EFFECT OF PARAPLOWING ON SOIL PROPERTIES AND CROP YIELD UNDER IRRIGATED MANAGEMENT

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ABSTRACT

Limitations on water infiltration and soil aeration through compaction processes have the potential to limit production in irrigated agricultural fields. This project was conducted to determine the impact of sub-soiling with a paraplow (Howard Rotavator) on soil physical properties and processes that are important in affecting soil-water relations and productivity. The paraplow was the subsoiler selected for use in this study because of its ability to loosen the soil at the depth of plowing while producing minimal surface disturbance. The research plots were located on Chernozem and Vertisol soils in the Brown soil zone in the Lake Diefenbaker irrigation district near Birsay, SK. Irrigated and dryland sites were used for comparison. Sub-soiling was able to consistently reduce bulk density of the soil and effects persisted for one to two years under normal precipitation conditions.

Excessively wet conditions (2010 and 2011) reduced the effectiveness of the sub-soiling. Tillage induced porosity in the soil was associated with a greater infiltration capacity measured in the field. Yield benefits in crops grown (canola, flax, wheat) from sub-soiling were variable under the wet conditions of 2010 and 2011. A greater benefit was observed under the normal precipitation conditions of 2012 on sites that were paraplowed in 2011. Subsoiling at a depth of 45cm and a row spacing of 45cm (manufacturer's recommended configuration) was more effective than shallower depth and wider row spacing treatments. A significant yield benefit was only observed at the dryland site established in 2011, and limited yield benefit was observed in the irrigated sites. Over the three years of the study, annual yields from sub-soiling were on average about 5% higher than the un-tilled control. However, yield benefits were variable depending on crop and year. Given an estimated cost of subsoiling of ~$30 per acre, a benefit of sub-soiling that lasts one year would produce close to break-even conditions, and sub-soiling benefits that are consistent and last longer than one year are needed to be cost effective.

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TABLE OF CONTENTS

List of Tables

LIST OF FIGURES

LIST OF ABBREVIATIONS

α	Hydraulic parameter
ρ_b	Oven dried soil bulk density
ρ_w	Field moist bulk density
θ_g	Gravimetric water content
θ_v	Volumetric water content
ASTM	American Society for Testing and Materials
CEC	Cation exchange capacity
D	Ponded water depth
EC	Electrical Conductivity
ESP	Exchangeable sodium percentage
K_{fs}	Field saturated hydraulic conductivity
SOC	Soil organic carbon
PR	Penetration resistance

Control	Undisturbed control
CF	Conventional fall paraplow treatment
CS	Conventional spring paraplow treatment
CS11	Conventional spring paraplow treatment – Tilled in 2011
SF	Shallow fall paraplow treatment
WF	Wide fall paraplow treatment
WS	Wide spring paraplow treatment

1 INTRODUCTION

Water is often the main factor limiting agricultural production in southern Saskatchewan (Campbell et al., 2005; Noorbakhsh et al., 2008). With irrigation farmers are able to adjust the quantity of water to supply to meet the crop needs. However, even with the ability to add water, limitations in behavior of the water in the soil such as infiltration may still exist. Characteristics of the soil such as texture, structure, and chemistry have an impact on infiltration, water storage and plant accessibility. Soil texture and chemistry are not easily manipulated, but soil structure can be modified. The study described in this thesis is focused on the mechanical soil loosening that can be achieved via a Paraplow tillage implement (Howard Rotavator, England). Using subsoil tillage as a tool for soil moisture management may help maximize crop production by enhancing water and nutrient use efficiency (Aase et al, 2001; Franzluebbers et al., 2007; Grevers and de Jong, 1993).

The Paraplow is a deep tillage implement produced by Howard Rotavator in England. It can be described as a bent-leg, soil-loosening implement effective for breaking down compacted layers and improving drainage. The unit used in this study is depicted below (**Fig. 1.1**) and more photos are provided in the appendix. Paraplowing should be effective at loosening soils that become compacted under the moist conditions of irrigation and thereby improve soil conditions for crop growth. The primary objective of this study was to evaluate the efficacy and persistence of the paraplowing treatment in different soil types. This was achieved by monitoring bulk density, soil moisture content, penetration resistance, and hydraulic conductivity and crop yield. These observations were then used to assess the efficacy of different paraplow depth and spacing configurations and the timing of tillage: fall or spring. An economic evaluation was conducted using estimated costs of conducting the paraplowing operation in relation to the economic benefit achieved, using yield response data from the study. The study was conducted at three sites in the Brown soil zone. The sites are located about 5 km south of Birsay, Saskatchewan and each site encompasses a different type of soil: Chernozem, Solonetz, and Vertisol. The fields are irrigated using water from Lake Diefenbaker. Lake Diefenbaker Irrigation District accounts for 40,870 hectares of Saskatchewan's 138,000 hectares of irrigated land (Saskatchewan Ministry of Agriculture, 2008).

Fig. 1.1. Paraplow in operation.

2 Literature Review

Crop production in southern Saskatchewan occurs to a large extent on predominately Chernozemic soils formed over glacio-till and glacio-lacustrine deposits (Soil Classification Working Group, 1998). Chernozemic soils have inherently good soil structure and typically do not require subsoiling to achieve satisfactory crop yields and subsoiling is not generally a recommended practice in Saskatchewan (SSCMS, 2005). In recent years, however, there has been renewed interested in the practice as a means to alleviate compaction. Compaction can occur naturally in the soil or be induced by heavy machinery traffic or tillage. Others have looked to subsoiling as way of managing soil water, especially with regard to improving infiltration rate (Clark et al., 1993). With a number of producers already engaging in the activity; now is the time to reevaluate the practice. Much of the research surrounding paraplowing and subsoiling in Canada was conducted in the late 1980's (Grevers and de Jong, 1992; Grevers and de Jong, 1993; McConkey et al., 1997; Pierce et al., 1992). The work in Saskatchewan focused on dryland Chernozems and Solonetzic soils, and their structural and hydraulic limitations to crop production (Grevers and de Jong, 1992; Grevers and de Jong, 1993; McConkey et al., 1997). Since then there has been little research in this area. As adoption of reduced tillage farming methods grew among farmers and researchers, their interest in deep tillage and deep tillage research declined.

There are a number of different subsoilers available for loosening soil. With a focus on non-inversion subsoilers, most subsoilers on the market today consist of three main components described as follows. First, a coulter disk is used to break the soil surface followed by a straight tillage leg capable of loosening soils to a depth of 45 cm or deeper. Affixed to the tillage leg is a point or tip. The points come in various shapes, sizes, and materials. Smaller points create fewer disturbances and require less draft. Larger points create a greater disturbance, and are often winged to cover a greater surface area. Some subsoilers have additional attachments following the tillage legs such as a packer or harrow to even out the soil surface. Examples of tillage units like this are Agrowplow AP30 deep tillage plough, Blue-Jet SubTiller 4, Case IH Ecolo-Til 2500 in-line ripper, or John Deere 2100 Minimum Till Ripper. Alternatively subsoilers can have a bent-leg design. These subsoilers have a reduced draft requirement and less surface disruption than straight leg subsoiler (Raper, 2005). In addition to applying force upward and in the direction of travel, the bent-leg design also applies more lateral force on the soil when compared with straight shanks (Raper, 2005). This has the potential to provide a greater loosening effect and was the reason the bent-leg, Howard Paraplow was selected for use in this project. The term paraplow is used generically throughout this study to describe this specific type of tillage operation Other terms that are commonly encountered in literature and often relate to the specific equipment design, include bent-leg subsoiler, paratill (Clark et al, 1993; Truman et al., 2003), zone-subsoiling (Aase et al., 2001; DeJong-Hughes and Johnson, 2009) and zone-tillage (Pierce et al., 1992). Subsoiling is a broad term that may be used to collectively cover all the different equipment configurations and can include more aggressive forms of tillage.

In 1986, it was estimated that soil compaction contributed to a 10% reduction in crop yields across Canada and cost producers greater than $130 million dollars each year (Acton and Gregorich, 1995). There have been no estimates made since, and the Prairie Provinces were not included in the 1986 estimate due to insufficient data. It has also been stated that there is little evidence that soil compaction limits crop production in Saskatchewan (McConkey, 1987). When research was conducted in the late 1980's, it was believed that subsoiling with the paraplow and other low disturbance forms of deep tillage produced inferior results to other more intensive forms of deep tillage such as deep plowing or ripping (Grevers and de Jong, 1992). This is still the belief of producers and researchers in areas where intensive tillage is still a common practice. Farming practices have changed a great deal since then, with agriculture production using much higher inputs and the adoption of reduced tillage practices. In the United States and internationally, some research has been conducted post 1990's to evaluate subsoiling as means of addressing soil compaction issues and/or as a method of soil water management (Aase et al, 2001; Franzluebbers et al., 2007; Lopez-Fando and Pardo, 2009; Wolkowski, 2000)

Bulk density (ρ_b) is an indicator of soil porosity and an important soil property affecting root growth and water relations. The ρ_b and porosity are inversely related, as ρ_b increases, porosity decreases and vice versa. It is well documented that subsoiling is effective at initially reducing ρ_b (Aase et al, 2001; Franzluebbers et al., 2007; Grevers and de Jong, 1992; Grevers and de Jong, 1993; McConkey et al., 1997; Lopez-Fando and Pardo, 2009; Pierce et al., 1992; Wolkowski, 2000). However, it appears that the effects do vary in terms of their persistence over time. Grevers and de Jong (1993) found that with ripping Solonetzic soils in Saskatchewan, the soil loosening effects lasted two to three years. Wang et al. (2009) found that subsoiling effects lasted two years in a Manitoba Red River clay soil with deep ripping. Using a slant-legged subsoiler, Carter (1988) observed that the depth of soil loosening was reduced by 30 to 60% over a five month period following the imposition of the subsoiling treatment. Franzluebbers et al. (2007) observed that subsoiling with a paraplow was effective in lowering the density of the soil for only ≤1 year in the Southern Piedmont, USA. Pikul Jr. and Aase, (2003) found that in most cases the effects only persist for a single growing season and the benefits of the operation can be difficult to predict.

Subsoiling affects the soil physical and hydraulic properties as well as root growth (Lampurlanes and Cantero-Martinez, 2003; Muktar et al., 1985). Truman et al. (2003) observed greater infiltration and reduced runoff with paratilling when compared with no till and conventional tillage practices. Truman et al. (2003) also concluded that paratillage was more effective than a cover crop at stabilizing a highly erodable Rhodic Paleudult under simulated rainfall. Clark et al. (1993) found that paratillage improved infiltration but was only effective for a period of up to one year before reconsolidation occurred. Pikul Jr. and Aase (2003) state that subsoiling with a paratill can produce tillage-induced preferential flow paths in the soil, contributing to increased water infiltration and thereby helping to eliminate runoff. Soil structure describes the size, shape, and strength of peds and the pore spaces between them, indicating how individual soil granules bind together to form aggregates (Bengough and Mullins, 1990). The arrangement of the soil particles affects the soil porosity, as well as the ability of the soil to resist erosion and compaction. Soil porosity regulates air and water movement within the soil, impacting soil aeration, water storage and availability, nutrient transport and availability (Carter and Ball, 1993). Weaker aggregates and soil compaction have been reported to be the dominant sources of soil structural degradation in Canada (Acton and Gregorich, 1995). A soil with good soil structure is able to resist degradation and does not restrict yield potential (Acton and Gregorich, 1995). An important goal of subsoiling is to enhance soil structure resulting in improved crop yields. With varying degrees of effectiveness, the debate remains open on whether subsoiling is an effective practice for agricultural soils. Responses to subsoiling tend to be site or grower specific, varying with the soil, climate, and grower practices (Wolkowski, 2000).

A number of researchers have studied the effects of subsoiling on crop yield (Aase et al, 2001; Busscher et al., 2000; Grevers and de Jong, 1993; Sojka et al., 1997; Wolkowski, 2000). Studies that looked only at the below ground properties, tended to recommend subsoiling as a viable practice, citing favorable attributes such as reduced soil bulk density and soil strength, increased root penetration, or improved air permeability (Sojka et al., 1997). The studies that also included crop yield and an economic analysis tended to show variable results on these parameters that are of most importance to the producers when deciding to adopt the practice (Aase et al, 2001, Busscher et al., 2000; DeJong-Hughes and Johnson, 2009; Grevers and de Jong, 1993). Aase et al. (2001) found no yield benefit with growing barley or dry beans after paratilling a silt loam soil in Idaho. Wolkowski (2000) subsoiled six locations in Wisconsin and observed a significant crop yield response to subsoiling at only two of those six locations. At the two sites, they observed an annual benefit on a potato crop and back-to-back significant grain yield increases on corn and soybeans in rotation. Grevers and de Jong (1993) examined subsoiling in a number of locations around Saskatchewan. In Solonetz soils, Grevers and de Jong (1993) observed grain yield increases of 10-47% over the control but found no yield response when subsoiling Chernozems. Wang et al. (2009) subsoiled a clay soil in Manitoba and found the crop had increased plant density and more rapid plant emergence with subsoiling. Other studies found that paraplowing improved soil properties and plant growth; however there was limited grain yield response and, due to the high cost of the operation, paraplowing was not economical (DeJong-Hughes and Johnson, 2009; Franzluebbers et al., 2007). The end goal for engaging in subsoiling is to improve crop production, and without measureable yield increases attributed to subsoiling, the practice is not economically viable (Franzluebbers et al., 2007)

Penetration resistance (PR) is a measure of soil strength often used as an indicator of soil compaction and subsoiling effectiveness (Aase et al., 2001; Kumar et al., 2012). PR is also commonly referred to as soil cone index or soil strength in other literature (Bengough and Mullins, 1990; Lampurlanes and Cantero-Martinez, 2003; Kumar et al., 2012). Penetration resistance is a measurement that encompasses a number of soil properties, namely bulk density (porosity), moisture content, texture, and soil structure (Grant and Lafond, 1993; Lampurlanes and Cantero-Martinez, 2003; Kumar et al., 2012). In order to sustain plant growth a soil must exhibit enough mechanical strength to anchor the plant during its entire life cycle and also prevent the destruction of water and air pathways in the soil from the force applied to the soil surface by vehicular and animal traffic (Bengough and Mullins, 1990). Dense soil layers can also act as mechanical impedance to plant growth (Bengough and Mullins, 1990). The critical value for PR impacting root growth is 3 MPa, where roots are unable to penetrate the soil; root growth begins to be impeded at 2 MPa (Aase et al., 2001; Arkin and Taylor, 1981). Busscher et al. (2000) determined that for every megapascal (MPa) decrease in mean profile cone index wheat yields increased 1.5 to 1.7 Mg ha^{-1} and soybean yields increased 1.1 to 1.8 Mg ha^{-1}. Pierce et al. (1992) did a study on a sandy loam in Michigan, and found that zone tillage with paraplow and similar zone tillage implements reduced cone index significantly in the layer from 15-30 cm and though the bulk density increased over a two-year period the cone index of the soil remained below one MPa. Previously the soil had a cone index of greater than two MPa's. Pierce et al. (1992) looked at paraplowing with 51 cm spacing and 76 cm spacing. Both treatments yielded similar results in the first growing season but the residual effects of the paraplow did not last as long with the wider spacing. Lopez-Fando and Pardo (2009) examined how the chemical properties of the soil changed as result of paraplowing and other tillage methods in an agricultural region of Spain. They found that paraplowing had little effect on the distribution of nutrient compared to no-till. They did not look at yield but recommended incorporating paraplowing every second year due to the positive impact on various physical characteristics.

In soils where water infiltration is limited, runoff and soil erosion can pose significant environmental and agronomic concerns. Farmers utilizing irrigation desire to maximize the efficiency of water used in their irrigation systems. An important component of maximizing the yield produced per unit of water applied is to ensure that applied water enters into the soil rather than running off. Field representatives from the Ministry of Agriculture, Irrigation Branch had reported that many irrigation farmers in the study area utilized for the research in this thesis have anecdotally observed reduced water infiltration on land without periodic tillage (i.e. on direct seeded land). These farmers had requested research be done evaluating subsoiling as a means to loosen possible compacted soil layers and increase infiltration (Garth Weiterman, 2009, Personal Communication).

