THE EFFECT OF TILLAGE PRACTICES AND SOIL COMPACTION ON THE PHYSICAL PROPERTIES AND PRODUCTIVITY OF A CLAY SOIL

by

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THE EFFECT OF TILLAGE PRACTICES AND SOIL COMPACTION ON THE PHYSICAL PROPERTIES AND PRODUCTIVITY OF A CLAY SOIL

BY

JOHN L. FITZMAURICE

A Thesis/Practicum submitted to the Faculty of Graduate Studies of the University of Manitoba in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

ABSTRACT

This study was initiated to investigate the effects of tillage and zero tillage practices on soil physical properties and crop growth. The research plot was on an Osborne clay (Rego Humic Gleysol) near Brunkild, Manitoba which had been zero tilled for the previous 8 years. Tillage treatments were initiated by cultivating the zero tilled field in the fall of 1990. All plots were seeded with hard red spring wheat (Triticum aestivum cv. Katepwa) in the spring of 1991 and barley (Hordeum vulgare cv. Argyle) in the spring of 1992. The four soil physical properties (oxygen diffusion rate, soil temperature, soil water content, and soil strength) which directly affect plant growth were monitored at various times during the growing season. Crop tillering, above ground dry matter production, root density and final yield were determined. In 1992 the effects of wheel traffic on soil strength, aeration, moisture and above ground crop growth were also monitored.

Soil temperature in the upper 20.0 cm was not affected by tillage treatment throughout the 1991 and 1992 growing seasons. Oxygen diffusion rate was similar for zero tilled and conventionally tilled treatments. However, the oxygen diffusion rate was below the critical level of 0.2 $\mu g \cdot cm^{-2} \cdot min^{-1}$ at a depth of 10.0 cm or greater in both 1991 and 1992. Conventionally tilled soil had higher gravimetric water contents in the upper 10.0 cm at the time of seeding than did zero tilled soils in the 1992 growing season. Soil strength was not found to differ consistently between tillage treatments. However, zero tilled soils tended to have higher mean soil strengths in the upper 10.0 cm in 1991. This difference disappeared in 1992, perhaps due to higher overall soil water contents resulting from heavy rainfall and the effects of having to reseed the plots.

Soil physical properties generally were not affected by wheel traffic in 1992. Soil aeration, strength and moisture did not vary between on and off tire tracks. At

high soil moisture contents in 1992, conventionally tilled soils compacted by tire traffic tended to have significantly higher water contents than similarly compacted zero tilled soils. The growth and yield of the barley crop on the tire tracks was significantly reduced from off tire tracks for the entire 1992 growing season.

Plant data obtained indicated that on these poorly drained heavy clay soils, cereal grain production in 1991 or 1992 was not affected by zero and conventionally tilled treatments.

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INTRODUCTION

Seeding practices in Western Canada have undergone dramatic changes in the last two decades, particularly through the introduction of zero tillage. Farm machinery has also increased in weight placing larger loads the soil which may result in soil compaction. Tillage loosens the soil, thereby alleviating soil compaction and creating favorable conditions for crop germination and growth. If tillage is discontinued or reduced then soil compaction may reach levels which could be detrimental to crop growth.

Soil compaction is defined as "the compression of an unsaturated soil body resulting in the reduction of the fractional air volume" (Hillel 1982). As the soil is compacted the bulk density of the soil increases and the mean pore diameter decreases. These changes in bulk density and pore size distribution can affect plant growth by altering the soil properties that directly affect plant growth. The soil physical properties that directly affect plant growth are soil temperature, aeration, water, and strength (Letey 1985).

In Manitoba, clay soils represent a large portion of the arable land. These soils are characterized by a high degree of microporosity resulting in low infiltration rates, poor aeration and high water holding capacity. An increase in soil microporosity and strength due to soil compaction associated with zero tillage could be detrimental to plant growth and productivity on clay soils.

Previous research has determined that higher soil temperature for a conventionally tilled Osborne heavy clay soil than zero tilled soils was the not due to altered soil physical properties but rather the result of higher crop residue cover (Gauer 1981). However, the temperature differences were not sufficient to affect the growth and yield of cereal crops. Due to decreased evaporation, soil moisture levels of zero tilled soils were found to be higher than conventionally tilled soil treatments early in the growing season (Gauer 1981). Tessier et al (1990) found that tillage treatments had little effect on soil moisture contents of a clay soil. Soil strength of zero tilled clay soils are often found to be higher within the top 10.0 cm when compared to conventionally tilled soils (Martino 1991, Grant and Lafond, 1993). In response to higher soil strengths, Martino (1991) found that root growth was slightly decreased within the top 30.0 cm. Studies by Martino (1991) suggested that at high water contents, soil aeration of an imperfectly drained heavy clay would be insufficient to supply the needs of the plant.

An agronomic study was conducted in the 1991 and 1992 growing season on a clay soil in Manitoba which had been under a zero tillage management system for the previous 8 years. The purpose of this study was to investigate the effect of tillage practices on soil physical properties and their importance to crops at emergence, tillering, anthesis, and maturity stages of plant growth.

LITERATURE REVIEW

1.0 Soil Water

1.1 Effect of Soil Water on Plant Growth

Water can be considered an essential "element" in plant growth. It is important as a constituent of plant tissue; as a transport medium for nutrients in plants and soil; and affects many of the soil physical properties that influence plant growth. The availability of soil water for plant growth is complex due to its interaction with other soil physical properties. If soil strength, aeration, and temperature are maintained at levels that are considered favorable for plant growth, the water content of the soil will become a limiting factor to plant growth. Water content affects plant growth directly if its supply is insufficient to meet the demands by the plant. Ultimately the rate and quantity of water supplied to the plant is a function of the hydraulic conductivity of the soil.

Seed germination occurs when water is imbibed through the seed coat. The rate at which water enters into the seed is a function of the water potential gradient between the soil and the seed (Bouaziz and Bruckler 1989c) and the hydraulic conductivity of the soil. As soil water potential increases the time needed for a plant seed to germinate is decreased (Lafond and Fowler, 1989b). An optimum soil water potential exists for a plant seed after which increasing water potential has little or no effect upon the rate of germination. This was demonstrated by Bouaziz and Bruckler (1989a) who found that the germination rate of winter wheat was not limited by water potentials of 0.0 to -0.09 MPa and some seeds can germinate at matric potentials as low as -3.0 MPa. Emergence is similarly affected by increases in water availability as illustrated by Cutforth et al. (1986) who determined that time needed for emergence of three different corn cultivars was reduced by increasing water content of a clay loam and a loamy sand soil.

Decreases in soil water potential result in decreases in plant root elongation rates. Ehlers et al. (1983) found that elongation of oat roots decreased with decreasing water content until soil water potential was -1.5 MPa (permanent wilting point) at which point root growth ceased. Wheat also reacts similarly to decreasing water potential. For example, Bouaziz and Bruckler (1989c) found that the length of wheat roots after 17 days at -0.02 MPa water potential was twice that of seedlings grown at -1.31 MPa. Peas have been shown to maintain a constant rate of root elongation between -1.8 and -3.5 bars, at lower water potentials roots were visibly shorter and thinner (Eavis 1972). In a typical field situation water availability increases with depth. Since root elongation is promoted by increasing water content, this would encourage root growth downward into the moist soil layer (Dwyer et al. 1988).

Increased soil water has long been known to increase plant growth and its conservation is the primary reason for summerfallowing in the Brown soil zones of the Canadian Prairies. A decrease in soil water potential has been related to a decrease in shoot growth (Frank et al. 1987) and grain yield (Greevers et al. 1986) in wheat. Water use is highest and most critical for wheat growth prior to anthesis (French and Schultz 1984). This was reflected in the results of Frank et al. (1987) who found that water stress reduced the length of the spike at this development stage. This translated into fewer spikelets per head and hence decreased maximum achievable yields. Henderson (1991) found that water stress after anthesis in deep ripped plots prevented an increase of dry matter production from being converted into increased grain yields. However, only a small number of experiments have investigated changes in soil water content and it's effect on soil physical properties that directly affect plant growth.

1.2 Factors Affecting Soil Water

Water content of a soil is a function of the amount of water that enters the soil surface if capillary rise from a water table is ignored. The speed at which water moves into the soil is known as the infiltration rate. Beven and Germann (1982) divided the infiltration of water into the soil into three stages. In the first stage all water that arrives at the soil surface is absorbed by micropores connected to the surface. Infiltration in the micropores can be described by Darcy's law, therefore hydraulic conductivity is proportional to the second power of the radius of the pore. At the second stage, the amount of water arriving at the surface is greater than the ability of the micropores to absorb and transfer it, therefore resulting in an excess. This water flows over the surface and enters the macropores. This creates secondary surfaces along the sides of macropores for infiltration of water into the soil at deeper depths. The third stage occurs when the supply of water to the soil surface exceeds the capacity of micro and macropores to transport water into the soil, ponding of water will occur and may result in overland flow of water. The stage of infiltration obtained during a rainfall event is affected by antecedent soil water content, and the intensity and duration of the precipitation event in addition to inherent soil properties. A prediction of infiltration based upon Darcy's law may not apply to the second and third stages of infiltration due to the variations in size and number of macropores in the soil.

The rate at which water moves through a soil is governed by the saturated and unsaturated hydraulic conductivity of the soil. An increase in porosity and pore size can result in increased saturated and unsaturated hydraulic conductivity. Voorhees et al. (1986) found that saturated hydraulic conductivity of a clay loam soil decreased by 50% as bulk density increased from 1.05 to 1.25 $Mg \cdot m^{-3}$. Large pores are important for saturated hydraulic conductivity and a decrease in their number results in a decrease in the hydraulic conductivity (Jorge et al. 1992). Voorhees et al. (1986) plotted hydraulic conductivity against macroporosity and found a positive relationship between them. It has also been determined that the unsaturated hydraulic conductivity is sensitive to decreases in soil porosity. Carnache et al. (1984) found that the unsaturated hydraulic conductivity of four soils with moderate to fine textures was decreased by a 10% decrease in total porosity at various water potentials.

Internal soil properties such as saturated and unsaturated flow of water are important, but of equal importance are soil surface conditions which can affect the amount of water that is available for infiltration into the soil. Soil surface conditions such as surface residues, roughness and soil crusting can change the proportion of precipitation that enters the soil or flows overland into drainage systems. Increased surface roughness restricts the rate of overland flow and therefore increases the time available for water to enter the soil. Tillage increases soil surface roughness resulting in increased equilibrium infiltration rates (Mwendera and Feyen, 1993). However, Bouma et al. (1977) studied runoff on an Australian vertisol and concluded that tillage induced surface roughness was not as efficient as surface residues in reducing runoff. Soil surfaces exposed to rainfall tended to form crusts due to rainfall impact which may reduce the entrance of water into the soil. Burch et al. (1986) found that application of a simulated rainfall of 42 $mm \cdot h^{-1}$ to a clay soil for 30 min resulted in a 100 fold reduction in the effective hydraulic conductivity due to subsequent crusting of the soil surface. This in turn reduced the infiltration of water into the soil.

1.3 Evapotranspiration

Loss of soil moisture occurs through the movement of water into the atmosphere to satisfy the atmospheric demands. Water can be lost to the atmosphere from the soil surface (evaporation) and through the plant (transpiration). The plant utilizes little of the water removed from the soil and losses due to transpiration often account for over

90% of the total amount absorbed (Hillel 1982). Soil physical and chemical properties can limit the uptake of water by roots. This can result in water stress when the plant can no longer supply its own and the atmospheric demands for water. Plant roots can only extract water at a rate that the soil can supply water to the root surfaces which is a function of the unsaturated hydraulic conductivity of the soil.

The rate of evaporation from a bare soil surface decreases with decreasing soil water potential. As the soil at the surface dries, water from beneath rises to the soil surface through capillary rise in response to lower soil water potential at the surface. The movement of water to the surface through the liquid phase is related to the hydraulic conductivity of the soil. As the soil dries fewer soil pores will be filled with water; these water filled pores are essential for the movement of liquid water within the soil. As a result, evaporation from the soil surface proceeds at a constant rate until the volume of water filled pores continuous to the soil surface from deeper soil depths decreases and upward movement of water can no longer meet the atmospheric demands at the soil surface. As water movement decreases, the percentage of water supplied through the diffusion of vapour through the dry surface layer increases. Eventually, the transfer of water through the dry surface layers decreases to a very low constant rate with evaporative loss diminishing almost to zero.

1.4 Effect of Tillage on Soil Water

Zero tilled soils often have higher soil moisture contents than conventionally tilled soils (Blevins et al. 1983a, Radke et al. 1985, Gantzer and Blake 1978). This relationship between tillage and soil moisture levels is expected when infiltration and hydraulic conductivity reported for tilled and no tilled soils is considered. Infiltration rates of tilled soils were found to be higher than no tilled soils (Pikul et al. 1990). Lindstom and Onstad (1984) found that not only was the infiltration rate of tilled soils higher when compared to zero tilled soils, but also the saturated hydraulic conductivity increased. Some authors however have reported that increased saturated hydraulic conductivity is limited to the tilled layer. Culley et al. (1987) found that the surface 10 cm of a clay loam soil was found to have higher saturated hydraulic conductivity when tilled and that below the depth of tillage no differences due to tillage were present. Others have also reported little difference between tilled and no tilled soils within the tilled layer (Blevins et al. 1983b). After studying the pore size distribution of tilled and no tilled soils, Hill et al. (1985) concluded that tilled soils would have higher saturated hydraulic conductivity while no tilled soils would have higher unsaturated hydraulic conductivity.

Crop residue levels differ significantly between conventionally and zero tilled soils and have been found to be responsible for changes in soil water content (Wilhelm et al. 1989). An increase in surface residues not only decreases surface runoff but also decreases soil crusting and the rate of evaporation. Soil crusting is dependent upon tillage as well as the degree of residue cover and the extent of crop canopy closure (Lodgson et al. 1993). Radcliffe et al. (1988) concluded that soil surface crusting was the dominant factor affecting infiltration of short-term rainfall events on a sandy clay loam soil and that removal of residues from the no tilled plots resulted in a dramatic drop in the infiltration rates. Reduced evaporation on zero tilled plots is due to the higher crop residue levels than conventionally tilled soils. This resulted in higher soil water levels for zero tilled than conventionally tilled (Tanaka and Aase 1987, Pikul et al. 1990, Blevins et al. 1983b). This effect would be strongest early in the growing season before the crop canopy completely shades the soil surface (Greevers et al. 1986, Blevins et al. 1983a, Gauer et al. 1982). In addition to reducing soil temperatures, surface residues lower evaporative losses through decreased windspeeds near the soil surface (Smika 1983).

2.0 Soil Temperature

2.1 Effect of Soil Temperature on Plant Growth

Plant seeds need a minimum temperature for germination to occur, which in wheat has been shown to occur as low as 1.9 °C (Khah et al. 1986). There appears to be little direct effect of temperature upon final percent germination. Hampson and Simpson (1990) found that variations in temperature between 6 to 34°C have no effect on final percent germination of Katepwa spring wheat if water stress is absent. After the minimum requirements for soil temperature is reached, the main effect of soil temperature is on the rate at which germination proceeds. The rate at which germination occurs appears to be related to the rate at which water is imbibed into the seed (Hampson and Simpson (1990). Lafond and Baker (1986) demonstrated that the imbibition of water into wheat kernels increased with increasing temperature, however no relationship between water uptake rate and germination rate could be found. Germination rate increases until an optimum soil temperature is achieved, which for wheat is at approximately 25°C (Wilson and Hottes, 1927). At higher temperatures, the germination rate may actually decrease as the seed begins to suffer from heat stress. Plant emergence from the soil is similarly affected by soil temperature, with emergence rate often being found to be lower in cooler soils (Lodgson et al. 1987, Al-Darby and Lowery 1987, Wilhelm et al. 1989). A 1°C drop in soil temperature, between 5°C and 20°C, was found to delay the emergence of winter wheat 1.3 days, (Lafond and Fowler, 1989b).

Decreasing soil temperature also decreases root growth, however the optimum temperature for root growth is lower than that for shoot growth (Miller 1986). Abbas Al-Ani and Hay (1983) determined that optimum temperature for root growth of cereals in a hydroponics system was at or above 25°C. They also found a three fold increase in oats seedling root length occurred when temperature was increased from 15°C to 25°C. Lodgson et al. (1987) obtained similar results with four day old corn seedlings. The seedlings had a mean total root length of 14 mm at 17°C and of 327 mm for 25°C. Mean root diameters may also increase with decreasing soil temperatures (Lodgson et al. 1987). Lateral root growth in winter wheat was found to be dramatically reduced by dropping soil temperature to 8°C from 16°C and resulted in significantly larger mean root diameters (Miyaska and Grunes, 1990). Miyaska and Grunes (1990) attribute the increase in mean root diameter to a higher proportion of main root axis with colder soil temperature.

Soil temperature affects shoot growth until the meristematic region emerges from the soil (Wilhelm et al. 1989, Wilkins et al. 1988) after which shoot growth is controlled by air temperature. This partially explains the relationship between increased shoot growth early in the growing season and soil temperature reported in the literature (Lodgson et al. 1987, Addae et al. 1991). The growth stage at which the meristematic region emerges from the soil occurs later in corn than cereal crops such as wheat and partially explains a greater effect of higher soil temperature on early corn growth (Beauchamp and Lathwell 1967).

2.2 Factors Affecting Soil Temperature

Soil temperature is governed by the ability of a soil to absorb shortwave and longwave radiation or emit longwave radiation from the surface. Soil thermal properties determine the flow of heat within the soil profile.

The amount of short-wave radiation absorbed is dependent upon the reflection coefficient or albedo of the surface. The reflection coefficient of a soil surface is dependent upon soil colour, water content, organic matter, particle size, and smoothness of the surface.

Colour can dramatically alter the reflection coefficient of the soil. Soil colour as defined by Watts (1974) includes natural soil colour, surface colorants, and thick or impervious mulches. As the soil colour becomes darker, the reflection coefficient decreases. Placing white perlite on a red soil increased the reflection coefficient from 17% to 34% (Watts 1973). Mulches such as straw cover can increase the reflection coefficient at the soil surface (Gausman et al. 1975, van Wijk et al. 1959). As organic matter level increases the soil colour becomes increasingly dark. A loam soil which had 0.8% organic matter absorbed 8.2% more of the total radiation than the same soil after the organic matter was oxidized (Bowers and Hank 1965).

Water content at the soil surface can affect the reflection coefficient. As moisture content at the soil surface is increased the albedo decreases. Solar radiation is trapped by water through reflection off the meniscus formed between soil particles by water (Monteith and Unsworth 1990). Bowers and Hank (1965) concluded that a change in moisture content from 0.8% to 20.2% on a loam soil increased the amount of total solar radiation absorbed from 14.2% to 18.3%. Similar results were found between a wet and dry dark clay (van Wijk and Schotte Ubing 1963). Soil particle size can also have an effect on the reflection coefficient. Reflectance has been shown to increase logarithmically as clay particle size increases. However, increasing particle size above 400 μm had little effect upon the albedo (Bowers and Hank 1965).

The degree of surface roughness can affect the total surface area available to absorb solar radiation. This has been used to explain the increase in soil temperature accompanying ridge tillage found in Southwestern Ontario (Stone et al. 1989).

Once solar radiation has been absorbed by the soil or mulch surface, the radiation is changed to thermal energy. Thermal energy is then transferred from the surface to the soil profile below or up into the atmosphere. At this point soil temperature becomes dependent on soil thermal properties, i.e. volumetric heat capacity, thermal conductivity and thermal diffusivity.

Volumetric heat capacity is the amount of energy needed to raise the temperature of one unit volume of soil one degree celsius. A volume of soil is comprised of several different components, each of which has its own heat capacity. The volumetric heat capacity of a soil can be determined through the summation of the product of the heat capacity and proportion of each component (soil minerals, organic matter, and water). De Vries (1963) determined that the heat capacity of a soil can be calculated using the equation $C = 0.46\ Xm + 0.60\ Xo + 1.0\ Xw$. The terms Xm, Xo, and Xw represent the volumetric fraction of soil mineral, organic matter, and water in the soil respectively. Since the mineral component of a specific soil doesn't vary significantly and the organic matter content is generally small, the volumetric heat capacity of the soil is linearly related to water content.

Thermal conductivity is the amount of heat transferred through the soil per unit temperature gradient. It can also be calculated from individual soil components. However, the calculation must also include factors for the area of soil particle contact. Addition of water to a dry soil can increase the thermal conductivity in a nonlinearly due to the transfer of heat through evaporation and condensation of water. An optimum water content for heat transfer occurs at the point where movement of heat through the vapour phase has become limited by the filling of soil pores with water. The thermal conductivity of wet soils are virtually independent of water content (Monteith and Unsworth, 1990).

Thermal diffusivity is the ratio of thermal conductivity to volumetric heat capacity. It defines the rate at which temperature changes in the soil. Soil temperature changes are closely related to the thermal diffusivity of a soil. Both thermal conductivity and diffusivity of a soil are affected by changes in the bulk density of the soil and water content.

2.3 Effect of Tillage upon Soil Temperature

Soil temperature is altered by changes at the surface and within the soil profile as the result of tillage practices. Zero tillage is characterized by an increase in surface residues which influence soil temperature (Wilhelm et al. 1989, Logan et al. 1991, Wilkens et al. 1988, Carter and Rennie 1985). In temperate regions, growing season soil temperature differs the most between conventional and zero tillage in the spring as the soil begins to warm up. Maximum soil temperature has been found to be lower under zero tillage than conventional tillage, while minimum temperatures are often higher (Gauer et al. 1982, Carter and Rennie 1985, Loeppky et al. 1989). A decrease in the maximum temperature is often explained through increased residue cover with zero tillage. An increase in residue cover increases the reflection coefficient, resulting in less solar energy being available to warm the soil. Soil reflection coefficient for a ploughed soil in England was found to be 13% of total radiation received, the direct drilled soil had a reflection coefficient of 21% (Hay et al. 1978). Differences in soil temperature between tilled and direct drilled soils are greatest early in the growing season. Later in the growing season, the crop canopy shades the soil surface and differences in soil temperature dissappear. However, Carter and Rennie (1985) determined that soil temperature was higher for zero tillage when the wheat crop was in the Feekes 5-10 growth stages and was the result of shorter shoot length under zero tillage. Minimum soil temperature are higher for zero tilled soils than conventionally tilled soils due to the lower level of thermal energy lost to the environment at night (Hay et al. 1978). The residue surface acts as an insulating layer which allows heat energy to remain within the soil profile (van Wijk 1959). Differences between the minimum temperatures for the two tillage systems are generally not as large as for maximum temperatures during the growing season (Gauer et al. 1982, Wilhelm et al. 1989, Wall and Stobbe 1984). Removal of surface residues from zero tilled soils generally result in similar soil temperature as that found for tilled soils (Gupta et al. 1984, Gupta et al. 1983)

Thermal diffusivity of the soil has also been shown to change in response to tillage. Zero tilled soils has been shown to have an increase thermal diffusivity when compared to conventionally tilled soils (Johnson and Lowery 1985, Potter et al. 1985, Carter and Rennie 1985). Hay et al. (1978) found that direct drilling increased the soil moisture content and bulk density over ploughed soils and this was manifested in higher thermal diffusivity for direct drilling. Changes in thermal diffusivity would be related to changes in thermal conductivity and volumetric heat capacity. Zero tilled soils were found to have the highest volumetric heat capacity of four tillage treatments studied (Johnson and Lowery 1985). Potter et al. (1985) determined that volumetric heat capacity was sensitive to water contents, however no differences due to tillage practice was found. They also found that thermal diffusivity was higher for zero tilled soils than for other tillage treatments and concluded that this occurred because thermal conductivity for zero tilled soils was 20% greater than tilled treatments. Improved soil structure often reported with zero tillage may alter thermal conductivity and diffusivity since structure promotes water vapor movement and heat conduction (Kaune et al. 1993).

