STRAW INCORPORATIONS THROUGH TILLAGE PRACTICES UNDER HEAVY CLAY SOIL CONDITIONS

BY

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A thesis submitted to the Faculty of Graduate Studies
in partial fulfillment of the requirements for the degree of

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ABSTRACT

Excessive straw from cereal harvest can hinder effective seedbed preparation if tillage implements and soil cutting tools cannot handle the straw loads. To remedy the problem, many farmers resort to straw burning as the most convenient way to manage surface straw. Straw burning can enhance the timeliness of tillage operations, but its leaves the soil with little surface cover and protection from wind erosion. This could be detrimental to soils in the Prairie Provinces where wind erosion is extensive and damaging. Farmers in these regions need to adopt tillage practices and implements that maintain a protective cover on the soil's surface.

This study provided a valuable opportunity to test various implements on residue cover, incorporated straw, tillage depth, and draft force requirement during tillage operations on clay soils in the Red River region over a two-year period. Seedling emergence, final population, and yield were assessed as well. The results are intended to enhance farmers' confidence in adopting suitable tillage practices that will reduce straw burning practices on clays prior to tillage. The results of this study indicated that all tillage treatments were able to maintain an adequate residue cover while surface straw was incorporated into the soil without prior burning. The recommended tillage practice will depend on the amount of straw cover the producer wants to maintain, tillage depth, and the available tractor power. The no tillage system seemed to have provided the best condition for seedling emergence, final population, and yield within the two-year period.

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1. INTRODUCTION

Cereal crops are grown primarily for grain; however, the production of residues in the form of straw is unavoidable. Though some of this residue is removed and used as fuel, feed, and for commercial purposes, most of it remains in the field to be burnt or incorporated into the soil. Surface straw loads greater than 4 – 5 Mg/ha can create tillage problems (Valanzo et al. 1997) and can hinder effective seedbed preparation by plugging the implements and soil cutting tools. To remedy the problem, many farmers resort to straw burning as the most convenient way to manage surface straw.

Straw burning can be beneficial, because it enhances the timeliness of tillage operations; however, it increases the soil's susceptibility to erosion, reduces soil moisture, and soil infiltration (Valzano et al. 1997). In addition, this practice contributes to massive soil degradation and the emission of greenhouse gases into the atmosphere (Lamarca 1996). The smoke given off during straw burning affects neighbouring communities and vehicular traffic on adjacent highways. Concerns about these negative effects have led to an increased interest in alternatives to manage surface straw residues on farms. Consequently, many researchers (Johnson 1988; Hanna et al. 1995; Wagner and Nelson 1995) began to explore different tillage implements that can incorporate residue into the soil without the need to practise straw burning.

Census data reveals that conventional tillage is used on 69% of Canada's arable land, conservation tillage on 24%, and no-tillage on 7 % (Statistics Canada 1997). Of the three practices, conventional tillage leaves the least residue on the surface because it incorporates most of the straw into the soil. This tillage practice can be detrimental to the soil in Manitoba, because it leaves the soil with very little surface cover for protection against wind erosion.

Wind erosion is a problem on many farms but it is more extensive and damaging in the Prairie provinces. Because of this, farmers in these regions need to consider adopting tillage practices that reduce wind erosion by maintaining an adequate surface cover on the soil. Wischmeier and Smith (1978) noted that an adequate straw cover (greater than 30 %) on the soil surface reduces soil erosion. Other researchers (Laflen et al. 1978) found that a 20 to 30% straw cover at planting time will reduce erosion by 50 to 90% compared to that occurring on a bare soil surface.

There are many constraints that prevent local farmers from adopting tillage practices that reduce straw burning (Larney et al. 1997) A major concern is the handling of excessive straw from cereal harvest. Many farmers are concerned that high levels of surface residue will decrease soil warm up for spring seeding; and if the straw is incorporated, they fear that nitrogen immobilization could increase (Malhi et al. 1993). Some farmers may be willing to make a change in tillage practice; however, they may lack the capital to purchase a new tillage implement, or may lack adequate information about the performance of new and existing implements with regards to their local field conditions.

This study provided a valuable opportunity to test various implements on residue cover, incorporated straw, tillage depth, and draft force requirement during tillage operations on clay soils in the Red River region over a two-year period. Seedling emergence, final population, and yield were assessed as well. The results of the study are intended to enhance farmers' confidence in adopting suitable tillage practices that will reduce the practice of straw burning on clays prior to tillage.

The general objective of the study was to find alternatives to straw burning in the Red River region through straw incorporation via existing and innovative tillage systems and implements. The specific objectives were as follows:

1. To quantify the effect of tillage implements on surface straw and incorporated straw.
2. To determine the draft force and power requirement of tillage tools.
3. To determine the effects of tillage implement on plant emergence, uniformity of seeding depth, and crop yield.
4. To recommend a suitable tillage practice and implement for efficient straw incorporation that will reduce or stop straw burning.

2.0 LITERATURE REVIEW

2.1 Straw management practices in agriculture

The production of residues in the form of straw is unavoidable in cereal production even though the primary objective is to produce grain. Most times, more than one half of the crop production efforts result in residues (Unger 1994). This residue can be managed in different ways depending on the amount left and the results desired. Common management practices include baling, burning, incorporating, or retaining the straw on the soil surface. The straw management practice a producer decides to use will have immediate short term implications and many long term environmental and economic consequences.

The straw left in the fields after the harvest can obstruct tillage implements during seedbed preparation and affect the performance of seeders. Valzano et al. (1997) observed that surface straw loads greater than 4 – 5 Mg/ha hindered the preparation of effective seedbeds. In addition, high levels of straw can delay the timelines of tillage operations resulting in crop production losses. To avoid such delays, many cereal grain producers find straw burning to be an effective and convenient tool to reduce excess residue loads prior to tillage.

While straw burning can be important in assisting normal tillage operation, its negative effects are damaging to the soil. This practice affects surface-soil hydraulic properties (Valanzo et al. 1997), reduces soil cover, and leaves the soil susceptible to both wind and water erosion. When substituted for a pesticide, straw burning destroys a great quantity of beneficial insects and other organisms living in the upper part of the soil. To burn the soil or to take out this valuable organic material is a destruction of the biological diversity of the soil (Lamarca 1996).

In any discussion on straw management practices, it is important to identify the position of the straw in relation to the soil. Straw on the surface of the soil is named surface straw or straw cover, and straw in the soil is referred to as incorporated straw. Regardless of its position, straw exerts many effects on the soil; and to a great extent, it determines the productivity and sustainability of a cropping system.

2.2 Surface straw

2. 2.1 Effects on crop growth. Soils can be cold and wet at the onset of spring. A straw cover can aggravate this problem by keeping the soil wet and colder for a longer period, thereby shortening the length of the potential growing season. Aston and Fischer (1986) found that plots with high residue content had cooler soil temperatures and reduced early season growth of wheat. On the contrary, Tripathi et al. (1985) reported faster emergence under paddy straw than with bare soil. This was attributed to the soil water effect being greater than the temperature effect. Unger (1986) found delay in corn emergence with high wheat straw compared to low levels for no-till plots. The delayed emergence was associated with reduced soil temperatures caused by high surface residues. Generally, a reduction in plant counts and speed of emergence in the presence of excessive surface straw can be attributed to many factors, most of them acting with each other. The effect of soil temperature can be the most pronounced among all these factors.

Seeds need a minimum temperature for germination to occur. After the minimum temperature requirement is satisfied, the main effect of the soil temperature is on germination rate. Hampson and Simpson (1990) observed that germination rate of seeds is related to the rate at which water is imbibed into the seed; while Laford and Baker (1986) demonstrated that imbibition of water into wheat seeds increased with increasing temperatures. The researchers concluded that the rate of germination increases to a maximum as soil temperature increases to an optimum, after which further increases in temperature cause a decrease in germination due to heat stress. Plant emergence is affected in a similar way by soil temperature, with the rate being lower in cooler soils (Lodgson et al. 1987; Al-Darby and Lowery 1987).

Low soil temperature can affect root growth. Lodgson et al. (1987) found a three-fold increase in the root length of corn seedlings when the temperature was increased from 15 to 25°C. The seedling root length ranged from 14 mm at 17 °C to 327 mm at 25°C. Root diameters may also increase with decreasing soil temperatures (Lodgson et al. 1987). Miyasaka and Grines (1990) observed that the lateral root growth in winter wheat was reduced dramatically by dropping soil temperature to 8 °C from 16 °C and resulted in significantly larger root diameter. This increase in root diameter was attributed to a higher proportion of main root axis with colder soil temperature. In spite of these results, Borresen (1999) reported that normal and double amounts of chopped straw on the soil surface increased grain yield by 0.29 Mg/ha during a five-year study.

Seedling emergence and plant establishment are influenced by soil microclimate. The thermal properties of the soil play an important role in influencing the microclimate (Ghauman and Lal 1985). The position of crop residue, on soil surface or in soil, has an effect on the soil microclimate. Wuest et al. (2000) found that residue position had a significant effect on emergence. They noted that residue mixed with or above the seed delayed emergence when compared to residue on the soil surface or residue 30 mm below the seed. The residue can prevent the coleoptiles from growing straight to the soil surface. Surface residue can affect seeder performance in terms of seed placement and the extent of soil seed contact. Often, reduction in plant population can be linked to failure to drop seed uniformly and failure to achieve effective furrow closure. Under such conditions, less seeds may be dropped in the furrow at the appropriate depth. The seeds may fail to germinate or may die due to lack of water (Unger and Fulton 1990).

2.2.2 Effects on soil properties. Surface straw management can be a complex interaction of many physical and biological components in the soil ecosystem. The magnitude of change of soil physical properties depends not only on the specific residue-tillage cropping system, but also on the type of soil, climate, and time of year (Unger and Fulton 1990).

The positive influences of surface straw generally last longer than that of incorporated residue because of a slower decomposition rate (Unger 1994). The researcher observed that surface straw could increase soil aggregate size and stability at the soil surface more than residues partially incorporated, buried, or removed (Unger 1994). Improved aggregation is important at the soil surface because it helps improve infiltration, aeration, resistance to crusting, and resistance to erosion. The residue diminishes the impact of raindrop and, therefore, minimizes the sealing effect of the rainfall. Kladivko et al. (1986) observed that after tillage systems have been established, no-till systems tend to have greater soil aggregate stability than other tillage practices that partially or totally buries the straw (Kladivko et al. 1986).

Surface residue appears to be the main factor in determining the soil thermal properties among tillage systems (Azooz et al. 1995). Soil thermal conductivity determines how a soil warms or cools with exchange of energy by conduction, convection, and radiation. Surface residues may affect the soil thermal regime and reduce grain yield (Kaspar et al.1990). Many researchers are of the view that a soil may warm up slower in the spring if it is partially or completely covered with crop residues.

2.2.3 Benefits of straw cover. Some researchers (Jolota and Prihar 1979; Brun et al. 1986; Unger 1986) have reported the beneficial effect of crop residue on soil water. Jalota et al. (2001) found that surface straw increased water storage in soil under low evaporative rainy conditions. Unger (1978) showed that high wheat residue levels (8 to 12 Mg/ha) increased storage of fallow season precipitation. He also reported that lower levels (1 to 4 Mg/ha) resulted in significant increases in water storage. Excessive soil water in the spring, in no-till plots can have negative effects on crop growth. However, in the summer months, when soils may be prone to drought stress, this stored water can offset the early seasons negative influence, leading to better plant population and yields.

The best protection from wind erosion results from maintaining an adequate amount of residue cover on the soil surface from harvest to canopy closure of succeeding crop (Sprague and Triplett 1986). As surface cover decreases, the potential for erosion control increases. An adequate straw cover is needed to protect the soil during windy conditions (Unger 1994).

2.3 Incorporated straw

2.3.1 Straw incorporation and tillage. The effects of straw incorporation on soil productivity are difficult to separate from tillage effects, because incorporation is accomplished through some type of tillage (Unger 1994). In many cases, some studies have reported that a longer time is needed to observe the effects of incorporated straw. For example, Carter and Rennie (1982) found no significant differences in biomass between no-till and tilled treatment after two years, but they did find differences in microbial biomass after four years.

2.3.2 Effects on crop growth. Incorporated straw can have detrimental effects on emergence. Wuest et al. (2000) found that residue position and distribution in the horizon had a significant effect on emergence. Seedlings whose roots encounter residue may lag behind in growth and height. Straw residue below the seed cannot hinder coleoptiles growth; therefore, any difference in height among seedlings can be attributed to the roots. The residue of some crops and weeds are known to have harmful effects on subsequent crops or soils. They produce chemicals (allelochemicals) that may affect the germination, growth, and development of other crops (Unger 1994). This chemical effect that is exerted by the straw on a subsequent plant is known as allelopathy. After the plant dies, these allelochemicals from the plant residue can be released directly into the soil (Chase et al. 1991). Some of the microorganisms that decompose the residue are the same ones that produce allelochemicals. Tillage and incorporation of straw can assist in spreading these chemicals in the soil to some extent. Hence, straw incorporation can have detrimental effects on subsequent crops (Graham et al. 1986).

Although moisture is essential for the decomposition of crop residues, an excess of moisture can stimulate the production of allelochemicals. For example, when the residue of small grain crops such as rye, wheat, and oats are sufficiently moist, they produce high levels of allelochemicals. Newly planted crops in the residue of such plants could, therefore, be at high risk from allelochemical production. These chemicals can destroy or inhibit crops that are planted during the first six weeks of the rainy season (Lamarca 1996). The management of the residue can lessen the effect of allelopathy.

2.3.3 Effect on soil physical properties. Straw has a lower density than soil. Its incorporation into the soil will produce an initial decrease in soil bulk density because of the loosening action of tillage and the immediate incorporation of low-density straw. Hill

(1990) reported that the bulk density in a tilled plot decreased initially in comparison to that of no-till plots with surface residue only. He explained that incorporated straw creates voids between soil aggregates and clods. The pore volume created during the residue burial exceeds the volume of the incorporated straw. As a result, the bulk density of the soil decreases immediately after straw incorporation.

Tillage and incorporation speeds up the decomposition of straw and organic matter. In addition, the tillage effect on bulk density is short-lived because the soil settles back to its pre-tillage density after a while. This was confirmed by Unger (1994) who observed that, over a long time tillage and incorporation can lead to lower soil organic matter and poorer soil structure. Hence, in well-established tillage systems, soils with surface straw will have a lower density than soil from which straw has been removed or burnt over the long term.