There are number of different methods for measuring soil water infiltration. For one-dimensional flow, ring infiltrometers are effective tools for measuring field saturated hydraulic conductivity (K_{fs}) and are commonly used for field measurements (Bouwer, 1986 and Reynolds, 2008). The tool consists of a cylindrical ring inserted into the soil. Water is then ponded to provide one or more specific heads inside the ring, and the rate of flow out of the ring into the soil is measured. The double ring method is a common approach for measuring hydraulic conductivity (Lai et al., 2012) and is an established ASTM standard method for measuring hydraulic conductivity (Reynolds, 2008). For this reason, this instrument was selected for use in this thesis research. The purpose of the additional ring is to constrain the flow in the inner ring and provide a buffer to any divergent flow (Reynolds, 2008). Some researchers feel that there is no real advantage to adding an outer ring. In this respect, the outer ring is not entirely efficient, as there is still divergent flow that causes an overestimation of K_{fs} just as the single ring does (Reynolds, 2008; Wu et al., 1997). To estimate the K_{fs} value using the ring infiltrometer, the pressure head can be maintained in a constant or falling state. A single constant head and multiple constant head approach (Reynolds, 2008) were considered for use in the current thesis research, but ultimately a simplified falling head (SFH) method (Bagerello et al., 2008, 2012) was selected. The SFH method requires simple equipment and multiple measurements can be ran simultaneously (Bagerello et al., 2008). For a more detailed description see the methods and materials section of this thesis.

3 METHODS AND MATERIALS

3.1 Sites and General Overview of Experiments

Three centre pivot irrigated field sites were selected in the fall of 2009 to represent different soil conditions under irrigation that are commonly encountered in southern Saskatchewan. The three sites represent soils where paraplowing may vary in its ability to produce beneficial effects: Vertisol soils (clay), Solonetz (clay loam), and Chernozem (silty clay loam). The selection of different soil types is intended to give a good indication of how a sub-soil tillage operation is impacted by soil type, and even within a field or farm. These three different soil types may be encountered in irrigated fields in the Lake Diefenbaker area. Vertisols are soils of high clay content and pose workability issues when wet. Solonetzic soils are soils that have a natural "hardpan" Bnt horizon (Soil Classification Working Group. 1998); generally about 10-15 cm below the surface and so have natural structural limitations. Different soil types will show if the natural chemical and physical properties of the soil will affect the effectiveness or persistence of the tillage operation. The 2010-11 field season was excessively wet. Rain events starting in May and continuing throughout the summer caused flooding at the Solonetz site (**Fig. A5**). The site also received a large deposition of topsoil from run-off during rain events. Some spring soil samples were collected prior to the rain events but the decision was made to abandon because it was felt that no reliable data could be obtained from this site going forward. In response to losing this site, two new sites were established on an adjacent field (SW18-24-7-W3) in 2011. On this field, one site is located within the area of the pivot irrigation system (termed Chernozem 2) and the other is located in the dryland corner (termed Chernozem Dryland). This pairing was included to demonstrate suitability of paraplowing for both irrigated and dryland agricultural production.

The three sites established in 2009 consisted of five treatments and a control replicated four times in a completely randomized block design. Each individual plot measured 6 m by 18 m, covering 108 m^2. In 2011, two new sites (Chernozem 2 and Dryland) were established to evaluate longevity of the tillage treatments under more normal precipitation conditions than were encountered in 2010. The 2011 experiment was also set up as a completely randomized block design with six replicates, comparing one conventional paraplow treatment (CS11) to a control and having the same plot size as the 2009 sites.

Treatments were selected to compare various timing of tillage (Spring & Fall), as well as different paraplow configurations (tillage depth and shank spacing). Tilling shallower and removing every second leg to produce a wider spacing were the configurations evaluated in addition to the normal recommended equipment setting. The experiment in 2011 was set up to compare dryland and irrigated production with one site located within the irrigated area of the pivot and the other located in the dryland corner. For a detailed summary of the treatments see **Table 3.1**. The sites were seeded and managed in accordance with the cooperators current management schemes for the fields. A summary of the crops grown over the various seasons is provided in **Table 3.2**

Table 3.1. Overview of the paraplow tillage treatments.

Treatment		Paraplow setup		Tillage Timing
		Shank Spacing	Tillage Depth	
		cm	*cm*	
C	Undisturbed Control	-	-	-
CF	Conventional Fall	45	45	Fall 2009
WF	Wide Fall	90	45	Fall 2009
SF	Shallow Fall	45	30	Fall 2009
CS	Conventional Spring	45	45	Spring 2010
WS	Wide Spring	90	45	Spring 2010
CS11	Conventional Spring 2011	45	45	Spring 2011

Table 3.2. Location, soil and cropping descriptions for the study sites.

Site	Land Location	Soil Texture†	Year	Crop Grown
2009-10				
Solonetz	NW-18-24-7-W3	CL	2009	Hybrid Canola
			2010	None (flooded)
Chernozem	SW-18-24-7-W3	SiCL	2009	Hybrid Canola
			2010	Hard Red Spring Wheat
			2011	Flax
			2012	Hard Red Spring Wheat
Vertisol	SW-25-24-8-W3	C	2009	Hard Red Spring Wheat
			2010	Hybrid Canola
			2011	Durum Wheat
			2012	Flax
2011				
Chernozem 2 Irrigated	SW-18-24-8-W3	SiCL	2010	Hard Red Spring Wheat
				Flax
			2011	Hard Red Spring Wheat
			2012	
Chernozem 2 Dryland	SW-18-24-8-W3	SiCL	2010	Hard Red Spring Wheat
			2011	Flax
			2012	Hard Red Spring Wheat

† CL – Clay Loam, C –Clay, SiCL – Silty Clay Loam

3.2 Treatments and tillage

The experimental control consisted of the undisturbed soil under minimal tillage (10+ years) cropping practice employed by the collaborators at each site. Each of the remaining treatments involved a paraplow tillage operation with varied spacing and depths. Fall sub-soil treatments were carried out on October 20, 2009 using a 220hp tracked Caterpillar tractor and included the CF, WF, and SF treatments (see Fig 3.1 for description). The soil gravimetric water content when the tillage took place was 29% and 26% (0-15 cm) at the Vertisol and Chernozem respectively. At depth (15-30 cm) the water content was 26% and 22%. The CF treatment is paraplowing to a depth of 45 cm and at a spacing of 45 cm, which is the manufacturers intended set up or configuration for the implement. The WF treatment is paraplowing with every second shank removed (90 cm shank spacing) tilling to a depth of 45 cm. When paraplowing with the machine in this configuration, depth control was more difficult as it was drawn deeper into the ground, sometime exceeding the intended tillage depth of 45 cm as much as 10 cm. The SF treatment was a shallow depth of paraplowing with 45 cm spacing, and tilling to a depth of 30 cm. The CS and WS treatments were conventional and wide spacing paraplow treatments conducted on April 27, 2010. The gravimetric water content at time of tillage was 30% and 28% at the soil surface (0-15 cm) at the Vertisol and Solonetz, respectively. The moisture at depth (15-30 cm) was 29% and 25%. A schematic of paraplow set up is shown in **Fig. 3.1**. Due to availability, a different tractor was used to till the spring treatments. An 180hp front-wheel assist New Holland tractor was utilized. The change of tractor is not believed to have an effect on the outcomes of study. This same tractor was used to paraplow the Chernozem 2 Irrigated and Chernozem 2 Dryland plots in the spring of 2011. The gravimetric water content at surface (0-15 cm) when tillage took place in spring 2011 was 33% and 27% for Irrigated and Dryland, respectively. At depth (15-30 cm) the gravimetric water content was 28% and 34%.

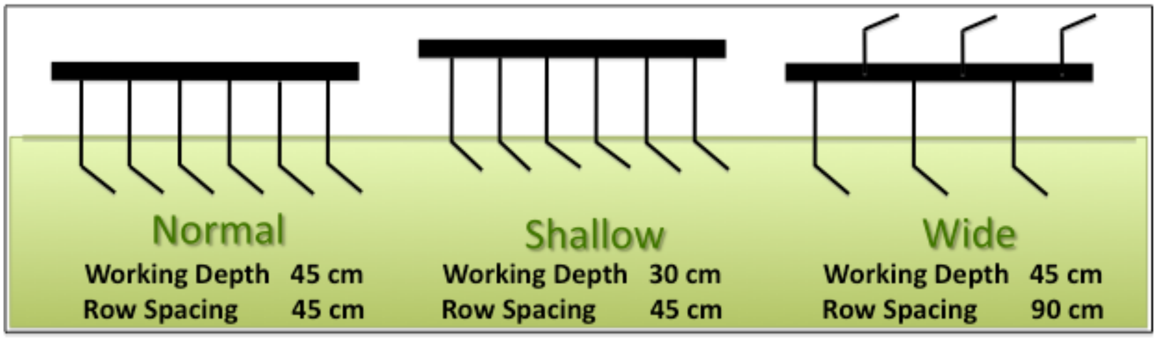

Fig. 3.1. Diagram of paraplow configurations evaluated in the study.

3.3 Sampling procedures

Soil sampling took place in the spring of 2010 (April before seeding) and fall (September after harvest) to evaluate soil bulk density and moisture content. The initial spring soil sampling was done following seeding on May 20, 2010, which was twenty-three days after paraplowing. This timing was selected to coincide with soil environment that the plant is experiencing during germination. Measurements of the soil physical properties in 2011 showed that the previous paraplowing treatments had little or no effect on measured properties at the original sites (Chernozem & Vertisol), so soil samples were not collected at these sites in 2012. Soil sampling was also completed in Fall 2011, Spring 2012, and Fall 2012 on the Chernozem 2 and Chernozem Dryland sites. Soil cores were collected using a truck-mounted hydraulic punch.

In the spring of 2010, two soil cores were collected from each plot with care taken to sample close to paraplowed furrows and between the furrows. In the fall, two soil cores were collected ~30 cm apart across the width of the tillage treatment to encompass some of the spatial variability in the treatment. It was impossible to distinguish the furrow from the inter-furrow in the fall. When sampling in 2011 and 2012, only the control and conventional treatments were sampled via the collection of a single core from each plot. Spatial variability was less of a concern in these treatments and the smaller sample size reduced the volume of soil being removed from the field.

Crop harvest samples were collected from each of the plots in the fall. For the 2012 season, three individual square meter harvest samples were collected from each plot at the Chernozem 2 and Chernozem Dryland sites established in 2011. A single square meter was collected from the control and normal paraplowing operations at the Chernozem and Vertisol sites each year. These samples were weighed to determine overall biomass yield then threshed to obtain a grain yield. The samples were cleaned, and then weighed to determine grain yield.

3.4 Weather observations throughout the study

The project was challenged by extreme weather conditions in 2010. Abnormally high amounts of precipitation were received in the months of May, June and July, exceeding the 10 year monthly average (2002-12) by 251%, 129%, 210% respectively (**Fig. 3.2**). This made sampling difficult and may have had an effect on the persistence of the tillage operation. The rain caused extended periods of flooding and soil deposition from erosion at the Solonetz site.

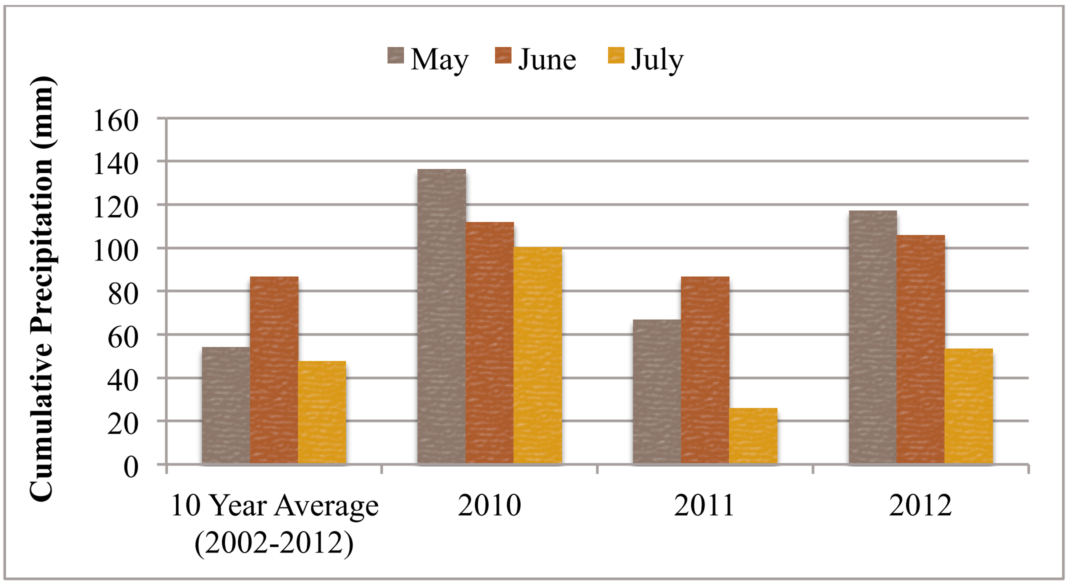

Fig. 3.2. Precipitation observed at nearby weather station (Lucky Lake, SK; WMO ID – 71455) during the first three months of the growing season (May-July) compared with the 10 year average.

3.5 Soil Properties

Prior to imposing the subsoiling treatments, soil samples were taken from the control plots in the experimental sites and used to determine various soil properties including pH and electrical conductivity (EC), soil texture, soil organic carbon (SOC), exchangeable and soluble cations (Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}). Using the exchangeable cation data, the CEC and Ca:Na ratio were calculated and the soluble cations were used to calculate ESP. The soil pH and EC were determined using a 1:2 soil:water suspension (Nelson and Sommers, 1982) measured with a Calomel glass electrode assembly on a Beckman 50 pH meter (Beckman Coulter, Fullerton, CA, USA) and Accumet AP85 pH/EC meter (Accumet, Hudson, MA, USA), respectively. Particle size distribution was done using a Horiba LA-950 Particle Size Distribution Analyzer (Horiba Instruments Inc., Irving, CA, USA) after a pre-treatment with bleach (sodium hypochlorite) to remove organic matter. SOC was measured using a LECO C632 carbon combustion analyzer (LECO corporation, St. Joseph, MI, USA) using the methods outlined in Wang and Anderson (1998) following a 6% H_2SO_3 pre-treatment to remove the inorganic C (Skjemstad and Baldock 2008). A determination of exchangeable cations was performed using 1.0*M* NH_4OAc (Hendershot et al., 2008). The extract was analyzed using atomic emission spectroscopy (Varian SpectrAA200 Atomic Absorption Spectrometer; Varian Inc., Palo Alto, CA, USA). With the exchangeable cations known, the exchangeable Ca/Na ratio was calculated. According the criteria in *The Canadian System of Soil Classification* (Soil Classification Working Group, 1998), soils with a B horizon, with a exchangeable Ca:Na ratio of 10 or less are considered soils of the Solonetzic Order. The NO_3^--N levels were determined using 2*M* KCl extracts (Keeney and Nelson, 1982). In this procedure, 5.0 g of soil was extracted with 50 mL of 2*M* KCl solution (Maynard et al., 2008). The soil:KCl suspension was shaken on a rotary shaker at 142 rpm for 1 h, then filtered through VWR 454 filter paper into plastic vials. The vials were capped and placed in the fridge/freezer to await colorimetric analysis on the Technicon AutoAnalyzer II (Technicon Industrial Systems, Tarrytown, NY, USA). The site names and description (Chernozem, Vertisol, Solonetz) are based upon a visual inspection of the soil horizons in the soil pits that were excavated at the sites. The Ca:Na ratio of the Solonetz did not meet the criteria for classification as a true Solonetzic soil according to *The Canadian System of Soil Classification* (Soil Classification Working Group, 1998). The soil did exhibit the structural and physical properties of characteristic of that solonetzic order with a blocky, prismatic structure.

3.6 Penetration Resistance

Penetration resistance (PR) is a field-based assessment of soil strength or resistance to penetration. Penetration resistance is defined in equation (1), where F_p is the force required to push the probe through the soil and A_p is the cross-sectional area of the penetrometer cone (Bengough and Mullins. 1990):

$$PR = F_p / A_p \qquad \text{(Eq. 1)}$$

Penetration Resistance was measured at the Vertisol, Chernozem and Solonetz sites on May 19, 2010, using a recording cone penetrograph (Eijkelkamp Agrisearch Equipment, The Netherlands) with a 2 cm index cone. The instrument was inserted into the soil in the plot and used to graph soil strength over the depth increment from 0-75 cm. For each measurement the instrument was inserted into the soil three times and an average curve established. The numerical PR values were then recorded at points along the curve representing each 5 cm increment of soil depth. This was repeated twice per plot. Measurements were taken within tillage treatments adjacent to the furrow and also directly between furrows. Penetration resistance can be thought of as representing the resistance to penetration by growing roots or by tools such as a seed or fertilizer opener and is related to soil bulk density, moisture, organic matter content and soil texture (Bengough and Mullins, 1990). The soil moisture at the time of sampling is indicated in **Table 4.4**, and description of soil texture can be found in **Table 4.2**. Soil moisture and texture varied between sites making them difficult to compare. Little variation between soil moisture and texture was found within a single site and the time of the measurement, allowing for a valid comparison of the treatments. Changes in PR value between treatments at a single site will be indicative of differences in bulk density. Bulk density is a measure of the density of the bulk soil that includes soil particles and the pore space between. Bulk density is inversely related to porosity. As a targeted measure, bulk density can be used to identify compacted layers within soil and determine if a tillage operation leads to increased porosity. Moisture content was documented at the time the measurements were made in the field and soil texture is known. Bulk density was measured as described below.