3.0 Soil Aeration

3.1 Effect of soil Aeration on Plant Growth.

Respiration below the soil surface is dependent upon the ability of oxygen to move from areas of supply (atmosphere, air filled pores) to areas of demand (plant roots, soil micro organisms). A decrease in root growth is often related to a decrease in oxygen content of the soil air (Hill and Cruse 1985, Schumacher and Smucker 1981, Sojka and Stolzy 1980). A minimum of 10% air filled porosity is needed to allow sufficient movement of oxygen to root surfaces (Carter 1988, Archer and Smith 1972, McAfee et al. 1989, Bridge and Rixon 1976). However, the critical air filled porosity may increase with increasing bulk densities (Eavis 1972) and clay content (Hodgson and Macleod 1989a).

The rate at which oxygen diffuses through a film of water and is reduced by a platinum electrode (oxygen diffusion rate) is considered to represent the movement of oxygen to a plant root (Lemon and Erickson 1952, Glinski and Stepniewski 1985). Oxygen diffusion rate of 0.2 $\mu g \cdot cm^{-1} \cdot min^{-1}$ is critical for root elongation and levels between 0.2 and 0.4 $\mu g \cdot cm^{-1} \cdot min^{-1}$ (Erickson 1982) are considered limiting. Insufficient levels of oxygen in the soil result in decreased root length (Box 1986, Letey et al. 1962, Voorhees et al. 1975), and shallow rooting (Agnew and Carrow 1985). Plant roots can adapt to limiting oxygen supply with time (Lodgson et al. 1987, McMicheals and Quisenbury 1993) and may modify their physical structure. The formation of aerenchyma tissue in response to insufficient soil aeration increases root porosity (Agnew and Carrow 1985, Box 1986).

Shoot growth and grain yield may also be reduced by poor soil aeration (Letey et al. 1961, Agnew and Carrow 1985). This was illustrated by Anaya and Stoltzy (1972) who found that the grain yield of wheat grown at 0.9% oxygen with a water suction of 0.008 MPa was half that of wheat grown at 4.3% oxygen with a similar water potential.

3.2 Factors Affecting Soil Aeration

The movement of gases between the soil and atmosphere is dependent on two processes; mass flow and diffusion flow through soil pores and plant tissues. Mass flow occurs due to a pressure gradient between the atmosphere and the soil. Gases can also be transported into the soil through mass flow of water into the soil. Differences in temperature, atmospheric pressure, water content and wind can result in pressure gradients (Glinski and Stepniewski 1985). However, the level at which mass flow occurs in soils is not considered a major factor in determining soil aeration levels that affect plant growth. Diffusion of gases into the soil is of a much greater significance (Glinski and Lipeic 1990). While mass flow is affected by the size of soil pores, diffusion is a function of the concentration gradient, pore continuity, pore shape, pore size, and air filled porosity.

Factors that alter these soil physical parameters alter the diffusion of air into the soil. A change in bulk density causes changes in the porosity of a soil which may affect soil aeration. Currie (1984) found that dry soils with a bulk density of 0.86 $g \cdot cm^{-3}$ had a diffusion coefficient that was 38% larger than a soil with a bulk density of 1.29 $g \cdot cm^{-3}$. Voorhees et al. (1975) stated that increasing the bulk density of a soil layer through compaction would increase the number of water filled pores and affect the gaseous diffusion across a compacted layer. Increasing the bulk density of a heavy clay soil from 1.32 to 1.44 $g \cdot cm^{-3}$, decreased the diffusion coefficient of compacted soils to 10% of the uncompacted soils (McAfee et al. 1989).

Water content can have a dramatic effect on the diffusion coefficient of a soil. Even small increases in water content can have adverse effects upon the aeration of soils through the filling of pore necks (Hodgson and Macleod 1989a, Eavis 1972). The ability of oxygen to diffuse through air is 10 000 times greater than its ability to diffuse through water (Grable 1966), hence the rate of oxygen flow in the soil would be greatly reduced. Salam et al. (1984) found that decreasing the volumetric water content of a silt loam by 10%, gas diffusion coefficient increased from 1.7×10^{-3} to 46.9×10^{-3} $cm^2 \cdot min^{-1}$. Similar trends were found by Ball (1981) and McAfee et al. (1989).

Microbial respiration in the soil will increase the amount of oxygen required within the rhizosphere above levels needed for plant roots alone. Ishii and Kadoya

(1991) found that soils containing undecomposed organic material consumed 3.7 to 5.6 times as much oxygen as the control (no organic material added). Soil respiration also fluctuates in response to diurnal changes in soil temperature and water content (Clay et al. 1990).

Soil organic matter and clay content alter the physical structure of the soil creating high levels of spatial variability over relatively short distances. The diffusion of oxygen into the soil would depend on location with regards to soil structure and in particular to variations between inter and intra crumb pores. Measurements of soil aeration at micro sites indicate that soils may contain aerobic and anaerobic sites simultaneously (Fluhler et al. 1975). Oxygen diffusion rate as determined with platinum microelectrodes has been found to be strongly correlated with soil structure (Bakker and Bronswijk 1993). Levels of variability found in the field using this method may be an indication of soil structure and therefore describe soil conditions with regard to aeration (Callebaut et al. 1982).

Soils that are partially comprised of swelling clay minerals tend to display a more complicated relationship between soil water and aeration. A soil that swells upon wetting may not be responsive to slight changes in soil water unless they were within the range of residual shrinkage (Bakker and Bronswijk 1993). Desiccation cracks that are common in soils of high clay content are excellent channels for air flow into the soil due to the continuity and large size. The addition of water to a soil characterized by swelling may result in the closure of desiccation cracks, thereby decreasing air filled porosity and restricting air movement into the soil as macroporosity is also lost (Currie 1984).

3.3 Effect of Tillage on Soil Aeration

Tillage practices alter the soil physical properties that are important in the exchange of gases between the atmosphere and the soil. Air filled porosity of a soil is often found to be higher in the tilled layer than untilled layer (McGarry 1988, Carter 1990). Carter (1988) determined that the top 8.0 cm of a tilled sandy loam soil had improved aeration due to an increase in macropores critical for air movement when compared to a direct drilled soil. However. Campbell et al. (1986) found that the relative diffusivity of air into a zero tilled soil was greater than that of a chisel ploughed soil. Gantzer and Blake (1978) concluded that zero tilled soils had higher gas exchange rates due to an increase in biochannels. These biochannels are relatively less tortuous and of simpler geometry than normal soil pores and thus would facilitate gaseous exchange which otherwise would have been restricted by the decreased porosity of zero tilled soil. Gauer et al. (1981) found that the oxygen diffusion rate of a clay loam was lower at the 5.0 cm depth for zero tilled soils compared to conventionally tilled treatments. However, zero tillage had a higher supply of oxygen at 10.0 cm. Martino (1991) determined that three Manitoban soils with different textures (loamy sand, silty clay loam, heavy clay) showed no difference in oxygen diffusion rate at 10.0 cm between zero and conventional tillage.

Soil tillage alters the water and temperature cycles of the soil which in turn influence the rate at which the microbial population consumes oxygen and thereby affects the oxygen supply in the soil. Studies by Clay et al. (1990) in Minnesota found that lower soil temperatures at a depth of 15 cm early in the growing season as the result of zero tillage caused an increase in the redox potential of the soil over that of rototilled soils. This was attributed to a decrease in the oxygen consumption by microbes.

Cultivation of heavy textured soils within the plastic range may affect the air filled porosity and the oxygen flux density. In the plastic range cultivation results in smearing and remolding of the soil at or immediately below the depth of cultivation. Smearing and remolding would increase the discontinuities of pore channels while dramatically increasing the tortuosity of the soil pores. An Australian vertisol cultivated at a water content of 0.27 $Mg \cdot Mg^{-1}$ had a lower air filled porosity than the same soil cultivated at a water content of 0.20 $Mg \cdot Mg^{-1}$ (Hodgson and Macleod 1989b). The air filled porosity of the smeared and molded soil was less than 0.15 $m^3 \cdot m^{-3}$ for all sampling occasions while soil cultivated when dry had air filled porosity in excess of 0.15 $m^3 \cdot m^{-3}$ even at high gravimetric water content. The diffusion of oxygen through the soil was found to have a higher sensitivity to the previously mentioned treatments than air filled porosity due to its dependence on tortuosity and continuity of the pores.

4.0 Soil Strength

4.1 Effect of Soil Strength on Crop Growth

Penetration of the soil by plant roots is physically impeded by the mechanical resistance or strength of the soil. Root growth is restricted to soil pores which are larger than the root diameter or those that can be enlarged by the plant root. Resistance to widening of the soil pore constitutes the mechanical resistance of the soil. The larger the mechanical resistance the more energy must be expended by the plant to enlarge the soil pore. When soil strength reaches excessively high levels, root growth patterns and morphology can be altered. These alteration in turn may affect plant growth and yield.

An increase in mechanical resistance has often been associated with decreased root elongation and length (Mcfee et al. 1989, Gerard et al. 1982, Abbas Al-Ani and Hay 1983). Bengough and Mullins (1990) determined that elongation of pea roots decreased by 50 to 60% of unimpeded roots by increasing root penetration resistance from 0.27 to 0.46 MPa. Root elongation rate in a soil layer with a soil strength of 1.8 MPa was 55% that of a layer of 0.06 MPa (Bengough and Young 1992). In the same experiment it was shown that even after growing through a compacted layer into loose soil, root growth was still only 65% of a soil in which there was no compacted layer. As the plant tries to compensate for a restricted rooting depth, increased lateral root production is often noted (Schumacher and Smucher 1981, Ellis et al. 1977, Barley 1962).

A common instrument used to determine mechanical resistance is a soil penetrometer. Soil strength as measured by the penetrometer has often been related to root growth (McMicheal and Quisenberry 1993, Miller 1986). The level at which soil strength impedes root elongation varies to a considerable degree with plant species and penetrometer used but usually ranges between 2.0 and 3.0 MPa (Atwell 1993). Research by Martino (1991) also suggested that 2.0 MPa was the maximum soil strength for root growth on three soils of varying textures in Manitoba.

Plant roots undergo morphological changes in response to increased soil strength. Root diameters have been found to increase as soil strength increases (Eavis 1972). Braim et al. (1990) found dry root weights for soils of low soil strength were only slightly higher than soils of high strength despite having three times the root length. This would indicate greater root diameter in soils of high soil strength. Increased root diameter can assist the movement of plant roots through soils of high mechanical impedance in that radial expansion of the root behind the root tip may dramatically reduce the mechanical impedance encountered at the tip (Abdalla et al. 1969).

High soil strength can reduce shoot growth by limiting nutrient and water availability through a diminished root system. When root growth is restricted the volume of soil from which nutrients and water can be obtained is decreased. Nutrients that are immobile within the soil, such as phosphorus and potassium can be exhausted by high root densities (Boone and Veene 1982). The growth of wheat seedling shoots can be decreased by high soil strength even though analysis of the plant shoot indicated that water and soil nutrient levels were not deficient (Masle and Passioura 1987). After a more detailed investigation Masle et al. (1990) concluded that mechanical impedance induces the production of an unknown chemical factor within the plant which retards shoot growth, increasing the availability of carbohydrates for root growth.

4.2 Factors Affecting Soil Strength

Bulk density and water potential of the soil are the most important factors affecting soil strength. Soil water potential is often negatively correlated with soil strength (Jayawardane and Blackwell 1990, Gerard et al. 1982, Voorhees 1983). Ayers and Perumpral (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 soils strength decreased. Similar results were also obtained by Tollner and Verma (1984). Soil water affects the strength of a soil by bonding soil particles together through the surface tension at the soil water interface within soil pores (Snyder and Miller 1985). Removal of water from the soil pores increases the tension of the air water interface resulting in higher soil strength initially. As the soil continues to dry the number of water-air interfaces decreases and soil strength decreases (Mirreh and Ketcheson 1972). Generally, increases in soil water contents within the range commonly found in the field result in decreased soil strength (Hill and Cruse 1985, O'Sullivan and Ball 1982, Carter 1990). Byrd and Cassel (1980) determined that soil strength of a Norfolk sandy loam increased monotonically with decreasing water content.

Generally, a soil is found to increase in soil strength as bulk density increases (O'Sullivan and Ball 1982, Douglas 1986, Perumpral 1987, Ellis et al. 1977). This relationship is also true for soils with a high swelling clay content at the same water contents (Jayawardane and Blackwell 1990). Tollner and Verma (1984) determined that soil strength of a sandy clay soil held at a constant gravimetric water content, increased linearly with increasing bulk density. This relationship was also noted by Groenvelt et al. (1984) who calculated that penetrability of a 150 μm diameter probe increased linearly with bulk density.

Bulk density is the dominant factor affecting soil strength at low moisture contents but has minimal effect on soil strength at high moisture contents (Perumpral 1987). Using water content in addition to bulk density as the independent variables affecting soil strength did not increase the correlation coefficient over that of bulk density alone if the soil strength was greater than 2.0 MPa (Busscher et al. 1987). At soil strengths below 2.0 MPa the addition of water as a variable increased the correlation coefficient significantly (Busscher et al. 1987).

Soil organic matter and texture are two important components in the determination of soil strength. Gerard et al. (1982) found that soil strength increased with increasing clay content. As clay content increases from 25% to 75% the soil water content at which soil strength reached a maximum increased (Ayers and Perumpral 1982). The effect of particle size is probably the result of changes in the desorption curve which in turn affect the tensile strength of the soil (Snyder and Miller 1985). Organic matter contributes to the aggregation of agricultural soils which in turn enhance the soils resistance to increasing soil strength through compactive forces (Soane 1990). This indicates that soil structure has a modifying effect upon soil strength.

Changes in soil porosity can affect soil strength, probably through its effect on water content. Macropores and cracks may create localized regions of decreased soil strength affecting the overall soil strength. Carter (1990) concluded that soil strength was related to soil porosity and specifically macroporosity. In field trials conducted by Carter (1990) macropore volume (>150 μm in diameter) accounted for 50 to 67% of the variability in soil strength of loamy sand to loam soils as measured by a soil penetrometer.

Expansion of water upon freezing can ameliorate compacted soils through the formation of horizontal and vertical microfractures (Kay et al. 1985). Voorhees (1982) observed that after one winter during which the soil was frozen, soil strength decreased while a corresponding change in soil bulk density did not occur. Decreased soil strength was attributed to microfractures creating planes of weakness within the soil. Soils prone to volume change form cracks and macropores upon drying. These desiccation cracks may contribute to decreased soil strength despite higher bulk densities of the aggregates and lower water contents (Marshall and Holms 1988)

4.3 Effects of Tillage on Soil Strength

Soil strength of agricultural soils often increases upon the cessation or reduction of tillage. Higher soil bulk densities has often been noted near the surface of no tilled soils when compared to tilled soils. Therefore, zero tilled soils would be expected to have higher soil strengths than conventionally tilled soils. Increases in soil strength in no tilled soils are generally limited to the surface. Below the normal depth of tillage there is no effect (Hill and Meza-Montalvo 1990, Unger and Fulton 1990, Cassel and Nelson 1985). In Saskatchewan, Grant and Lafond (1993) found higher soil strength in the surface 10 cm of a zero tilled than conventionally tilled clay soils. At depth below the tilled layer no differences in soil strength could be found. The strength of soils with high clay contents have also been found to be unaffected by tillage. (Gerik et al. 1987, Larney and Kladivko 1989).

The relationship between soil strength and water content appears to differ with tillage practices. Hill (1990) noted that no tilled soils had higher soil strengths than tilled soils at any given matric potential and that the difference between treatments increased with decreasing soil water potential. Temporal changes in soil strength may occur within the growing season due to compaction of the cultivated soil by rainfall impact, internal erosion, and wet/dry cycles. As would be expected, soil strength under conventional and minimum tillage increased as the time from seeding increased (Addae et al. 1991). Hodgson et al. (1977) obtained similar results for tilled soils, while the soil strength of zero tilled soils changed little over the growing season.

Much of the tillage research in the past has utilized moldboard plows and rototillers for tillage operations. Shallower cultivation practices may not affect soil physical properties to a similar degree. Hammel (1989) concluded that minimum tillage (chisel plant in fall or shallow disking in spring) showed no significant decrease in soil strength when compared to no tillage. The same study found soil strength from soils that were tilled using a moldboard plow were significantly lower near the surface when compared to the minimum and zero tilled treatments. This is in agreement with results of Ellis et al. (1977) who showed that shallow tine cultivation did not significantly reduce soil strength when compared to direct drilling.

An increase in biopores, cracks and other localized areas of reduced soil strength could allow root growth to continue in what would normally be considered a impermeable layer to root growth. Ehlers et al. (1983) determined that roots were able to grow into soils of higher soil strength under zero tillage than under conventional tillage due to the presence of vertically continuous biopores that present almost no resistance to growth. Regression analysis indicated that root growth ceased at 3.6 MPa in tilled soil and 4.69 to 5.1 MPa for zero tilled soils.

5.0 Interactive Effect of Soil Physical Properties and Root Growth

A complex relationship exists between soil physical properties and root growth. When root growth is affected by one soil physical property, that effect may result in reduced abilities in overcoming other soil physical limitations. An experiment using drybean roots exposed to mechanical impedance showed higher oxygen consumption per unit fresh weight than that of unimpeded roots (Schumacher and Smucker 1981). The axial root pressure of a pea root was found to decrease from 11.0 to 5.0 bars when the oxygen level was decreased from 8.0 to 3.0% (Eavis et al. 1969). This indicates a decreased ability to enter soils of high strength. In addition, decreased levels of soil oxygen have been found to increase water use (Sojka et al. 1972). However the reverse has also been found to occur (Anaya and Stolzy 1972). A decrease in water content may reduce root growth through increasing soil strength or through its function as an essential element in plant growth. Ehlers et al. (1983) concluded that within the available water range soil strength was the principal factor controlling root growth of oats. Similar results were found by Martino (1991). Lower soil temperatures have been found to decrease the sensitivity of corn roots to moisture contents (Cutforth et al. 1985) and water uptake by roots (Miller 1986).

6.0 Literature Summary

The physical manipulation of the soil through tillage or the cessation of tillage can affect the soil physical properties that directly affect plant growth. Soil physical properties that directly affect plant growth are soil temperature, aeration, water, and strength (Letey 1985).

Conventionally tilled soils are generally found to have higher soil temperatures than zero tilled soils early in the growing season. Differences in soil temperature between conventional and zero tillage are often related to differences in surface residues. A decrease in residues is correlated to a decrease in albedo of the soil surface. This results in an increase in solar radiation absorbed by the soil. As crop canopy develops and shades the soil surface, differences often dissappear.

Decreases in the amount of surface residues also increases losses of soil moisture through evaporation. Moisture contents on zero tilled soils are generally higher later in the season as a result of reduced evaporation. Infiltration rates of soils are also decreased on conventionally tilled soils due to higher surface crusting and a decrease in continuous vertically oriented biopores and cracks. However, increased total porosity of the tilled layer may also result in increased infiltration rates.

Strength of agricultural soils often increases upon the cessation or reduction of tillage. Soil bulk density near the surface of no tilled soils is higher than tilled soils. As a result, zero tilled soils have a higher soil strength than conventionally tilled soils. Increases in soil strength in no tilled soils are generally limited to the surface. Differences in soil strengths between tillage systems disappear below the tilled layer.

An increase of soil porosity in the surface of tilled soils generally improves transfer of air into the soil. It is the expected that conventionally tilled soils will have increased soil aeration within the tilled layer. This effect would be more pronounced on soils with high soil moisture contents. The continuity of pores within a zero tilled soil may result in an increase in soil aeration below the depth of tillage.

Early in the growing season, crop growth is generally reduced on zero tilled soils when compared conventionally tilled soils. This appears to be mainly the result of decreased soil temperatures. Later in the growing season increased moisture reserves of zero tilled soils usually result in improved growth and similar grain yields as conventionally tilled soils. Higher bulk densities or soil strength on zero tilled soils can also reduce root and shoot growth on zero tilled soils.

Results in assessing the influence of soil properties on crop growth can vary greatly among research projects. This variability can often be attributed to differences in soil texture, climate, and tillage method. Long term tillage experiments have found that in zero tillage treatments, the change in soil properties with time becomes smaller.

Materials and Methods

1.0 Site Description

The experiment was established on an Osborne clay soil (Ehrlich et al, 1953) near Brunkild, Manitoba (NE 19-6-1W) in the fall of 1990. These soils are poorly drained due to their lack of topographic relief and high levels of microporosity. The experiment used a randomized complete block design with four replicates and two treatments (i) conventional tillage and (ii) zero tillage. Each replicate was split in two for conventional and zero tillage, then subdivided into twelve subplots. Each subplot represented one of four crop growth stages (emergence, tillering, anthesis, and maturity) in one of three years (see Figure 1).

2.0 Field Operations

The field had been zero tilled and cropped to cereal grains and canola under continuous cropping for 8 years previous to initiation of conventionally tilled treatments in the fall of 1990. Zero tilled plots were left undisturbed (excluding disturbance due to seeding).

The first tillage operation performed on the conventionally tilled plots was performed just prior to freeze-up in the fall of 1990, using a cultivator set to a depth of 12 cm. This procedure was repeated in the spring of 1991 and 1992 before seeding and in the fall of 1991 after harvest. On May 13th, 1991 spring wheat (Triticum aestivum cv. Katepewa) was seeded at a rate of 100 $kg \cdot ha^{-1}$ and the crop was fertilized to soil test recommendations for the entire field. All seeding operations were performed by the farmer using a zero till hoe drill (Amazone NT 375) with 0.18 m seed row spacing. Total seeding width was 7.3 m and the drill was pulled by a 130 horsepower tractor

South

Rep 1		Rep 2		Rep 3		Rep 4	
Conventional	Zero	Conventional	Zero	Zero	Conventional	Conventional	Zero
Y2	T3	Y1	T1	Y2	T2	Y3	T1
Y1	T1	Y1	T3	Y1	T4	Y1	T3
Y3	T3	Y3	T4	Y3	T4	Y3	T4
Y1	T2	Y3	T1	Y3	T3	Y2	T3
Y3	T2	Y1	T4	Y1	T1	Y1	T2
Y3	T1	Y3	T2	Y1	T2	Y1	T1
Y1	T4	Y1	T2	Y1	T3	Y3	T2
Y2	T1	Y2	T4	Y2	T3	Y2	T2
Y2	T4	Y2	T2	Y3	T2	Y2	T4
Y2	T2	Y2	T3	Y2	T4	Y2	T1
Y1	T3	Y3	T3	Y3	T1	Y1	T4
Y3	T4	Y2	T1	Y2	T1	Y3	T3

Y1 = 1991

Y2 = 1992

Y3 = 1993

T1 = Emergence

T2 = Tillering

T3 = Anthesis

T4 = Crop Maturity

Figure 1. Plot diagram for research site near Brunkild, Manitoba.

with front wheel assist. In the spring of 1992, spring wheat (Triticum aestivum cv. Katepwa) was seeded and fertilized to test recommendations for the entire field on May 15th. However, mechanical problems with the seeding equipment resulted in highly variable crop emergence. The crop was terminated with glyphosate at the recommended rate on June 2. The entire plot was harrowed prior to reseeding to break up soil clods formed in the previous seeding attempt. Harrowing was performed using an all terrain vehicle pulling a 1.2 m section of diamond tooth harrows. The crop was reseeded to barley (Hordeum vulgare cv. Argyle) at 134 $kg \cdot ha^{-1}$ on June 9. No additional fertilizer was added during the second seeding operation.

