infiltration is observed in soils that are more heavily cracked (Zhao et al. 2002) and soils with many large pores (macropores) such as sandy soils or well-structured soils. The rate of infiltration is directly dependent on hydraulic conductivity. A study by Zhao et al. (2002) found that under the same moisture saturation, the hydraulic conductivity of sandy soils was the highest while clay soils was the lowest, with results varying by up to two magnitudes. Infiltration rates were found to be higher initially in sandy soils due to high potential at the start of infiltration while water infiltration in clay soils was slower. Infiltration rates tend to decrease as the soil becomes more saturated because of decreased hydraulic gradients. Poorer infiltration also commonly occurs in highly compacted soils due to dense barriers that prevent water movement. Runoff occurs when the precipitation rate exceeds the infiltration rate and can increase soil susceptibility to erosion.

1.6. Soil Compaction

Soil compaction is defined as “the process by which soil grains are rearranged to decrease void space and bring them into closer contact with one another, thereby increasing the bulk density” (Hamza and Anderson 2005). Soil compaction is a serious global problem that is responsible for land degradation, reduced environmental quality and crop failure (Khan et al. 2012; Krummelbein et al. 2010). Soil compaction can occur through natural processes such as the formation of a fragipan horizon however, the main cause is from heavy vehicle traffic on the site during cultivation and landscape reconstruction activities (Khan et al. 2012). Compaction is a chronic problem on most land areas that continuously till the soil because soil deformation increases with number of tractor passes (Khan et al. 2012). Ploughing at the same depths for many years can compact the subsoil and subsequent plough layers (Ahmad 2009) and is frequent in agricultural areas. Altered mine soils are referred to as “reclaimed mine soils” and consist of soil with replaced overburden and topsoil. Reclaimed mine soils are commonly heavily compacted due to frequent traffic from topsoil hauling and replacement (Shrestha and Lal 2011).

Soils with high clay fractions are the most susceptible to compaction. A study by Khan et al. (2012) showed that compaction reduced physical soil quality with increasing levels of clay in the soil. Soils with higher clay contents are especially susceptible to compaction under wet conditions due to the increase in weight with water and the force of gravity reducing the volume and pore space (Khan et al. 2012; Brady and Weil 2003). Sandy soils however tend to resist compression due to low porosity and the shape of the individual particles (Brady and Weil 2003).

Soil compaction reduces plant-available water in the soil by altering the pore size distribution, causing a significant decrease in macropores. By doing so, the soils bulk density is increased while porosity and aeration are decreased (Sojka et al. 1997). Low aeration can result in the buildup of toxic gasses in the soil (Brady and Weil 2002) due to reduced air and water flow. Hydraulic conductivity is also reduced as a result of decrease average pore size. “Vehicular compaction affects pore size distribution and water retention because the decrease in soil volume can only occur as a result of the reduction of pore space volume and size” (Startsev and McNabb 2001).

Compaction also reduces and slows water infiltration in the soil as the result of the reduction of macropores. Poor infiltration from increased soil strength can lead to waterlogged conditions in the topsoil by inhibiting movement into the subsoil (Brady and Weil 2002). This can increase erosion and surface runoff, which is especially problematic during periods of heavy precipitation.

Vegetation growth is directly impacted by compaction. Compaction increases the soil mechanical resistance by creating hard barriers that are difficult for plant roots to pass through (Nevens and Reheul 2003). Changes in the soil water balance and other soil physical properties from soil compaction are less favorable for plant growth compared to un-compacted soil, such as (Raper and Kirby, 2006):

- Poor aeration and waterlogging at field capacity, reducing root respiration
- Increased soil strength making it more difficult for roots to elongate and explore the soil
- Excessive runoff and soil erosion from reduced infiltration capacity

Soil compaction is a major limiting factor in restoring native vegetation (Shrestha and Lal 2011). Increases in bulk density were found in all reclaimed mine soils tested in a study by Shrestha and Lal (2011). Loss of productivity due to reduced water movement, aeration and root growth was also observed (Shrestha and Lal 2011). For agriculture, compaction can result in yield reductions and loss of profitability (Brady and Weil 2002). A study by Oussible et al. (1992) showed that compaction of a clay loam soil resulted in reduced grain yields of 12-23% and straw yields of 9-20%.

1.7. Subsoil Ripping

Subsoil ripping or subsoiling is the process of alleviating compacted subsoil using machinery with specially designed shanks that are able to penetrate into deep layers to break up hard peds. When done correctly, subsoiling can cause the creation of large macropores. Subsoil loosening can be effective for vegetation production in cases where restricted root growth or poor aeration is the factor for limiting water and nutrient uptake (Olesen and Munkholm 2007). It is often conducted on pasture land for its positive effects on crop yield (Sojka et al. 1997).

There are many important factors to consider in selecting a ripping procedure for a particular area. The type of machinery is important and should be compatible with the particular environmental conditions. Some equipment requires more horse power to penetrate and break up the soil, especially if the soil has high clay content. Soil also cannot be overly saturated during the ripping process because shanks will slide into the soil without ripping it and can actually increase the level of the compaction. Some procedures are more economical than others and some are more effective long term.

Studies have shown that ripping is able to alter the pore size distribution and increase plant-available water and infiltration capacity, leading to greater vegetation success. Chapman and Allbrook (1987) found an increase in pasture root length as a result of increased macroporosity after subsoiling. Loosening hard barriers is also beneficial for plant root expansion in the deeper soil layers. Harrison et al. (1994) discovered that mechanical loosening created pores which allowed pasture roots to penetrate in previously inaccessible horizons.

Subsoiling can be beneficial for improving soil health. A study by Sojka et al. (1997) comparing the differences between compacted and subsoiled (decompacted) silty clay textured soil found increased porosity, hydraulic conductivity and air permeability in subsoiled plots compared to compacted plots. Improved soil physical conditions can lead to increased vegetation growth. Harrison et al. (1994) found increased rates of root growth over the growing season and a more extensive pasture root system after subsoiling. They concluded overall improved soil physical conditions after the ripping treatment. Subsoiling can also decrease erosion by increasing rate of infiltration in the soil. A study by Sojka et al. (1993) found a 278% decrease in erosion with zone subsoiling.

Care must be taken after subsoiling an area to assure compaction does not reoccur. Compaction can re-occur very easily during crop turn over (seeding) or by machinery re-entering the site.

1.8. Research Objectives

The overall goal of this study was to assess the effects of subsoil ripping by comparing soil physical properties in ripped (decompacted) and unripped (compacted) soil to determine if subsoiling would ultimately create more positive growth conditions for plant establishment at an area undergoing landscape reconstruction at Genesee Coal Mine which is situated between the Dry

Mixedwood Natural sub-region and Central Parkland Natural sub-region of Alberta.

Chapter two focuses on soil physical properties, soil water retention characteristics and soil hydraulic properties through the use of laboratory techniques. Chapter three involved observing soil moisture dynamics and characteristics that influenced soil water content between February 1st and July 31st, 2013 through a snow survey, topography survey and data sensors that measured soil temperature and volumetric water content for the two treatments.

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2. Chapter 2 – Soil Physical and Moisture Retention Properties

2.1 Introduction

Mining disturbances in the Boreal Forest and Aspen Parkland Natural regions, Alberta, have resulted in the loss of native tree cover, especially dominant tree species to the regions, trembling aspen (*Populus tremuloides*) (Peltzer et al. 2000; McCartney 1993). Revegetation of mine tailings is a required practice in the province and is often done by first converting disturbed land to agricultural land which helps to initially improve soil conditions by decreasing erosion, increasing organic matter and increasing soil moisture retention properties (Pollster 2000; AESRD 2014). Cover crops are initially used for restoration due to their hardiness and their ability to improve soil conditions over time. These include oats, agronomic grasses, alfalfa and barley (Pollster 2000; AESRD 2014). Reclamation with these species however does not produce an accurate representation of the natural biodiversity of the landscape and usually only meets short term reclamation goals in the White Zone area of Alberta. Due to this, native species are being used more frequently to meet long term reclamation goals of restoring natural land cover and to resume important ecological processes in the environment (Maryati 2013; Mukhopadhyay et al. 2013).

Problems surrounding successful revegetation include soil compaction as a result of heavy vehicle traffic on the site during soil reconstruction activities and intensive agricultural production (Horn et al. 1995). Reclaimed mine soils are highly compacted because of repeated movement of heavy equipment used to haul and replace topsoil materials (Shrestha and Lal 2011). Changes in soil strength occur with increasing trafficking frequency. The negative outcomes of soil compaction include reduced soil physical quality such as increased soil bulk density, decreased hydraulic conductivity, decreased soil moisture retention and increased soil strength (Horn et al. 1995; van Dijck and van Asch 2002). The pore size distribution is also affected with respect to the mean pore diameter, the total number of pores and/or their function (Horn et al. 1995). Compaction of the soil reduces the total porosity of the soil (i.e., decreases the void ratio) and also changes the pore size distribution by decreasing the proportion of macropores and increasing the proportion of micropores through the rearrangement of and changes in the shape and size of soil aggregrates in structured soils (Hazma and Anderson, 2005).

Studies have found that changes in the pore size distribution and increased bulk density reduced vegetation growth by reducing plant available water (Harrison et al. 1994). Other studies found evidence of reduced soil physical quality with compaction. For example, a study by Berisso et al. (2012) observing the impacts of soil compaction on soil physical properties of a loamy soil in southern Sweden found increased bulk density, reduced total porosity and reduced water content on repeatedly trafficked soil. In addition, diffusivity was reduced and oxygen was critically low in the soil profile causing reduced aeration.

A widely used method of mitigating compaction is by applying a special subsoil ripping technique to the soil such as subsoiling or deep ploughing in the compacted layer (van Dijck and van Asch 2002). Specialty designed shanks are used to break up compacted layers to increase infiltration and drainage by altering the pore size distribution and increasing macropores. A study by Bangita and Rao (2012) on the effects of subsoil ripping on a compacted sugar cane plantation (wheel track zones) and yield performance found improved soil physical properties after subsoiling including improved bulk density and decreased soil strength. In addition, soil water intake rates were improved leading to greater volumetric water contents. Subsoil ripping was shown to improve soil conditions leading to greater sugarcane productivity. Previous studies by Chapman and Allbrook (1987), Sojka et al. (1993) and Sojka et al. (1997) have also shown improved soil physical properties and bulk density after undergoing a subsoil ripping treatment. This in turn, has led to improved vegetation growth.

2.2 Research Objectives:

This chapter focuses on the impact of subsoil ripping treatment on soil physical properties and soil water retention characteristics at a reclaimed mine tailings site in Genesee Prairie Mine, Alberta. Specific objectives are as follows:

- Compare soil physical properties of ripped and unripped plots for soil penetration-resistance measurements, particle size distribution, bulk density and void ratio.
- Compare variability in soil moisture retention characteristics at different depths for ripped and unripped soil plots.
- Compare variability in saturated hydraulic conductivity (k_{sat}) at different depths in ripped and unripped soil plots.

2.3 Methodology

2.3.1 Site Description

The experimental site was located at Genesee Prairie Mine, approximately 70 km west of Edmonton in Leduc County. The research plot was located at NW1/4-20-050-02 W5M within the Genesee Mining Operations permit area. The site is situated between the Dry Mixedwood Natural sub-region of the Boreal Forest Natural Region and Central Parkland Natural sub-region of the Parkland Natural Region of Alberta. Average daily temperatures in this area range between 16.5^{o}C and -11.7^{o}C with a mean annual temperature of 2^{o}C. Annual mean precipitation is 536-mm, mostly in the form of rain (Navus Environmental Inc. 2010).

Land use surrounding the mine site and on reclaimed land within the mine is primarily agriculture, but patches of aspen (*Populus tremuloides*) and aspen-white spruce (*Populus tremuloides-Picea glauca*) forest remain. The dominant natural soil type is Orthic Gray Luvisol from the Cooking Lake soil series (Navus Environmental Inc. 2010). The reclaimed areas on the mine have been rated as poor for agriculture use, with a rating of class three (moderately severe limitations) due to lack of soil structure suitability (Navus Environmental Inc. 2010). Prior to disturbance, wildlife activity in the area was limited to ungulate browsing and included white tail deer, mule deer and moose (Navus Environmental Inc. 2010). The north, east and west sides of the site are currently bordered by country roads and reclaimed land area.

In the area of the mine where the research site is located, mining activities began in 1990 and ended in 1992. Topsoil from the site was salvaged and used on other areas of the mine. Soil reconstruction began in 1992 and ended in 2001. Soil reconstruction involved applying fly ash materials to spoil piles and leveling them out. Subsoil from the area was salvaged and placed on top of the fly ash and soil piles between 1991 and 1997. Compacted areas were ripped with a subsoiler prior to topsoil addition. Rocks that were brought to the surface from the subsoiler were hand-removed from the site. Topsoil was added between 1993 and 1999. A cover crop of cascade oats (*Avena sativa*) and creeping red fescue (*Festuca rubra*) were seeded to help control erosion in areas with topsoil added. A grass/legume mix was under-seeded to help improve soil structure and fertility. The mix included alfalfa (*Medicago sativa*) a deep rooting perennial plant. The site remained in forage until 2003 and was then used for annual cropping between 2005 and 2009. The field was reclaimed to alfalfa for approximately 5 years. Subsoil ripping was executed in the fall of 2010 following an application of glyphosate herbicide in preparation for the research outlined in this thesis and a broader research program.

2.3.2 Experimental Design

A 575-m x 25-m plot within the reclaimed area was established for this research in 2010 (Fig. 2.1). Glyphosate herbicide was applied in order to kill the alfalfa and other weeds prior to aspen planting. Two soil treatments were of interest, unripped (compacted) and ripped (decompacted). A subsoil ripping treatment was executed in half of the site in 2010 using a McNabb winged subsoiler D7R XR Caterpillar. The east and west 36-m edges of the site were compacted soil plots. The rest of the site alternated between unripped and ripped soil every 72 meters. The site was divided into 6 blocks, each containing 2, 36 x 25-m plots with 1 unripped and 1 ripped plot (Fig. 2.2). There were 20-m buffer areas established in the middle of each block where the treatment changed (Fig. 2.2). Each plot was further divided into 4, 9 x 12-m subplots, each randomly assigned to 1 of 4 vegetation covers. There were 48 established subplots in total. Vegetation was planted in the summer of 2012.