2.3.4 Effect on organic matter. Tillage can affect straw decomposition. Buried straw decomposes much faster than above ground residue (Douglas et al. 1980). The timing of the tillage may also affect residue decomposition and N immobilization. Freshly incorporated residue would immobilize substantial N, but if it were incorporated two months before cropping then much of the immobilized N would be remineralized and available to crops.

The main factor that determines the mineralization of N in crop residue is the carbon to nitrogen ratio of the residues. The narrower the ratio, that is, the larger the proportion of nitrogen they contain, the greater the mineralization of nitrogen. Incorporating huge amounts of straw into the soil can result in the immobilization of mineral nitrogen. This nitrogen ceases to be vulnerable to leaching, but it adds to the pool of nitrogen that could be mineralized subsequently. This increases soil fertility over a period of time, if the management of mineralizaion is done carefully.

Incorporated straw can increase N_2O emissions; particularly after fall tillage. The straw increases metabolic activity from local anaerobic zones giving favourable sites for denitrification and contributing significantly to the emission of N_2O (Flessa and Beese 1995). These, along with variability of soil water content, contribute significantly to high spatial variability of emissions (Ambus and Chritensen 1994). The contribution of crop residues to N_2O emissions and the complex interactions with soil properties are still subjected to considerable uncertainty (Beauchamp 1997).

2.3.5 Benefits Straw incorporation can reduce the susceptibility of soil to erosion and compaction as a result of improvements in its structure and aggregate stability. On the contrary, McGregor et al. (1990) showed that recently incorporated wheat straw, 0 to 7 Mg/ha provided no more erosion protection than 1 to 3 Mg/ha of surface wheat straw in rainfall simulator studies. In field studies, they found that recently incorporated straw had no effects in reducing runoff.

There are short and long term benefits from straw incorporation. The short-term benefits of incorporated straw include improved drainage and localized reduction in bulk density.

Ball et al. (1990) reported that long-term improvements from straw incorporation were greatest under shallow tillage and included increased resistance of surface aggregates to compaction and water erosion.

2.4 Selection of tillage systems.

2.4.1 Description of tillage system. Tillage systems and implements are numerous and diverse and their names differ from location to location. As a result, the precise description of a tillage system can be difficult. To simplify the problem, a tillage system can be identified according to its ultimate objective such as conventional or conservation tillage; or they can be described according to the primary implement used, for example, disking and plowing (Dickey et al. 1992).

A chisel plow is a common primary tillage implement. It is considered to be an intermediate tool in terms of draft force requirement. The plow produces a rough surface and leaves about 50 to 70% of the existing residue on the surface of a field depending on the chisel point selected, shank spacing, operating speed, and depth (Dickey et al. 1992). On soils where erosion is not a primary concern, twisted points, 76 or 101 mm wide, can be used to bury more residue (Dickey 1992).

Tandem disks leave about 40 – 70 % of the existing surface straw in the field after a single pass. The amount of residue remaining would depend on the type of residue, the angle of the gangs, and the depth of tillage. Disk tends to pulverize the soil more than chisel plows and other tillage implements. The draft force would vary depending on the depth of tillage and disk angles.

Field cultivators are considered to be light implements when compared to chisel plows. They are normally used for secondary tillage; however, their use as primary tillage implements is common on many farms today. Cultivators operate at depths of 76 to 127 mm (3 to 5 in). Hence, when used continuously as primary tillage implements, they till at a constant depth that causes the soil to compact at that depth and eventually to form a hardpan below their normal tillage depth.

2.4.2 Factors for consideration. There is no single solution for tillage problems; however, the general agreement is that reduced tillage and no-tillage save time and do not reduce yields. In practice, the response to reduced tillage has been variable; the different effects appear because of local conditions and priorities to specific factors or processes (Guerif et al. 2001). There are still gaps in knowledge that need to be filled before a complete assessment of tillage effects is available for different crops under different soil and climatic conditions. As the effects become known, tillage systems will be refined and their adoption will be more attractive.

Tillage systems are site, soil, and crop specific (Sprague and Tripllett 1986); their effects must be assessed and they should be selected according to local constraints. The adoption of new tillage practices requires a careful consideration of all benefits and potential undesirable effects. The system selected should create the best condition for crop growth with minimum undesired effects, while ensuring timeliness of operation.

Tillage has both direct and indirect effects on residue fragmentation and decomposition as well as seed placement within the seedbed. The choice of efficient tillage practices requires consideration of factors that affect germination and emergence, crop residue distribution, and soil structure. In addition, tillage practices change soil water content, temperature, aeration, and the degree of mixing of crop residues within soil. Kladivko (2001) showed that the degree of tillage disturbance of the soil and the resulting location of the crop residue affects soil water content, soil temperature, aeration, and the degree of contact between organic materials and mineral soil particles.

2.5 Performance of soil engaging tools.

Shovels, sweeps, and spikes are the most common types of soil cutting tools. Each comes in numerous shapes, widths, and styles. Their performance can differ depending on the tillage implement frame they are fitted on, tool spacing, and target tillage depth. Therefore, the selection of the right tool to achieve one or multiple desired objectives on depth, residue cover, incorporated straw, and surface roughness, can be a very difficult task.

Surface residue is a key parameter in assessing the performance of a soil-engaging tool. It can be expressed both as the percent of residue cover and as the percent of straw remaining after a tillage operation. Johnson (1988) found that sweeps fitted on a chisel plow leave the largest residue cover (greater than 70% straw remaining) while the twisted shovel and the disk left the least (52 to 57 % remaining). Hanna (1995) observed that the use of sweeps and reversible shovels on a chisel plow buried 7 to 14% less residue cover than 76 mm (3 in) twisted shovels. Sweeps and shovels have minor effects on surface cover. Twisted shovels leave the roughest soil surface and sweeps leave the smoothest soil surface. Johnson (1988) observed that soil-engaging tools had less effect on roughness than residue.

2.6 Factors which affect straw incorporation and tillage.

2.6.1 Soil penetration resistance. The resistance to the widening of the soil pores by the root constitutes the mechanical resistance or strength of soil. The larger the mechanical resistance, the greater is the amount of energy that must be expended by the root to penetrate the soil. When the soil strength reaches excessively high levels, root growth patterns and morphology alters. These alterations will eventually affect plant growth and yield.

The penetration resistance measured by a cone penetrometer is related to the pressure required to form a spherical cavity into the soil large enough to accommodate the cone (Vaz et al. 2001). The penetration resistance is related to root growth and penetration (Micheal and Quiensenberry 1993). Some researchers (Gerard et al. 1982) have shown that increases in mechanical resistance decrease root elongation and growth.

The threshold level at which soil strength hinders soil root elongation varies with plant species, but usually ranges between 2.0 and 3.0 MPa (Atwell 1993). Letey (1995) reported threshold values as low as 1.8 MPa. As the penetration resistance approaches the threshold level, rooting depth is restricted. The plant tries to compensate for the restricted rooting depth by increasing lateral root production (Schumacher and Smucher 1981).

Increased soil strength can cause changes in root morphology. The diameter of the root tends to increase when soil strength is excessive. The increased diameter helps increase root penetration through soils of high mechanical resistance. Soil strength above the agronomic threshold level can cause serious setbacks in plant growth and establishment as a result of the reduced root system. The shallow roots limit the availability of nutrients and water due to the reduced volume of soil from which the plant can absorb nutrients and water. In such situations, an unknown chemical factor within the plant that retards shoot growth increases the availability of carbohydrates for root growth.

Soil strength depends on several factors, but it is affected remarkably by soil water content and bulk density. Many researchers (Gerard et al. 1982, Voorhees 1983) have shown that soil water is often negatively correlated with soil strength. Ayers and Perumpa (1982) demonstrated that adding water to a completely dry soil increased soil strength so that a maximum value occurred at some intermediate water content beyond which soil strength decreased. Soil strength is affected when soil water bonds the soil particles through the surface tension at the soil water interface within soil pores (Snyder and Miller 1985). The tension of the air water interface increases as the water is removed from soil pores. This results in higher soil strength initially. However, as the soil continues to dry, the number of soil water-air interfaces decreases and soil strength decreases.

The freezing – thawing process changes soil physical conditions. Bullock et al. (1988) observed that the disruption of soil aggregates by freezing could be more pronounced than a single pass of most tillage equipment. Hence the expansion of water upon freezing can alleviate compacted soils through the formation of vertical and horizontal microfractures (Kay et al. 1985). Voorhees (1983) observed that the soil strength decreases after winter, but a corresponding change in bulk density did not occur. The decreased soil strength was attributed to micro fractures creating planes of weakness within the soil. These cracks can contribute to decreased soil strength in spite of higher soil bulk density and lower moisture content (Marshall and Holmes 1988).

The mechanical resistance of soils tends to increase when tillage is reduced or stopped. Soil bulk density near the surface of no-till plots tends to be higher than that of conventionally tilled plots. Therefore, the soil strength of no-till plots would be higher than the conventionally tilled plots (Vyn and Raimbult 1993). Other researchers (Hao et al. 2000) did not find this relationship. The increase in soil strength in no-till soil is limited to the soil surface. Unger and Fulton (1990) observed that below the normal tillage depth there are no differences in soil strength. The strength of soils with high clay contents is unaffected by tillage (Gerik et al. 1987).

The relationship between soil strength and water content differs between tillage practices. No-till soils tend to have higher soil strengths than tilled soils at any given matric potential (Hill 1990). Soil strength may change during the growing season due to compaction of the cultivated soil by rainfall impact, and wet and dry cycles. The soil strength under conventional and minimum tillage increased as the time from seeding increased. Hodgson et al. (1977) reported similar findings for tilled soil, but the soil strength of the no-till plots changed little over the growing season. Materechera and Banda (1997) indicated that the penetration resistance in tillage was strongly related to the soil water content, which depends on precipitation. Therefore, the pattern in changes in penetration resistance in the soil during the growing season generally mirrored that of the rainfall.

2.6.2 Soil compaction. Compaction refers to an increase in density or reduction in soil porosity of a soil in response to mechanical stresses (Addiscott and Dexter 1994). These stresses are caused by agricultural traffic or tillage implements, or can be internal as effective stresses induced by soil sealing when soil dries. Irrespective of the type of stress, internal or external, compaction will occur only if a certain level of stress, called pre-compaction stress, is exceeded. Hence soil strength and pre-compaction stress is sensitive to water content. Wet soil usually has a lower value of pre-compaction stress than dry soil and is, therefore, more susceptible to compaction damage (Addiscott and Dexter 1994).

Tillage destabilizes soil and makes it more susceptible to compaction through both a reduction in pre-compaction stress and an increase in pressure concentration. As a result, traffic causes less compaction on no-till soil than on tilled soil. Compacted soil with high bulk density restricts plant rooting and moisture movement only when bulk density exceeds limits of 1.6 – 1.7 Mg/m^3; below this the effect is minimal (Sprague and Triplett

1986). Compacted layers are formed in soil naturally or by excessive tractor traffic. The principal factor influencing compaction on clay is applied pressure rather than water content at the time of compaction.

A compacted layer or hardpan can be commonly found in fields that are tilled continuously at shallow depths. The presence of a hard pan in a field can be an obstacle if change to a no-till system is desired. The hardpan can be located at variable depths depending on the depth of penetration by tillage tools. The hardpan impedes the normal flow of water and air through the soil (Larmaca 1996).

3.0 METHODOLOGY

3.1 Site description

Field plots were established in the fall of 2000 at the Carl Classen farm (SW 33-9-3W) near Fannystelle, Manitoba. The dominant soil types at the site are the Red River and Osborne series. These are fine clay soils with slow infiltration rates. Prior to the study, the field had been under continuous cultivation with cereal crops. During the fall of each year, an air-seeder field cultivator was used for seedbed preparation. Tillage depth was usually shallow, between 51 and 76 mm (2 to 3 in). In the spring, the same implement was used for seeding. At harvest, crop residues were left on the field. A chopper-spreader on the harvester and a single pass of a harrow left the surface straw uniformly distributed in the field

3.2 Field equipment

All tillage equipment used in this study were manufactured by John Deere (John Deere & Co Moline, IL. 61265). A 317 kW (425 hp) John Deere tractor, model 9400, was used to pull all equipment during field trials.

3.2.1 Tandem disk. The tandem disk (Fig. 1) consisted of two opposed front gangs of spherical disks that throw soil outward from the centre of the implement. Two rear gangs throw soil back towards the centre. The disks of the front gang were spaced at 228 mm (9 in), while those of the rear gang were at 279 mm (11 in). The front and rear working

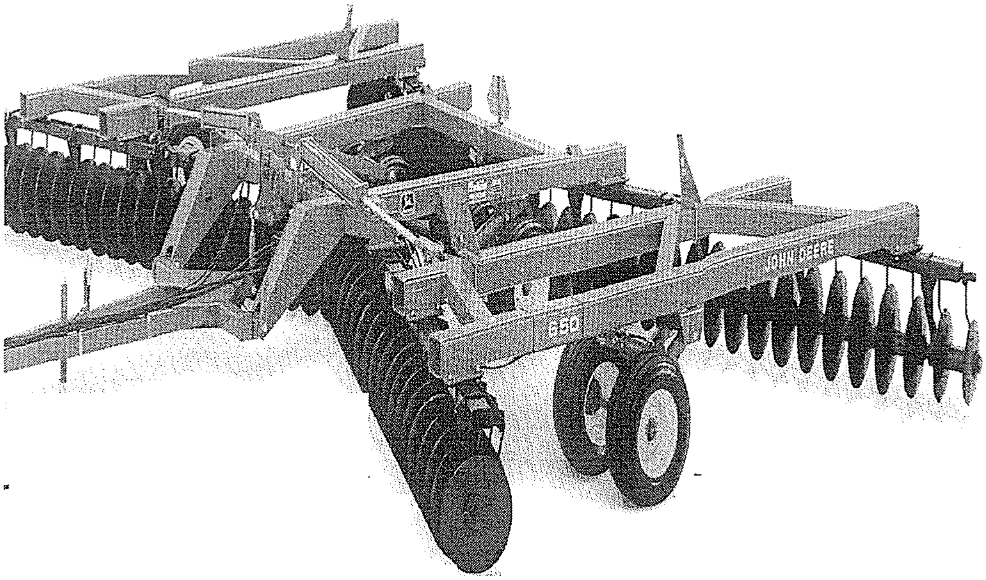

Fig. 1 Tandem disk used in 2000 for field trial

angles were 17° and 15°, respectively. The diameter of the each disk was 550 mm (22 in). The implement's working width was 11m (36 ft).