After maturity samples were obtained, the farmer was allowed to remove the crop in 1991 with a commercial combine. This insured that the straw was adequately chopped and distributed over the plot area.

3.0 Soil Physical Properties

3.1 Bulk Density

Bulk density was determined by augering the soil to the required depth and diameter and then determining the oven dry weight of the soil removed (Zwarich and Shaykewich 1969). The Iwan type auger used created cylindrical holes approximately 11.0 cm in diameter with a flat bottom. All soil removed from the hole was sealed in plastic bags to prevent moisture loss. The oven dry weight of the soil was determined on a subsample in the laboratory. The diameter and height from which the soil was removed was measured with a caliper and a ruler. Bulk density was determined at emergence and maturity in both years at 0-15, 15-30, 30-45, and 45-60 cm depth. Duplicate samples from each replicate were obtained for conventionally and zero tilled treatments in 1991 and 1992. Bulk density was measured on tire tracks at crop maturity in 1992. In addition bulk density was also calculated for the 5.0, 10.0, 20.0 cm depths from the cores used for pore size distribution determination.

3.2 Gravimetric Water Content

Gravimetric soil moisture was determined by oven drying samples (approximately 200g) for 48 hours at 105°C. Times and depths of sampling are shown in Table 1 and 2. Duplicate samples from each replicate were obtained for conventionally and zero tilled treatments in 1991 and 1992. Areas travelled over by the tractor tires at seeding in 1992 were also sampled at tillering, anthesis, and crop maturity at the same depths as tillage treatments.

Table 1. Sampling depths (cm) for gravimetric water content at emergence, tillering, anthesis, and harvest in 1991.

Crop Growth Stage			
Emergence	Tillering	Anthesis	Harvest
0-10	0-10	0-10	0-5
10-20	10-20	10-20	5-10
20-30	20-30	20-30	10-20
30-60	30-60	30-60	30-45
			45-60

Table 2. Sampling depths (cm) for gravimetric water content at seeding, emergence, tillering, anthesis, and harvest in 1992.

Seeding	Emergence	Tillering	Anthesis	Harvest
0-15	0-10	0-10	0-10	0-10
15-30	10-20	10-20	10-20	10-20
30-45	20-30	20-30	20-30	20-30
45-60	30-40	30-40	30-40	30-40
	40-50	40-50	40-50	40-50
	50-60	50-60	50-60	50-60

3.3 Soil Strength

Soil strength was measured by a cone penetrometer at crop emergence, tillering, anthesis, and maturity. A hand held Bush recording cone penetrometer was used (Anderson et al. 1980). The penetrometer was equipped with a 30° cone and a 12.83 mm diameter base and was then pressed into the soil at a rate of approximately 3.0 $cm \cdot sec^{-1}$. Soil strength was recorded every 3.5 cm to a depth of 52.5 cm. Values were obtained between the seed rows in both years. Fifteen measurements were obtained at each depth, 30.0 cm apart for each replicate by treatment subplot except at maturity 1992 when ten measurements were made. All measurements were off the tire tracks in 1991. Whenever moisture content was not recorded at the same approximate time as soil strength, additional moisture content samples were obtained to 60.0 cm for each replicate by treatment subplot. Areas travelled over by the tractor tires at seeding were also sampled at tillering, anthesis, and crop maturity in 1992.

3.4 Oxygen Diffusion Rate

Soil aeration was quantified by determining the oxygen diffusion rate (Lemon and Erickson 1952). The oxygen diffusion rate was measured through the reduction of oxygen on a platinum microelectrode with an electrical potential of -650 mV. The electrode was allowed to equilibrate for 4.5 minutes and readings were made relative to an Ag/AgCl reference electrode at crop emergence, tillering, anthesis, and crop maturity. Oxygen diffusion rate in each plot was characterized by inserting 10 electrodes to 2.5, 5, 10, and 20 cm depth. Duplicate samples from each replicate were obtained for conventionally and zero tilled treatments in 1991 and 1992. These electrodes were in an area of $\approx$ 0.3 m by 0.3 m. Gravimetric water content was determined at the 2.5, 5, 10, and 20 cm depths for each set of oxygen diffusion rate measurements. Areas travelled over by the tractor tires at seeding were also sampled at tillering, anthesis, and crop maturity in 1992.

3.5 Soil Temperature

Soil temperatures were determined with thermistors inserted into the soil. The resistance of thermistors were measured using a resistance meter. The thermistors apparatus consisted of wooden dowels in which the thermistors were installed at distances of 2.5, 5.0, 10.0, and 20.0 cm from the top of the dowel. A hole as deep as and slightly smaller than the diameter of the dowel was augered near the centre of a treatment, into which the dowels were placed. The wires from the thermistors were then attached to a wooden stake approximately two meters away. One thermistor apparatus was installed in one zero and one conventionally tilled plot in each replicate at the time of seeding and left in place until after the crop was harvested. Resistance through the thermistors was recorded twice weekly at 12:00 noon in 1991. Hourly fluctuations in soil temperature recorded by Gauer (1981) indicated that maximum soil temperature would be reached at approximately 2:00 PM. Therefore time of measurement was changed to 2:00 PM from 12:00 noon for 1992. The resistance was converted to temperature using an polynomial equation derived from a table of conversion values given by the manufacturer of the thermistors. Thermistors were calibrated each spring to ensure accuracy of conversion tables. No measurements were obtained on the tire tracks in 1991 or 1992 growing season.

3.6 Pore Size Distribution

Pore size distribution was determined using the method as described by Danielson and Sutherland (1986). Undisturbed soil cores were obtained in the spring of 1991 at crop emergence using copper core cylinders pushed into the soil. Duplicate samples from each replicate were obtained for conventionally and zero tilled treatments. Soil cores measured 3.9 cm diameter by 1.6 cm height were taken from the 5, 10, and 20 cm depth. Three cores cylinders were then inserted into the soil in succession. After the third core was forced into the soil, a vertical stack of three cores was formed with the middle of the second core being at the desired depth of sampling. The stack of cores was then removed from the soil and the middle core was separated from the top and bottom core. A thin metal wire was used to separate the cores. The wire was pulled through the cores cutting one core from the other leaving a smooth surface. Each core was then saturated with water in the laboratory using a sintered glass funnel apparatus and applying a suction of 0.1 kPa. A drying curve was obtained by subjecting the sample to 1.0, 2.5, 4.9, 9.8 kPa of suction from a hanging column of water using sintered glass funnels. A pressure membrane apparatus was used for suctions of 33, 50, 100, and 1500 kPa. Pore volumes at saturation, field capacity, and pernament wilting point were approximated by suctions of 0.1 kPa, 50 kPa, and 1500 kPa. Data was presented as percent of core volume (19.11 ml) at time of sampling .

3.7 Particle Size Analysis

Soil samples were obtained by auger for the 0-10, 10-20, 20-30, and 30-60 cm depth and air dried. Two samples were obtained from each replicate for all depths. Organic matter was oxidized with heated hydrogen peroxide while dispersion of remaining soil colloids was obtained by adding water and using a mechanical mixer.

The soil had been determined to be slightly saline. Soluble salts were removed by centrifuging the samples. A chemical dispersion agent (Sodium-Hexametaphoshate) was then added to the samples. The pipette method of particle size analysis (Gee and Bauder, 1986) was then performed on the samples.

3.8 Particle Density

Samples were obtained at the 5, 10, and 20 cm soil depths for each replicate. The Pycnometer method was used to determine the particle density as outlined by Blake and Hartge (1986). Four samples were obtained from each replicate for all depths.

3.9 Field Capacity

Samples were obtained at the 0 to 10, 10 to 20, 20-30, and 30 to 60 cm depths from each replicate in the spring of 1991. In situ field capacity was determined using the method outlined by Cassel and Nielson (1986).

4.0 Chemical Properties

4.1 Organic Matter Content

Soil organic matter content was determined from samples taken in the spring of 1991. Organic carbon was determined by the method of Yeomans and Bremner (1988), then soil organic matter was calculated by multiplying percent organic carbon by 1.724 (Nelsons and Sommers, 1986). Duplicate samples were obtained for conventionally and zero tilled treatments at 0-10, 10-20, 20-30, and 30-60 cm depths.

4.2 pH and Salinity

Soil pH was determined using a pH meter and a soil paste made with 0.1 M $CaCl_2$ solution. Electrical conductivity was determined using an electrical conductivity meter and on a 2 to 1 dry soil to water paste. Soil samples used were from the same sample as those used in particle size analysis. Soil depths analyzed were 0-10, 10-20, 20-30, and 30-60 cm depths for all replicates.

5.0 Plant Characteristics

5.1 Root Density

Root density was determined at the 0 to 15 and 15 to 30 cm depth using the core break method (Bohm 1979). All sampling in both years was performed after maturity and off the tire tracks. A core sampler that removed a core, 7.5 cm in diameter and 15.0 cm high was used. Five and two cores per plot were sampled in 1991 and 1992, respectively. The number of visible roots on the surface at the point of breakage on both halves were counted. In 1991 the cores were removed from the field and roots were counted within a 2 days of sampling. Cores were frozen the day of sampling in 1992 and root counts were performed at a later date.

5.2 Tillers Per Plant

Tillers per plant were determined by removing whole plants from the soil and counting the number of tillers for each plant. Measurements were obtained from a 0.55 m^2 area near the end of tillering. Samples from each replicate were obtained for conventionally and zero tilled treatments in 1991 and 1992. Areas travelled over by the tractor tires at seeding were also sampled in 1992.

5.3 Crop Yield

Above ground dry matter production was determined at tillering, anthesis, and maturity for both years by cutting the crop at the ground level, air drying and weighing the sample obtained. Plant and spike numbers were determined for tillering and anthesis, respectively. Samples obtained at crop maturity were also used to determine the number of plant heads, grain yield, thousand kernel, and straw weight. Area sampled was 0.55 m^2 area at tillering and anthesis and 1.65 m^2 at crop maturity. Areas travelled over by the tractor tires at seeding were also sampled at tillering, anthesis, and crop maturity in 1992.

6.0 Precipitation and Air Temperature

Precipitation was recorded automatically using a chart recording rain gauge located at the site. Air temperature was determined from thermistors installed above the crop canopy on the north side of a white wooden stake and were recorded at the same time as soil temperature was determined.

7.0 Statistical Analysis

Soil and plant data was analyzed statistically using S.A.S for personal computers (SAS Institute Inc. 1988). General linear model procedure was used to perform analysis of variance on all measurements. Tillage, tire track and tillage by tire track interaction effects were analyzed.

RESULTS AND DISCUSSION

1.0 Site Characteristics

Soils from the plot site were characterized by determining field capacity, particle size distribution, organic matter content, pH, and electrical conductivity in the spring of 1991 (Table 3). Clay content was 73% in the 0 to 10 cm depth and increased to 77.8% below 30 cm. Sand content decreased with depth from 8% near the surface to 6% at the 30 to 60 cm depth. The silt content at the plot site varied from 16.5% to 18.8%. The soil textural class at the plot site is heavy clay.

The gravimetric water content at field capacity (determined in the field) was 56.5 % at the 0 to 10 cm depth (Table 3). This was higher than data reported by the Manitoba Land Resource Unit (personal communication) for similar soils. Gravimetric water content at field capacity was considerably lower at the 10 to 20 cm depth (43.8%) and gradually decreased to 37.5% at the 30 to 60 cm depth.

Table 3. Selected soil characteristics for the experimental site at Brunkild, Manitoba.

Depth (cm)	Particle Size Analysis			Field Capacity (% Gravimetric)	Organic Matter (%)	pH	Salinity (dSm^{-1})
	Sand %	Silt %	Clay %				
0-10	8.5	18.5	73.0	56.5	6.5	7.8	0.6
10-20	7.1	16.9	76.0	43.8	5.2	7.7	0.6
20-30	6.2	18.8	75.0	39.9	3.6	7.9	0.6
30-60	5.7	16.5	77.8	37.5	3.3	8.0	0.7

Soil organic matter content was determined to be 6.5% at the surface and decreased to 3.3% at 30 to 60 cm. Soil pH varied from 7.7 to 8.0 which indicated that the site was slightly alkaline and varied little as soil depth increased.

Soils at the research site were slightly saline (0.6 dSm^{-1}) for the entire depth sampled (0 to 60 cm). Many of the heavy clay soils in this region are non-saline but have some associated saline phases (Ehrlich et al. 1953). The salt content, however, was not considered sufficiently high to be detrimental to cereal crops.

2.0 Pore Size Distribution

Soil porosity and the size distribution of soil pores can be altered by different management systems. Pore size distribution of conventionally and zero tilled soils were determined for a wide range of matric potentials. Samples were obtained from soil depths of 5.0, 10.0 and 20.0 cm at crop emergence in 1991.

At a soil depth of 5.0 cm, pore volume (percent of total core volume) above field capacity was 19.9% and 19.2% for conventionally and zero tilled soils, respectively (Table 4). Conventionally and zero tilled soils had pore volumes of approximately 23% between field capacity (-49.9 KPa) and permanent wilting point (-1497.7 KPa). Pore volume below the permanent wilting point was 30.9% for conventionally tilled soils and 33.8% for zero tilled soils. Differences between conventionally and zero tilled soils were not significant. Similar trends in soil porosity existed between conventionally and zero tilled soils at the 10.0 cm (Table 5) and 20.0 cm (Table 6) soil depth. The lack of difference between conventionally and zero tilled treatments is in agreement with results obtained by Martino (1991).

Table 4. Pore size distribution (% of core volume[1]) at the 5.0 cm soil depth for conventionally and zero tilled soils.

	Tillage Treatments		CV	P value
	Conventional	Zero		
Saturation to Field Capacity	19.9	19.2	27.8	0.724
Field Capacity to Permanent Wilting Point	23.2	23.1	4.35	0.900
Permanent Wilting Point to Oven Dry	30.9	33.8	34.5	0.667
Total Pore Volume	73.9	76.1	16.2	0.813

1 core volume = 19.11 ml

Table 5. Pore size distribution (% of core volume[1]) at the 10.0 cm soil depth for conventionally and zero tilled soils.

	Tillage Treatments		CV	P value
	Conventional	Zero		
Saturation to Field Capacity	14.9	14.9	16.0	0.968
Field Capacity to Permanent Wilting Point	20.6	21.5	7.2	0.232
Permanent Wilting Point to Oven Dry	33.2	34.7	19.9	0.674
Total Pore Volume	68.6	71.1	9.2	0.454

1 core volume = 19.11 ml

Table 6. Pore size distribution (% of core volume[1]) at the 20.0 cm soil depth for conventionally and zero tilled soils.

	Tillage Treatments		CV	P value
	Conventional	Zero		
Saturation to Field Capacity	14.7	14.3	16.0	0.851
Field Capacity to Permanent Wilting Point	19.6	18.8	6.5	0.404
Permanent Wilting Point to Oven Dry	40.5	34.5	26.3	0.273
Total Pore Volume	74.7	67.6	14.31	0.231

1 core volume = 19.11 ml

Table 7. Gravimetric water content at field capacity (F.C.) and permanent wilting point (P.W.P) for conventionally and zero tilled soils at the 5.0 cm, 10.0 cm, and 20.0 cm depth.

Depth	Conventional Tillage		Zero Tillage	
(cm)	F.C.	P.W.P	F.C.	P.W.P
5.0	45.6	27.3	48.8	30.5
10.0	42.6	27.6	45.2	29.1
20.0	44.8	31.6	38.6	26.1

The extent of soil swelling from increasing soil moisture levels can be shown by a comparison of total porosity of the cores at time of sampling (based on a core volume of 19.11 ml) compared to total porosity at saturation. At the 5.0 cm depth both conventionally and zero tilled soils had a total porosity of 56% (Table 8). However, total porosity at saturation was greater than 74% for both treatments (Table 4). This would indicate a 18% increase in volume that may be attributed to the swelling of clay minerals. Saturation water contents greater than total porosity at field moisture contents is not unexpected if the swelling nature of the clay minerals is considered. Similar results have been reported by Unger and Fulton (1990).

Table 8. Bulk density, particle density, total porosity and gravimetric water content at time of sampling for pore size distribution cores[1] from soil depths of 5.0, 10.0, and 20.0 cm depths.

Depth (cm)	Bulk Density ($g \cdot cm^{-3}$)	Particle Density ($g \cdot cm^{-3}$)	Total Porosity (%)	Gravimetric Water Content (%)[2]
5.0	1.12	2.58	56.5	40.3
10.0	1.20	2.60	54.1	37.9
20.0	1.30	2.67	50.9	36.3

1 Data from conventionally and zero tilled treatments were combined
2 Gravimetric water content at sampling

3.0 1991 Results and Discussion

3.1 1991 Growing Season Climate

Air temperature was recorded twice weekly from seeding to harvest at the Brunkild research site. The first forty days after seeding, air temperature at Brunkild was higher than the normal recorded by Environment Canada at Starbuck, Manitoba (Figure 2a). Air temperature then cooled to levels lower than normal for the following 20 days. In the final twenty days of the 1991 growing season air temperature varied around the normal ending with a short period of high temperatures prior to harvest.

Precipitation during the growing season was considerably higher than normal. Accumulated precipitation from seeding (May 14th) to harvest (August 19th) totaled 309 mm. Normal precipitation for this period would be 200 to 205 mm (Ash et al. 1992). Two large rainfall events which totaled 118 mm (Figure 3) occurred within an 11 day period in 1991. These high intensity rainfall events resulted in an accumulation of water in shallow depressions throughout the plot site. The duration of inundation was extensive enough to affect crop growth regardless of treatment.

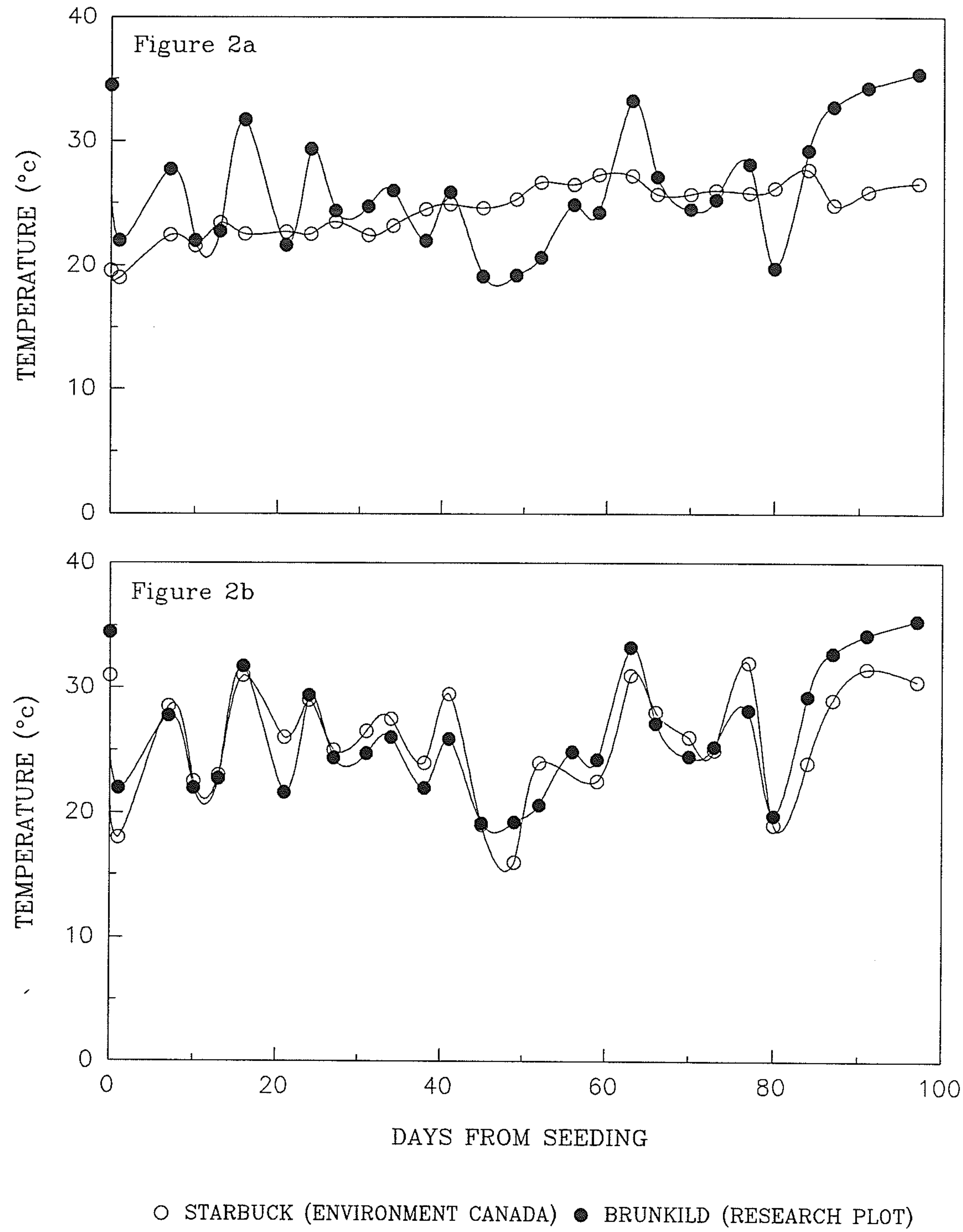

Figure 2a. Climatic normals (maximum daily air temperature) recorded at Starbuck, Manitoba and 1991 air temperature data from the research plot near Brunkild, Manitoba (seeded May 14). **2b.** Comparison of 1991 maximum air temperatures recorded at Starbuck and Brunkild, Manitoba .