Subplots contained one of the following vegetation covers, randomly assigned: aspen (*Populus tremuloides*), aspen and brome (*Populus tremuloides-Bromus* *inermis*) mix, pure brome (*Bromus inermis*) or control. Aspen was planted at 1-m spacing's at 10,000-stems/ha. Brome was planted at 20,000-plants/ha and the aspen-brome mixed plots were planted at 20,000-plants/ha. Glyphosate herbicide was used to control weeds in the vegetation and control plots and was sprayed twice per growing season. Aspen was also planted within buffer areas to control for potential edge effects. Plastic mulch was used for weed control in buffer areas.

2.3.3 Field Sampling and Measurements

Soil samples were collected from the site in July 2011. Sampling consisted of extracting 216 disturbed and un-disturbed soil cores (108 each) from both ripped and unripped plots using a Geoprobe hydraulic coring rig. Samples were taken 10-m apart in a grid pattern in each plot (Fig. 2.2). Two cores were collected per sampling location, one disturbed and one undisturbed sample. Undisturbed cores were collected using 5-cm diameter PVC liners in the steel soil sampling core. Soil cores were later extracted from the PVC liners and wrapped with heat-activated shrink wrap and cut into 5-cm pieces for lab analysis of soil moisture retention and hydraulic conductivity. Disturbed cores were extracted the same way, but without PVC liners and immediately cut into 15- or 30-cm pieces (0-15, 15-30, 30-60 and 60-90-cm) and placed into separate labeled bags. Disturbed cores were used for analysis of soil physical properties including bulk density and particle size distribution in the laboratory.

In addition to collecting samples, a simple soil penetration-resistance test was executed in the field using a thin, one meter long metal rod hand-pressed into the soil. The rod was pressed down into the soil until refusal and the rod length into the ground was recorded. Depths were recorded in the north, middle and south transects running across all plots at approximately 1-m apart in a grid pattern. A hand-held GPS system was used to determine locations for each measurement within the plots. In total, 146 depths were recorded for the site.

2.3.4 Soil Physical Properties

Particle size distribution (PSD) was measured on disturbed samples using the hydrometer method outlined by Day (1965). Samples from all 4 depths of 3 sampling locations out of 9 per plot were chosen in a diagonal pattern running south-west to north-east on the site for PSD. In total, 59 ripped and 68 unripped samples were analyzed. Rocks were removed from the soil samples and they were ground to break up large aggregates and passed through a 2-mm sieve. An industrial milkshake mixer was used to mix 50-g of ground soil with 10-ml of 15% sodium hexametaphosphate and distilled water. The mixture was blended for 20 minutes and then placed in a 1000-ml graduated cylinder with added distilled water to the 1000-ml mark. Readings were taken with a hydrometer at .30, 1, 2, 3, 4, 5, 10, 30, 60 and 120 minutes and 24 hours. Temperature was recorded for each reading. Calculations were corrected for temperature and the hydrometer reading. Percent of sand, silt and clay was determined for soil in both treatments and the texture class was determined for the soil. Readings were in grams of material in suspension.

Bulk density (BD) is a soil physical parameter commonly used to assess degree of compaction (Saffih-Hdadi et al. 2009). BD was calculated using all 108 disturbed soil samples from the site. BD was determined for 4 depths (0-15, 15-30, 30-60 and 60-90-cm) for both treatments. BD was calculated using wet (initial/field) weights of the soil and air-dried weights after two to three weeks of air drying (before grinding).

2.3.5 Moisture Retention Curve

The moisture retention curve evaluates the relationship between water content ($cm^3\ cm^{-3}$) and soil matric potential (cm) (Hillel 1982). Soil-moisture retention curves were measured using a tension table and pressure plate extractor in the laboratory outlined by Reynolds and Topp (2006). Undisturbed core sections from each plot were used at even-numbered depths (0-5, 10-15, 20-25, 30-35-cm). Two soil cores from each plot were chosen at random, totaling 24 cores.

Saturated core sections were first covered with cheesecloth from the bottom then placed on a tension table containing de-aired water. The cheesecloth prevented the soil from adhering to the tension table and pressure plates. Hydraulic contact between the cores and tension table was established and the cores were left to saturate (equilibrate) for 3 to 4 days. The plate and cores were covered with plastic to prevent evaporative water loss. The saturated core weight was recorded and the water reservoir height was changed to 50-cm (0.05-bar) and left for 3-4 days. This procedure was repeated for 100-cm (0.1 bar). Soil cores were weighed between each change in suction.

Cores were then placed in pressure chambers for further water extraction at the following potentials: 0.5, 1, 3, 5 and 15-bar. Cores were left at respective pressures for 5-7 days (depending on water outflow) then weighed before moving to the next potential. At the end of the experiment, core height and radius were measured before oven drying overnight at 105^{o}C and then the final weights were recorded. The water content for each point was determined.

Data from this experiment was analyzed using the Dexter et al. (2008) model for moisture retention. The model considers the influence of different pore sizes (matrix and structural pores) on water retention properties which in turn, determines how the soil functions. The Dexter et al. (2008) water retention equation may be written as:

$$w = C + A_1 e^{(-h/h1)} + A_2 e^{(-h/h2)} \quad [1]$$

Where

w = the gravimetric water content (g g^{-1})

C = residual water content (g g^{-1})

A_1 = matrix water (within aggregates; g g^{-1})

A_2 = structural water (between aggregates; g g^{-1})

h = matric potential (cm)

h_1 = matric potential at which matrix pores empty (cm)

h_2 = matric potential at which structural pores empty (cm)

2.3.6 Soil-Void Ratio and the Moisture Retention Curve Model of Dexter et al. (2008)

The soil-void ratio (e, cm^3 cm^{-3}) is the ratio of the volume of soil voids to the volume of soil solids (Dexter et al. 2008) and is generally calculated as:

$$e = f\frac{\rho_s}{\rho_b} \quad [2]$$

where f is the soil porosity (cm^3 cm^{-3}), ρ_s is the particle density (g cm^{-3}) and ρ_b is the bulk density (g cm^{-3}). Equation [2] was used to calculate the void ratio on the disturbed soil samples (0-15, 15-30, 30-60, 60-90-cm depths).

Dexter (2008) noted that the gravimetric water content, at saturation, w_{sat} (g g^{-1}), is directly proportional to the total void ratio, (Dexter et al. 2008):

$$w_{sat} = e\frac{\rho_w}{\rho_s} \quad [3]$$

where ρ_w (g cm^{-3}) is the density of water. Rearranging Eq. [3] results in an expression for the void ratio:

$$e = w_{sat}\frac{\rho_s}{\rho_w} \quad [4]$$

In the Dexter model, w_{sat} is the sum of the C, A1 and A2 parameters which Dexter et al. (2008) interpret as the residual (i.e., adsorbed), matrix (i.e., intra- or within aggregates) and structural (inter- or between aggregates) soil water respectively. Substituting w_{sat} = C + A1 + A2 into Eq. [4], expressions for residual, structural and matrix void ratios can be derived:

$$e = (C + A1 + A2)\frac{\rho_s}{\rho_w} \quad [4b]$$

$$e = C\frac{\rho_s}{\rho_w} + A1\frac{\rho_s}{\rho_w} + A2\frac{\rho_s}{\rho_w} \quad [4c]$$

$$e = e_{residual} + e_{matrix} + e_{structural} \quad [4d]$$

According to Eq. [4c], residual, matrix and structural void ratios were calculated using the C, A1, and A2 parameters from the Dexter et al. (2008) model fitted to the moisture retention data measured on the undisturbed cores (0-5, 10-15, 20-25 and 30-35-cm depth increments).

2.3.7 Saturated Hydraulic Conductivity

Hydraulic conductivity describes the relationship between soil water-flux density and a hydraulic gradient. Saturated hydraulic conductivity (k_{sat}) was measured using the falling head method (un-steady state flow) for fine grained and compacted soils as outlined by Klute and Dirksen (1986). Undisturbed core sections from the 12 plots were used for this analysis. Data was generated for only half of the core sections selected in this experiment possibly due to heavy compaction inhibiting water flow in many of the cores. Conductivity was measured for core sections at the following depths: 5-10, 25-30, 45-50, 65-70, and 75-80-cm. The procedure first required sealing the outer perimeter of the cores into a 9-cm PVC tube with hot wax to assure water flow only occurred from the top and bottom. Cores were saturated from the bottom-up using de-aired water for up to two weeks. Cheesecloth was applied to the bottom of the cores to assure soil did not fall out during saturation. Cores were vertically clamped to lab stands and 3-4-cm of water was added to the top (soil water pressure head), within the PVC pipe. The top of the cores were then covered with a small piece of film to remove water loss from evaporation. The bottom of the core was submerged in 1-cm of water to maintain saturation during the measurement. The initial height of the hydraulic head and time were measured, and again measured when change in water height was evident. Water levels were carefully monitored over 8 hours.

Saturated hydraulic conductivity using the falling head method was calculated using the following equation from Klute and Dirksen (1986) which is based on Darcy's Law:

$$\mathrm{k}sat = \frac{L}{t1-t0}\, ln(\frac{b1+L}{b0+L}) \qquad [3]$$

where

L = length of soil core (cm)

t0 = initial time (min)

t1 = time at x water level height (min)

b0 = initial water level height (cm)

b1 = water level height at time x (cm)

2.4 Results

Results from the soil penetration-resistance test showed that the metal rod reached deeper depths in ripped soil compared to unripped soil for each of the south, middle and north line (Tab. 2.1). On average, the rod was able to penetrate 47-cm before encountering strong resistance in the ripped treatment compared to 32-cm for the unripped treatment.

Particle size distribution results showed relatively similar amounts of sand, silt and clay for soil in both treatments over the four depth intervals (Fig. 2.3). In both treatments, the sand fraction increased with depth from approximately 40% in the 0-15-cm increment to approximately 50% in the 60-90-cm increment. The increase in sand fraction with depth corresponded to a decrease in silt fraction with depth. Clay fraction remained relatively constant (~20%) with depth. Despite these trends, texture was classified as loam throughout the profile.

The ripping treatment had the biggest impact on bulk density for the 0-15 and 15-30-cm depth increments (Fig. 2.4). Average bulk density for the 0-15-cm depth was 1.47-g cm^{-3} for the unripped and 1.19-g cm^{-3} for the ripped. For the 15-30-cm depth, average bulk density was 1.91-g cm^{-3} and 1.65-g cm^{-3} for unripped and ripped treatments respectively. Differences in average bulk density were not apparent for the 30-60 and 60-90-cm depth increments, but it is interesting to note that variability in bulk density at these depths was lower in the ripped treatment.

Results showed differences in moisture retention curves for the two treatments (Fig. 2.5). Subsoil ripping had a clear effect on water retention at matric potentials greater than 10^4 (15-bar). Soil from ripped plots had, on average, lower gravimetric water contents (g g^{-1}) with increasing potentials (Fig. 2.5). Lower residual water content was also shown for ripped plots. The average residual water content at -15,000-cm was 0.181-g g^{-1} for unripped soil and 0.146-g g^{-1} for ripped. The slope of the moisture retention curve is greatest at 5-cm below ground.

A higher total void ratio was observed for ripped soil down to 60-cm (Fig. 2.6). The average total void ratio for unripped soil was 0.447, while for ripped soil the average total void ratio was 0.623. The greatest differences were found in the 0-15-cm depth; unripped soil had a void ratio of 0.801 and ripped soil had a void ratio of 1.269. Void ratios for 15-30-cm depths also differed, with 0.416 for unripped and 0.616 for ripped soil. Differences in void ratios decreased with depth. Void ratio averages were relatively similar for depths past 60-cm with a ratio value of 0.274 for unripped and 0.270 for ripped soil.

Results similarly showed higher matrix and structural void ratios for ripped soil for the top 30-cm compared to unripped (Fig. 2.7). The average matrix and structural void ratios for the unripped and ripped treatment were 0.141 and 0.164 respectively. Greatest differences were found in the 0-5-cm depth with a matrix + structural void ratio of 0.229 for unripped soil and 0.282 for ripped soil. Differences in these void ratios decreased with depth. The smallest differences were found in the 30-35-cm depths; with similar void ratios of 0.084 and 0.077 for unripped and ripped soil respectively.

Results obtained for saturated hydraulic conductivity showed no differences between treatments. Cumulative distribution functions (CDF) of the k_{sat} for the ripped and unripped treatments are presented in Figure 2.8. The CDF is used to define the probability that a given (observed) value is less than or equal to the value of x. Conductivity data was analyzed using the CDF because the large range of conductivity values which were not normally distributed – arithmetic means are not appropriate for such data. Visual inspection of the CDFs showed no distinct differences in conductivities that fall within the computed range of probabilities for ripped and unripped samples (Fig. 2.8).

2.5 Discussion

Results from the soil penetration-resistance test show evidence of decreased soil strength in the ripped plots and therefore, reduced compaction. These results indicate that penetration resistance experienced by plant roots is likely reduced in the ripped treatments. Increased soil strength resulting from compaction reduces plant root elongation, effectively limiting the depth of the root zone, plant available water, aeration and access to moisture and nutrients (Tardieu 1993). Increased soil strength increases the mechanical resistance of root penetration, making it difficult for plant roots to exploit a large soil volume (Alameda et al. 2012). Plant roots typically respond to mechanical stress through reduced stem elongation and allocation to root growth (Alameda et al. 2012). Grzesiak et al. (2013) found significant morphological differences in leaf number, dry stem mass, leaves and roots as well as an increase in the shoot to root ratio in severely compacted soil compared to low-compaction soil. Results from the penetration-resistance test measurements showed lower mechanical resistance after subsoiling, which likely indicates a better environment for plant growth. Based on these results, the ripping treatment appears to have increased the depth of the root zone.