3.7 Soil Sampling for Determination of Bulk Density and Volumetric Water Content

Soil sampling took place every year in the spring (April) and fall (September after harvest). Samples were collected using a truck-mounted hydraulic punch. Two soil cores with a diameter of 5.175 cm were extracted from each plot. In the first sampling completed on May 20, 2010 the samples were systematically collected within and between the furrows of the sub-soiling, as these could be visually identified. The soil cores were divided into five separate segments: 0-15 cm, 15-30 cm, 30-45 cm, 45-60 cm, and 60-90 cm. With the known diameter and length of each segment, the volume was calculated. Each sample was then weighed to provide a determination of field moist bulk density (ρ_w). After the samples were weighed, the sample was then homogenized by hand mixing and a 10 g sample was then oven-dried at 105 degrees Celsius for 24 hours (Topp et al., 2001). The sample was then weighed to provide a determination of the gravimetric water content (θ_g). From the ρ_w and θ_g, dry soil bulk density (ρ_b) and volumetric water content (θ_v) were calculated. ρ_b is a measure of porosity and will reveal if the sub-soil operation has improved porosity of the soil, while the θ_v will show if there is an effect on water storage.

3.8 Field Saturated Hydraulic Conductivity (K_{fs})

Field-saturated hydraulic conductivity is a measure of one dimensional water infiltration. The study utilized two different instruments to measure K_{fs}: a large single ring, and a double ring infiltrometer (**Fig. 3.3**.). The double ring had an inner ring diameter of 200 mm and the outer ring had a diameter of 300 mm. The single large ring was conducted with a square of dimensions 580 mm by 420 mm. The large ring was utilized because it covers a greater surface area ,enabling the entire area loosened by a single leg of the paraplow to be encompassed in the measurement Infiltrometers are typically cylindrical in shape, and it was recognized that the square shape of the large infiltrometer may also have led to greater preferential flow in the corners affecting the absolute K_{fs} value. Still, as a relative value to compare the effect of treatments, this approach is considered valid. Due to a limitation in number of large rings available and logistics of administering the water, the large ring measurement was performed only in the first block of replicates, but the measurement was replicated three times. This was also done to avoid applying large volumes of water across the entire site area that could possibly impact future measurements. The double ring set up was used to measure K_{fs} across each individual plot. The double ring had a smaller footprint in the plot area and required less water; reducing the effect on the following crop and soil measurements.

Fig. 3.3. Double ring infiltrometer apparatus (left) & large ring infiltrometer apparatus (right) in field – Summer 2010.

The K_{fs} measurements were completed at the Chernozem site on July 21, 2010. The Vertisol site was to be done the following day but was delayed due to rain and completed on July 26, 2010. The timing of infiltration was planned for July because that time is when the farmers typically start irrigating.

To set up the infiltrometer apparatuses, the large rings were inserted into the soil to a 10 cm depth. This restricts lateral flow, which is a common problem with single ring measurements. The double ring was inserted into the soil 5 cm, with water first applied to the outer ring to limit lateral flow. The infiltration method used was a simplified falling-head technique for measurement for rapid determination of K_{fs} adapted from Bagarello, et al (2004). The equation for K_{fs}, is based on analysis of Philip (1992) for falling head one dimensional cumulative infiltration and is listed below:

$$K_{fs} = \frac{\Delta\theta}{(1-\theta)t}\left[\frac{D}{\Delta\theta} - \frac{\left(D-\frac{1}{\alpha}\right)}{(1-\Delta\theta)}\, ln\left(1 + \frac{(1-\Delta\theta)D}{(\Delta\theta)\left(D+\frac{1}{\alpha}\right)}\right)\right] \quad \text{(Eq.2)}$$

The variables required determine K_{fs} are 1) a measurement of the initial volumetric water content (ϑ_1) and the water content following infiltration (ϑ_2), 2) the time it took to infiltrate (t), 3) the depth that the water was ponded at t=0 (D), and 4) a hydraulic parameter (α). Soil samples were collected, weighed and dried using an oven dry method to determine ϑ_1 and ϑ_2. Each infiltration measurement was timed from the beginning of the experiment (t=0) until there was no longer any water ponded on the surface, in order to determine t. Water was applied to the infiltrometer with a ponding depth (D) of 5 cm. 12 m^{-1} was the value used for α, this is a common value used for agricultural soil (Bodhinayake and Si. 2004). A follow up study evaluating the SFH method found that using an estimated value for α versus an actual measured value had no significant effect on the measurement (Bagerello et al., 2012).

3.9 Statistical Analysis

Each site was set up as a randomized complete block design. Statistical Analysis was performed using SPSS, Version 19.0 (IBM Corp. Released 2010. Armonk, NY: IBM Corp.). A main effects model utilizing General Linear Model function was used for comparison of the means and a post-hoc test was performed using Fisher's Least Significant Difference means comparison test.

4 RESULTS AND DISCUSSION

4.1 Site Background Information

A description of the basic properties of the soil at each of the sites in the sub-soiling study is provided in **Table 4.1 & 4.2**. In general, soils were of low organic matter (<2% organic C), neutral to alkaline in pH, non-saline and non-sodic. Textures ranged from silty clay loam to clay.

4.2 2010 Growing Season Results and Discussion

4.2.1 Soil Penetration Resistance

Penetration resistance (PR) measurements were taken on May 19, 2010. The PR effectively showed the depth of tillage and degree of loosening in each of the treatments. The paraplowed treatments showed loosening of the soil down to 40 cm (**Fig. 4.1**). For example, in the Vertisol soil, the conventional (normal configuration) paraplow treatments and control were significantly different ($p<0.10$) down to 35 cm, with significantly lower soil strength for both CF and CS paraplow treatments compared to the control. The measured soil strengths for fall and spring sub-soiling were not significantly different. Overall, both treatments were effective in loosening the soil in both Chernozem and Vertisol sites (**Fig. 4.1** & **Fig. 4.2**).

Table 4.1. Soil chemical properties at Solonetz, Chernozem, and Vertisol sites.

Site	Depth	%OC	pH	EC	Ca		Na	
	cm			*dS/m*	*cmol/kg Mean*	*cmol/kg s.d.*	*cmol/kg Mean*	*cmol/kg s.d.*
Solonetz	0-15	1.33	7.59	0.32	17.2	1.34	0.34	0.06
	15-30	0.89	7.77	0.30	23.7	1.58	0.41	0.08
	30-60	0.52	8.01	0.31	23.8	0.95	0.85	0.22
Chernozem	0-15	1.71	7.66	0.36	20.8	4.89	0.27	0.04
	15-30	1.21	7.73	0.25	21.5	5.46	0.27	0.03
	30-60	0.91	7.94	0.27	22.3	3.72	0.35	0.25
Vertisol	0-15	1.55	7.95	0.31	27.6	2.02	0.57	0.10
	15-30	0.99	8.01	0.35	26.8	0.98	0.79	0.22
	30-60	0.87	8.13	0.44	25.8	0.73	1.46	0.40

Site	Mg		K		CEC		Ca:Na Ratio	ESP
	cmol/kg Mean	*cmol/kg s.d.*	*cmol/kg Mean*	*cmol/kg s.d.*	*cmol/kg Mean*	*cmol/kg s.d.*		
Solonetz	10.8	1.24	0.15	0.03	28.5	2.27	51.8	0.01
	13.9	0.68	0.17	0.02	38.2	2.05	58.6	0.01
	18.2	0.63	0.30	0.06	43.2	1.22	29.4	0.02
Chernozem	11.1	1.53	0.12	0.02	32.2	6.09	78.7	0.01
	15.6	3.66	0.13	0.02	37.5	8.96	79.0	0.01
	19.2	4.46	0.15	0.07	42.0	5.41	81.7	0.01
Vertisol	14.6	0.99	0.22	0.03	43.0	1.08	49.1	0.01
	18.9	2.00	0.29	0.07	46.9	1.24	36.4	0.02
	21.8	1.17	0.49	0.11	49.6	0.92	18.9	0.03

s.d. denotes standard deviation
ESP denotes exchangeable sodium percentage

Table 4.2. Soil texture at Solonetz, Chernozem, and Vertisol sites.

Site	Soil Depth	Sand		Silt		Clay		Textural Class
	cm	%	*s.d.*	%	*s.d.*	%	*s.d.*	
Solonetz	0-15	30.0	3.39	34.7	3.08	35.3	1.51	Clay Loam
	15-30	22.1	2.32	34.2	1.45	43.7	3.52	Clay
	30-60	19.7	5.20	35.4	3.47	44.9	5.63	Clay
Chernozem	0-15	19.7	4.13	42.0	1.11	38.3	4.84	Silty Clay Loam
	15-30	15.2	5.19	39.3	2.06	45.6	5.63	Silty Clay
	30-60	12.1	4.68	39.5	3.75	48.5	4.15	Silty Clay
Vertisol	0-15	16.7	1.63	34.4	1.36	48.8	2.02	Clay
	15-30	14.4	1.41	33.9	1.50	51.7	2.03	Clay
	30-60	11.8	3.77	36.3	1.84	51.9	3.34	Clay

s.d. denotes standard deviation

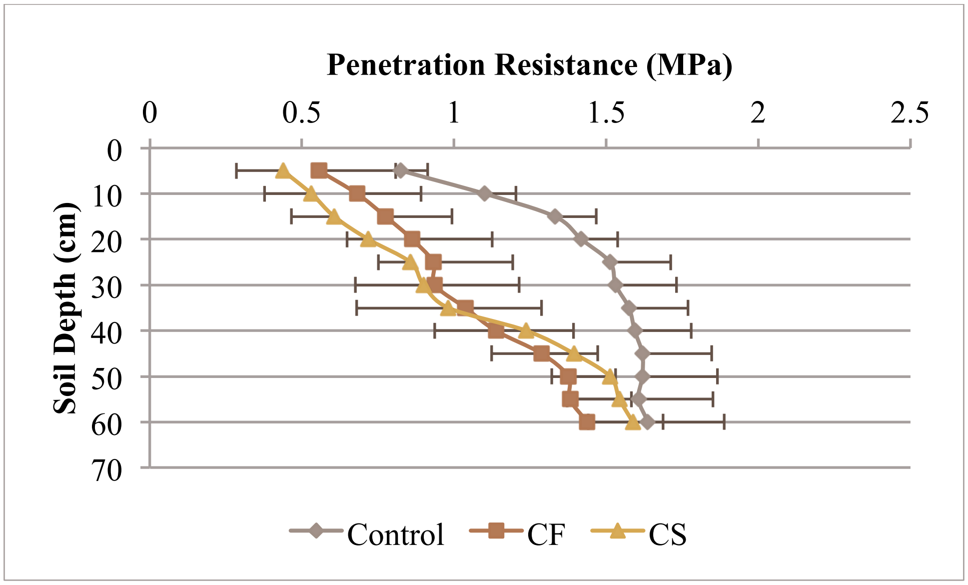

Fig. 4.1. Penetration resistance measured in spring 2010 at the Vertisol site (Error Bars = standard deviation.).

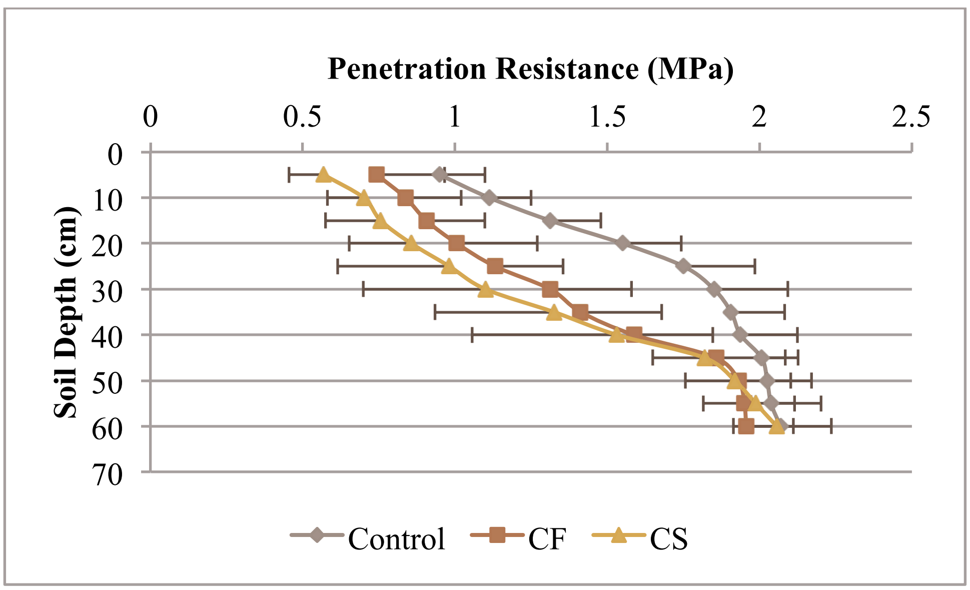

Fig. 4.2. Penetration resistance measured in spring 2010 at the Chernozem site (Error Bars = standard deviation).

Penetration resistance is often used to identify compacted layers within the soil. No or little evidence of compaction was evident within the PR measurements. If the soil were compacted, a distinct spike in PR would be observed in the graph of the control. If there were an isolated region of compaction such as in the wheel tracks, it would not be evident because of the plot design, which specifically avoided wheel track locations. Isolated areas may be identifiable by observing individual lines recorded by the pentrograph on the recording sheet, but no areas of compaction were observed. Therefore it would appear that, at least on these irrigated soils, the soil compaction that was suspected was not actually present or detectable in the fields. The PR measurement did show that sub-soil tillage loosened the soil down to the target tillage depth of 45 cm. Even loosening was identified down to 35 cm in the CF and CS treatments, but only down to 20 cm in the SF, WF and WS treatments (**Fig. 4.3** & **Fig. 4.4**). This is mostly related to the uneven loosening pattern created by the wide row spacing treatments. As such, wider than normal configuration (i.e. 90 vs 45 cm row spacings) and shallower sub-soiling (30cm versus 45 cm depth) is expected to be less effective. The results of this study agree with those of Pierce et al. (1992) in Michigan, who found that zone tillage with a paraplow and similar zone tillage implements reduced PR. Pierce et al. (1992) also compared 51 cm spacing and 76 cm spacing and while both treatments gave similar results in PR in the first growing season, the residual effects of the paraplow did not last as long with the wider spacing. In the current study, the wide spacing treatment was also not as effective.

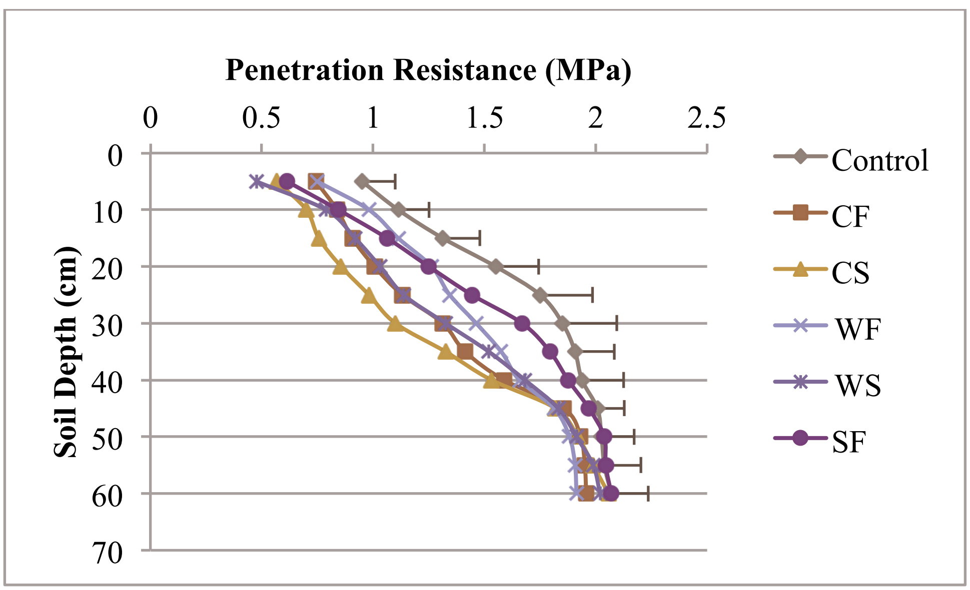

Fig. 4.3. Penetration resistance measured at the Chernozem site – all treatments (Error Bars = standard deviation).