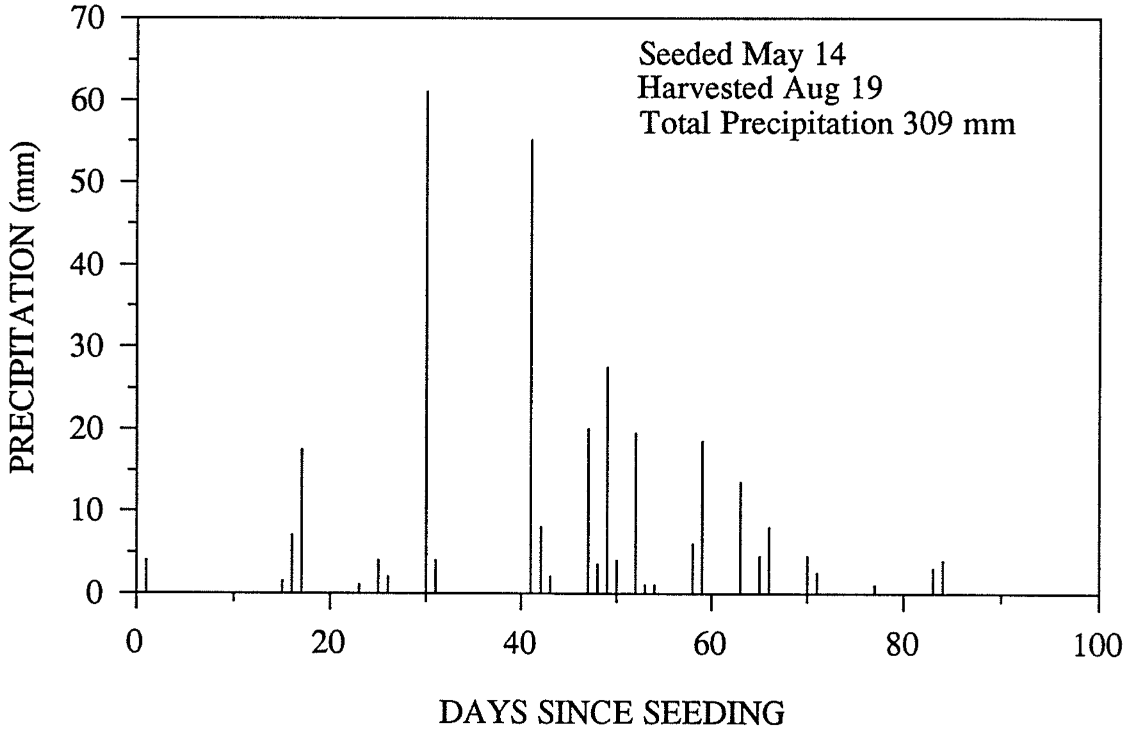

Figure 3. Precipitation during the 1991 growing season at Brunkild, Manitoba (seeded May 14).

3.2 Effect of Treatment on Soil Physical Properties

3.2.1 Soil Temperature

Soil temperatures (Figure 4a) ranged from 17.3°C to 25.8°C over the growing season at the 2.5 cm depth for zero tilled plots. Conventionally tilled soils ranged from 17.3°C to 26.3°C. Statistical analysis was not performed on temperature data but variation between tillage treatments was generally less than 1°C. This is contrary to results of Gauer (1981), who found conventionally tilled plots had higher soil temperature than zero tilled soils. Difference between tillage treatments decreased as soil depth increased (Figures 4 and 5). Average soil temperature over the 1991 growing season for the zero and conventionally tilled treatments decreased from 20.6°C to 16.3°C as depth increased from 2.5 cm to 20 cm. A general increase in soil temperature occurred as the season progressed at depths below 5.0 cm. Soil temperature at 2.5 cm and 5.0 cm fluctuated with that of the atmosphere (Figure 4) and did not increase through the growing season.

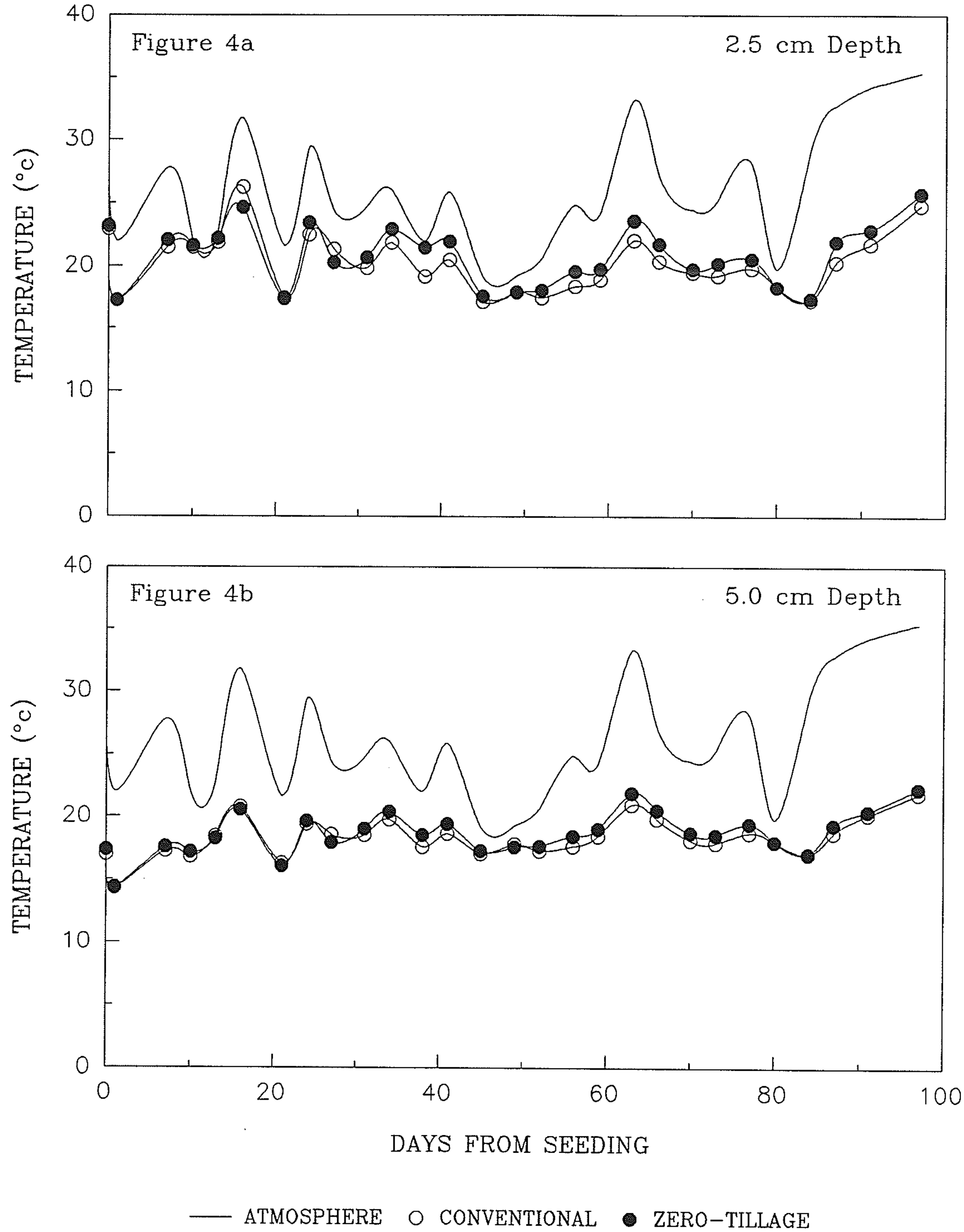

Figure 4a and 4b. Soil temperature for conventionally and zero tilled soils at 2.5 and 5.0 cm depth in 1991 (seeded May 14).

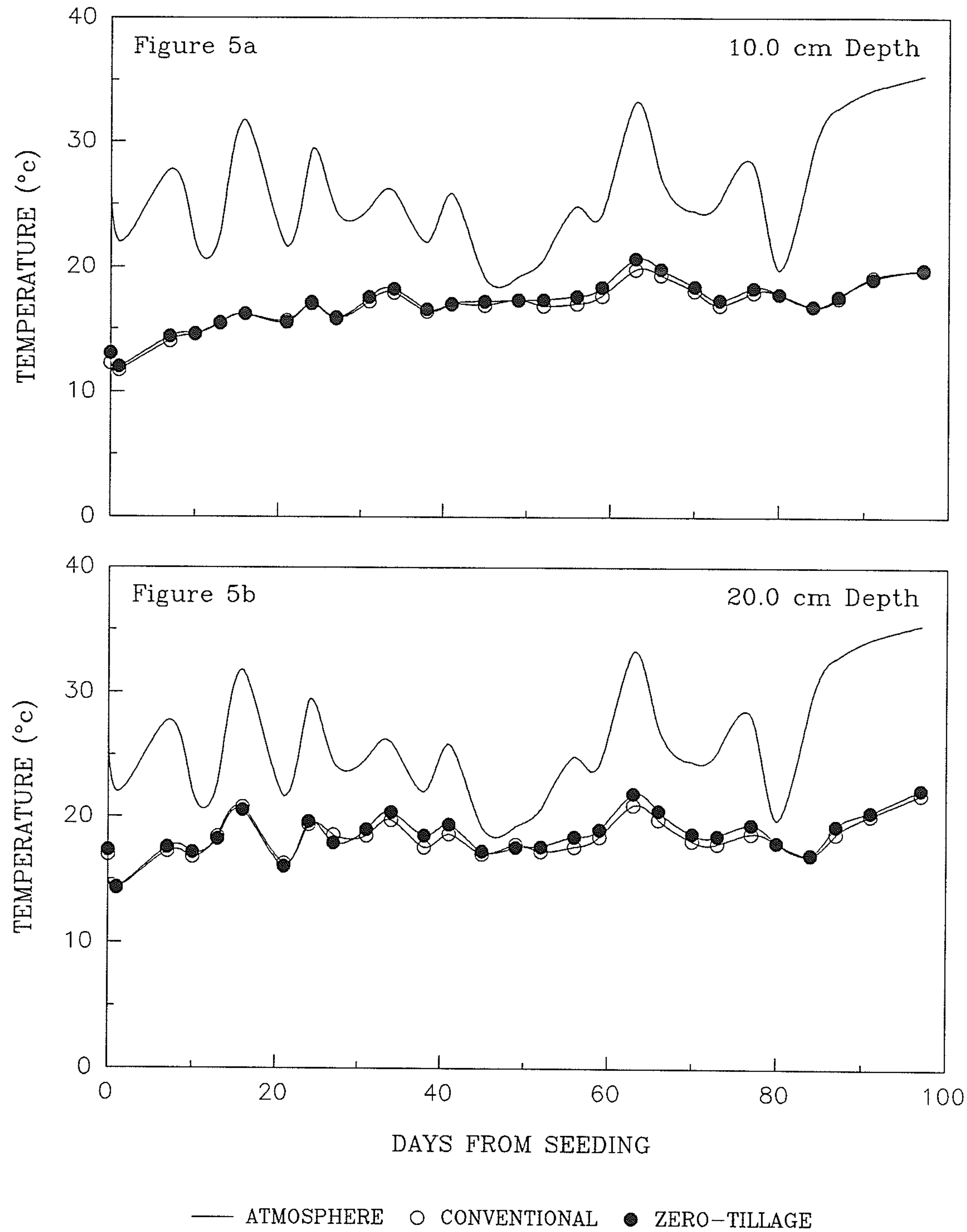

Figure 5a and 5b. Soil temperature for conventionally and zero tilled soils at 10.0 and 20.0 cm depth in 1991 (seeded May 14).

3.2.2 Bulk Density

Two methods (auger and core) are often used for determining bulk density in the field. The auger method is susceptible to errors arising from volume determinations and uneven soil removal. Bulk density determined by inserting cores into the soil can result in the compaction of soil in the core. In addition, the small sample size using the core method may not be sufficient to overcome spatial variability of heavy clay soils, or cracking under dry soil conditions. It was decided to use the auger method in this project. Values obtained did not correspond to those reported for similar soils and were not considered sufficiently accurate for calculating volumetric water content. Therefore, bulk density values are not presented in this report.

3.2.3 Soil Water

Soil moisture content is generally reported using volumetric percentage. In this project, soil bulk density values necessary to calculate volumetric water content were not available for all sampling periods or were highly variable and inconsistent with reported values. Gravimetric water content of the soil was used in this study.

Gravimetric water content of the 0 to 30 cm soil depth varied from 43.2% to 36.5% for conventionally tilled plots, and from 42.0% to 35.6% for zero tilled plots at crop emergence (Table 9). Soil water content for the 30 to 60 cm depth was 33.8% for conventionally tilled soils and 34.8% for zero tilled soils. The differences between tillage treatments were small and not statistically significant (α=0.05). Zero tilled soils did tend to have lower soil moisture levels than conventionally tilled soils near the surface (P=0.064).

Table 9. Percent gravimetric water content at emergence (May 28) for conventionally and zero tilled soils in 1991.

Depth (cm)	Tillage Treatments		CV	P value
	Conventional	Zero		
0-10	43.2	42.0	2.59	0.064
10-20	39.0	38.3	6.67	0.632
20-30	36.5	35.6	6.71	0.496
30-60	33.8	34.8	9.74	0.563

Near the end of tillering, soil moisture content had increased from that recorded at emergence (Table 10). Moisture content was highest for the 0 to 10 cm soil depth (53.1% and 53.3% for conventionally and zero tilled soils, respectively). Soil moisture levels decreased rapidly between 10 and 30 cm on both tillage treatments. The 20 to 30 cm soil depths had moisture contents of 40.2% for conventional tillage and 39.0% for zero tillage treatments. Below 30 cm water content changed very little from that measured at time of emergence. Soil moisture contents approached or exceeded field capacity for all depths sampled. No significant differences in soil moisture content between zero and conventionally tilled soils was found at tillering in 1991(Table 10).

Table 10. Percent gravimetric water content at tillering (June 19) for conventionally and zero tilled soils in 1991.

Depth (cm)	Tillage Treatments		CV	P value
	Conventional	Zero		
0-10	53.1	53.3	5.60	0.896
10-20	45.3	44.3	9.84	0.645
20-30	40.2	39.0	11.58	0.606
30-60	35.6	36.6	11.13	0.627

At anthesis in 1991, soil moisture content was 47.0% for conventionally and 48.5% zero tilled soil in the top 10 cm (Table 11). Moisture levels decreased to 33.9% and 35.6% for conventionally and zero tilled soils, respectively. The effect of the tillage treatments on soil moisture at this crop growth stage was not significant (α=0.05) in the upper 30 cm of the soil profile. Zero tilled soils however did have significantly higher soil moisture levels than conventionally tilled soils for the 30 to 60 cm soil depth. Increased crop growth (Table 26) and lower crop residue levels on conventionally tilled soils may have increased the loss of soil moisture through evapotranspiration.

Table 11. Percent gravimetric water content at anthesis (July 25) for conventionally and zero tilled soils in 1991.

Depth (cm)	Tillage Treatments		CV	P value
	Conventional	Zero		
0-10	47.0	48.5	4.22	0.293
10-20	39.6	41.8	7.69	0.336
20-30	37.3	38.6	3.52	0.201
30-60	33.9	35.6	2.16	0.024

After anthesis evapotranspiration greatly exceeded precipitation and gravimetric soil water contents at harvest decrease dramatically in the surface horizons (Table 12) when compared to anthesis. Soil moisture levels for conventionally and zero tilled soils were below the permanent wilting point (Table 7) at harvest for the 0 to 10.0 cm depth. Environmental conditions just prior to crop maturity were characterized by high atmospheric temperatures and low precipitation, and could account for the low soil moisture contents. Moisture content below 30 cm was similar for both tillage treatments, 35.0% and 35.7% for conventional and zero tillage treatments, respectively. Moisture levels at this depth changed little from anthesis. There were no significant differences in soil moisture at all depths sampled.

Table 12. Percent gravimetric water content at harvest (August 14) for conventionally and zero tilled soils in 1991.

Depth (cm)	Tillage Treatments		CV	P value
	Conventional	Zero		
0-5	22.6	25.0	21.19	0.602
5-10	31.5	29.1	21.38	0.679
10-20	35.8	33.6	8.92	0.430
20-30	36.2	35.2	8.94	0.728
30-60	35.0	35.7	7.74	0.771

Soil moisture is often reported to be higher under zero tillage than conventional tillage systems. Differences are attributed to a decrease in evaporation from zero tilled soils due to increased residue cover. Significant differences in soil moisture contents occurred only at anthesis at the 30 to 60 cm depth (Table 11). At this point the gravimetric soil moisture content of zero tilled soils reached a seasonal high of 35.6 % for that depth, conventionally tilled soils were slightly lower at 33.9 %. Similar soil moisture levels between tillage treatments correspond to results obtained by Gerik et al (1987).

Gravimetric soil moisture remained relatively constant over the growing season for the 30 to 60 cm depths. Soil moisture ranged between 33.8 % and 35.7 % for both treatments over the entire growing season. This would be the result of the poor drainage and very slow infiltration rate of Osborne clay soils, and reflected in their soil classification (Rego Humic Gleysol). Generally, soil moisture was within the available water range for most sampling times and depths in 1991.

3.2.4 Soil Strength

Soil strength as determined by the cone penetrometer is considered an accurate means of determining the mechanical impedance encountered by plant roots (Anderson et al. 1980). Using this method it is generally assumed that 2.0 MPa represents the maximum soil strength through which plant roots will continue to elongate. Soil strength was determined at the time of crop emergence, tillering, anthesis, and maturity. Penetrometer measurements were taken at every 3.5 cm to a depth of 52.5 cm for both conventionally and zero tilled plots. As soil water content increases within the range commonly found in the field, soil strength is generally found to decrease (Hill and Cruse 1985, O'Sullivan and Ball 1982, Carter 1990). Therefore, soil water content was obtained at the same location and time as soil strength measurements.

At crop emergence, soil strength for the 3.5 cm depth was significantly greater for zero tillage than conventional tillage, 0.40 and 0.13 MPa, respectively (Table 13). Zero tilled soils continued to have significantly greater soil strength than conventionally tilled soils to a depth of 10.5 cm, which would approximate the depth of tillage. At the 14.0 cm depth and down to 52.5 cm, conventionally tilled soils had greater (but not always significantly different) soil strengths. Differences in soil moisture between conventionally and zero tilled soils may account for differences below a soil depth of 30.0 cm. Conventionally tilled heavy clay soils have been found to have lower soil strength within the tilled layer than zero tilled soils due to mechanical manipulation of the soil (Grant and Lafond, 1993).

Table 13. Soil strength (MPa) for conventionally and zero tilled soils at emergence (May 28) in 1991.

Depth (cm)	Tillage Treatments		CV	P value
	Conventional	Zero		
3.5	0.13	0.40	47.76	0.055
7.0	0.25	0.94	30.58	0.013
10.5	0.53	0.96	18.26	0.021
14.0	0.84	0.91	11.86	0.412
17.5	0.95	0.89	7.74	0.331
21.0	1.01	0.91	5.71	0.084
24.5	1.05	0.95	4.43	0.052
28.0	1.06	0.98	2.71	0.025
31.5	1.08	0.99	2.57	0.016
35.0	1.10	1.00	4.45	0.062
38.5	1.12	1.01	4.67	0.046
42.0	1.16	1.01	5.29	0.034
45.5	1.21	1.04	5.79	0.033
49.0	1.26	1.09	9.75	0.131
52.5	1.36	1.15	15.08	0.216

Table 14. Gravimetric water percentage for soil strength measurements on conventionally and zero tilled soils at crop emergence (May 28) in 1991.

Depth (cm)	Tillage Treatment	
	Conventional	Zero
0-5	41.4	39.1
5-10	37.6	38.1
10-20	35.8	36.7
20-30	37.2	37.3
30-60	32.7	34.9

Soil strength measurements at tillering (Table 15) showed that zero tilled soils had significantly (α=0.05) higher soil strengths (0.32 MPa) than conventionally tilled soils (0.23 MPa) at a depth of 3.5 cm. Zero tilled soils continued to have higher soil strengths than conventionally tilled soils for the 7.0 and 10.5 cm depths. Soil strengths at depths below 10.5 cm varied little between conventionally and zero tillage and ranged from 0.90 MPa to 1.19 MPa. Differences in soil strength below the tilled layer were not significant (α=0.05). Higher soil strength for zero tilled soils near the surface was similar to results obtained at emergence.

Table 15. Soil strength (MPa) for conventionally and zero tilled soils at crop tillering (June 19) in 1991.

Depth (cm)	Tillage Treatments		CV	P value
	Conventional	Zero		
3.5	0.23	0.32	13.64	0.044
7.0	0.42	0.75	14.51	0.011
10.5	0.73	0.87	6.48	0.028
14.0	0.94	0.90	9.86	0.532
17.5	0.97	0.93	9.05	0.581
21.0	0.97	0.94	1308	0.737
24.5	1.02	0.96	13.39	0.566
28.0	1.00	0.99	10.77	0.927
31.5	1.02	1.01	12.62	0.919
35.0	1.05	1.03	12.04	0.816
38.5	1.06	1.02	12.63	0.713
42.0	1.11	1.04	13.28	0.551
45.5	1.13	1.09	13.45	0.729
49.0	1.20	1.10	9.22	0.273
52.5	1.19	1.12	16.00	0.595

Table 16. Gravimetric water percentage for soil strength measurements on conventionally and zero tilled soils at crop tillering (June 19) in 1991.

Depth (cm)	Tillage Treatment	
	Conventional	Zero
0-5	44.2	39.7
5-10	43.0	41.0
10-20	40.4	38.7
20-30	37.1	35.4
30-60	36.2	34.0

At anthesis, soil strength for the 3.5 cm soil depth was approximately 0.2 MPa and increased to a maximum of approximately 1.40 MPa at 52.5 cm for both tillage treatments. Soil strength was not found to differ significantly between tillage treatments. Soil moisture content was 5.0 to 10.0% greater at anthesis than at tillering in the top 10 cm of the soil (Table 18). High soil moisture contents in the upper 10 cm at anthesis may have masked differences in soil strength that were apparent earlier in the season.

Table 17. Soil strength (MPa) for tillage treatments at anthesis (July 25) in 1991.

Depth (cm)	Tillage Treatments: Conventional	Tillage Treatments: Zero	CV	P value
3.5	0.22	0.25	13.07	0.274
7.0	0.42	0.46	20.09	0.591
10.5	0.69	0.64	25.12	0.744
14.0	0.84	0.78	7.97	0.368
17.5	0.95	0.85	4.68	0.069
21.0	1.00	0.89	6.58	0.184
24.5	1.03	0.94	10.33	0.372
28.0	1.09	0.97	13.03	0.397
31.5	1.11	1.00	11.87	0.389
35.0	1.12	1.04	15.39	0.606
38.5	1.17	1.10	17.84	0.748
42.0	1.23	1.18	15.15	0.758
45.5	1.30	1.26	13.00	0.785
49.0	1.35	1.31	13.04	0.801
52.5	1.43	1.40	13.64	0.864

Table 18. Gravimetric water percentage for soil strength measurements on conventionally and zero tilled soils at anthesis (July 25) in 1991.

Depth (cm)	Tillage Treatment: Conventional	Tillage Treatment: Zero
0-5	48.6	50.0
5-10	43.6	44.0
10-20	37.5	39.2
20-30	37.7	36.7
30-60	32.6	32.5

At harvest, soil strength for conventionally tilled soils ranged from 0.24 MPa to 0.93 MPa for soil depths of 3.5, 7.0, and 10.5 cm (Table 17). Zero tilled soils ranged from 0.54 to 1.76 MPa for the same soil depths. Penetrometer readings in the top 10.5 cm were highly variable and no significant differences due to tillage treatment were found (α=0.05). Soil moisture content at this time was the lowest encountered throughout the 1991 growing season (Table 18). Variability in penetrometer measurements would be expected to increase with decreasing soil moisture due to preferential drying of the soil near macropores and cracks. This would result in soil strengths decreasing as distance from soil cracks and macropores increase. Periods of low water content would create the largest spatial variation in soil moisture levels. Between 28.0 cm and 52.5 cm conventionally tilled soils had lower soil strengths (1.22 MPa to 1.34 MPa) than did zero tilled soils (1.34 to 1.43). Differences were either significant (α=0.05) or indicated a strong trend (α=0.1) existed. Soil moisture contents at this time were similar for both tillage treatments and could not be used to explain differences in soil strength.

