SUBSURFACE AND SURFACE TILLAGE PRACTICES AND THEIR EFFECTS ON STRUCTURE, PERMEABILITY AND CROP YIELD IN A CHERNOZEMIC AND SOLONETZIC SOIL

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ABSTRACT

Fall tillage on the Canadian prairies may involve subsurface tillage (subsoiling) and surface tillage operations. These tillage practices alter soil physical properties such as aggregation, strength, bulk density, air and water permeability that can subsequently affect growth and yield of following crops. Reclaiming compacted Chernozemic and Solonetzic soils with hardpan B horizons may be possible through subsoiling operations to loosen the soil to depth e.g. ~30cm, while surface tillage operations such as tandem disc and vertical tillage can be used to get rid of recalcitrant crop residues like flax straw by incorporation to ~ 10cm. The objective of this study was to evaluate the effect of subsurface and surface tillage on soil physical properties and subsequent crop yield. Subsoiling treatments were applied to wheel traffic compacted and non-compacted Chernozemic and Solonetzic soils at a site in south-central Saskatchewan, Canada. Subsoiling increased air permeability in the compacted Chernozemic soil from 4.5×10^{-7} m sec^{-1} to 2.9×10^{-6} m sec^{-1}. The subsoiler also significantly reduced soil bulk density and soil strength in both soil types. Subsoiling increased crop production on only one soil type; the long-term wheel traffic compacted Solonetzic soil, which had the highest soil strength (> 2000 kPa), where canola grain yield was increased by 1,100 kg ha^{-1}. Effects of the subsoiling on soil physical properties and crop yield diminished greatly in the second year after subsoiling. Vertical tillage in the Chernozemic soil to incorporate flax straw tended to decrease water infiltration and air permeability compared to the raking and burning treatment and the no-till, no-burn control. Surface tillage of the flax stubble using tandem disk or vertical tillage implement, raking and burning, and direct seeding into the flax stubble all had similar wheat and pea yields in the in the first and second year of the study. When considering fall tillage, subsoiling may be most effectively applied to long-term wheel traffic compacted areas of a field with identified high soil strength. Surface tillage, raking and burning to reduce perceived residue interference may not be required if residue chopping and spreading by the combine at harvest is effective.

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LIST OF ABBREVIATIONS

SCB	South Central Butte Chernozemic Site
NCB	North Central Butte Solonetzic Site
FRM	Flax Residue Management Site
SFH	Simplify Falling-Head
EC	Electrical Conductivity
OC	Organic Carbon
MWD	Mean Weight Diameter
ρ_b	Bulk Density
xi	Mean Diameter
wi	Weight of the aggregates
S	Modulus of Rupture
F	Breaking force
L	Distance between briquette support
b	Width of the briquet
d	Thickness of the briquet
K_{fs}	Hydraulic Conductivity
ϑ_1	Initial volumetric water content
ϑ_2	Water content after infiltration
t_a	Time of infiltration
D	Depth to which the water was ponded at t=0
α	Hydraulic parameter

1 INTRODUCTION

Soils are the natural medium for plant growth, and the most common available resource for crop production (Thorne and Thorne, 1979). In agriculture, there are many factors that influence crop yields such as temperature, wind, precipitation, light, and most of these are difficult to control by the grower. However, to obtain high yields, aspects that can be controlled by the grower include selection of superior seeds, fertilizers, mechanical equipment (field preparation, seeding and residue management), and effective control of pests and diseases. The soil is a key part of the agricultural production system in which physical, chemical, and biological properties are constantly changing during the natural development, and also as a result of anthropogenic processes such as plowing or tillage (Horn and Baumgartl, 2002). The physical, chemical, and biological attributes of the root environment can have a profound influence on growth and crop yield. In particular, compaction in soils can impose significant changes in the surface and subsurface characteristics of the root zone (Soane et al., 1994). The research work conducted for this thesis addresses soil physical condition as a limitation for production. Studies were conducted to evaluate how soil conditions and crop yield can be improved through subsurface and surface tillage practices involving subsoiling and vertical tillage, respectively. Issues addressed are compaction from long-and short-term wheel traffic, and accumulation of crop residues such as flax straw that interfere with seeding operations. The study was conducted in south-central Saskatchewan at the border of the Brown and Dark Brown soil climatic zones in farm fields near Central Butte in the province of Saskatchewan. The investigations were focused on determining the influence of subsurface subsoiling and surface vertical and tandem disc tillage on water and air permeability, soil structure, and crop yield during the years 2016 and 2017. The study site enabled evaluation of tillage effects on two major soil orders: Chernozemic and Solonetzic soils found in the Canadian prairies.

Solonetzic soils are found in the western provinces of Canada. They are characterized by Bnt horizons with prismatic or columnar structure that are very hard when it is dry, and have an exchangeable sodium percentage on the exchange complex greater than 15% (Soil Classification Working Group, 1998). High concentrations of Na in the Bnt horizon and its dense nature affects productivity and workability as the air, water, and penetration by roots and seeding tools are limited (Miller and Brierley, 2011). Further deterioration in soil physical condition from wheel traffic on these soils may be particularly detrimental to production. Reclaiming sodic soils with hardpan B horizons may be possible through subsoiling to loosen the B horizon. Subsoiling can also result in more permeable strata, reducing soil strength and density and increasing infiltration (Thorne & Thorne, 1979; Ewen, 2015). In this thesis, subsoiling of wheel traffic affected areas of a field as a means to improve permeability, structure and crop yield in Solonetzic and Chernozemic soils was investigated. Comparisons were made between tillage applied to areas affected by compaction and those that were not in both soil types.

Chernozemic soils are characterized by having an Ah horizon with an accumulation of organic matter of at least 10 cm depth that meets the color criteria (Soil Classification Working Group, 1998). These types of soils are commonly found in the Canadian Interior Plains, the southern part that is often referred to as the prairies (Pennock et al., 2011). Accumulations of surface crop residue may impede the ability of seeding implements to create a good seed-bed for germination of following crops, particularly in no-till systems where crop residues tend to accumulate on the surface (Schoenau and Campbell, 1996) Surface tillage using a disc with a rolling basket that throws and buries crop residue is termed “vertical tillage” and is becoming a more common practice on the Canadian prairies to deal with recalcitrant crop residues like flax straw that interfere with seeding operations and to deal with ruts created by field travel during wet conditions. In the Chernozemic soil, the effect of vertical tillage and tandem disking on soil permeability, structure and yield of crops following flax were also assessed.

The work in this thesis project therefore evaluated the effects of subsurface tillage (subsoiling) and surface tillage (vertical tillage) (Figure 1.1). It is believed that subsoiling and vertical tillage can alter several important properties in Chernozemic and Solonetzic soils, including hydraulic conductivity (infiltration), air permeability, and soil structural attributes including aggregate size and stability, as well as crop yield. I hypothesize that these operations will have beneficial effects on permeability, structure and crop productivity, and that the effect will depend on soil conditions and type. The general objectives of the work were 1) to determine the effect of subsoiling of long-and short-term wheel-traffic-compacted soils on soil water and air permeability, structure and yield and; 2) to evaluate the impact of surface tillage including vertical and tandem disc tillage on soil properties and yield, utilizing field research sites located on farm fields near Central Butte, Saskatchewan The thesis organization is manuscript-style, with a general introduction, literature review, two chapters on the research work with the first chapter covering subsoiling and the second chapter covering the vertical tillage studies, and finally a synthesis and conclusion chapter.

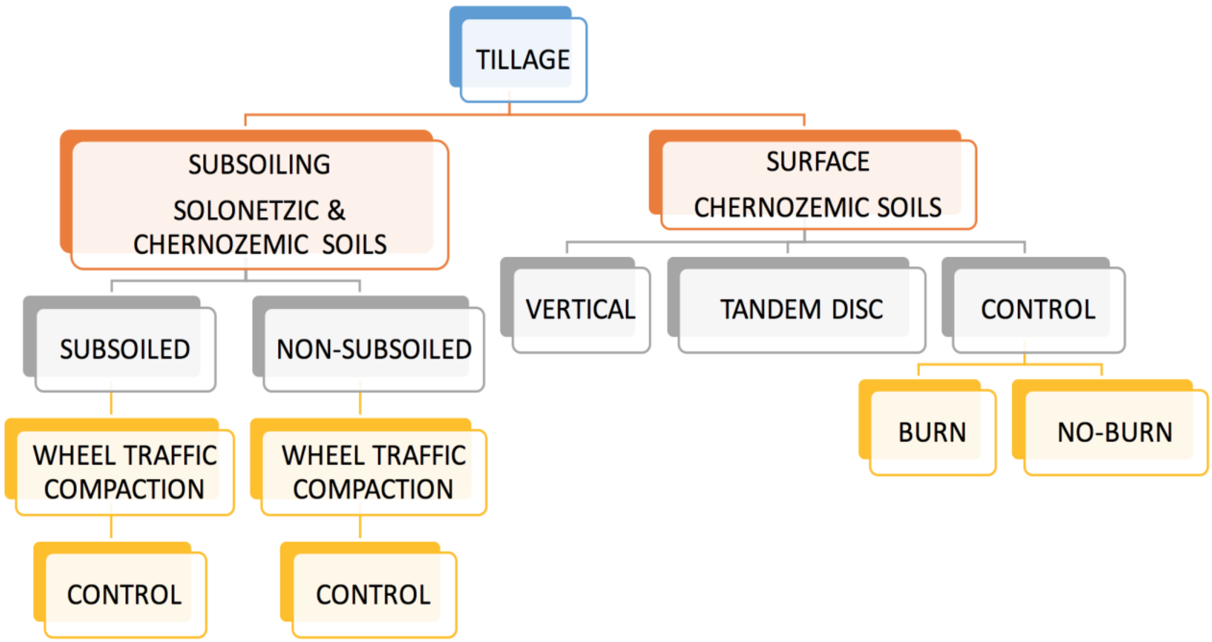

Figure 1.1. Study design.

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2 LITERATURE REVIEW

2.1 Soil Physical and Chemical Conditions and Tillage Practices

Saskatchewan has 44% of Canada's total cultivated farmland acres. In 2015, Saskatchewan's average wheat yield was 37.2 bushels per acre, and canola had a similar yield of 36.5 bushels per acre (Statistics Canada, 2015). Limitations on yield in the prairies are largely environmental such as lack of moisture and heat units. Weeds, disease, and insect pressures also reduce yields in some instances as does lack of soil fertility. However, there are also other important soil-related aspects to consider so as to obtain high yields of these key crops in prairie agriculture, such as soil water and air permeability, soil structure, and how processes like compaction and tillage may influence them.

In the Canadian prairies, it is important to consider soil moisture, especially in semi-arid areas, because of lack of water (drought) but also because of certain years of excess soil moisture that leads to flooding and runoff (Lawford, 1992). Farmers require information on soil moisture relations that can help in the field operation planning and planting strategies, selection of the varieties to plant, and how much fertilizer is necessary for the growing season (Lawford, 1992). Soil structure is also important. The nature and size distribution of aggregates and soil porosity is an essential part of the overall soil quality, as it has a strong influence on soil water, air, and fertility conditions and subsequently its productivity (Russel and Wild, 1988). The soil structure can be disrupted and porosity, water, and air permeability reduced or destroyed by wheel traffic from heavy machinery or implements, especially when the soil conditions are wet (Russel and Wild, 1988). In Canada, field operations that can lead to compaction and therefore increased density and resistance to penetration, reduced porosity and permeability include seedbed preparation, seeding, spraying, and harvesting involving wheel traffic from tractors, implements, carts and trucks. As a result, excessive compaction may inhibit soil aeration, restrict water infiltration and uptake and the normal development of crop roots (Grant and Lafond, 1993; Sekwakwa and Dikinya, 2012). When the soil is compacted, the hydraulic conductivity is reduced to a low level due to a reduction in porosity and deformation of aggregates (Emerson, 1978). In 1986, a study by the Science Council of Canada estimated that soil compaction decreases crop yields by 10% every year (Acton and Gregorich, 1995).

Solonetzic soils are distinguished from Chernozemic soils by their poor structure, imperfectly drained, hard, and compact subsoils that are categorized by columnar structures. The B horizon typically has significant accumulation of clay, and the incidence of considerable amounts of exchangeable sodium and magnesium, and the parent material of these soils are frequently saline (Acton & Ellis, 1978). Saline soils contain high levels of Cl and SO_4 salts of Na, Ca, Mg, and K (Sumner et al., 1998). Many soils in Saskatchewan that are Solonetzic are also affected by sub-soil salinity as well. Crop production in these types of soils can be difficult and were not the land of choice for settlers who came to the prairies in the early 1900's to grow crops. However, about 45 % of all Solonetz soils were indicated to be in annual crops in Canada by 1975, with the rest used as grazing land (FAO & UNESCO, 1975). Deep tillage technology was brought forward in the 1980's as a tool to alleviate subsoil compaction and improve physical properties and root and water penetration and also aid in leaching of the salts (Lal, 1995). Deep tillage to a depth of 30-50 cm mixes the Bnt horizon where Na is high with Ca brought in from the C horizon (Grevers & Tanner, 1986). The concept is that Na is displaced by the Ca, and, providing that there is an opportunity for leaching, the Na can be moved downward with precipitation water (Grevers & Tanner, 1986).

Dry areas are considered naturally predisposed to sodicity and salinization because of low precipitation and high evapotranspiration that restrict the downward leaching of the salts (Jame, 1992; Zinck & Metternicht, 2009). Some activities can further degrade the soils including compaction created by heavy machinery, waterlogging, and lack of organic matter (Zinck and Metternicht, 2009). According to Levy et al., (1998), the abundance of exchangeable sodium ions in the soil produces a destabilization in the soil structure, deterioration of soil hydraulic properties, and subsequent issues with crusting, erosion, poor aeration, etc. Soils with a high concentration of sodium are characterized by their poor physical properties such as low aeration and water infiltration (Oster and Jayawardane, 1998).

In Canada, Chernozemic soils are characterized by having dark-colored surface horizons due to the accumulation of organic matter from the decomposition of xerophytic or mesophytic grasses. Most of these types of soils are located in the cool, subhumid Interior Plains of Western Canada (Soil Classification Working Group, 1998). Saskatchewan is dominated by black, dark brown and brown Chernozemic soils characterized by a thick A horizon. Tillage has effects by changing soil structure and moisture over the growing season (Campbell, 2014). Pore space, which is vital as a pathway for water entering the soil and as a supplier of water and air to roots, can be altered by tillage (Acton & Gregorich, 1995). When soil physical structure is poor and inhibits root growth, deep ripping can reduce strength, increase pore space and the depth of rooting and therefore enhance the amount of water available to the crop (Verhoef and Egea, 2013). Deep tillage of soils can increase soil porosity, particularly vertical macropores. Unlike deep tillage that typically results in some inversion of the soil, "subsoiling" involves loosening the soil without inverting it and is utilized fundamentally to break through and fragment the compacted Bnt horizon (Grevers and de Jong, 1992). Also, in some salt-affected soils that are subsoiled, the soil-water infiltration and water recharge are improved that can then result in increased downward movement of salts (Grevers and de Jong, 1993).

2.2 Approaches to Addressing Structural Limitations Through Tillage

For the research project described in this thesis two types of tillage: sub-soiling and vertical tillage are evaluated. Some additional background on these tillage methods is provided here in the literature review of this thesis. The subsoiler used in the research was the John Deere 2100 Minimum-Till Ripper and its purpose was to break up the subsoil compaction with minimal surface soil disturbance. The subsoiler is an implement which works at depths of 30 to 50 cm to loosen and decrease the density of subsoil pans, promote water movement and plant root growth (McKyes, 1985; Lal, 1995). Roots also have an important function in addressing structural limitations in soil through expansion, the addition of organic matter, and stabilizing of soil aggregates (Tisdall and Oades, 1982). In order to improve and maintain high yield from crops on such soils; it is necessary to develop and stabilize the soil structure because poorly structured subsoils decrease crops productivity by limiting the development and performance of roots and also by inhibiting gaseous exchange, water storage and transport of water through the soil (Olsson, et al., 1994).

A “tandem disk” implement is a disc plow which has rigid steel round concave disks of 50 to 95 cm in diameter. The disks have sharpened and occasionally fluted edges, and often have self-cleaning scrapers to remove mud and debris from the disc as it rotates (McKyes, 1985). Vertical tillage is a term that is applied to many different types of tillage implements. However, for the purposes of this thesis, a “vertical tillage” implement is defined as one that typically has round concave disks similar in design to a tandem disk, along with a rolling “basket” that follows the discs. At high travel speeds (greater than 10 km hour) the rolling basket throws and mixes the loosened surface soil brought up by the discs, incorporating the residue and smoothing the surface. The John Deere Frontier TM5132 tandem disk and the John Deere 2623VT vertical tillage implements were used in the current study.

2.3 Characterization of soil physical properties and condition

Tillage can have significant effects on soil physical, hydraulic properties, along with grain and biomass yield (Grevers & de Jong, 1992; Cai et al., 2014; Elzubeir, 2014). The size and the stability of soil aggregates are often impacted by soil disturbances including tillage, which then influence hydraulic conductivity, water retention, soil crusts, and erodibility (Dexter, 1988). Hydraulic conductivity measures the capacity of the soil to conduct water (Ghildyal and Tripathi, 1987). There are different methods to measure soil water infiltration: the simplified falling head technique (SFH) to measure soil hydraulic conductivity has been widely used over the last 30 years. The instrument utilized in the current thesis research was a single square, and the reason for using a large square is to cover more surface area. Hydraulic conductivity is generally increased with increasing porosity and reduced soil density, which is in turn affected by soil texture and structure including aggregation (Ghildyal and Tripathi, 1987). Bole (1986), found that deep ripping over a 3.5 year period increased the hydraulic conductivity in Solonetzic soils. The hydraulic conductivity of the soil should be around 10^{-4} to 10^{-5} mm day^{-1} (Newman, 1969; Hasegawa & Sato, 1985).

When a load is applied to the soil such as through a tire, and pressure exceeds the aggregate strength, then the aggregates themselves will be destroyed, and the number of contact points between the single particles in the bulk soil is increased (Horn et al., 1995). The pore space in soil is comprised of macropores, mesopores, and micropores. The macropores are usually the spaces between soil structural units and as such, they are the main channel for rapid air and water movement (Tan, 2009). When there is compaction in soil, the mean pore size is reduced leading to reduced air permeability, water infiltration rate, and increased loss of water by runoff. Mesopores in soil located inside the peds have a principal function to store water and act as the pipeline for nutrients moving in or with water to root surfaces. The micropores found in the soil matrix have a primary purpose to retain soil moisture when the soil is dry (Tan, 2009).

2.3.1 Bulk Density

The bulk density (ρ_b) is a measure that reflects the porosity of the soil for the movement of air and water, and it is a parameter that helps to determine soil quality and ecosystem function (Lampurlanes & Cantero, 2003; FAO, 2006). Also, this parameter is an indicator of soil compaction (Hossain et al., 2015). Low bulk density values (< 1.0 – 1.3 g cm^{-3}) indicate a porous, friable soil with generally low penetration resistance, while high bulk density (1.6 - >1.8 g cm^{-3}) indicates poor conditions for plant root growth and exploration, as well as reduced aeration and water infiltration (FAO, 2006; Hazelton & Murphy, 2007; Hossain et al., 2015). Also, Latif et al., (2008) reported in their study that high compaction in the upper portion of the soil profile (15 cm) increased the bulk density and delayed the emergence and early root growth processes compared with the non-compacted areas.

2.3.2 Aggregate Size and Stability

The analysis of aggregate size and stability is useful when evaluating impacts of practices such as tillage, organic matter amendment, and resilience to erosion produced by wind and water (Nimmo and Perkins, 2002). The aggregates from extensively tilled soils are generally less structurally stable and are more easily dispersed by raindrop energies unlike those from undisturbed agricultural systems (Blanco and Lal, 2010). Intensive tillage interrupts the natural soil structural development and is associated with breakdown of stable aggregates and loss of soil organic matter (Huwe, 2000; Blanco & Lal, 2010).

Ideally, the size distribution of aggregates desired to arise from tillage is stated to be 80% of the aggregates being smaller than 20 mm, with the following size distribution: 40% of 20-10 mm, 40% of 10-2 mm, and 20% should be less than 2 mm (Olsson et al., 1994). Aggregates smaller than 250 μm should not comprise more than 15% (Dexter, 1988). Misra et al., (1986) reported that roots could easily penetrate or move aside aggregates smaller than 20 mm. Tillage can be of value in accomplishing the first fragmentation of the hardpan layer, resulting in large aggregates that may be broken down further (Spoor & Godwin, 1978; Olsson et al., 1994).

The aggregate stability is the resistance of the soil aggregates to breakdown by physical manipulation and water (Ghildyal and Tripathi, 1987). The water causes aggregate disintegration through wetting, swelling, and an explosion of entrapped air (Kemper, 1965; Ghildyal & Tripathi, 1987). On the wetting of the soil aggregates, many of the bonding particles become weaker, more flexible, and in some cases are dissolved (Kemper, 1965). Aggregate stability has effects on aspects of a soil's physical behavior. Especially, water infiltration and erosion can be affected by aggregate stability. For most cultivated lands, particle erosion results from runoff that is induced by the reduction of infiltration rate following rain, which is associated with surface sealing (Le Bissonnais, 1996). Aggregate breakdown and the detachment of soil aggregates by precipitation results in surface sealing and movement of detached particles with run-off water. The reduction of organic carbon content in cultivated soils contributes to land degradation problems such as runoff, crusting, and erosion as the organic matter acts as the cement to bond smaller particles into larger aggregates (Le Bissonnais, 1996; Le Bissonnais and Arrouays, 1997).

2.3.3 Soil Crusting

Soil crust formation may occur when disintegrated soil aggregates (resulting from the disruptive forces of rain, hail, wind, soil traffic and tillage) fill surface soil pores, and upon wetting, form into thin dense surface layers. The predominance of Na^+ on the exchange complex, expands the diffuse double layer and thereby greatly reduces aggregate strength, making the soil vulnerable to dispersion, and reorientation of particles, leading to the formation of a thin crust on the soil surface (Lal and Shukla, 2004). Exchangeable sodium percentage (ESP) is an indicator of soil vulnerability to dispersion, where a value of >15% is considered detrimental to aggregate stability (Le Bissonnais and Arrouays, 1997).

Dispersion, followed by pore plugging and crusting is one of the most active processes inducing in low water infiltration and fast crusting (Le Bissonnais and Arrouays, 1997). When water with very low electrolyte content (e.g., rainwater) is applied to sodic soils, the chemical dispersion mechanism due to thick diffuse double layers disintegrates soil aggregates, leaving clay particles to migrate into the soil with the infiltrating water, leaving larger sand and particles at the surface (Agassi et al., 1985). This process is known as clay illuviation.

Rain and/or hail also contribute to the formation of soil crusts. This force is applied principally by the impact of raindrops as the soil is wetted and dried by the sun as the soil dries (Jury and Horton, 2004). Raindrops and flowing water give the energy to separate soil particles and move them away, abrasion by particles carried by as a suspended matter in runoff water scours the surface and contributes to the overall breakdown of the aggregated structure at the soil surface (Hillel, 1982). Surface crusting is responsible for initiating runoff, favoring soil erosion, and it has adverse impacts on inhibiting seedling emergence and growth (Valentin and Bresson, 1998).

2.3.4 Soil Strength

Soil compaction affects seed germination, seedling emergence and root growth in part by increasing soil strength. The root growth of most crops is significantly reduced when the soil strength is above 2500 kPa (Krzic et al., 1999; Kuang et al., 2012; Osman, 2013). Penetration resistance or cone index (the insertion force divided by the cross sectional area base of the cone), as determined by a cone penetrometer, is usually used to measure soil strength (Borghei et al., 2008). In measurement, the soil interacts with the tip and shaft of the penetrometer (Mulqueen et al., 1977). Soil strength is highly influenced by soil moisture content, particularly if the soil contains clay minerals (Busschera et al., 1997; Kristýna et al., 2013).

There are several methods to characterize surface crusting issues that can be applied in the field and laboratory, such as assessing aggregate stability by the turbidimetry method. Soil strength assessment by the penetrometer measurement is a useful tool because it can identify zones of high soil strength quickly in the field. Also, modulus of rupture, which is the force required per unit area to break an intact soil block apart (Jury and Horton, 2004) is an indicator of potential soil crusting issues. The procedure is described by Richards (1953) and Reeve (1965).

There can be complex interactions among soil strength, water and nutrient uptake, and aeration effects of compaction. When there is compaction in a soil, the strength is increased, and the number of macropores decreases and some roots might fail to penetrate smaller pores. Also, the root elongation decreases and therefore root length is reduced (Osman, 2013). Roots do not only supply decomposable organic matter to the soil and support a large microbial population in different layers; also, roots exudates and decomposing roots can act as binding agents and enmeshing fine particles of soil into stable macroaggregates (Tisdall and Oades, 1982).

The root systems of plants, especially grasses can push through the soil as they exert considerable pressure which forces clay particles together and thus favors aggregate formation. However, the roots might occasionally penetrate aggregates and break up some of the clods, but this does not seem to be a major effect. Growing plants roots that are instrumental in aggregate formation can also keep aggregates small and separated (Allison, 1973).

2.3.5 Soil Permeability

From an agricultural perspective, the decrease in crop yield due to soil compaction is perhaps the most significant effect, and it is connected with the decrease of water entry and the air exchange (soil aeration) between the soil surface and the atmosphere (Horn, 1995). Plant growth is affected because soil aeration allows soil oxygen and carbon dioxide to diffuse into and out of the soil, equilibrating with O_2 and CO_2 levels above the soil surface. Lack of soil aeration results in depleted O_2 levels and excessive CO_2 which are detrimental to root and microbial respiration (Shukla and Lal, 2006). On the soil surface, sand, silt, and clay particles are subject to cohesion and binding from microbial formation of gums, polysaccharides, and other extracellular microbial metabolites (Mohapatra, 2008). Soil pore spaces are the medium that allows air, water, and microorganisms to move through soil, and when the soil is disturbed it can reduce the pore spaces. These changes create anaerobic conditions, and hence the microbial respiration can be negatively affected in different layers (Mohapatra, 2008).

Water content influences air permeability because the blockage of soil pores by water occurs either because the soil pores are too small (very few macropores), or the macropores are saturated due to poor drainage (deep water percolation), and the greatest reduction in air permeability occurs when macropores, the principal air conductors, are blocked (Ball and Schjønning, 2002). The reduction in air permeability with increasing water content is also related to soil type, mainly through the effect of soil structure (Schjønning et al., 1999). When clay content increases, the air permeability decreases faster with increasing water content due to clay soils having a greater proportion of micropores that quickly fill completely with water (Ball and Schjønning, 2002).