Fig. 2 Hoe-opener field cultivator (air seeder) used in 2000 and 2001

3.2.2 Hoe-opener field cultivator. The hoe-opener (Fig. 2) was owned by the producer. It was 12.2 m (40 ft) wide and consisted of hoe-openers mounted on C-shaped light-duty shanks. The cutting tools were spaced at 203 mm (8 in). This equipment was used by the producer as a tillage equipment and as an air seeder in his normal cropping practice.

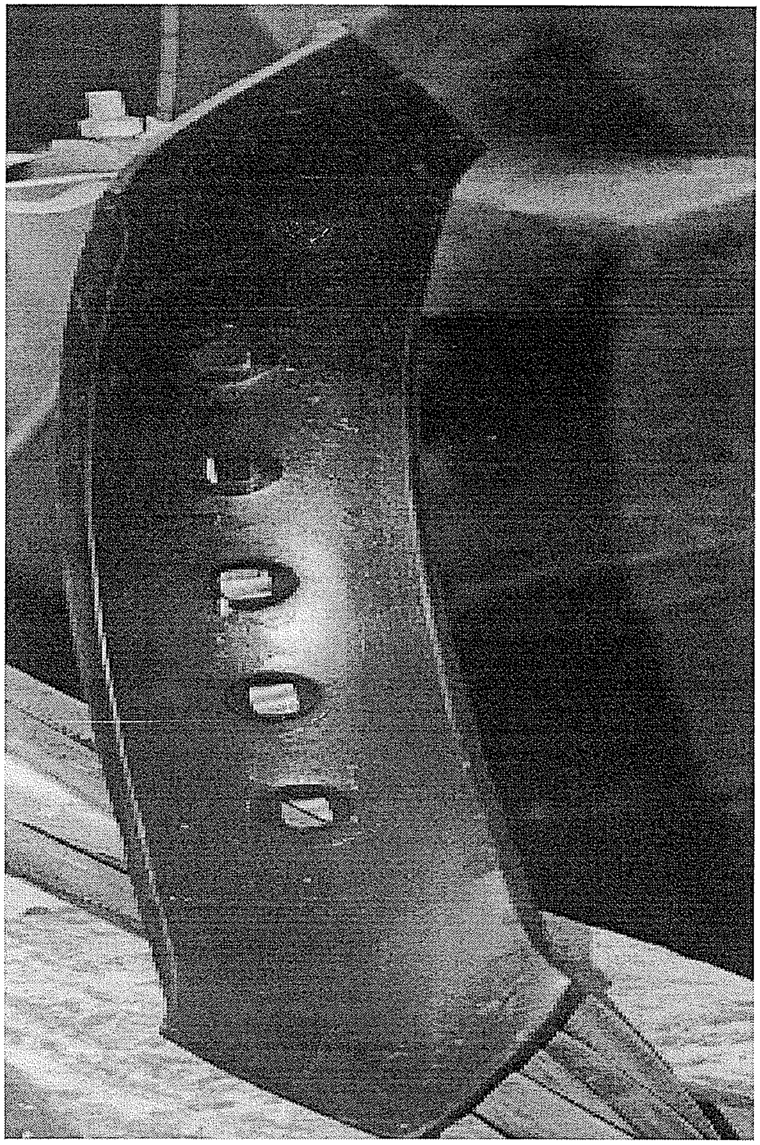

Fig. 3. Twisted shovel (101 mm (4 in) wide) used in tillage 2000 and 2001.

3.2.3 Twisted shovel, reversible shovel, and narrow sweep. Twisted shovels (Fig. 3), reversible shovels (Fig. 4), and narrow sweeps (Fig. 5) formed three separate tillage treatments. They were mounted separately on the tool bar frame (Fig, 6a). The tool bar

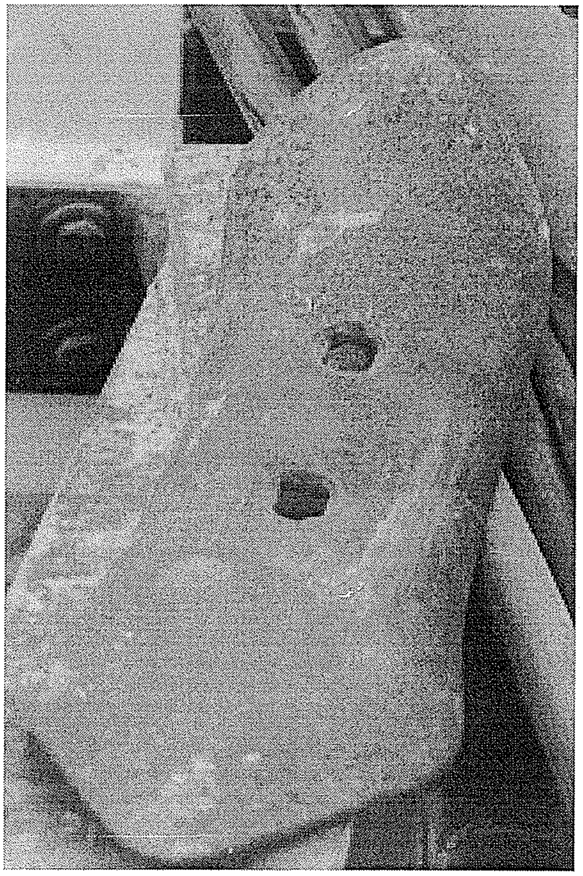

Fig 4. Reversible shovel (101 mm (4 in) wide) used in 2000 and 2001

frame used in 2000 consisted of medium-duty C-shanks spaced at 610 mm (2 ft) and had a working width of 8.2 m (27 ft). During 2001 tillage operations, a heavier toolbar frame (Fig. 6b) (Valmar Airflo Inc. Box 100 Elie, MB R0H 0H0) with "edge-on" shanks substituted the 2000 tool bar to attain greater depth (150 mm). The shanks were spaced at 610 mm and the working width of the implement was10.8 m (36 ft).

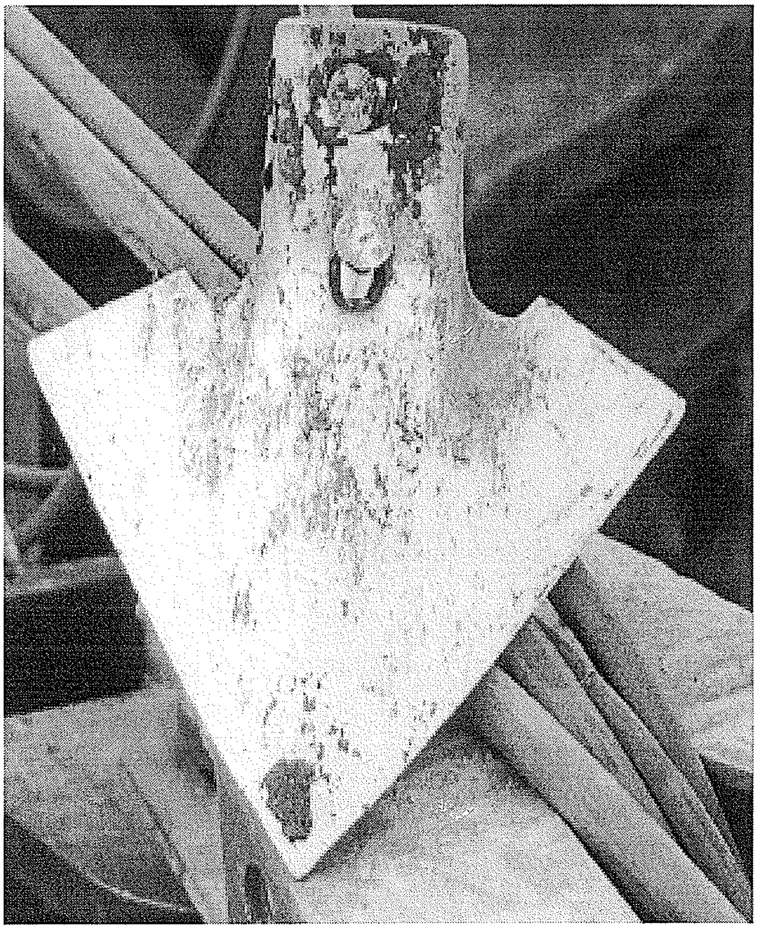

Fig 5. Narrow sweep (203 mm(8 in) wide) used in 2000 and 2001

(6a)

Fig. 6 Tool bar frames on which the twisted shovel, reversible shovel, and narrow sweep were mounted; (a) John Deere tool bar frame with C-shanks, used in 2000; (b)Valmar tool bar frame with " edge-on" shanks, used in 2001.

(6b)

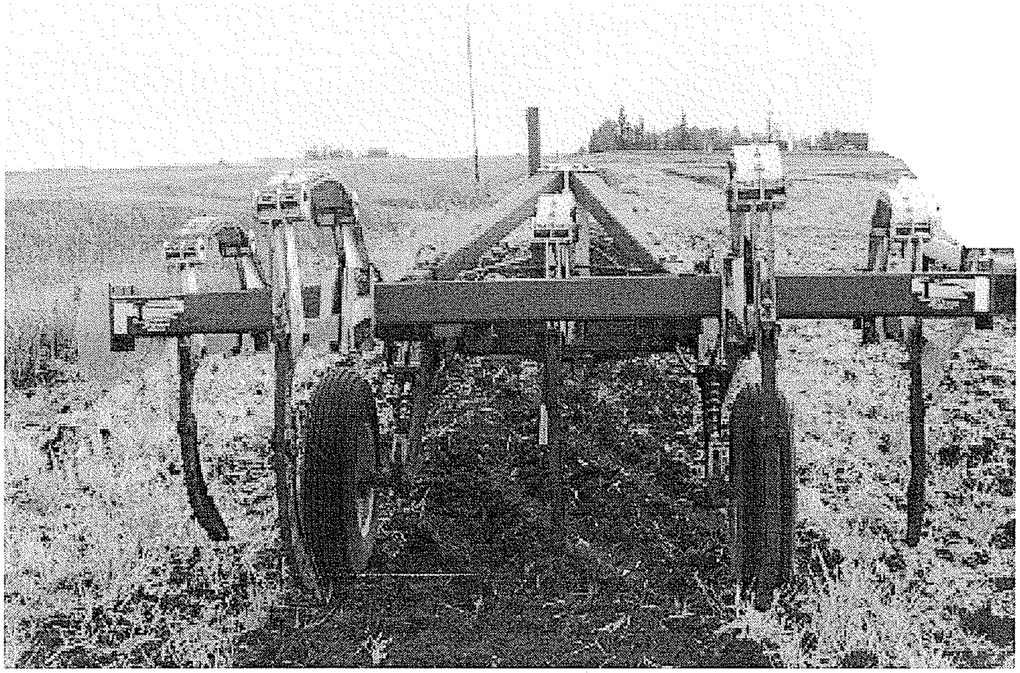

Fig. 7 Subsoiler used in 2001 tillage.

3.2.4 Subsoiler

The subsoiler (Fig. 7) is a primary tillage tool which is designed to till deeper than the chisel, disk, and cultivator. Subsoilers are used to alleviate compaction problems. The subsoiler used in this study was 3 m (10ft) wide and its shanks were spaced at 762 mm (30 in). It was introduced in 2001 tillage for deeper tillage.

3.3 Experimental design

Six tillage treatments were initiated in the fall of 2000: Hoe-opener (HO), Tandem disk (TD), Twisted shovel (TS), Reversible shovel (RS), Narrow sweep (NS), and No tillage (NT). Treatment HO represented the conventional tillage used by the producer. The NT plots were not tilled and were seeded directly with low disturbance hoe-openers. The experiment was completely randomized with four replications (Fig. 8). The plots were 92 m (300 ft) long. Their widths varied, being a multiple of the tillage implements' width, to accommodate harvesting with the producer's 9 m (30 ft) wide combine for future crop yield measurements. In the fall of 2001, another tillage treatment (sub-soiler (SS)) was added to the existing treatments to improve tillage depth and soil strength. The four plots of SS were laid out beside plot 24 (Fig.8)

3.4 Field operations

The first tillage operations were performed before soil freeze-up, on the 3 October 2000, on 24 plots. All 24 plots were seeded on 29 May 2001 and the crop was fertilized to soil test recommendations. Seeding was done with the 12.2 m (40 ft.) air-seeder cultivator equipped with low disturbance hoe-openers spaced at 203 mm (8 in). The seeder was pulled by a 313 kW (420 hp) tractor at a speed of 2.7 m/s (6 mph). The crop was harvested with a 9 m (30ft) wide combine at the end of the 2001 growing season. Tillage operations were repeated on the same plots on 19 October 2001; and an additional four plots for a subsoiler were initiated at that time. As aforementioned, the tool bar frame with C-shanks, which was used in 2000 tillage, was replaced with a heavy-duty cultivator equipped with edge-on shanks.

KEY:

HO – hoe opener

TD – tandem disk

TS – twisted shovel

RS – reversible shovel

NT – No tillage

NS – narrow sweep

SS – Subsoiler

NOTE:

Plots 1 to 24 were established in 2000.

In 2001, four plots were added besides plot 24, giving a total of 28.

Plot #	Treatment
1	HO
2	TD
3	TS
4	RS
5	NT
6	NS
7	TD
8	HO
9	TS
10	RS
11	NS
12	NT
13	NS
14	TS
15	HO
16	TD
17	NT
18	RS
19	NS
20	TD
21	HO
22	RS
23	TS
24	NT
25	SS
26	SS
27	SS
28	SS

Fig. 8 Plot layout for tillage treatment

3.5 Measurements

3.5.1 Soil penetration resistance. Penetration resistance was measured in the field immediately after an intensive rain event when moisture distribution along the soil profile seemed uniform. This would reduce the effect of moisture on the measurement of the penetration resistance. The measurements were done, before each tillage operation and before seeding, at 44 random locations for the 0 to 400 mm soil profile with a cone penetrometer (Model CP 20 Agridy Rimik Pty. Ltd., Toowoomba Austrialia). The penetrometer consisted of an inbuilt data logger, an 800 mm shaft, and a cone with a base area of 129 mm^2 and an apex angle of 30°. At each location, the penetrometer was inserted into the soil at an insertion speed of less than 33cm/s (ASAE 2000). The data for the soil penetration resistance was logged for every 25 mm (1 in) increment of soil depth. The mean value for the penetration resistance at each 25 mm increment was calculated.