Table 19. Soil strength (MPa) for conventionally and zero tilled soils at crop maturity (August 14) in 1991.

Depth	Tillage Treatments		CV	P value
(cm)	Conventional	Zero		
3.5	0.24	0.54	58.60	0.255
7.0	0.74	1.59	45.34	0.187
10.5	0.92	1.76	33.60	0.152
14.0	1.37	1.64	12.32	0.215
17.5	1.60	1.45	17.50	0.931
21.0	1.39	1.36	10.84	0.681
24.5	1.27	1.34	7.17	0.216
28.0	1.23	1.38	3.85	0.044
31.5	1.26	1.41	3.85	0.039
35.0	1.25	1.43	5.13	0.062
38.5	1.22	1.43	5.28	0.054
42.0	1.27	1.40	0.42	0.001
45.5	1.25	1.40	3.32	0.040
49.0	1.27	1.40	3.94	0.076
52.5	1.34	1.39	2.50	0.146

Table 20. Gravimetric water percentage for soil strength measurements on conventionally and zero tilled soils at crop maturity (August 14) in 1991.

Depth (cm)	Tillage Treatment	
	Conventional	Zero
0-5	22.6	24.4
5-10	31.5	29.1
10-20	35.8	33.6
20-30	36.2	35.9
30-60	35.0	35.7

Differences between tillage treatments were most noticeable within the tilled layer (0 to 15 cm) early in the growing season. Conventionally tilled soils are commonly found to have reduced soil strength within the tilled layer when compared to zero tilled soils (Grant and Lafond, 1993). These differences have been shown to decrease as time since seeding increases (Addae et al, 1991). Loosening of the soil through tillage results in a decreased soil bulk density and lower soil strengths.

In this project soil strength levels within the tilled layer did not exceed 1.0 MPa (Table 13 and 15) except at crop maturity for both conventionally and zero tilled. The emerging and established wheat plants would have encountered little resistance to root growth.

3.2.5 Oxygen Diffusion Rate

The platinum microelectrodes used to determine the oxygen diffusion rate (ODR) are effective only if soils are moist enough to encapsulate the electrode tip with water (Glinski and Stepniewski, 1985). It can be assumed that if the soil moisture levels are too low for ODR to be obtained, then soil pores would be free of water and the ODR would not be detrimental to plant growth. In a review of the literature, Erickson et al. (1982) concluded that root growth decreases once the ODR drops below 0.4 $\mu g \cdot cm^{-2} \cdot min^{-1}$ and ceases below 0.2 $\mu g \cdot cm^{-2} \cdot min^{-1}$.

The ODR at plant emergence was 0.33 $\mu g \cdot cm^{-2} \cdot min^{-1}$ on both zero and conventionally tilled plots at 5.0 cm (Table 21). These values are below the level considered limiting to root growth (0.4 $\mu g \cdot cm^{-2} \cdot min^{-1}$). At the 10.0 and 20.0 cm depths, oxygen supply for the two tillage treatments varied from 0.09 to 0.15 $\mu g \cdot cm^{-2} \cdot min^{-1}$, which is below the minimum ODR required for root growth. Differences in oxygen supply between tillage treatments were not significant (α=0.05). Soil moisture levels at the 2.5 cm depth was insufficient to allow ODR to be determined.

Table 21. Oxygen diffusion rate ($\mu g \cdot cm^{-2} \cdot min^{-1}$) for conventionally and zero tilled soils at emergence (May 28) in 1991.

Depth (cm)	Tillage Treatments		CV	P value
	Conventional	Zero		
2.5	na	na	----	----
5.0	0.33(41)[1]	0.33(39)	26.20	0.922
10.0	0.09(38)	0.16(38)	36.67	0.135
20.0	0.13(36)	0.12(37)	23.39	0.668

1 Values within parenthesis are percent gravimetric water content

Soil moisture at tillering was sufficient to obtain ODR measurements at all depths (Table 22). The oxygen diffusion rate at 2.5 cm depth for conventional and zero tillage exceeded 0.40 $\mu g \cdot cm^{-2} \cdot min^{-1}$ and was not considered limiting to root growth. The oxygen supply was 0.28 $\mu g \cdot cm^{-2} \cdot min^{-1}$ and 0.29 $\mu g \cdot cm^{-2} \cdot min^{-1}$ at the 5.0 cm depth for both conventionally and zero tilled plots respectively, and may have caused reductions in root growth. The oxygen diffusion rate at 10 and 20 cm soil depth was lower than the minimum oxygen diffusion rate considered necessary for root growth (Table 22). Oxygen supply varied little between tillage treatments and were not statistically different (α=0.05).

Table 22. Oxygen diffusion rate ($\mu g \cdot cm^{-2} \cdot min^{-1}$) for conventionally and zero tilled soils at tillering (June 19) in 1991.

Depth (cm)	Tillage Treatments		CV	P value
	Conventional	Zero		
2.5	0.41(40)[1]	0.45(44)	44.51	0.125
5.0	0.28(43)	0.29(44)	51.62	0.756
10.0	0.13(40)	0.12(41)	68.97	0.422
20.0	0.09(38)	0.10(35)	71.02	0.393

1 Values within parenthesis are percent gravimetric water content

At anthesis, soil moisture contents approached field capacity (Table 23). However, soil aeration was sufficient to supply plant demands for oxygen at the 2.5 and 5.0 cm depth for conventional and zero tillage. The oxygen diffusion rate of zero tilled soils was found to be significantly higher (α=0.05) than conventionally tilled soils (0.62 $\mu g \cdot cm^{-2} \cdot min^{-1}$ and 0.51 $\mu g \cdot cm^{-2} \cdot min^{-1}$ respectively). Oxygen diffusion rate varied from 0.18 $\mu g \cdot cm^{-1} \cdot min^{1}$ to 0.14 at a soil depth of 10 cm or greater for both tillage treatments. No significant differences (α=0.05) in ODR between tillage treatments was found below a soil depth of 2.5 cm.

Table 23. Oxygen diffusion rate ($\mu g \cdot cm^{-2} \cdot min^{-1}$) for conventionally and zero tilled soils at anthesis (July 25) in 1991.

Depth (cm)	Tillage Treatments		CV	P value
	Conventional	Zero		
2.5	0.51(44)[1]	0.62(53)	38.82	0.003
5.0	0.38(51)	0.40(52)	51.82	0.098
10.0	0.15(45)	0.18(46)	68.73	0.211
20.0	0.14(58)	0.14(44)	66.63	0.521

1 Values within parenthesis are percent gravimetric water content

Soil moisture levels at harvest decreased dramatically from anthesis to harvest. As a result, ODR readings could not be obtained for the 2.5 and 5.0 cm depths (Table

24). Conventionally tilled soils at crop maturity were found to have significantly higher ODR (0.32 $\mu g \cdot cm^{-2} \cdot min^{-1}$) at 10.0 cm than zero tilled soils (0.18 $\mu g \cdot cm^{-2} \cdot min^{-1}$).

Table 24. Oxygen diffusion rate ($\mu g \cdot cm^{-2} \cdot min^{-1}$) for conventionally and zero tilled soils at crop maturity (August 14) in 1991.

Depth (cm)	Tillage Treatments		CV	P value
	Conventional	Zero		
2.5	na	na	----	----
5.0	na	na	----	----
10.0	0.32(29)[1]	0.18(32)	63.16	0.001
20.0	0.22(33)	0.18(32)	80.71	0.195

1 Values within parenthesis are percent gravimetric water content

Despite occasional large differences in mean oxygen diffusion rate for the different tillage systems during the 1991 growing season, no consistently significant differences were determined. Variability of measurements were large due to the spatial variability which is an inherent property of these heavy clay soils. Soil aeration at 2.5 cm was adequate (> 0.4 $\mu g \cdot cm^{-2} \cdot min^{-1}$) and would not have limited root growth throughout 1991 growing season. Movement of oxygen within the soil at the 5 cm depth was often below the level needed by the plant and would have limited root growth to some extent. Generally, ODR at or below 10 cm was insufficient to supply the minimum requirements for plants (0.2 $\mu g \cdot cm^{-2} \cdot min^{-1}$) at all stages of growth in 1991. As a result, root growth would have been restricted to areas of improved aeration such as old root channels, cracks, and other macropores at soil depths greater than 10 cm depth (Bakker and Bronswijk, 1993). Only at crop maturity on conventionally tilled soils did ODR levels exceed the minimum required by plant roots at the 10 cm depth.

3.3 Effect of Treatments on Plant Characteristics

3.3.1 Root Density

Root density (roots·cm^{-3}) is often used as a means of estimating the effect of soil physical properties on root growth (Bohm 1979). Root density determined at harvest 1991 showed that plants on conventionally tilled soils had 2.3 roots·cm^{-3} at the 7.5 cm depth as compared 2.0 roots·cm^{-3} under zero tillage (Table 25). This slight increase in root density in favour of conventional tillage however was not statistically significant (α=0.05). Root density for the 22.5 cm depth were 1.3 and 1.5 roots·cm^{-3} for conventionally and zero tilled treatments, respectively. Differences at the 22.5 cm were not significantly different (α=0.05). Trends in root density between conventionally and zero tilled soils at the 22.5 cm depth were the opposite of the 7.5 cm depth. Ehlers et al (1983) found similar results and attributed them to an increase in biochannels below the depth of tillage in zero tilled soils.

The mean oxygen diffusion rate below a soil depth of 10.0 cm was determined to have been insufficient to supply the minimal requirements for root growth in 1991, yet root growth still occurred at the 22.5 cm depth (Table 21, 22, 23, and 24). This suggests that roots move preferentially into and through continuous biochannels and cracks in the soil matrix. These areas allow the diffusion of oxygen through the soil profile unrestricted by the barriers posed by water filled pores within the soil matrix. As a result higher oxygen levels near these channels would encourage root growth to deeper soil depths than the surrounding soil.

The existence of these biopores and cracks is supported by the high CV for ODR at all depths sampled. The variation in ODR levels would indicate most sampling periods and depths contained some measurements which were above the minimum required for crop growth. It is likely that these areas would be within the immediate proximity of the previously described soil pores or cracks.

Table 25. Wheat root density (number of roots$\cdot$cm^{-3}) for conventionally and zero tilled soils at crop maturity (August 14) in 1991.

Depth	Tillage Treatments		CV	P value
(cm)	Conventional	Zero		
7.5	2.3	2.0	23.10	0.108
22.5	1.3	1.5	24.62	0.189

3.3.2 Plant Characteristics and Yield

Crop growth is often affected by tillage practices. Many of these differences can be attributed to changes in soil physical properties. Differences in yield and other plant characteristics are often the combined effect of several soil properties. As a result, direct relationships between a single soil physical property and plant growth is often difficult to obtain. Nevertheless measurements of plant growth were determined at tillering, anthesis and harvest in 1991.

At the end of tillering, zero tilled treatments had an average dry matter weight of 184 g$\cdot$m^{-2}, which was 56% of the conventionally tilled treatments (Table 26). This probably was the result of zero tilled plots having 25% fewer plants than conventionally tilled plots. Plant numbers, while not significantly different, still showed a strong trend to higher plant numbers on conventionally tilled plots than on zero tilled plots. Higher plant numbers appear to indicate better growing conditions for conventionally tilled soils than zero tilled soils prior to tillering.

The extent of tillering can be considered a measurement of growing conditions at the time of tillering. Plant tillering did not differ between conventionally and zero tilled treatments. The advantage for plants growing under conventional tillage did not extended past seedling establishment. Soil temperature, water content and oxygen diffusion rate differed little between conventionally and zero tilled soils at emergence and were not the likely source of the lower plant numbers in zero tilled treatments. Lower plant numbers may be the result of higher soil strength at emergence and tillering for zero tilled soils than conventionally tilled soils. Soil strengths in the surface 10.0 cm at emergence and tillering were below 1.0 Mpa and probably would not have affected plant growth.

The trend for higher dry matter yields with conventional tillage was still evident at anthesis (Table 26). Once again this may be an artifact of the higher rate of seedling establishment for conventionally tilled soils versus zero tilled soils.

Table 26. Numbers of wheat plants, tillers, and dry matter yield for conventionally and zero tilled soils at tillering (June 19) and dry matter yield at anthesis (July 25) in 1991.

	Tillage Treatments		CV	P value
	Conventional	Zero		
Plant # (m^{-2}) at Tillering	240	180	7.22	0.012
Tillers/plant at Tillering	3.5	3.5	10.22	0.831
Dry Weight at Tillering ($g \cdot m^{-2}$)	331	184	30.69	0.079
Dry Weight at Anthesis ($g \cdot m^{-2}$)	753	359	4.26	0.031

Greater vegetative growth for conventionally tilled soils earlier in the growing seasons was reflected in higher straw weights at harvest (Table 27). Zero tilled soils had straw weights of 348.8 $g \cdot m^{-2}$ while conventionally tilled soils had a straw weight of 465.8 $g \cdot m^{-2}$ (Table 27). The differences between straw weights were not significant (α=0.05) at harvest. Grain yield and thousand kernel weight were very similar for zero and conventional tillage treatments. This indicates that neither tillage treatment provided an advantage for crop growth after spikelet formation and during seed filling in 1991.

Plant yield data for 1991 indicate that crop growth was greater under conventional tillage early in the growing season. This advantage did not translate into increase grain yields at harvest. Carter and Rennie (1985) also reported that higher plant growth for conventionally tilled than zero tilled soils early in the season did not result in higher grain yields. In addition, they also found that higher plant growth on conventionally tilled soils early in the season also resulted in higher straw weights at harvest. The difference in crop growth is generally attributed to lower soil temperatures on zero tilled soils. As stated earlier, soil temperature varied little between treatments. None of the observed soil properties explained the difference in crop growth under conventional and zero tillage. Cochrane et al. (1977) found that differences in crop growth between conventionally and zero tilled soils were the result of phytotoxins which are leached from crop residues. Since zero tilled soils have higher surface residue levels it would be expected that they would also have a higher release of phytotoxins.

Ponding of water in shallow depressions occurred periodically on the research plot in 1991. This resulted in increased spatial variability in plant data. At harvest, straw weight and grain weight had coefficients of variation (CV) of 63 and 44% respectively.

Table 27. Wheat grain, straw, total plant weight and thousand kernel weight for conventionally and zero tilled soils at crop maturity (August 14) in 1991.

	Tillage Treatments		CV	P value
	Conventional	Zero		
Grain Weight ($g \cdot m^{-2}$)	148	151	63.35	0.970
Straw Weight($g \cdot m^{-2}$)	466	349	44.23	0.690
Thousand Kernel Weight ($g \cdot m^{-2}$)	24.7	25.0	9.64	0.840

4.0 1992 Results and Discussion

4.1 1992 Growing Season Climate

Atmospheric temperature through the 1992 growing season was lower than the historical average recorded at the nearest Environment Canada climatological recording station (Starbuck, Manitoba) until 66 days after seeding (August 14th). This indicated that growing season temperatures were lower than normal for the region in 1992. After August 14th, air temperature fluctuated around the normal with no trends readily apparent (Figure 6a).

Accumulated total precipitation from seeding (June 9) to harvest (September 6) at the research site was 214 mm (Figure 7). This was lower than the average cumulative precipitation of 262 mm recorded by Environment Canada at Starbuck, Manitoba over the same period of time (Figure 7). Average or slightly below average precipitation indicated that good growing conditions would have occurred on these poorly drained clay soils. High antecedent soil moisture, intense rainfall events, and cool temperatures that reduced evaporation contributed to a wet growing season. As a result micro depressions within the plot became inundated with water on several occasions in the 1992.

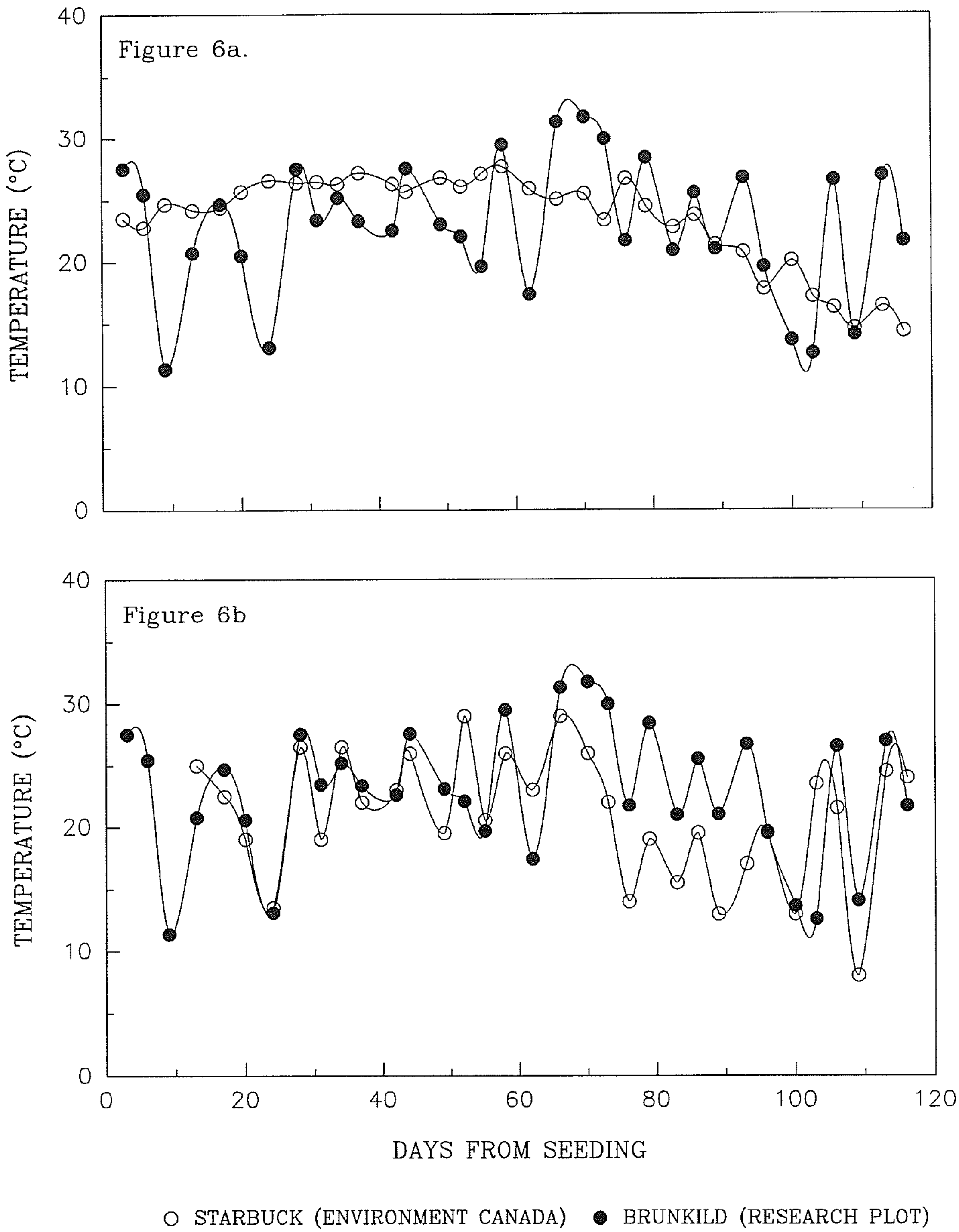

Figure 6a. Climatic normals (maximum daily air temperature) recorded at Starbuck, Manitoba and 1992 air temperature data from the research plot near Brunkild, Manitoba (seeded June 9). **6b.** Comparison of 1992 maximum air temperatures recorded at Starbuck and Brunkild, Manitoba .

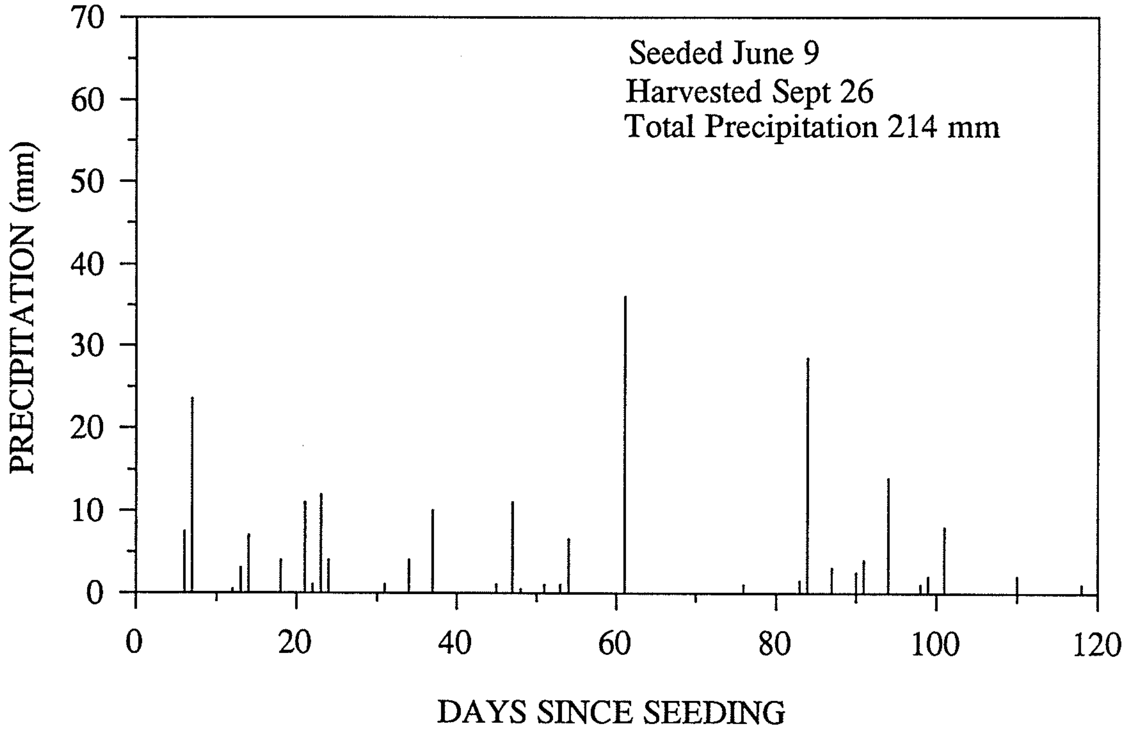

Figure 7. Precipitation during the 1992 growing season at Brunkild, Manitoba (seeded June 9).

4.2 Effect of Treatments on Soil Physical Properties

4.2.1 Soil Temperature

Beginning on June 12, air and soil temperature were measured at 2:00 PM, twice weekly. Conventionally and zero tilled soils were virtually identical with regards to temperature for each depth through out the 1992 growing season (Figures 8 and 9). Soil temperature ranged from 24.5°C to 10.4°C for conventionally tilled soils at the 2.5 cm soil depth. Zero tilled soils ranged from 25.6°C to 10.5°C at the same depth. Soil temperatures increased as the season progressed until 70 days after seeding (August 19th) after which temperature tended to decrease with time for all depths (Figures 8 and 9).