2.3.6 Soil Organic Matter and its Influence in Agricultural Soils

Soil organic matter content in soil is an essential attribute of soil fertility, contributes to soil moisture storage ability, and improves soil aggregation and resistance to physical degradation or erosion (Balesdent and Mariotti, 1996; Lickacz and Penny, 2001). Soil organisms are the living organic matter or biomass in soil, supporting plant health, breaking down plant residues and manures to recycle nutrients, and enhance soil structure (Bot and Benites, 2005). On cropland, crop residues are a source of organic matter, and residue management is important to enable field operations like seeding to be successfully completed. Residues generally have positive influence on soil water infiltration rates and reduce erosion (Magdoff and Weil, 2004). Partial mulching or returning crop residues to the soil are practices generally favorable for water management, soil fertility, crop yields, and erosion control (Jordán et al., 2010). Mulumba and Lal (2008) reported that mulch has favorable effects on soil aggregate stability due to organic matter helping to reduce aggregate breakdown by raindrop and soil moisture; Also, residue application helps to increase aggregation by fungal and bacterial activity in the soil.

Elliott and Efetha (1999) in their study showed that a zero-tillage cropping system on the Canadian prairies had more organic C, better structure, and infiltration in a rolling landscape than conventional tillage. Organic materials protect the soil from degradation, erosion, raindrop and hence soil crusting. However, heavy crop residues could delay spring seeding and crop growth because of extended cooler temperature and retention of excessive moisture (Zeleke et al., 2004). Large amounts of residue, especially tough and wiry crop residue that is resistant to decomposition, can cause interference with seeding due to plugging of the seeding equipment.

Crop residues added to the soil affect the rate of breakdown and build-up of organic matter reserves (Bot and Benites, 2005). Soil organic matter is a factor that has effects on soil physical characteristics such as water-holding capacity (Carter, 2002). In the prairies, moisture is usually a limiting factor, so it is recommended the straw should be left in the field over the winter so as to trap snow and to reduce erosion of valuable topsoil (Campbell, 1989).

In Saskatchewan, straw conservation and maintenance of soil organic matter at high levels may generate problems with tillage, and seeding operations, so when heavy crops from cereal and flax straw are obtained, burning may be used to clear the unwanted debris (Campbell, 1989; Dormaar et al., 1979). Farmers on the prairies have long been aware of the difficulties of selling the flax fiber produced in their flaxseed crop (Comeau, 2006). Therefore, flax producers often remove the straw from the fields before the next year's crop because the tough stem is slow to decompose and gets tangled in the seeding equipment at seeding time (Comeau, 2006). On the other hand, burning can affect the soil in different ways. First, animals living in the surface soil are destroyed and organic matter contribution from residue on the surface is reduced as carbon is lost as carbon dioxide during burning. This in the long-term, could have deleterious effects on soil structure, aeration, and drainage (Butterworth, 1985).

2.4 Hypothesis

Subsoiling and vertical tillage operations will impact water infiltration, air permeability, soil physical properties (aggregation, strength, density) and crop yield. Specifically, subsoiling of wheel traffic compacted Chernozemic and Solonetzic soils will increase water infiltration and the air permeability, reduce strength and density and increase yield, while vertical tillage conducted on a Chernozemic soil with flax stubble residue will reduce permeability and aggregation but have little or no impact on yield. It may well be that the surface layer of the soil becomes quite permeable and well aerated, while the depth just below the tillage implement is negatively effected; essentially the tillage concave blades “smear” the soil below the depth of tillage creating a tillage pan. The overall effect is reduced water infiltration, root growth etc. in the root zone.

A pea stubble field was chosen for the sub-soiling study because pea typically produces a low amount of surface crop residue, while flax stubble was chosen for the vertical tillage study because flax stubble is a crop residue that is difficult to seed into without either burning, baling or tilling to get rid of the residue.

2.5 Objectives

- To assess soil water content, infiltration, and air permeability as influenced by subsoiling and vertical tillage treatments in compacted and non-compacted Chernozemic and Solonetzic soils.
- To determine the effects of the tillage treatments on soil structural attributes, including aggregate size and stability.
- To evaluate the effects on yield of annual crops including canola (*Brassica napus*), peas (*Pisum sativum*) and wheat (*Triticum aestivum*).

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3 SUBSOILING TO ADDRESS SOIL COMPACTION IN A SOLONETZIC AND CHERNOZEMIC SOIL

3.1 Preface

This chapter examines the effect of subsurface tillage to a depth of ~30 cm on soil physical properties and crop yield responses in compacted and non-compacted Solonetzic and Chernozemic soils in south-central Saskatchewan.

3.2 Abstract

Compaction induced by field wheel traffic and dense layers in subsoil may adversely alter soil structure, impede soil aeration, restrict water infiltration and nutrient uptake, and inhibit plant root development, negatively affecting plant yields. We hypothesize that subsoiling may be a solution to improve soil physical conditions and crop yields in compacted Chernozemic and naturally dense Solonetzic subsoils. To test the hypothesis, a subsoiler operated at a working depth of ~30 cm was used to break and loosen soil at depth without inverting it. The research study sites were located near Central Butte, SK on farm fields containing Chernozemic and Solonetzic soils that had zones of wheel traffic compacted and non-compacted soil. Subsoiling increased air permeability in the compacted Chernozemic soil from 4.5×10^{-7} m sec^{-1} to 2.87×10^{-6} m sec^{-1}. In the compacted Solonetzic soil, subsoiling significantly decreased soil strength to 1579 kPa compared to 2376 kPa in the non-subsoiled treatment. Crop yields (wheat, peas) in the two subsequent years following the treatment were similar among tillage and compaction treatments in the Chernozemic soil. However, sub-soiling of the compacted Solonetzic soil resulted in a seed yield increase of canola of ~ 1000 kg ha^{-1} in the first year of study and no effect of treatment in the second year with wheat. Overall, subsoiling of the compacted soils tended to improve soil physical properties especially in the Solonetzic soils.

3.3 Introduction

In Canada, farmers, scientists, engineers, and the agriculture industry have dealt with many soil degradation issues over the years. In the prairies (Manitoba, Alberta, and Saskatchewan) erosion, reduction in organic matter stocks, and salinity have been identified as concerns and addressed through research and development, which has led to the adoption of better management practices (Awada et al., 2014). Another source of soil degradation brought forward more recently as a concern is soil compaction, arising from a series of wetter years on the prairies in the 2000's and the introduction of larger farm machinery. Compaction associated with large agricultural equipment and field operations conducted on wet soils can increase the bulk density, soil strength, and ultimately reduce crop yields (Dejong-Hughes, 2009).

Soil compaction decreases soil physical properties and increases erosion hazards, and around 4% of the total land area worldwide is affected by compaction (Oldeman, 1992). For example, Oussible et al., (1992) found in their study developed in Morocco that soil compaction reduced crop yield by 12 to 23 percent. However, tillage practices such as subsoiling might be used to improve soil physical conditions. Erbach et al., (1992) found in their study that subsoiling tillage tends to reduce soil penetration resistance and bulk density in Iowa. Also, in the southern United States subsoiling is used to reduce the effects of soil compaction and significantly increases crop productivity (Raper and Bergtold, 2007).

The Chernozemic soil order is dominant in the prairie regions of Canada, developed under grassland vegetation and with generally good soil structure and productivity. These soils include the Brown, Dark Brown, Black and Dark Gray great groups, reflecting differences in soil organic matter content as related to the moisture environment (semi-arid to sub-humid) that they were developed under (Fuller, 2010). The nature and behavior of Chernozemic soils are in a large part determined by the accumulation, decomposition, and transformations of soil organic matter that can support continued production of crops, but soil degradation through loss of organic matter leads to a reduction in crop productivity (Fuller, 2010; Pennock et al., 2011).

Soils of the Solonetzic order are mainly located in the western provinces in Canada, and they are characterized by their hard, dense Bn or Bnt horizons as a result of clay dispersion associated with high content of exchangeable Na (Pennock and Sanborn, 2016). These soils make up 6 to 8 million ha in Western Canada and a large proportion occur along the Missouri Coteau extending from Alberta south and eastward through Saskatchewan and the impermeable hardpan typically occurs at depths from 5 to 30 cm below the surface, but may also occur at the surface where the

A horizon has been lost by erosion (Lickacz, 1993; Miller and Brierley, 2011). This hardpan severely restricts plant root growth, water infiltration, and workability such as penetration by seeding tools. The variation in the hardpan depth often causes the crop to have a wavy growth pattern during periods little moisture (Lickacz, 1993) due to restricted rooting volume.

The size and mass of agriculture machinery used in crop production have increased considerably over the past half-century increasing the risk of soil compaction (DeJong-Hughes, 2009). Tillage is a common practice in many jurisdictions that can help improve soil conditions for plant root growth, permeability, temperature, and nutrients (Cockroft and Tisdall, 1978). While many soils in Western Canada are now managed under a no-till system in which seed and fertilizer are applied in a single operation using low disturbance, subsoiling tillage can be a tool to remediate subsoil compaction, dense layers and overcome physical limitations (Lal, 1995). As applied in this research work, subsoiling is the application of tillage equipment with a lifting foot at the bottom of a low-profile shank that creates a lifting or loosening action at the depth of operation, but with minimum mixing or disturbance of the surface layer. For a more complete review of subsoiling and its application, refer to the literature review of this thesis.

It is hypothesized that subsoiling tillage operations will have influence in soil physical properties (permeability, aggregate size, strength, and density) and crop yields in southern Saskatchewan. The objective of this study was to evaluate the effect of subsurface and surface tillage on soil physical properties and plant yield in wheel traffic compacted and non-compacted Chernozemic and Solonetzic soils in southern Saskatchewan, Canada.

3.4 Materials and Methods

3.4.1 Location of Study

The study was conducted in south-central Saskatchewan at the border of the Brown and Dark Brown soil-climatic zones near the town of Central Butte (Figure 3.1). In this general location, two sites were set up where subsoiling treatments were evaluated on compacted and non-compacted soils in each. One site was located on Chernozem (Brown Chernozem) soils that dominate south of Central Butte "South Central Butte site" while the other site was located on

Solonetz (Solodized Solonetz) soils that dominate north of Central Butte "North Central Butte site".

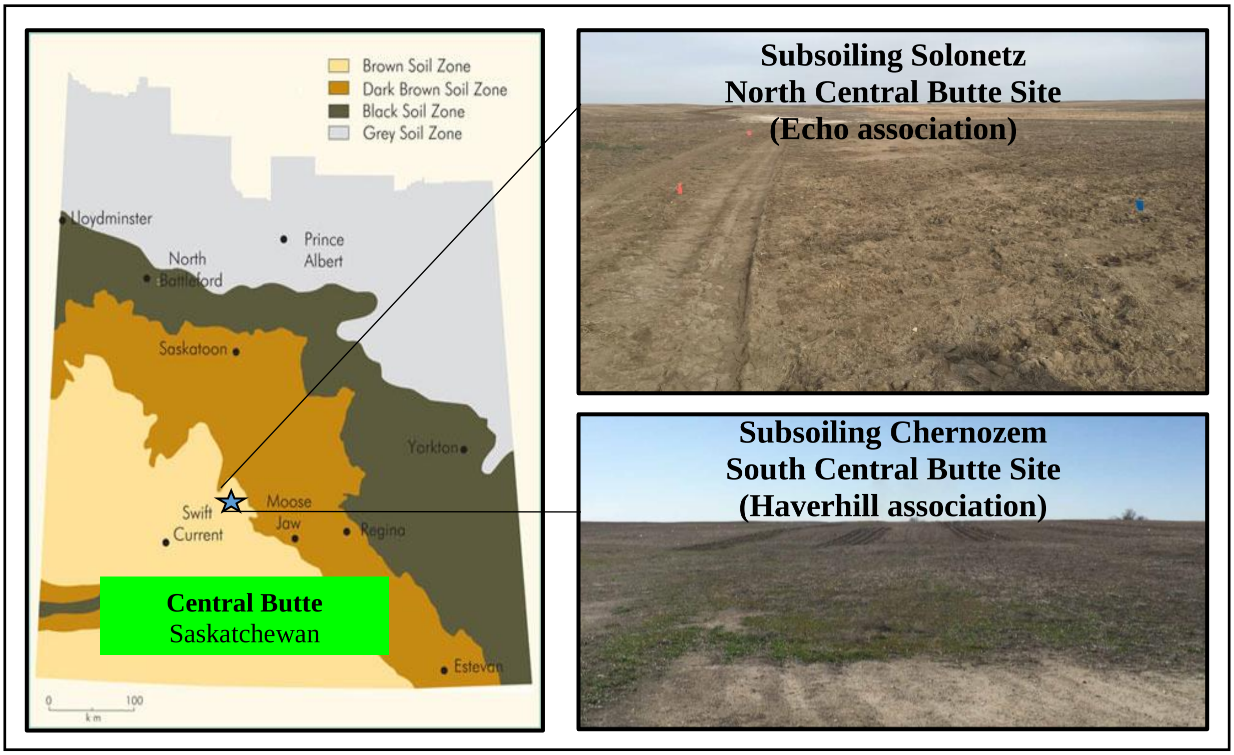

Figure 3.1 Geographical location of the Study in Central Butte.

3.4.2 Site Description

3.4.2.1 South Central Butte (SCB)

The subsoiling field study south of Central Butte SK, termed "South Central Butte (SCB)" was established in September 2015 after harvesting operations had concluded on a yellow pea (*Lathyrus aphaca*) field. The field trial was initiated on an annually cultivated field located at SE25-20-04-W3 (N 50.729607; W 106.422.086). This field is located 6.5 km south and 6.5 km east of the town of Central Butte, within the Rural Municipality of Enfield, No. 194. The soil at this site belongs to the Ardill-Kettlehut soil association and is dominantly an Orthic Brown Chernozem intermixed with a few Solodized Solonetz and Gleysolic. The soils are of loam texture overlying a moderately fine textured, moderately calcareous, saline shale modified glacial till parent material (Soil Classification Working Group, 1998). The soil at the Central Butte site occurs on a knoll and depression glacial till plain with gently undulating landscape (Soil Classification Working Group, 1998). Identified limitations include moderately stony and saline conditions occurring in low lying areas and sloughs covering 10-20 % of the landscape. Peas (*Pisum sativum*) were grown on the Central Butte site in 2015. A photo of the site looking southwest to northeast is provided in Figure 3.2.

Figure 3.2. South Central Butte site topography, October 2015.

3.4.2.2 North Central Butte (NCB)

The site was selected for evaluating the effect of subsoiling on a Solonetzic soil. The site is located north of Central Butte SK, in a field noted to have specific and identifiable regions of dense Solonetzic B horizons compared to the SCB site with very few true Solonetzic areas within the study field. The site was also established in Oct. 2015 after harvesting operations of pea had concluded. This field site trial, termed “North Central Butte (NCB)” was initiated on an annually cultivated field located at SE32-21-04-W3 (N 50.819619; W 106.512844). This field is located 1.6 km north of the town of Central Butte, within the Rural Municipality of Enfield, No. 194. The soil at this site belongs to the Echo soil association and is a Brown Solodized Solonetz formed on medium to fine textured, moderately calcareous, saline modified unsorted glacial till, dominated by local residual Cretaceous shale parent material (Soil Classification Working Group, 1998). The soil at the study site is predominantly Solonetzic with a dense hard B horizon restricting growth. Wheel traffic from grain hauling during harvest through the center of the experimental site over several years resulted in long-term compaction at the center of the treatment strips set up. The soil at the NCB site occurs on a knoll and depression glacial till plain with gently and roughly undulating landscape (Soil Classification Working Group, 1998). The experimental site area selected was a level, lower elevation location within the field. Peas were grown on the NCB site in 2015. A photo of the site is provided in Figure 3.3.

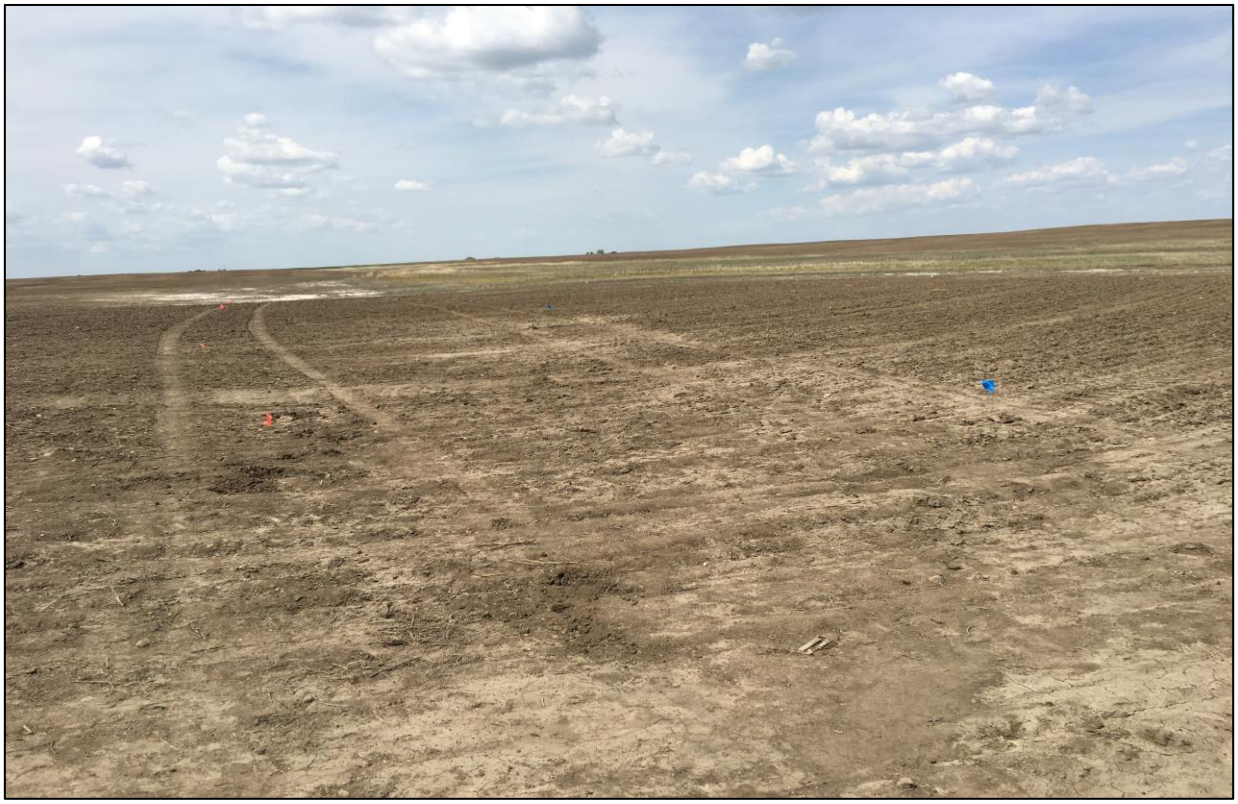

Figure 3.3. North Central Butte site topography, May 2016.

3.4.3 Treatments and Experimental Design

3.4.3.1 South Central Butte (SCB)

The SCB Precision Subsoiling field study was set up as a randomized complete block design (three treatment replicates) with plots laid out in August 2015 within a 30-ha field. Within each block that was replicated three times, treatments were randomized. At this site, short-term wheel traffic compaction areas were set up prior to imposition of the tillage treatments. The treatments consisted of no tillage on compacted and non-compacted zones, and tillage on compacted and non-compacted zones. The randomized blocks were first subdivided into two 0.30 ha sub plots consisting of a control treatment with no subsoiling tillage on wheel traffic compacted and non-compacted zones and subsoiled treatment with subsoil tillage on wheel traffic compacted and non-compacted zones. There were four replicates of each treatment. Alleyways separating the blocks were established to allow for equipment movement and access to all the treatment plots. Each treatment plot was 50.0 m running east-west by 60.0 m running north-south.

After the plots were marked out, a Ford F600 single axle 2700 kg grain truck equipped with 10x20 tires and dual rear wheels and loaded with hard red spring wheat (to a loaded weight of 10.0 t made three passes in the same wheel tracks prior to the subsoiling tillage operation in order to create zones of compacted soil and non-compacted soil within each main plot (Figure 3.4 and Figure 3.5).

A John Deere 2100 Minimum-Till Ripper subsoiler equipped with five standards (shanks) utilizing plow type shares spaced 76.0 cm apart and set to penetrate 30.0 cm into the soil, hitched to a John Deere 6170M front wheel assist tractor operated at 7.0 km hr^{-1}, was used to impose the subsoiling treatments on October 2nd, 2015 (Figure 3.6). The shares created a lifting action at the 30 cm depth of operation, loosening the soil at depth while minimizing soil disturbance at the surface (Figure 3.7).

Figure 3.4. Creating truck traffic compaction at South Central Butte site, August 2015.

Figure 3.5. Compacted soil created by truck travel at South Central Butte site, August 2015.

Figure 3.6. John Deere 2100 minimum tillage subsoiler mounted on John Deere 6170M tractor 3- point hitch.

Figure 3.7. Loosened soil (left) after one pass with the John Deere 2100 minimum-till subsoiler (right) at the South-Central Butte site in October 2015.

3.4.3.2 North Central Butte (NCB)

The NCB field study was set up as two treatments, replicated four times. The treatments consisted of a control treatment where no subsoiling tillage was performed and a subsoiled treatment that received subsoiling tillage. Plots measuring 20.0 m north-south by 8.0 m east-west were set up in the field. A field area was selected where a long-term (5 years) grain haul road extended across the plot area. Three transects were established with measurement points located in each of the replicated treatments. The following compaction scenarios were evaluated: 1) Pre-Subsoiling Compaction transect: where heavy vehicle and farm machinery wheel traffic occurred over the past 5 years; 2) Post-Subsoiling Compaction transect: in March 2016, a double axel single wheel livestock trailer and truck loaded with approximately three tonnes of bales traveled over the subsoiling treatment area three times; 3) No-wheel traffic transect: where no soil compaction was performed. The John Deere subsoiling tillage unit and equipment operation was the same as for the SCB site as previously shown (Figure 3.6 and Figure 3.7). Subsoiling tillage at the NCB site was conducted on October 2nd, 2015.

Figure 3.8. Subsoiling treatments at NCB Solonetzic site, October 2015.

3.4.4 Site Management: Seeding, Crop Protection, Harvest

3.4.4.1 South Central Butte (SCB)

The SCB site was seeded on May 18th, 2016 with Hard Red Spring Wheat (*T. aestivum* var Brandon) at 90 kg per ha with 190 kg ha^{-1} of 37-14-0 fertilizer side banded using a John Deere 1830 air hoe drill with paired row double shoot openers (Figure 3.9). Measurements of soil strength using an electronic cone RIMIK™ CP40II Penetrometer were made on June 3rd, 2016 along with gravimetric soil moisture. A soil density profile was created from soil samples obtained at 0-15, 15-30 and 30-60 cm in each plot using a Giddings truck mounted 5.08 cm coring unit on June 6th, 2016. Physical measurements of air permeability and water infiltration were made on June 8th, 2016 at each preselected point in the plots. Crop harvest was done on August 23rd, 2016, and the samples were taken with a square metre at each point. Soil samples were taken after harvest on September 22nd, 2016 at each point to create a soil density profile using 0-30 cm and 30-60 cm soil cores taken at each point.

Figure 3.9. John Deere 1830 Air Hoe Drill with paired row double shoot openers used to seed plots.

To evaluate carry-over effects of the treatments into a second year, on May 3rd, 2017 the plots were first sprayed with RT 540 glyphosate at 0.8 liters per acre and sulfentrazone at 88 mL acre^{-1}. On May 4th, 2017 the plots were seeded to green pea (*P. sativum* var Sage) at 170 kg ha^{-1} using the John Deere 1830 hoe drill. The pea seeds were treated with Vitaflo™ fungicide and received seed-applied peat-based Rhizobium inoculant (Cell Tech™). No fertilizer was applied. Soil strength was measured using the electronic RIMIK™ CP40II cone penetrometer on May 13th, 2017 along with gravimetric soil moisture. Soil samples were taken to a depth of 0-15, 15-30, and 30-60 cm to create a soil density profile using the Giddings truck mounted 5.08 cm coring unit on May 18th, 2017. Air permeability and water infiltration measurements were made the second week in May 2017 at each preselected point. Crop harvest was done on July 27th, 2017, and the samples were taken with a square metre at each point. Soil samples were taken after harvest on August 23rd, 2017 at each point to create a soil density profile using 0-30 cm and 30-60 cm soil cores taken at each point.

3.4.4.2 North Central Butte (NCB)

The NCB site was seeded on May 1st, 2016 with canola (LL252) at 5 kg ha^{-1} and fertilized with 180 kg ha^{-1} of 34-10-0-5 using John Deere 1830 hoe drill. Measurements of soil strength using an electronic cone RIMIK™ CP40II Penetrometer were made at each transect point on May 20th, 2016 along with soil moisture. Soil samples were obtained using a Giddings truck mounted 5.08 cm coring unit on May 24th, 2016, after seeding, at the transect points at 0-15, 15-30 and 30-60 cm depths. The samples were weighed, and % moisture was measured, and samples were used to create a soil density profile. At this time, surface 0-5 cm samples were also taken for modulus of rupture measurements. Water infiltration and air permeability were measured on June 10th, 2016. Crop harvest samples were collected on August 16th, 2016, and the samples were taken with a square metre at each point. Also, soil samples were taken on September 22nd, 2016 post-harvest at 0-30 and 30-60 cm at each point to create a soil density profile using the Giddings truck coring unit to a depth of 0-30 and 30-60 cm. The collected samples were frozen, thawed, weighed, and % moisture was measured.

The second cropping season after subsoiling at the NCB site began on May 15th, 2017 when the site was seeded to Hard Red Spring Wheat (*T. aestivum* var Brandon) at a rate of 80 kg ha^{-1} using the John Deere 1830 hoe drill. A fertilizer blend of 37-13-0 was applied at 150 kg product $acre^{-1}$ at the time of seeding. On May 10th, 2017, before seeding, the field site was sprayed with glyphosate at 0.4 L $acre^{-1}$+ florasulam at 40 ml $acre^{-1}$ (Pre-Pass). The NCB site was sprayed for weed control on June 7th, 2017 with fluoxapyr (0.125 litres $acre^{-1}$) + 2,4-D (0.340 litres $acre^{-1}$) + tralkoxydim (0.20 litres $acre^{-1}$) to control broadleaves and wild oats.

On May 18th, 2017, 0-15, 15-30 and 30-60 cm soil samples were obtained from the NCB site using a Giddings truck mounted 5.08 cm coring unit to assess soil bulk density and soil moisture. Measurements of soil strength using an electronic cone RIMIK™ CP40II Penetrometer (Figure 3.15) were conducted at the NCB site on each transect point on May 13th, 2017 and moisture content measured. Water infiltration and air permeability were measured May 15th - 19th, 2017. At this time, surface 0-5 cm samples were taken for modulus of rupture analyses. On August 21st, 2017, total biomass and grain yield from the wheat crop at the NCB site was determined by harvesting square metre samples at the treatment transect points in the study. Due to very dry conditions at the NCB site after harvest on August 23rd, 2017, the RIMIK™ CP40II Penetrometer was unable to penetrate the soil. Therefore, no soil penetration data was obtained at this time from this site. On August 23rd, 2017, 0-30 and 30-60 cm soil samples were obtained from the NCB site to assess soil bulk density and soil moisture.