3.5.2 Gravimetric water content and bulk density. At the same time of the penetration resistance measurements, soil core samples (25 mm diameter) were taken at 10 random locations in the field to determine the moisture content and bulk density of soil profiles. In the fall of 2000, samples were taken at the 0 to 50, 50 to 100, and 100 to 150 mm soil profiles. Before seeding and tillage in 2001, samples were taken at 100 mm (4 in.) increments up to 400 mm (16 in). All samples were dried in an oven for 24h at 105 °C and the soil moisture content and dry bulk density were calculated

3.5.3 Straw cover.

Prior to sampling straw cover in the field, digital images of straw and soil samples from the plots had to be analysed to determine the gray-level histogram for the soil image. The threshold value for the soil pixels from the histogram was then used in a digital imaging algorithm to determine surface straw cover.

3.5.3.1 Determination of gray-level histograms for soil image. A digital image can be considered a matrix whose row and column indices identify a point in the image and the corresponding matrix element value identifies the gray-level at that point. The elements of such a digital array are called pixels (Gonzalez and Woods 1998)

The gray-level spectrum of an image ranges from 0 to 255, corresponding to the degree of intensity of the pixels from black (0) to white (255). In a colour image, each pixel value is represented by gray-levels of Red (R), Green (G), and Blue (B). Because the gray-levels of each colour ranges from 0 to 255, then RGB [0 0 0] represents black and [255 255 255] represents white.

A gray-level histogram H(I) of an image I(x,y) is the frequency plot of gray-levels of pixels of that image without any reference to pixels' location (Ghazanfari et al. 1998). In an image processing algorithm, histogram development is initiated by a segmentation process which uses a threshold value to filter out the background. In this study, the gray-level histograms (Figs. 9a, b, and c.) were developed for the soil (Fig.10).

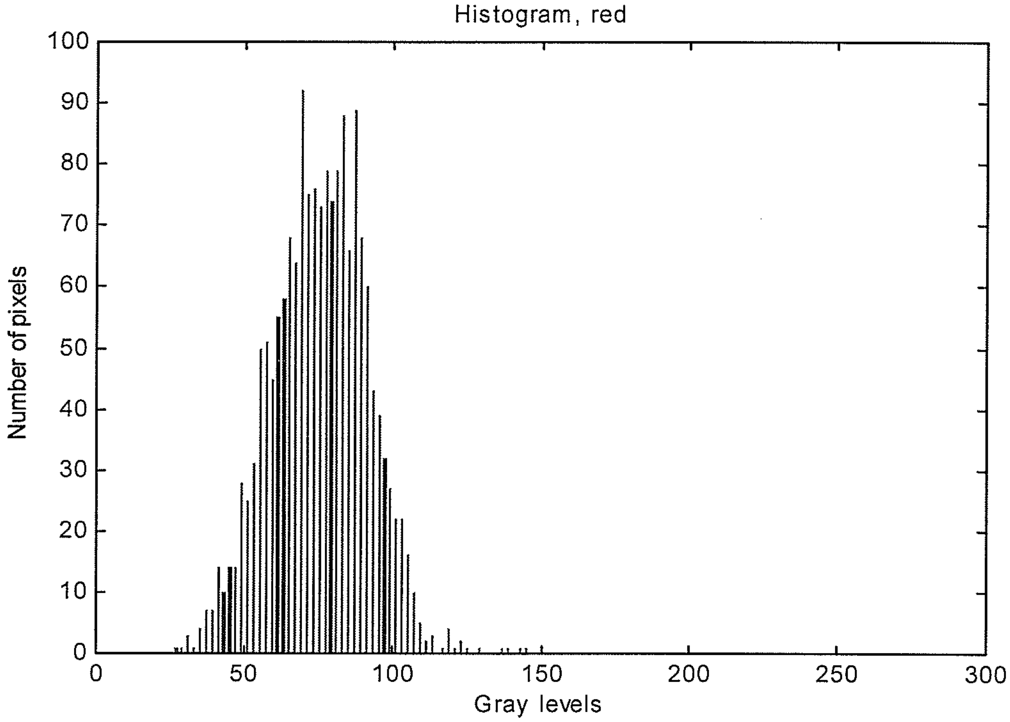

Fig. 9a Gray level histogram of soil block (Red)

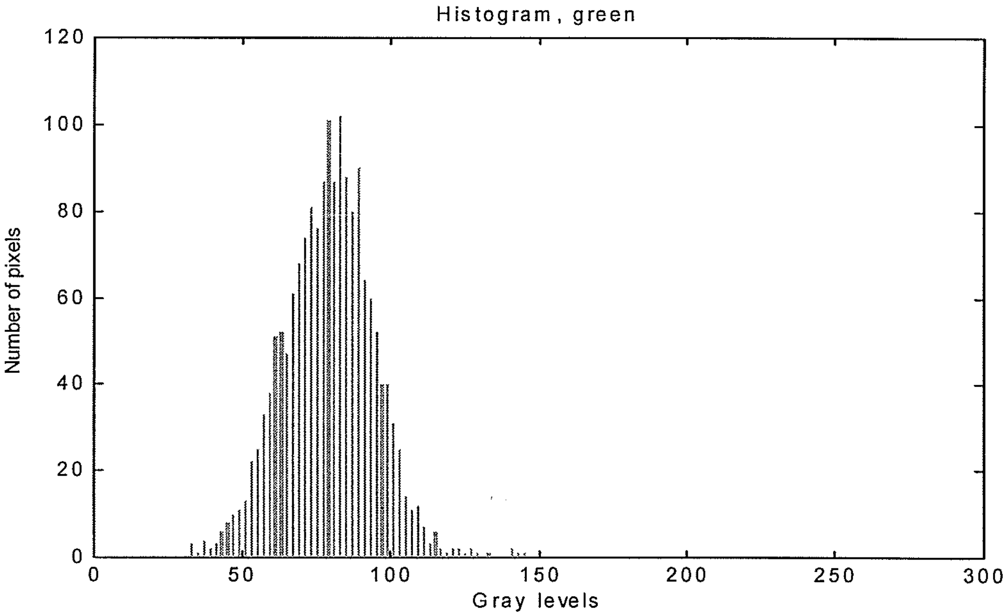

Fig. 9b Gray level histogram of soil block (Green)

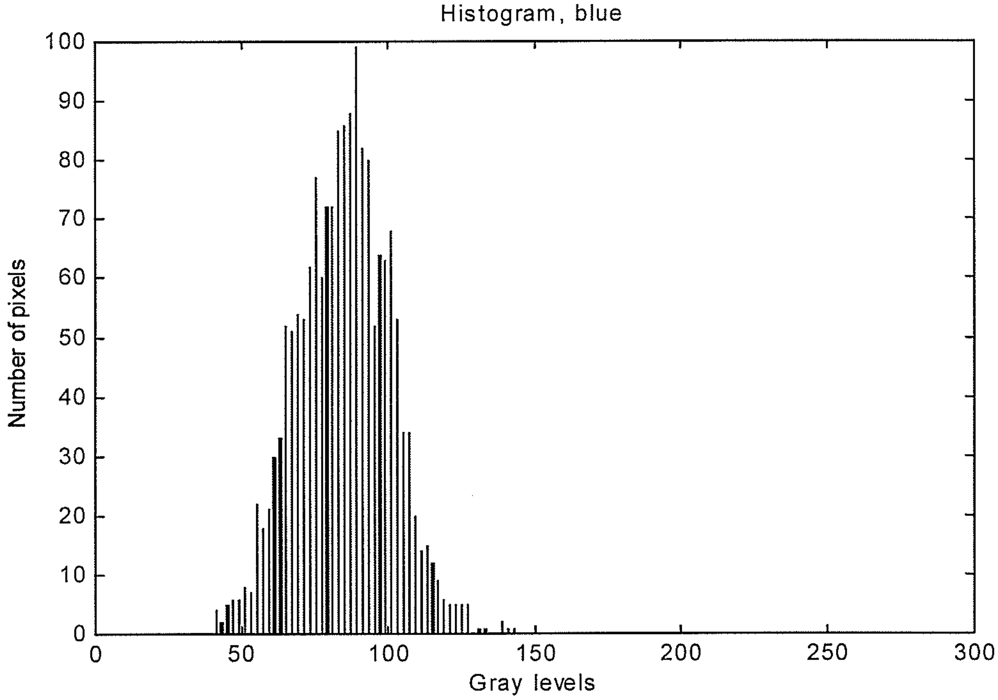

Fig. 9c Gray level histogram of soil block (Blue)

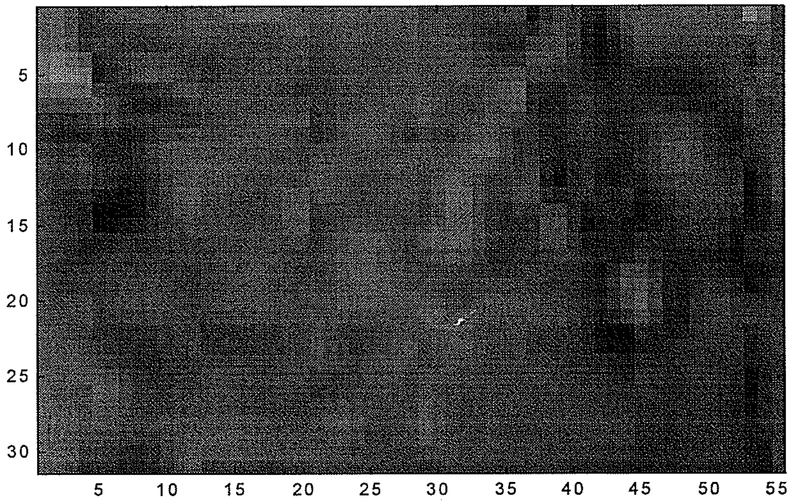

Fig. 10 Digital image of soil block

3.5.3.2 Determination of percentage of straw cover. Straw cover was measured prior to and after tillage operations. Three random locations were sampled on each plot. At each location, a 1 m^2 quadrat was placed flat on the surface of the plot (Fig. 11) and then photographed with a Canon digital camera. The digital images were downloaded to a personal computer and then stored in the TIF format (Fig. 12). The images were processed with the Image processing Toolbox Ver. 5.1 (Matlab Mathsworks1997, Natick, Ma. USA) to determine the percentage of straw cover.

To obtain the percentage of straw cover, thresholding was applied to each image (Fig. 13). In thresholding, an object of interest is separated from its background by assigning a threshold pixel value to it. The data from the gray-level histogram are used as the threshold value (Gonzalez and Woods 1998). In this study, the threshold values from the soil gray-level histograms (Red, Blue, and Green) were used as input values for the threshold. The pixels whose gray-level were less than 110 were considered as the soil pixel and were assigned a value of 0; while pixels with gray-levels greater than 110 were considered to be straw pixels and were assigned a pixel value of 255.

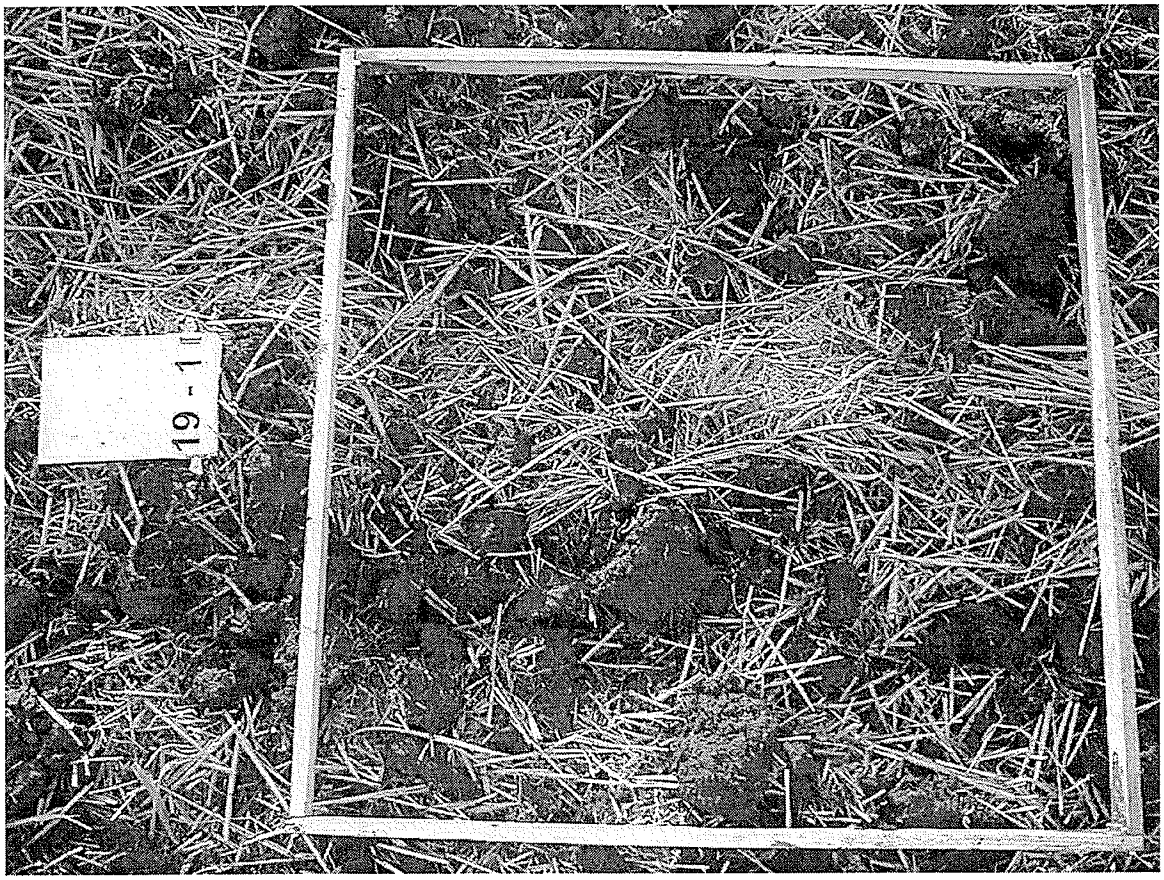

Fig. 11 Quadrat for sampling straw cover

Fig. 12 The TIF format of the photograph of soil and straw before thresholding

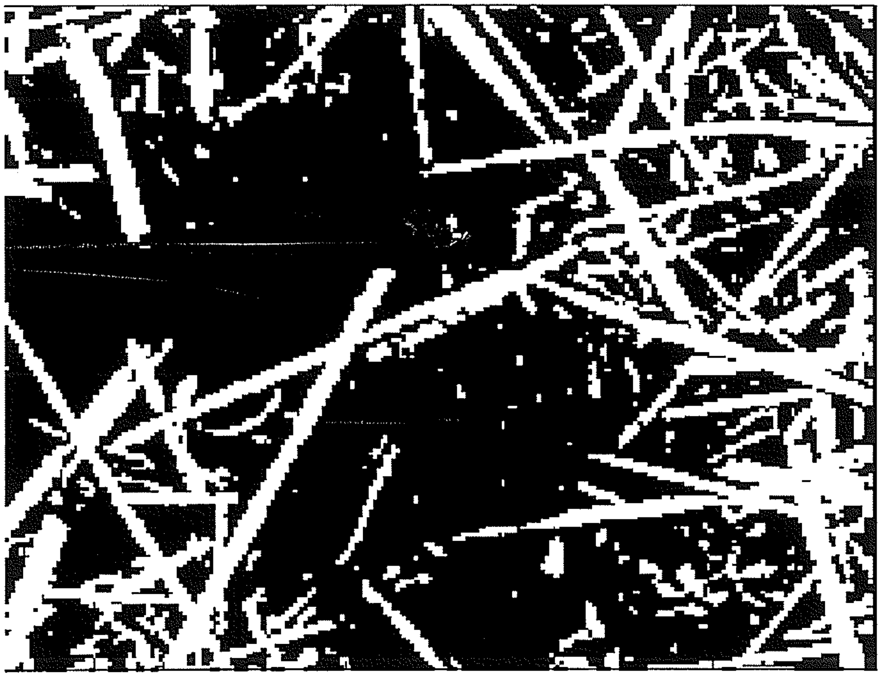

Fig. 13 Image of soil and straw after thresholding. The black colour represents the soil and the white represents the straw.