The 1992 growing season was also characterized by frequent cloud cover which could mask the effect of an increased reflective coefficient on zero tilled soils (Watts, 1973). Soil temperature measurements were not initiated until June 12. Thus, the effect of tillage treatment on soil temperature early in the growing season could not be assessed in 1992. Differences in soil moisture may have influenced soil temperature. Higher soil moisture contents of conventionally tilled soils at seeding and emergence in 1992 would have increased the volumetric heat capacity of these soils compared to zero tilled soils. An increase in volumetric heat capacity slows the warming of the soil resulting in lower soil temperatures. This effect may have negated any benefit derived from reduced residue coverage on conventionally tilled soils. A similar trend in soil moisture was also noted at emergence in 1991 and may explain the lack of temperature differences in that year. These results contrast those of Gauer et al. (1982) who determined that differences in crop residue was the major factor causing soil temperature variations between conventionally and zero tilled soils.

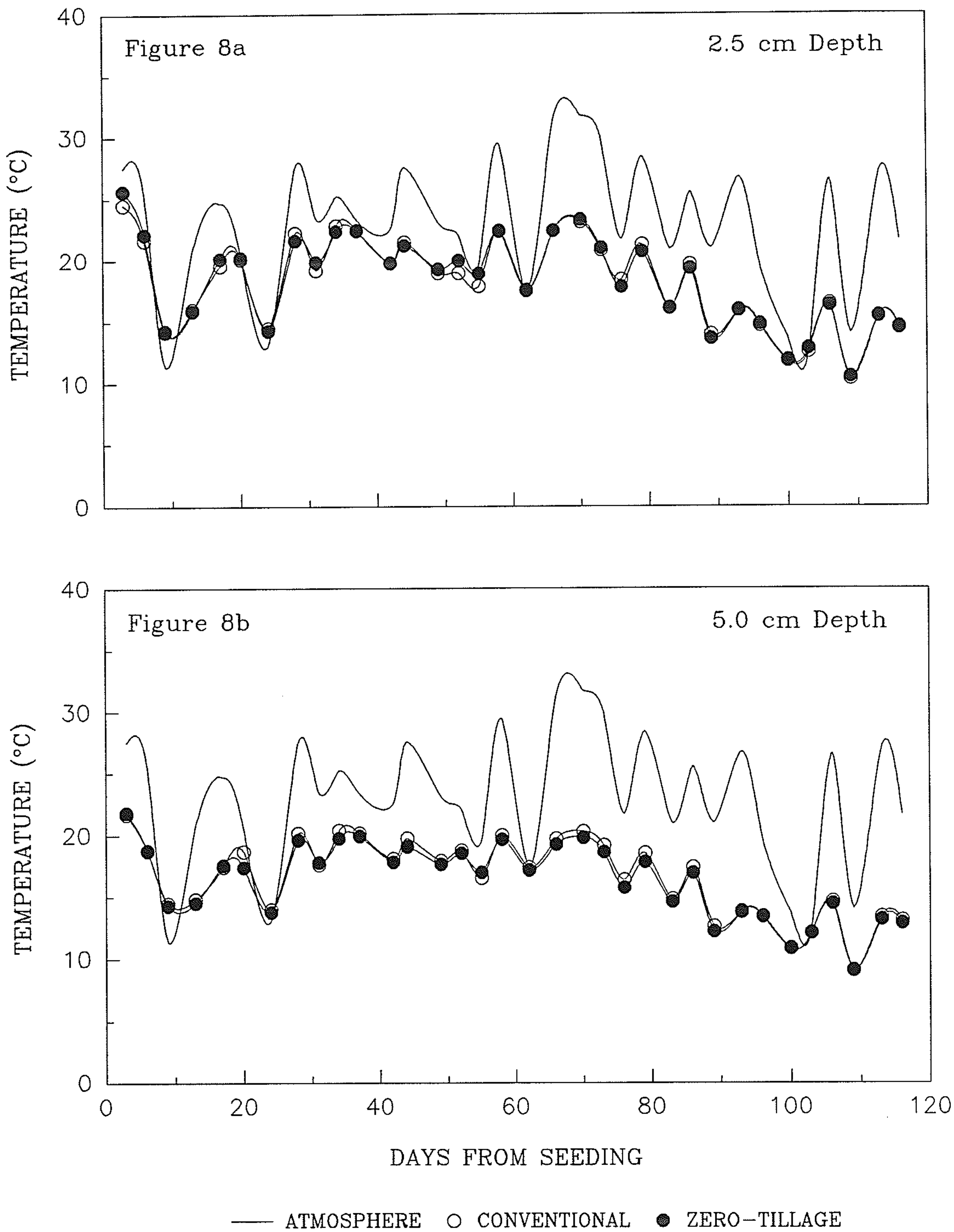

Figure 8a and 8b. Soil temperature for conventionally and zero tilled soils at 2.5 and 5.0 cm depth in 1992 (seeded June 9).

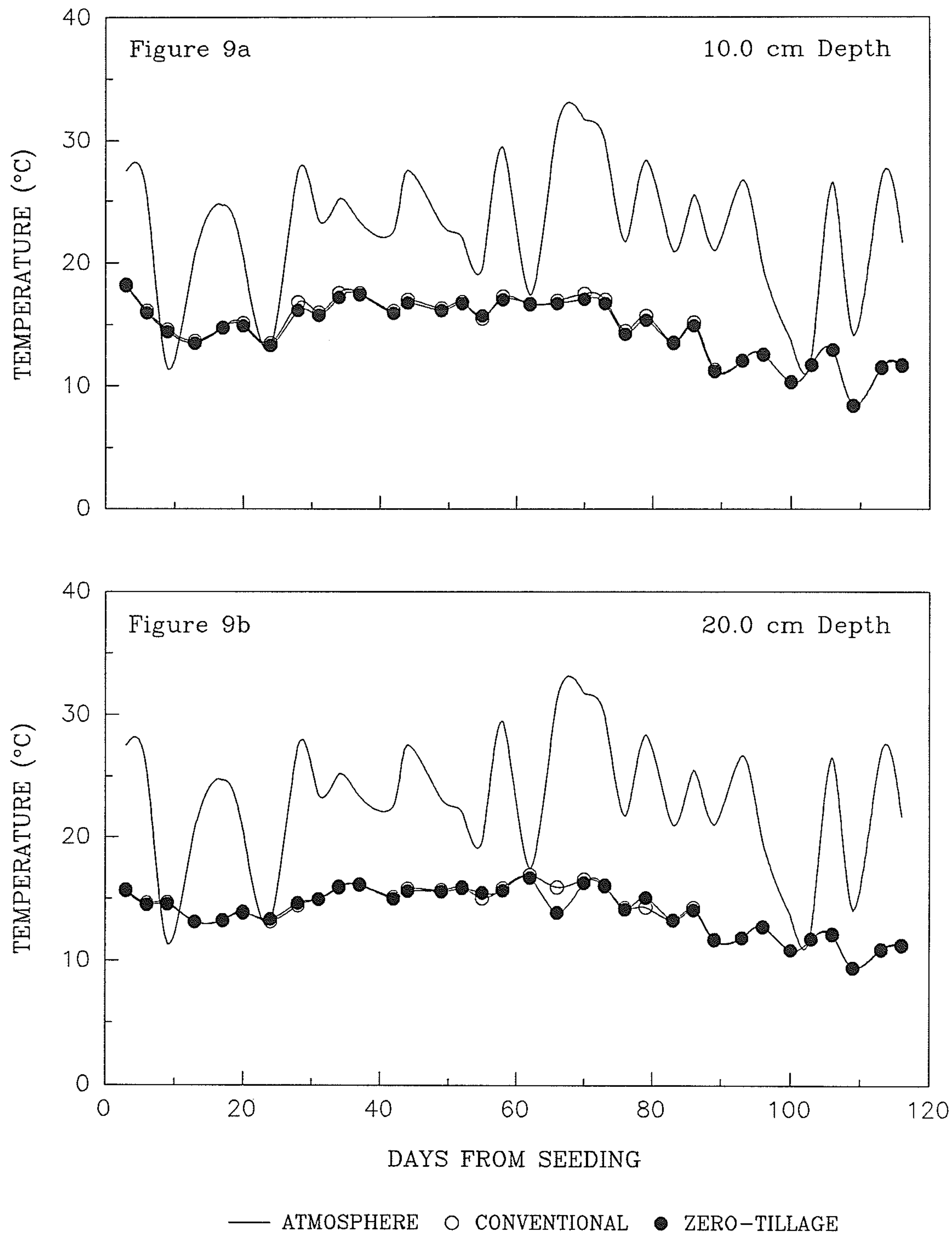

Figure 9a and 9b. Soil temperature for conventionally and zero tilled soils at 10.0 and 20.0 cm depth in 1992 (seeded June 9).

4.2.2 Soil Water

Gravimetric soil moisture contents exceeded 50% near the soil surface (Table 28) for conventionally and zero tilled treatments at seeding in 1992. Conventionally tilled soils had a water content of 59% for the 0 to 15 cm depth, which was significantly (α=0.05) higher than the 51.7% determined for zero tilled soils. Water content decreased with depth but was still 41.4% to 43.0% at 60 cm. Comparison of the soil water content showed no significant (α=0.05) differences between treatments at depths below 15.0 cm. Moisture levels approached or exceeded field capacity (Table 3) for all depths sampled. The trends for higher soil moisture on conventionally tilled treatments over zero tilled soils were consistent to those found at emergence in 1991.

Table 28. Percent gravimetric water content at seeding (June 9) in 1992 for conventional and zero tillage treatments.

Depth (cm)	Tillage Treatments		CV	P value
	Conventional	Zero		
0-15	59.0	51.7	4.28	0.022
15-30	51.8	47.5	7.53	0.199
30-45	47.3	44.7	7.10	0.341
45-60	41.4	43.0	5.01	0.383

To better characterize soil moisture levels with regard to penetrometer measurements soil moisture contents at emergence, tillering, anthesis, and crop maturity were sampled every 10.0 cm to a depth of 60.0 cm. Soil moisture levels decreased through the entire profile by the time the crop had emerged for both tillage treatments (Table 29). The moisture content for conventionally tilled soils was 47.3% for the 0 to 10.0 cm depth and decreased to 37.9% for the 50 to 60 cm depth. Zero tilled soils ranged from 44.9% to 37.5% for the same soil depths. Conventionally tilled soils had slightly higher soil moisture at most soil depths sampled (Table 29).

Differences in soil moisture due to treatment at emergence had diminished from that recorded at seeding and were not statistically significant (α=0.05).

Table 29. Percent gravimetric water content at emergence (June 29) in 1992 for conventional and zero tillage treatments.

Depth (cm)	Tillage Treatments		CV	P value
	Conventional	Zero		
0-10	47.3	44.9	6.68	0.161
10-20	42.6	41.1	6.99	0.318
20-30	41.3	38.9	9.21	0.235
30-40	39.6	37.9	7.55	0.295
40-50	36.3	36.3	14.61	0.585
50-60	37.9	37.5	4.81	0.587

Evaporation decreased soil moisture levels through the entire soil profile by the end of crop tillering for both tillage treatments (Table 30). Soil moisture for the 0 to 10 cm depth was 39.0% for conventionally tilled and 36.8% for zero tilled soils. Conventionally and zero tilled soils decreased to 36.3% and 34.6% gravimetric water content respectively for 50 to 60 cm soil depth. Zero tilled soils had lower soil moisture level for all depths sampled at tillering in 1992. Statistical analysis showed that conventional tillage treatments had significantly (α=0.05) higher moisture content than zero tillage treatments from 10 cm to 40 cm (Table 30). Gravimetric water content between 10 and 40 cm varied from 39.8% to 37.9% and 36.6% to 35.3% for conventionally and zero tilled soils, respectively.

Table 30. Percent gravimetric water content at tillering (July 22) in 1992 for conventionally and zero tilled treatments.

Depth (cm)	Tillage Treatments		CV	P value
	Conventional	Zero		
0-10	39.0	36.8	8.47	0.265
10-20	39.8	36.6	2.14	0.004
20-30	39.4	36.2	3.23	0.013
30-40	37.9	35.3	3.21	0.021
40-50	37.0	34.7	5.46	0.105
50-60	36.3	34.6	5.51	0.183

1 Mean value of off and on tire tracks was used for each tillage treatment

Investigations into the effects of wheel traffic at seeding were initiated at tillering in 1992. Soil moisture was 38.7% on tire tracks and 37.1% off tire track treatments at the 0 to 10 cm depth (Table 31). Moisture levels then decreased to approximately 35% at the 50 to 60 cm depth. No significant differences in soil water content were found when comparing areas compacted by vehicular traffic to those not traveled on (Table 31).

Table 31. Percent gravimetric water content at tillering (July 22) for on and off tire tracks in 1992.

Depth (cm)	Tire Track Position[1]		CV	P value
	On	Off		
0-10	38.7	37.1	10.32	0.459
10-20	38.7	37.9	6.92	0.546
20-30	37.5	38.1	7.87	0.715
30-40	36.2	37.0	6.65	0.569
40-50	35.8	35.9	7.21	0.971
50-60	35.7	35.3	5.35	0.672

1 Mean value of zero and conventional tillage treatments was used for each tire track treatment

Soil depths at which a significant difference in soil moisture between tillage treatments had occurred were also found to have significant tillage by tire track interaction effect (Table 32). Wheel traffic increased soil water content on conventionally tilled treatments but reduced soil moisture levels on zero tilled treatments. Carnache et al (1984) also discovered an increase in soil moisture with compaction on tilled soils. This was noted only for poorly drained sites with a impermeable Bt horizon, similar to soils at the Brunkild site. Higher soil moisture was related to the low permeability of the subsoil, lower evaporative losses due to decreased unsaturated hydraulic conductivity (caused by compaction), and reduced crop growth decreasing water consumption. This may not hold true for zero tilled soils which react differently to wheel traffic. In this experiment, compaction from wheel traffic created micro depression on the tilled soil. Similar depressions were not found on the zero tilled treatments. Soil compaction due to wheel traffic has been reported to be higher on conventionally than zero tilled treatments (Hill and Meza-Montalvo 1990). Zero tillage commonly results in a denser layer of soil at the surface and would be affected by compaction to a lesser degree than tilled soils.

Table 32. Percent gravimetric water content at tillering (July 22) for conventionally, zero tilled treatments and location with regards to tire tracks in 1992.

Depth	On Tire Tracks		Off Tire Tracks		Tillage x Track	
(cm)	Conventional	Zero	Conventional	Zero	CV	P Value
0-10	38.0	36.1	40.0	37.5	11.70	0.899
10-20	41.0	34.5	38.7	38.7	7.16	0.096
20-30	42.2	34.1	36.7	38.4	5.58	0.018
30-40	40.5	33.5	35.4	37.1	5.05	0.019
40-50	38.6	33.1	35.3	36.3	3.59	0.016
50-60	37.1	33.4	35.5	35.9	3.60	0.051

When the crop reached anthesis (Table 33), differences in soil moisture due to tillage treatments were no longer evident. Loss of soil moisture through evaporation and transpiration resulted in lower gravimetric water contents than at tillering. Soil moisture levels ranged from 37.1% at the surface to 33.8% at a soil depth of 60.0 cm for both tillage treatments. Differences in soil water content between tillage treatment were less than 1% and not statistically significant.

Table 33. Percent gravimetric water content at anthesis (August 18) for conventionally and zero tilled treatments in 1992.

Depth (cm)	Tillage Treatments		CV	P value
	Conventional	Zero		
0-10	37.1	36.6	10.20	0.828
10-20	34.7	34.9	5.40	0.877
20-30	33.2	33.6	3.07	0.582
30-40	33.3	33.4	1.85	0.911
40-50	33.7	33.8	5.21	0.961
50-60	34.4	33.8	4.00	0.434

1 Mean value of off and on tire tracks was used for each tillage treatment

Soil moisture levels on tire tracks at anthesis was similar to areas that were not traveled on during seeding (Table 34). Gravimetric water content off tire tracks ranged from 37.0% for the 0 to 10 cm soil depth to 33.6% at the 50 to 60 cm depth. On tire tracks ranged from 36.7 to 34.4 for the same soil depths. Differences were not found to be statistically different (α=0.05).

Table 34. Percent gravimetric water content at anthesis (August 18) for on and off tire track treatments in 1992.

Depth (cm)	Tire Track Position[1]		CV	P value
	On	Off		
0-10	36.7	37.0	8.66	0.898
10-20	35.4	34.2	6.16	0.338
20-30	34.2	32.6	9.07	0.379
30-40	33.8	32.9	7.71	0.560
40-50	33.7	33.8	12.01	0.942
50-60	34.4	33.6	3.69	0.291

1 Mean value of zero and conventional tillage treatments was used for each tire track treatment

Interactions between tillage and tire tracks (Table 35) was significant for the 0.0 to 10.0 cm depth (α=0.05). Soil moisture under zero tillage increased from 35.3 % off tire tracks to 37.9% on tire tracks in the 0 to 10 cm depth. Conventionally tilled soils decreased in soil moisture from 38.2% off tire tracks to 36.0% on tire tracks for the same depth. Below a soil depth of 10 cm soil moisture levels were similar for conventional ly and zero tilled soils, on and off the tire tracks.

Table 35. Percent gravimetric water content at anthesis (August 18) for conventionally, zero tillage and location with regard to tire tracks in 1992.

Depth	On Tire Tracks		Off Tire Tracks		Tillage x Track	
(cm)	Conventional	Zero	Conventional	Zero	CV	P Value
0-10	36.0	37.9	38.2	35.3	1.82	0.006
10-20	33.6	34.8	35.9	35.0	6.48	0.413
20-30	31.6	33.6	34.9	33.5	7.29	0.273
30-40	32.4	33.4	34.2	33.3	4.21	0.257
40-50	33.6	34.0	33.8	33.5	4.69	0.690
50-60	33.6	33.7	35.1	33.8	2.90	0.255

At maturity, soil moisture content (Table 36) increased to levels greater than at anthesis (Table 33). Zero tilled treatments had lower soil moisture level than did conventionally tilled treatments in the top 10 cm (40.3% and 45.6%, respectively). The difference was not significant at α=0.05, but a strong trend was present (p=0.06). Below 10 cm soil moisture contents were similar for zero and conventional tillage treatments with a maximum of 42.2% for 10 to 20 cm depth decreasing to a minimum of 35.2 % at 50 to 60 cm depth. Differences below 10.0 cm were not statistically significant.

Table 36. Percent gravimetric water content at crop maturity (September 26) for conventionally and zero tilled treatments in 1992.

Depth (cm)	Tillage Treatments		CV	P value
	Conventional	Zero		
0-10	45.6	40.3	11.69	0.058
10-20	42.2	40.3	10.32	0.283
20-30	39.1	38.6	9.95	0.733
30-40	37.6	36.7	5.77	0.146
40-50	36.6	34.9	10.80	0.322
50-60	36.4	35.2	13.86	0.525

1 Mean value of off and on tire tracks was used for each tillage treatment

Analysis of wheel track effects at harvest showed no significant differences in soil moisture between on and off tire tracks for all depths measured (Table 37). The effect of wheel tracks on the soil moisture content for the conventionally tilled treatments reappeared at harvest. This is demonstrated by the significant interaction between tire tracks and tillage treatments for the soil depths between 10 cm and 50 cm (Table 38). Compaction from tractor tires at seeding resulted in higher soil moisture levels for conventionally tilled soils, but had little effect upon soil moisture levels of zero tilled soils. These results are similar to trends in soil moisture found at tillering for conventional tillage in 1992.

Table 37. Percent gravimetric water content at crop maturity (September 26) for on and off tire track treatments in 1992.

Depth (cm)	Tire Track Position[1]		CV	P value
	On	Off		
0-10	43.8	42.1	5.56	0.131
10-20	42.4	40.2	10.5	0.247
20-30	40.0	37.7	19.70	0.449
30-40	37.9	36.3	14.48	0.348
40-50	37.6	33.7	16.09	0.165
50-60	35.5	36.1	9.04	0.667

1 Mean value of zero and conventional tillage treatments was used for each tire track treatment

Table 38. Percent gravimetric water content at crop maturity (September 26) for conventionally and zero tilled treatments, and location with regard to tire tracks in 1992.

Depth	On Tire Tracks		Off Tire Tracks		Tillage x Track	
(cm)	Conventional	Zero	Conventional	Zero	CV	P Value
0-10	47.1	40.5	44.0	40.1	8.25	0.284
10-20	44.4	40.3	40.0	40.3	4.85	0.006
20-30	41.7	38.4	36.6	38.8	9.24	0.043
30-40	39.2	36.6	33.8	38.5	9.31	0.004
40-50	40.1	35.1	32.5	34.7	13.64	0.070
50-60	36.4	34.6	36.4	35.7	7.15	0.571

Soil moisture in 1992 showed similar trends early in the season between tillage treatments as 1991. Zero tillage treatments had lower moisture levels than conventional tillage treatments at seeding and tillering in 1992. These differences in the 0 to 10 cm depth disappeared as overall soil water contents decreased. Increasing soil moisture contents at harvest in 1992 resulted in a trend ($p=0.058$) for higher soil moisture levels for conventional than zero tillage treatments. Trends in soil moisture levels at harvest were similar to those reported at seeding in 1992.

Below a soil depth of 10 cm differences in soil moisture due to tillage treatment occurred only at tillering in 1992. This difference in soil moisture was associated with significant interaction between tillage and tire track treatments. At crop maturity a similar interaction was also found for the same soil depths. In both sampling periods, conventional tillage had an increase in soil moisture due to compaction from tire tracks. Soil moisture content of zero tilled soils decreased with compaction or remained unchanged.

4.2.3 Soil Strength

Soil strength at emergence was less than 1.0 MPa for the entire soil profile (Table 39) of conventionally and zero tilled soils. Soil strength increased from 0.11 MPa to 0.82 MPa in the top 10.5 cm for conventionally tilled treatments. Zero tilled soils had soil strengths of 0.1 MPa and 0.72 MPa for the same depths. An extra seeding operation in 1992 may have eliminated the difference in soil strength noted at emergence in 1991. Below 10 cm soil strength increased gradually to a maximum of 1.02 MPa for conventionally tilled and 1.00 MPa for zero tilled soils. Conventional tilled soils had a higher soil strength than zero tilled soil for most depths below 10.5 cm. The variation in soil strength with tillage treatment were significant (α=0.05) at soil depths of 31.5 and 42.0 cm. However, the trend for greater soil strength under conventional tillage than zero tillage existed from 24.5 to 49.0 cm with P-values at or below 0.1. As soil moisture levels decrease, soil strength generally increases (Snyder and Miller, 1985). Soil moisture levels at emergence (Table 29) were actually higher for conventionally tilled soils than zero tilled soils. This would indicate that differences in soil strength may not be due to soil moisture alone, but may be significantly affected by other soil factors such as bulk density. This would be contrary to results of Perumpral (1987) who found that soil strength at high moisture contents was not affected by bulk density. Bulk density values were unavailable for comparison in this experiment.

Table 39. Soil strength (MPa) for conventionally and zero tilled soils at emergence (June 29) in 1992.