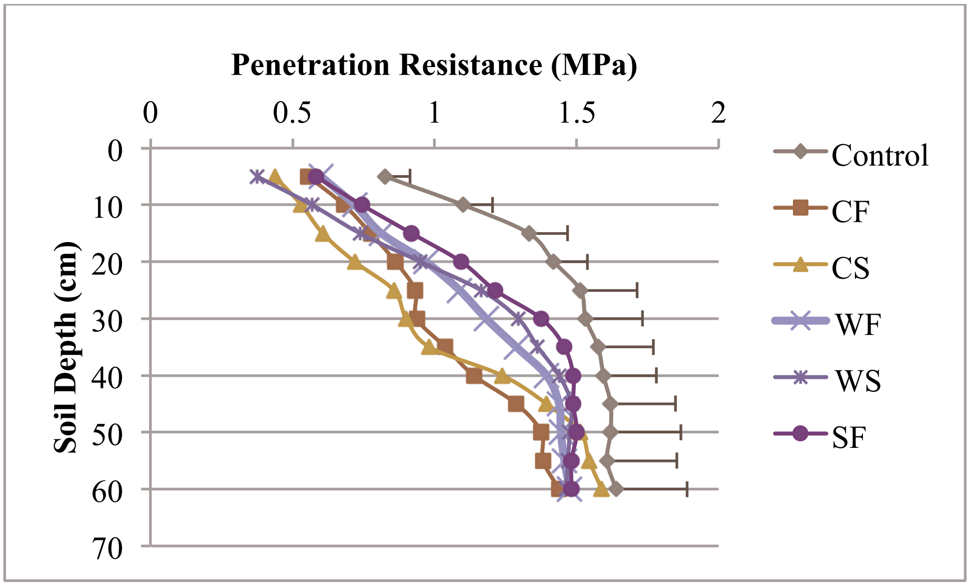

Fig. 4.4. Penetration resistance measured at the Vertisol site – all treatments (Error Bars = standard deviation).

4.2.2 Effect of Shank Row Spacing and Depth

The effect of the set-up configuration of the paraplow machine was only monitored in the first growing season (2010). Overall, the paraplow in the conventional setup from the manufacturer (45 cm row spacing, 45 cm sub-soiling depth) was the most effective in decreasing penetration resistance (**Fig. 4.3** & **Fig. 4.4**), bulk density (**Table 4.3**) and ultimately enhancing infiltration (**Fig. 4.7** & **Fig. 4.8**). The wide row spacing treatments were somewhat effective less effective, due to uneven loosening evident in the PR measurements (**Fig. 4.5**).

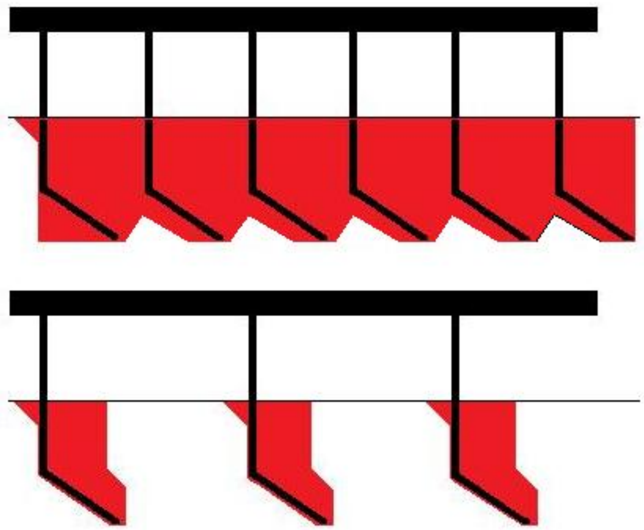

Fig. 4.5. Observed loosening pattern comparing conventional (45 cm) and wide (90 cm) treatments

The alteration from normal, conventional treatment that appeared to have the greatest impact was a shallower than normal depth of sub-soiling. Most of the other treatments had very little surface disturbance while the shallow (30 cm depth) paraplow treatment left the soil surface uneven with clods of soil that would produce a less than optimal seed bed.

4.2.3 Bulk Density and Water Content

Heavy rains affected the initial soil sampling in the spring. Sampling was completed at the Vertisol site, a partial set of soil samples was collected from the Solonetz site, and no samples could be collected from the Chernozem site in spring 2010. The rain continued for a period of two weeks leaving the soil completely saturated. During this time the Solonetz site was flooded for an extended period and received erosional deposition, leading to the decision to abandon the site. The bulk density values for the sites for spring and fall sampling in 2010 are shown in **Table 4.3** and the volumetric water contents are shown in **Table 4.4**.

Table 4.3. Bulk Densities (ρ_b) measured at the sites in 2010.

Site	Depth	Treatment												
	cm	Control		CF		WF		SF		CS		WS		LSD 0.05
		Mean	*s.d.*	*Mean*	*s.d.*	*Mean*	*s.d*	*Mean*	*s.d.*	*Mean*	*s.d.*	*Mean*	*s.d.*	
		---------- $Mg\ m^{-3}$ ----------												
Spring 2010														
Solonetz†														
	0-15	1.26	0.18	1.35	0.09	1.24	0.12	1.32	0.11	1.15	0.05	1.27	0.13	0.17
	15-30	1.49	0.11	1.45	0.08	1.49	0.07	1.47	0.03	1.53	0.20	1.49	0.15	0.14
	30-45	1.60	0.10	1.69	0.11	1.69	0.12	1.65	0.08	1.70	0.09	1.64	0.09	0.13
	45-60	1.66	0.09	1.70	0.08	1.72	0.21	1.55	0.12	1.73	0.06	1.71	0.10	0.19
	60-90	1.75	0.12	1.50	0.45	1.64	0.06	1.66	0.07	1.67	0.06	1.98	0.80	0.52
Vertisol														
	0-15	1.24	0.07	1.00	0.15	1.13	0.13	1.21	0.17	1.01	0.12	1.09	0.17	0.13
	15-30	1.45	0.11	1.35	0.11	1.39	0.13	1.37	0.09	1.27	0.12	1.30	0.19	0.13
	30-45	1.48	0.07	1.50	0.07	1.55	0.07	1.47	0.63	1.49	0.07	1.41	0.24	0.12
	45-60	1.49	0.05	1.49	0.08	1.48	0.07	1.58	0.04	1.54	0.07	1.44	0.25	0.12
	60-90	1.43	0.17	1.48	0.09	1.39	0.22	1.46	0.10	1.49	0.11	1.36	0.25	0.15
Fall 2010														
Chernozem														
	0-15	1.19	0.13	1.28	0.09	1.26	0.10	1.20	0.10	1.23	0.12	1.25	0.07	0.12
	15-30	1.42	0.05	1.31	0.12	1.42	0.13	1.42	0.10	1.39	0.06	1.45	0.08	0.13
	30-45	1.57	0.17	1.59	0.10	1.55	0.04	1.48	0.11	1.54	0.07	1.57	0.07	0.11
	45-60	1.57	0.15	1.58	0.11	1.68	0.03	1.55	0.12	1.61	0.09	1.60	0.07	0.11
	60-90	1.91	0.83	1.53	0.22	1.38	0.43	1.59	0.19	1.59	0.11	1.64	0.12	0.45
Vertisol														
	0-15	1.31	0.07	1.37	0.08	1.33	0.11	1.35	0.05	1.39	0.08	1.33	0.04	0.10
	15-30	1.44	0.06	1.46	0.09	1.47	0.03	1.47	0.08	1.45	0.04	1.51	0.04	0.07
	30-45	1.54	0.10	1.48	0.08	1.50	0.10	1.53	0.06	1.60	0.08	1.48	0.01	0.09
	45-60	1.58	0.06	1.55	0.04	1.55	0.04	1.52	0.12	1.60	0.01	1.55	0.02	0.07
	60-90	1.57	0.13	1.44	0.10	1.48	0.04	1.43	0.20	1.60	0.19	1.50	0.17	0.20

† For Solonetz site in spring of 2010, some treatments have only two replicates.

Table 4.4. Volumetric Water Content (θ_v) measured in 2010.

Site	Depth	Treatment												
	cm	Control		CF		WF		SF		CS		WS		LSD 0.05
		Mean	*s.d.*	*Mean*	*s.d.*	*Mean*	*s.d.*	*Mean*	*s.d.*	*Mean*	*s.d.*	*Mean*	*s.d.*	
		----------					$\% \, m^3 m^{-3}$					----------		
Spring 2010														
Solonetz†														
	0-15	32	2.9	34	5.7	36	5.3	32	2.0	30	1.3	32	2.0	5.1
	15-30	38	1.9	37	2.8	37	1.3	37	2.1	39	4.3	41	3.1	3.9
	30-45	40	3.3	38	0.8	40	2.0	40	2.0	41	2.4	40	1.6	3.3
	45-60	41	1.9	38	4.1	38	5.0	39	3.1	41	2.3	41	1.9	4.5
	60-90	43	3.5	35	11	44	2.4	40	3.6	44	3.9	49	21.0	13.0
Vertisol														
	0-15	37	3.3	31	4.0	38	4.8	36	7.8	32	4.0	29	5.5	5.2
	15-30	42	2.4	37	3.9	40	3.5	39	6.7	37	3.0	36	6.4	4.7
	30-45	42	2.4	40	3.9	41	2.3	41	3.0	41	4.6	38	6.9	4.3
	45-60	44	3.4	40	4.1	44	1.5	42	2.8	40	4.6	38	9.2	5.0
	60-90	44	6.0	41	5.1	43	4.2	41	7.3	36	4.8	39	7.7	5.5
Fall 2010														
Chernozem														
	0-15	31	5.4	36	3.4	33	3.4	34	2.8	35	5.7	33	1.1	4.5
	15-30	38	1.7	37	4.7	38	2.7	41	3.1	40	3.1	42	2.2	4.1
	30-45	38	4.2	39	3.3	40	3.4	41	3.3	40	3.7	39	3.1	3.2
	45-60	38	3.4	39	3.5	38	5.7	38	2.8	36	5.8	38	4.7	4.9
	60-90	41	10	36	3.1	30	9.8	35	5.4	35	5.5	35	4.5	8.9
Vertisol														
	0-15	33	1.8	37	3.5	36	4.3	36	2.9	45	17	35	1.4	9.8
	15-30	39	3.1	40	3.3	42	3.6	40	4.5	41	3.4	41	3.2	4.5
	30-45	49	7.3	37	5.8	39	3.9	42	1.7	43	8.6	38	5.0	7.1
	45-60	44	4.1	41	4.6	45	3.9	43	5.2	48	15	41	3.1	9.7
	60-90	50	12.0	45	14.0	44	2.4	40	5.9	41	6.9	39	5.4	12.0

† For Solonetz site in spring of 2010, some treatments have only two replicates.

Soil cores were removed close to the furrow and between furrows at each plot in the Spring 2010. The bulk densities along with the PR measurements help to identify any variations in the uniformity of the subsoiling treatments across the plot area. The conventional treatments produced the most uniform loosening pattern with less than 0.1 Mg m^{-3} differences in the bulk densities in the top three sampling depths (**Fig. 4.6**). The spring wide treatment was the least uniform with variability of 0.2 Mg m^{-3} at the 15-30, 30-45, and 45-60 cm soil depths. The treatments that were tilled in the fall were less variable than the spring treatments. The tillage induced porosity in the wide treatment was diminished much more rapidly than the conventional set up, as observed the PR (**Fig. 4.3** & **Fig. 4.4**) and ρ_b measurements (**Table 4.3**). Volumetric water content was measured over the course of the study (**Table 4.4**). At the Vertisol in spring 2010, lower water contents were observed in the top 15 cm of the soil in the conventional paraplow treatments. This may be indicative of improved hydraulic conductivity through upper portion of the soil horizon in this treatment. Further analyses found no changes or trends in volumetric water content between treatments when soil sampling took place in the spring and fall.

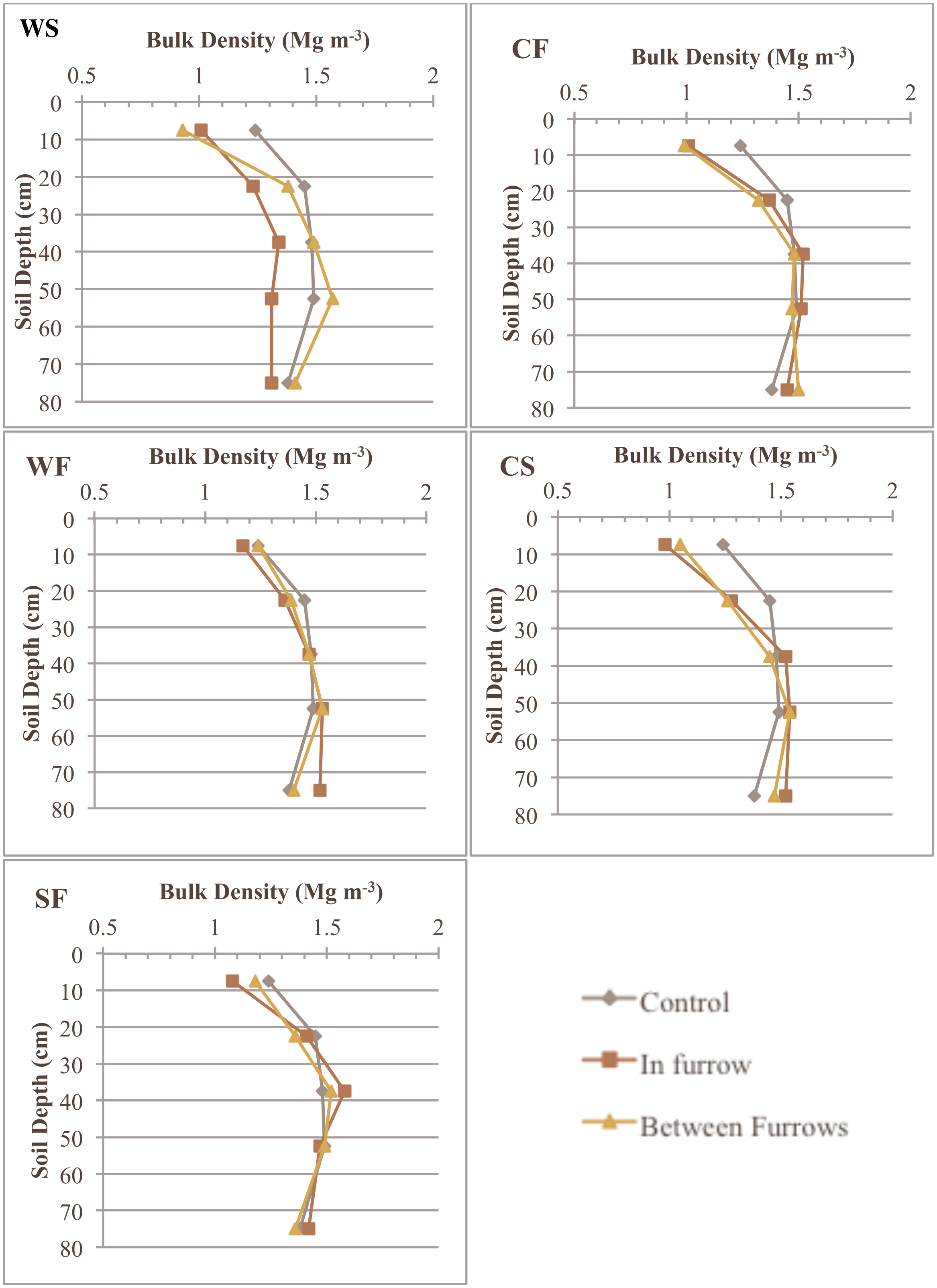

Fig. 4.6. Bulk densities observed near and between furrows compared to the control at Vertisol site.

Soil sampling for density and soil water continued on the conventional normal configuration paraplow treatments into 2011 and the results are provided in the Appendix. In 2011, no significant effects were observed among treatments, with exception of the 30-45 cm sample depth at the Chernozem, which may be indicative of a residual tillage effect.