3.5.4 Incorporated Straw. This measurement was done only in 2000. The mass of straw incorporated into the soil was determined at three random locations on each plot. A core sample, 101 mm internal diameter (4 in), was taken to a depth of 150 mm (6 in) at each location. Each sample was then cut into three sections, 0 – 50, 50 – 100, 100 – 150 mm (0 to 2, 2 to 4, and 4 to 6 in). A composite sample was made from sections from the same depth for each plot. The straw was separated from the composite sample by using a method that involved the use of a root washing machine (Kolesnikov 1971). The root washer consists of a sink, screen and, overhead garden hose to wash out the straw from the soil. The large lumps of soil were first crushed with a rolling pin or meat-tenderizing hammer. The ground sample was placed on the screen and sprayed with water. The material left on the screen was then transferred to an ice cream pail to which water was added. The crop residue floated to the surface and the heavier soil particles remained at the bottom. The mixture of water and residue was poured carefully onto the screen to prevent the soil at the bottom of the pail from draining out. The pail was then filled with water and poured onto the screen to separate more residues from the soil. The process was repeated until all the straw was separated. The straw collected was placed in an envelope and dried at 60° C for 72h. Mean value for the mass of incorporated straw at each depth was calculated for each plot. The straw collected in this way included some coarse organic matter from previous tillage operations.

3.5.5 Draft force requirement. Draft force requirement for each tillage implement was measured and recorded using a Deor draft dynamometer (ST AgriTech, 56 Demers Place, WPG, MB R3V 1W4) and a data logger (ProDAS, Michigan Scientific Corporation, 321E Huron St., Mifford, MI 48381). The dynamometer was fitted between the tractor and the implement (Fig. 14) and was connected to the data logger in the tractor cab. Data for all draft measurements were logged on two channels for 40 s at a sample rate 200 s^{-1} and a scan rate of 100 Hz as the tractor pulled the implement at a constant speed of 1.7 m/s (3.75 mph) for all operations.

Fig. 14 The dynamometer used for measuring draft force requirement.

(The dynamometer was fitted between the implement and the tractor).

This speed is the approximate speed used by the producer for tillage operations. Mean value for the data from the two channels was calculated for each plot. Rolling resistance of the implements' wheel was subtracted from the draft force data. Measurements of rolling resistance were made as a tractor pulled the implement when the soil cutting tools were not engaged. The draft force for the tandem disk could not be measured during tillage 2000 of because of time constraints. The disk had to be returned to the manufacturer promptly and as a result there was insufficient time to set up the dynamometer on the tractor and the implement.

3.5.7 Tillage depth. Tillage depth was determined immediately after tillage operations. The measurements were taken at 10 random locations on each plot. At each location, the loose soil was removed from the furrow made by the soil-cutting tool. A piece of board was placed across the furrow on the undisturbed soil surface. The tillage depth was measured from the bottom of the furrow to beneath the board. The mean depth for a tillage treatment was calculated for each plot.

3.5.8 Seeding depth. Seeding depth was determined by measuring the chlorophyll-free length (CFL) of the seedlings (Tessier et al. 1991) after the final plant count was completed (34 days after first emergence). A total of five plants were uprooted from each row used for plant counting and their CFL (the distance from the seed remnants to the onset of the green stem colour) was measured as the affective seeding depth. The vertical distribution of the seeds in the furrow was characterized by the standard deviation of the CFL in each seed row.

3.5.9 Plant population and speed of emergence. Plant counts were made in 600 mm (2 ft) long staked rows at 15 random locations on each plot, 4, 7, and 10 d after the first seedling emergence, and weekly thereafter until a stable count was obtained. Stable emergence counts were retained as final plant population and the data was normalized to plants per square meter. Speed of emergence (Tessier et al. 1991) was calculated as follows:

$$\text{Speed of emergence} = (\sum Ni/di)/A$$

Where:

Ni is the number of new seedlings counted per day (di)

A is area (m^2)

3.5.10 Crop yield

In the latter stage of the growing season, the crops were attacked by fusarium. Though the incidence of the disease was not quantified, it appeared that it was prevalent on all plots. Upon maturity, the crop was harvested with the producer's 9.2 m (30 ft) combine. On each plot, a 30 m (100 ft) strip of crop was harvested. The weight of the grain and the yield for each treatment were determined.

3.6 Data analysis

Analysis of variance (ANOVA) (SAS Institute 1996) was used to test the main effects of the variables studied. The means for the treatments were considered as dependent variables in the ANOVA. Duncan Multiple Range Tests were applied and statistical inferences were made at the 0.05 level of significance.

4.0 RESULTS AND DISCUSSION

4.1 Site characteristics

4.1.1 Soil characteristics and pre-tillage residue. The experimental site was characterized by determining percentage of straw cover, mass of surface straw, gravimetric moisture content, bulk density, and soil strength before the initiation of tillage. The average residue cover prior to tillage was 70% (S.D. = 2) and represented a load of 4.1 Mg ha^{-1} (3658 lb/ac). Gravimetric water content was 32, 34, and 35% (dry basis) at the 0 to 50, 50 to 100, and 100 to 150 mm depths respectively. The bulk densities for the 50 mm increment horizons were 1.27, 1.45, and 1.53 Mg/ m^3 respectively.

4.1.2 General characteristics of soil strength for the site

The soil strength or cone penetration resistance was measured prior to tillage to characterize the experimental site and to determine a suitable depth for actual tillage operations. It was measured again in the spring to detect any changes that might have occurred after the soil was allowed to freeze in the winter. To characterize the site and to determine the required tillage depth, the mean soil strength for all treatments at each depth was considered (Figure 15 and 16). The impact of tillage treatments on soil strength was analysed by comparing the means of soil strength for each tillage treatment at the same depth (Table I, II, and III).

Prior to tillage 2000, the soil strength increased continuously as penetration depth increased and reached a maximum value of 1700 kPa at the 125 mm (5 in) depth (Fig. 15). From this depth, the penetration resistance decreased and then remained constant at 1200 kPa beyond 250 mm (10 in). It appears that a compacted or resistant layer was located between the 50 to 125 mm (2 to 5 in) depths. Wheel traffic of previous field operations such as seeding and harvesting with mechanical equipment, and continuous tillage at shallow depths may have enhanced the conditions for the occurrence of that resistant layer.

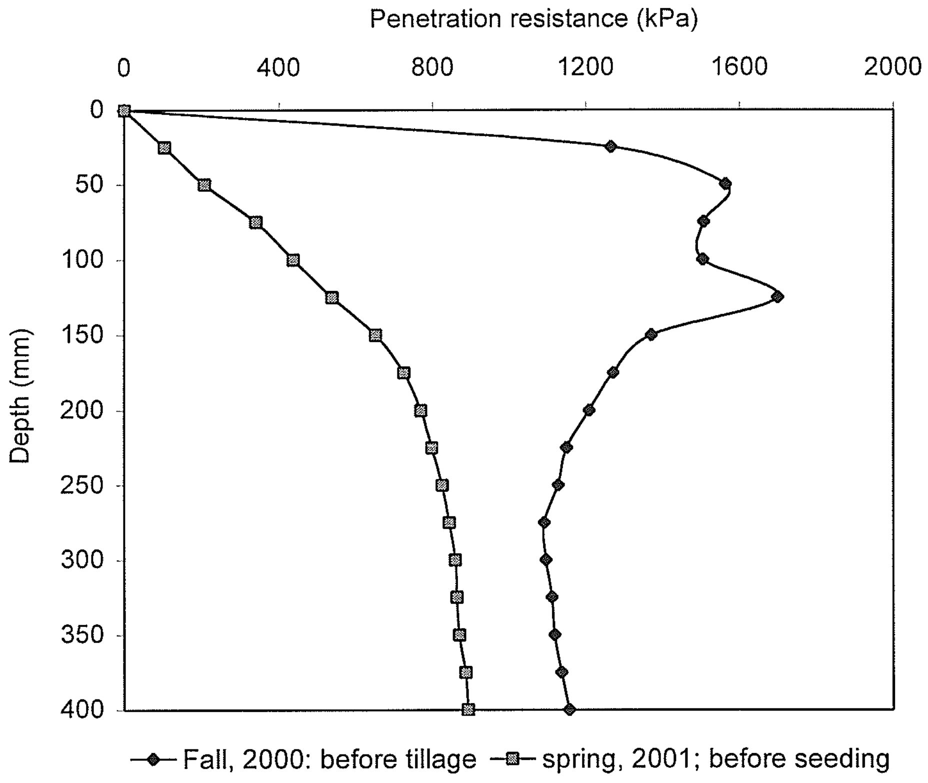

Fig. 15. Cone penetration resistance of soil before tillage operations, 2000, and before seeding in spring of 2001. (Each value represents the mean of 44 insertions).

The maximum value of 1700 kPa observed in the field prior to tillage is close to the agronomically-important threshold (1800 kPa) for root penetration of cultivated crop (Letey 1995). Hence, the behaviour of the 50 to 125 mm (2 to 5 in) layer on the site could be a potential limiting factor for root development, plant performance, and tillage operations. The severity to which this layer can become a limiting factor would be dependent on the level of moisture in the soil. Francis et al. (1987) observed that soil strength could increase as a soil dries.

When soil penetration resistance increases, the plant's ability to absorb available water and nutrients from the soil profile decreases. If this situation persists, the plant will suffer from water stress and nutrient deficiency. This stress could affect the physiological functions of the plant and consequently crop yield. Therefore, if crop performance has to be enhanced, the resistant layer must be broken up by tillage to enhance water infiltration and root growth.

In the spring of 2001, before planting, the soil strength had decreased throughout the profile (Fig. 15). Soil penetration resistance was generally lower than that observed in the previous year before tillage trials. The decrease in soil strength may be attributed to the effects of the snow cover, that is, soil freezing in winter and thawing in the spring. Bullock et al. (1988) observed that the disruption of soil aggregates by freezing could be more pronounced than a single pass of most tillage implements.

During the second year trial, for fall tillage 2001 and before seeding in spring 2002, the soil strength displayed a similar trend as that of first year trial. The penetration resistance throughout the soil profile had increased before tillage 2001 and generally decreased at spring 2002 (Fig. 16). The increase in soil strength before tillage 2001 could be as a result of the hardening of the soil and tractor traffic from chemical spraying and harvesting.

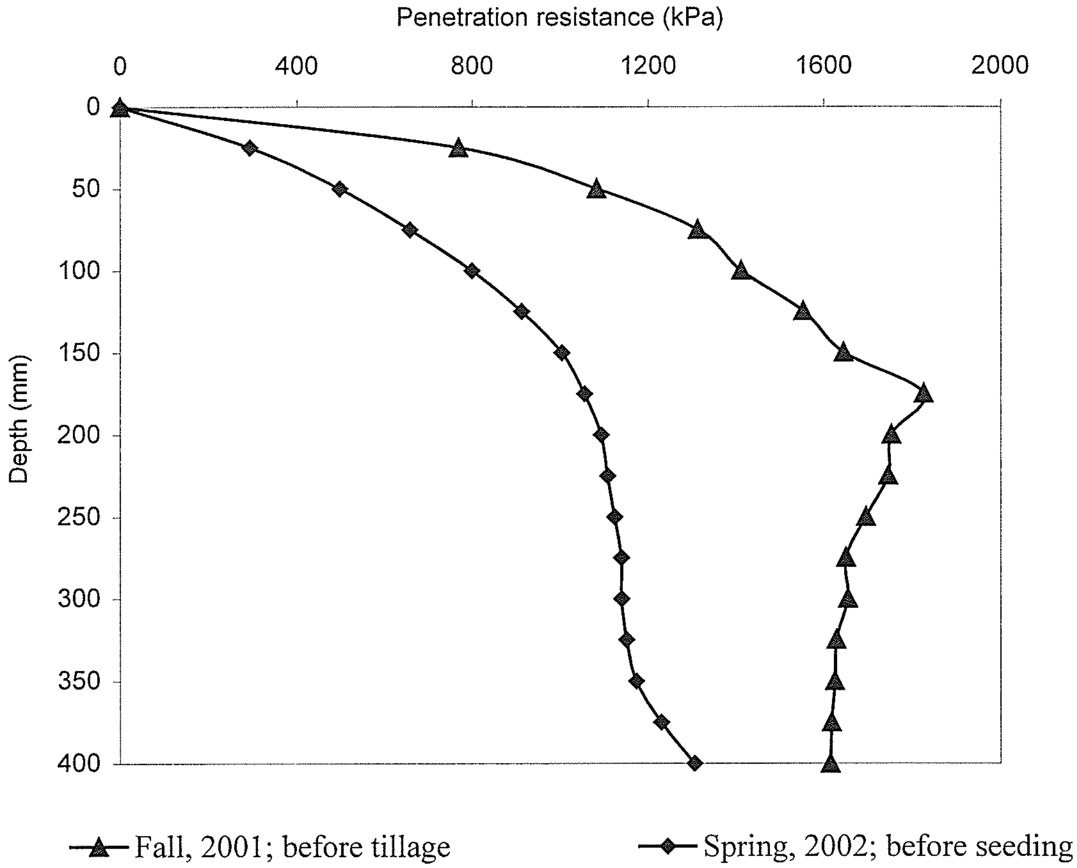

Fig. 16. Cone penetration resistance of soil before tillage 2001 and before seeding 2002. (Each value represents the mean of 44 insertions).