Depth (cm)	Tillage Treatments Conventional	Zero	CV	P value
3.5	0.11	0.10	17.11	0.783
7.0	0.49	0.56	15.27	0.293
10.5	0.82	0.72	10.04	0.150
14.0	0.72	0.70	7.35	0.730
17.5	0.71	0.69	6.62	0.648
21.0	0.75	0.74	2.62	0.566
24.5	0.80	0.74	3.87	0.077
28.0	0.85	0.80	3.19	0.064
31.5	0.89	0.77	3.89	0.013
35.0	0.91	0.84	4.92	0.097
38.5	0.96	0.86	6.65	0.103
42.0	0.99	0.86	3.83	0.015
45.5	0.99	0.91	5.83	0.129
49.0	1.00	0.93	4.70	0.098
52.5	1.02	1.00	4.40	0.564

At tillering, soil strength was similar to levels recorded at emergence for both tillage treatments (Table 40) for the 3.5 cm depth. Soil strength increased below 3.5 cm, reaching a maximum soil strength of 1.55 MPa at 10.5 cm for zero tillage and 1.26 at 14.0 cm depth for conventional tillage. At soil depths greater than 14.0 cm, soil strength ranged from 0.96 MPa to 1.10 MPa and 1.04 MPa to 1.22 MPa for conventionally and zero tilled soils respectively. Moisture content under the zero tilled treatment was generally about 2% lower than that of conventionally tilled soils (Table 30) at all sampling depths and may have affected soil strength. Differences in soil strength were significant (α=0.05) at the 10.5 cm and 17.5 cm depth only.

The effect of tire track on soil strength were measured at tillering in 1992. Areas affected by wheel traffic had slightly higher soil strengths than areas not traveled on (Table 41) though not significantly (α=0.05). Soil strength off tire tracks ranged from 0.09 MPa at the surface to a maximum of 1.29 MPa at 14.0 cm. Soil resistance measured on tire tracks was 0.09 MPa and 1.47 MPa for the same depth.

Table 40. Soil strength (MPa) for conventionally and zero tilled soils at tillering (July 22) in 1992.

Depth (cm)	Tillage Treatments		CV	P value
	Conventional	Zero		
3.5	0.09	0.10	18.95	0.297
7.0	0.56	0.86	51.44	0.194
10.5	1.20	1.56	7.45	0.006
14.0	1.26	1.51	17.11	0.124
17.5	1.10	1.27	8.9	0.050
21.0	1.01	1.12	7.91	0.089
24.5	0.96	1.07	13.28	0.213
28.0	0.98	1.04	12.43	0.411
31.5	1.00	1.05	10.10	0.382
35.0	0.99	1.10	11.76	0.180
38.5	1.03	1.14	11.06	0.135
42.0	1.05	1.16	11.43	0.190
45.5	1.06	1.16	8.40	0.130
49.0	1.06	1.18	7.40	0.062
52.5	1.10	1.22	6.43	0.525

1 Mean value of off and on tire tracks was used for each tillage treatment

Table 41. Soil strength (MPa) for on and off tire track treatments at tillering (July 22) in 1992.

Depth (cm)	Tire Track Position[1]		CV	P Value
	On	Off		
3.5	0.09	0.09	7.38	0.861
7.0	0.73	0.68	17.78	0.489
10.5	1.48	1.27	37.30	0.480
14.0	1.47	1.29	36.76	0.538
17.5	1.22	1.15	30.65	0.714
21.0	1.09	1.04	22.02	0.662
24.5	1.03	1.00	13.49	0.652
28.0	1.03	0.99	6.10	0.577
31.5	1.05	1.00	10.10	0.403
35.0	1.07	1.02	11.86	0.398
38.5	1.11	1.06	5.92	0.217
42.0	1.25	1.08	4.18	0.158
45.5	1.13	1.09	5.86	0.313
49.0	1.14	1.10	6.30	0.358
52.5	1.16	1.15	5.16	0.742

1 Mean value of zero and conventional tillage treatments was used for each tire track treatment

Soil moisture levels decreased from tillering to anthesis and a corresponding increase in soil strength occurred (Table 42). Zero tilled treatments generally had higher soil strengths than conventionally tilled treatments at all depths sampled. However, statistical analysis indicated no significant differences between tillage treatments at any depth (α=0.05). Soil strength was 0.11 MPa at 3.5 cm for conventionally and zero tilled soils. At a depth of 17.5 cm, soil strength increased to 1.73 MPa for conventionally tilled soils and 1.83 MPa for zero tilled soils. Below 17.5 cm, soil strength decreased for both conventional and zero tillage treatments. Since moisture contents were similar for all treatments (Table 30), differences in soil strength could not explained by differences in soil water content. Neither tillage treatment exceeded a soil strength of 2.0 MPa, the upper limit for root growth. Soil strength did reach levels sufficient to reduce root growth at anthesis.

Table 42. Soil strength (MPa) for conventionally and zero tilled soils at anthesis (August 18) in 1992.

Depth	Tillage Treatments		CV	P value
(cm)	Conventional	Zero		
3.5	0.11	0.11	17.48	0.853
7.0	0.68	0.73	25.45	0.587
10.5	1.52	1.60	21.42	0.670
14.0	1.72	1.78	24.67	0.792
17.5	1.73	1.83	26.24	0.675
21.0	1.66	1.71	22.25	0.820
24.5	1.61	1.71	25.56	0.651
28.0	1.57	1.74	27.24	0.494
31.5	1.54	1.76	26.38	0.374
35.0	1.53	1.75	26.94	0.393
38.5	1.50	1.74	22.52	0.282
42.0	1.45	1.70	22.68	0.245
45.5	1.42	1.63	21.33	0.291
49.0	1.44	1.56	15.97	0.381
52.5	1.47	1.60	14.68	0.342

1 Mean value of off and on tire tracks was used for each tillage treatment

At anthesis, wheel traffic did not affect soil strength in the top 17.5 cm (Table 43). Below 17.5 cm, areas affected by tire tracks had a lower mechanical resistance than those that were not (α=0.05). Differences in soil strength cannot be explained by differences in soil moisture, which were similar for both tire track treatments (Table 34).

Table 43. Soil strength (MPa) for on and off tire track treatments at anthesis (August 18) in 1992.

Depth (cm)	Tire Track Position[1]		CV	P value
	On	Off		
3.5	0.11	0.11	22.17	0.737
7.0	0.70	0.65	19.05	0.212
10.5	1.64	1.48	14.96	0.261
14.0	1.71	1.79	12.18	0.501
17.5	1.75	1.81	9.27	0.549
21.0	1.59	1.78	4.71	0.017
24.5	1.54	1.78	6.47	0.022
28.0	1.51	1.80	3.95	0.003
31.5	1.49	1.81	2.94	0.001
35.0	1.48	1.80	1.46	0.001
38.5	1.47	1.76	1.16	0.001
42.0	1.47	1.68	3.76	0.006
45.5	1.43	1.63	7.01	0.035
49.0	1.42	1.58	5.29	0.028
52.5	1.45	1.62	1.95	0.002

1 Mean value of zero and conventional tillage treatments was used for each tire track treatment

Zero tilled soils at crop maturity had significantly higher (α=0.05) soil strengths than conventionally tilled soils to a depth of 14.0 cm (Table 44). Soil moisture in the 0 to 10 depth was also higher for conventional tilled soils than zero tilled soils and may have affected soil strength. At 35.0 cm, conventional tillage had a soil strength of 1.08 MPa which was lower than that of the zero tilled soil (1.29 MPa).

Soil strength from 35 to 52.5 cm increased to 1.16 and 1.31 MPa for both conventional and zero tillage, respectively. Differences in soil strength between tillage treatments at depths greater than 35.0 cm were statistically significant ($\alpha=0.05$). Soil moisture at depths greater than 30 cm was slightly higher for conventionally tilled than zero tilled soils, and may partially explain differences in soil strength.

Table 44. Soil strength (MPa) for conventionally and zero tilled soils at harvest (September 26) in 1992.

Depth	Tillage Treatments		CV	P value
(cm)	Conventional	Zero		
3.5	0.14	0.17	7.63	0.038
7.0	0.49	0.60	10.77	0.030
10.5	0.70	0.88	5.10	0.003
14.0	0.82	0.98	14.39	0.001
17.5	0.92	1.02	12.49	0.182
21.0	0.93	1.04	13.53	0.185
24.5	0.96	1.08	8.41	0.060
28.0	1.02	1.14	11.48	0.152
31.5	1.05	1.23	11.42	0.072
35.0	1.08	1.29	8.25	0.022
38.5	1.10	1.33	3.72	0.002
42.0	1.12	1.34	7.00	0.014
45.5	1.15	1.35	6.18	0.014
49.0	1.15	1.33	6.96	0.026
52.5	1.16	1.31	6.23	0.029

1 Mean value of off and on tire tracks was used for each tillage treatment

Mean soil strength at crop maturity increased from a minimum of 0.15 and 0.16 MPa at 3.5 cm to a maximum 1.22 and 1.28 at 45.5 cm for on and off tire tracks, respectively (Table 45). This is similar to the trend for higher soil strengths off tire tracks than on tire tracks recorded in the previous sampling period. Differences between tire track treatments at crop maturity in 1992 were not statistically significant.

Table 45. Soil strength (MPa) for on and off tire track treatments at harvest (September 26) in 1992.

Depth (cm)	Tire Track Position[1] On	Tire Track Position[1] Off	CV	P value
3.5	0.15	0.16	31.59	0.943
7.0	0.55	0.54	19.64	0.807
10.5	0.82	0.76	9.10	0.241
14.0	0.90	0.89	8.33	0.762
17.5	0.96	0.98	13.15	0.723
21.0	0.96	1.01	11.30	0.395
24.5	1.00	1.05	15.47	0.583
28.0	1.03	1.12	19.54	0.475
31.5	1.10	1.18	23.38	0.573
35.0	1.14	1.23	28.00	0.614
38.5	1.17	1.27	26.70	0.592
42.0	1.19	1.27	24.86	0.080
45.5	1.22	1.28	22.62	0.683
49.0	1.21	1.27	17.83	0.593
52.5	1.22	1.26	14.85	0.692

1 Mean value of zero and conventional tillage treatments was used for each tire track treatment

Soil strength within the tilled layer tended to be higher for zero tilled than conventional tilled soils except at high soil moisture contents. However, differences were not statistically significant. Below the tilled layer zero tilled soils tended to have higher soil strengths.

A general relationship appeared to exist between soil moisture content and soil strength for the various sampling times. A decrease in soil moisture between emergence and tillering for both treatments was accompanied by an increase in soil strength. Similar changes in soil strength with changes in soil moisture occurred between other sampling periods in 1992. This trend did not occur within the 1991 or between the 1991 and 1992 growing seasons. Soils strength approached 2.0 MPa and would have been sufficient to reduce root growth in 1992.

4.2.4 Soil Aeration

The oxygen diffusion rate of the soil at crop emergence was generally below the rate considered limiting to crop growth (0.4 $\mu g \cdot cm^{-2} \cdot min^{-1}$) for the 2.5 and 5.0 cm depth (Table 46) for both tillage treatments. At depths below 5.0 cm, oxygen diffusion rate was below the minimum rate (0.2 $\mu g \cdot cm^{-2} \cdot min^{-1}$) needed for root growth to occur. The low oxygen diffusion rates recorded at all depths could be the result of the high soil moisture contents, which was exceeded 40%, and microporosity for depths sampled. No significant difference (α=0.05) in oxygen diffusion rate between conventionally and zero tilled soils was found at emergence in 1992.

Table 46. Oxygen diffusion rate ($\mu g \cdot cm^{-2} \cdot min^{-1}$) for conventionally and zero tilled soils at emergence (June 29) in 1992.

Depth (cm)	Tillage Treatments		CV	P value
	Conventional	Zero		
2.5	0.34(42)[1]	0.45(41)	15.97	0.094
5.0	0.28(45)	0.25(45)	45.14	0.760
10.0	0.08(45)	0.11(41)	101.85	0.689
20.0	0.06(40)	0.10(40)	59.05	0.343

1 Values within parenthesis are percent gravimetric water content

The oxygen diffusion rate at tillering was 0.30 $\mu g \cdot cm^{-2} \cdot min^{-1}$ for both conventionally and zero tilled soils at a soil depth of 2.5 cm. At 5.0 cm zero tillage had an oxygen diffusion rate of 0.25 $\mu g \cdot cm^{-2} \cdot min^{-1}$ and conventionally tilled soils had an ODR of 0.18 $\mu g \cdot cm^{-2} \cdot min^{-1}$ at the same depth. Zero tilled plots were similar to conventionally tilled plots with oxygen diffusion rates of 0.11 $\mu g \cdot cm^{-2} \cdot min^{-1}$ and 0.12 $\mu g \cdot cm^{-2} \cdot min^{-1}$ for the 10.0 and 20.0 cm depth. Statistical analysis indicates that soil oxygen content was not affected by tillage treatment except at the 5.0 cm depth.

A decrease in soil water content (Table 47) from emergence would be expected to result in higher ODR at tillering. However, the oxygen diffusion rate was found to be lower at tillering than at emergence. As the season progressed the biological sink for oxygen by soil microbes and plant roots would have increased with increases in soil temperature. An increase in microbial respiration would have lowered the oxygen concentration in soil air, thereby decreasing ODR.

Table 47. Oxygen diffusion rate ($\mu g \cdot cm^{-2} \cdot min^{-1}$) for conventionally and zero tilled soils at tillering (July 22) in 1992.

Depth (cm)	Tillage Treatments		CV	P value
	Conventional	Zero		
2.5	0.30(35)[2]	0.30(36)	14.23	0.745
5.0	0.18(37)	0.25(35)	14.77	0.027
10.0	0.10(39)	0.11(36)	13.99	0.200
20.0	0.12(37)	0.12(35)	10.78	0.538

1 Mean value of off and on tire tracks was used for each tillage treatment
2 Values within parenthesis are percent gravimetric water content

The effects of compaction from wheel traffic on oxygen diffusion rate was determined at tillering in 1992. Oxygen diffusion rate was compared using combined data from conventionally and zero tilled plots (Table 48). All depths measured were found to have similar oxygen diffusion rates between on and off tire tracks (α=0.05) and were of the same magnitude as that found with tillage treatments.

Table 48. Oxygen diffusion rate ($\mu g \cdot cm^{-2} \cdot min^{-1}$) for on and off tire tracks at tillering (July 22) in 1992.

Depth (cm)	Tire Track Position[1]		CV	P value
	On	Off		
2.5	0.29(37)[1]	0.31(35)	28.49	0.720
5.0	0.20(38)	0.23(35)	36.91	0.473
10.0	0.09(39)	0.12(36)	48.42	0.306
20.0	0.11(37)	0.14(37)	21.70	0.108

1 Mean value of zero and conventional tillage treatments was used for each tire track treatment
2 Values within parenthesis are percent gravimetric water content

At anthesis, oxygen diffusion rate ranged from a maximum of 0.22 $\mu g \cdot cm^{-2} \cdot min^{-1}$ at 5.0 cm to a minimum of 0.09 $\mu g \cdot cm^{-2} \cdot min^{-1}$ at 20.0 cm for both conventionally and zero tilled treatments. The entire soil profile was below or near the critical oxygen diffusion rate needed for root growth (Table 49). Conventionally tilled plots were not found to differ significantly (α=0.05) from zero tilled plots for all depths sampled.

Table 49. Oxygen diffusion rate ($\mu g \cdot cm^{-2} \cdot min^{-1}$) for conventionally and zero tilled soils at anthesis (August 18) in 1992.

Depth	Tillage Treatments		CV	P value
(cm)	Conventional	Zero		
2.5	0.19(30)[2]	0.19(32)	24.45	0.965
5.0	0.22(34)	0.21(36)	30.65	0.825
10.0	0.12(36)	0.13(36)	37.97	0.564
20.0	0.09(34)	0.10(36)	25.49	0.571

1 Mean value of off and on tire tracks was used for each tillage treatment
2 Values within parenthesis are percent gravimetric water content

Tire traffic had virtually no effect on soil oxygen diffusion rates for all depths sampled at anthesis in 1992 (Table 50). However, areas compacted by the passage of the tractor at seeding had a significantly lower (α=0.05) oxygen diffusion rate at 20.0 cm than off tire track positions (0.09 $\mu g \cdot cm^{-2} \cdot min^{-1}$ versus 0.11 $\mu g \cdot cm^{-2} \cdot min^{-1}$). ODR on and off tire tracks were below the minimum diffusion rate required for root growth for all depths sampled at anthesis.

Table 50. Oxygen diffusion rate ($\mu g \cdot cm^{-2} \cdot min^{-1}$) for on and off tire tracks at anthesis (August 18) in 1992.

Depth	Tire Track Position[1]		CV	P value
(cm)	On	Off		
2.5	0.21(32)[2]	0.17(29)	55.21	0.525
5.0	0.20(37)	0.22(33)	16.60	0.262
10.0	0.11(38)	0.14(34)	25.84	0.100
20.0	0.09(37)	0.11(34)	12.87	0.024

1 Mean value of zero and conventional tillage treatments was used for each tire track treatment
2 Values within parenthesis are percent gravimetric water content

A significant interaction between tillage treatment and tire track treatments in ODR occurred at the 5.0 cm depth (Table 51). Zero tilled soils had oxygen diffusion rates of 0.22 $\mu g \cdot cm^{-2} \cdot min^{-1}$ and 0.18 $\mu g \cdot cm^{-2} \cdot min^{-1}$ for off and on tire tracks, respectively. Conventionally tilled soil had an oxygen diffusion rate of 0.21 $\mu g \cdot cm^{-2} \cdot min^{-1}$ off the tire tracks and 0.24 $\mu g \cdot cm^{-2} \cdot min^{-1}$ on the tire tracks.

Table 51. Oxygen diffusion rate ($\mu g \cdot cm^{-2} \cdot min^{-1}$) for conventionally and zero tilled soils, on and off tire tracks at anthesis (August 18) in 1992.

Depth	On Tire Tracks		Off Tire Tracks		Tillage x Track	
(cm)	Conventional	Zero	Conventional	Zero	CV	P Value
2.5	0.20(31)	0.22(34)	0.18(30)[1]	0.16(30)	44.36	0.697
5.0	0.22(35)	0.18(40)	0.21(34)	0.24(42)	7.35	0.025
10.0	0.12(37)	0.09(40)	0.12(35)	0.17(33)	35.76	0.148
20.0	0.09(35)	0.08(39)	0.10(34)	0.12(33)	19.30	0.426

1 Values within parenthesis are percent gravimetric water content

At harvest, no statistical difference (α=0.05) in oxygen diffusion rate was noted between conventionally and zero tilled treatments (Table 52). As before the oxygen diffusion rate was sufficient for plant growth only at the 2.5 cm depth. At the 5.0 cm depth, oxygen diffusion rate was 0.25 $\mu g \cdot cm^{-2} \cdot min^{-1}$ for conventional tillage and 0.17 $\mu g \cdot cm^{-2} \cdot min^{-1}$ for zero tillage treatments. Both conventional and zero tillage treatments had an ODR of 0.05 $\mu g \cdot cm^{-2} \cdot min^{-1}$ at 20.0 cm. Despite an increase in soil moisture at harvest when compared to anthesis, ODR increased. This may be attributed to a reduction in microbial respiration and to reduced demand for oxygen from plant roots at crop maturity.

Table 52. Oxygen diffusion rate ($\mu g \cdot cm^{-2} \cdot min^{-1}$) for conventionally and zero tilled soils at harvest (September 26) in 1992.

Depth (cm)	Tillage Treatments[1]		CV	P value
	Conventional	Zero		
2.5	0.39a(43)[2]	0.41a(46)	11.19	0.393
5.0	0.25a(48)	0.17a(47)	77.00	0.394
10.0	0.09a(44)	0.07a(44)	83.28	0.670
20.0	0.05a(40)	0.05a(40)	21.79	0.642

1 Mean value of off and on tire tracks was used for each tillage treatment
2 Values within parenthesis are percent gravimetric water content

Tire tracks had very little effect upon soil water content and the resulting oxygen diffusion rate at harvest (Table 53). On and off tire track treatments ranged from 0.40 $\mu g \cdot cm^{-2} \cdot min^{-1}$ to 0.5 $\mu g \cdot cm^{-2} \cdot min^{-1}$ in their oxygen diffusion rate. Differences between tire track treatments were slight and not significant (α=0.05).

Table 53. Oxygen diffusion rate ($\mu g \cdot cm^{-2} \cdot min^{-1}$) for on and off tire tracks at harvest (September 26) in 1992.

Depth (cm)	Tire Track Position[1]		CV	P value
	On	Off		
2.5	0.40(45)[2]	0.40(45)	16.26	0.998
5.0	0.22(47)	0.20(48)	42.43	0.825
10.0	0.07(45)	0.09(44)	30.81	0.252
20.0	0.05(40)	0.06(40)	33.42	0.356

1 Mean value of zero and conventional tillage treatments was used for each tire track treatment
2 Values within parenthesis are percent gravimetric water content

In summary, differences in ODR between treatments (tillage or tire track) were not significant in 1992 for most depths. This may be due to the high water contents and microporosity of these heavy clay soils, which would restrict movement of air into the soil from the atmosphere regardless of treatment. Oxygen diffusion rate for 1992 was below the minimum level needed for root growth at soil depths greater than 5.0 cm. Soil within the upper 5.0 cm of the soil was often at levels which would negatively affect root growth (0.2 to 0.4 $\mu g \cdot cm^{-2} \cdot min^{-1}$).

4.3 Effect of Treatments on Plant Characteristics

4.3.1 Root Density

The length of the 1992 growing season was reduced by the late date at which reseeding occurred. To ensure that a final harvest would be obtained, barley was seeded in 1992. Since wheat was used in 1991 direct comparisons of root growth between growing seasons was not possible.

Root density on conventionally tilled soils as determined using the core break method was 0.89 and 0.33 roots$\cdot$cm^{-3} at the 7.5 cm and 22.5 cm depth respectively. Zero tilled soils had root density of 1.14 and 0.32 roots$\cdot$cm^{-3} at the same depths. Differences between tillage treatments at the 7.5 cm depth was significant (α=0.05). The oxygen diffusion rate was lower on the conventionally tilled treatments than on the zero tilled treatments at emergence and tillering in 1992. Later in the growing season oxygen supply to roots did not vary significantly between tillage treatments. Poor aeration early in the season may have resulted in decreased root growth in the upper 15 cm of the soil profile.

The 22.5 cm soil depth showed little differences in root growth between conventionally and zero tilled soils. The oxygen diffusion rate at the 20.0 cm depth was below the minimum needed for root growth for all sample periods and treatments.

As in 1991, root growth occurred below 10.0 cm despite insufficient mean oxygen diffusion rates. Variability of oxygen diffusion rates was large (see CV for ODR) and areas within the soil may have been sufficient to support root growth. Since soil aeration can be improved near cracks and biopores within the soil (Bakker and Bronswijk, 1993), root growth may occur in these areas, thereby avoiding aeration stress.

Table 54. Barley root density (number of roots·cm^{-3}) for conventionally and zero tilled soils at crop maturity (September 26) in 1992.

Depth (cm)	Tillage Treatments		CV	P value
	Conventional	Zero		
7.5	0.89	1.14	8.36	0.025
22.5	0.33	0.32	25.14	0.856

4.3.2 Plant Characteristics and Yield

In the spring of 1992, spring wheat (Triticum aestivum cv. Katepewa) was seeded on May 15th. However, mechanical problems the seeding equipment resulted in poor crop emergence. The crop was terminated with glyphosate at the recommended rate on June 2. The entire plot was harrowed using an all terrain vehicle pulling a 1.2 m section of diamond tooth harrow to break up clods formed by the initial seeding operation. This delayed seeding 17

resulted in a shorter growing season and therefore the plot was reseeded to a faster maturing cereal, barley (Hordeum vulgare cv. Argyle). The research plot was reseeded on June 9.