4.2.4 Field Saturated Hydraulic Conductivity Measurements

Field saturated hydraulic conductivity measurements were taken in July 2010 using a large single ring and double ring infiltrometers (Bagarello et al., 2004) to provide a measure of field saturated hydraulic conductivity (K_{fs}). Overall, there was a significant ($p<0.10$) increase in K_{fs}, after sub-soiling with the paraplow (**Fig. 4.7** & **Fig. 4.8**). Paraplowing resulted in enhanced infiltration capacity of water in 2010 as revealed in higher K_{fs} values (**Fig. 4.7** & **Fig. 4.8**) that were consistent with the measured effects of the treatments on lowering bulk density and increasing porosity as discussed in the previous section. Overall, the Vertisol site had lower hydraulic conductivity and infiltration compared to the Chernozem site, which is explained by higher clay content of the Vertisol soil. The increases in hydraulic conductivity from paraplowing were variable, depending on the site. At the Vertisol site, two of the three fall paraplowing treatments were quite similar to the control, much like the bulk densities, suggesting the effects of paraplowing may not be as persistent in soil of high clay content. The Chernozem site showed evidence of increased K_{fs} in conventional paraplowed soils (45 cm depth 45 cm spacing) in fall and especially in spring. Wide spacing (90cm) did not produce significantly higher infiltration than controls in these two soils, indicating that the wide spacing is relatively ineffective in enhancing infiltration regardless of soil type or time of year imposed. There was also evidence at the Chernozem site that the effects of paraplowing may persist beyond five months. The spring treatments appear to have the greatest influence on hydraulic conductivity. At the Vertisol site, two of the three fall paraplowing treatments were quite similar to the control. This trend is consistent with the fall bulk density measurements. This suggests that the sub-soiling effects are being degraded over time.

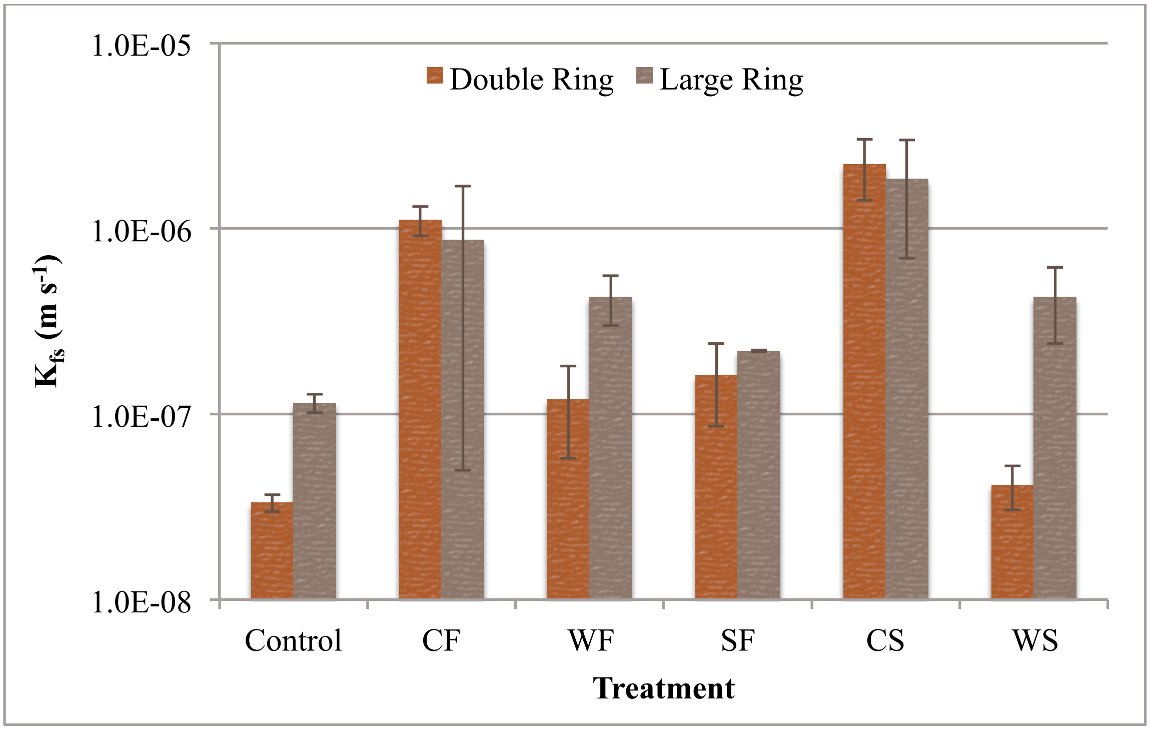

Fig. 4.7. K_{fs} measured using large and double ring infiltrometers at Chernozem site (Error Bars = standard error).

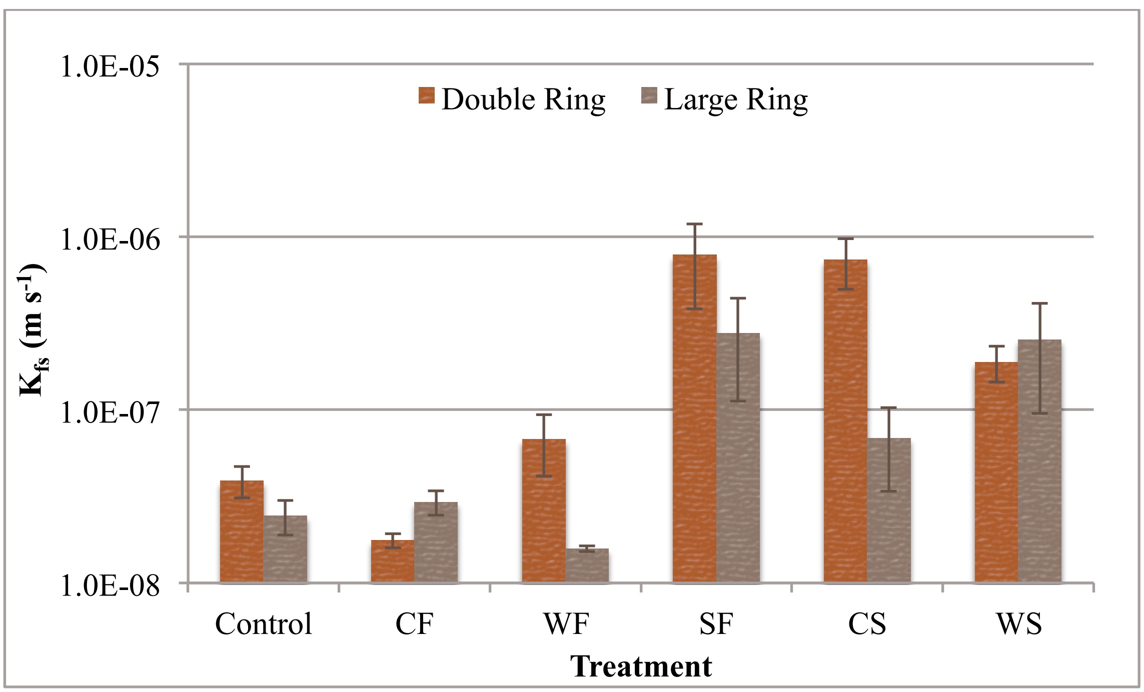

Fig. 4.8. K_{fs} measured using large and double ring infiltrometers at Vertisol site (Error Bars = standard error).

4.2.5 2010 Crop Yields

Small and variable effects on crop yield were observed at the two sites (**Fig. 4.9** & **Fig. 4.10**). At the Chernozem site, with conventional configuration (CF - 45 cm row spacing, 45 cm depth), mean wheat grain yield was 281 and 314 kg/ha higher than the control in the fall and spring paraplow treatments respectively. However, these yield increases were not statitistically significant ($p<0.10$). There were no significant effects of any of the paraplow sub-soiling treatments on canola yield compared to the control at the Vertisol site.

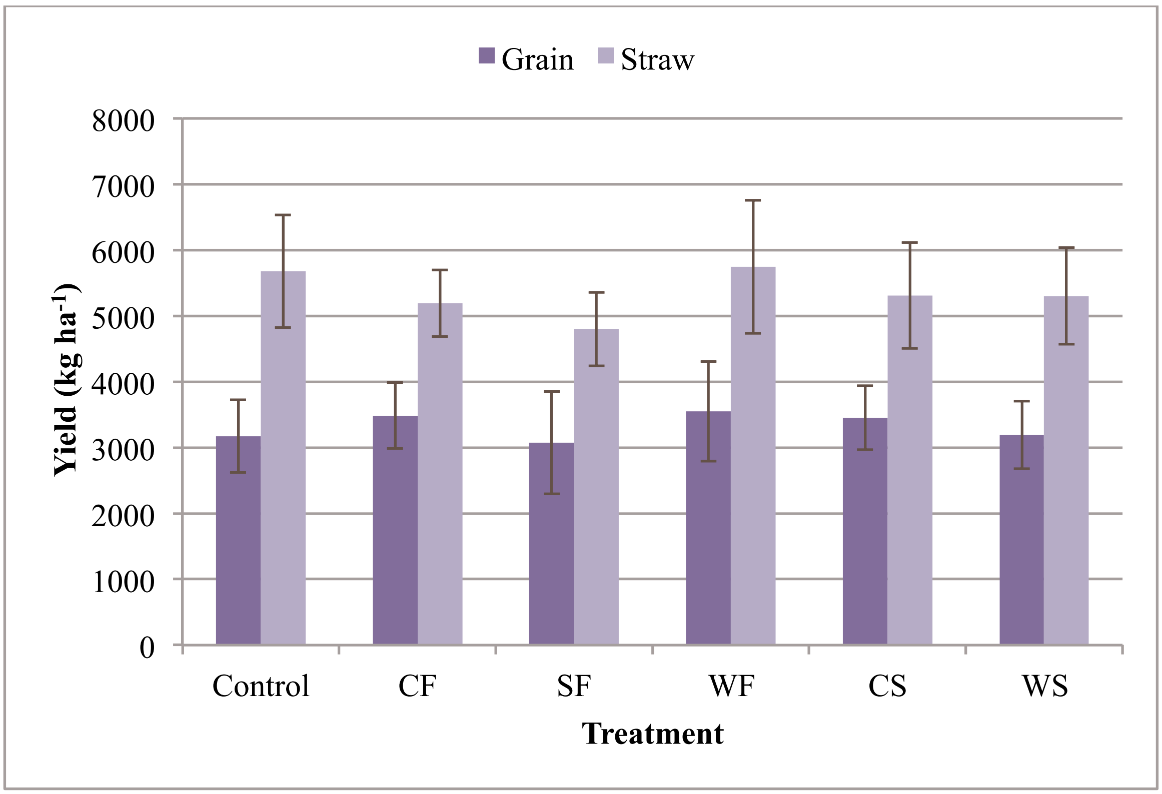

Fig. 4.9. Wheat harvest grain and straw yield at the Chernozem site in 2010 – Hard Red Spring Wheat (Error Bars = standard deviation).

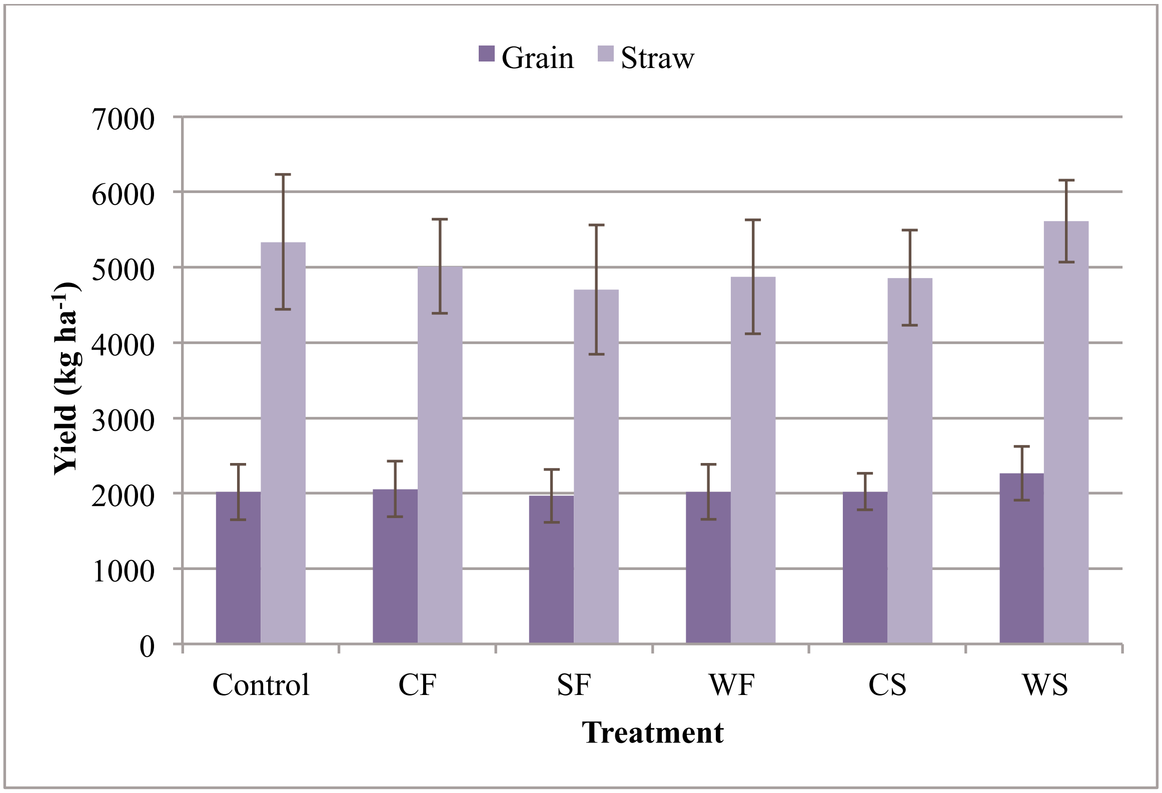

Fig. 4.10. Canola harvest grain and straw yield at the Vertisol site in 2010 - Canola (Error Bars = standard deviation).

4.2.6 Soil and Plant N

Soil and plant nitrogen was monitored throughout the study. With the exception of soil nitrate in the spring of 2010, paraplowing had limited effect. In spring of 2010 some differences were observed in soil nitrate content (**Table 4.5**). All soil and plant N data are provided in appendix.

Table 4.5. Soil profile NO_3-N concentrations (μg NO_3-N g^{-1} soil) in spring of 2010.

Treatment	Sampling depth			
	0- 30 cm		30 -60 cm	
	Mean	*s.d.*	*Mean*	*s.d.*
	μg g^{-1}	μg g^{-1}	μg g^{-1}	μg g^{-1}
Chernozem				
Control	31	16	19	11
CF	31	20	17	13
SF	6.6	4.4	12	7.8
WF	22	15	4.4	1.1
CS	10	7.1	6.0	2.4
WS	17	9.7	9.7	4.1
LSD 0.10	12			
Solonetz				
Control	3.7	1.4	6.9	3.8
CF	6.7	1.8	14	3.9
SF	5.6	2.8	8.3	6.0
WF	6.1	5.3	8.2	2.7
CS	5.4	2.3	9.7	3.2
WS	8.5	6.0	13	9.0
LSD 0.10	3.2			
Vertisol				
Control	2.6	0.47	3.2	0.1
CF	2.4	0.35	2.9	1.0
SF	2.0	0.65	4.2	1.6
WF	3.2	0.87	2.7	0.5
CS	2.6	0.64	3.3	0.8
WS	2.5	0.42	3.2	0.7
LSD 0.10	0.52			

There is some indication that paraplowing may affect soil profile nitrogen content in soils during periods of excessive wetness such as spring 2010. Soil profile nitrate was generally higher in paraplowed treatments relative to the undisturbed control at the Solonetz, while at the Chernozem site nitrate was lower. Soil nitrate concentrations at the Vertisol were relatively unaffected by paraplow treatment. Paraplowing may have reduced losses of the fall applied N at the Solonetz by increasing aeration and reducing denitrification. For the Chernozem site, in which the N was spring applied, the paraplowing treatments may have increased N leaching and/or denitrification losses. Limited impact of the paraplow treatments on distribution of nitrate in the soil profile of the Vertisol agrees with results of Lopez-Fando and Pardo (2009) who found that paraplowing had little effect on the distribution of nutrient compared to no-till.

4.3 2011 & 2012 Growing Season Results and Discussion

The 2011 season provided an opportunity to set up two new sites (Chernozem 2 Irrigated, Chernozem 2 Dryland) under more normal precipitation conditions and compare effects of irrigation versus dryland, and also monitor second year effects from treatments imposed in fall 2009 and spring 2010. A dryland comparison enables evaluation of treatment persistence under dry versus moist soil conditions and the impact of wet-dry cycling on the longevity of the treatments. The ρ_b was measured in the fall following sub-soiling with the paraplow. A reduction of about 0.2 Mg m^{-3} in ρ_b was observed in the top 30 cm of soil associated with sub-soiling (**Fig. 4.11**). Compared to the persistence of tillage treatments imposed in fall 2009 and spring 2010 which experienced very wet conditions, a more persistent effect was observed in the new sites established in 2011. **Fig. 4.11** shows the bulk densities measured in Fall 2011, Spring 2012, and Fall 2012 (Top to Bottom). The significant treatment effects on density are summarized in **Table 4.6** and volumetric water content results are shown in **Fig. 4.12**.