Similarities in PSD results for ripped and unripped plots were a result of the conditions of the ripping treatment. Ripping was done via lifting and breaking up of the soil rather than turning or mixing. This allowed the distribution of particles to be relatively the same in both treatments. According to Day (1965), the distribution of particle sizes is one of the most stable soil characteristics, being little modified by cultivation or other practices. Ploughing could potentially impact the depth distribution of particle sizes by lifting and turning the soil, but this was not observed here. It is the pore size distribution, not the particle size distribution that determines moisture retention curve, but particle and pore sizes are correlated in soil therefore it is important to quantify both texture and pore size distribution when assessing the soil for conditions favorable to plant growth (Campbell 1985).

Results of the PSD indicated a loam texture for this soil. Loamy textured soils are considered one of the best soil types because of ideal proportions of sand, silt and clay particles and therefore have greater total porosity and high plant-available water. Optimum soil structure is defined as soil having the widest range of possible uses (Pagliai et al. 2004). Thus, positive results for plant growth are optimistic in ripped plots due to favourable soil texture.

While the ripping treatment did not alter soil texture, there is evidence to suggest it changed soil structure and total porosity. The subsoiling treatment lifted the soil and broke up the massive structure of the compacted layers, leaving it less densely packed in the plough layer. The lowest bulk densities in both treatments were observed at the surface layers of 0-15-cm which was likely due to higher organic matter content at the surface from previous under-seeding and alfalfa cropping in previous years. Increased organic matter in the soil has been shown to improve bulk density, porosity and water holding capacity. Lower bulk density in ripped soil is attributed to the positive effect of the ripping treatment on compacted soil. Soil with high bulk density usually indicates a poor environment for root growth, reduced aeration and undesirable changes in hydraulic function such as reduced water infiltration and drainage (Brady and Weil 2002). A study by Byrd et al. (2002) showed bulk density of more than 1.7-g cm^{-3} of compacted mine site soil found little or no growth in trees. Our average bulk densities between 0-30-cm for ripped and unripped were 1.42-g cm^{-3} and 1.69-g cm^{-3} respectively. These results show improved environments for plant growth in ripped plots due to greater total porosity and reduced soil strength, especially in the top 30-cm.

Differences in moisture retention curves were observed in ripped and unripped soil. The higher porosities apparent in the bulk density and void ratio results in the ripped soil plots (Figs. 2.4 and 2.6) do not appear to translate into higher saturated water contents as would be expected, except in the 0-5-cm layer (Fig. 2.5). Results indicated overall higher porosity in ripped soil plots. Gravimetric water content values were generally lower for ripped soil possibly indicating higher proportions of macropores that were created by the subsoiling treatment which drained even at very high potentials. These large pores released water under lower pressure potentials (Matthews et al. 2010). Therefore, even though the ripped soils had greater pore volumes than the unripped soils, it was not apparent in the moisture retention measurements. Overall, decompaction seemed to have a positive effect on water retention. Higher gravimetric water contents were observed for unripped soil and likely indicate higher proportions of micropores. Water held in micropores at very high potentials (10^4 cm) is not available to plants under natural field conditions. Lower residual water content was also evident in decompacted plots which may be the result of reduced microporosity. It is likely that plant-available water is greater in decompacted soil because of greater macroporosity and improved pore size distribution as a result of the ripping treatment.

Higher total and matrix + structural void ratios (Eq. 4c; 4d) were found in ripped soil. This could potentially mean more plant-available water in ripped plots. Total void ratio results showed fewer residual pore spaces in decompacted soil. This is a positive indicator of increased plant-available water (Brady and Weil 2002). The ripping treatment was likely able to fracture the very dense massive structure created during soil reconstruction into a more structured soil and appears to have increased the between and within aggregate pore volumes. Subsoiling likely changed the ratio of large to small pores and therefore changed the soils functionality. The pore size distribution of soil is sensitive to compression stress. Tebrugge and During (1999) found a 50% reduction in the volume of course pores from the pressure of tractor wheels. Overall, results indicated improved pore size distributions after subsoiling.

The cumulative distribution functions of the saturated hydraulic conductivity overlap (Fig. 2.8) indicating there was no apparent difference in saturated hydraulic conductivity between the ripped and unripped soils. Given the influence of the ripping treatment on the pore size distribution discussed above, it would be expected that the saturated hydraulic conductivity of the ripped treatment should be greater than the unripped treatment. These observations may be explained by the sample preparation, namely the hydraulic conductivity samples were in refrigerated storage for a much longer period of time than the moisture retention curve samples. Further, saturated conductivity is measured on saturated samples and samples remained saturated for many days during hydraulic conductivity measurements so swelling of the samples may be have counteracted some of the increased porosity of the ripping treatment.

2.6 Conclusions

The objectives of this chapter were to compare differences in soil physical properties in unripped (compacted) and ripped (decompacted) soil at the reconstructed study site situated between the Dry Mixedwood Natural sub-region and Central Parkland Natural sub-region at Genesee Prairie Mine, Alberta. More specifically, the impact of the ripping treatment on soil physical properties, water retention characteristics and hydraulic properties in ripped and unripped soil was of interest. This research was executed to determine if improved soil physical conditions created through subsoiling would improve the soil physical and water retention properties related to plant growth. The long-term impacts of the improved soil properties from the ripping treatments on trembling aspen growth and establishment will be carried out in future research.

Soil penetration-resistance results showed evidence of decreased soil strength and potential deeper rooting zone. Improved mechanical resistance for plant roots is also likely after ripping. Similarities in PSD results were due to the conditions of the ripping treatment and the ploughing technique. The ripping treatment decreased bulk density (increased porosity) and changed the pore size distribution significantly in the top 30 cm and to a lesser extent in the 30-60 cm depths. Moisture retention curve results showed decreased water content in ripped soil with increasing pressure gradient, indicating easier water extraction in ripped plots. This is likely the result of greater macropores created by the ripping treatment. Results are a reflection of greater plant-available water in ripped soil. Void ratio results show improved pore size distributions through increased matrix and structural pore spaces as well as reduced residual pore spaces after the ripping treatment. Saturated hydraulic conductivity could not be accurately measured for our samples using the conventional method used. CDF analysis show overlapping data for ripped and unripped plots, however it is very likely that

k_{sat} is greater for ripped soil based on observed influence of subsoiling on the pore size distribution. Additional analysis is needed to compute the k_{sat} of the soil.

Results from this experiment allow us to demonstratepositive impacts of ripping on soil physical properties through improved soil water conditions. Subsoil ripping may create positive conditions for long term trembling aspen establishment in these environments.

2.7 Tables

Table 2.1 Soil penetration-resistance measurement averages with standard deviations for the south, middle and north lines at the site in 2011 for ripped and unripped soil plots.

Line (location)	Ripped (cm)	STDEV	Unripped (cm)	STDEV	Diff. (cm)	Diff. (STDEV)
South	41.88	8.46	28.43	8.22	13.44	0.24
Middle	44.34	11.17	26.52	7.96	17.82	3.22
North	55.44	10.96	41.33	9.35	14.11	1.61
Average	47.29	10.20	32.48	8.51	15.12	1.69

2.8 Figures

Figure 2.1 Location of the 575-m x 25-m experimental site within the reclaimed area at Genesee Prairie Mine.

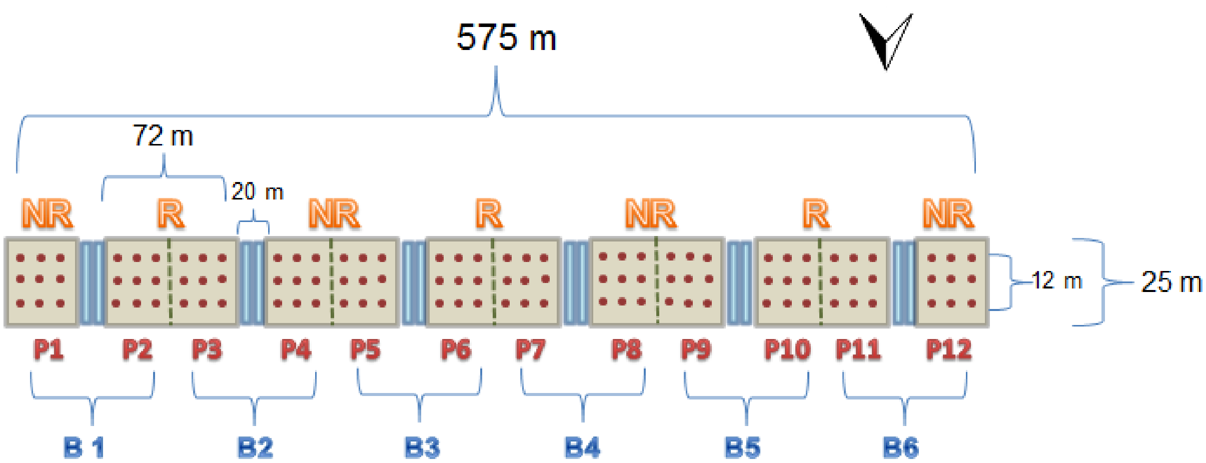

Figure 2.2 Experimental plot layout of the study site showing alternating unripped and ripped plots and soil sampling locations (red dots). B=Block, P=Plot. Vertical lines represent 20-m buffer areas between treatments. Subplots are not represented here.

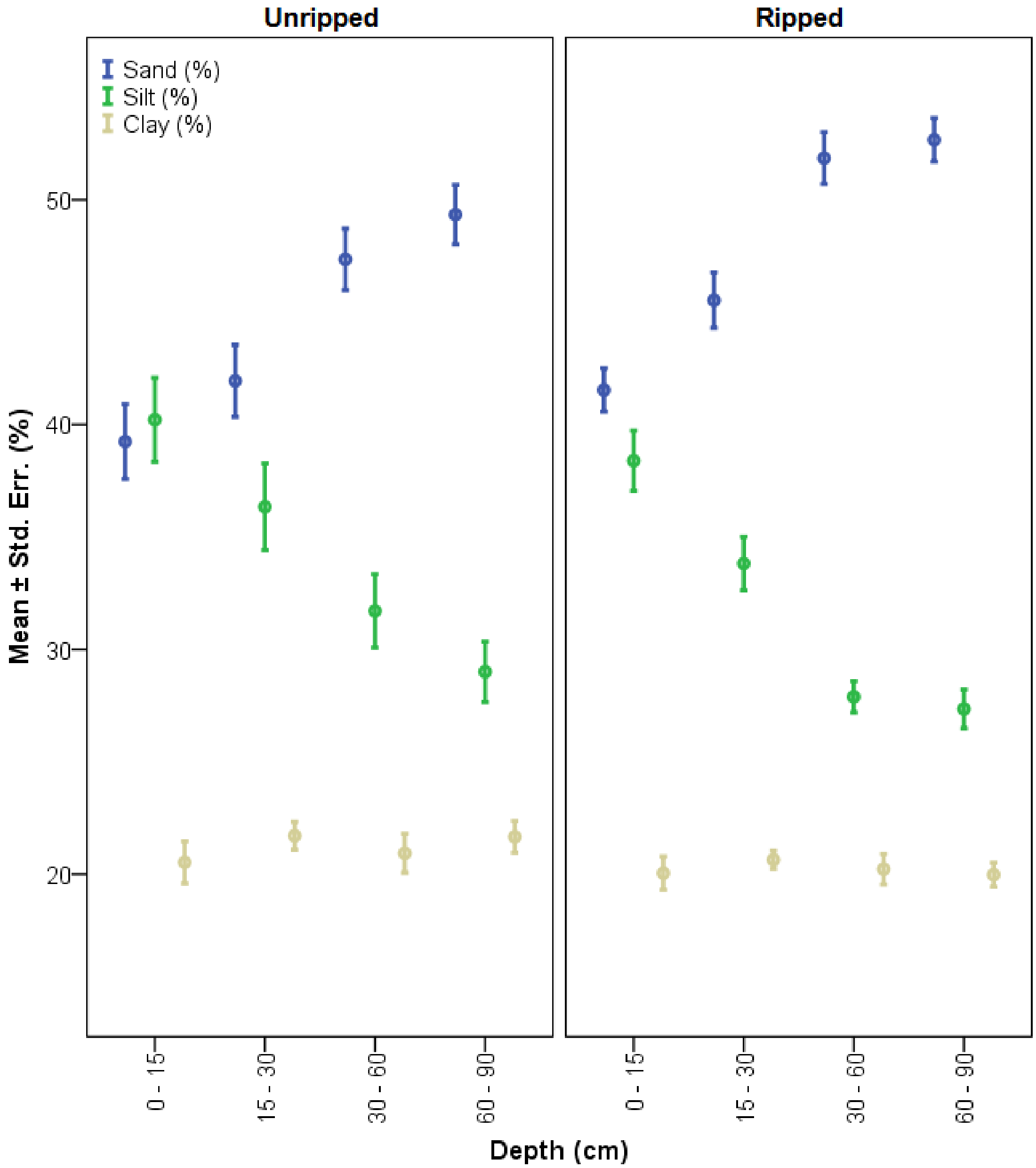

Figure 2.3 Particle size distribution by hydrometer showing the distribution of sand, silt and clay for four depths (0-15, 15-30, 30-60 and 60-90-cm) in ripped and unripped soil plots.