3.4.5 Climatic Conditions 2016, 2017

The first growing season of the study (2016) at the SCB and NCB sites, was wet. The monthly precipitation and air temperature during 2016 are shown in Figure 3.10. The precipitation received from May to August was 38.87 % above the 18-year average (Figure 3.12) (Canada Environment, 2018). However, the 2017 growing season was considered a dry year because there was not much precipitation during 2017 until the end of the season in October (Figure 3.11). In 2017 the precipitation from May to August was 48.58 % lower than the 18-year average (Figure 3.12) (Canada Environment, 2018).

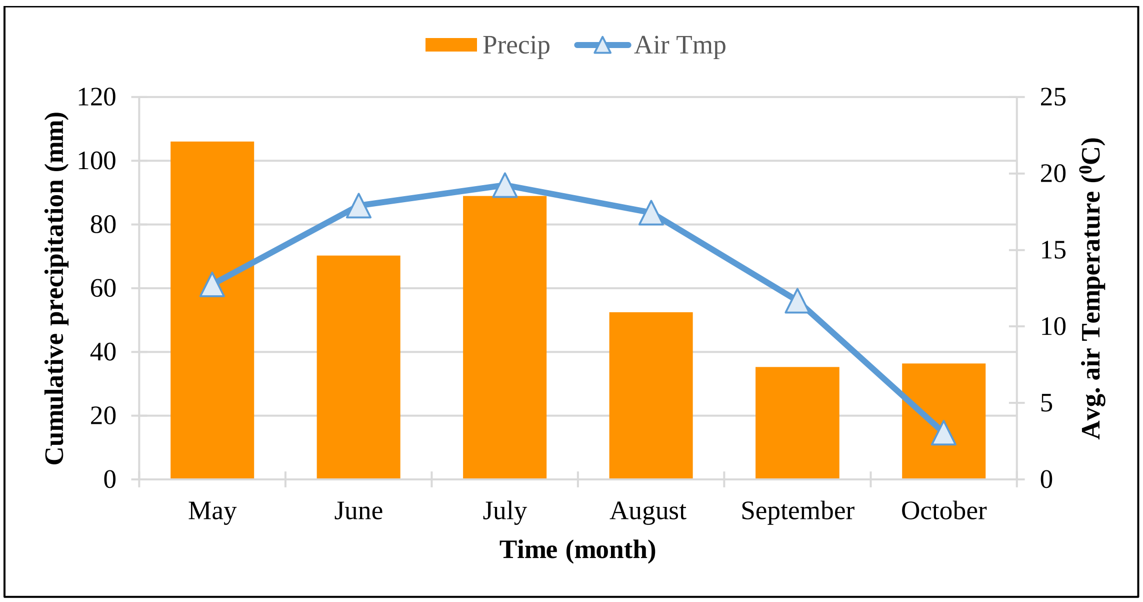

Figure 3.10. May to October monthly precipitation (mm) and average air temperature (°C) for year 2016 at Central Butte. Data from Schoenau farm meteorological station.

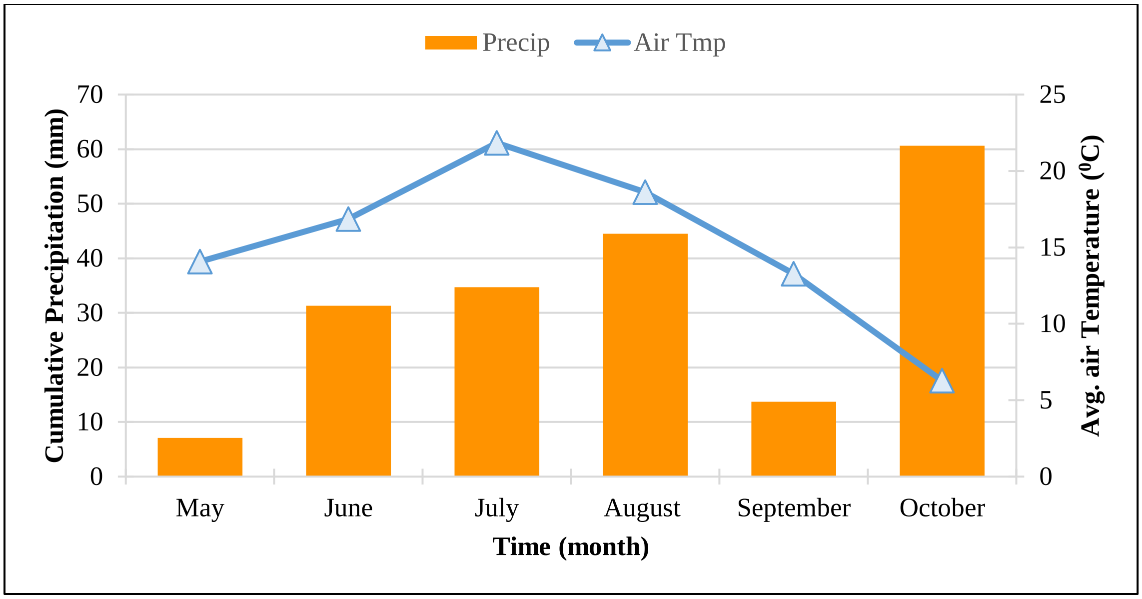

Figure 3.11. May 12th to October monthly precipitation (mm) and average air temperature (°C) for year 2017 at Central Butte. Data from Schoenau farm meteorological station.

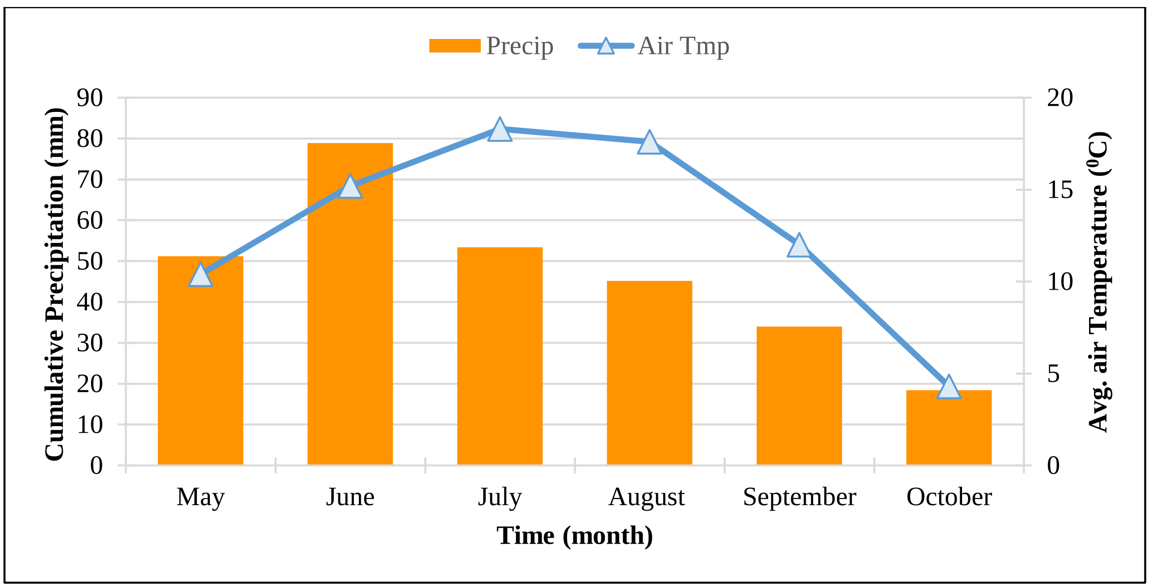

Figure 3.12. Growing season monthly precipitation and average air temperature historical averages from 1981-2010 at the Elbow, SK weather station (Environment Canada).

3.4.6 Soil Sampling and Analysis

Measurements of the modulus of rupture, aggregate size, and stability were made at sampling points in the plots at SCB and NCB in 2016 and 2017. Samples were taken in May 2016, two days after seeding from each plot with a flat square shovel to a depth of 10 cm (Figure 3.13). Every sample was wrapped, taped, and transported in plastic containers to maintain their undisturbed state (Figure 3.13). After returning to the lab, the samples were laid out on trays and allowed to air dry for three days. Each sample was gently separated by hand into smaller fractions and then air dried for another seven days. In the second year, 2017, soil samples were taken after seeding in May using the same method as 2016.

Figure 3.13. Undisturbed soil samples from NCB and SCB sites.

3.4.6.1 Bulk Density and Moisture

A soil density and moisture content profile were created from soil samples obtained at each sampling point at depths of 0-15, 15-30, and 30-60 cm using a Gidding truck mounted a 5.08 cm coring unit (Figure 3.14) in the spring of 2016 and 2017. Soil samples in the fall of 2016 and 2017 were taken to a depth of 0-30 and 30-60 cm.

Figure 3.14. Field core sampling for bulk density and moisture using a Gidding truck mounted hydraulic punch unit.

3.4.6.2 Soil Strength

Measurements of soil strength were made at the SCB site sampling points in Spring 2016 and 2017. Measurements of soil strength using an electronic RIMIK™ CP40II Cone Penetrometer (Figure 3.15) were conducted at the NCB site at each sampling point in Spring 2016 and 2017. Due to dry conditions at the NCB site in Fall 2017, the RIMIK™ CP40II Penetrometer was unable to penetrate the soil. Therefore, no soil penetration data was obtained at this time from this site.

Figure 3.15. Rimik CP40-II penetrometer measuring soil resistance at South Central Butte site.

3.4.6.3 Aggregate Size

The method of Nimmo and Perkins (2002) was used to determine aggregate size distribution. The dried samples that were taken in May 2016 and 2017 at both study sites were gently placed in the feed bin in the motorized sieving machine (Figure 3.16). The sieve separated the soil into seven average aggregate sizes (0.25, 0.90, 1.94, 4.89, 12.33, 25.05, and 44.06 mm) (Figure 3.17). The different size fractions of soil were collected by passing through different series of sieves and then weighed to calculate the aggregate size distribution. The method to express the size distribution of aggregates is the Mean Weight Diameter (MWD) as provided below:

$$MWD = \sum_{i=1}^{n} x_i w_i$$

(Eq.3.1)

Where the "x_i is the mean diameter of any particular size range of aggregates separated in the process of sieving, and the w_i is the weight of the aggregates in that size range as a fraction of the total dry weight of the sample analyzed" (Hillel, 1982b).

Figure 3.16. Motorized sieve machine.

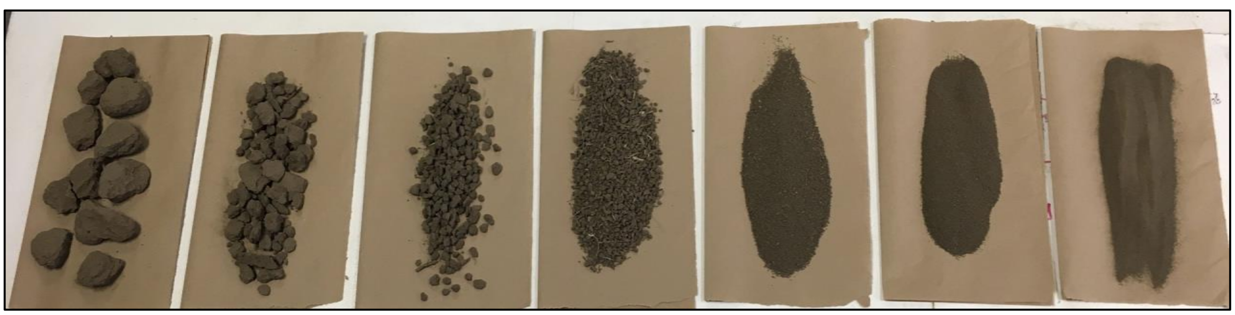

Figure 3.17. Soil aggregates after sieving process.

3.4.6.4 Modulus of Rupture

The modulus of rupture test is a simulation of soil crust formation in the field that may occur when the soil is wetted and then undergoes drying by direct heating from the sun (Reeve, 1965). Furthermore, the modulus of rupture is used to demonstrate the inclination of unstable soils to fill and form a dense surface top or crust that inhibits germination (Hillel, 1980). Only the NCB site samples were used in this study since Solonetzic soils with their higher sodium and clay dispersion are more susceptible to crusting. Modulus of rupture (S) was assessed using the method of Reeve (1965).

$$S = \frac{3\,Fl}{2bd^2}$$

(Eq.3.2)

Where, F is the breaking force applied at the center of the briquet beam span, L is the distance between the briquette end supports, b is the width of the briquet, and d is the depth or thickness of the briquet (Reeve, 1965).

Soil briquettes were formed using a dry soil that was passed through a sieve of 0.250 mm. The special briquet molds were made from 3/8-inch stainless steel which dimensions are 3.5 cm by 7 cm by 1 cm high. Whatman® #42 filter papers were cut into a rectangular shape that was used as bottoms of the briquettes. The insides of the molds were covered with a thin layer of petroleum jelly, so the soil would not stick to the molds. The molds were placed on the filter papers and then in a screen-bottom tray. Using a cylindrical stem large funnel, the soil was dumped into the funnel with a single rapid motion and moving around inside the mold to have a uniform smooth filling of the mold (Figure 3.18). The excess soil was removed so as to have a uniform soil depth in the mold level with the upper surface of the mold. The screen-bottom tray was placed in a soaking tank filled with water and allowed the briquettes to wet by capillary action over one hour (Figure 3.18). After the one-hour period, the samples were placed in an oven to be dried overnight at 50 °C. Finally, the molds were removed from the briquettes, and the length, width, and thickness were measured of each sample.

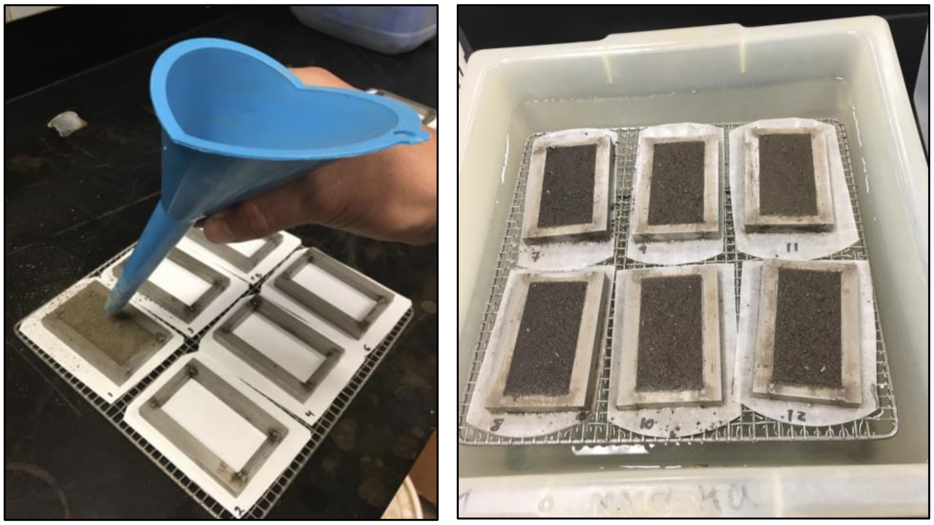

Figure 3.18. Soil dumping process into the molds and wetting.

The breaking force was measured using the modulus of rupture apparatus (Figure 3.19) described by Reeve (1965) and Richards (1953). It has a briquet support and knife edge assembly that has two parallel bars 5 cm apart for supporting the soil briquet (Figure 3.19). The breaking force was applied from a third overlying bar that is centrally located and parallel with respect to the supporting bars which were located on the platform of the balance. A beam balance was used to measure and apply the load to the briquet-breaking apparatus located on the balance platform. A jet of water that was set up to a rate of 60 g min^{-1} that was directed toward a deflector on the end of the beam that intercepts the water and directs it into the vessel, that it accumulates as long as the briquet remains unbroken. A vertical drop of the end of the balance beam occurs when the briquet is broken, and that movement automatically stops the accumulation of water in the vessel. The volume accumulated of water in the vessel was weighed to calculate the breaking force.

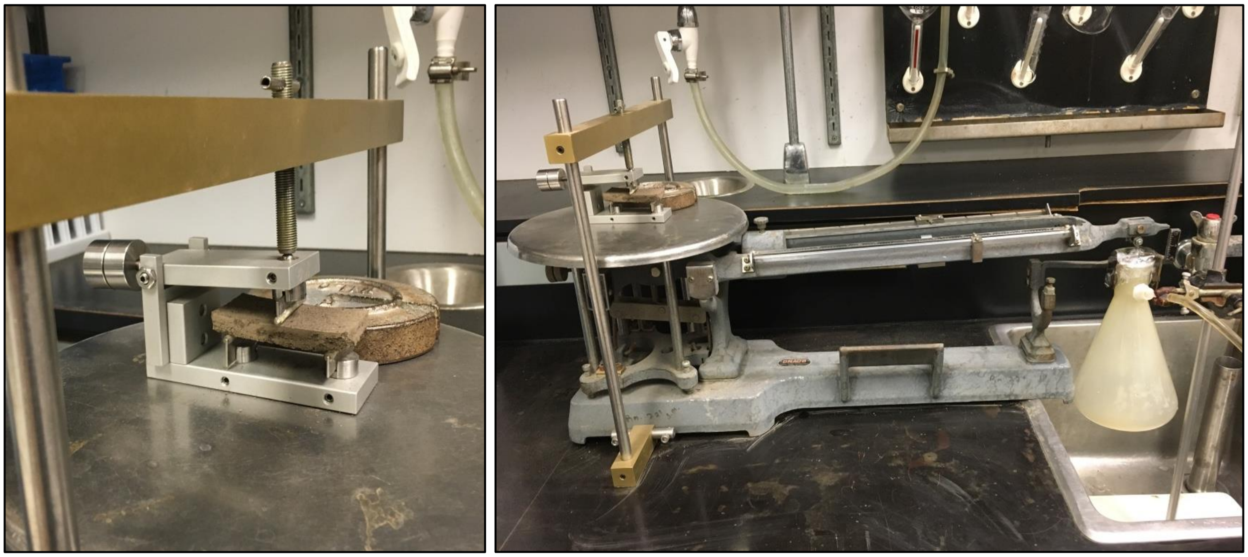

Figure 3.19. Modulus of rupture apparatus.

3.4.6.5 Air and Water Permeability

The air permeability of the soil is an assessment of the convective transmission of air through soil under an applied total pressure gradient (Grant and Groenevelt, 2008). The air permeability offers information about the size and the continuity of air-filled pores (Hillel, 1980). The instrument to measure air permeability in the field is the air permeameter (Figure 3.20) and the technique followed was that described by Huang et al., 2016. The method consists of inserting a 15 cm diameter steel tube to a depth of 10 cm into the soil (Ball and Schjønning, 2002). The tube was sealed, and different air flow rates were applied using the flow controller (FMA6500 by OMEGA Engineering Inc.). Four different air flow rates were applied (0.5, 0.7, 0.9, and 1.2 L min^{-1}) and the pressures were recorded at each flow rate. The linearity between the air flow and the pressure was checked before recording.

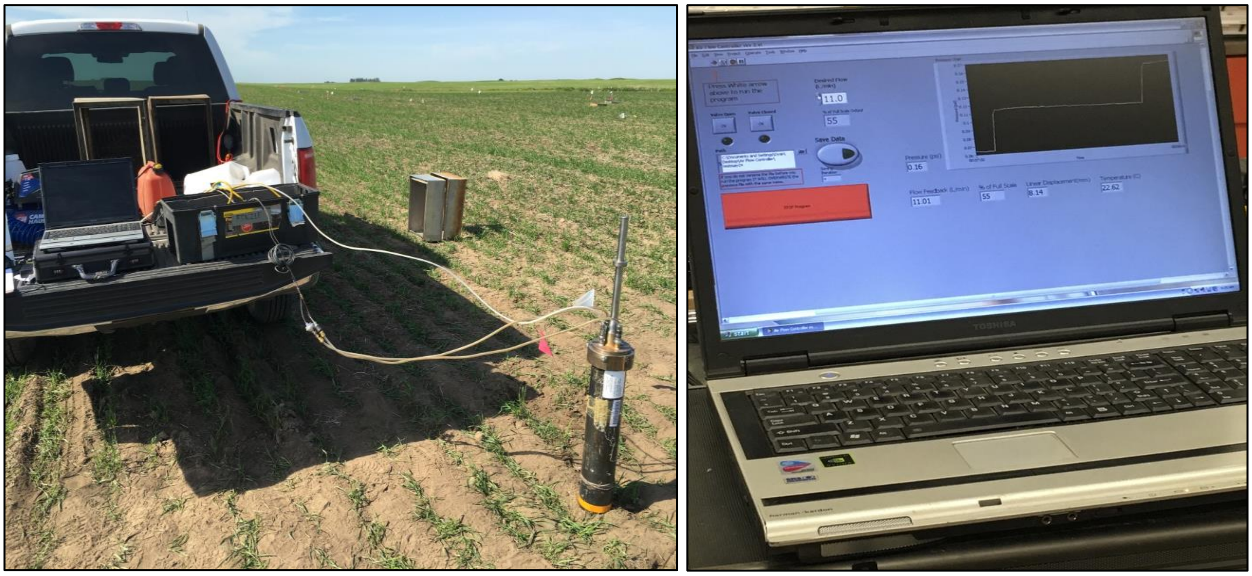

Figure 3.20. Air permeameter measurement at South Central Butte (SCB) site used to assess the convective transmission of air through soil under an applied total pressure gradient.

To determine hydraulic conductivity (K_{fs}), the method utilized was the simplified falling-head (SFH) technique designed by Bagarello et al. (2004). The method involved applying 10 L of water onto the soil surface using a single ring (stainless steel square) which was inserted into the soil to a depth of 12 cm. Measurement was made of the time from the application of the water to disappearance of the water. The water was added using a perforated plastic bag to add the water quickly but with limited disturbance of the soil surface. A single large square ring of dimensions 580 mm by 420 mm (Figure 3.21) was used to cover a substantial surface area including the furrow and the area in between. PVC cores were used to take a soil sample to a depth of 5 cm outside of the square ring and inside of the ring after the infiltration (Figure 3.21). The equation to determine the K_{fs} is based on the formula of the simplified falling head technique as listed below:

$$K_{fs} = \frac{(\Delta\theta)}{(1-\Delta\theta)t_a}\left[\frac{D}{(\Delta\theta)} - \frac{(D+\frac{1}{\alpha^*})}{(1-\Delta\theta)}\ln\left(1+\frac{(1-\Delta\theta)D}{(\Delta\theta)\left(D+\frac{1}{\alpha^*}\right)}\right)\right]$$

(Eq.3.3)

To determine the K_{fs}, it is necessary to know variables such as (I) initial volumetric water content (ϑ_1) and the water content after the infiltration (ϑ_2), (II) the time that it takes the infiltration (t_a), (III) the depth to which the water was ponded at t=0 (D), (IV) the hydraulic parameter (α) (Bagarello et al., 2004; Ewen, 2015).

Figure 3.21. Square ring and PVC cores installed to determine hydraulic conductivity at SCB and NCB sites.

In 2017, hydraulic conductivity was determined using the field-saturated hydraulic conductivity method described by Zeleke et al., (2004). The method consisted of inserting the ring into the soil to 12 cm (the same square rings used in the first year of the study were used in 2017). Then, the rings were filled with water to the top (approximately 11 cm) using a perforated plastic bag trying to reduce the disturbance of the soil surface, and the initial water depth and time were measured. Then, the time was recorded at every 1.5 cm drop in water level. If the water failed to infiltrate 1.5 cm in 60 minutes, the time was recorded and the water level at that point and every 20 minutes thereafter the water volume was measured up to three hours.

3.4.6.6 Crop Grain and Straw Yields

Square meter above-ground crop samples removed from the plots at harvest in 2016 and 2017 were dried at 35^{o}C and weighed to determine total biomass yield. The samples were then threshed, cleaned, and weighed to determine grain yield.

3.4.7 Statistical Analysis

To analyze the effect of treatments conducted during the 2016 and 2017 year the Statistical Analysis Software (SAS) was used. At the location of the North Central Butte the site was set up as a two treatment, so all the collected data at this site was analyzed following the SAS T-TEST. The plots selected at the SCB Precision Subsoiling field study was arranged as a randomized complete block design, so crop yield and bulk density (Spring 2016 and 2017) were performed using SAS-PROC GLIMMIX, but physical measurements and bulk density (Fall 2016 and 2017) were performed using SAS-PROC T-TEST.

3.5 Results and Discussion

3.5.1 South Central Butte Site (SCB): Chernozemic Soil

3.5.1.1 Bulk density

3.5.1.1.1 SCB Spring 2016 and 2017

Table 3.1 Bulk density at SCB site spring 2016 and 2017.

Treatment		Bulk Density					
		0-15 cm		15-30 cm		30-60 cm	
		2016	2017	2016	2017	2016	2017
		---g cm^{-3}---					
Subsoiled	Compacted	1.39b	1.41a	1.57b	1.65a	1.62a	1.71a
	Non-Compacted	1.43b	1.49a	1.56b	1.60ab	1.60ab	1.71a
Non-Subsoiled	Compacted	1.56a	1.41a	1.62a	1.62ab	1.61ab	1.64a
	Non-Compacted	1.51a	1.42a	1.54b	1.56b	1.56b	1.63a
P value		<0.0001*	0.6332	0.0039*	0.1719	0.1989	0.4095

† Means followed by the same letter are not significantly different at $P \leq 0.05$
*Significantly different at $P \leq 0.05$

The subsoiling plots at the SCB site were sampled at three depths for bulk density and moisture content in the spring of 2016 and 2017 after subsoiling treatments were imposed in the fall of 2015 and after the seeding operation was completed. The wheel traffic compaction induced in the fall of 2015 significantly increased the bulk density in the 15-30 cm depth measured in the spring of 2016 (Table 3.1). Lack of effect on the surface density could be explained by the surface soil lifting action of the hoe drill seeding openers. Twum and Nii-Annang (2015), reported in a study of effect of repeated heavy equipment traffic at a mining site in Germany, that areas that received compaction had increased soil density at depth. The subsoiling treatment had a significant effect ($P \leq 0.05$) on lowering soil bulk density in the 0-15 cm depth in both compacted and non-compacted soil areas in spring of 2016. The subsoiling was effective in reducing surface density in the first year of the study. In the 15-30 cm depth, subsoiling also significantly reduced density measured in the spring of 2016, but there was no effect at the 30-60 cm depth.