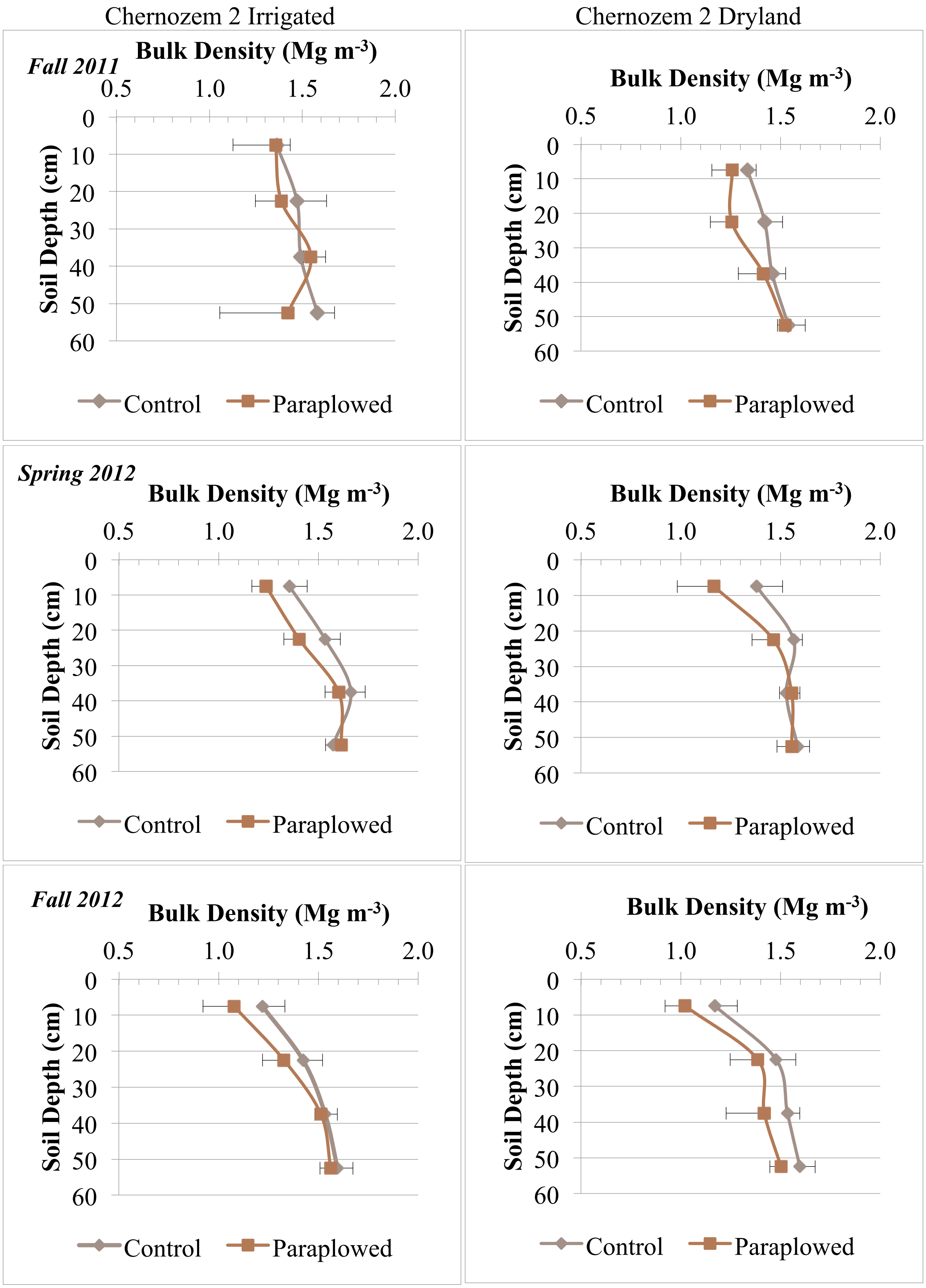

Fig. 4.11. Summary of bulk densities at Chernozem 2 Irrigated (left) and Chernozem 2 Dryland (right) sites in fall 2011, spring 2012 and fall 2012 (Error Bars = standard deviation).

It appears that the soil loosening effects from the paraplow sub-soiling are still evident up to one year after paraplowing. Significant ($p<0.10$) effects were observed in the top two sampling depths (0–15 cm and 15–30 cm). The measurements from the fall of 2012 do show some signs of loss of the treatment effect, with only the Chernozem 2 Irrigated 15–30 cm depth measurement still showed a significant reduction in density. The tillage effect may persist longer under irrigated conditions as the soil experiences fewer wet-dry cycles throughout the season compared to a dryland cropping system, provided that the soil is not completely saturated like it was in 2010 at the original sites. Clark et al. (1993) found that paratillage improved infiltration but was only effective for a period of up to one year before reconsolidation occurred.

Table 4.6. Observed significance of differences between the bulk densities measured in Conventional Spring paraplow and Control treatments.

Sampling Depth	**Fall 2011**		**Spring 2012**		**Fall 2012**	
cm	*Irrigated*	*Dryland*	*Irrigated*	*Dryland*	*Irrigated*	*Dryland*
	---------------------------------- Mg m^{-3} ----------------------------------					
0 -15	*	-	**	*	-	-
15-30	***	**	*	*	**	-
30-45	-	-	-	-	-	-
45-60	-	-	-	-	-	*

*** treatments are significantly different $p \geq 0.01$
** treatments are significantly different $p \geq 0.05$
* treatments are significantly different $p \geq 0.1$

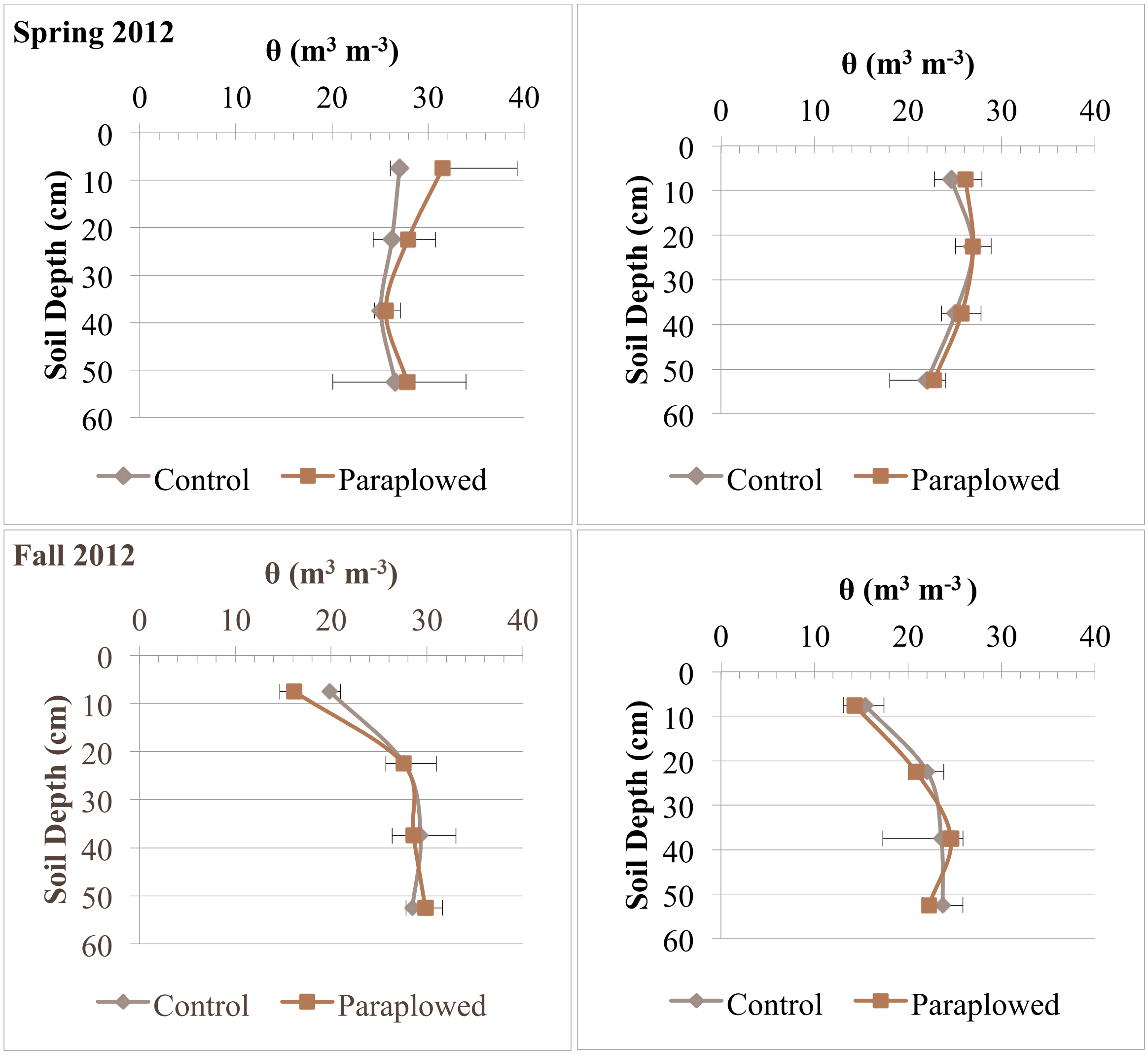

Fig. 4.12. Summary of volumetric water content (m^3 m^{-3}) at Chernozem 2 Irrigated (left) and Chernozem 2 Dryland (right) sites in spring 2012 and fall 2012 (Error bars = standard deviation).

4.4 Crop Yields & Economic Analysis

Overall, paraplowing did not have a significant effect on crop yield in 2011 and 2012 under irrigated conditions (Chernozem, Vertisol, Chernozem 2 Irrigated) when comparing treatments (**Fig. 4.13** & **Fig. 4.14**). However, some significant ($p<0.05$) yield benefit was observed with paraplowing at the Chernozem 2 Dryland site in 2012. This suggests that under dryland conditions, a yield benefit may be realized that could be attributed to better rooting and water relations as a result of the paraplowing operation. Where water is not limiting, as in an irrigated cropping system, the benefit of a factor like increased water storage would be less pronounced.

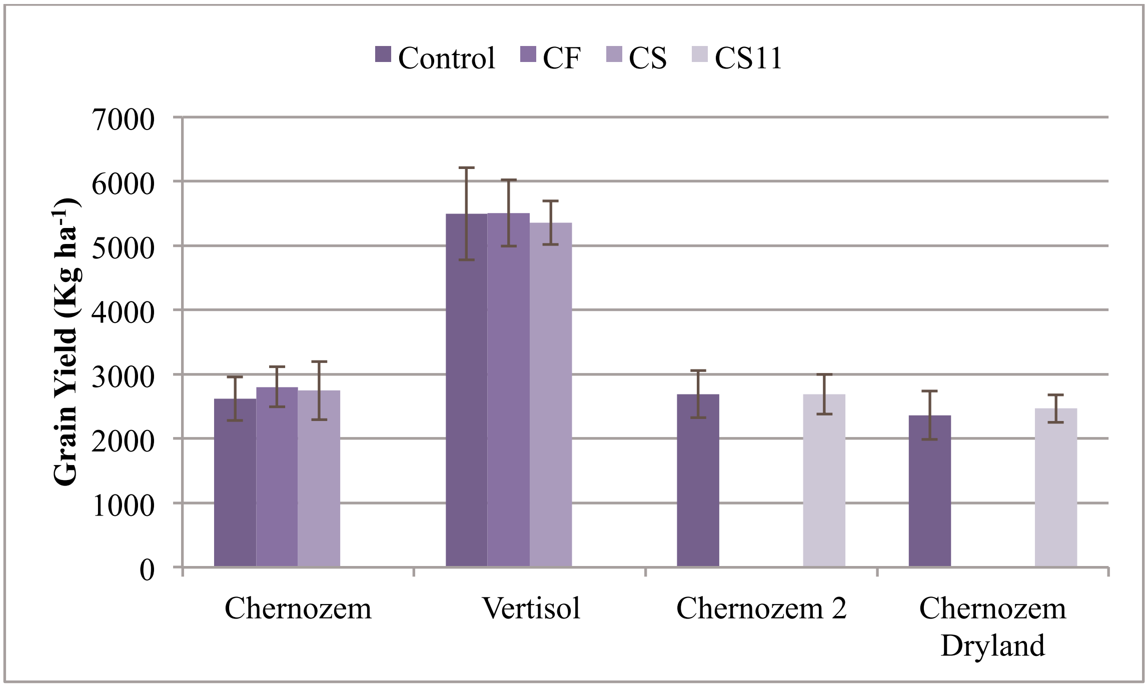

Fig. 4.13. Mean grain yield at all sites in 2011 (Error Bars = standard deviation).

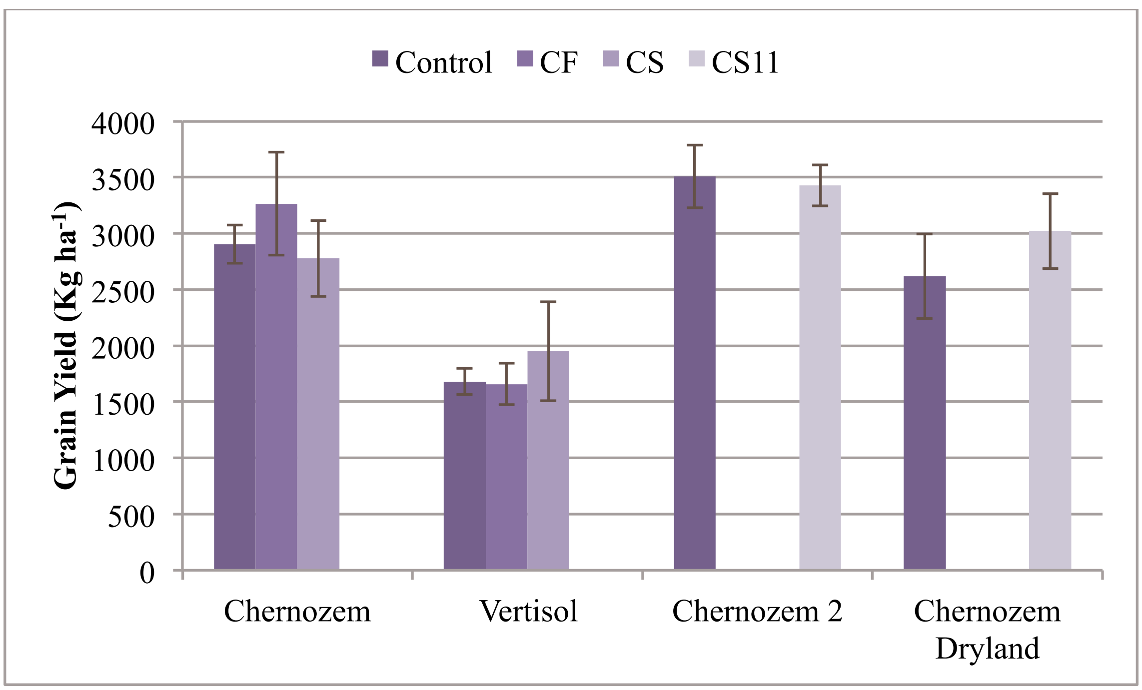

Fig. 4.14. Mean grain yield at all sites in 2012 (Error Bars = standard deviation).

A simplifed statistical model was utilized to compare the paraplowed treatments (CF & CS or CS11) to the control. The results are shown below (**Fig. 4.15** & **Fig. 4.16**), presented as grain yield in paraplow treatment as a percentage of the control yield.