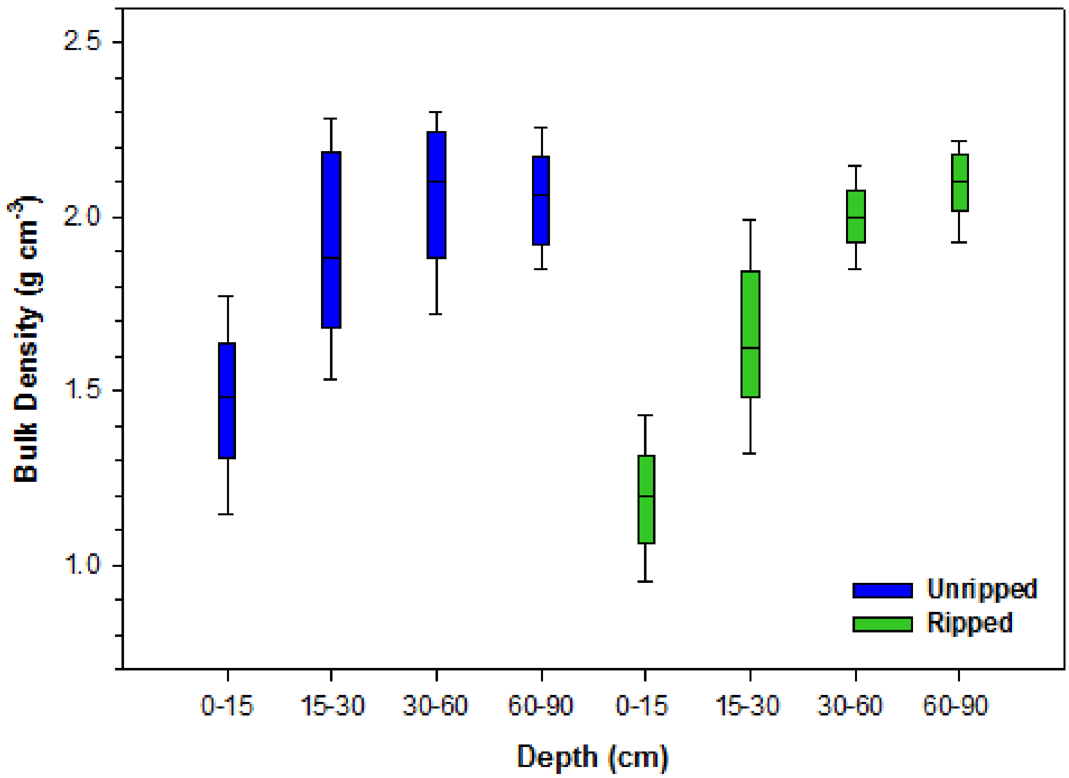

Figure 2.4 Bulk density box and whisker diagrams for four depths (0-15, 15-30, 30-60 and 60-90-cm) for ripped and unripped soil plots.

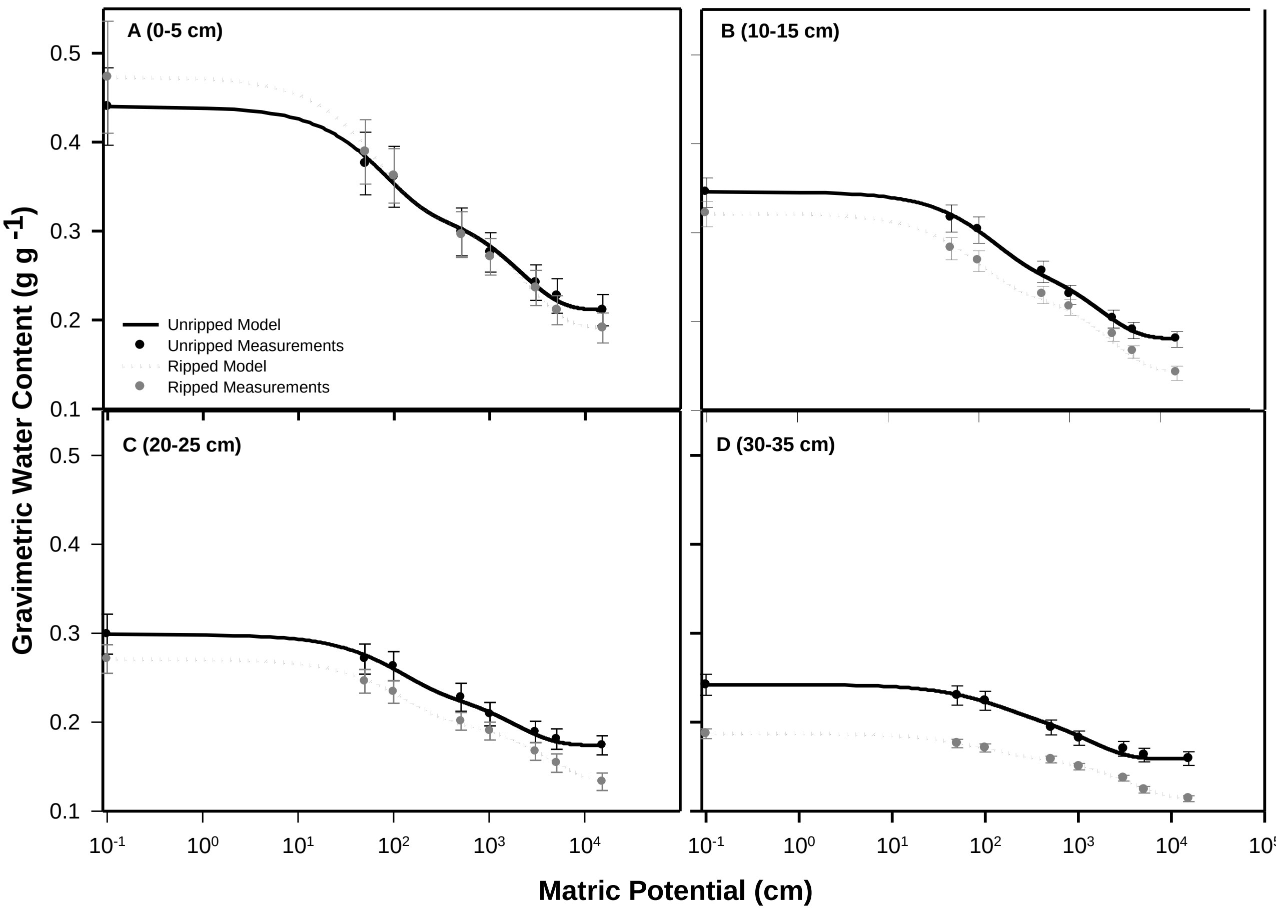

Figure 2.5 Soil moisture retention curves with average gravimetric water content and matric potential for 4 depths (0-5, 10-15, 20-25 and 30-35-cm) for ripped and unripped soil plots fitted to the Dexter model for moisture retention.

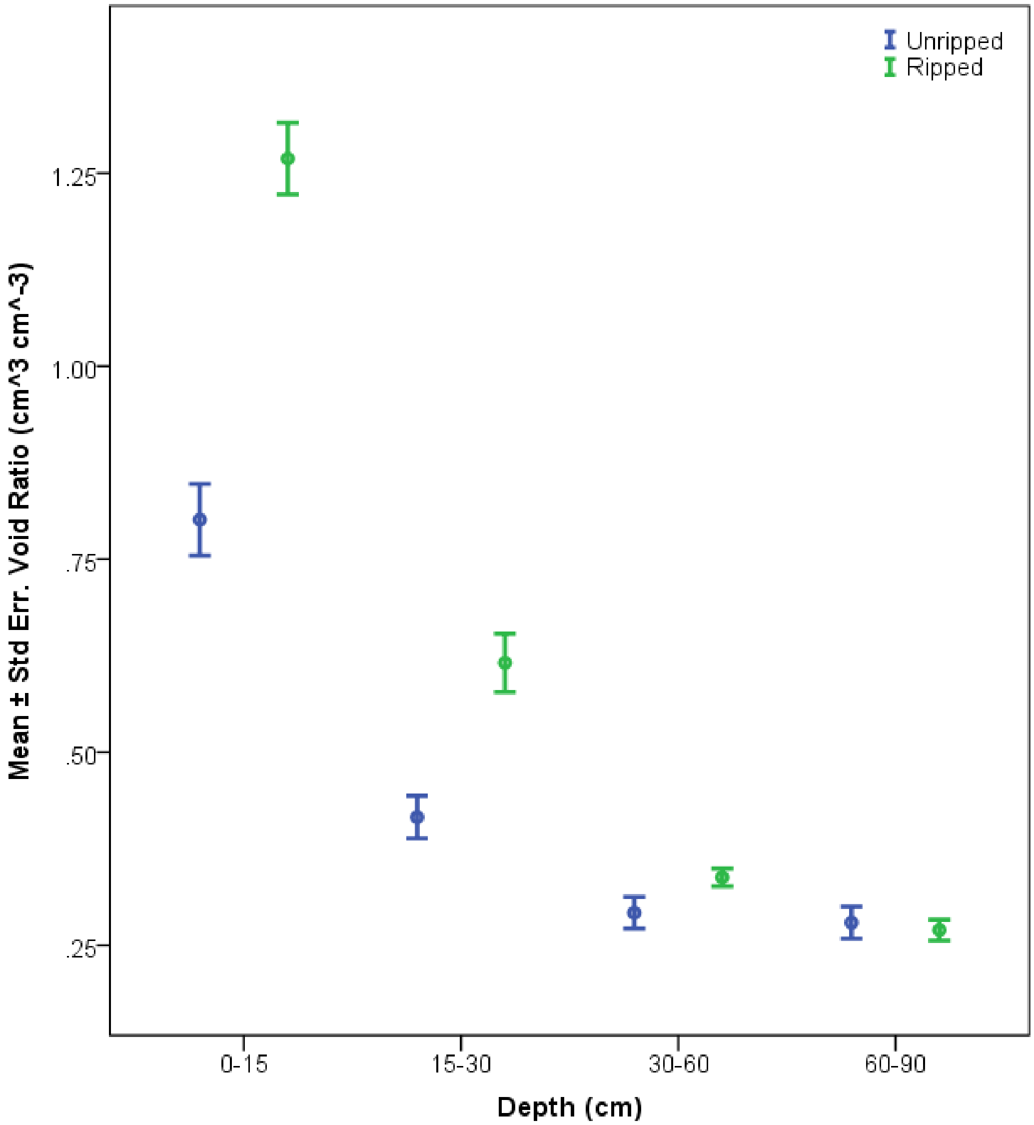

Figure 2.6 Total void ratio calculated with Eq. [2] on the disturbed samples as a function of depth for ripped and unripped soil plots.

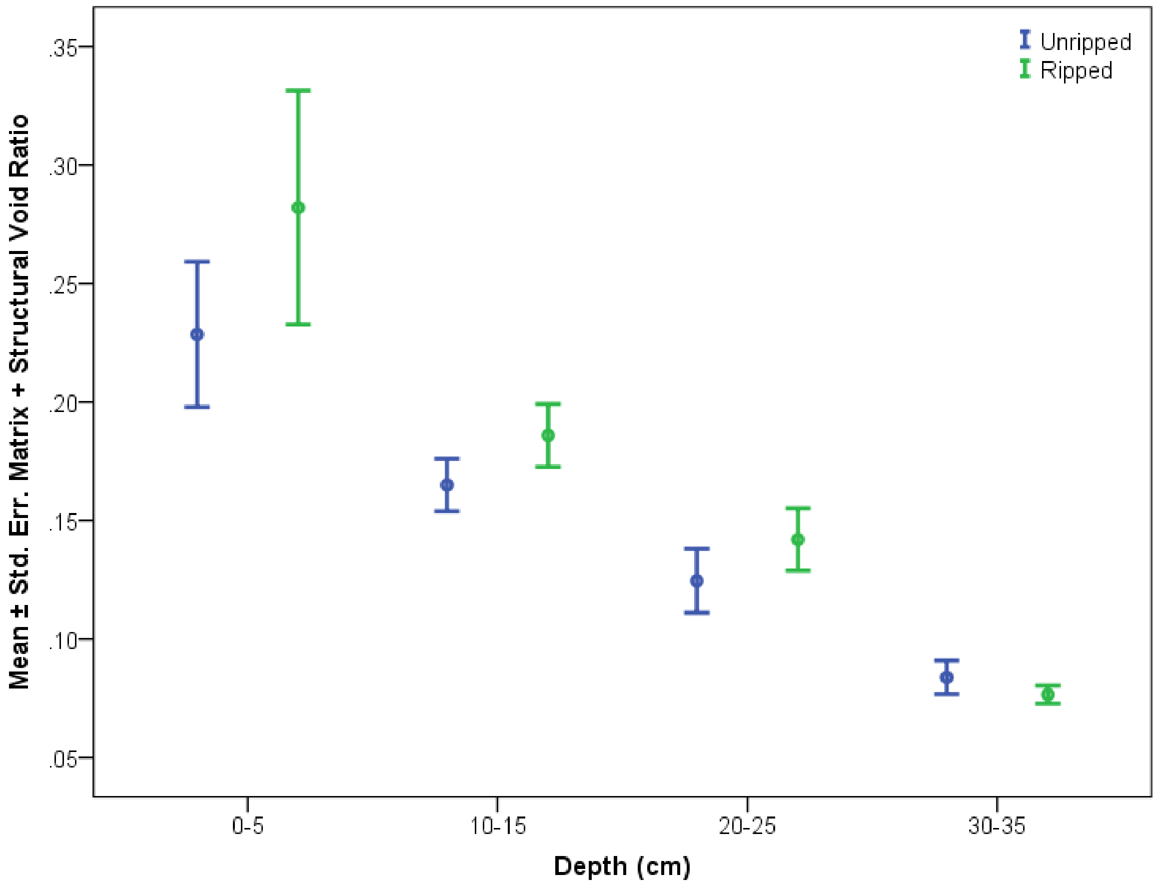

Figure 2.7 Matrix + structural void ratios for four depths (0-15, 15-30, 30-60 and 60-90-cm) for ripped and unripped soil plots fitted to the Dexter model for void ratio.