The changes in soil strength through the growing season, from spring 2001 and before tillage 2001 (Figure 15 and 16), may also be due to consolidation or setting of the soil, experimental errors, and the impact of wet and dry cycles. The penetration resistance of a soil is strongly related to the water content (Materecha and Banda 1997), which depends on precipitation. Therefore, the pattern of changes in soil strength before tillage in 2000 and 2001 could have mirrored the changes in precipitation in these two years. The decrease in soil strength from fall tillage to planting for both years could be caused by the disruption of soil aggregates as the soil freezes in the winter and thaws in the spring.

4.1.3 Soil strength and the impact of tillage treatments

Table I. Cone penetration resistance (kPa) for tillage treatments at seeding 2001.

Tillage	Sample depth (mm)					
treatments	25	50	75	100	125	150
	Soil strength (kPa)					
NT	108 ab	240 ab	371 a	474 a	586 a	689 a
NS	88 b	207 ab	341 a	415 a	482 a	597 a
TD	104 ab	215 ab	338 a	416 a	496 a	642 a
RS	172 a	300 a	384 a	460 a	570 a	683 a
TS	98 ab	174 b	319 a	451 a	561 a	664 a
HO	79 b	163 b	302 a	415 a	558 a	642 a

TD, TS, RS, NS, HO, and NT - See Table I for explanation

* Means in the same column and followed by the same letter do not differ significantly P=(0.05) according to Duncan's Multiple Range Test

A comparison of soil strength for the 25 mm depth of all tillage treatments before seeding, in spring of 2001, indicates that soil strength for RS was significantly higher than that of HO and NS (Table I). The soil strength for NT, NS, TD, TS, and HO were almost similar at that depth. At the 50 mm depth, soil strength for RS was significantly higher than that of TS and HO, but almost similar for NT, NS, TD, TS, and HO. Beyond the 50 mm depth, soil strength was not significantly different.

Table II. Cone penetration resistance (kPa) before fall tillage 2001.

Tillage treatments	Sample depth (mm)							
	25	50	75	100	125	150	175	200
	Soil strength (kPa)							
NT	774 a	973 a	1266 a	1462 a	1546 ab	1644 a	1720 a	1653 a
NS	829 a	1249 a	1523 a	1595 a	1702 ab	1754 a	1748 a	1719 a
TD	725 a	1084 a	1210 a	1259a	1296 b	1258 a	1459 a	1368 a
RS	447 a	821 a	1412 a	1107 a	1407 ab	1814 a	2019 a	1961 a
TS	686 a	1015 a	1264 a	1426 a	1633 ab	1793 a	1934 a	1949 a
HO	982 a	1427 a	1647 a	1591 a	1803 a	1844 a	1705 a	1594 a

TD, TS, RS, NS, HO, and NT - See Table I for explanation

Means in the same column and followed by the same letter do not differ significantly P=(0.05) according to Duncan's Multiple Range Test

For tillage impact, it was observed that the soil strength before tillage 2001 was similar for all treatments for all depths, except at the 100 – 125 mm depth (Table II). Generally, it appeared that soil strength was similar throughout the profile at the end of the growing season, before tillage, regardless of the type of fall tillage that was used in the preceding fall. Gerik et al. (1987), and Larney and Kladivko (1989) observed that the strength of soils with high clay content was unaffected by tillage.

Table III. Cone penetration resistance (kPa) before seeding in spring of 2002.

Tillage treatments	Sample depth (mm) 25	50	75	100	125	150	175	200
	Soil strength (kPa)							
NT	429 a	727 a	826 a	921 a	992 a	1048 ab	1015 a	1138 ab
NS	298 ab	448 b	569 b	636 b	709 b	858 b	936 a	939 b
TD	289 ab	451 b	658 ab	798ab	905 a	949 ab	1015 a	1071 ab
RS	259 b	469 b	625 b	819 ab	967 a	1079 ab	1152 a	1206 a
TS	235 b	483 b	650ab	828 a	1006 a	1106 a	1133 a	1153 ab
HO	191 b	361 b	563 b	761 ab	833 ab	911 ab	943 a	996 ab

TD, TS, RS, NS, HO, and NT - See Table I for explanation

Means in the same column and followed by the same letter do not differ significantly P=(0.05) according to Duncan's Multiple Range Test.

In the spring of 2002, before seeding, soil strength for NT at the 25 mm depth was significantly higher than that of RS, TS, and HO (Table III). Soil strength for NS, TD, RS, TS, and HO were almost similar at that depth. At the 50 mm depth, NS, TD, RS, TS, and HO had similar soil strength. This similarity was partially reflected at the 75 mm depth. At depths of 100, 125, and 150 mm, soil strength for NS was lower than that of TS. At these depths, NT, TD, RS, TS and HO were almost similar. There were no significant differences in soil strength at the 175 mm depth.

4.2 Tillage depth

The results of the tests for soil strength prior to tillage 2000 served as a guide for setting the tillage depth for the implements. Hence, during tillage operations in the fall of 2000, the resistant layer that was found between the 50 to 125 mm (2 to 5 in) layer in the field (Fig. 15) was targeted for tillage. To this effect, the target depth for tillage operations was set as 150 mm (6 in) for all the treatments except for the field cultivator hoe opener (HO). This implement (HO) cannot till below 100 mm (4 in) because it is a light and does not penetrate deeply into the soil (Reeder1992).

None of the implements tested in 2000 were able to achieve the targeted depth of 150 mm (6 in) (Table I). The trip force, 2.5 kN (550 lb), of the shanks on the John Deere tool bar frame was insufficient for deeper tillage. The implement and soil-cutting tools could not transmit all the force applied by the tractor to the soil to penetrate the hard layer. The HO tilled to the shallowest depth, 66 mm (2.5 in). Among all the implements tested, the TD, the NS, and RS showed no significant differences in tillage depth. The TS tilled deeper than the HO, but shallower than all the other implements.

The impact of the soil strength on tillage tools during 2000 tillage trials was greater than anticipated. Because of this, the tool bar frame used for the TS, RS, and NS treatments had to be substituted with a heavier frame for tillage operations in the fall of 2001. A subsoiler (SS) was also recommended for second year of tillage trials.

Table IV. Tillage depths for implements during tillage operations in the fall of 2000 and fall of 2001.

Tillage	Tillage depth in 2000		Tillage depth in 2001	
treatments	(mm)	(in)	(mm)	(in)
TD	104a	4.0	103a	4.0
TS	94b	3.5	154b	6.0
RS	103a	4.0	152b	6.0
NS	106a	4.0	156b	6.0
HO	66c	2.5	88d	3.5
NT	NA	NA	NA	NA
SS	NA	NA**	264a	10

TD – Tandem disk, HO – Hoe opener, TS – Twisted shovel, RS – Reversible shovel, NS – Narrow sweep, and NT - No tillage.

* Means in the same column and followed by the same letter do not differ significantly (P=0.05) according to Duncan's multiple range test.

** NA - Not applicable.

An important concern during 2001 tillage operations was to increase tillage depth beyond 150 mm in order to improve the soil for better crop root penetration and water infiltration. All treatments except the TD and HO were able to till deeper than 150 mm (6 in.) (Table I). However, these did not till deep enough to penetrate the entire resistant soil layer that occurred at the 150 – 250 mm depth (Fig. 16). The subsoiler, with heavy-duty shanks spaced at 760 mm (30 in.), was very effective in penetrating the resistant layer in the field. Tillage depth of the SS was 264 mm (10.4 in).

4.3 Effects of tillage on surface residue cover

Each plot was estimated to have 4.1 Mg/ha (3658 lb/ac) of straw before tillage 2000. This level of straw could affect tillage operations if effective implements for residue management are not available. Although not quantified, it was observed that little plugging occurred during tillage operations.

Percentage of residue remaining, the ratio of residue cover after tillage to residue cover before tillage, was calculated for each implement; it indicates the percentage of the pre-tillage residue an implement leaves in the field after tillage. Pre-tillage residue cover in fall 2000 was about 70%, represented by NT. After tillage, the surface cover for each plot was reduced significantly (Table IV). The hoe-opener left the largest cover (80 % of the residue remaining) and the tandem disk the least (64% of the residue remaining) (Table IV).

Residue remaining after tillage operations in 2000 ranked from high to low as follows: HO; TS; RS and NS; TD. No significant differences in residue cover were observed between the reversible shovel and the narrow sweep. With the exception of the tandem disk, which differed significantly, the twisted shovel differed slightly from the other implements in reducing residue cover.

Table V. Mean residue cover and residue remaining after tillage operations in the fall of 2000.

Tillage treatments	Residue cover (%)	Residue remaining (%)
TD	45d*	64
TS	52bc	74
RS	49cd	70
NS	47cd	67
HO	56b	80
NT	70a	100

TD – Tandem disk, HO – Hoe opener, TS – Twisted shovel, RS – Reversible shovel, NS – Narrow sweep, and NT - No tillage.

* Means in the same column and followed by the same letter do not differ significantly (P=0.05) according to Duncan's multiple range test.

** NA - Not applicable.

The pre-tillage residue cover was lower, 67% (S.D. = 3), for fall 2001 (Table V). The similar trends in residue cover and residue remaining were observed among the six treatments in 2001as in 2000 (Table IV). The SS, which was a new treatment in 2001, left the least surface cover (23%). The performances of the implements in reducing surface residues were consistent for both years, despite the use of a heavier cultivator frame for the NS, RS, and TS in 2001.

Table VI. Mean residue cover and residue remaining after tillage operation in the fall of 2001.

Tillage treatments	Residue cover (%)	Residue Remaining (%)
TD	40d	59
TS	50b	75
RS	43cd	64
NS	43cd	64
HO	49bc	73
NT	67a	100
SS	23e	34

TD – Tandem disk, HO – Hoe opener, TS – Twisted shovel, RS – Reversible shovel, NS – Narrow sweep, NT - No tillage, and SS – subsoiler.

* Means in the same column and followed by the same letter do not differ significantly (P=0.05) according to Duncan's multiple range test.

** Not applicable.

All the implements, with the exception of SS, left an adequate residue cover (greater than 30 %) that could be classified as conservation tillage (Lindwall et al. 1994) for the Red River and Osborne clays because they are highly erodable by wind if dry and uncovered. Therefore, if a producer's primary objective is to protect the soil against wind erosion then any of the following: HO, NS, RS, or TS could be adopted. However, whichever one is selected may influence tillage depth, quantity of incorporated straw, draft force requirement, and seedling emergence.

4.4 Incorporated straw

Residue was present in all the soil profiles, 0 to 150 mm (0 to 6 in), for the NT treatment. This indicates that some residue (coarse organic matter) was already present in the soil prior to tillage operations and the method used to collect and separate the incorporated residue from the soil could not eliminate any residue that was incorporated prior to tillage. The mass of coarse organic matter for the NT treatments at a particular depth can be considered as a baseline for the mass of incorporated straw for all tillage treatments at that depth. The quantity of coarse organic matter present at the different depths prior to 2000 tillage were as follows: 0.59 Mg/ha (527 lb/ac) at 0 – 50 mm (0 –2 in) depth and 0.10 Mg/ha (89 lb/ac) at 50 – 100 mm (2 – 4 in) depth.

The TD buried the most straw, 1.13 Mg/ha[1] (1008 lb/ac), at the 0 to 50 mm (0 to 2 in) depth (Table VI). There were no significant differences between the TS, NS, and HO in incorporating residue into the soil at the 0 to 50 mm (0 to 2 in) depth (Table VI). The mass of straw incorporated for the RS differed slightly from that of the other treatments.

At the 50 to 100 mm (2 to 4 in) depth, there was a general reduction in the mass of residue incorporated by all implements; however, the TD buried a significantly greater mass of straw than the HO and the NT treatments. At that depth, the mass of the incorporated residue did not differ significantly among the other treatments. The residue content at 100 to 150 mm (4 to 6 in) depth did not differ significantly between the implements. The average mass of residue present at that depth was 0.06 Mg/ha (S.D. = .02).

Table VII. Mean mass of barley straw buried at 0 – 50 mm and at 50 – 100 depths in a clay soil during tillage operations in the fall of 2000.

	Sample depth	
Tillage treatment	0 –5 0 mm (0-2 in.)	50 - 100 mm (2 - 4 in.)
	Mass of straw in Mg/ha⁻ and (lb/ac)	
TD	1.13 (1008)a	0.96 (857)a
TS	0.73 (651)ab	0.43 (384)ab
RS	0.23 (205)b	0.68 (609)ab
NS	0.43 (384)ab	0.36 (321)ab
HO	0.46 (411)ab	0.30 (268)b

TD, TS, RS, NS, and HO - See Table I for explanation

* Means in the same column and followed by the same letter do not differ significantly P=(0.05) according to Duncan's Multiple Range Test

All the tillage implements incorporated most of the residue at the 0 to 50 mm depth. The incorporation of residue into the soil can be beneficial if the carbon/nitrogen (C:N) ratio remains at an adequate level (less than 20:1) in the soil, specifically in the 0 to 50 mm (0 to 2 in) depth. Residue incorporated into the soil at that depth will increase the microbial population throughout this profile (Carter and Rennie 1982; Doran 1980). A diverse microbial population in this layer may protect the plant from diseases. It is, therefore, expected that increased residue incorporation by tillage will increase soil microbial activity which has beneficial implications to crop growth.