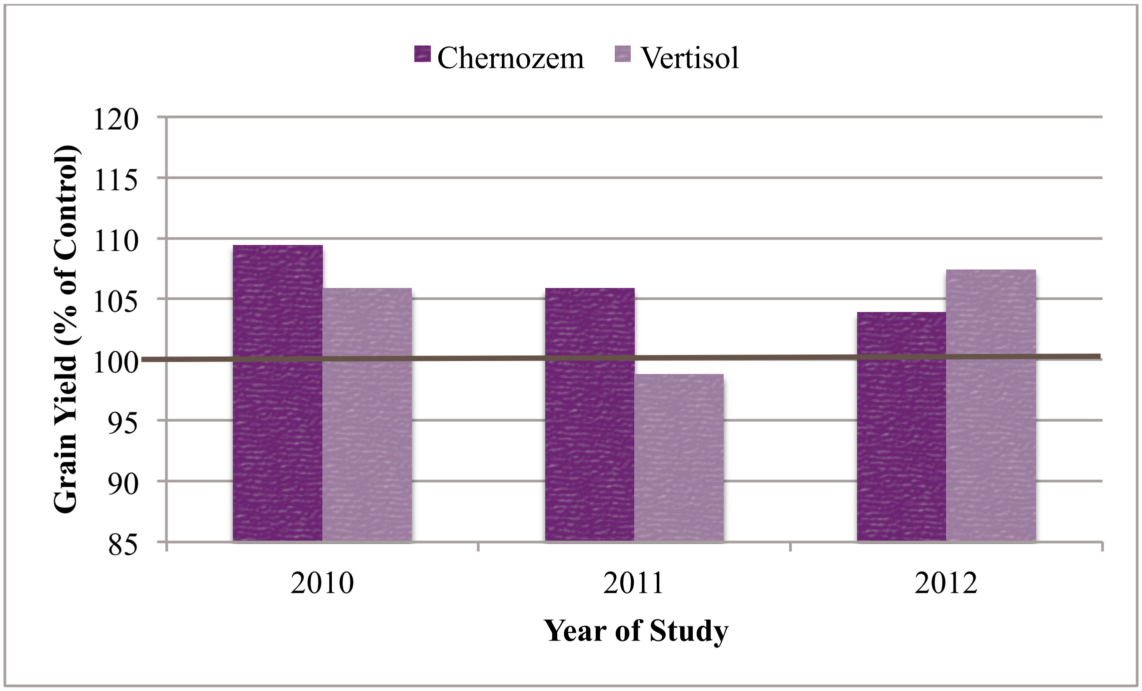

Fig. 4.15. Mean grain yield in paraplow treatments (CF and CS combined) in the Chernozem and Vertisol soils as a percentage of the control.

The trend in the grain yield on the Chernozem indicates a small yield benefit from paraplowing, albeit deteriorating over time. The grain yield was more variable at the Vertisol site, possibly due the environmental conditions, crop rotation, or soil processes within the soil. After two years, there were no significant effects on measured bulk density at this Vertisol site, so the effects on yield must be related to some other factor that may be affected by paraplowing. The yield response although not significant, may be attribruted to enhanced aeration under wet conditions or the improved infiltration capacity.

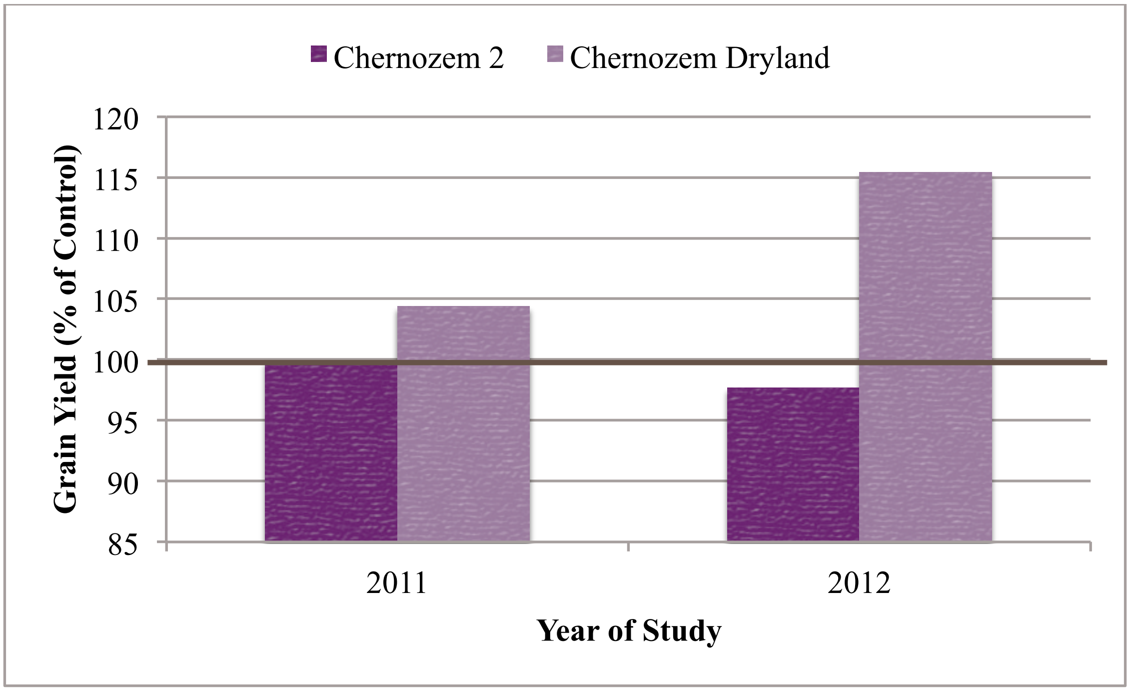

Fig. 4.16. Mean paraplow yield on Chernozem 2 (CS11) soil as a percentage of the control.

For the Chernozem 2 Irrigated and Chernozem 2 Dryland sites established in 2011 (**Fig. 4.16**), it is evident that paraplowing has a greater impact on grain yield under dryland management. Unlike the irrigation, dryland yields may be limited by water. Enhanced snowmelt infiltration in a dry year may contribute to increased grain yields. When assessing the yield performance at the dryland site, it is important to remember that the dryland corners were fertilized as if they were irrigated. For the Chernozem 2 Irrigated site, paraplowing had little or no effect on grain yield, unlike the original Chernozem site that was established in 2009. This may be a product of the sites being in slightly different landscape positions, and the fact that the tillage operations occurred at different times and under different soil and environmental conditions.

Over the course of the study, with the exception of the Vertisol in 2011 and the Chernozem 2 irrigated site, the paraplow treatments out yielded the control, but in most cases the yield increases were not statistically significant at the 0.05 probability level. The average difference between paraplowed treatments and the un-tilled control was about five percent higher crop yield in the paraplow treatments.

The small and variable effects of subsoiling on crop yield observed in this study are in agreement with many other studies such as Aase et al. (2001) who found no yield benefit for barley or beans after paratilling a silt loam soil in Idaho. In Solonetz dryland soils in Saskatchewan, Grevers and de Jong (1993) did observe significant grain yield responses but not when subsoiling Chernozem soils. Unfortunately, in the current study, the soil with solonetzic characteristics was lost to flooding. In Manitoba, subsoiling heavy clays resulted in improved early season crop growth (Wang et al. 2009).

Farmers are looking at subsoiling to improve productivity of their operation. It is important to assess if tillage operation is economical, the cost of the operation must be calculated and compared to the benefit realized in additional crop yield and its economic value. The approximate cost of paraplowing is \$30 per acre (\$74 ha^{-1}) using Alberta Agriculture and Rural Development Machine Cost Calculator (Nibourg, 2008). A plow was selected as the implement with modifications that were made to reflect the specific design configuration of the paraplow that was used in the current study (**Table 4.7**).

Another calculator was used to calculate the cost, the Saskatchewan Ministry of Agriculture's tool: *Farm Machinery Custom and Rental Rate Guide Calculator.* It came up with a very similar cost evaluation. There are a number of variables that could increase the cost of tillage from average cost point, namely tillage speed, increased maintenance costs, annual use (number of acres). Below is an example of paraplowing conducted under extremely dry or compacted conditions, where the annual maintenance cost has been increased to \$2500 and the tillage speed was reduced to 3 mph, increasing the cost to ~\$50 ac^{-1} (\$124 ha^{-1}) (**Table 4.8**).

Table 4.7. Cost of paraplowing using Alberta Agriculture and Rural Development - Machinery Cost Calculator (Nibourg, 2008).

Data and assumptions	**Tractor - Front Wheel Assist 225 HP**	**Plows 5 X 16" Semi 3-point**	
A Purchase price	$214375.00	$40000.00	
B Planning period (years)	10	15	
C Residual Value (at end of planning period)	$107187.50	$4000.00	
D Annual hours of use (total use all operations)	400	150	
E Fuel Usage (litres per hour)	37.00		
F Fuel Cost ($ per litres)	$0.80		
G Labour cost ($ per hour)	$20.00		
H Annual repair cost	$6431.25	$800.00	
I Expected Return on Capital	4.50%		
J Marginal tax rate	25.00%		
K Rate of inflation	2.00%		
L CCA class rate	30%	20%	
M Working width (ft)	10	10	
N Working speed (mph)	4.5	4.5	
O Field Efficiency (%)	70.00%	70.00%	
P Acres per Hr	3.89	3.89	
Cost Results			
Ownership Costs	**Tractor - Front Wheel Assist 225 HP**	**Plows 5 X 16" Semi 3-point**	**Total**
1. Capital recovery ($ per year)	$10551.02	$2190.88	
2. Insurance and housing ($ per year)	$2143.75	$400.00	
3. Total annual ownership costs	$12694.77	$2590.88	
4. Total ownership costs per hour	$31.73	$17.27	$49.00
Operating Costs			
1. Fuel Cost	$8880.00		
2. Lubrication	$1332.00		
3. Repairs	$6431.25	$800.00	
4. Labour	$8000.00		
5. Total annual operating costs	$24643.25	$800.00	
6. Total annual operating costs per hour	$61.60	$5.33	$66.93
Total Costs			
1. Total annual costs	$37338.02	$3390.88	
2. Total cost per hour	$93.34	$22.60	$115.93
3. Total cost per acre	$23.99	$5.80	$29.79

Table 4.8. Cost of paraplowing using Alberta Agriculture and Rural Development - Machinery Cost Calculator (Nibourg, 2008) – Heavy compacted soil or dry conditions.

Data and assumptions	**Tractor - Front Wheel Assist 225 HP**	**Plows 5 X 16" Semi 3-point**	
A Purchase price	$214375.00	$40000.00	
B Planning period (years)	10	15	
C Residual Value (at end of planning period)	$107187.50	$4000.00	
D Annual hours of use (total use all operations)	400	150	
E Fuel Usage (litres per hour)	37.00		
F Fuel Cost ($ per litres)	$0.80		
G Labour cost ($ per hour)	$20.00		
H Annual repair cost	$6431.25	$2500	
I Expected Return on Capital	4.50%		
J Marginal tax rate	25.00%		
K Rate of inflation	2.00%		
L CCA class rate	30%	20%	
M Working width (ft)	10	10	
N Working speed (mph)	3	3	
O Field Efficiency (%)	70.00%	70.00%	
P Acres per Hr	2.56	2.56	
Cost Results			
Ownership Costs	**Tractor - Front Wheel Assist 225 HP**	**Plows 5 X 16" Semi 3-point**	**Total**
1. Capital recovery ($ per year)	$10551.02	$2190.88	
2. Insurance and housing ($ per year)	$2143.75	$400.00	
3. Total annual ownership costs	$12694.77	$2590.88	
4. Total ownership costs per hour	$31.73	$17.27	$49.00
Operating Costs			
1. Fuel Cost	$8880.00		
2. Lubrication	$1332.00		
3. Repairs	$6431.25	$2500	
4. Labour	$8000.00		
5. Total annual operating costs	$24643.25	$2500.00	
6. Total annual operating costs per hour	$61.60	$16.66	$78.26
Total Costs			
1. Total annual costs	$37338.02	$5090.88	
2. Total cost per hour	$93.34	$33.93	$127.26
3. Total cost per acre	$36.46	$13.25	$49.71

To apply a break-even analysis using the initial cost calculations, the producer will need to obtain about an additional \$30 per acre (\$74 ha^{-1}) worth of yield. For the two crops grown on the Chernozem 2 site in 2011: flax and hard red spring wheat, the producer would have to realize a yield increase of 3-5 bu ac^{-1} from paraplowing to break even, assuming prices similar to the current market value (2012).

With a 5% yield increase from a 20 bushel per acre flax crop equating to 1 bushel per acre, valued at \$12.00 per bushel, the increased gross return of \$12.00 per acre would not cover the cost of the paraplowing. Therefore the benefits would need to persist beyond the first year in order to break even or achieve economic benefit. The only way annual subsoil tillage could be justified is with higher value crops than currently grown in the region, assuming similar crop yield responses. Similar to the results of this thesis, other studies showed that while paraplowing improved soil properties and plant growth, there was limited grain yield response and, due to the high cost of the operation, paraplowing was not economical (Franzluebbers et al., 2007). The results of my study suggest that benefits may extend beyond the first year into the second, but the effect diminishes over time and degree of persistence is dependent on soil and environmental conditions. High moisture as from above normal precipitation or irrigation, and high clay content appear to reduce the persistence of the sub-soiling effects.

Farmers may observe other benefits aside from crop yield that may make them consider subsoiling. Due to the favorable soil properties induced by subsoiling such as reduced density and increased infiltration capacity, a farmer may benefit from improved operational efficiency, soil-water management, and reduced environmental degradation. An example of operational efficiency may be that as a consequence of improved saturated hydraulic conductivity, there are fewer or smaller sloughs allowing the farmer to seed the field earlier or the ability to seed more acres of the field with less overlap from having to turn all the time. Another example may be a reduction in the frequency of in-season crop flooding or field operators getting equipment stuck in the mud. Improved infiltration will result in less runoff and water erosion. Benefits like this are difficult to quantify but may also justify engaging in subsoiling.

5 Synthesis, Conclusions and Recommendations

In this study, subsoiling improved the soil conditions for plant growth by reducing soil density and strength, and improved water infiltration capacity of the soil. Potential benefits that may arise include less ponding of water on the soil surface, better aeration and conditions for root growth (Aase et al, 2001; Bengough and Mullins. 1990). However, the grain yield response that was observed on the different soils over the course of this study was small and variable, with average yield benefits from sub-soiling only averaging out to be about 5%. These results are similar to that reported in past research in prairie soils and elsewhere. (Mermut et al, 1992; Grevers and de Jong, 1992; Grevers and de Jong, 1993; Hamilton-Manns et al., 2002; Wang et al., 2009). The optimum configuration for sub-soiling with the paraplow in terms of alteration of soil properties and improvement of crop yield was the conventional, normal recommended configuration of 45 cm shank spacing and 45 cm depth. Wider spacing and shallower depths generally had no, or negative effects, compared to the control. Small differences were observed when comparing the spring and fall timing of tillage. Subsoil tillage is reported to be most effective in normal to dry soil conditions (Grevers and de Jong, 1993) as long it not so dry as to cause soil surface disturbance or greatly increase the draft requirement to pull the equipment. Lower soil moisture levels are typically observed in the fall. While drier conditions typically encountered in fall may be more conducive for effective soil loosening, the freeze-thaw and wet-dry cycles between fall tillage and seeding in the spring maybe sufficient to degrade some of the tillage effects. Producers may find greater success with either depending on soil conditions. It is recommended that future work be conducted on evaluation of subsoiling under drier conditions than those encountered in the current study.

The persistence of the tillage effects and crop response was variable. The calculated costs of paraplowing (\$30-50 ac^{-1} or \$74-123 ha^{-1}). Farmers should aim to recover the cost of the operation with tangible benefits such improved crop yield. With the limited yield benefits observed (average 5% increase), more than one season of benefits from the subsoiling appears to be needed in order to recover the costs or obtain a net economic benefit. The variability in response along with the high costs of tillage makes it challenging for this operation to be economical. Monitoring of subsoiling effects beyond 2 years is recommended for future studies.

The soil forming factors and natural processes within the soil are the primary regulators of soil physical and hydraulic properties. Chernozems have inherently good soil structure for crop growth, and if impediments to plant growth exist in soil structure, it is likely due to compaction caused by wheel traffic from heavy agricultural equipment. A greater number of inherent soil structural issues have been identified in Gray Luvisols (Saskatchewan Soil and Crop Management Subcouncil, 2005). However, across the entire agricultural region of Saskatchewan farmers are growing more concerned about compaction, especially with the recent wet conditions experienced in the past few years. It is possible that the incidence of compaction on Saskatchewan soils and its negative effects may be understated and require a re-evaluation.

In the case of Solonetz soils, the structural impedances to crop growth are typically large and can be both natural and anthropogenic in origin. Natural impedances may be more difficult to resolve with tillage in Solonetz soils, as the natural soil processes such as dispersion and eluviation continue on over time, and may require rather severe and disruptive tillage to address. Solonetz soils have a dense "Bnt" horizon arising from the translocation of clay dispersed from elevated concentrations of Na^+ (Soil Classification Working Group, 1998). The Bnt horizon is identifiable by its blocky, prismatic structure and low permeability (Soil Classification Working Group, 1998), Grevers and de Jong (1992;1993) found that non inversion forms of tillage like the paraplow used in this study were ineffective at breaking down this layer and the deep tillage that mixed the soil was more effective in these instances. Solonetz soils may also be more susceptible to compaction and smearing as a result of the dispersed nature of the clays coupled with low organic matter content.