In 2017, bulk densities were similar among all treatments, indicating that the effect of compaction and subsoiling diminished over the one-year period. The greatest effect of the subsoiling treatment is evident in the upper depths where the lifting and shattering action of the subsoiler implement shank and plow type shares reduces soil bulk density. According to Grevers and de Jong (1993), subsoiling reduced soil density in one of the Chernozemic soils that were used in a study of tillage effects in Saskatchewan. Evans et al. (1996) also reported that subsoiled areas had lower bulk densities than non-subsoiled areas, even two years after the subsoiling treatment was imposed near Morris, Minnesota. However, in the current study in 2017, soil bulk density values increased slightly in all the treatments at the three different depths (0-15, 15-30, and 30-60 cm) that were measured and there were no significant effects of subsoiling on density in this Chernozemic soil (Table 3.1). During the winter and the 2017 growing season, the site did not receive a large amount of precipitation (Figure 3.11). Possibly, the shortage of moisture in the soil may have increased soil density with fewer wet-dry cycles and prolonged shrinkage of clay mineral interlayers.

3.5.1.1.2 **SCB Fall 2016 and 2017**

Table 3.2. Bulk density at SCB site in fall 2016 and 2017.

Treatment		Bulk Density			
		0-30 cm		30-60 cm	
		2016	2017	2016	2017
		---------------------g cm^{-3}----------------------			
Subsoiled	Compacted	1.48	1.48	1.59	1.53
	Non-Compacted	1.47	1.42	1.55	1.46
Non-Subsoiled	Compacted	1.57*	1.57	1.54	1.54
	Non-Compacted	1.41*	1.43	1.51	1.59
P value	Subsoiled vs Non-Subsoiled	0.6338	0.3133	0.3659	0.7091
	Compacted vs Non-Compacted	0.0041*	0.0041*	0.5106	0.8681

*Significantly different at P ≤ 0.05.

At the South Central Butte (SCB) Chernozem site, soil bulk density was measured in the fall of 2016 and 2017 at two depths: 0-30 cm and 30-60 cm (Table 3.2). As in the spring of the first year, in the fall of 2016 the effect of the wheel traffic on compaction was still evident in higher bulk density in the compacted treatment. In the fall of 2016, soil density in the 0-30 cm depth was significantly reduced in the subsoiled compacted treatment. Similarly, You et al., (2017) in a study in northeast China in grain producing land reported that tillage reduced soil bulk density in compacted areas. By August of 2017 at the SCB site, 22 months after the subsoiling treatment was imposed in October 2015, there were no significant differences among the subsoiled and non-subsoiled treatments and bulk densities were similar among treatments. At the SCB site, none of the bulk densities, even those measured in the spring after the fall compaction treatment, had bulk densities above 1.8 g cm^{-3} , a level near or above where significant impediment to root growth might be expected for many crops (Hazelton and Murphy, 2007).

3.5.1.2 Soil Penetrometer Resistance (Strength)

Soil strength was measured at the South Central Butte (SCB) site using the soil cone penetrometer in spring 2016 and 2017, after the fall 2015 subsoiling treatments and after seeding. Soil moisture content at the time of measurement was near field capacity (see Appendix for soil moisture contents). Penetration resistance is highly dependent on moisture content (Hazelton and Murphy, 2007).

3.5.1.2.1 **Penetration Resistance SCB – Spring 2016.**

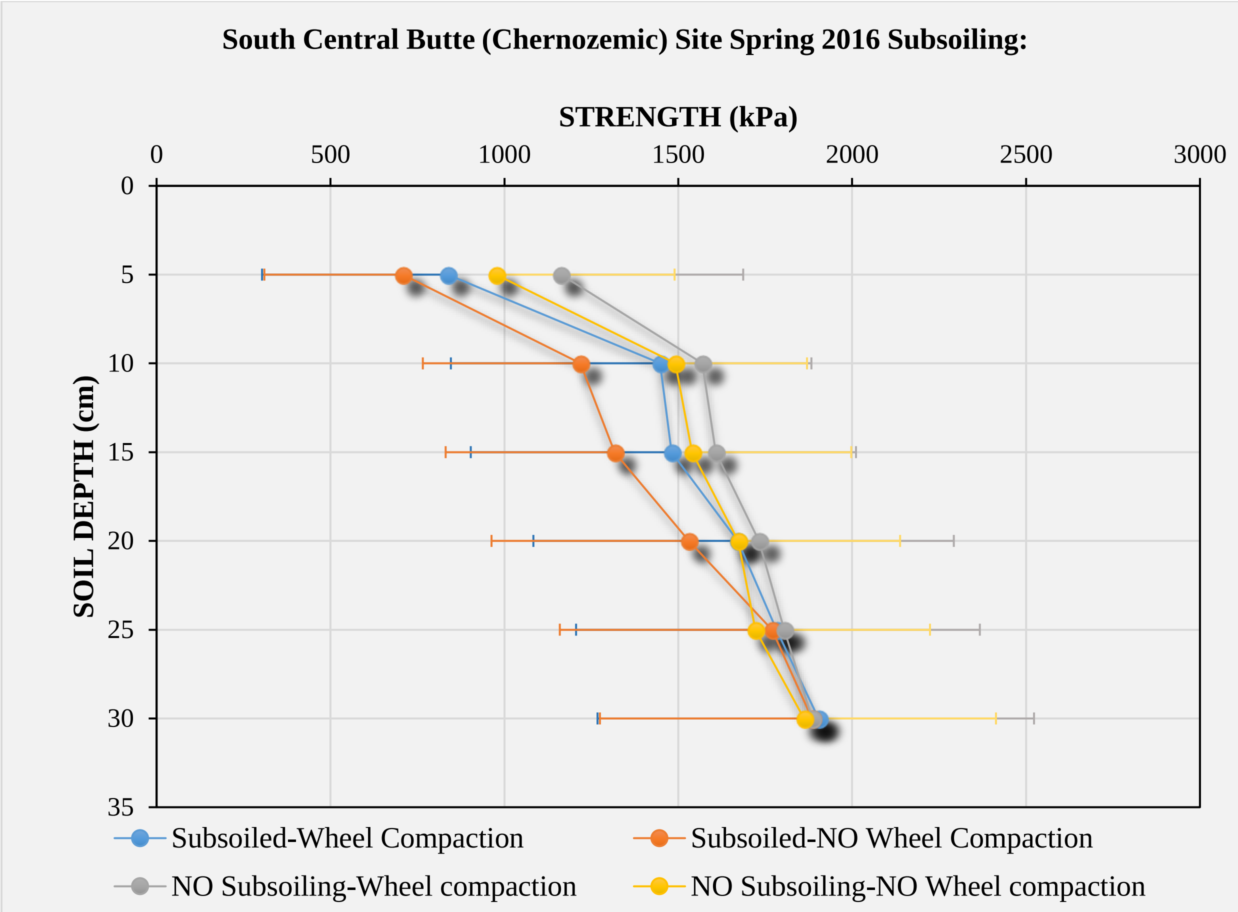

Figure 3.22. Soil strength (penetration resistance kPa) at SCB site measured using a Rimik cone penetrometer in spring of 2016. Error bars are standard deviation of the mean.

The soil strength (kPa) measured at the South Central Butte (SCB) Chernozem site in June 2016, eight months after subsoiling treatments, was significantly ($P \leq 0.10$) lower in the 0-15 cm soil depth in the subsoiled compacted and non-compacted treatments compared to the non-subsoiled treatment (Figure 3.22). As expected, the areas that were compacted by wheel traffic from three truck passes in the fall of 2015 had the highest soil strength. Kuht et al., (2012) also reported on their study at Southern Estonia in a barley field that soil penetration resistance was 1.4 – 2.0 times higher after double compaction and 1.5 - 2.1 times higher after four wheel traffic events created by a tractor. The subsoiling resulted in significantly reduced soil strength of the compacted soil compared to non-subsoiled compacted soil. Soil strength was reduced by subsoiling of compacted and non-compacted areas in the top ~20 cm of soil and the effect tended to diminish with depth (Figure 3.22).

3.5.1.2.2 **Penetration Resistance SCB – Spring 2017**

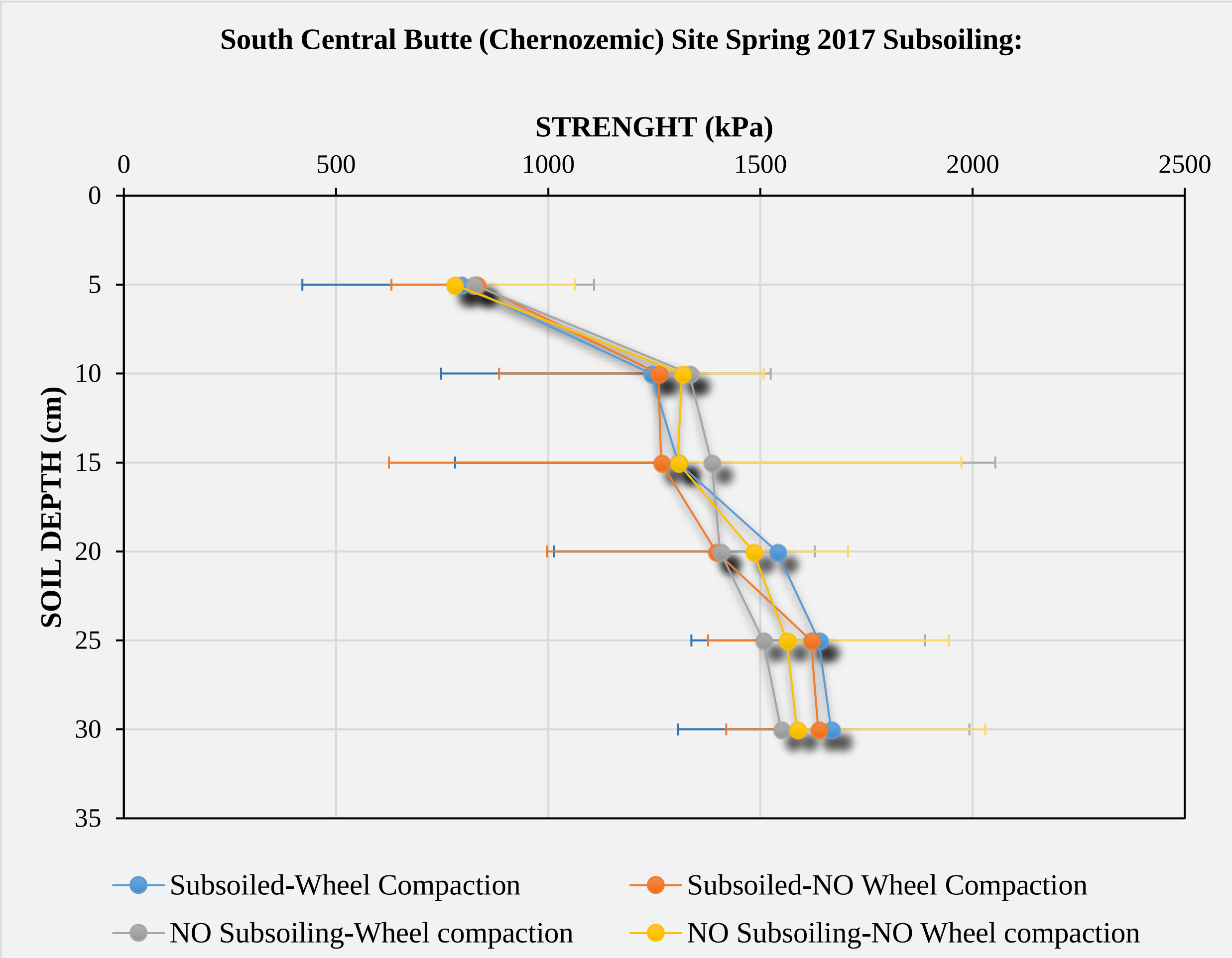

Figure 3.23. Soil strength (penetration resistance kPa) at SCB site measured using a Rimik cone penetrometer in spring of 2017. Error bars are deviation of the mean.

The effects of subsoiling and compaction on soil strength in the Chernozem at SCB in the second year following the treatments were not evident, as the soil strength values were similar, especially at the surface where they were nearly identical (Figure 3.23). This suggests that the effects of compaction and subsoiling are not long-lasting in this type of soil, with freeze-thaw and wet-dry cycles alleviating the effects of compaction and tillage on both bulk density and soil strength. Repeated seasonal cycles of freeze-thaw can naturally alleviate soil compaction through a process in which water in the pore space expands during freezing and contracts during thawing (Jabro et al., 2014). Also, Henry (2007) indicated that the decrease in penetration resistance and bulk density observed in agricultural soils over the winter was attributed to the disruptive effects of frequent freezing, with expansion and contraction, on soil structure.

3.5.1.3 Aggregate Size

The surface (0-10 cm) soil samples collected from the South Central Butte site (SCB) Chernozemic soil two to seven days after seeding in May of 2016 and 2017 were subjected to measurement of aggregate size (Table 3.3).

Table 3.3. Aggregate size in soil samples collected after seeding in the 2016 and 2017 growing seasons at the SCB site.

Treatment		Measurements 0-10 cm Aggregate Size MWD 2016	2017
		----------------mm----------------	
Subsoiled	Compacted	14.4*	12.0
	Non-Compacted	15.5*	12.5
Non-Subsoiled	Compacted	15.1	12.6
	Non-Compacted	14.2	14.4
P value	Subsoiled vs Non-Subsoiled	0.7413	0.5766
	Compacted vs Non-Compacted	0.6558	0.2678

MWD denotes Mean Weight Diameter.
*Significantly different at $P \leq 0.05$.

At the SCB site in the spring of 2016 the subsoiled compacted soil had slightly but significantly ($P \leq 0.05$) smaller aggregates than the subsoiled non-compacted soil (Table 3.3). In the compacted soil, the B and C horizons would be at reduced depth from the surface, such that subsoiling might result in mixing of more soil of lower horizons with the surface horizon where the soil is compacted. However, the overall treatments effects in 2016 were small and in 2017 there were no significant differences in aggregate size associated with subsoiling or compaction. Overall, the soil aggregates tended to be smaller in 2017 than 2016. Different crop grown in 2017 (peas) compared to 2016 (wheat) may be a factor. Also, the 2016 season was wetter than the 2017 season. The wetting process can be extremely disruptive. Ion hydration and osmotic swelling forces pull water in between clay platelets, pushing them apart and producing swelling of the aggregates in which they are incorporated (Kemper and Rosenau, 1986). If the aggregates are quickly wetted, the wetted section can swell significantly compared to the dry section, producing a shear plane to accompany the wetting front which can break many of the bonds (Kemper and Rosenau, 1986).

3.5.1.4 Air and Water Permeability

Table 3.4. Air permeability and hydraulic conductivity measured in June 2016 and 2017 at the SCB site.

Treatment		Measurements			
		0-10 cm			
		Air Permeability		Hydraulic Conductivity	
		2016	2017	2016	2017
		-------------------------cm min^{-1}-------------------------			
Subsoiled	Compacted	$1.72x10^{-2}$	$6.72 x10^{-4}$	$4.95x10^{-2}$	$1.20x10^{-1}$
	Non-Compacted	$2.49 x10^{-2}$	$6.12 x10^{-4}$	$7.86 x10^{-2}$	$1.42 x10^{-1}$
Non-Subsoiled	Compacted	$2.70 x10^{-3}$	$1.23 x10^{-3}$	$1.58 x10^{-2}$	$1.78 x10^{-1}$
	Non-Compacted	$8.28 x10^{-3}$	$1.10 x10^{-3}$	$4.77 x10^{-2}$	$1.30 x10^{-1}$
P value	Subsoiled vs Non-Subsoiled	0.0315	0.0745	0.2055	0.5142
	Compacted vs Non-Compacted	0.0007*	0.2688	0.2803	0.6157

*Significantly different at $P \leq 0.05$.

Air permeability and hydraulic conductivity were performed in spring of 2016 and 2017 after seeding using the air permeameter for air permeability and the single ring method for hydraulic conductivity. The measurements were taken in the soil surface (0-10 cm). Air permeability was lowest in the non-subsoiled compacted soil in the first year of the study (2016), but this disappeared in the second year (2017) after subsoiling (Table 3.4). Subsoiling increased air permeability, especially in the compacted soil, in 2016. In 2017, however, there were no significant ($P > 0.05$) influences of treatment on air permeability. For hydraulic conductivity, there were no significant effects ($P > 0.05$) among treatments. The finding of no significant effect of subsoiling on hydraulic conductivity in this study differs from other studies that have shown that deep tillage resulted in significantly increased infiltration (Pikul and Aase, 2003; Williams et al., 2006; Ewen, 2015). Nevertheless, in 2016, there was a trend toward higher infiltration in subsoiled treatments. The effect of compaction on reducing infiltration and subsoiling on increasing infiltration is consistent with impacts on soil porosity as revealed in bulk density measurements.

3.5.1.5 SCB Site Crop Yields

3.5.1.5.1 SCB site wheat yields – 2016

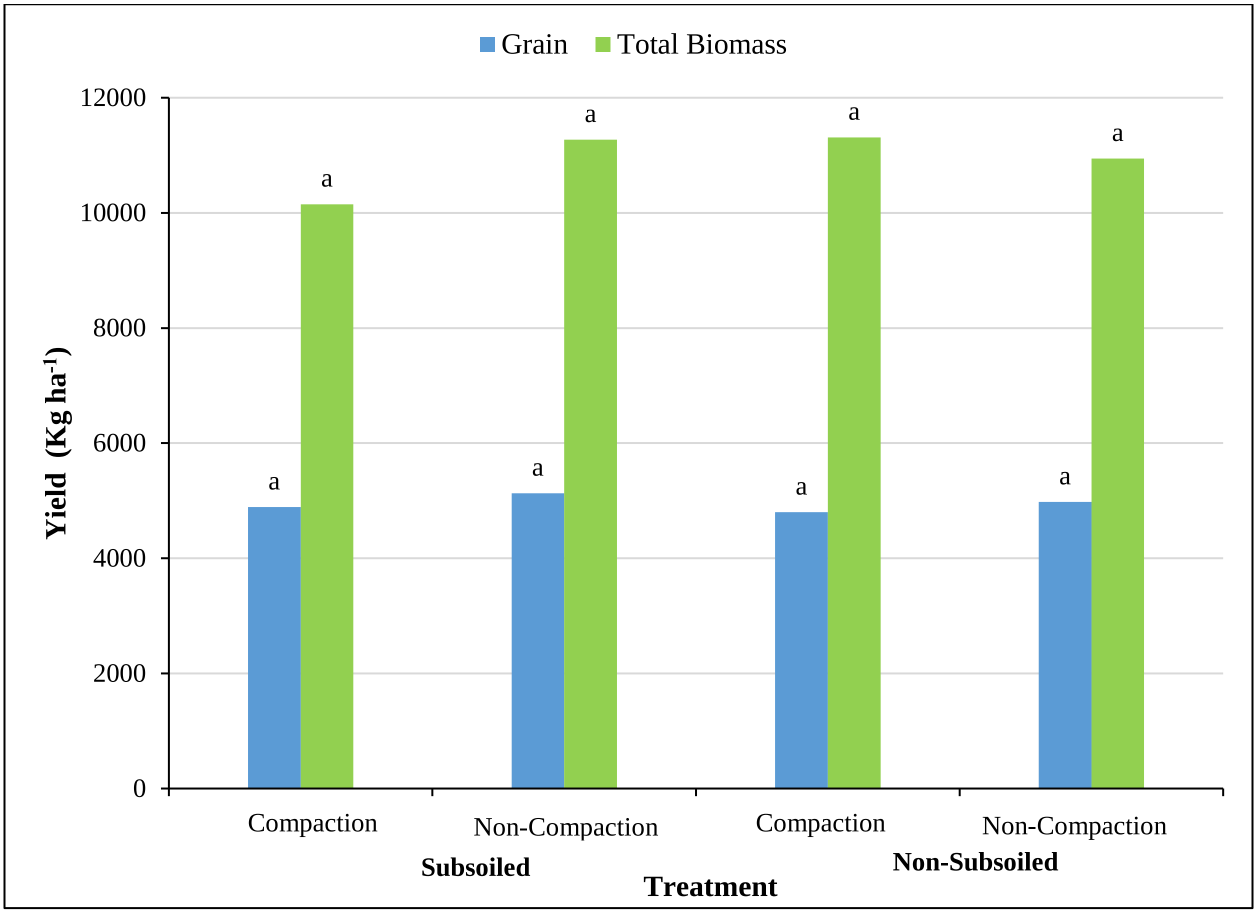

Figure 3.24. Wheat grain and total biomass (grain + straw) yields (Kg ha^{-1}) at the SCB site in 2016. For a crop component, values that are followed by the same letter are not significantly different ($P > 0.05$).

Wheat grain and total biomass yield at the SCB site showed very little effect of the compaction/subsoiling treatments (Figure 3.24), with similar grain yields and no significant difference ($P > 0.05$) among the treatments. This agrees with previous studies in Saskatchewan that subsoiling did not have effects on crop yield (McConkey et al., 1997), and other locations such as in a study by Murdock et al., (1999) that found that crop yield was very similar between tilled and no-tilled treatments near Zanesville, Ohio. Lack of significant effects of the compaction and subsoiling treatments on yield at the SCB site is consistent with soil strength values of only around ~1200 kPa in the wheel traffic compacted area. Also, plant root growth is generally said to be restricted beyond 2500 kPa (Busscher and Sojka, 1987; Busscher et al., 1995). The values for soil strength of around 1000 kPa in the top 10 cm (measured with Rimik instrument in loamy Chernozem after seeding with soil moisture conditions close to field capacity) indicate no large concerns for any detrimental effects on wheat yield from the wheel traffic compaction that occurred in the previous fall. There was also limited or no effect of compaction and subsoiling on general soil physical properties and permeability at the SCB site, in line with lack of significant yield effects.

3.5.1.5.2 **SCB site pea yields – 2017**

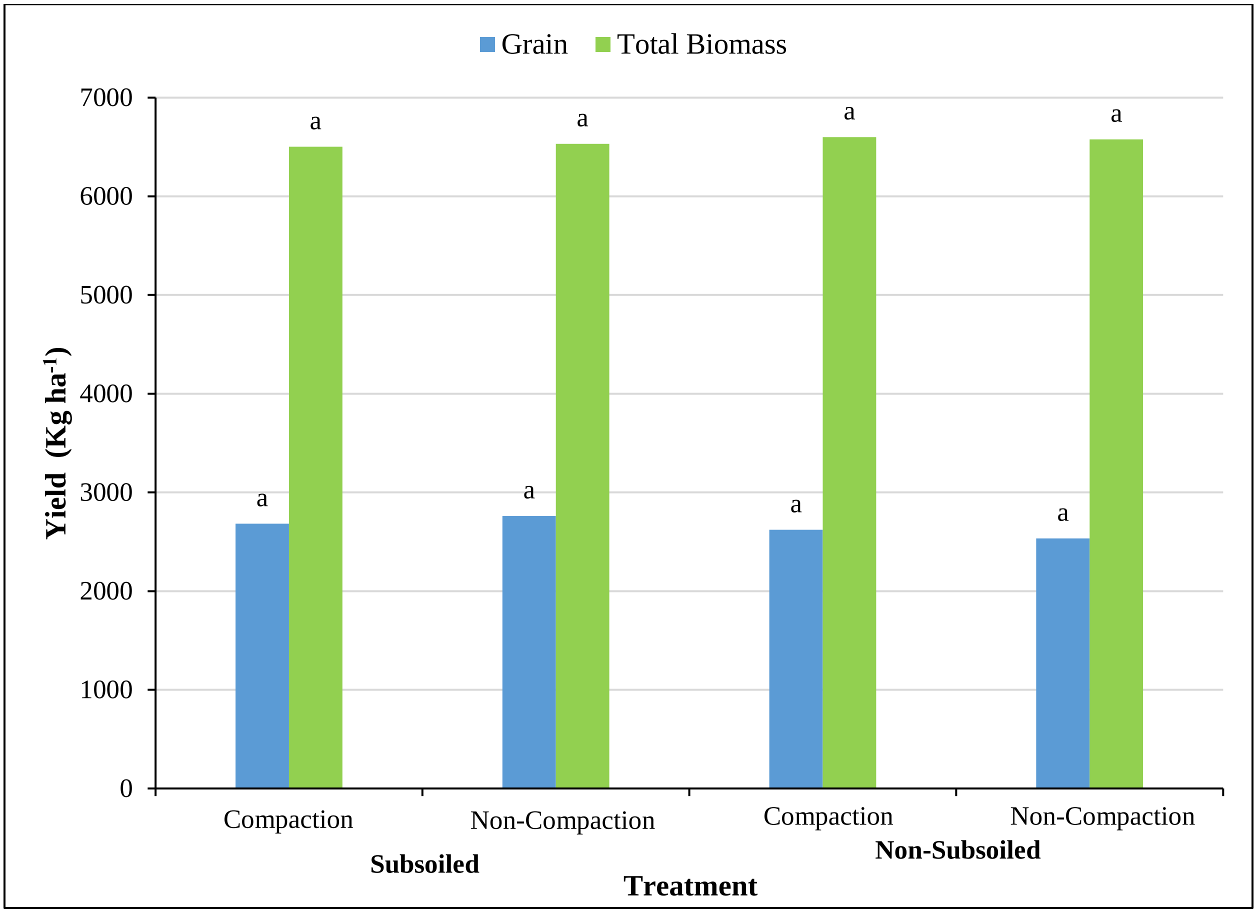

Figure 3.25. Pea grain and biomass (grain + straw) yields (kg ha^{-1}) at the SCB site in 2017. For a crop component, values that are followed by the same letter are not significantly different (P > 0.05).

At the SCB site in 2017, the pea plant total biomass and grain yields were also not significantly affected (P > 0.05) by compaction or subsoiling, and the yields were very similar among the different treatments (Figure 3.25). Increases in crop yield associated with subsoiling have been reported by Varsa et al., (1997), with crop yield increased even 5 years after the subsoiling treatment in corn fields. The total biomass production was high relative to grain yields, a consequence of dry, hot conditions in June and especially July that led to flower abortion and poor pod fill. Similar total biomass and grain yield across treatments indicate no effect of compaction or subsoiling on pea growth the second year after the compaction and subsoiling treatments were implemented. The subsoiling and wheel traffic compaction treatments did not have any evident effect on pea grain yields at the SCB site in 2017, nor was there any noteworthy trends. The lack of treatment effects on pea yield in 2017 is not particularly surprising given that there were no yield differences in wheat grown on the plots in 2016.

3.5.2 North Central Butte Site (NCB): Solonetzic Soil

3.5.2.1 Bulk Density

3.5.2.1.1 NCB Spring 2016 and 2017

Table 3.5. Bulk density at NCB site in spring 2016 and 2017.