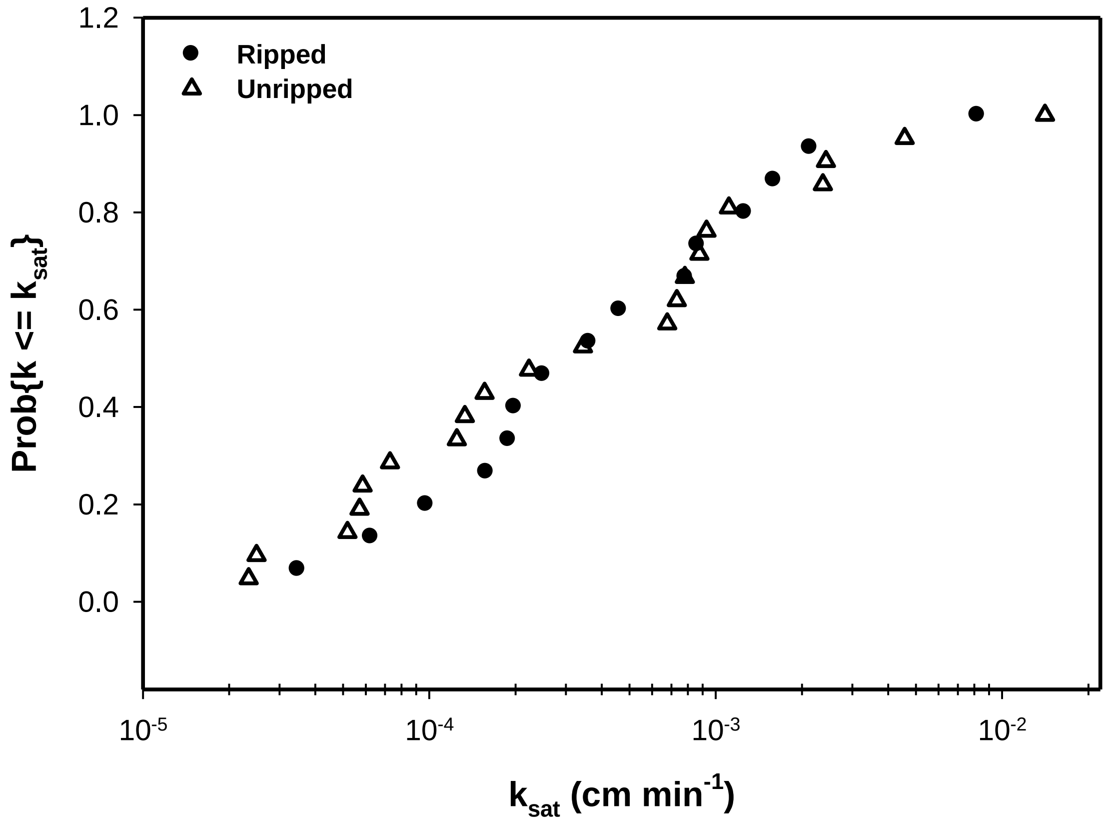

Figure 2.8 Saturated hydraulic conductivity data analyzed using the Cumulative Distribution Function (CDF). Analysis showed no variation in ripped and unripped probabilities.

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Chapter 3 – Soil Infiltration Properties

3.1 Introduction

Trembling aspen (*Populus tremuloides*) forests have been severely impacted by mining disturbances in the Boreal Forest and Aspen Parkland regions of Alberta resulting in a severe decline of less than 10% of native stands remaining today (Adams et al. 2003). Mine tailings are commonly revegetated to agriculture using cover crops after disturbance which may help conserve soil for future, native species reclamation. Reclaimed mine soils are highly compacted because of repeated movement of heavy equipment used to haul and replace topsoil materials (Shrestha and Lal 2011) and therefore reforestation may be rendered or unsuccessful. Unfavourable ecological problems that occur as a result of soil compaction include excessive mechanical impedance, lack of oxygen, plant-available water and nutrients and deteriorated physical-chemical processes (Horn 1995). According to Omuto and Gumble (2009) “Infiltration and water retention characteristics are soil hydraulic properties that govern entry of water into the soil surface and its subsequent movement or storage in the soil”. Soil compaction results in an anisotropic pore system, in which water infiltration is impeded (Horn 1994). Reduced water flow abilities from soil compaction are the result of changes in the pore size distribution. Compaction causes the formation of hard barriers in the soil from the tightening of aggregates and a reduction in macropores which are important for providing water to vegetation. Byrd et al. (2002) states:

> As a result of heavily compacted soils, porosity is reduced allowing for little infiltration and percolation, and an increased potential for surface runoff…the promotion of soil macropores can minimize surface runoff, maximize infiltration and percolation and leads to little erosion (Byrd et al. 2002).

Adequate water infiltration is important for the soil water balance in Alberta. The prairie regions have experienced significant land use modifications over the last 100 years including converting to cropland which impacts water balance (Zaitlin et al. 2007). These modifications have increased surface runoff in cultivated areas and runoff events are higher in croplands than in grass-covered uplands (Zaitlin et al. 2007). Less runoff in grass-covered upland areas is due in part to increased macroporosity from burrowing organisms leading to increased infiltration in these areas (Zaitlin et al. 2007). Macropores are important in reducing erosion and runoff by improving infiltration in the soil. Altering the pore size distribution through land use modifications including compaction has been shown to reduce infiltration (van Dijck and van Asch 2002). Subsoil ripping or subsoiling has been shown to alleviate the impacts of compaction and improve soil water dynamics by altering the pore size distribution to improve infiltration rates (van Dijck and van Asch 2002). The subsoil ripping process involves the use of specially designed shanks to penetrate the subsoil and break up large peds. Breaking up the soil can increase macropores and increase water entry in the soil. This has been shown to be beneficial for improving vegetation growth in studies by Bangita and Rao (2012), Harrison et al. (1994) and Oussible et al. (1992). Subsoil ripping is becoming an increasingly desirable method for improving soil conditions for plant growth in ecosystem reconstruction studies.

3.2 Research Objectives

This chapter focused on comparing soil moisture and temperature dynamics for ripped and unripped treatments and observing characteristics that influence soil water content between February 1st and July 31st, 2013 at 10- and 30-cm depths at an area undergoing soil and landscape reconstruction at Genesee Prairie Mine, Alberta. The primary objective was to compare the soil water dynamics especially during snowmelt in the ripped and unripped treatments.

3.3 Methodology

3.3.1 Site Description

The site description was previously described in detail in Chapter 2, Section 2.3.1. Briefly however, the experimental site was located at Genesee Prairie

Mine which is situated between the Dry Mixedwood Natural sub-region of the Boreal Forest Natural Region and Central Parkland Natural sub-region of the Parkland Natural Region of Alberta. The area was mined between 1990 and 1992 and reclamation took place between 1992 and 2001. The end result was agricultural land that remained in forage until 2003. Annual cropping occurred between 2005 and 2009. The field was reclaimed to alfalfa for approximately 5 years. Subsoil ripping was executed in the fall of 2010 in preparation for the research outlined in this thesis.

3.3.2 Experimental Design

The experimental design of the research site was described in detail in Chapter 2, Section 2.3.2. In summary however, the research site was a 575-m x 25-m plot (Fig. 3.1) with two treatments; unripped (compacted) and ripped (decompacted). Half of the site underwent a subsoil ripping treatment in 2010 using a McNabb winged subsoiler D7R XR Caterpillar. Treatments alternated between compacted and uncompacted in 6 established blocks with 20-m buffer areas between treatments. Subplots were established by dividing plots into 4, 9 x 12-m sections, each randomly assigned to 1 of 4 vegetation covers. There were 48 established subplots in total.

Within each subplot, EM50 Decagon Data Loggers (Decagon Devices, Inc. Pullman, WA, USA) were installed in the summer of 2012 by digging a small trench with a shovel. Sensors collecting volumetric water content with corresponding temperatures were placed at 10- and 30-cm depths in unripped plots and 10-, 30- and 60-cm depths in ripped plots (Tab. 3.1). Information from the probe cables were sent to the data loggers every two hours from January 1st to July 31st, 2013.

3.3.3 Soil Water Content Measurements

Data from all 48 subplots were collected the first time from the field on May 13th, 2013. Data from the 4 subplots of each treatment within each block were averaged to compare ripped and unripped data for each block. Volumetric water content data was averaged per day for each subplot for 10- and 30-cm soil depths between February 1st and July 31st. We were only interested in data over the spring snowmelt therefore January data was omitted. Sensor data at 60 cm for ripped plots were not used because we are only interested in comparing treatments and unripped data was not available (Tab. 3.1).

The decagon soil moisture sensors use a standard calibration to convert soil dielectric permittivity to volumetric water content. This standard calibration (Topp et al. 1980) was developed for soils that were not compacted. Because the soil dielectric permittivity is sensitive to the relative proportions of soil solids, water, ice and air, the following semi-empirical dielectric mixing model was used to convert soil dielectric permittivity to volumetric water content (Roth et al. 1990):

$$\theta_v = \frac{\sqrt{\varepsilon_{soil}}}{\sqrt{\varepsilon_w}-\sqrt{\varepsilon_a}} - \frac{(1-f)\sqrt{\varepsilon_s}-f\sqrt{\varepsilon_a}}{\sqrt{\varepsilon_w}-\sqrt{\varepsilon_a}} \quad [1]$$

where ε_{soil} is the dielectric permittivity of the soil measured by the soil water sensors, ε_w, ε_a, and ε_s are the dielectric permittivities of soil water, air and solids and f is the soil porosity (m^3 m^{-3}). ε_w, ε_a, and ε_s are well known values (81, 1 and 5) and can be looked up in tables. To estimate volumetric water contents, the average porosity of the ripped and unripped soils were inserted into Eq. [1].

3.3.4 Snow Survey

A snow survey was conducted on March 1st, 2013 to determine snow-water equivalent (SWE) of the site by collecting snow depth and density information. Snow depth measurements were taken every 10 meters using a standard ruler and snow samples were collected every 20 meters along two east and west transects (north transect and south transect) spanning all of the research plots (Figs. 3.2 and 3.3). Samples were collected with a 4.6-cm diameter PVC (polyvinyl chloride) pipe pushed into the snow pack until contact with the ground was reached. Depth of snow in the PVC pipe was recorded in centimeters. Snow samples were collected, transferred to individual bags and then weighed in the laboratory. Depth (cm) and mass (g) of snow were used to calculate snow density. Snow density was used to compute snow water equivalent (SWE (cm)) values. The amount of water in the snow pack was obtained using 61 snow samples and 53 snow-depth measurements. Snow Water Equivalent (SWE) was calculated using the following equation:

$$SWE = dsw\ x\,\frac{\rho sw}{\rho w} \qquad [1]$$

dsw = depth of snow (cm)

ρsw = density of snow (g cm^{-3})

ρw = density of water (g cm^{-3})

3.3.5 Meteorological Measurements

Precipitation and temperature information from Tomohawk, Alberta between February 1st and July 31st, 2013 was used for this research. Climate information downloaded from the Agriculture and Rural Development, Alberta's weather station website (Agroclimatic Information Service, AB, Canada). Tomahawk is located 60.6-km west of the Genesee mine area.

3.3.6 Topographic Survey

A topographic survey was conducted between August and October, 2013 using a Leica FlexLine TS09 surveyor (Leica Geosystems AG, Heerbrugg, Switzerland). Considering the length of the site, the total station was set up at 3 different locations. GPS coordinates were taken at each location for reference. Survey points were taken every 3-m (rise/run) in a grid pattern. Survey points were also taken for each of the 48 sensor locations. Topography data was analyzed using Surfer 9 (Golden Software, Inc.) and a constructed 3D map.

3.4 Results and Discussion

3.4.1 Topography

The topographic survey of the site showed slight, natural sloping to the north. The black dots in the middle of the site represented sensor locations (Fig. 3.1). The elevation between the east and west transects varied by approximately 6-m for the 575-m long site (average slope of 1%; Fig. 3.1). Slightly concave or more depressed areas were evident at two locations; in the middle of the site, between ripped plots of blocks 3 and 4 and towards the west of the site, between ripped plots of blocks 5 and 6 (Fig. 3.1). The rest of the site was shown to be relatively flat. Interpretation of results did not show a wide range of topographic variation for the site because sloping was gradual and no dramatic changes in elevation were evident.

3.4.2 Variation in Snow-Water Equivalent

The March 1st snow survey results showed little variation in SWE in the north and south strips at the site (Fig. 3.2). One slight variation was observed on the eastern side of the research plots with the south transect having relatively higher SWE values compared to the north. This was likely from variation in topography, considering the natural topography of the site is slightly sloping to the north and snow is often redistributed to concave areas of the landscape by wind (Fig. 3.2). The average depth and density for the north strip were 20.41-cm and 0.288-g cm^{-3} while the south strip had values of 22.31-cm and 0.30-g cm^{-3} respectively (Tab. 3.2). The SWE values for the north and south strip were 5.91-cm and 6.69-cm respectively, averaging 6.3-cm or 63-mm of water in the snow pack on March 1st, 2013. Despite the small difference in average SWE in the north and south transects and the low average variability within the transections (CV = 23% for the north and 22% for the south transect; Tab. 3.2), SWE varied as much as 50 to 100% over short distances in some locations within and between both transects (i.e. an increase of 4.0 – 7.5-cm between 140 to 170-m of the north transect). This variability, however, appears to be consistent for both treatments, but significant spatial variability may confound treatment differences.