Vertisols are extremely active soils, which work to degrade tillage effects rapidly. Low water infiltration rate and a high draft requirement are characteristics of these soils. The high clay content of these soils cause cracking and argillipedotubation (Soil Classification Working Group, 1998), which is a self-mixing or churning created by the shrinking and swelling. These processes can result in the more rapid deterioration over time of positive effects induced by subsoiling like increased infiltration rate. Changes to bulk density and structure can occur throughout the growing season in these soils (Brierley et al., 2011).

In both the Chernozem and Vertisols soils evaluated in this study, paraplowing was effective in improving the soils infiltration capacity. It is not known whether this would also be the case for the Solonetz soil, as this site was lost due to flooding. K_{fs} measured in the paraplowed treatments was one order of magnitude greater compared with the control at the Chernozem site. K_{fs} was enhanced in paraplowed treatments at the Vertisol site but only for the spring treatment, indicating that effects in the Vertisol may not be as long lasting as in the Chernozem. Overall, even if infiltration capacity can be enhanced in the short-term, it is beneficial to producers from less ponded water in the spring and enhanced water use during the growing season.

Most soils in Saskatchewan do not likely require subsoiling to achieve satisfactory yields. However, there may be some areas or certain environmental conditions where subsoiling may be of benefit to producers, such as where soil compaction is evident. There was no evidence of soil compaction to begin with in the soils that were utilized in this study. The immediate effects of no-till subsoiling are well documented and are generally regarded as improving the soil environment for plant growth (Grevers and de Jong, 1992; Grevers and de Jong, 1993; Pierce, et al., 1992). However, there is still a knowledge gap when evaluating the persistence of the effects and the economics of the operation. Future research, specifically focusing on persistence may be of benefit if it is region and soil specific. However persistence will remain variable to some degree because of environmental factors such wet-dry cycling, freeze thaw, and climate. A better understanding of the persistence will also help producers make economic decisions, as a multi-year benefit is most often required to recover the cost of tillage. To improve the economics of subsoiling, consideration may be given to mapping fields for soil compaction and only applying the subsoiling operation to the specific areas of a field where soil compaction has been identified, such as wheel tracks, travel and loading areas.

6 LITERATURE CITED

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7 APPENDIX

Table A1. Observed significance in bulk density (ρ_b) and θ_v between the treatment and the control

Site	Depth	Time of Sampling							
	cm	Spring 2010		Fall 2010		Spring 2011		Fall 2011	
		CF	CS	CF	CS	CF	CS	CF	CS
ρ_b									
Chernozem	0-15			-	-	-	-	-	-
	15-30			-	-	-	-	-	-
	30-45			-	-	-	*	-	**
	45-60			-	-	-	-	-	-
Vertisol	0-15	***	***	-	-	-	-	-	-
	15-30	*	***	-	-	-	-	-	-
	30-45	-	-	-	-	-	-	-	-
	45-60	-	-	-	-	-	-	-	-
θ_v									
Chernozem	0-15			-	-	-			
	15-30			-	-	-			
	30-45			-	-	*			
	45-60			-	-	-			
Vertisol	0-15	**	***			-			
	15-30	***	***			-			
	30-45	-	-			-			
	45-60	**	**			-			

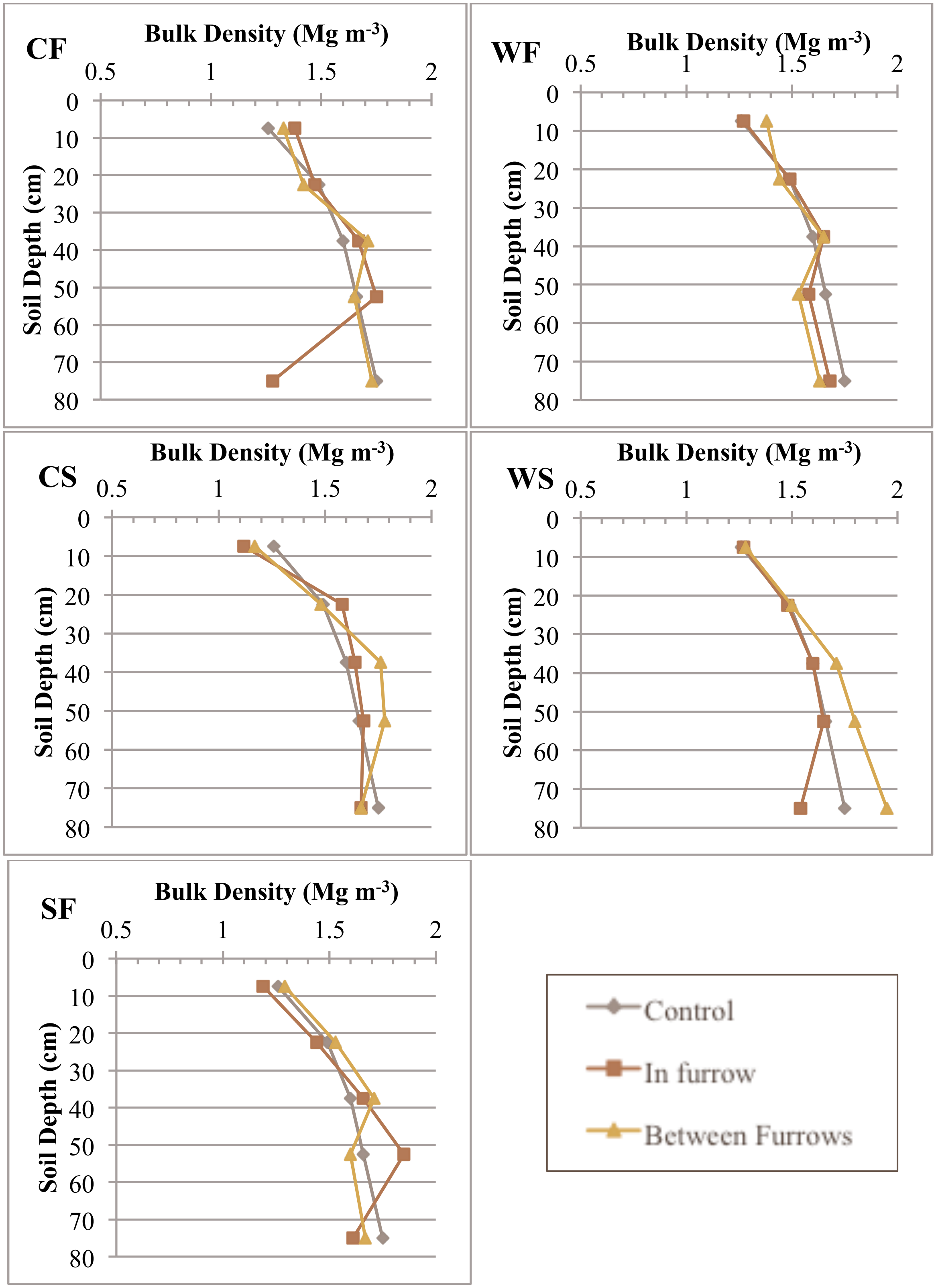

Fig. A1. Bulk Densities evaluating tillage uniformity for each treatment at Solonetz site.

Table A2. Summary of θ_v observed in the conventional treatments at Chernozem site

Site	Depth	Treatment						
	cm	Control		CF		CS		LSD 0.05
		Mean	*s.d.*	*Mean*	*s.d.*	*Mean*	*s.d.*	
Spring 2010	0-15	-	-	-	-	-	-	-
	15-30	-	-	-	-	-	-	-
	30-45	-	-	-	-	-	-	-
	45-60	-	-	-	-	-	-	-
Fall 2010	0-15	31	5.4	36	3.4	36	5.7	8.4
	15-30	38	1.7	37	4.7	40	3.1	7.0
	30-45	38	4.2	39	3.3	40	3.7	5.3
	45-60	38	3.4	39	3.5	36	5.8	3.7
Spring 2011	0-15	33	1.2	37	3.3	35	4.6	6.1
	15-30	40	3.8	49	12	45	11	19
	30-45	39.	3.4	43	6.2	41	1.9	4.0
	45-60	37	4.1	38	6.3	38	3.2	6.7
Fall 2011	0-15	29	1.0	29	2.6	30	0.9	3.2
	15-30	37	2.2	38	3.1	39	3.7	6.1
	30-45	37	2.2	38	8.3	47	3.7	8.6
	45-60	44	5.0	34	10	39	4.1	11

Table A3. Summary of θ_v observed in the conventional treatments at Vertisol site

Site	Depth	Treatment						
	cm	Control		CF		CS		LSD 0.05
		Mean	*s.d.*	*Mean*	*s.d.*	*Mean*	*s.d.*	
Spring 2010	0-15	37	3.3	31	4.0	32	4.0	4.1
	15-30	42	2.4	37	3.9	37	3.0	3.5
	30-45	42	2.4	40	3.9	41	4.6	4.3
	45-60	44	3.4	40	4.1	40	4.6	3.6
Fall 2010	0-15	33	1.8	37	3.5	45	17	
	15-30	39	3.1	40	3.3	41	3.4	
	30-45	49	7.3	37	5.8	43	8.6	
	45-60	45	4.1	40	4.6	48	15	
Spring 2011	0-15	54	12	45	2.5	56	16	14
	15-30	41	4.4	40	2.0	48	15	16
	30-45	52	18	41	5.0	50	12	17
	45-60	53	18	44	3.9	44	3.0	19
Fall 2011	0-15	30	4.1	35	8.0	39	7.0	13
	15-30	38	4.2	36	3.5	39	2.9	7.0
	30-45	38	10	30	12	42	16	27
	45-60	32	3.6	25	10	32	4.6	13

Table A4. Summary of the bulk densities observed in the CF & CS treatments at Chernozem site

Site	Depth	Treatment						
	cm	Control		CF		CS		LSD 0.05
		Mean	*s.d*	*Mean*	*s.d*	*Mean*	*s.d*	
Spring 2010	0-15	-	-	-	-	-	-	-
	15-30	-	-	-	-	-	-	-
	30-45	-	-	-	-	-	-	-
	45-60	-	-	-	-	-	-	-
Fall 2010	0-15	1.19	0.13	1.28	0.09	1.23	0.12	0.20
	15-30	1.42	0.05	1.31	0.12	1.39	0.06	0.16
	30-45	1.57	0.17	1.59	0.10	1.54	0.07	0.24
	45-60	1.57	0.15	1.58	0.11	1.61	0.09	0.20
Spring 2011	0-15	1.19	0.12	1.28	0.09	1.23	0.12	0.20
	15-30	1.42	0.45	1.31	0.23	1.39	0.06	0.16
	30-45	1.57	0.10	1.59	0.10	1.54	0.07	0.24
	45-60	1.57	0.15	1.58	0.11	1.62	0.09	0.20
Fall 2011	0-15	1.22	0.07	1.22	0.04	1.18	0.07	0.05
	15-30	1.55	0.15	1.46	0.16	1.46	0.10	0.27
	30-45	1.53	0.02	1.62	0.12	1.86	0.03	0.11
	45-60	1.68	0.14	1.54	0.36	1.80	0.13	0.39

Table A5. Grain N concentration from 2010 harvest

	Mean		*s.d*	N
	------------ mg/g ------------			
Chernozem				
Control	63.1	ab	11.3	4
CF	68.5	ab	4.29	4
WF	73.0	b	11.3	4
SF	57.0	a	10.7	4
CS	66.9	ab	10.0	4
WS	61.7	ab	3.86	4
LSD 0.05	13.7			
Vertisol				
Control	56.3	ab	6.22	4
CF	58.2	ab	3.09	4
WF	57.8	ab	9.57	4
SF	41.7	a	23.7	4
CS	59.7	b	6.27	4
WS	67.5	b	12.7	4
LSD 0.05	17.9			

Table A6. Straw N concentration from 2010 harvest

Treatment	Mean		*s.d*	N
	------------ mg/g ------------			
Chernozem				
Control	26.4	ab	10.1	4
CF	25.0	ab	9.94	4
WF	31.2	b	9.43	4
SF	16.5	a	5.55	4
CS	24.9	ab	6.07	4
WS	23.0	ab	15.2	4
LSD 0.05	14.2			
Vertisol				
Control	11.7	a	2.47	4
CF	11.1	a	1.22	4
WF	11.0	a	1.25	4
SF	11.1	a	1.68	4
CS	13.2	a	3.96	4
WS	14.7	a	4.41	4
LSD 0.05	4.32			

Table A7. Summary of crop yield data from harvest 2010

Treatment	Total Biomass		Grain Yield		Straw Yield	
	Mean kg ha^{-1}	*s.d* kg ha^{-1}	*Mean* kg ha^{-1}	*s.d* kg ha^{-1}	*Mean* kg ha^{-1}	*s.d* kg ha^{-1}
Chernozem - Hard Red Spring Wheat						
Control	8845	1196	3171	550.9	5674	855.0
CF	8675	788.6	3485	502.3	5190	509.6
WF	9288	1556	3548	754.2	5741	1008
SF	7869	1178	3071	775.8	4797	558.4
CS	8760	1231	3452	488.0	5308	802.7
WF	8491	886.8	3193	515.0	5298	731.9
LSD 0.10	786.0		408.6		477.2	
Vertisol – Hybrid Canola						
Control	7350	1129	2015	365.7	5335	893.4
CF	7068	956.5	2057	367.8	5011	622.6
WF	6893	1070	2018	363.1	4875	758.5
SF	6669	1122	1965	350.8	4704	860.0
CS	6883	781.8	2023	357.5	4860	629.7
WF	7874	881.1	2263	357.5	5611	546.1
LSD 0.10	678.5		232.9		486.1	

Table A8. Summary of crop yield data from harvest 2011

Treatment	Total Biomass		Grain Yield		Straw Yield	
	Mean kg ha^{-1}	*s.d* kg ha^{-1}	*Mean* kg ha^{-1}	*s.d* kg ha^{-1}	*Mean* kg ha^{-1}	*s.d* kg ha^{-1}
Chernozem - Flax						
Control	6107	842.8	2620	339.4	3487	587.9
CF	6394	287.3	2804	309.0	3590	208.0
CS	6156	843.0	2747	452.0	3409	432.8
LSD 0.05	1156		454.3		739.8	
Vertisol - Durum						
Control	9779	971.0	5493	718.9	4286	537.2
CF	9958	909.5	5505	512.8	4453	463.5
CS	9233	556.4	5353	339.5	3881	382.2
LSD 0.05	1497		677.5		887.6	

Table A9. Summary of crop yield data from harvest 2012

Treatment	Total Biomass		Grain Yield		Straw Yield	
	Mean kg ha^{-1}	*s.d.* kg ha^{-1}	*Mean* kg ha^{-1}	*s.d.* kg ha^{-1}	*Mean* kg ha^{-1}	*s.d.* kg ha^{-1}
Chernozem - Hard Red Spring Wheat						
Control	7718	566.9	2906	170.8	4812	535.3
CF	8453	365.0	3265	460.3	5187	592.9
CS	7428	835.7	2776	336.4	4651	751.5
LSD 0.05	862.6		576.2		1176	
Vertisol - Flax						
Control	3855	200.7	1681	115.2	2174	103.2
CF	4108	210.5	1659	183.3	2449	222.2
CS	4625	903.1	1952	442.0	2673	469.9
LSD 0.05	874.8		446.7		516.7	

Table A10. Summary of crop yield data from Dryland and Irrigated sites

Treatment	Total Biomass		Grain Yield		Straw Yield	
	Mean kg ha^{-1}	*s.d.* kg ha^{-1}	*Mean* kg ha^{-1}	*s.d.* kg ha^{-1}	*Mean* kg ha^{-1}	*s.d.* kg ha^{-1}
2011 - Flax						
Dryland						
Control	5007	659.5	2363	365.6	2643	308.5
CS11	5120	387.4	2468	116.1	2652	300.1
LSD 0.05	864.7		365.4		538.4	
Irrigated						
Control	5984	760.6	2694	287.4	3290	480.3
CS11	5866	602.6	2692	204.2	3174	407.6
LSD 0.05	430.2		220.0		217.7	
2012 - Hard Red Spring Wheat						
Dryland						
Control	6847	1316.8	2618	376.1	4229	951.7
CS11	8001	1120.2	3021	334.0	4980	827.5
LSD 0.05	1227		403.3		916.1	
Irrigated						
Control	8424	619.1	3509	281.4	4915	401.2
CS11	8377	551.3	3426	183.1	4950	425.4
LSD 0.05	654.9		194.2		615.6	

Fig. A2. Paraplowing – Spring 2010 with paraplow in the wide set up

Fig. A3. Seed bed disturbance at the Vertisol site following spring paraplowing 2010

Fig. A4. Paraplow in ground tilling 45 cm deep

Fig. A5. Flooding at the Solonetz site in 2010 that resulted in abandonment

Fig. A6. Brett Ewen setting up the penetrograph

Fig. A7. Cory Fatteicher extracting soil extracting soil core with a truck mounted punch