4.5 Draft force requirement

4.5.1 Draft force of implement and tool

Draft force for all the implements except for TD was measured during tillage operations in the fall of 2000 and 2001. Among all the implements evaluated in 2000, the HO required the highest draft force, 62.87 kN (14133 lb), due to its large working width and greater number of soil-cutting tools (Table. V). Among the RS, NS, and TS, the TS required the least draft force: 35.19 kN (7911 lb).

The draft force requirement for each soil-cutting tool was calculated by dividing the mean of the implement draft force by the number of soil cutting tools on the implement. The draft force requirement per tool opener was the least for the HO and greatest for the NS (Table VII). Draft force per meter of implement width was calculated for the various implements. The NS required the highest draft per meter of implement width and the TS the least

Because RS, TS, and NS shared the same tool bar frame and had the same tool spacing, a comparison of their draft requirement will reveal the effects of cutting tools on draft force. The type of cutting tools affected the draft force requirement significantly (Table VII). Of the three implements, the NS required the most draft force per tool. This occurred because the NS has a greater cutting width than the other soil cutting tools. The difference in draft force requirement for the TS and RS was insignificant; however, the RS tilled deeper.

Table VIII. Mean draft force requirement per implement, per soil-cutting tool, and per meter of implement width during tillage operations in the fall of 2000.

Tillage treatment	Draft Force of implement (kN)	Draft Force of implement (lb)	Width of implement (m)	Number of soil-cutting tools	Draft/ soil - cutting tool (kN)	Draft/ soil - cutting tool (lb)	Draft/ width (kN/m)
TS	35.19	7911	8.2	14	2.51b*	564	4.29
RS	37.42	8412	8.2	14	2.67b	598	4.56
NS	49.67	11166	8.2	14	3.55a	796	6.06
HO	62.87	14133	12.2	60	1.05c	236	5.15

TS, RS, NS, and HO - See Table I for explanation.; Because of various constraints, the draft force for the tandem disk was not measured.

* Means in the same column and followed by the same letter do not differ significantly P=(0.05) according to Duncan's multiple range test.

** The draft force per tool opener was calculated by dividing the mean of the implement draft force by the number of soil cutting tools on the implement.

There was a general increase in draft requirement per tool for all implements in 2001 because of increased tillage depth (Table VIII). However, the same trend in draft requirement per tool observed in 2000 among the TS, RS, and NS was repeated in 2001. The TS and RS performed similarly in depth and draft force, but the NS required more force to till at the same depth as TS and RS.

Table IX. Mean draft force requirement per implement, per soil-cutting tool, and per meter of implement width during tillage operations in the fall of 2001.

Tillage treatment	Draft Force of implement (kN)	(lb)	Width of implement (m)	Number of soil-cutting tools	Draft / soil - cutting tool (kN)	(lb)	Draft/ width (kN/m)
TS	82.38	18520	11	18	4.58c*	1030	7.49
RS	74.90	16838	11	18	4.16c	935	6.81
NS	97.94	22018	11	18	5.44b	1223	8.90
HO	49.40	11106	12.2	60	0.82d	184	4.05
SS	48.72	10952	3	5	9.74a	2190	16.24

TS, RS, NS, HO, TD, and SS - See Table II for explanation.

* Means in the same column and followed by the same letter do not differ significantly P=(0.05) according to Duncan's multiple range test.

** The draft force per tool opener was calculated by dividing the mean of the implement draft force by the number of soil cutting tools on the implement.

Srivastava et al. (1993) have reported that the draft force requirement of implements increases with depth. Because of their narrow and convergent shape, it is expected that both the TS and RS will require less draft force than the NS during tillage operations. For lower draft requirement, a producer may select the TS or RS during tillage and achieve the same tillage depth; however, he may need to consider the effects of these cutting tools on residue cover, straw incorporation, and the amount of soil being cut prior to using them.

4.5.2 Comparison of draft force and draft rating. Daft force can be estimated by using the specified parameters in the equation below to determine the draft rating of an implement (ASAE D497.4 Jan 1998). Typical draft rating was calculated as:

$$D = F_i [A+B(S)+C(S)^2]WT$$

Where:

D	is implement draft N
F	is a dimensionless soil texture adjustment parameter (see ASAE D497.4 Jan 1998)
i	1 for fine, 2for medium, and 3 for coarse textured soils
A, B and C	are machine- specific parameters (see ASAE D497.4 Jan 1998)
S	field speed (km/h)
W	is the machine width (m) or number of tools
T	is tillage depth (cm) for major tools

For both years of tillage trials, the actual draft for all tillage treatments, except for TS, were within the estimated range determined by the equation specified by the ASAE Standards (Table IX and X). The equation gave a lower value for TS for both years. For NS, the draft force could not be determine from the equation, because the parameters that were required to do the calculations were not given for this tool.

Table X. Actual and estimated draft force (kN) for fall tillage operations in 2000.

Tillage treatment	Actual Draft force (kN)	Estimated draft range (kN)*
TS	35.19	10.98 – 32.93
RS	NA	NA
NS	49.67	21.90 – 65.71
HO	62.87	37.21 – 111.63

TD, TS, RS, NS, and HO - See Table I for explanation

* The draft force range represents ± 50% of the calculated value for all treatments except NS which was calculated at ±45% (see ASAE D497.4 Jan 1998)

NA – Parameters were not available in the ASAE Standards 1998

Table XI. Actual and estimated draft force (kN) for fall tillage operations in 2001.

Tillage treatment	Actual Draft force (kN)	Estimated draft range (kN)
TS	82.38	23.12 – 69.36
RS	NA	NA
NS	97.94	47.57 – 125.41
HO	49.40	37.21 – 111.63
SS	48.72	19.19 – 57.58

TD, TS, RS, NS, and HO - See Table I for explanation

* See Table for explanation

NA – See Table for explanation

4.6 Power requirements

The power requirement for each soil-cutting tool was calculated as follows:

$$P_{tool} = F \bullet v$$

Where:

P_{tool} = power requirement of the tool (kW)

F = draft force of the tool implement (kN)

v = ground speed (m/s)

Table XI shows the computed values for the power requirement of the various implements used during tillage in 2000 and 2001. For any of the tools, power requirement would increase as its speed and tillage depth increase.

The power required by a tractor to pull a tool during tillage is equal to the power requirement of that tool divided by the overall efficiency of the tractor.

This can be expressed as follows:

$$TP = (P_{tool})/E$$

where:

TP = tractor power (kW)

P_{tool} = power requirement of the tool (kW)

E = overall efficiency of the tractor

Table XII. Computed power requirement of tool and estimated tractor power on a Red River – Osborne clay soil for tillage 2000 and 2001. (The ground speed of the tractor was 1.7 m/s (3.75 mph)).

	Tillage 2000			Tillage 2001		
Tillage treament	Depth (mm)	Tool power (kW)	Tractor power required (kW)	Depth (mm)	Tool power (kW)	Tractor power Required (kw)
TS	94	4.28	5.33	154	7.79	9.70
RS	103	4.54	5.67	152	7.07	8.84
NS	106	6.03	7.54	156	9.23	11.54
HO	66	1.78	2.23	88	1.39	1.74
SS	ND	ND	ND	264	16.56	20.70

TS, RS, NS, HO, and SS - See Table II for explanation.

ND – Not determined during 2000 tillage

Tractor power required by tools is estimated and listed in table VII. Tractor efficiency (E) was assumed to be equal to 0.8. Because of greater tillage depth during 2001, the tractor power for all tools increased. The data estimated for tractor power can be used to determine the number of tools that can be pulled by a given tractor.

4.7 Seed placement

The standard deviation or the vertical seed scatter index (Fig. 17) was calculated to evaluate seed placement.

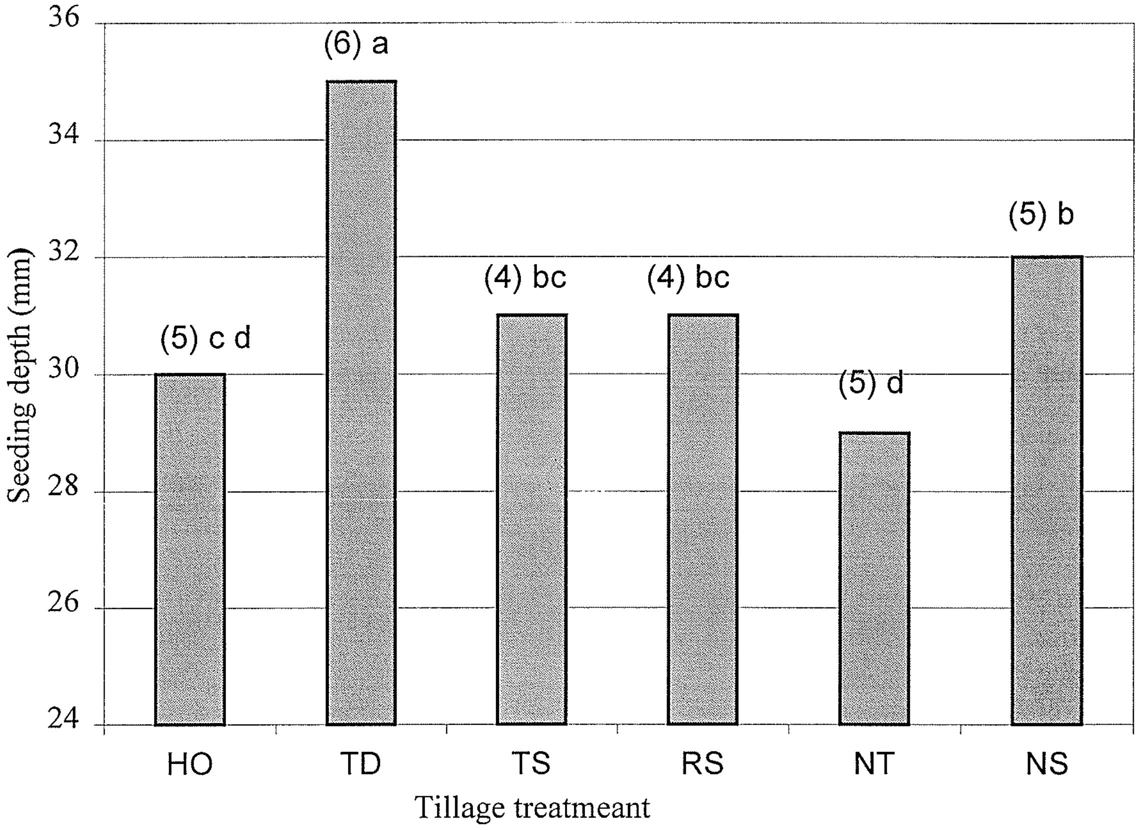

Fig. 17 Mean and standard deviation of seeding depth for tillage treatments during spring 2001. Numbers in brackets represent the standard deviation or seed scatter index. Bars with similar letter did not differ significantly (P=.05) according to Duncan's multiple range test.)

Significant differences in seeding depth were observed between tillage treatments. Seed placement was deepest (36 mm) for disk treatment and shallowest (29 mm) for NT plots. The NS permitted a deeper placement of the seed (32 mm) than the remaining three treatments which had slight differences in seeding depth.

The target depth, between 25 to 50 mm (1 to 2 in), for seeding was achieved for all tillage systems. Seeding out of this range could have negative effects on yields. Seeds sown too deep can experience delay in emergence and can become susceptible to root rot; while shallow seeding could result in inadequate seed covering which could reduce germination. Rapid emergence will allow seedlings to get ahead of the weeds.

The data for seeding depth and fall tillage depth were correlated. The correlation (r =0.53) indicates that there is a slight relationship between seeding depth and tillage depth. NS, TD, and RS had the same level of tillage depth, but the TD system recorded the highest seeding depth. A possible explanation is that the TD plots were more pulverized than the NS plots so the seeder would be able to get deeper into these plots. Other variables may also have exerted influence in seeding depth.

The vertical seed scatter index, standard deviation (Fig. 17), evaluates the uniformity of seed placement in the furrow. A small index indicates better uniformity of seed placement. TD plots permitted the greatest scatter (6 mm). The use of other tillage implements resulted in a seedbed that allowed more uniformity in seed placement. Uniformity in seeding depth can result in uniformity in emergence and plant establishment which may be beneficial to harvest because seed maturity would be similar for the plots.

4.8 Seed performance

4.8.1 Speed of emergence. The speed of emergence was expressed as the average number of seedlings that emerged per day per unit area (m^2). The NT plots had the highest speed of emergence among all the tillage treatments. The TD treatment encouraged the slowest emergence (Fig. 18). Seedling emergence for TS, RS, HO, and NS were similar.

The trends observed in speed of emergence correlated with the trends in seeding depth ($r = -0.69$). Hence, the correlation partly explains that slower emergence is likely to occur when seeds are sown deeper. The seeding depth may explain 48% ($R^2 = 0.48$) of the variability in emergence. The other 52 % variability in the data may be attributed to other characteristics of the furrow, seedbed, and random errors.

High levels of residues, such as those on no-till plots, can result in lower soil temperatures during spring (Aston and Fisher 1986; Bristow 1988; Unger 1994). Lower soil temperatures can delay seedling emergence. The higher emergence of the seedling on the NT plots could be attributed to lower seeding depth, 29 mm (1 in).

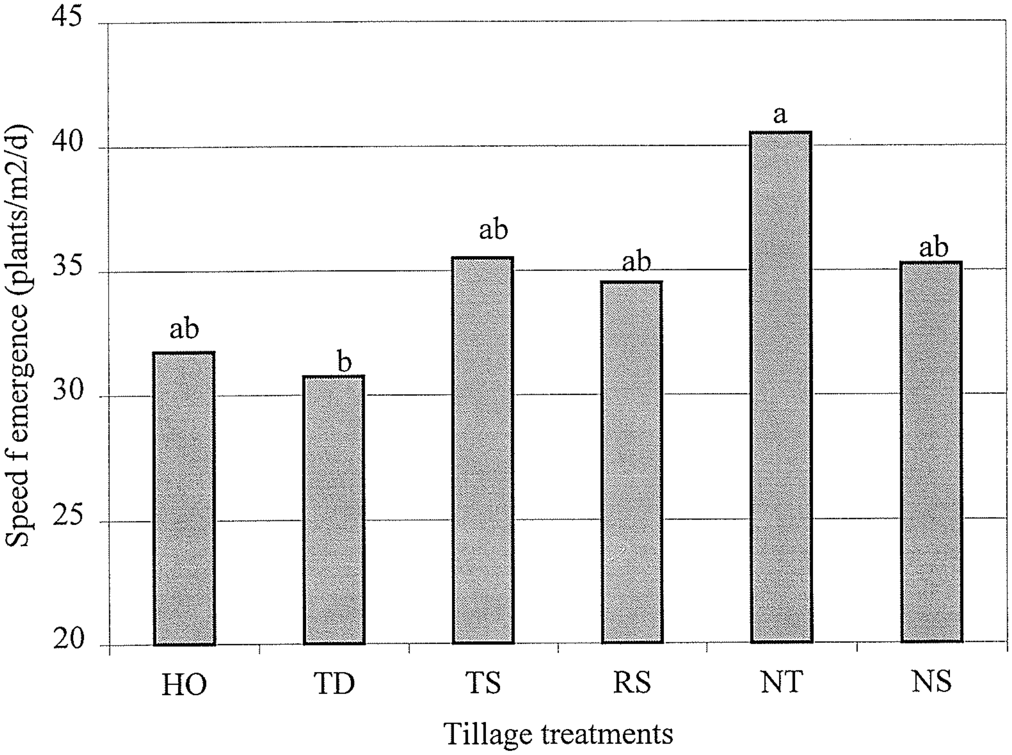

Fig. 18 Seeding emergence for seeded plots. (Columns with similar letter did not differ significantly (P=.05) according to Duncan's multiple range test).