3.4.3 Soil Water Content

3.4.3.1 Climate

Temperature and precipitation patterns greatly affected soil water content at the site. This was evident due to trends observed in the Tomahawk weather data (Fig. 3.3) which corresponded to the trends in water content in the soil (Figs. 3.5 and 3.6). Temperature in February and March remained below $0^{o}C$ for the majority of the winter allowing the available water in the soil pores to remain mostly frozen during this time (Fig. 3.3). The increase in air temperature in the beginning of April (Fig. 3.3) allowed phase change to occur resulting in thawing of the snow and soil that continued until the end of the month. It was during this time when the soil water content increased and reached a peak at around April 27^{th} (Figs. 3.5 and 3.6). The soil began to steadily dry out after this causing the water content to decrease while air temperature increased into the spring. Water that was lost in the soil during this period was likely from evapotranspiration and drainage and it was not replaced by precipitation from lack of rainfall events for the first 3 weeks of May. The first major precipitation events in the spring occurred on May 24^{th} with 25.6-mm and May 25^{th} with 13.3-mm of rain that resulted in the infiltration of rainwater in the soil and the increase in soil water content during the first week of June (Figs. 3.5 and 3.6). Fewer and sparser rainfall events occurred after this period, causing the soil water content to slightly fluctuate. Another major rainfall event occurred on June 18^{th} with 11.2-mm of rain, resulting in rainfall infiltration and increase in water content. The increase in temperature to $23^{o}C$ on July 2^{nd} (Fig. 3.3) and subsequent increased evapotranspiration was the likely cause of the dramatic decrease in water content allowing the soil to further dry out with fewer rainfall events to replace soil water lost to evapotranspiration. The precipitation event that occurred on July 15^{th} with 15.4-mm of rainfall resulted in another evident increase in water content of the soil (Fig. 3.3).

3.4.3.2 Soil Temperature

Changes in soil temperature were fairly similar for ripped and unripped soil. Temperatures were relatively warmer at 10-cm compared to 30-cm during the growing season (Fig. 3.4). This was caused by naturally warmer soil temperatures at shallower layers from increased contact with solar radiation (Olchev et al. 2009). Soil temperature data further suggested that the soil was mostly completely frozen during the winter months, considering the soil temperature remained below $0^{o}C$ the entire winter. The slight increase in soil temperature just above $0^{o}C$ during the first 3 weeks of April suggested beginning of the soil thawing period. During this thawing period, the observed increase in soil water content is likely a result of the melting of ice in the soil pores to liquid water. This nature of the Decagon dielectric sensors is such as phase changes in soil water are “seen” as changes in soil water content even though there may not be any change in the total mass of water in the soil. It is possible that there was some infiltration of snowmelt during the first 3 weeks of April, but it is likely minor compared to the much warmer 4^{th} week of April (Figs. 3.4, 3.5 and 3.6). The increase in soil temperature to $7^{o}C$ at 10-cm (Fig. 3.4-A) and $5^{o}C$ at 30-cm (Fig. 3.4-B) and corresponding increases in soil water content during the last week of April is likely a combination of continued soil thawing and infiltration of snowmelt. A greater temperature peak was also observed for the 10-cm depth on April 27^{th} during the end of the snowmelt infiltration period suggesting greater water-filled pores compared to the 30-cm depth. This was caused by higher amounts of moisture at or near the soil surface (Willis et al. 1961) available for infiltration as well as the longer time it takes for water filled pores to thaw in deeper soil layers. It was likely that water in pores remained frozen for longer periods of time at 30-cm as suggested by the lower volumetric water contents in May (Fig. 3.6). The onset of the growing season corresponded to soil drying from evapotranspiration and drainage. Any increase in water content after this was due to precipitation events during the growing season (May-July).

3.4.3.3 Soil Moisture Dynamics

Soil Moisture Response to Precipitation Events

The 4 major rainfall events recorded at Tomohawk during the spring and summer of 2013 were on May 24th with 25.6-mm, May 25th with 13.3-mm, June 18th with 11.2-mm and July 15th with 15.4-mm of precipitation. This was observed by increases in water content shortly after rainfall had occurred. For example, the series of rainfall events that occurred starting on May 24th and 25th and continuing into the first week of June were marked by the increases in soil water content (Figs. 3.6 and 3.7). This trend was also evident for the other two rainfall events however rainfall events in the summer were not as isolated and continual overall increases in water content were observed as a result of more frequent rainfall. These occurrences are the result of the rainfall infiltration rate of a loamy soil i.e., hydraulic conductivity of the soil (Cheng et al. 2011) as well as the time of year (rainfall periods). A study by van Dijck and van Asch (2002) observing compaction of loamy soils found that the saturated hydraulic conductivity of topsoil was 1-3 times greater than that of subsoil as a result of compaction.

It appeared that soil at 10-cm responded more dramatically to fluctuations in rainfall and drying patterns as shown by more abrupt increases and decreases (spikes) in volumetric water content while 30-cm showed less dramatic spikes (Figs. 3.6 and 3.7). This was likely the result of a slower percolation rate at 30-cm which is expected at greater depths. If this rate is too slow and water at the surface cannot infiltrate fast enough, runoff can occur due to prolonged surface saturation (Borsi et al. 2004).

In contrast to snowmelt infiltration, it did not appear that greater amounts of rainwater infiltrated at a particular depth and water content at 10- and 30-cm varied for each block with rainwater infiltration (Figs. 3.6 and 3.7). This was due to more water retained at the surface layers (Cheong et al. 2012) as well as the wet climate of fall 2012, allowing the soil water content to be initially high and any infiltration during 2013 contributed to the increasing water content of the soil.

Soil Temperature Response to Air Temperature

Fluctuations in soil temperature were dependent on air temperature. It would be expected that the deeper subsoil would remain many degrees warmer in the winter months than the surrounding air because of greater thermal insulation provided by the above soil layers and greater ice content, meaning that the soil essentially becomes a heat source in the winter (Kodesova et al. 2013). This is especially significant during freezing and thawing periods when the soil would respond very slowly to changes in the outside air temperature. Results showed that soil temperature remained below $0^{o}C$ and stayed within the range of 0 to -$1^{o}C$ for the entire months of February and March, while the air temperature fluctuated between 2 and -$15^{o}C$ (Figs. 3.6 and 3.7). Similar observations were evident during the thawing period (April) where the temperature of the soil remained between 0 and $1^{o}C$ while the outside air temperature fluctuated between 12 and -$7^{o}C$ (Figs. 3.6 and 3.7). Air and soil temperature fluctuations became more synchronous during the spring after the soil thaw period, starting around May 15th. By summer, the reverse occurred and the soil temperatures became cooler than the surrounding air, especially at 30-cm. This was expected due to the soil becoming a heat sink during the warmer months (Kodesova et al. 2013). These trends impact the rate at which soil thaws and when it starts to infiltrate into the pores at various depths. Lower water contents were evident at 30-cm during snowmelt infiltration and seasonal fluctuations in air temperature impacting soil temperature are the cause of this from temperature lag and slower thaw rates.

3.4.3.4 Effects of Ripping on Soil Moisture Dynamics during Snowmelt

The soil thawing curve showed greater water contents for ripped plots between February and July of 2013 with increasing temperatures, compared to unripped plots (Fig. 3.7). The thawing curve is a plot of soil moisture content versus soil temperature. For both the 10- and 30-cm depths, the ripped treatment showed greater water contents over most soil temperatures less than $5^{o}C$ and especially $0.2^{o}C$ and less. Further, at both depths, the minimum soil temperature was greater in the ripped treatment compared to the unripped treatment. This indicates that in the ripped treatments, the soil did not freeze as much as the unripped treatments. Because the ripped soil did not freeze to the same extent it did not require as much heat to thaw which facilitated snowmelt infiltration during spring snowmelt. The reason for this is likely due to changes in the soil thermal properties because of changes in bulk density and pore size distribution caused by the ripping treatment (see Section 2). Lesser heat required for ripped plots is the result of greater amounts of macropores created by the ripping treatment and the altering of the pore size distribution. Runoff is likely greater in compacted plots (Raper and Kirby 2006) due to reduced water infiltration from fewer macropores.

3.5 Conclusions

The objective of this chapter was to compare soil moisture and temperature dynamics for ripped (uncompacted) and unripped (compacted) soil at 10- and 30-cm depths by observing the influence of snowmelt and rainwater infiltration on soil water content, especially during snowmelt, between February 1st and July 31st, 2013 for the 6 established blocks at the reconstructed study site situated between the Dry Mixedwood Natural sub-region and Central Parkland Natural sub-region at Genesee Prairie Mine, Alberta. More specifically, this chapter involved analyzing the impacts of topography, snow-water equivalent, climate, soil temperature and a soil thawing curve on ripped and unripped soil the site. This research was executed to ultimately determine if improved soil physical conditions created through subsoiling would improve the soil water balance and benefit long term trembling aspen growth on a previously disturbed area that is undergoing reconstruction.

Site topography was shown to play a minimal role in any variation in soil water content for ripped and unripped soil for the 6 blocks, but the observation period was short – only one winter and growing season. This was due to little topographic variation across the site, where no dramatic changes in elevation existed. Snow-water equivalent results showed little variation in the distribution of snow cover at the site and which was likely due to uniform topography. SWE was not shown to be a limiting factor in soil water content.

Increases in soil temperature in April allowed thawing of the soil and snowmelt infiltration causing the soil water content to increase. Greater snowmelt infiltration was observed at 10-cm compared to 30-cm. Four major precipitation events caused increases in soil water content during the spring and summer months. Rate of infiltration depended on the hydraulic conductivity of the soil. The 10-cm depth responded more dramatically to rainfall patterns compared to 30-cm due to slower percolation rate at greater depths. Fluctuations in soil temperatures were directly dependent on changes in air temperatures. It was expected that the soil remain many degrees cooler or warmer than the surround air depending on the grounds response to temperature changes. These trends affected when the soil freezes and thaws and subsequently infiltrates.

The soil thawing curve showed greater water contents in ripped soil compared to unripped. The ripped soil did not freeze to the same extent as unripped soil which was evident by higher temperatures in ripped soil below 0^oC. Greater macropores created by the ripping treatment allowed lesser heat for soil thawing in ripped plots.

Results from this experiment allow us to conclude the positive impacts of subsoil ripping on soil water dynamics. Subsoil ripping may create positive conditions for long term trembling aspen establishment in these environments due to improved infiltration and drainage.

3.6 Tables

Table 3.1 Soil sensor placement below the soil surface in unripped and ripped subplots for the study site at Genesee Prairie Mine, Alberta. Italicized probes were not used in this experiment.

Soil Treatment	Sensor	Depth
Unripped	5TM: VWC (cm cm^{-3}) Probe Temp. (^{o}C) Probe	10-cm
	5TM: VWC (cm cm^{-3}) Probe Temp. (^{o}C) Probe	30-cm
Ripped	5TM: VWC (cm cm^{-3}) Probe Temp. (^{o}C) Probe	10-cm
	5TM: VWC (cm cm^{-3}) Probe Temp. (^{o}C) Probe	30-cm
	5TM: *VWC (cm cm^{-3}) Probe* *Temp. (^{o}C) Probe*	60-cm

Table 3.2 Snow survey analysis for south and north strips at the site showing average snow depth (cm), snow density (g cm^{-3}), and snow water equivalent estimates with calculated standard deviation (for SWE) and coefficient of variation (%) for the March 1st, 2013 snow pack for the Genesee Prairie Mine, Alberta study site.

Line (Strip)	Depth (cm)	ρsw (g cm^{-3})	SWE (cm)	STDEV	CV (%)
North	20.414	0.288	5.91	1.387168377	23
South	22.31	0.30	6.69	1.469255986	22

Figures 3.7

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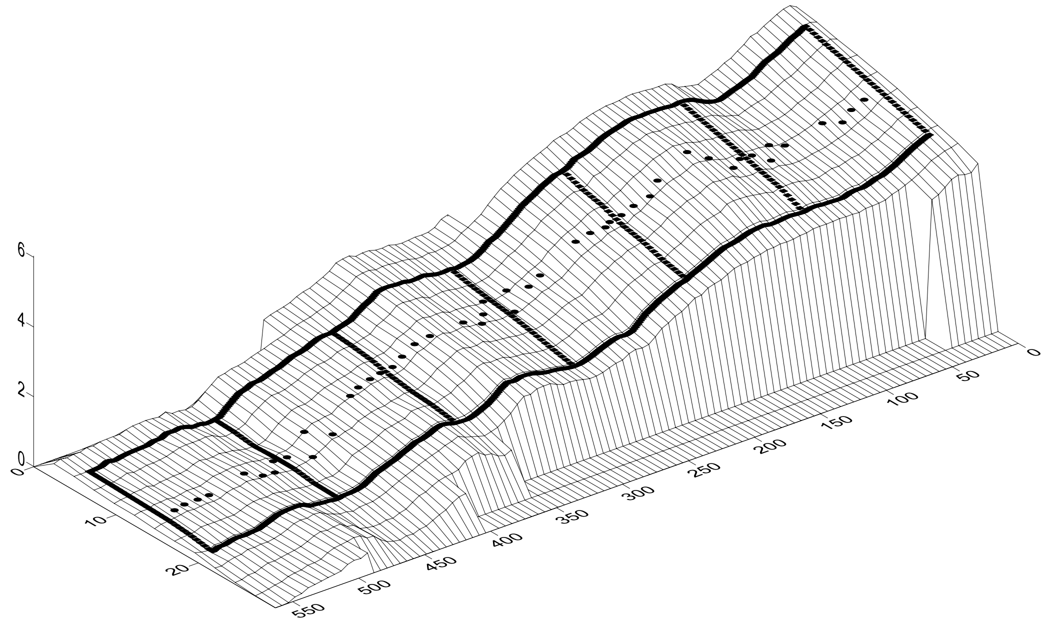

Figure 3.1 3D interpretation of the Genesee Prairie Mine, Alberta study site with treatment blocks (see Fig. 2-2) superimposed. Dots in the middle of the site represent sensor locations with 4 sensors per plot and 48 sensors in total.