Treatment		Bulk Density					
		0-15 cm		15-30 cm		30-60 cm	
		2016	2017	2016	2017	2016	2017
		----------g cm^{-3}----------					
†Pre-Compacted	Subsoiled	1.58	1.49	1.65	1.50	1.78	1.71
	Non-Subsoiled	1.61	1.55	1.68	1.63	1.81	1.79
‡Post-Compacted	Subsoiled	1.52	1.49	1.70	1.46	1.76	1.75
	Non-Subsoiled	1.63	1.53	1.78	1.53	1.79	1.82
§Control	Subsoiled	1.41*	1.47	1.77	1.71	1.79	1.77
	Non-Subsoiled	1.57*	1.40	1.78	1.75	1.80	1.74
P value	Subsoiled vs Non-Subsoiled	0.0623	0.5965	0.4132	0.2960	0.5380	0.4475
	Pre-Compacted vs Control	0.0505	0.4243	0.0260*	0.0881	0.8461	0.9345

†Pre-compacted is long-term (5 year) wheel traffic compaction prior to subsoiling.
‡Post-compacted is compaction by wheel traffic after subsoiling.
§Control is uncompacted soil.
*Significantly different at $P \leq 0.05$.

As expected, soil density was generally higher in the NCB soil (Table 3.5) than the SCB soil (Table 3.1), especially in the 15-30 cm depth. This is explained by the Solonetzic nature of the NCB soil, with the profile having a Solonetzic B horizon starting at approximately 15 cm depth (visual observation). Compaction increased bulk densities compared to the control. This corroborates findings by Gameda et al., (1987) who reported on their study conducted in Quebec, Canada that areas that were compacted contributed to substantial increases in bulk density especially where clay content was higher. For the soil bulk density measured in spring of 2016 after seeding in May at NCB site, there was no significant effect ($P > 0.05$) of subsoiling on compacted soil. However, there was a trend of decrease in soil density in subsoiled pre and post - compacted areas compared to the non-subsoiled areas in the 0-15cm and 15-30cm depths, as was observed for the SCB Chernozemic soil. Subsoiling resulted in significantly lower bulk density in the non-compacted control soil. The pre-compacted soil did not respond as much to the subsoiling, possibly because the subsoiler equipment had more difficulty in lifting and shattering the dense soil. In spring of 2017, 19 months after the subsoiling treatment was imposed, there were no significant differences among treatments, but the subsoiled compacted treatments did have slightly lower mean bulk densities for all depths. Overall, it appears that the effect of the subsoiling on reducing bulk density has diminished in the second year following the subsoiling treatment.

3.5.2.1.2 **NCB Fall 2016 and 2017**

Table 3.6. Bulk density at NCB site in fall 2016 and 2017.

Treatment		Bulk Density			
		0-30 cm		30-60 cm	
		2016	2017	2016	2017
		g cm^{-3}			
†Pre-Compacted	Subsoiled	1.66	1.66	1.80	1.72
	Non-Subsoiled	1.69	1.68	1.81	1.77
‡Post-Compacted	Subsoiled	1.45	1.56	1.63	1.67
	Non-Subsoiled	1.53	1.61	1.75	1.73
§Control	Subsoiled	1.57	1.62	1.78	1.76
	Non-Subsoiled	1.57	1.65	1.80	1.72
P value	Subsoiled vs Non-Subsoiled	0.4856	0.6098	0.6427	0.7231
	Pre-compacted vs Control	0.1078	0.6144	0.9014	0.9170

†Pre-compacted is long-term (5 year) wheel traffic compaction prior to subsoiling.
‡Post-compacted is compaction by wheel traffic after subsoiling.
§Control is uncompacted soil.

Soil bulk densities measured at 0-30 cm and 30 cm depths in the fall of 2016 and fall of 2017 after harvest were not significantly different among treatments and subsoiling had no significant effect on bulk density (Table 3.6). Sojka et al., (1997) in a study conducted on New Zealand's North Island reported that subsoiling decreased soil bulk density in fields that were compacted by 15 years of conventional cropping. Overall, the dense nature of the soil at the NCB site, with bulk density values approaching 1.8 g cm^{-3} in the 30-60 cm depth, is likely an impediment to deep root growth. In this dense soil, the subsoiler design used had little effect on reducing density in the soil profile. An implement with more pronounced lifting and shattering action may be needed in Solonetzic soils such as these at NCB site.

3.5.2.2 Soil Penetrometer Resistance (Strength)

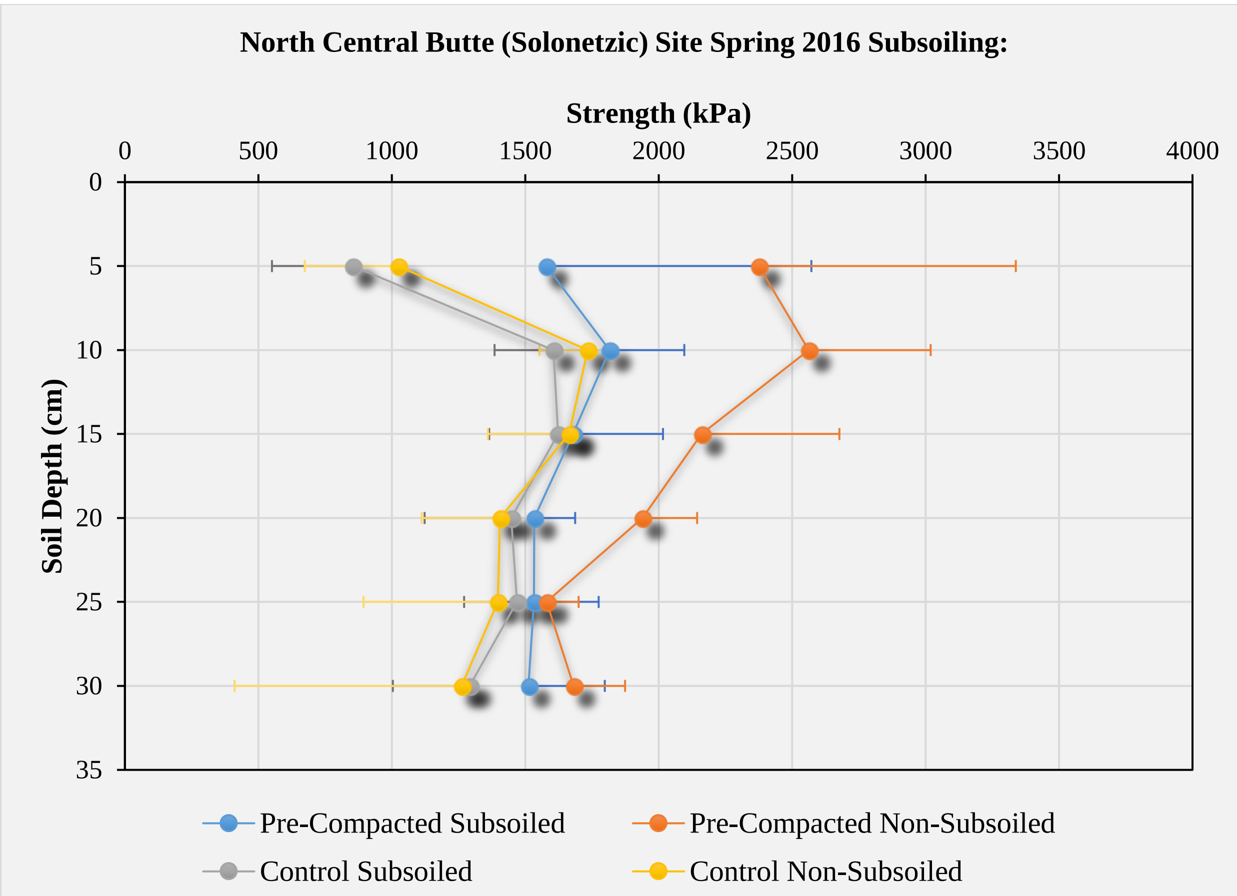

Figure 3.26. Soil strength (penetration resistance kPa) at NCB site measured using a Rimik cone penetrometer in spring of 2016. Error bars are standard deviation of the mean. Pre-compacted is long-term (5 year) wheel traffic compaction prior to subsoiling, post-compacted is compaction by wheel traffic after subsoiling, and control is uncompacted soil.

The cone penetrometer was used to measure soil strength in the spring of 2016 and 2017. At the time of measurement after seeding in the spring, the soil moisture content of the profile was near field capacity. In the spring of 2016, the long-term (5-year) compaction by wheel traffic (pre-compacted non-subsoiled) resulted in the highest soil strength at the surface, and sub-soiling in the fall of 2015 significantly reduced the soil strength measured the following spring to a depth of about 25 cm, with the effects decreasing with depth (Figure 3.25). As expected, the uncompacted control soil had the lowest strength and subsoiling slightly reduced the soil strength in plots where there was no compaction. Overall, subsoiling treatments were effective in significantly reducing soil strength of compacted soil and eliminating issues of high soil strength in wheel traffic affected areas of the field. While having limited effect on bulk density, the lifting and shattering action created by the subsoiler significantly reduced the soil compaction (resistance) created by the wheel traffic compaction and natural conditions of this Solonetzic soil. Overall, the soil strength values in this Solonetz soil (Figure 3.26) were considerably higher than in the SCB Chernozem (Figure 3.22), with the long-term compacted soil without subsoiling having penetration resistance values ~ 2500 kPa. The critical level of penetration resistance for root growth is reported to be ~ 2500 kPa (Busscher et al., 1986). Therefore, it is anticipated that root growth would be impeded in the areas affected by long-term compaction, while subsoiling greatly reduced soil strength and therefore would be expected to contribute to increased root growth. Borghei et al., (2008) reported in their study conducted in the northwest of Iran that there was a significant effect of subsoiling, with cone penetration decrease of up to 43% in areas that the subsoiling tillage (10-50 cm of depth) was performed.

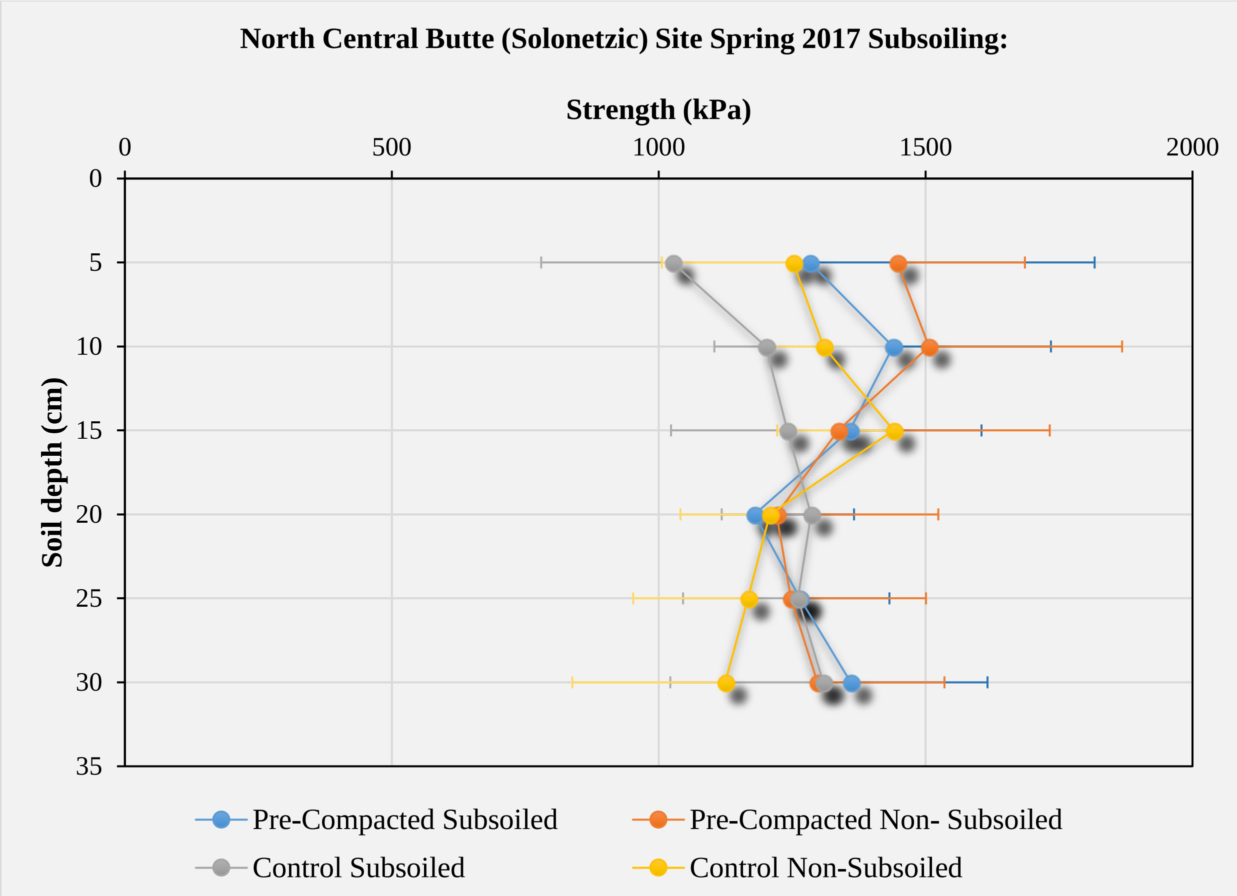

Figure 3.27. Soil strength (penetration resistance kPa) at NCB site measured using a Rimik cone penetrometer in spring of 2017. Error bars are standard deviation of the mean. Pre-compacted is long-term (5 years) wheel traffic compaction prior to subsoiling, post-compacted is compaction by wheel traffic after subsoiling, and control is uncompacted soil.

At the NCB site in the spring of 2017, 19 months after the subsoiling treatment was performed, the soil strength values in the top 20 cm were lower in subsoiling treatments (Figure 3.27). However, there were no significant differences among treatments. The penetration resistance in the control in spring of 2017 was similar to 2016, but the penetration resistance of the pre-compacted soils decreased in all treatments (Figure 3.26). This might be attributed to the natural process of freezing and thawing over the winter time; hence, compacted soil is remediated by this process. Jabro et al., (2014) reported that freezing and thawing significantly decreased the penetration resistance in compacted soils in northeastern Montana. Also, the shanks of the subsoiler may bring some calcium carbonate up from depth, resulting in some displacement of Na from the clays by the Ca.

3.5.2.3 Aggregate Size

Table 3.7. Aggregate size in soil samples collected after seeding in the 2016 and 2017 growing seasons at the NCB site.

Treatment		Measurements 0-10 cm Aggregate Size MWD 2016	2017
		----------------mm----------------	
†Pre-Compacted	Subsoiled	13.0	13.7
	Non-Subsoiled	13.4	13.8
‡Post-Compacted	Subsoiled	12.4	14.4
	Non-Subsoiled	14.1	13.6
§Control	Subsoiled	10.0	11.7
	Non-Subsoiled	11.6	13.1
P value	Subsoiled vs Non- Subsoiled	0.2022	0.7030
	Pre-compacted vs Control	0.0072*	0.0079*

†Pre-Compaction is long-term (5-year) vehicle traffic induced soil compaction occurring prior to subsoiling treatment being imposed at the North Central Butte (NCB) site in Oct. 2015.
‡Post-Compaction is vehicle traffic induced soil compaction treatment occurring in April 2016 after subsoiling treatment being imposed at the North Central Butte (NCB) site in Oct. 2015.
§Control is no vehicle traffic induced soil compaction treatment.
*Significantly different at $P \leq 0.05$.

The aggregate size at NCB site was measured using the dry sieving method, and there was no significant effects ($P > 0.05$) of subsoiling on aggregate size in both years in compacted and non-compacted soils (Table 3.7). Overall, compaction did result in aggregates of larger size. This may be attributed to a more massive structure resulting from compaction pressure in Solonetz soils that, when disrupted by tillage, results in large lumps. Jaiyeoba (2003), reported in their study that tillage practices reduce MWD, but this was surface tillage in a Nigerian soil with very different properties than the soil used in the current study. Also, Filho et al., (2002) determined lower aggregate size under tillage systems compared to zero tillage in a study in Brazil. The sodium saturated clays in the NCB soil along with low organic matter content leads to a massive structure due to dispersion and production of large lumps when the soil is tilled as shown in (Figure 3.8).

3.5.2.4 Modulus of Rupture

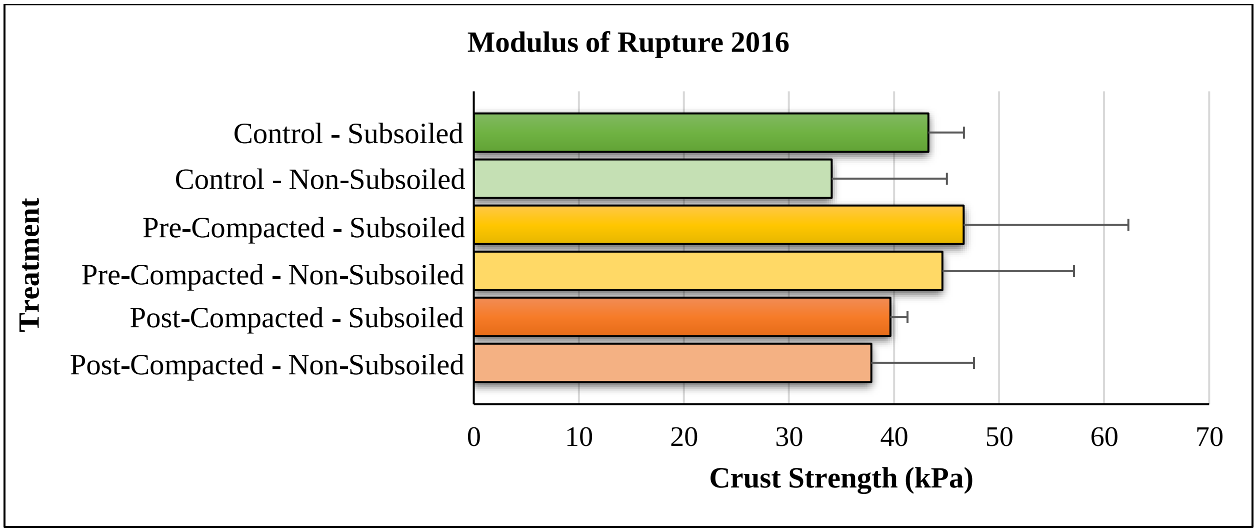

Figure 3.28. Modulus of Rupture measured at NCB site in spring 2016. Values are from two replicates of each treatment.

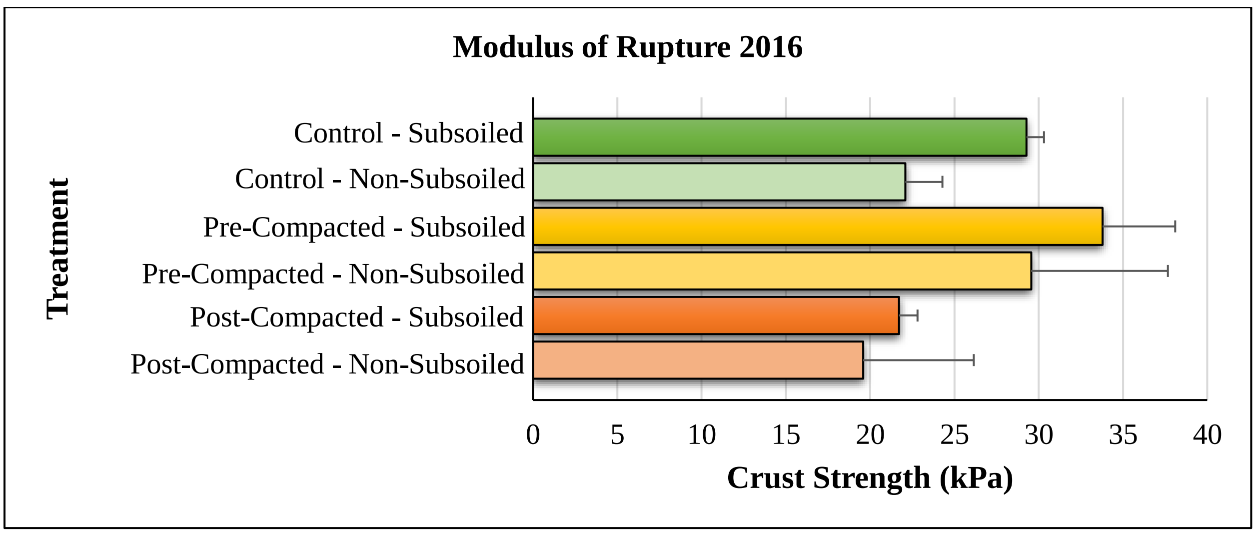

Figure 3.29. Modulus of Rupture measured at NCB site in spring 2017. Values are from two replicate measurements of each treatment.

Modulus of rupture was determined on samples that were taken from 0-5 cm depth in the spring of 2016 and 2017 after seeding to assess soil crust strength, attempting to simulate the effect of wetting and drying of the surface and development of a crust as it occurs in the field. In both 2016 and 2017 a similar pattern was evident in which pre-compacted soil through long-term wheel traffic had higher crust strength and subsoiling resulted in lower crust strength (Figure 3.28; Figure 3.29). The subsoiler that was used on this site was observed to lift the B and C horizon and likely caused some mixing of calcium carbonate with the surface A horizon. The calcium cations brought to the surface may have resulted in some displacement of the Na which was subsequently leached down, reducing the tendency of the soil clays to disperse and form a hard crust structure. Tanton et al., (1990) found in their study on the Seyhan Plain in Southern Turkey that by subsoiling, it was possible to leach up to 60% of the leachable salts from the soil.

3.5.2.5 Air and Water Permeability

Table 3.8. Air permeability and hydraulic conductivity measured in June 2016 and 2017 at the NCB site.

Treatment		Measurements 0-10 cm Air Permeability 2016	2017	Hydraulic Conductivity 2016	2017
		---cm min^{-1}---			
†Pre-Compacted	Subsoiled	$6.90x10^{-3}$	$7.86\ x10^{-4}$	$6.32x10^{-2}$	$2.13x10^{-1}$
	Non-Subsoiled	$5.87x10^{-3}$	$6.42x10^{-5}$	$1.65x10^{-2}$	$1.67x10^{-1}$
‡Post-Compacted	Subsoiled	$3.12\ x10^{-3}$	$7.44x10^{-4}$	$8.32x10^{-3}$	$7.94x10^{-2}$
	Non-Subsoiled	$2.49\ x10^{-3}$	$7.20x10^{-4}$	$5.05x10^{-2}$	$5.73x10^{-2}$
§Control	Subsoiled	$2.99x10^{-3}$	$1.37x10^{-3}$	$2.86x10^{-2}$	$1.28x10^{-1}$
	Non-Subsoiled	$3.84x10^{-3}$	$3.64x10^{-4}$	$6.23x10^{-3}$	$1.17x10^{-1}$
P value	Subsoiled vs Non-Subsoiled	0.9125	0.0559	0.0748	0.0632
	Pre-compacted vs Control	0.9125	0.3292	0.4416	0.2654

†Pre-Compaction is long-term vehicle traffic induced soil compaction occurring prior to subsoiling treatment being imposed at the North Central Butte (NCB) site in Oct. 2015.
‡Post-Compaction is vehicle traffic induced soil compaction treatment occurring in April 2016 after subsoiling treatment being imposed at the North Central Butte (NCB) site in Oct. 2015.
§No vehicle traffic induced soil compaction treatment.

Small and variable effects of treatments on air permeability were observed at the NCB site (Table 3.8). There is some indication that subsoiling is increasing air permeability in compacted areas because subsoiling increased air flow in both the first and second year of the study, although the effects were not significant ($P > 0.05$). This is consistent with the limited effect of the subsoiling on bulk density (porosity) at the NCB site (Table 3.6).

The effects of tillage on hydraulic conductivity is an important consideration as higher measured hydraulic conductivity indicates a greater rate of water entry into, and movement within, the soil.

In 2016, water infiltration was not significantly (P > 0.05) affected by subsoiling in pre-compacted and post-compacted areas (Table 3.8). As for air permeability, the observed lack of large and significant effect of subsoiling on hydraulic conductivity agrees with the limited effect on density and porosity (inverse of density) in this soil. These findings do not match with Mukhtar et al., (1985) who reported in their study in Iowa that the effect of tillage treatments on soil water infiltration varied, but deep tillage produced the highest infiltration rates. However, in the treatment where the soil was compacted following subsoiling, water infiltration appeared to be reduced as a result of the compaction that occurred after the tillage treatment. In the current study, subsoiling in control plots where there was no compaction tended to have higher hydraulic conductivity after the first year of treatment. In 2017, there were no significant differences among the treatments in hydraulic conductivity, but in 2017 the infiltration rate was slightly higher in all three subsoiled treatments. A reason for the observed increase in hydraulic conductivity may be attributed to the lack of precipitation in 2017 (Figure 3.11), such that the soil was unsaturated at the time of the infiltration measurement.

3.5.2.5.1 **NCB Site Crop Yields**

3.5.2.5.2 **Crop Yields NCB site canola yields - 2016**

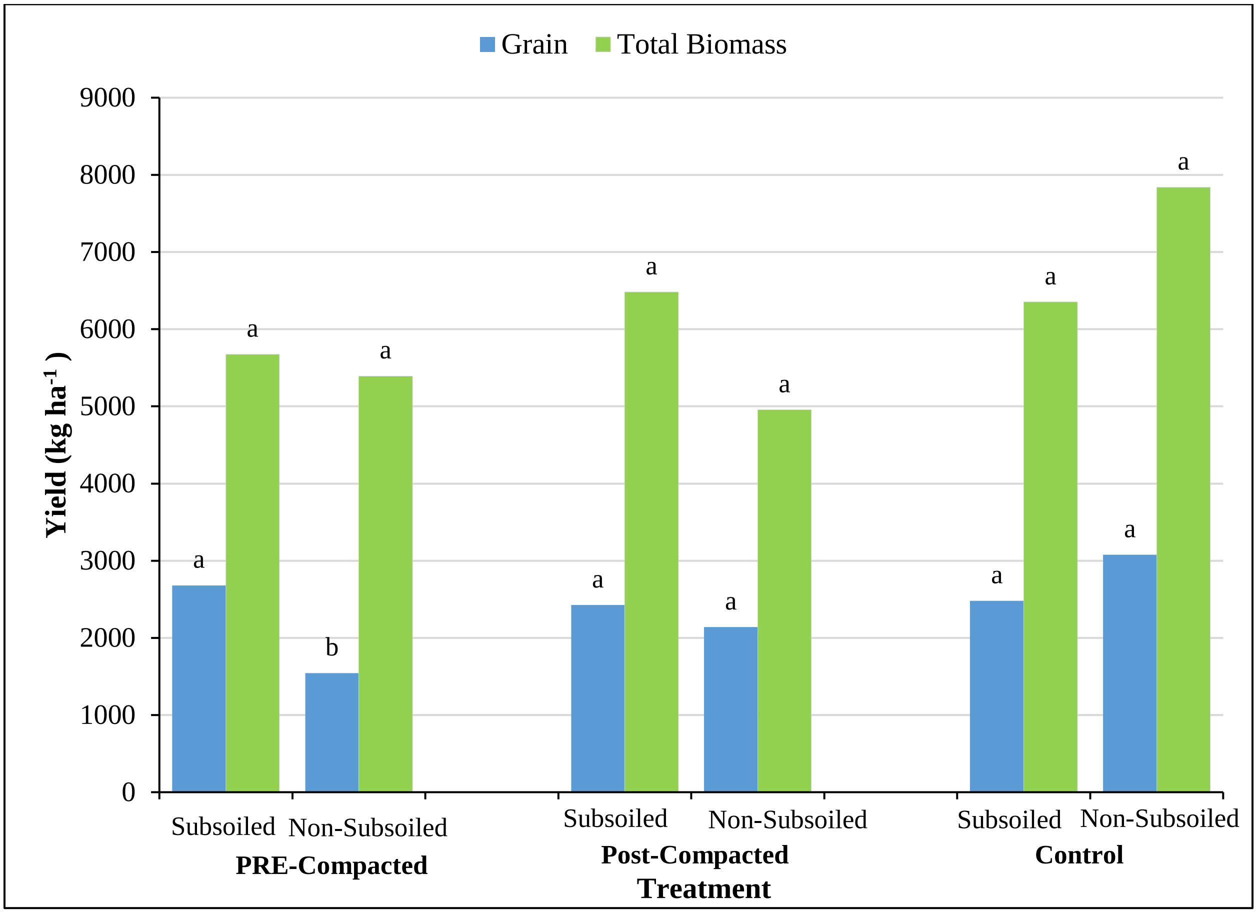

Figure 3.30. Canola grain and total biomass yields at the NCB site in 2016. Pre-compacted is long-term (5-year) wheel traffic compaction prior to subsoiling, post-compacted is compaction by wheel traffic after subsoiling, and control is uncompacted soil. For a given crop component and compaction treatment, values followed by the same letter are not significantly different ($P > 0.05$).