Though residue cover reduces soil temperature, if the seeds are not sown too deep in the soil, the soil zone could be warmed up rapidly enough to prevent any setbacks in emergence (Tanaka et al. 1997). Better emergence in NT may be attributed to better soil-seed contact due to lack of incorporated straw.

Lower emergence for the TD may be attributed to poor soil-seed contact, because more straw was incorporated in its 0 to 50 mm (0 to 2 in) layer during fall tillage. Wuest et al. (2000) found that residue position could have a significant effect on emergence. Poor cover can lead to higher levels of evaporation of soil water in the spring, and excessive soil temperature. Both of these can hinder seedling emergence. The greater variability in the seeding depth on TD plots could have been another possible cause of poor seedling emergence on these plots. A number of variables, such as seeding depth, residue position, tillage method, and depth of tillage, can influence speed of emergence; however, no single factor acting alone could be held accountable for speed of emergence.

4.8.2 Final plant populations. Plant count for NT treatment (280 plants/m^2) was significantly higher than counts of the other tillage systems (Fig. 19). No significant differences in plant counts were registered among TD, NS, RS, TS, and HO treatments. The conditions created by the NT seem to have favoured emergence and establishment.

The data for emergence and final plant populations were correlated (r=.96). This indicates the presence of a strong relation between seedling emergence and plant establishment. Speed of emergence explains 92% (R^2) of the variability in final plant establishment. Rapid emergence resulted in better plant establishment. This is the case for the no-till treatment where faster emergence occurred. The contrary is true for the TD; slower emergence resulted in reduced final plant population.

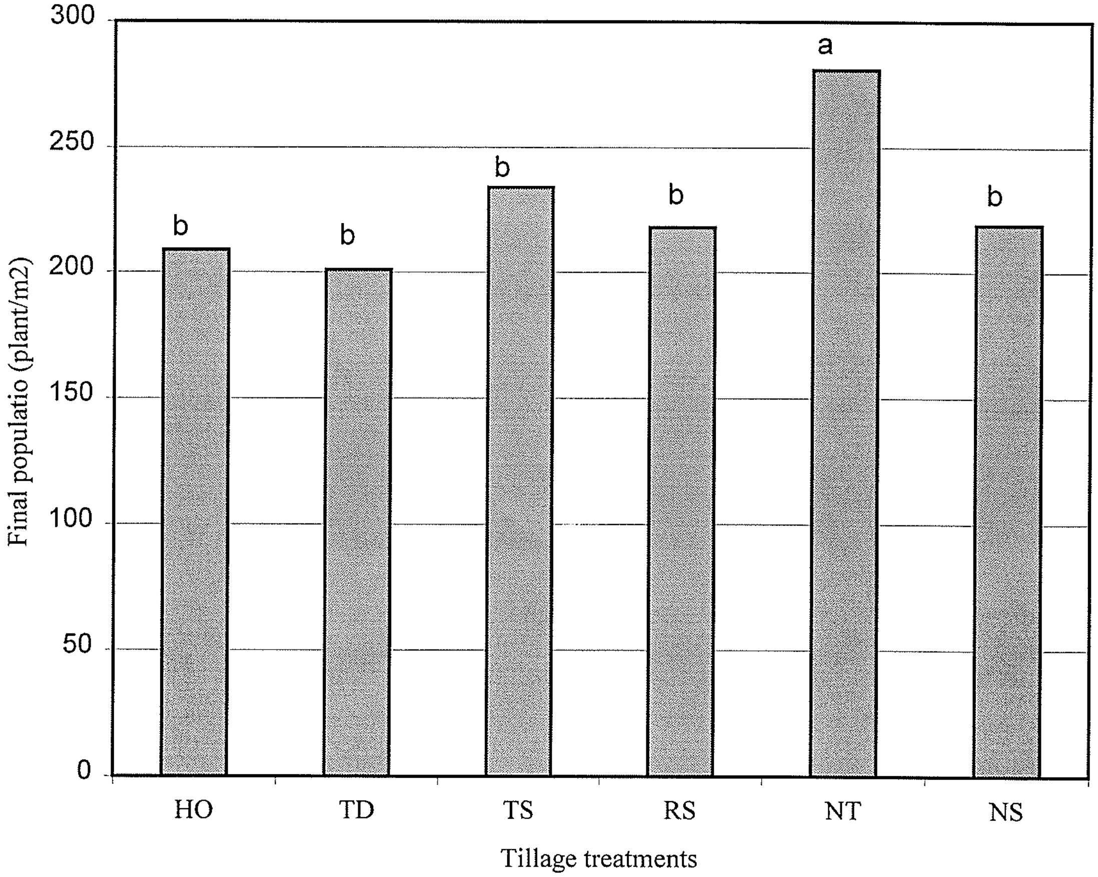

Fig. 19 Final plant population (plants/m ^{2}) for different tillage treatments on a heavy clay soil, 2001. Columns with similar letter did not differ significantly (P=.05) according to Duncan's multiple range test).

4.9 Crop yield

During the latter stage of the crop, all plots were attacked by fusarium. The incidence of the disease was not quantified. Visual observation and estimation were made to determine the extent of the disease on the plots. No-till plots seemed to have been affected the most. The disease was prevalent on all of the neighbouring farms.

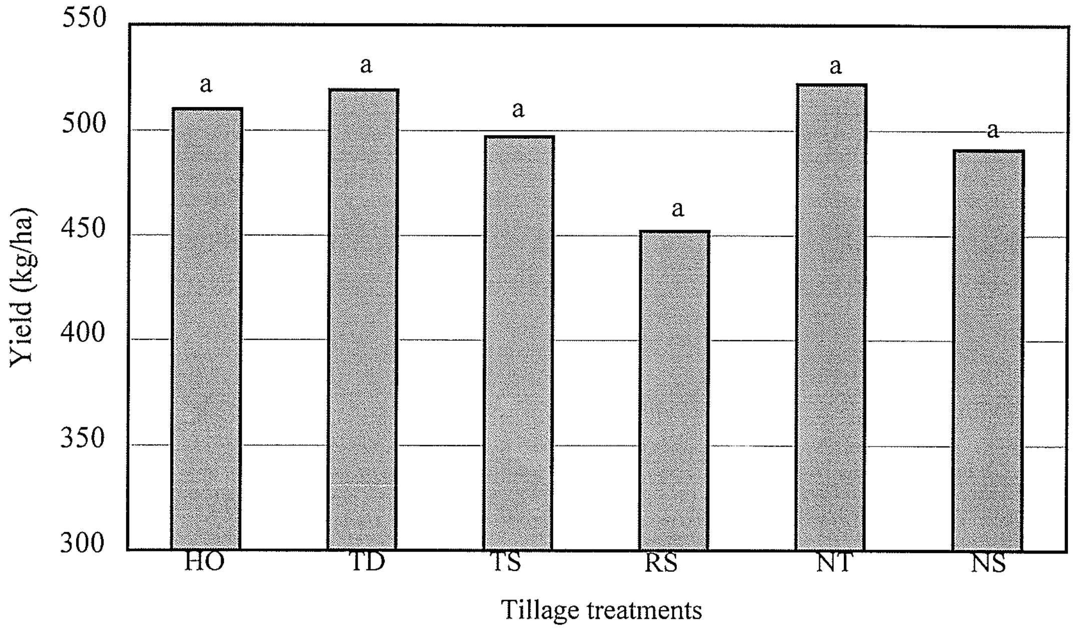

Fig. 20. Crop yield (Kg/ha) for different tillage treatments on a heavy clay soil, 2001. Columns with similar letter did not differ significantly (P=.05) according to Duncan's multiple range test.

The statistical difference in yield reduction among the treatments could not be determined. The yield for NT (580 kg/ha^1), though not significantly different from that of the other treatments, was the highest (Fig. 20). Because plant counts were high for NT, one would expect a significantly higher yield from that treatment; however, the significance was not detected due to highly variable data. Crop yield may have been reduced by the attack of fusarium and horizontal root growth (from visual observation) due to the hard pan. Also, the 2001 growing season was particularly dry; this may have contributed to low yields. The residue on the soil surface of NT increases water storage for plants use (Jalota et al. 2001). If a water stress or drought occurs, this water will be available to the plant and the ill effects of the drought, such as reduction in yield, will be compensated.

5.0 CONCLUSION

Pre-tillage assessments of soil strength for fall 2000 and 2001 indicated that a resistant layer was present in the field each year. Each resistant layer appeared to compacted and may have been produced as a result of tractor traffic during the growing season and during harvest. However, in the spring before planting, the soil strength reduced significantly. This reduction in soil strength may be attributed to the effects of freezing and thawing of the soil. It appears therefore, that the resistant layer would occur temporarily every year. It forms during the growing season and remains until the soil is tilled below previous tillage depth and allow to freeze and thaw. An adjustment in farm management strategies, such as greater emphasis on no-tillage and reduction in tractor traffic during the growing season, would help in alleviating the resistant layer that appears in the field every year.

Tillage implements can have a significant effect on residue, soil, and crop productivity. The data from the study support the following:

The disk, twisted shovel, reversible shovel, narrow sweep, and hoe-opener left adequate residue cover that could offer protection to the soil from erosion. Among these implements, the tandem disk maintained the least straw cover, up to 40%, (59% residue remaining) and the hoe-opener the most, up to 56%, (80% straw remaining). The reversible shovel and the narrow sweep left the same amounts of straw (up to 70% residue remaining) on the soil surface.

The choice of tillage implement cannot be based solely on residue cover. Depth and power requirement must be considered. Tillage depth for the implements differed significantly. The trip force of the shanks, type of soil cutting tool, and the weight of the implements could be responsible for the differences in tillage depth. When used on the same tool bar frame, the narrow sweep, twisted shovel, and the reversible shovel could till at similar depths, however, the narrow sweep would need the most power during operation. The hoe-opener cultivator produced the shallowest seedbed, less than 100 mm (4 in) deep.

Pre-tillage straw levels, 4.1 Mg/ha (3658 lb/ac) in fall 2000 could be considered high. However, all the implements incorporated most of this residue at the 0 to 5 mm (0 to 2 in) depth. Incorporated straw at that depth was similar for all implements with the exception of the tandem disk; it incorporated the most straw into the soil. Straw incorporation decreased greatly between the 50 to 100 mm (2 to 4 in) layer, while no significant addition of straw was detected for all implements at the 100 and 150 mm (4 to 6 in) layer.

Draft force was affected significantly by the type of soil-cutting tool and the tillage depth. Greater tillage depth required greater tractor power. Among all the implements (exclusive of the subsoiler) the narrow sweep required the greatest draft force per tool and the hoe-opener the least. The twisted shovel and the reversible shovel required the same draft force. Although it tilled at a similar depth with the reversible shovel and the twisted shovel when it shared the same tool bar frame, the narrow sweep required more draft force than either implement.

The power requirement of an implement depends on tool type, tool spacing, tillage depth, and travel speed. The estimated tractor power can be used to select the number of tools for a given tractor to till at a given depth.

The conditions on the no-tillage plots enhanced emergence, final population, and yield. This may be attributed to ideal seeding depth, increased water storage, and good soil seed contact.

Of the systems tested there are those with greater merits than others. The tandem disk pulverises the soil during tillage, and it incorporates a great amount of straw into the seedbed. These two factors can influence seed placement and seedling emergence.

The use of the reversible shovel, narrow sweep, and the twisted shovel on a heavy duty frame will leave adequate surface cover, enhance tillage depth for root proliferation, and provide favourable crop response in emergence and population. However, the narrow sweep will need more tractor power than the other treatments. Hence the reversible shovel or the twisted shovel could be a suitable system for managing excessive straw on clay soils without having to burn any straw prior to tillage.

No-tillage is another suitable option that could be explored. This treatment had the best emergence and final population. The system could be alternated with the reversible shovel or the narrow sweep for maintaining good seedbed condition for infiltration and root development.

The data collected over the two-year period indicates that the use of a subsoiler to alleviate soil strength and the temporary compaction that may exist prior to fall tillage may not be necessary. However, the use of the subsoiler can be use to improve water infiltration and aeration, which could impact on crop yield.

6.0 RECOMMENDATIONS

A wider range of innovative tillage systems and implements should be tested to determine their performance and suitability for tillage and straw incorporation on clay soils. This information will assist farmers in selecting suitable implements that are compatible to their local conditions.

Tool spacing will affect the amount of straw cover, draft force, and seedbed conditions. In this study, the effect of different tool spacing was not studied. Implements such as the twisted shovel, reversible shovel and narrow sweep should be evaluated at smaller tool spacing, for example, at 300 mm (12 in).

Longer term studies are required to determine if the no-tillage system is superior to the other systems for seedling emergence and final plant population.

The subsoiler should be used in long term experiments to evaluate its effects on the performance of seedlings, crop development, and yield.

A comparative study should be undertaken to determine if alfalfa, grown in a rotation on the no-tillage plots, could be as effective as the subsoiler in alleviating soil strength for better crop root penetration and water infiltration.

The soil strength should be monitored closely to determine the behaviour of the clay soils; this will facilitate the selection of adequate tillage implements by farmers as their confidence in the performance of these implements would be enhanced.

Studies should be done to determine the rate of decomposition of incorporated straw for the various tillage systems.

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