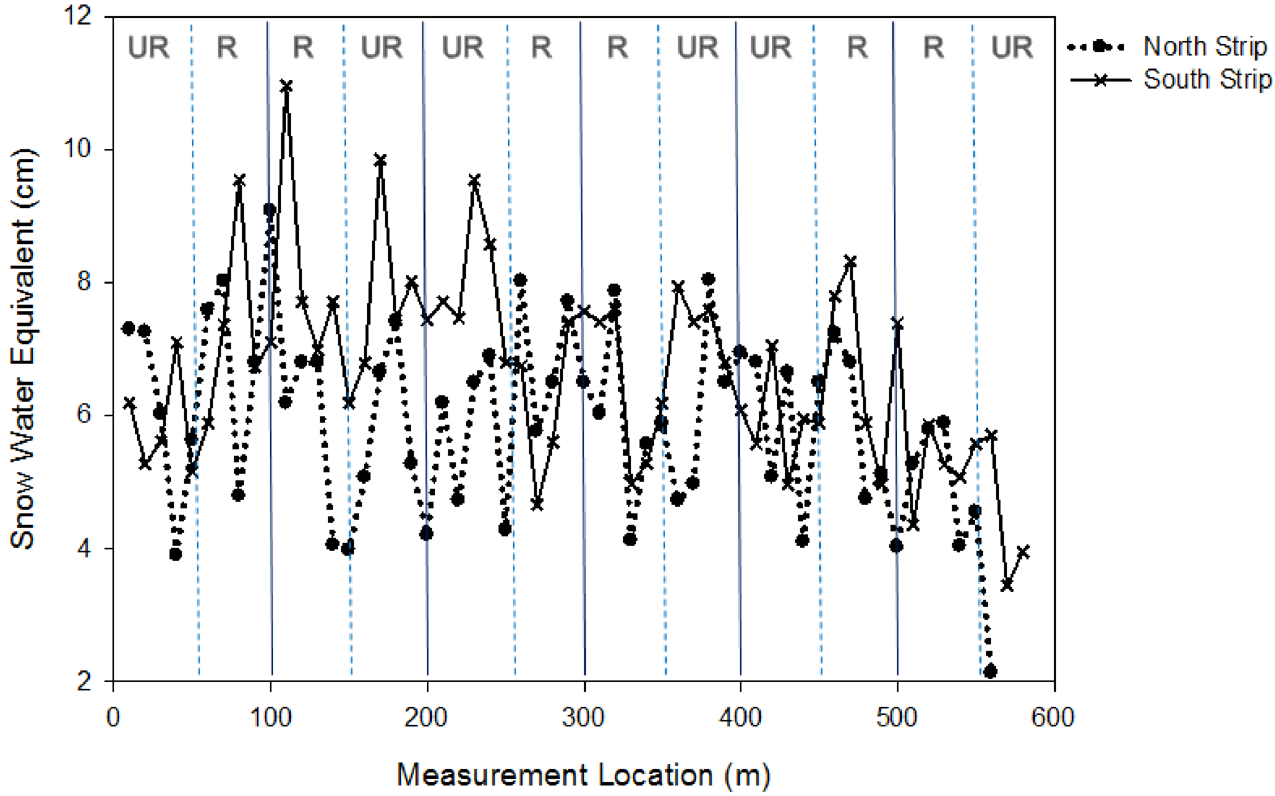

Figure 3.2 Snow water equivalent (cm) estimates across the site for the south and north transects for March 1st, 2013. Solid vertical lines represent each block. Dotted vertical lines separate each block into ripped or unripped plots. Measurements run east to west (0-600 m) on the site.

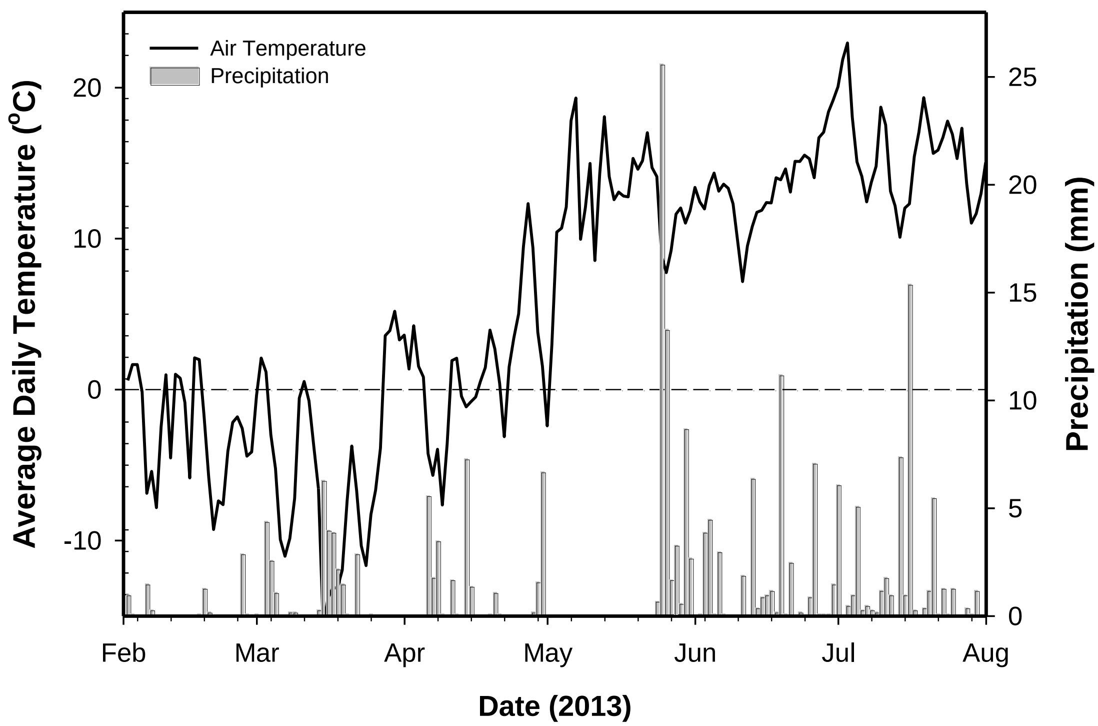

Figure 3.3 Precipitation and average daily temperature for Tomahawk, AB between February 1st to July 31st, 2013. Data retrieved from Agriculture and Rural Development, AB.

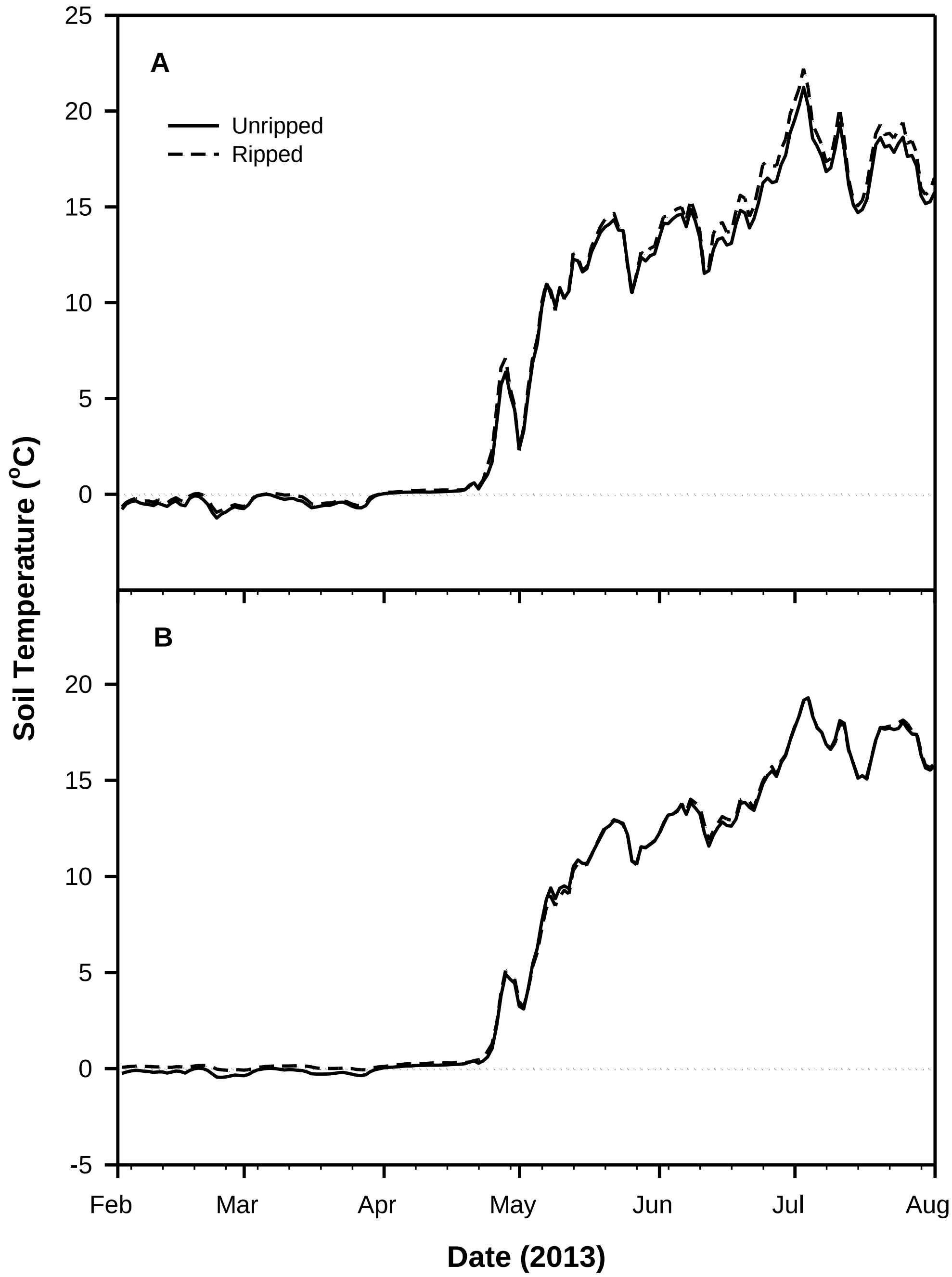

Figure 3.4 Average daily soil temperature for blocks 1-6 at A. 10- and B. 30-cm February 1st and July 31st, 2013.

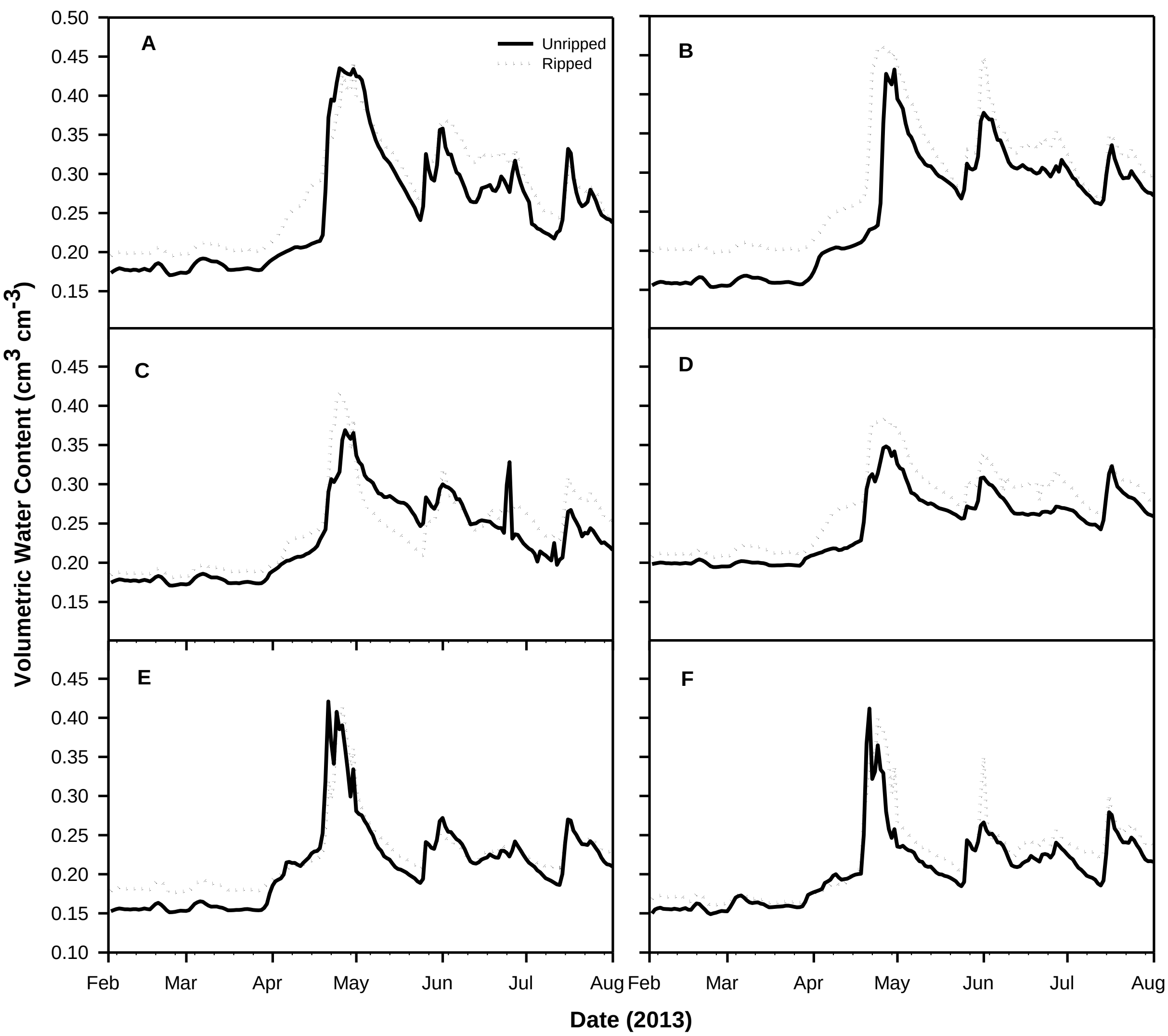

Figure 3.5 Average daily volumetric water content for ripped and unripped soil for blocks A. 1, B. 2, C. 3, D. 4, E. 5, F. 6 at 10-cm below the soil surface between February 1st and July 31st, 2013.