At the NCB site in 2016, canola was grown to determine the subsoiling tillage effects on yield (Figure 3.30). The long-term (5-year) wheel traffic compacted soil (pre-compacted) had significantly ($P \leq 0.05$) lower grain yield than the other treatments, and subsoiling increased the canola grain yield from ~1500 kg ha^{-1} to ~ 2800 kg ha^{-1} in the pre-compacted soil. This may be especially related to the effect of the subsoiling of the long-term wheel traffic compacted soil on reducing the soil strength below the critical value (Figure 3.26), as this was the largest treatment effect on a physical property observed at this site. Compaction of the soil by wheel traffic that occurred post-subsoiling (post-compacted) did not significantly reduce the yield compared to the control, but yields tended to be lower and there was a small benefit where the soil had been subsoiled prior to compaction.

The reduction of soil strength likely improved plant root growth, nutrient and water uptake which is reflected in crop yield. The results reported from this study are consistent with that of Zhai et al., (2017) who found in Huang-Huai-Hai Plain in China maize crop response to deep tillage was positive and significant as well. They indicated that subsoil below the tilled topsoil stores large nutrient stocks and can retain water even under drought conditions and was able to be accessed by roots as a result of the deep tillage reducing the soil strength. The large amount of precipitation received at the site in this study in 2016 (Figure 3.10) likely was a factor in muting the crop yield responses to subsoiling. Other studies have shown subsoiling tillage improved crop yield in prairie soils. Grevers and de Jong, (1992), in their five-year study, found that subsoiling of a Solonetzic soil in Saskatchewan improved crop yield.

3.5.2.5.3 NCB site wheat yields – 2017

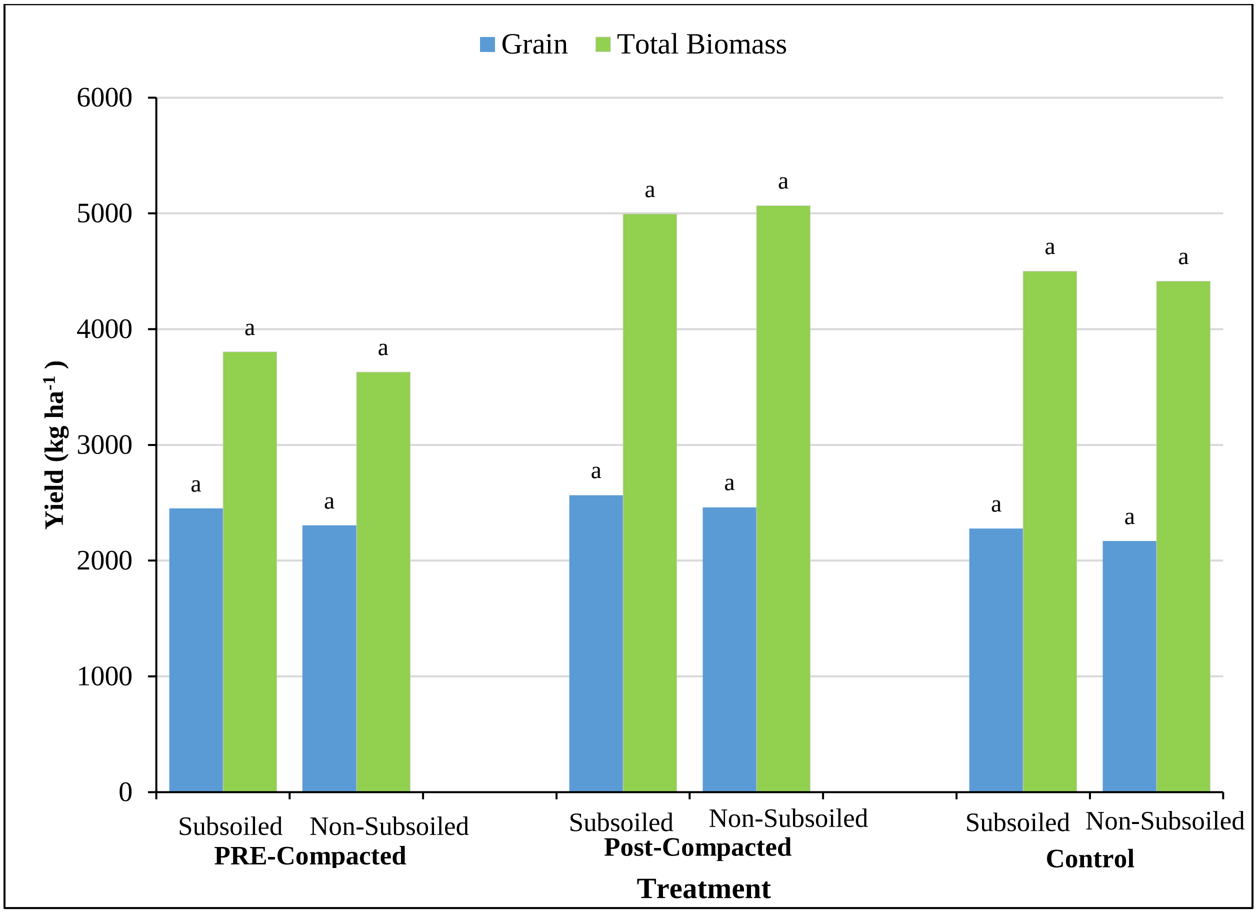

Figure 3.31. Wheat grain and total biomass yields at the NCB site in 2017. For a given crop component and compaction treatment, values followed by the same letter are not significantly different (P > 0.05).

At the NCB site where hard red spring wheat was grown 2017, there were no significant subsoil treatment effects (P > 0.05) on wheat total plant biomass (grain plus straw) or grain yield (Figure 3.31). Wheat grain yield was similar among the treatments ranging from ~2100 to 2400 kg ha^{-1}. The effect of the compaction and subsoiling treatments on crop yield has diminished over the 19 months after application to the point where there was no impact on wheat yield in the 2017 crop year. A natural amelioration of the compacted condition by freeze-thaw and wet dry cycles during 2016 and 2017, as well as the ability of wheat roots to more effectively penetrate dense soil compared to the canola grown in 2016 may explain lack of compaction and subsoiling effects persisting into the second year after treatment. It is well documented that roots of many crops have reduced soil penetration abilities when resistance approaches levels of ~2500 kPa (Busscher et al., 1986; Kuang et al., 2012).

The results in 2017 match with Holmstrom and Carter, (2000) who found that subsoiling did not improve grain yield at the study they performed in a Prince Edward Island potato field. However, the growing season precipitation was low in 2017 (Figure 3.11) so effects of treatments on soil profile characteristics, especially those related to moisture storage and availability, would be expected to be revealed to a greater extent under these low rainfall conditions compared to a high rainfall environment like Prince Edward Island.

3.6 General conclusion

Subsoiling with a minimum till subsoiler to a depth of 30 cm was effective in reducing soil density and strength, and increasing soil hydraulic conductivity and air permeability in compacted and non-compacted areas of Solonetzic and Chernozemic soils. The favorable effect of improvement in soil conditions was evident in increased canola yields of the compacted Solonetz in the year following subsoiling. It appears that Solonetzic soils exposed to long-term wheel traffic are most likely to respond to subsoiling tillage.

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4 A COMPARISION OF FLAX RESIDUE MANAGEMENT PRACTICES IN A BROWN CHERNOZEM: VERTICAL TILLAGE, TANDEM DISC TILLAGE, AND RAKING AND BURNING VERSUS DIRECT SEEDING

4.1 Preface

In the previous chapter, we described a study of the impact of low disturbance subsoiling at a depth of ~30 cm as a means to improve physical condition and productivity of compacted Solonetzic and Chernozemic soils. This chapter deals with an investigation of surface (0-10 cm) tillage practices and raking and burning as approaches to address potential crop residue interferences with seeding.

4.2 Abstract

The accumulation of crop residue at the soil surface can interfere with field operations like seeding, negatively affecting germination and emergence and hence crop yield. Vertical tillage and tandem disc implements are used to manage residue and alter soil physical conditions, mainly at the soil surface. Also, raking and burning is used as an alternative for management of difficult crop residues such as flax straw. The objective of this study was to evaluate the effect of surface tillage on soil physical properties and crop yield in a Chernozemic soil in southern Saskatchewan, Canada. The research study site was located near Central Butte, SK. Tillage, raking and burning did not significantly affect aggregate size. However, vertical tillage in the Chernozemic soil tended to decrease water infiltration and air permeability compared to the un-tilled soil, which may be explained by an increase in the number of fine pores. Crop yields of wheat (*Triticum aestivum*), and peas (*Pisum sativum*) were not significantly different by vertical tillage, tandem disc or burning treatments, indicating that with good straw management, no tillage, raking or burning may be required in order to obtain good yield.

4.3 Introduction

Management practices by prairie growers, such as tillage, raking and burning of crop stubble in the fall, can potentially influence important soil physical and chemical properties related to soil quality and productivity. Large amounts of crop residues accumulating on the soil surface can slow spring soil warming and interfere with direct seeding operations, resulting in uneven germination and emergence, and hence negatively affect crop production (Wayne et al., 1994). Flax stubble can pose particular challenges in interference with seeding, often referred to as the "straw problem", as long, tough stem fibers of the flax straw wrap themselves around seeding tools (Saskatchewan Flax Development Commission, 1992). Tillage and other crop residue management practices employed in annual crop production play an important role in affecting soil properties and also how the soil receives and retains moisture (Moore, 2015). Overall, the three widely recognized aims of tillage are; 1) incorporation of organic matter into the soil, 2) control of weeds, and 3) improvement of soil structure (Hillel, 1982A).

Tillage that promotes the greatest degree of soil disturbance also tends to be the most effective in burying crop residues, with disc harrows typically used in the fall to chop, spread and incorporate residues. The degree of residue incorporation has a major effect on the initial rate of decomposition (Paustian et al., 1997), and incorporation of residue generally increases decomposition rate (Schoenau and Campbell, 1996). Tillage can also disrupt aggregates and expose the organic matter inside to microbial decomposition. Aggregate stability is a function of soil organic matter content, soil texture, cation exchange capacity, tillage and cropping systems, manure application, and residue management. Organic matter supplies the cementing and binding agents and promotes microbial processes responsible for the enmeshment of soil particles into stable aggregates (Blanco and Lal, 2010). Maintaining high soil aggregate stability was noted to be important in conserving soil productivity by reducing soil erosion and organic matter losses and minimizing environmental pollution derived from soil degradation (Taylor and Amézketa, 1999).

Management of crop residues to avoid seeding problems can begin right at harvest by using a combine harvester with good straw chopping capabilities, and harvesting under dry conditions which promotes crop residue maceration in the combine (Saskatchewan Flax Development Commission, 1992). This strategy management may allow seeding directly into the stubble without any pre-seeding tillage or other residue management technique. As well as tillage, controlled burns in the field may be also be used to further clear the land of crop residue as well as kill weeds and reduce viability of weed seeds (Henkel, 2015). There are many negative issues associated with burning, including risk of fire escape, reductions in air quality from smoke, contribution to atmospheric carbon dioxide, and potential negative impacts on the soil itself from the loss of residue organic matter and its protective cover. However, the ash deposited after the burning can help to fertilize the soil through release of the occluded mineral nutrients such as phosphorus, potassium, calcium, magnesium and micronutrient metals for crop use (Scheuner et al., 2004).

It is hypothesized that the approach to managing flax residue (tillage, raking and burning) will directly influence surface soil physical properties and yield of following crops. In this study, aggregation, air and water permeability and yield of wheat and pea grown the following two years after tillage and raking and burning treatments were imposed on flax stubble is evaluated. The influence of two different types of surface tillage implement: 1) tandem disc consisting of sharp-edged convex discs that roll obliquely to the direction of movement, thus cutting the soil in a manner similar to that of a moldboard plow and 2) combination of disc and a rolling basket, called vertical tillage are compared to raking and burning as practices for residue management in flax straw. The research was conducted in 2016 and 2017 on a Brown Chernozem in south-central Saskatchewan.

4.4 Materials and Methods

4.4.1 Location of Study

The study was conducted in south-central Saskatchewan at the border of the Brown and Dark Brown soil-climatic zones near the town of Central Butte (Figure 4.1). In this general location, the study site was set up where surface tillage treatments could be evaluated on a flax stubble field that was harvested in September of 2015. The study was located on dominantly Chernozem (Brown Chernozem) soils that dominate what is termed the “Flax Residue Management” (FRM) site.

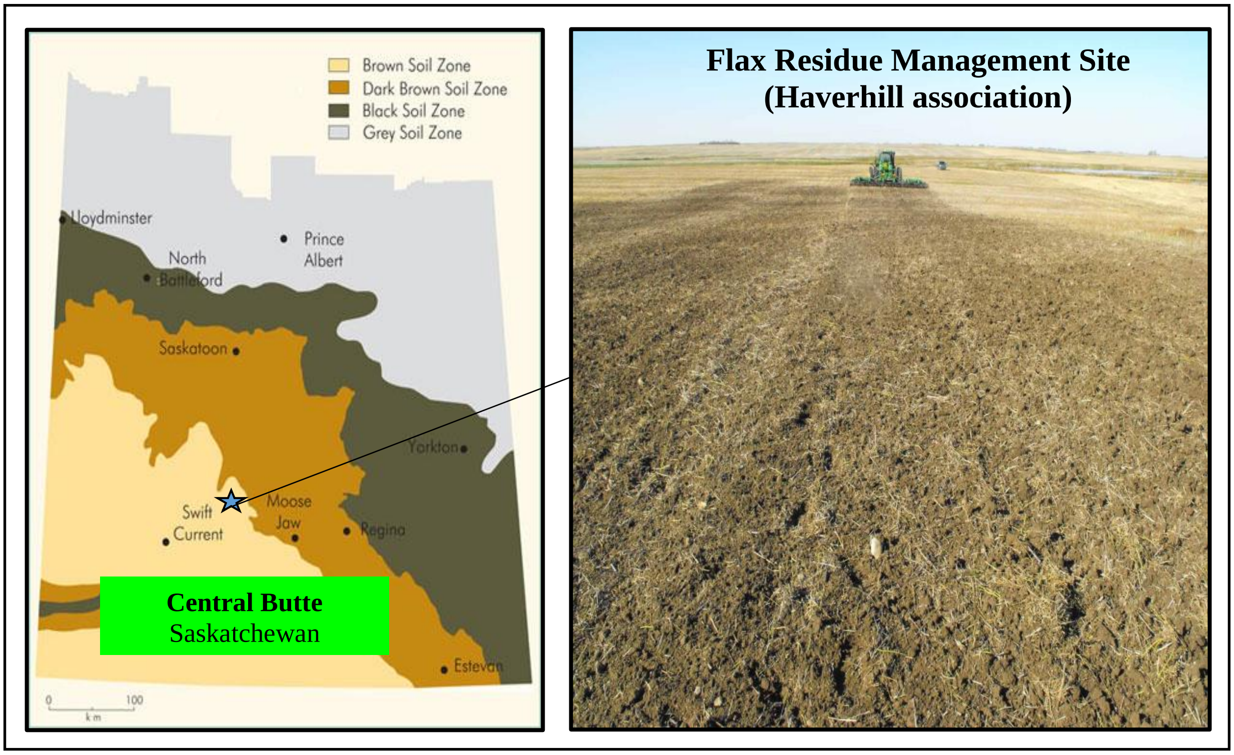

Figure 4.1. Geographical location of the study site near Central Butte, SK.

4.4.2 Site Description

4.4.2.1 Flax Residue Management Site (FRM)

The Flax Residue Management study site near Central Butte SK was established in September 2015 after harvesting operations had concluded on a flax (*L. usitatissimum* var. Sorrel) stubble field. The field is located at SW30-20-03-W3 (N 50.720064; W 106.417990). This field is located 8.0 km south and 6.5 km east of the town of Central Butte, within the Rural Municipality of Eyebrow, No. 193. The soil at the FRM site belongs to the Haverhill Soil Association and is predominantly Orthic Dark Brown Chernozem along with a few Brown Solonetzic series soils at toe-slopes of catenas. The organic matter concentration of the 0-10 cm depth in the field is 1.9 % and the pH is 6.9. The texture is loam over medium to moderately fine textured, moderately to strong calcareous, saline, unsorted glacial till parent material (Soil Classification Working Group, 1998). The soil at the FRM site occurs on a knoll and depression glacial till plain with gently undulating landscape (Soil Classification Working Group, 1998) (Figure 4.2). Identified limitations include moderately stony and saline conditions occurring in low lying areas and sloughs covering 10-20 % of the landscape. The study plots were located in the non-saline upland portion of the field. Flax (*Linum usitatissmum* var. Sorrel) was grown on the FRM site in 2015. The yield of the flax crop in 2015 averaged 1900 kg ha^{-1} in this field and was harvested with a John Deere CTS combine equipped with a straw chopper in the first week of September 2015. Distribution of the residue after harvest is shown in Figure 4.2.

Figure 4.2. Landscape at the Flax Residue Management Site (FRM) in October 2015.

4.4.3 Treatment and Experimental Design

The Flax Residue Management experiment was set up as a randomized complete block design (three treatments, with four replicates of each treatment) with plots laid out in the fall of 2015. Transect measurement points spaced 10.0 m apart and numbering 15 points per treatment plot were established. Alleyways separating the blocks were established to allow for equipment movement and access to all the treatment plots.

The treatments were as follows:

1) A treatment where no tillage was performed, and the plots were divided into two sections in which one section was raked and burned (Figure 4.3), and in the other section the straw was not raked and not burned (control). This treatment was imposed on April 25, 2016.

2) A tillage treatment termed "vertical tillage" where a John Deere 2623VT vertical tillage unit measuring 10.21 m wide (Figure 4.4) hitched to a John Deere 9560R 4WD tractor

operated at a speed of 10.0 km hr^{-1} and to a depth of 5.0 cm was used to vertically lift the upper 5.0 cm of the soil surface with disks followed by baskets with hydraulic down pressure to mix the flax crop stubble into the upper ~ 5 cm of soil (Figure 4.4).

3) A tandem disc treatment where a John Deere Frontier TM5132 tandem disk measuring 9.91 m wide (Figure 4.5) hitched to a John Deere 9510RT track tractor operated at a speed of 10.0 km hr-1 and operated to a depth of 10.0 cm to cut and horizontally throw the soil and mix the flax crop stubble into the soil (Figure 4.5). Both the vertical and tandem disc treatments were imposed on plots on October 8, 2015. Visibly, the vertical tillage treatment left the soil surface smoother (Figure 4.4) with fewer large lumps compared to the tandem disc treatment (Figure 4.5).

Figure 4.3. Raking and burning flax crop stubble windrow at FRM prior seeding wheat crop in April 2016.

Figure 4.4. John Deere 2623VT vertical tillage implement, October 2015.

Figure 4.5. John Deere Frontier TM5132 tandem disk, October 2015.

4.4.4 Site Management: Seeding, Crop Protection, Harvest

4.4.4.1 2016 Growing Season

On May 18, 2016, the FRM site was seeded to hard red spring wheat (*Triticum aestivum* var Brandon) at a rate of 90 kg ha^{-1} with 190 kg ha^{-1} of 37-14-0 fertilizer side banded using a John Deere 1830 hoe drill with paired row openers on 25.4 cm (10 inch) row spacing (Figure 4.6), 60 kg N ha^{-1} and 20 kg P_2O_5 ha^{-1} as urea and mono-ammonium phosphate blend was placed in the band between the paired rows of seed. Physical measurements of air permeability and water infiltration were made on June 8th, 2016 at each preselected point in the plots. The wheat was sprayed with fluroxypyr, 2,4-D and clodinafop on June 12th, 2016. Crop harvest was performed on August 16th, 2016, and the harvest samples were taken by harvesting above-ground biomass (grain + straw) with a square metre taken at each sampling point. Harvest samples were returned to the University of Saskatchewan, air-dried, threshed, and grain samples were cleaned and weighed to determine grain yield.

Figure 4.6. John Deere 1830 Air Hoe Drill with paired row double shoot openers used to seed and fertilize the plots at the FRM trial site.

4.4.4.2 2017 Growing Season

The second cropping season at the FRM site began on May 3rd, 2017 when the plots were sprayed with RT 540 glyphosate at 0.8 litres per acre and sulfentrazone at 88 mL per acre. On May 4th, 2017 the plots were seeded to green pea (*Pisium sativum* var Sage) at 170 kg ha^{-1}. The pea seeds were treated with Vitaflo™ fungicide and received seed applied peat-based *Rhizobium* inoculant (Cell Tech™). No fertilizer was applied.

Water infiltration (hydraulic conductivity) and air permeability measurements were done in the field on May 15th - 19th, 2017. In the first week of August 2017, total biomass and grain yield from the pea crop at the FRM site was determined by harvesting metre samples at the transect points in the replicate treatment plots of the study. As in 2016 for the wheat, 2017 pea harvest samples were returned to the University of Saskatchewan, air-dried, threshed, and grain samples were cleaned and weighed to determine grain yield.

4.4.5 Climatic Conditions

The first growing season of the study (2016) at the FRM site was wetter than normal. The monthly precipitation and air temperature during 2016 are shown in (Figure 4.7). The precipitation received from May to August was 39 % above the 18-year average (1981-2010) for the nearest Environment Canada meteorological station (Elbow, ~ 40 km from study site) (Figure 4.9). However, the 2017 growing season was considered a dry year because there was not much precipitation during 2017 until the end of the season in October (Figure 4.8). In 2017, the precipitation from May to August was 49 % lower than the 18-year average.

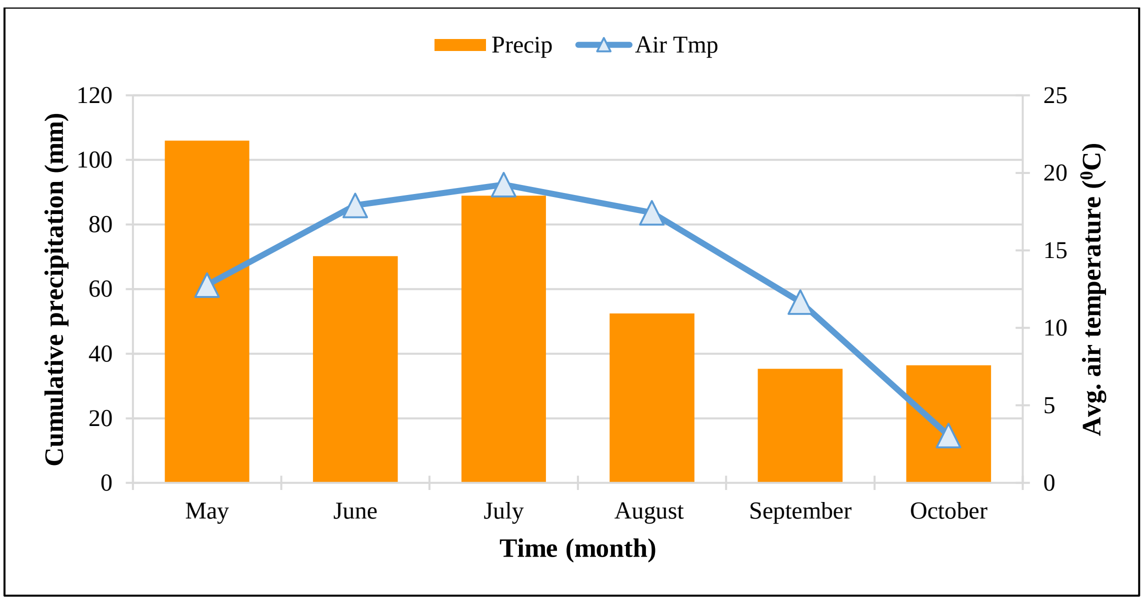

Figure 4.7. May to October monthly precipitation (mm) and average air temperature (°C) for 2016 at FRM site. Data from Schoenau farm meteorological station.

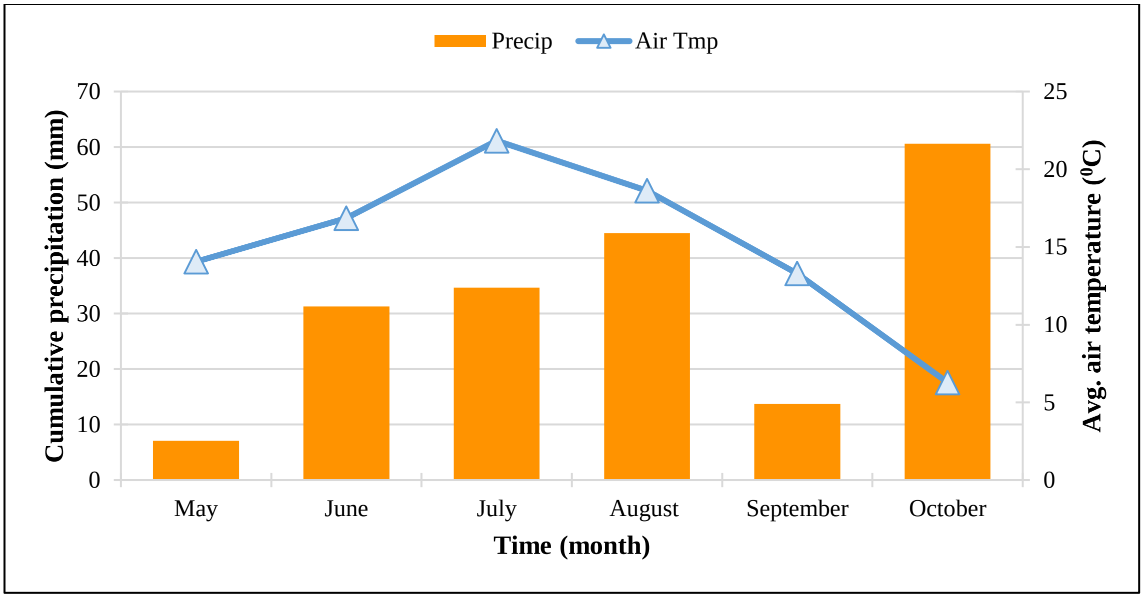

Figure 4.8. May to October monthly precipitation (mm) and average air temperature (ºC) for 2017 at FRM site. Data from Schoenau farm meteorological station.