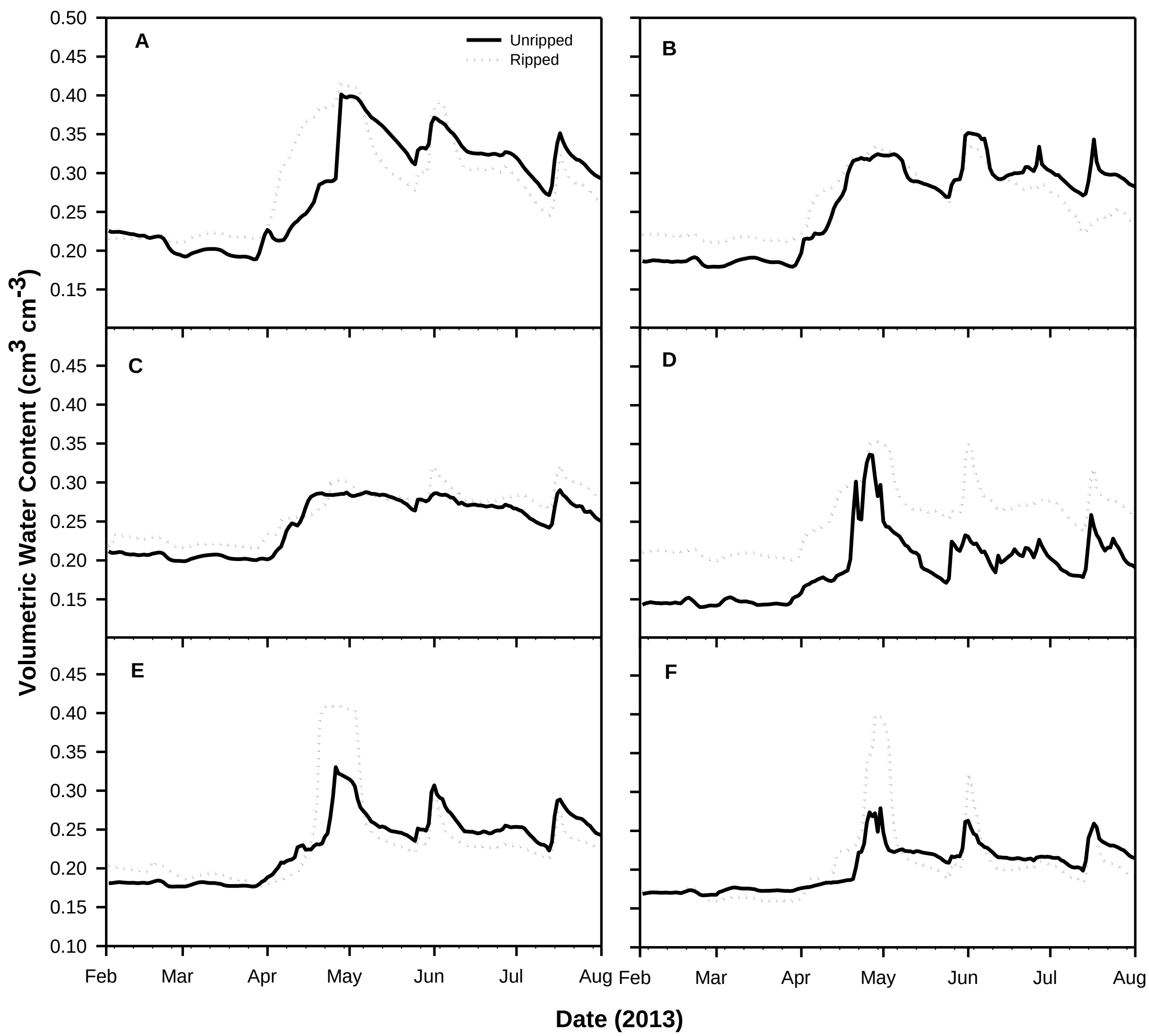

Figure 3.6 Average daily volumetric water content for ripped and unripped soil for blocks A. 1, B. 2, C. 3, D. 4, E. 5, F. 6 at 30-cm below the soil surface between February 1st and July 31st, 2013.

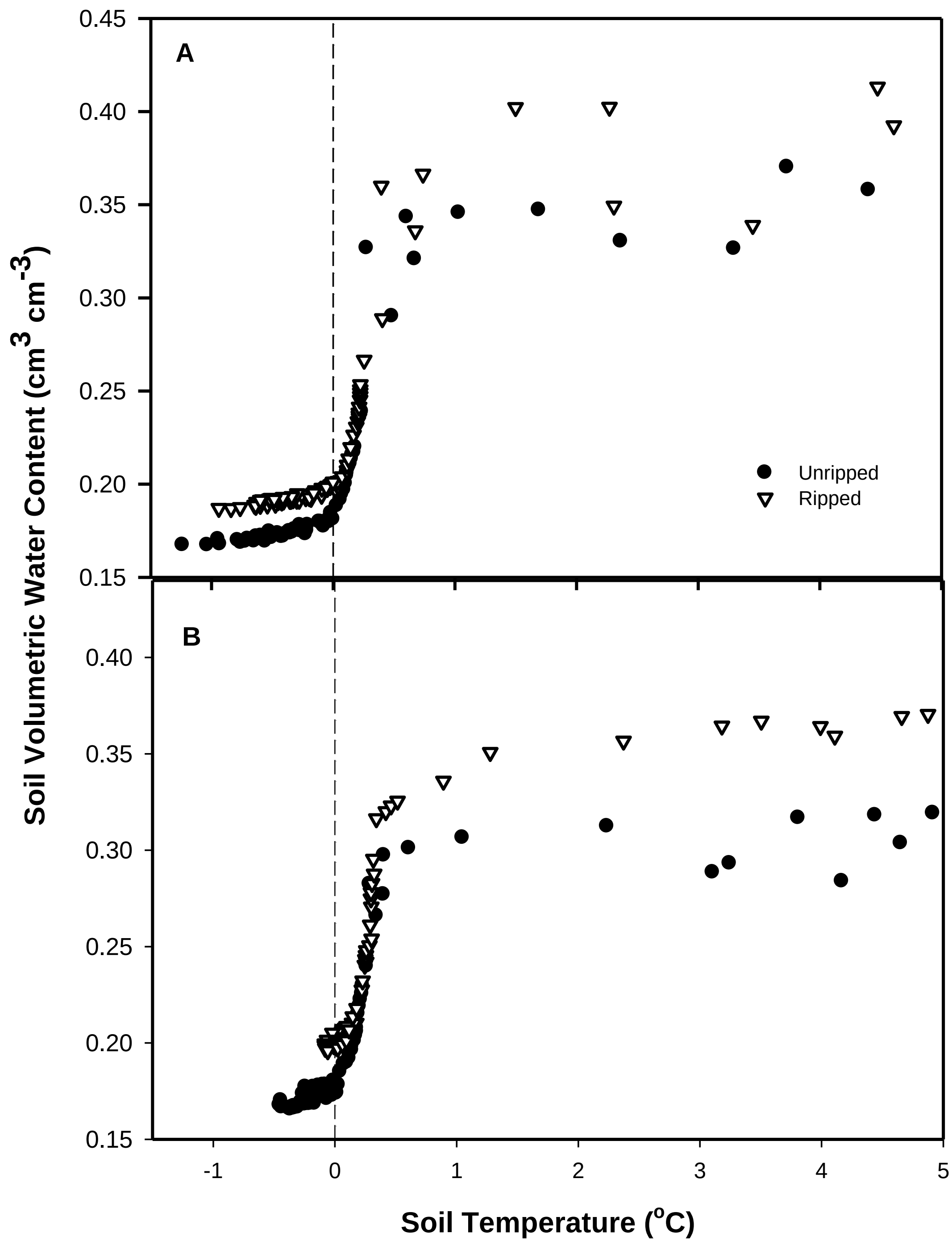

Figure 3.7 Soil thawing curve showing volumetric water content as a function ofsoil temperature between -1 to 5°C at A. 10- and B. 30-cm.

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Chapter 4 – General Conclusions

4.1 Research Summary

Subsoil ripping treatments were established at a mine tailings research site at Genesee Prairie Mine, Alberta to assess the possibility of improving soil physical properties and soil water balance in soils compacted during reconstruction. This research was executed as part of a larger research project to determine if trembling aspen (*Populus tremuloides*) establishment would improve after subsoil ripping due to improved soil physical conditions.

Chapter 2 goals included observing differences in soil physical properties and soil water retention characteristics by comparing bulk density, soil strength, hydraulic conductivity, moisture retention and void ratio differences between unripped soil (compacted) and ripped (decompacted) soil. Chapter 3 goals were to observe differences in soil water content for ripped and unripped soil at 10- and 30-cm depths by observing the impacts of snow-water equivalent, topography, climate, soil temperature, snowmelt infiltration and rainwater infiltration characteristics with respect to volumetric water content between February 1st and July 31st, 2013 for the 6 established blocks. Major findings of this research were as follows:

- Ripping decreased soil strength and increased the depth of the rooting zone.
- Bulk density was improved with ripping, especially in the top 30-cm and to a lesser extent the 30-60-cm depth.
- The ripping treatment that was imposed did not change the depth distribution of sand, silt and clay due to the nature of the treatment where the soil was not mixed or turned over.
- Moisture retention results showed decreased water content in ripped soil with increasing pressure gradient, indicating improved plant-available water from increased macroporosity.
- Differences in void ratios in ripped and unripped soil indicated increased matrix and structural pore spaces in decompacted plots. Residual pore spaces were also reduced in the ripped treatment.

- Saturated hydraulic conductivity could not be accurately measured using the described method outlined by Klute and Dirksen (1986). CDF analysis showed no distinct differences in conductivities that fall within the computed range of probabilities for ripped and unripped samples. More research needs to be conducted to determine the relative k_{sat} of the soil.
- Little topographic variation was observed across the site and therefore is likely not a significant factor in differences in soil water content due to relatively uniform slope and elevation.
- Little variation in snow-water equivalent was observed in the north and south strips and therefore, it is likely not a limiting factor in the soil water content due to even spread of snow cover.
- Climate patterns and soil temperature determined thaw times, rate of thaw and time of snowmelt infiltration at the site.
- Greater snowmelt infiltration was observed at 10-cm compared to 30-cm due to greater soil temperatures at this depth. This resulted in higher water contents at 10-cm.
- Four major rainfall events during spring and summer resulted in rainwater infiltration and maximum increases in soil water content about a week after the rainfall event.
- Greater spikes in water content were observed in soil at 10-cm due to rate of rainwater infiltration and hydraulic conductivity.
- The soil thawing curve showed greater water contents for ripped plots compared to unripped as a result of the ripping treatment. Ripped soil did not freeze to the same extent as unripped and therefore less heat was needed to thaw the soil.
- Results from this research allow us to demonstrate the benefits of subsoil ripping on soil physical properties and soil water content in compacted soils and likely improved environments for plant growth.

4.2 Recommendations

This research demonstrates that soil physical properties and water balance can be improved to increase the success of trembling aspen and other vegetation in compaction-affected soils. Results from this research suggest that improvement of the soils pore size distribution through the use of many lab and field techniques can lead to improved soil conditions for vegetation.

It is recommended that compaction level is monitored at regular intervals and the effect of natural re-compaction that occurs over time on soil physical properties before and after revegetation must be considered. Human-caused re-compaction with machinery re-entering the site should be avoided.

It is recommended that care be taken in the selection of ripping equipment and appropriate machinery and shanks should be selected for the soil substrates of interest including undisturbed or severely disturbed soil environments.

Care in handing soil samples should be taken to avoid disturbing them to assure adequeate results can be measured. This includes appropriate method of extraction, adequate preparation and suitable storing procedures.

Care should be taken while performing landscape activities to prevent or lessen the level of compaction during landscape reconstruction. Suggestions to reduce severity of compaction include:

- Reduce soil tillage operations on the site.
- Reduce ploughing frequency (number of passes) across the landscape.
- Reduce the weight of the machinery on the landscape or if possible, use wider tires to reduce pressure.
- For agriculture activities, harvesting should be done when soils are dry to avoid further compaction.
- Increase organic matter in the soil. Maintaining crop residue is encouraged.

4.3 Future Research

Knowledge of the impacts of soil compaction on soil physical properties and soil water dynamics is important for re-vegetation projects in the natural regions of Alberta. Additional research is required to fully understand the effects of subsoil ripping on vegetation growth, especially long term. Results of this study indicate improved soil physical properties and water balance after ripping. Areas for future research include:

- Monitoring of soil compaction of the study site in consideration for the natural re-compaction that occurs over time. This will likely change the results found in this thesis with respect to bulk density and pore size distribution.
- Understanding of plant physiological processes with respect to water and nutrient use in disturbed and undisturbed soils.
- Trembling aspen water use differences in ripped vs. unripped soil at different depths.
- Monitoring changes to soil over time including soil organic matter levels and changes to compaction with respect to bulk density in areas with varying levels of vegetation.
- The impact of subsoil ripping in different soil substrates and textures and its effect on soil physical properties and soil water content.
- The impact of compaction on soil physical properties in environments affected by varying disturbances including forest fires and floods and in different regions of the province.
- The effect of vegetation growth in steep slopes on reconstructed mine soils.
- Experimenting with different types and sizes of subsoiling shanks and comparing results.
- Experimenting with different subsoiling techniques and comparing results.
- Apply and compare void-ratio results to pore size distribution procedure outlined by (Vomocil 1965).
- Research on methods to measure saturated hydraulic conductivity of the soil at the site with consideration for handling method and preparation of soil samples for these experiments.

- Observation of the behavior of freeze-thaw cycles and snowmelt infiltration and changes to soil water content over many field seasons.
- Monitoring runoff behavior in ripped and unripped soil after rainfall events.
- Conduct experiments undergone in Chapters 2 and 3 but at deeper soil depths for ripped and unripped soil.

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