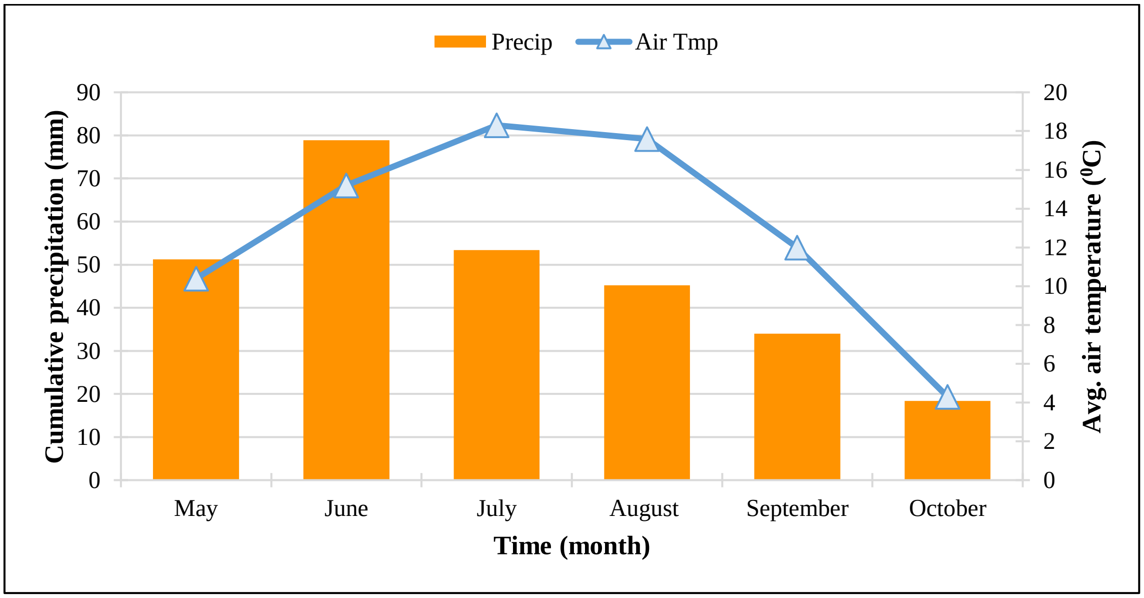

Figure 4.9. Growing season monthly precipitation and average air temperature historical averages (1981-2010) at the Elbow, SK Environment Canada weather station.

4.4.6 Soil and Plant Sampling and Analysis

Measurements of aggregate size and stability were made at sampling points in the plots at the FRM site in 2016 and 2017. For these assessments, samples of soil were taken two days after seeding from each plot with a flat square shovel to a depth of 10 cm (Figure 4.10). Every sample was wrapped, taped, and transported in plastic containers to maintain their undisturbed state

(Figure 4.10). After returning to the lab, the samples were laid out on trays and allowed to air dry for three days. Each sample was gently separated by hand into smaller fractions and then air dried for another seven days. Samples were separated into size fractions using a series of sieves in a motorized sieving machine (Figure 4.11).

Figure 4.10. Undisturbed samples removed from the field two days after seeding for measurement of aggregate size and stability.

4.4.6.1 Aggregate Size

The method of Nimmo and Perkins (2002) was used to determine aggregate size distribution. The dried samples were gently placed in the feed bin in the motorized sieving machine (Figure 4.11). The sieve separated the soil into seven average aggregate sizes (0.25, 0.90, 1.94, 4.89, 12.33, 25.05, and 44.06 mm) (Figure 4.12). The different size fractions of soil were collected by passing through different series of sieves and then weighed to calculate the aggregate size distribution. The method to express the size distribution of aggregates is the Mean Weight Diameter (MWD) as provided below:

$$MWD = \sum_{i=1}^{n} x_i w_i$$

(Eq. 4.1)

Where the "x_i is the mean diameter of any particular size range of aggregates separated in the process of sieving, and the w_i is the weight of the aggregates in that size range as a fraction of the total dry weight of the sample analyzed" (Hillel, 1982b).

Figure 4.11. Motorized sieve machine used to determine aggregate size.

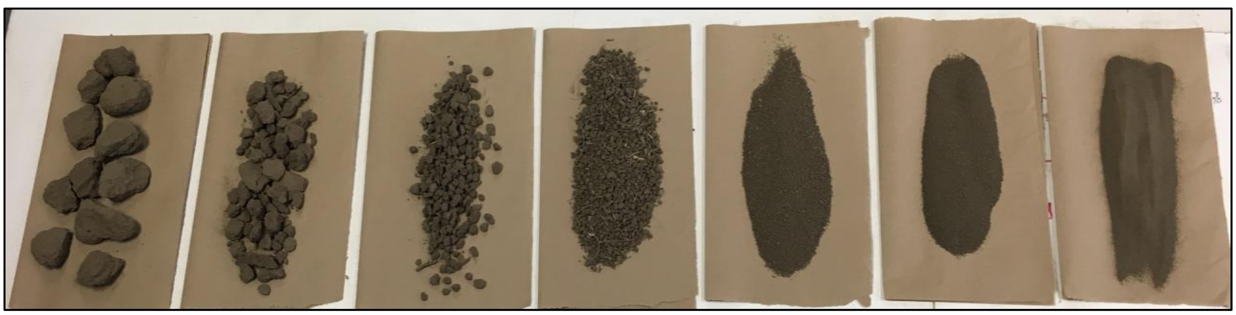

Figure 4.12. Soil aggregates after sieving process.

4.4.6.2 Aggregate Stability

The soil is vulnerable to external destructive forces such as the wind, repeated machinery traffic, and rainfall that can affect its physical properties. Aggregates near to the surface tend to get crushed, disrupted and/or destroyed by these forces. The loss of large pores in the soil and aggregates causes a reduction in the hydraulic conductivity and also contributes to the formation of crusts at the surface of the soil (Marshall and Holmes, 1979). The aggregate stability is a measure that indicates the resistance of aggregates to break down when they are exposed to potentially disruptive processes (Hillel, 1982b). The soil samples collected after seeding were used to determine aggregate stability. Soil solutions were measured using a spectrophotometer "UV mini 1240" following the turbidimetric method of Williams et al., (1966).

The smallest fraction (0.250 mm) from the dry sieving method was used to determine aggregate stability. A weight of 0.25 g of aggregate fraction soil was placed on a Whatman® #42 filter paper. A block was covered with cheesecloth and partially submerged in a container with distilled water. The filter paper and soil were placed on this block and allowed to wet by capillary action over one hour. After the one-hour period, the wet soil samples were placed into tubes by rinsing the filter paper until the final volume of 45 mL was reached. The tubes were sealed with rubber stoppers and placed together in the end-over-end shaker for two minutes. After shaking, the samples were allowed to stand for an additional two minutes to settle. Approximately 3 mL of the suspension was pipetted into cuvettes and placed on the instrument. Care was taken in the transfer of the solution from the plastic tubes so that aggregates at the bottom were not disturbed. The spectrophotometer "UV mini 1240" was used to take the transmission reading at 625 nm wavelength. The tubes were returned to the end–over–end shaker for 20 more minutes. After shaking, the samples were allowed to stand for two minutes and the same methodology was followed for the transmission reading.

4.4.6.3 Air and Water Permeability

The air permeability of the soil is an assessment of the convective transmission of air through soil under an applied total pressure gradient (Grant and Groenevelt, 2008). The air permeability offers information about the size and the continuity of air-filled pores (Hillel, 1980). The instrument to measure air permeability in the field is the air permeameter (Figure 4.14) and the technique followed was that described by Huang et al., 2016. The method consists of inserting a 15 cm diameter steel tube to a depth of 10 cm into the soil (Ball and Schjønning, 2002). The tube was sealed, and different air flow rates were applied using the flow controller (FMA6500 by OMEGA Engineering Inc.). Four different air flow rates were applied (0.5, 0.7, 0.9, and 1.2 L min^{-1}) and the pressures were recorded at each flow rate. The linearity between the air flow and the pressure was checked before recording.

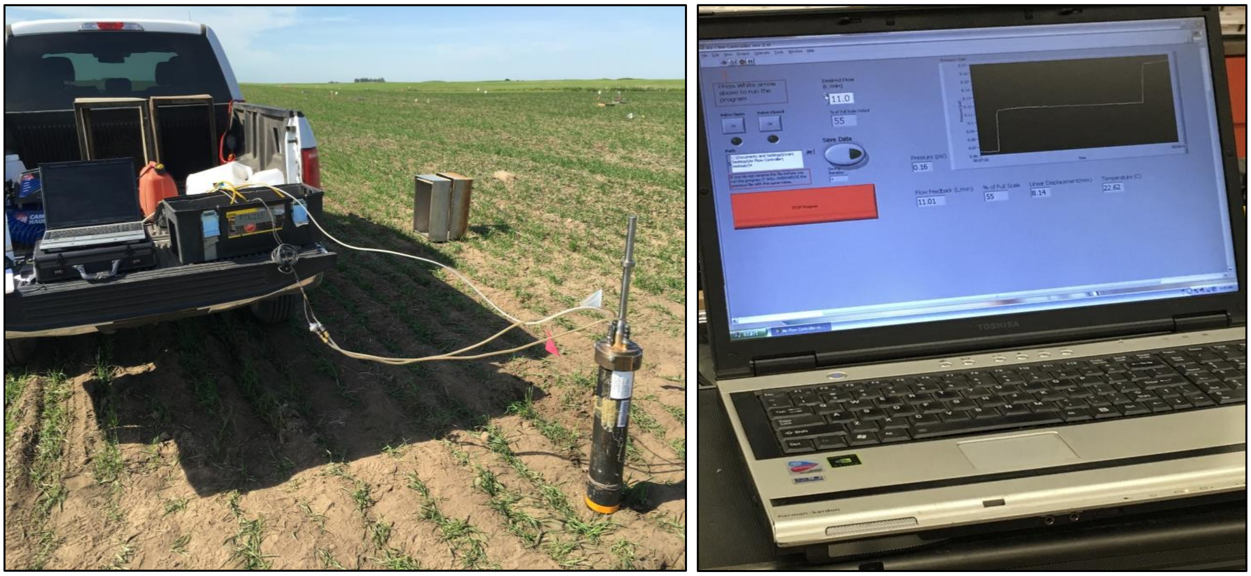

Figure 4.13. Air permeameter measurement used to assess the convective transmission of air through soil under an applied total pressure gradient.

To determine hydraulic conductivity (K_{fs}), the method utilized was the simplified falling-head (SFH) technique designed by Bagarello et al., (2004). The method involved applying 10 L of water onto the soil surface using a single ring (stainless steel square) which was inserted into the soil to a depth of 12 cm. Measurement was made of the time from the application of the water to disappearance of the water. The water was added using a perforated plastic bag to add the water quickly but with limited disturbance of the soil surface. A single large square ring of dimensions 580 mm by 420 mm (Figure 4.14) was used to cover a substantial surface area. PVC cores were used to take a soil sample to a depth of 5 cm outside of the square ring and inside of the ring after the infiltration (Figure 4.14). The equation to determine the K_{fs} is based on the formula of the simplified falling head technique as listed below:

$$K_{fs} = \frac{(\Delta\theta)}{(1-\Delta\theta)t_a}\left[\frac{D}{(\Delta\theta)} - \frac{(D+\frac{1}{\alpha^*})}{(1-\Delta\theta)}\ln\left(1+\frac{(1-\Delta\theta)\mathrm{D}}{(\Delta\theta)\left(D+\frac{1}{\alpha^*}\right)}\right)\right]$$

(Eq. 4.2)

To determine the K_{fs}, it is necessary to know variables such as (I) initial volumetric water content (ϑ_1) and the water content after the infiltration (ϑ_2), (II) the time that it takes the infiltration (t_a), (III) the depth to which the water was ponded at t=0 (D), (IV) the hydraulic parameter (α) (Bagarello et al., 2004; Ewen, 2015).

Figure 4.14. Square ring and PVC cores installed to determine hydraulic conductivity at FRM site.

In 2017, hydraulic conductivity was determined using the field-saturated hydraulic conductivity method described by Zeleke et al., (2004). The method consisted of inserting the ring into the soil to 12 cm (the same square rings used in the first year of the study were used in 2017). Then, the rings were filled with water to the top (approximately 11 cm) using a perforated plastic bag trying to reduce the disturbance of the soil surface, and the initial water depth and time were measured. Then, the time was recorded at every 1.5 cm drop in water level. If the water failed to infiltrate 1.5 cm in 60 minutes, the time was recorded and the water level at that point and every 20 minutes thereafter the water volume was measured and time up to three hours.

4.4.6.4 Crop Grain and Straw Yields

Square metre above-ground crop samples removed from the plots at harvest in 2016 and 2017 were dried at 35^{o}C and weighed to determine total biomass yield. The samples were then threshed, cleaned, and weighed to determine grain yield.

4.4.7 Statistical Analysis

To analyze the effect of treatments conducted during the 2016 and 2017 year the Statistical Analysis Software (SAS) program package was used. Crop yields were analyzed using SAS-PROC GLIMMIX since all transect points in all treatment replicate plots were measured for yield, while physical measurements such as permeability, aggregate size and stability were performed using SAS-PROC T-TEST as only selected transect points in treatment replicate plots were used for the physical measurements.

4.5 Results and Discussion

4.5.1 Aggregate Size and Stability

Table 4.1. Aggregate size and stability in surface (0-10 cm) soil samples collected after seeding in the 2016 and 2017 growing seasons at the FRM site.

Treatment		Measurements			
		0-10 cm		0-10 cm	
		Aggregate Size MWD		Aggregate Stability	
		2016	2017	2016	2017
		------------mm------------		-------------%-------------	
Till	Tandem Disc	12.67	12.58	90*	90*
	Vertical	11.61	13.29	93*	92*
No-Till	Burn	12.43	13.26	94	90
	No Burn	12.58	12.30	95	91
P value	Till vs No Till	0.6672	0.9007	0.0006*	0.7805

* Significantly effects at P ≤ 0.05.

The measurements of surface soil aggregate size and stability in the residue management treatments were completed during the 2016 and 2017 seasons and are shown in Table 4.1.

Aggregate size was not significantly affected by tandem disc and vertical tillage in the first or second year after the study. There was also no effect of burning. Similar results were found by Cook et al., (1992) who reported that aggregate size was not significantly affected in vertisol soils in Australia after different tillage managements were imposed. Also, they stated that the influence of soil organic carbon in the soil is important because it reduces clay dispersion and therefore maintains soil structure. Chernozemic soils developed under grassland such as those used in the current study are generally considered to be high in organic matter, consistent with a lack of effect of tillage on aggregate size. Burning and no burning treatments also did not significantly affect aggregate size after the first and second year of the study. Are et al., (2009) reported in their study conducted in southwestern Nigeria that burning versus not burning straw materials in the field also did not have significant effects on aggregate size.

In contrast to aggregate size, aggregate stability was significantly ($P < 0.05$) affected by tillage, with lower aggregate stability in tandem disc than in vertical tillage, and overall lower aggregate stability with tillage compared to without tillage. Increasing degree of soil disturbance therefore appears to be associated with decreased aggregate stability in this soil. This could be explained by the greater incorporation reducing the amount of crop residue at the surface contributing to formation of organo-mineral complexes. Chaney and Swift, (1984) reported in their study testing the influence of organic matter on aggregate stability, that soil organic matter was directly related to aggregate stability in agricultural soils in Scotland. In this thesis research at the FRM study site in Saskatchewan, burning treatments did not have any effect on aggregate stability in the first and second year of the study. This is not surprising considering that the burn does not involve any physical disturbance and the amount of organic matter lost in burning of the residue is small in comparison to the total amount of organic matter contained in stable humus in the soil (Jobbágy and Jackson, 2000).

4.5.2 Air and Water Permeability

Table 4.2. Air and water permeability (hydraulic conductivity) measured at the FRM site in spring of 2016 and 2017.

Treatment		Measurements			
		0-10 cm		0-10 cm	
		Air Permeability		Hydraulic Conductivity	
		2016	2017	2016	2017
		cm min^{-1}			
Till	Tandem Disc	1.17×10^{-2}	1.34×10^{-3}	1.09×10^{-1}	6.03×10^{-2}
	Vertical	3.65×10^{-3}	7.86×10^{-4}	6.02×10^{-2}	8.60×10^{-2}
No-Till	Burn	1.57×10^{-2}	2.09×10^{-2}	5.37×10^{-2}	6.88×10^{-2}
	No Burn	2.39×10^{-2}	7.26×10^{-4}	6.91×10^{-2}	7.52×10^{-2}
P value	Till vs No Till	0.0249*	0.5817	0.3853	0.9304

*Significantly different at $P \leq 0.05$.

As shown in Table 4.2, the vertical tillage treatment had the lowest air permeability in the first-year (2016) after tillage treatments had been applied (Table 4.2). This is attributed to the downward pressure of the rolling baskets and intense mixing of the 2015 flax crop stubble and the soil mineral and resident (pre-2015 crop surface and sub-surface) organic materials, which increases the proportion of fine soil pores, reducing the infiltration and flow of air. In 2017, air permeability differences between the tandem disc, vertical tillage and the no-till treatments had diminished to the point where there were no significant effects between treatments and all treatments had similar air permeability. Stubble burning is a convenient practice employed in cropping systems to reduce high amounts of stubble loads and it is reported to have effects on soil hydraulic properties (Valzano et al., 1997). For example, the ash particles that are left on the soil after the burning process can plug macropores (Mallik et al., 2016). However, there were no significant crop stubble burning effects or tillage treatment effects on water infiltration (hydraulic conductivity) in 2016 or 2017.

4.5.3 Crop Grain and Straw Yields

4.5.3.1 FRM site wheat yields – 2016

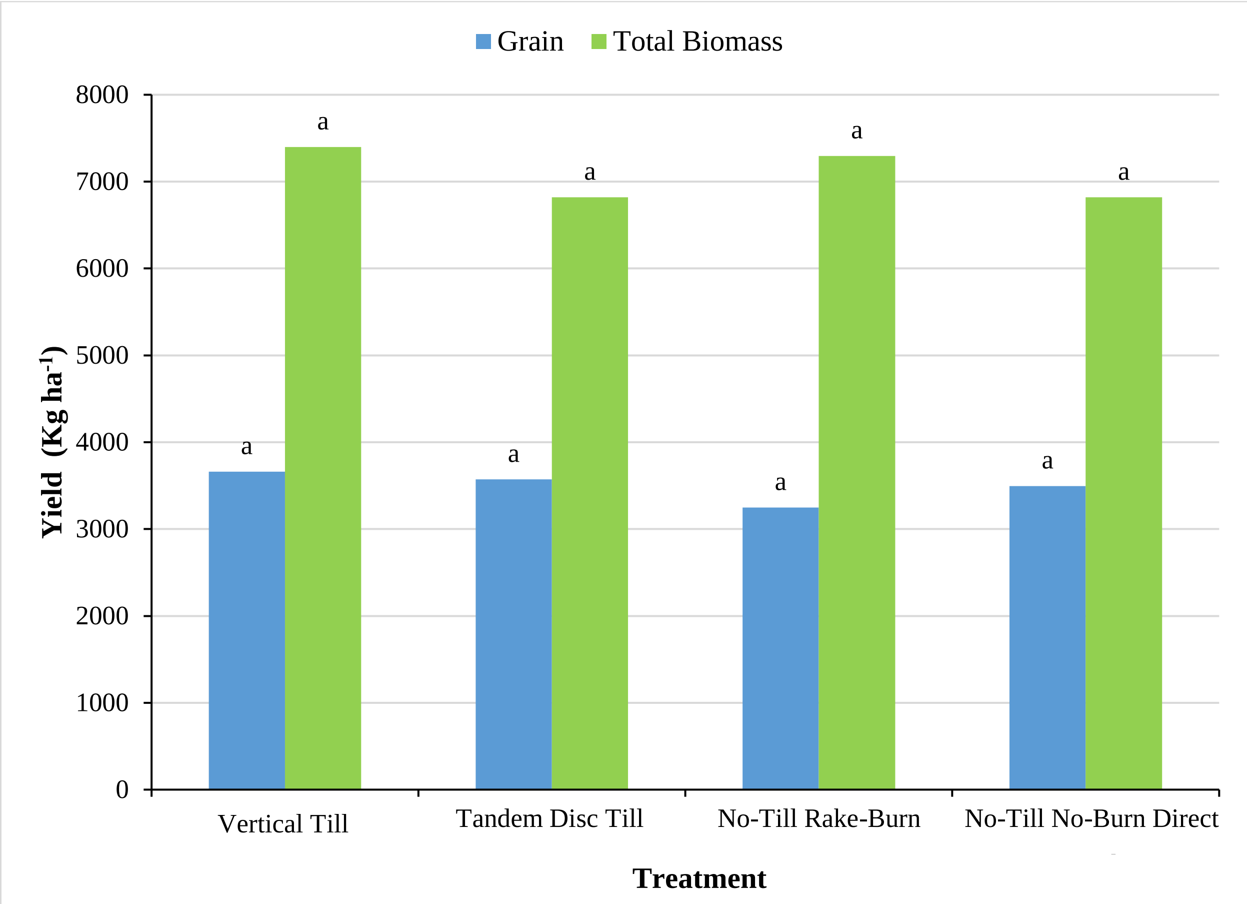

Figure 4.15. Wheat yield at FRM site treatments in 2016.

Wheat was the crop grown in the flax residue management study in 2016 as the first crop after the residue management treatments were imposed. There was no significant effect of treatment on grain or total biomass yield (Figure 4.15), and all treatments had similar mean yields of spring wheat of ~ 3500 kg grain ha^{-1} in 2016. These results indicate that tillage or burning post-harvest flax residue for one year has relatively little influence on yield of the crop the following year. Lack of difference in yield between no-till, no burn direct seeding into flax residue and the various post-harvest residue management practices (vertical and tandem disc tillage, raking and burning) demonstrates that with good residue management achieved during the harvesting process (chopping and spreading by combine), direct seeding into flax stubble can give equivalent yields and better returns compared to some type of post-harvest residue management like tillage that has associated costs. Direct seeding is more economical as there is no equipment and operational costs of tillage, or time spent or air quality concerns that are associated with residue burning.

4.5.3.2 FRM site pea yields – 2017

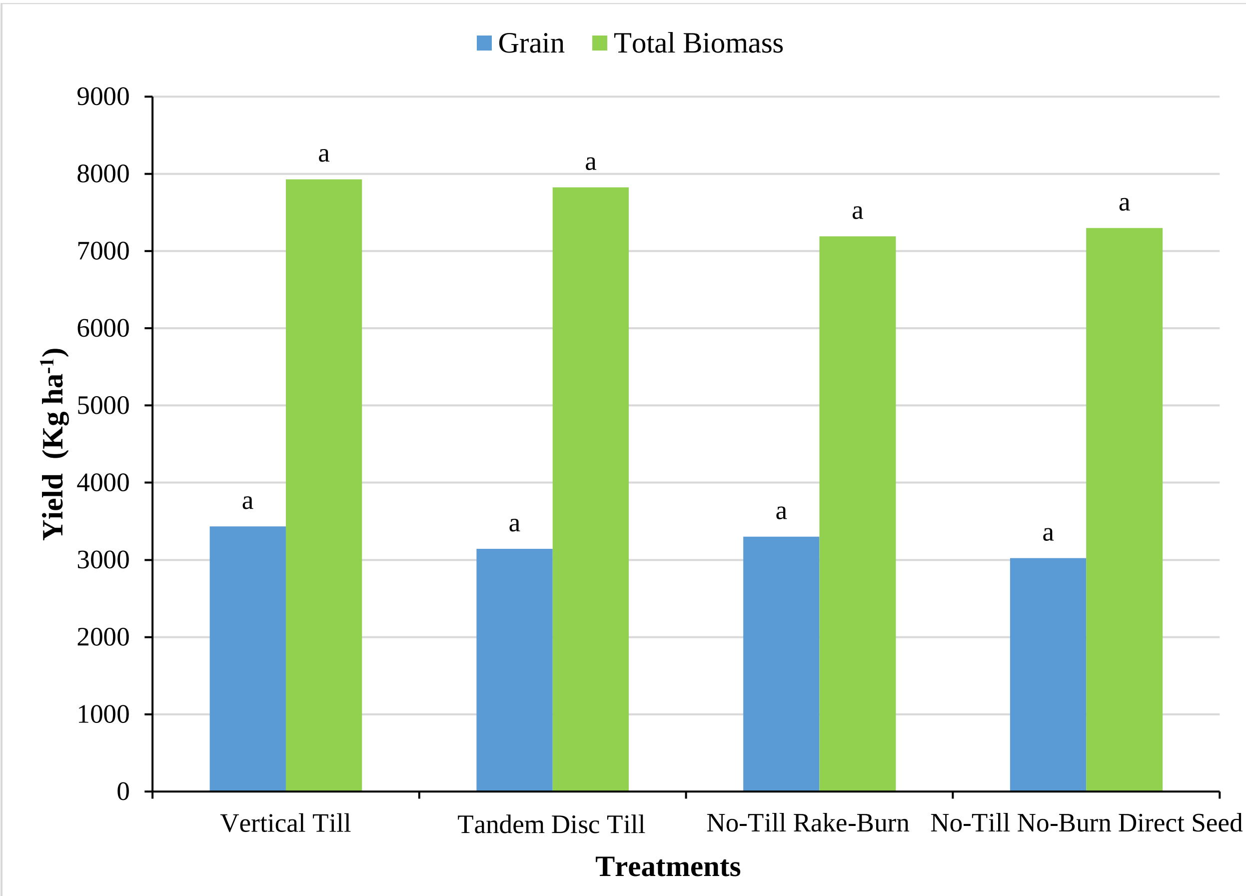

Figure 4.16. Pea yield at the FRM site in 2017.

Yields of pea grown in 2017 (Figure 4.16) were only slightly lower than the wheat yields of 2016 at the FRM site. Although 2017 was considerably drier than 2016, this was compensated for by reduced disease pressure on the peas. In the second year after the FRM treatments were imposed, the pea yields were also similar and there were no differences ($P > 0.05$) in 2017 pea total biomass and grain yields (Figure 4.16) among the treatments. Chakraborty et al., (2008) stated that in India, retaining mulch is one of the most important agronomic practices in conserving soil moisture and influencing physical properties and therefore was responsible for improved crop yield in their study. However, similar total biomass and grain yields were observed across the burn and no burn treatments (Figure 4.16) in the current study. This may be explained by good moisture conditions in the first year of the study (2016) which also provided good residue coverage of wheat straw that helped conserve moisture during the drier 2017 season at the FRM site.

Vertical tillage is widely accepted as a suitable tillage practice for stubble fields with heavy residue and areas of fields overgrown with weeds in order to chop and incorporate residue organic matter into the soil. This makes the soil surface smoother for seeding, reducing plugging problems, and promoting spring warming of the soil for quicker seed germination by reducing residue cover and blackening the soil (Hillel, 1982B; Singh, 2017). Also, tillage provides mechanical control of weeds by uprooting and dessication and there is less consumption of herbicides too (Villalobos et al., 2016). However, tillage will dry the soil surface which may be undesirable under dry conditions when the tillage is conducted just prior to seeding in the spring and there is no rain. As well, loss of surface residue protective cover can expose the soil to erosive forces of wind and water. However, the vertical tillage treatment in this project was conducted in the fall, with surface soil moisture replenished by snowmelt and spring rains prior to seeding. Also, there was no post-treatment wind or water erosion events. This is consistent with the observed lack of tillage treatment effect on crop yield in the first and second year of this study.

4.6 General conclusion

Vertical tillage decreased air permeability in the first year of study, and in both the first and second year after the treatments were imposed, vertical tillage improved aggregate stability. However, there was no effect of the tillage, raking and burning of flax stubble treatments on yield of wheat and pea in the following two years compared to the control no-till, no-burn direct seeding into flax stubble. This is consistent with overall limited treatment impacts on the soil properties measured. The tillage, raking and burning residue managements would produce a negative economic return based on the results from this study, as there is a cost associated with the practices, but no additional yield returns obtained.

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5 SYNTHESIS AND CONCLUSIONS

Potentially effective applications of tillage include 1) subsoiling to reduce density and strength issues such as created by wheel traffic compaction; and 2) surface tillage such as may be used to deal with recalcitrant crop residues like flax stubble. The effects of these practices on soil properties and subsequent crop yield in prairie soils deserve investigation.

In this study, there were two main objectives:

1. To evaluate the effect of subsoiling on soil physical properties and crop yields over two years in wheel traffic compacted and non-compacted Chernozemic and Solonetzic soils.

2. To determine the influence of surface tillage (tandem disc, vertical tillage), and raking and burning of flax stubble on soil physical properties and crop yield over two years in a Chernozemic soil.

Subsoiling for Dense Soils

To address the first study objective, subsoiling tillage was performed on 1) an annually cropped field with normal structure (Chernozemic soil) and with induced compaction by wheel traffic in specific locations and 2) an annually cropped field with naturally hard and dense Solonetzic B subsoil (Solonetzic soil). Treatments of subsoiling to ~ 30 cm depth with a minimum till subsoiler were applied in the fall of 2015 to wheel traffic compacted and non-compacted zones. In the following 2016 and 2017 growing seasons, soil parameters measured included bulk density, soil penetration resistance, aggregation, water infiltration, and air permeability. Crop yield was measured in 2016 and 2017. The following are important findings and recommendations from the subsoiling research work.

Chernozemic Soil Subsoiling Study

- Wheel traffic increased density of the Chernozemic soil and subsoiling reduced density in both compacted and non-compacted treatments. Soil density was significantly reduced in the first year of the study (2016) in the 0-30 cm depth, but the effect was diminished in the second year (2017). On this study, long-term wheel traffic compaction was not evaluated.

- Wheel traffic compaction increased soil strength of the Chernozemic soil and subsoiling significantly reduced soil strength in the top ~20 cm of soil. Concomitant with the effect of subsoiling on density, effects on reducing soil strength were greatest in the first year with no effects evident in the second year. The loosening and shattering effect of the subsoiling implement appears to diminish over time.

- Subsoiling slightly reduced the mean aggregate size, evident especially in the first year of the study.

- Air permeability in the first year was increased by subsoiling, consistent with the observed greater porosity, but this disappeared by the second year after subsoiling. However, water infiltration was not significantly affected by compaction or subsoiling treatments in this soil in either 2016 or 2017.

- The wheel traffic compaction and subsoiling treatments did not have any effect on wheat grain yield at the Chernozemic study site in 2016, nor were there any noteworthy trends. Similarity in yields among treatments is consistent with the density and soil strength values that were below critical thresholds, even in the wheel traffic compacted treatments. Similar pea yield across treatments in 2017 were in line with lack of any significant treatments effects on the soil properties measured.

Solonetzic Soil Subsoiling Study

- Compaction from wheel traffic over many years significantly increased the density of the Solonetzic soil. Subsoiling of the Solonetzic soil was effective in reducing surface soil density in the 0-15 cm and 15-30 cm depths, with the degree of decrease greatest in non-compacted soil. The lifting and shattering action of the subsoiler implement shank and plow type shares reduces soil bulk density and, as observed in the Chernozemic soil, the effect was diminished in the second year. Overall, the subsoiling implement was not as effective in reducing density in the Solonetzic soil as compared to the Chernozemic soil.

- Compaction of the Solonetzic soil by wheel traffic increased soil strength above critical levels (>2000 kPa) and subsoiling of the compacted soil was effective in reducing soil strength. In this soil, there was a trend for subsoiling treatments to have reduced soil strength in the second year after subsoiling as well.

- Compaction by wheel traffic in the Solonetzic soil resulted in slightly larger aggregates but there was no significant effect of subsoiling on aggregate size in the years following the treatments at this site.

- Effects of subsoiling on water and air permeability in the Solonetzic soil in both 2016 and 2017 were small, variable and non-significant, consistent with the lesser effect that subsoiling had on density in this soil compared to the Chernozem. However, there was some indication that subsoiling may be increasing air permeability in compacted soil in the first year of study.

- Subsoiling of the Solonetzic soil affected by long-term wheel traffic compaction significantly increased improved canola grain yields in 2016. However, there was no effect on the yield of wheat grown in the second year in 2017. This is consistent with the significant reduction in penetration resistance values of the soil in compacted treatments that were subsoiled compared to those that were not, and thus would be anticipated to respond to treatment. These findings indicate that a precision subsoiling strategy in which highly compacted areas of fields are identified, and only these areas have the subsoiling treatment applied, would be of considerable benefit and efficiency.

In summary, subsoiling with a minimum till subsoiler to a 30 cm depth in the fall was generally effective in reducing soil density and strength to that depth in the first year in non-compacted and compacted Chernozemic and Solonetzic soils. The degree of reduction in density achieved by the implement was greater in the Chernozem than in the Solonetzic soil. Lesser effects of subsoiling were observed on aggregation and permeability in both soils, but it appears that air permeability at the surface is affected more by subsoiling than hydraulic conductivity. For it to be worthwhile for growers to utilize subsoiling to address compaction, there must be a positive yield benefit. The only subsoiling treatment that produced a significant positive yield benefit was subsoiling on the long-term wheel traffic compacted Solonetzic soil and this was only observed in the first year. These findings are consistent with this compacted soil having significant root penetration/exploration issues as evidenced by its very high soil strength values. Also, important to note is the evidence for natural reclamation through freeze-thaw and wet-dry cycles from short-term (1-year) wheel traffic compaction that was observed in the Chernozem soil. Hydraulic conductivity was overall greater in the Chernozem than the Solonetzic soil as expected. The Chernozemic, with more organic matter and better structure than the Solonetzic, to begin with, appears more resilient to compaction and tillage treatment.

Based on the responses to subsoiling tillage identified in this study, it is recommended that efforts be undertaken by growers to first identify the specific soil types and compaction conditions most likely to produce positive yield response by using maps of soil type (e.g., Solonetzic vs. Chernozemic), records of traffic history, and use of soil penetration resistance measurements to compare areas within the field. This may be followed by application of subsoiling only to these fields (e.g., Solonetz) or areas of fields (e.g., field travel roads, seeder, combine load and unloading points at field entrances) identified as potentially responsive. This precision approach is recommended as an effective and economical approach to using subsoil tillage to significantly improve yield and provide economic benefit, rather than subsoiling entire farms or fields where benefits may be dubious.

Surface Tillage for Residue Management

To achieve the second objective of this thesis research three management practices (tandem disc, vertical tillage, raking and burning) were evaluated for their influence on soil properties and crop production in a Chernozemic soil. Surface tillage treatments were applied in the fall of 2015 and measurements of physical properties including aggregate size and stability, air and water permeability, and crop grain and straw yields were made during the 2016 (wheat) and 2017 (pea) growing season. The following are important findings and recommendations from the surface tillage residue management strategies research work.

- Vertical tillage and tandem disc tillage treatments did not significantly affect aggregate size (MWD) in the surface (0-10 cm) soil in the first and second years following the treatment. Raking and burning also did not influence the aggregate size.

- Aggregate stability was affected by tillage system, with slightly lower aggregate stability in tandem disc treatments compared to vertical tillage treatment in both 2016 and 2017. This is attributed to a greater depth of incorporation of residue in the tandem disc treatment, that would reduce organic matter available at the surface for binding particles together. There was a trend for raking and burning to decrease aggregate stability, but it was not significant.

- Vertical tillage tended to decrease air permeability and water infiltration rate compared to other treatments in the first year, which may be explained by an increase in the number of fine pores created by the pressure imposed by the rolling baskets attached to the vertical tillage implement. There were no crop stubble burning effects on water infiltration or air permeability in 2016 or 2017.

- Crop yields (2016 wheat, 2017 peas) were not significantly affected by any of the residue management strategies, including tillage and raking and burning, and were similar among all treatments. Direct seeding into the flax residue was successful because the flax crop was harvested when conditions were dry, and the residue was evenly distributed by the straw chopper on the combine. Tillage or raking and burning to reduce flax straw residue interference therefore was not needed to maximize yield under the conditions of this study. There were also no problems with equipment plugging identified in the field that would be considered an inconvenience or delay operations.

To summarize, in the first year after treatments were imposed, vertical tillage of the flax stubble appeared to reduce air permeability while tandem disking increased permeability. Tillage treatments in general also resulted in reduced aggregate stability compared to no-till in 2016. However, these effects had largely disappeared by the second year (2017). A reduction in aggregate stability from tillage may be of concern related to increased erodibility following the tillage operations. The raking and burning treatment in spring of 2016 had relatively little influence on soil physical properties but may be of concern if conducted repeatedly over several years due to organic matter loss as carbon dioxide in burning. There were no differences in water infiltration (hydraulic conductivity) observed among stubble tillage and burning treatments in either year.

From these results it would be recommended to deal with potential crop residue management issues at the outset at harvest, by harvesting on warm, dry days conducive to good straw chopping and spreading, and using an effective chopping mechanism on the combine. Under these conditions, no further apparent benefit from tillage with tandem disc or vertical tillage unit or raking and burning was observed. The surface tillage effects of these machines were to further chop and incorporate residue, with some reduction in aggregate stability and some small effects on air permeability. Surface tillage and burning may be warranted and useful in parts of fields with heavy dense weeds and cattails such as sloughs, but incorporation of surface crop residue and loss of protective cover in uplands along with reduced aggregate stability can pose erosion concerns. Also, organic matter in the soil is one of the key factors to control aggregate stability, and the organic material supply cementing and binding agents and promote microbial processes responsible for the enmeshment of soil particles into stable aggregates.

Recommendations for Future Research

The research in this study required consideration of best approaches to measurement of different soil physical properties to achieve the intended objectives, and compromise is often involved. To assess water permeability (hydraulic conductivity), a single large square of dimensions 580 mm by 420 mm was used because of its ability to cover a large surface area and encompass tillage channels and the area in between. A double ring infiltrometer is the most widely used approach for assessing water infiltration, but this was not used due to the available equipment having an inner ring diameter of only 200 mm and the outer ring a diameter of 300 mm. Measurement of hydraulic properties in future studies using a larger double ring infiltrometer and comparison to the large metal square technique would be valuable.

In the subsoiling study, the electronic RIMIK™ CP40II cone penetrometer was successfully used, and it was valuable in revealing significant differences among the treatments. However, the dependency of cone resistance on soil moisture content was duly noted and an instrument that could measure resistance and relative soil water content simultaneously would be desirable.

Subsoiling improved soil physical parameters and crop yield especially in long-term wheel traffic compacted areas in the Solonetzic site under the conditions of this study. However, in the second year of the study there were no significant differences in crop yield, and the effect of subsoiling appears to diminish over time in terms of its effects on soil physical properties and yield benefits. A longer time period of evaluation on a wider variety of soils and moisture contents during the subsoiling would be beneficial. In both the subsoiling and surface tillage studies, it was noted that the relationship between soil physical parameters and influence on yield can be complex. For example, high soil strength may be said to generally impede root growth, but the magnitude of the effect will depend on the crop grown and its rooting characteristics, along with the chemical, physical and biological condition of the soil as this affects root health and vigor. Unfortunately, no measurements of root characteristics were made in the current study. A better understanding of relationships between alteration of soil conditions through tillage or other disturbance and root growth, morphology would be valuable in more reliably predicting the effects of tillage management on crop yield.

6 APPENDIX

Table A1. Volumetric water content at subsoiling South Central Butte Spring 2016-2017.

Treatment		Volumetric Water Content					
		0-15 cm		15-30 cm		30-60 cm	
		2016	2017	2016	2017	2016	2017
		cm^3 cm^{-3}					
Subsoiled	Compacted	0.28b	0.18bc	0.32a	0.18b	0.33ab	0.17c
	Non-Compacted	0.28b	0.18c	0.31ab	0.18b	0.31b	0.18bc
Non-Subsoiled	Compacted	0.34a	0.20a	0.33a	0.21a	0.34a	0.22a
	Non-Compacted	0.33a	0.20ab	0.30b	0.20ab	0.31b	0.20ab
P value		<0.0001*	0.1318	0.0366*	0.1252	0.0234*	0.0719*

† Means followed by the same letter are not significantly different at P ≤ 0.05.
*Significantly different at P ≤ 0.05.

Table A2. Volumetric water content at subsoiling South Central Butte Fall 2016-2017.

Treatment		Volumetric Water Content			
		0-30 cm		30-60 cm	
		2016	2017	2016	2017
		cm^3 cm^{-3}			
Subsoiled	Compacted	0.25	0.26	0.27	0.19
	Non-Compacted	0.22	0.23	0.26	0.18
Non-Subsoiled	Compacted	0.29	0.25	0.26	0.20
	Non-Compacted	0.27	0.20	0.27	0.22
P value	Subsoiled vs Non-Subsoiled	0.0047*	0.7946	0.7520	0.2395
	Compaction	0.1101	0.3524	0.8577	0.3679

† Means followed by the same letter are not significantly different at P ≤ 0.05.
*Significantly different at P ≤ 0.05.

Table A3. Volumetric water content NCB Spring 2016-2017.

Treatment		Volumetric Water Content					
		0-15 cm		15-30 cm		30-60 cm	
		2016	2017	2016	2017	2016	2017
		$cm^3\ cm^{-3}$					
Pre-Compacted	Subsoiled	0.26	0.18	0.37*	0.22	0.34	0.18
	Non-Subsoiled	0.28	0.18	0.41*	0.20	0.38	0.19
Post-Compacted	Subsoiled	0.26	0.17	0.36	0.22	0.36*	0.20
	Non-Subsoiled	0.30	0.18	0.38	0.21	0.31*	0.18
Control	Subsoiled	0.26	0.18	0.37	0.25*	0.33	0.18
	Non-Subsoiled	0.30	0.19	0.36	0.21*	0.38	0.20
P value	Subsoiled vs Non-Subsoiled	0.0168*	0.2962	0.1866	0.2257	0.1926	0.9298
P value	Pre-compacted vs Control	0.6306	0.5628	0.0755	0.6051	0.6844	0.5312

*Significantly different at $P \leq 0.05$.

Table A 4. Volumetric water content NCB Fall 2017.

Treatment		Volumetric Water Content			
		0-15 cm		30-60 cm	
		2016	2017	2016	2017
		$cm^3\ cm^{-3}$			
Pre-Compacted	Subsoiled	0.26	0.24*	0.32	0.28
	Non-Subsoiled	0.32	0.33*	0.37	0.32
Post-Compacted	Subsoiled	0.22	0.15	0.28	0.20
	Non-Subsoiled	0.21	0.14	0.26	0.21
Control	Subsoiled	0.21	0.20	0.28*	0.29
	Non-Subsoiled	0.28	0.28	0.36*	0.30
P value	Subsoiled vs Non-Subsoiled	0.1047	0.1751	0.0177*	0.4048
P value	Pre-compacted vs Control	0.1608	0.2644	0.2884	0.6482

*Significantly different at $P \leq 0.05$.

Table A5. Chemical analysis FRM Fall 2016.

Treatment	Depth	NO_3	SO_4	P	K	Cu	Zn	pH	EC	OC
		Soil Chemical Properties								
	cm	ug g^{-1}							dS m^{-1}	%
Raked & Burn	0-10	3.40	25.60	16.56	366.82	0.83	0.86	7.13	294.30	1.16
	10-30	2.73	219.78	6.64	263.08	0.91	0.26	7.35	953.45	0.83
No Burn	0-1 0	3.23	44.81	11.37	324.85	0.77	0.44	7.46	340.50	1.11
	10-30	2.76	120.98	6.56	218.60	0.84	0.22	7.62	630.10	0.88
Treatment		0.8768	0.3981	0.2429	0.3848	0.5495	0.1574	0.2251	0.4013	0.9917
Depth		0.0184*	0.0033*	<0.0001*	<0.0001*	0.1008	0.0003*	0.0357*	0.0033*	<0.0001*
Treatment*Depth		0.6747	0.1887	0.0109*	0.9429	0.9255	0.0790	0.7710	0.2399	0.1262

*Significantly different at $P \leq 0.05$.

Table A6. Chemical analysis FRM Fall 2017.

Treatment	Depth	NO_3	SO_4	P	K	Cu	Zn	pH	EC
		Soil Chemical Properties							
	cm	ug g^{-1}							dS m^{-1}
Raked & Burn	0-10	7.88	70.81	16.75	372.36	0.63	0.67	7.27	379.30
	10-30	2.02	249.66	4.66	218.54	0.91	0.21	7.50	1013.7
No Burn	0-10	5.98	51.37	11.43	360.58	0.66	0.50	7.53	296.75
	10-30	1.78	233.41	3.40	165.80	0.82	0.14	7.59	994.55
Treatment		0.0906	0.8061	0.0229*	0.4312	0.7724	0.1351	0.3561	0.8444
Depth		<0.0001*	0.0001*	<0.0001*	<0.0001*	<0.0001*	<0.0001*	0.0130*	0.0053*
Treatment*Depth		0.0811	0.9718	0.0459*	0.2504	0.1544	0.1916	0.1597	0.8916

*Significantly different at $P \leq 0.05$.

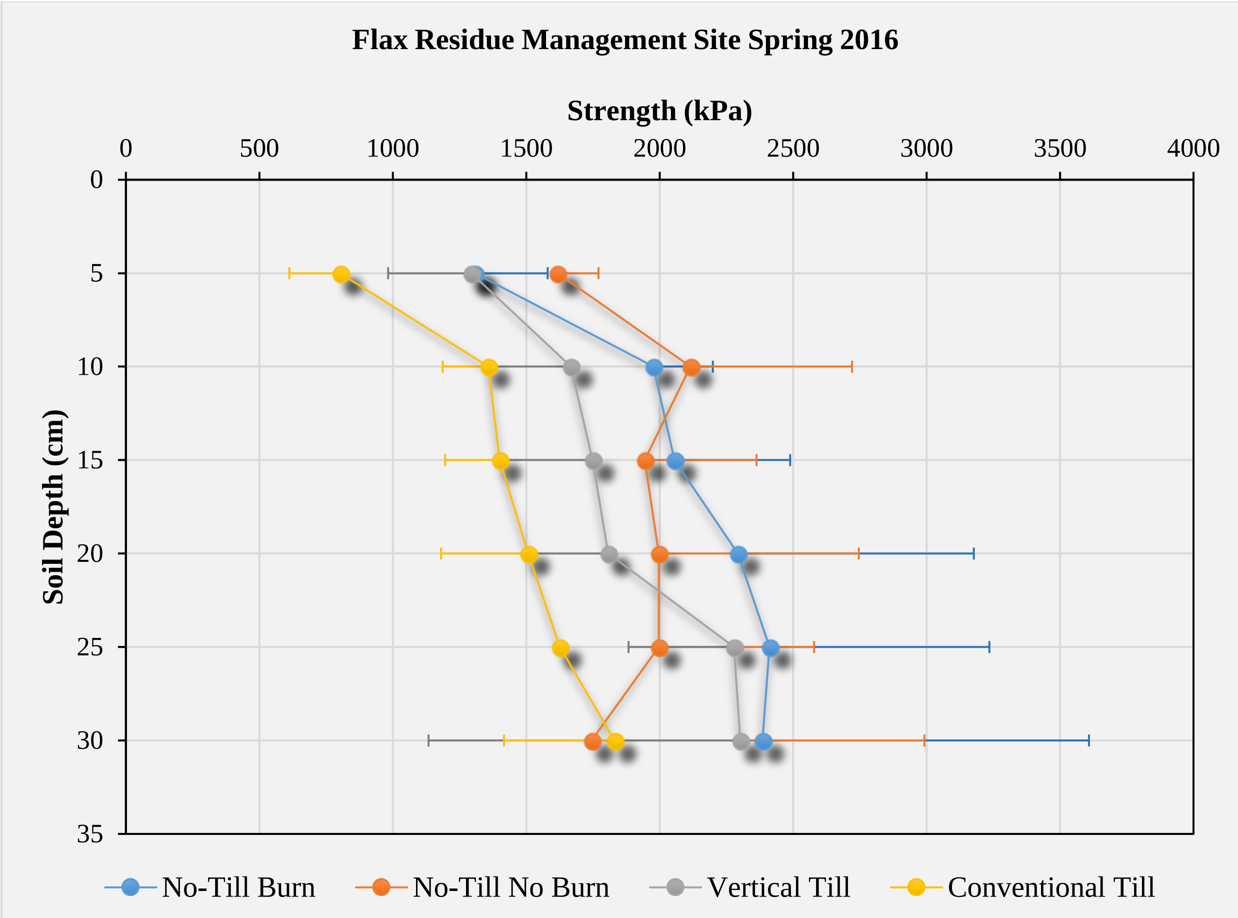

Figure A1. Soil strength (penetration resistance kPa) at FRM site measured using a Rimik cone penetrometer in spring of 2017. Error bars are standard deviation of the mean.

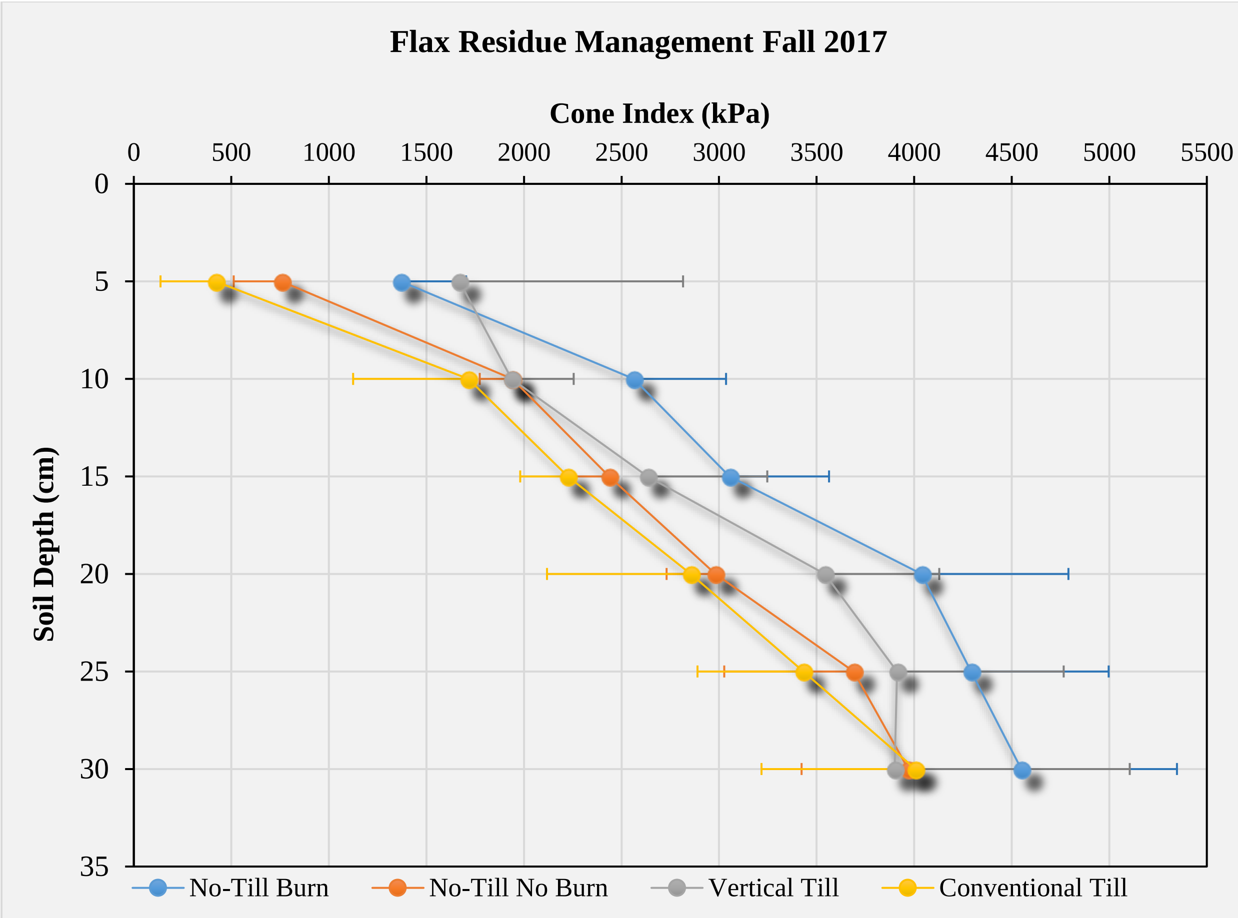

Figure A2. Penetration resistance in FRM fall 2017 site 22 months after vertical tillage and tandem disc, and 18 months after crop residue burning.