Plant numbers for conventionally and zero tilled treatments (320 and 298 per m^2 respectively) indicated that differences in growing conditions between zero and conventionally tilled treatments prior to tillering were slight (Table 55). Tillers per plant on conventionally tilled soils (1.7) however were significantly higher than on zero tilled soils (1.5). This indicates that growing conditions at tillering favored plant growth on conventionally tilled treatments over zero tilled treatments. An increase in tillers, however, did not result in higher plant weights for conventionally tilled treatments (Table 55). Differences in tillers per plant may be due to a trend for lower soil strength on conventional than on zero tillage treatments at tillering (Table 40).

Table 55. Numbers of plants, tillers, and dry matter yield for conventionally and zero tilled soils at tillering (July 22) in 1992.

Depth (cm)	Tillage Treatments[1]		CV	P value
	Conventional	Zero		
Number of plants (m^{-2})	298	320	17.58	0.489
Tillers/Plant	1.7	1.5	5.65	0.029
Plant Weight ($g \cdot m^{-2}$)	233	226	66.55	0.935

1 Mean value of off and on tire tracks was used for each tillage treatment

Differences in plant weight due to tillage treatments indicated that between the end of tillering and anthesis zero tilled soils had a significant advantage over conventionally tilled soils with regards to plant growth. Yields were 321 $g \cdot m^{-2}$ and 604 $g \cdot m^{-2}$ for conventionally and zero tilled soils, respectively (Table 56). Zero tilled soils had a higher number spikes per m^2 than conventionally tilled soils (309 and 254, respectively). Differences in plant weight and number of heads were statistically significant (α=0.05). Soil physical properties measured at anthesis cannot explain the large differences in plant growth between conventionally and zero tilled soils.

Table 56. Numbers of barley spikes and dry matter yield for conventionally and zero tilled soils at anthesis (August 18) in 1992.

Depth (cm)	Tillage Treatments[1]		CV	P value
	Conventional	Zero		
Number of Spikes (m^{-2})	254	309	11.16	0.040
Plant Weight ($g \cdot m^{-2}$)	321	604	26.44	0.020

1 Mean value of off and on tire tracks was used for each tillage treatment

As with harvest in 1991, differences in growth during the season did not result in significantly higher yields. Differences in the number of spikes per square metre for conventionally and zero tilled soils at anthesis were not apparent at harvest (Table 57). Zero tilled treatments had lower grain (137 g) and straw yield (234 g) compared to conventionally tilled (165 g and 255 g). Thousand kernel weight did not differ conventional tillage (31.2 g) and zero tillage (30.6 g).

Table 57. Barley straw yield, grain yield, total dry matter yield, thousand kernel weight, and numbers of spikes for conventionally and zero tilled soils at harvest (September 26) in 1992.

	Tillage Treatments[1]		CV	P value
	Conventional	Zero		
Number of Spikes (m^{-2})	280	256	14.83	0.319
Grain Weight ($g \cdot m^{-2}$)	165	137	32.19	0.336
Straw Weight ($g \cdot m^{-2}$)	255	234	32.02	0.621
1000 kernel weight (g)	31.2	30.6	7.28	0.601

1 Mean value of off and on tire tracks was used for each tillage treatment

As the 1992 season progressed, a visible decrease in plant growth occurred in areas affected by wheel traffic versus those that were not. Plant growth was not only decrease but also delayed in development. Plant data was therefore obtained on and off the tire tracks at tillering, anthesis, and harvest in 1992.

Seedling establishment and survival as indicated by plant numbers at tillering appeared not to be significantly affected by tire traffic (Table 58). Tillers per plant and plant weights however were found to be significantly (α=0.05) reduced by tire traffic. Tillers per plant was 1.4 on tire tracks and 1.8 off tire tracks. Areas traveled over by the tractor at seeding had total plant weights of 147 $g \cdot m^{-2}$, which was 53 % of the areas not affected by wheel traffic. Oussible et al. (1993) also found that compaction limited tillering in wheat by 20%. They found that higher soil strength and bulk densities restricted root growth in the compacted treatment and resulted in decrease tillering. In this experiment, soil strength near the surface for areas subjected to wheel traffic was higher (though not significantly) than areas not traveled on. None of the other measured soil parameters varied with tire track treatments.

Table 58. Number of barley plants, tillers, and dry matter yield for on and off tire tracks at tillering (July 22) in 1992.

Depth (cm)	Tire Track Position[1]		CV	P value
	Off	On		
Number of plants (m^{-2})	335	283	23.45	0.245
Tillers/Plant	1.8	1.4	12.08	0.025
Plant Weight ($g \cdot m^{-2}$)	312	147	19.16	0.005

1 Mean value of zero and conventional tillage treatments was used for each tire track treatment

Crop growth on tire tracks continued to be depressed when compared to off tire tracks at anthesis. A trend ($\alpha=0.1$) toward higher number of spikes off tire tracks than on tire tracks was evident. Reductions in plant weights on tire tracks were similar to those found at tillering (Table 59).

Table 59. Numbers of barley spikes and dry matter yield for on and off tire track position at anthesis (August 18) in 1992.

Depth (cm)	Tire Track Position[1]		CV	P value
	Off	On		
Number of spikes (m^{-2})	311	252	17.99	0.103
Plant Weight ($g \cdot m^{-2}$)	625	299	33.71	0.025

1 Mean value of zero and conventional tillage treatments was used for each tire track treatment

Effects due to tire tracks on crop growth at harvest were similar to those reported at tillering and anthesis. Off tire track positions had 16% more barley heads than on tire track positions. However, the difference was not statistically significant

(Table 60). Straw weight was significantly (α=0.5) higher off tire track than on tire track positions. Grain yields on tire tracks were not significantly (α=0.5) lower than off tire tracks despite being only 63% of the non-tracked area. However, a strong trend did exist (P=0.6). Results obtained by Henderson (1991) also found that barley yields were reduced by approximately half due to compaction from tire tracks. Barley yields have also been reported to be significantly decreased by compaction on chiseled plowed and direct drilled soils due to water logging during seedling establishment (Campbell et al. 1986). Since sampling did not occur on and off tire tracks prior to tillering, it was not possible to determine if that was also true in this experiment. Higher thousand kernel weight off tire tracks versus on tire tracks indicate that during seed filling, plants growing on the tire tracks were restricted by their environment. Soil physical properties measured at anthesis or harvest do not explain why kernel weight would vary significantly.

Table 60. Barley straw yield, grain yield, total dry matter yield and numbers of spikes for on and off tire track position at harvest (September 26) in 1992.

Depth (cm)	Tire Track Position[1]		CV	P value
	On	Off		
Number of Spikes (m^{-2})	248	287	12.64	0.107
Grain Weight ($g \cdot m^{-2}$)	118	185	30.58	0.060
Straw Weight ($g \cdot m^{-2}$)	192	297	21.21	0.027
1000 kernel weight ($g \cdot m^{-2}$)	30.1	331.7	2.8	0.031

Summary and Conclusions

Soil physical properties that directly affect plant growth are commonly found to be significantly altered by tillage. However, very few studies have attempted to study all four factors (soil temperature, aeration, strength, and water content) in a field situation. This research project investigated the effect of tillage and zero tillage upon soil physical properties and crop growth of a poorly drained heavy clay soil in Manitoba in 1991 and 1992.

In both years the research plot site was characterized by intense rainfall events and cooler than normal temperatures. This created a situation in which micro depressions within the plot area periodically became inundated with water. These areas then added greatly to spatial and temporal variability in plant growth and soil properties. Micro depressions are a common occurrence on this generally flat landscape region.

Soil temperature was not affected by tillage in either year studied. However the frequency with which measurements were obtained may not have been sufficient to detect daily and hourly fluctuations in soil temperature. In addition the date of seeding in both years may have been too late for detection of temperature differences often reported in the literature early in the growing season. Higher moisture contents near the surface of conventionally tilled soils in both years may have increased the volumetric heat capacity of conventionally tilled soils, thereby negating the benefits of reduced residue cover.

In 1991 there was no significant effect due to tillage on soil water content in the top 60.0 cm. Gravimetric soil moisture levels for both tillage treatments at seeding in 1992 had exceeded 50% and had also approached or exceeded field capacity. At this time zero tilled treatments had a lower gravimetric soil water content than did conventionally tilled treatments. Generally conventionally tilled soils had higher soil moisture levels than did zero tilled soils in 1992. However, statistically consistent differences in soil moisture did not occur in 1992.

Areas which were affected by tire traffic in 1992 showed no significant difference in soil moisture when compared to areas not subjected to wheel traffic. A difference in soil moisture was associated with significant interaction between tillage and tire track treatments. At crop maturity a similar interaction was also found for the same soil depths. In both sampling periods conventional tillage had an increase in soil moisture due to compaction from tire tracks. Zero tilled soils showed a decrease with compaction or remained unchanged.

Generally, soil strength was found to increase with depth and decreasing soil moisture. No consistently significant trends in soil strength were observed in this experiment. However, some observations can be made with regard to the effect of tillage treatments. During the 1991 and 1992 growing season zero tilled treatments tended to have higher soil strengths in the top 10.0 cm than tilled treatments. Soil strength differences may have been masked by high moisture contents in 1991 and 1992. Below the tilled layer mean soil strength was greater for zero tilled plots. However, this difference was significant only at crop maturity in 1991 and emergence in 1992.

The effects of traffic on the plots was also determined in areas traveled over by the tractor tires during seeding in 1992. Soil strength was generally unaffected by tire traffic. Only at anthesis in 1992 was there a significant difference between on and off tire tracks. Soil strength did not exceed 2.0 MPa during the experiment for all treatments and as such would not by itself have completely restricted root growth at any depth or time during the experiment.

Soil aeration was often found to be limiting (ODR values between 0.2 to 0.4 $\mu g \cdot cm^{-2} \cdot min^{-1}$) and restrictive to root growth in the top 10.0 cm of the soil profile.

Oxygen supply below 10.0 cm was not sufficient to allow root growth for all sampling times and treatments (ODR values below 0.2 $\mu g \cdot cm^{-2} \cdot min^{-1}$). This would indicate that at soil moisture contents encountered during this experiment may have reduced root growth through poor soil aeration and therefore reduce the volume of soil explored by the plant roots. While mean oxygen diffusion rates were low, the variability was also great and areas within the soil existed that were more favorable to root growth at all depths. Generally, tillage and tire tracks had no significant effect on oxygen diffusion rate in 1991 or 1992.

Measurements of wheat root densities in 1991 indicated no clear difference between tillage systems used in this study. In 1992, barley had a lower root density at 7.5 cm for conventionally tilled than zero tilled treatments. This was probably due to higher soil moisture contents in the conventionally tilled plots early in the season. In addition higher antecedent soil moisture contents early in the season increased the possibility and duration of surface ponding. This would have created periods of high soil aeration stress at times when it was physically impossible to monitor the plots.

Data for above ground plant growth in 1991 and 1992 was highly variable. High levels of variability can be attributed to lower than normal temperatures, ponding of water in micro depressions, and spatial variability. Results indicated that plant growth in 1991 generally favored conventional tillage early in the growing season. This did not result in higher yields at harvest. Plant growth on zero tilled treatments were equal or greater than conventionally tilled treatments throughout the 1992 growing season. Barley yields were reduced by 25 to 50% on the tire tracks throughout the entire 1992 growing season.

Plant growth reflects the integration of the many factors that constitute the environment in which it occurs and not all of these were monitored in this experiment. Soil properties can vary greatly with time and position within the landscape or soil profile. This was illustrated in the variability often found in the properties monitored in this experiment. These properties should be monitored intensely to eliminate some of the temporal variability and better describe the soil environment in which the plant exists. The results do indicate that soil moisture content and its effect on soil aeration is an important aspect of crop production on these poorly drained clay soils.

It is concluded that on these poorly drained heavy clay soils neither zero or conventionally tilled treatments provided a distinct advantage with regards to cereal grain production in 1991 or 1992 and that intense rainfall events can result in major variation in crop growth. These results are in agreement with other studies performed on clay soils, utilizing similar field equipment and an established zero tillage treatment (Martino 1991, Grant and Lafond 1993, Tessier et al. 1990).

The growth and yield of the barley crop on the tire tracks was significantly reduced from off tire tracks for the entire 1992 growing season. Since this study used commercial equipment commonly utilized by agricultural producers the results of the tire compaction may have direct implications for commercial operations. This would mean that 25% of the field was at a disadvantage due to the effect of tire tracks and may result in significant reductions in yield. A direct relationship between soil physical properties and tire compaction was not demonstrated. The dramatic differences in yield warrant further investigation into the cause and extent of wheel traffic effects on cereal crop production on poorly drained heavy clay soils.

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Appendix A. Soil and air temperatures (° C) for the research site near Brunkild and maximum air temperatures (°C) for the climatological station at Starbuck in 1991.

Date	Days since seeding	Soil Temperature								Maximum Air Temperature		
		Conventional Tillage				Zero Tillage				Brunkild	Starbuck	
		2.5 cm	5.0 cm	10.0 cm	20.0 cm	2.5 cm	5.0 cm	10.0 cm	20.0 cm	1991	1991	Normal
May 14	0	22.9	17.0	12.3	10.1	23.2	17.4	13.1	10.9	34.5	31.0	19.6
May 15	1	17.3	14.3	11.8	10.8	17.3	14.4	12.0	11.1	22.0	18.0	19.0
May 21	7	21.5	17.3	14.1	12.3	22.1	17.6	14.4	12.5	27.8	28.5	22.4
May 24	10	21.5	16.8	14.6	13.4	21.6	17.2	14.6	13.6	22.0	22.5	21.6
May 27	13	21.9	18.4	15.5	14.2	22.2	18.3	15.4	14.3	22.8	23.0	23.4
May 30	16	26.3	20.8	16.2	14.9	24.7	20.6	16.2	14.8	31.8	31.0	22.5
June 4	21	17.4	16.3	15.7	15.2	17.4	16.1	15.6	15.1	21.6	26.0	22.7
June 7	24	22.5	19.4	17.1	15.5	23.4	19.6	17.1	15.5	29.4	29.0	22.5
June 10	27	21.4	18.6	15.9	15.1	20.3	17.9	15.9	15.3	24.4	25.0	23.5
June 14	31	19.9	18.5	17.3	16.8	20.7	19.0	17.6	16.8	24.8	26.5	22.4
June 17	34	21.9	19.7	17.9	17.1	22.9	20.4	18.3	17.1	26.0	27.5	23.2
June 21	38	19.2	17.6	16.4	16.6	21.5	18.5	16.6	16.5	22.0	24.0	24.5
June 24	41	20.5	18.6	17.0	16.4	22.0	19.4	17.1	16.4	25.9	29.5	24.9
June 28	45	17.1	17.1	16.9	17.3	17.6	17.3	17.3	17.6	19.1	19.0	24.6
July 2	49	17.9	17.8	17.4	17.2	17.9	17.6	17.3	17.3	19.3	16.0	25.3
July 5	52	17.4	17.3	16.9	16.7	18.1	17.6	17.4	16.9	20.6	24.0	26.7
July 9	56	18.4	17.6	17.1	16.8	19.6	18.4	17.6	17.1	24.9	22.5	26.5
July 12	59	18.9	18.4	17.7	17.4	19.7	19.0	18.4	17.9	24.3	31.0	27.3
July 16	63	22.1	20.9	19.8	18.9	23.6	21.9	20.7	19.6	33.2	28.0	27.2
July 19	66	20.4	19.8	19.4	19.3	21.8	20.5	19.9	19.6	27.1	26.0	25.7
July 22	70	19.5	18.1	18.1	18.4	19.7	18.7	18.4	18.6	24.5	25.0	25.7
July 25	73	19.3	17.9	16.9	17.2	20.2	18.5	17.3	17.3	25.3	32.0	26.0
July 29	77	19.8	18.7	17.9	17.6	20.6	19.4	18.3	17.4	28.1	19.0	25.8
August 1	80	18.3	18.0	17.8	17.9	18.3	18.0	17.8	17.9	19.7	24.0	26.2
August 5	84	17.3	17.0	16.8	16.9	17.4	17.1	16.8	16.9	29.3	29.0	27.7
August 8	87	20.3	18.7	17.5	17.5	21.9	19.3	17.6	17.5	32.8	31.5	24.8
August 12	91	21.8	20.1	19.2	18.9	22.9	20.4	19.1	18.9	34.3	30.5	25.9
August 18	97	24.8	21.8	19.7	19.3	25.8	22.3	19.9	19.0	35.4		26.6

Appendix B. Daily and cumulative precipitation (mm) recorded at the research site near Brunkild in 1991.

Date	Days since seeding	Precipitation	
		Daily	Cumulative
May 14	0	0	0
May 15	1	4	4
May 16	2	0	4
May 17	3	0	4
May 18	4	0	4
May 19	5	0	4
May 20	6	0	4
May 21	7	0	4
May 22	8	0	4
May 23	9	0	4
May 24	10	0	4
May 25	11	0	4
May 26	12	0	4
May 27	13	0	4
May 28	14	0	4
May 29	15	1	5
May 30	16	7	12
May 31	17	18	30
June 1	18	0	30
June 2	19	0	30
June 3	20	0	30
June 4	21	0	30
June 5	22	0	30
June 6	23	1	31
June 7	24	0	31
June 8	25	4	35
June 9	26	2	37
June 10	27	0	37
June 11	28	0	37
June 12	29	0	37
June 13	30	61	98
June 14	31	4	102
June 15	32	0	102
June 16	33	0	102
June 17	34	0	102
June 18	35	0	102
June 19	36	0	102
June 20	37	0	102
June 21	38	0	102

Appendix B (cont). Daily and cumulative precipitation (mm) recorded at the research site near Brunkild in 1991.

Date	Days since seeding	Precipitation Daily	Precipitation Cumulative
June 22	39	0	102
June 23	40	0	102
June 24	41	55	157
June 25	42	8	165
June 26	43	2	167
June 27	44	0	167
June 28	45	0	167
June 29	46	0	167
June 30	47	20	187
July 1	48	4	191
July 2	49	27	218
July 3	50	4	222
July 4	51	0	222
July 5	52	19	241
July 6	53	1	242
July 7	54	1	243
July 8	55	0	243
July 9	56	0	243
July 10	57	0	243
July 11	58	6	249
July 12	59	19	268
July 13	60	0	268
July 14	61	0	268
July 15	62	0	268
July 16	63	13	281
July 17	64	0	281
July 18	65	5	286
July 19	66	8	294
July 20	67	0	294
July 21	68	0	294
July 22	69	0	294
July 23	70	4	298
July 24	71	3	301
July 25	72	0	301
July 26	73	0	301
July 27	74	0	301
July 28	75	0	301
July 29	76	0	301

Appendix B (cont). Daily and cumulative precipitation (mm) recorded at the research site near Brunkild in 1991.

	Days since	Precipitation	
Date	seeding	Daily	Cumulative
July 30	77	1	302
July 31	78	0	302
August 1	79	0	302
August 2	80	0	302
August 3	81	0	302
August 4	82	0	302
August 5	83	3	305
August 6	84	4	309
August 7	85	0	309
August 8	86	0	309
August 9	87	0	309
August 10	88	0	309
August 11	89	0	309
August 12	90	0	309
August 13	91	0	309
August 14	92	0	309
August 15	93	0	309
August 16	94	0	309
August 17	95	0	309
August 18	96	0	309
August 19	97	0	309

Appendix C. Soil and air temperatures (°C) for the research site near Brunkild and maximum air temperatures (°C) for the climatological station at Starbuck in 1992.

Date	Days since seeding	Soil Temperature								Maximum Air Temperature		
		Conventional Tillage				Zero Tillage				Brunkild	Starbuck	
		2.5 CM	5.0 CM	10.0 CM	20.0 CM	2.5 CM	5.0 CM	10.0 CM	20.0 CM	1992	1992	Normal
June 12	3.0	24.5	21.7	18.3	15.7	25.6	21.8	18.2	15.6	27.5		23.5
June 15	6.0	21.6	18.8	16.1	14.6	22.1	18.8	16.0	14.5	25.5		22.8
June 18	9.0	14.2	14.5	14.6	14.7	14.3	14.3	14.4	14.6	11.4		24.7
June 22	13.0	16.0	14.8	13.6	13.2	15.9	14.5	13.5	13.2	20.7	25.0	24.2
June 26	17.0	19.6	17.4	14.8	13.3	20.2	17.6	14.7	13.3	24.7	22.5	24.4
June 29	20.0	20.1	18.7	15.1	14.0	20.3	17.4	14.9	13.9	20.5	19.0	25.7
July 3	24.0	14.5	14.0	13.5	13.2	14.3	13.8	13.3	13.4	13.1	13.5	26.6
July 7	28.0	22.3	20.2	16.8	14.5	21.6	19.6	16.2	14.7	27.5	26.5	26.4
July 10	31.0	19.2	17.6	16.0	15.0	19.9	17.8	15.8	15.0	23.5	19.0	26.5
July 13	34.0	22.9	20.4	17.6	16.0	22.4	19.8	17.3	15.9	25.2	26.5	26.3
July 16	37.0	22.5	20.2	17.6	16.2	22.5	19.9	17.5	16.1	23.4	22.0	27.2
July 21	42.0	19.9	18.1	16.2	15.2	19.8	17.9	15.9	15.0	22.6	23.0	26.3
July 23	44.0	21.5	19.8	17.1	15.8	21.3	19.1	16.8	15.6	27.6	26.0	25.7
July 28	49.0	19.0	18.0	16.4	15.7	19.3	17.7	16.2	15.6	23.1	19.5	26.8
July 31	52.0	19.0	18.8	16.9	16.0	20.0	18.6	16.8	15.8	22.1	29.0	26.1
August 3	55.0	17.9	16.6	15.5	15.1	19.0	17.0	15.7	15.5	19.7	20.5	27.1
August 6	58.0	22.4	20.0	17.3	15.9	22.4	19.7	17.1	15.7	29.5	26.0	27.7
August 10	62.0	17.6	17.4	16.7	16.9	17.5	17.2	16.8	16.7	17.4	23.0	25.9
August 14	66.0	22.4	19.7	17.0	16.0	22.4	19.3	16.8	13.9	31.3	29.0	25.1
August 18	70.0	23.2	20.3	17.6	16.6	23.3	19.8	17.1	16.3	31.7	26.0	25.5
August 21	73.0	20.9	19.2	17.1	16.0	21.0	18.7	16.8	16.1	30.0	22.0	23.4
August 25	76.0	18.4	16.4	14.5	14.3	17.8	15.8	14.3	14.2	21.7	14.0	26.7
August 28	79.0	21.3	18.6	15.7	14.4	20.7	17.9	15.4	15.1	28.4	19.0	24.5
September 1	83.0	16.1	14.9	13.6	13.3	16.1	14.6	13.5	13.3	21.0	15.5	22.8
September 4	86.0	19.6	17.4	15.2	14.3	19.3	17.0	14.9	14.1	25.6	19.5	23.8
September 7	89.0	14.0	12.6	11.4	11.8	13.7	12.2	11.2	11.7	21.0	13.0	21.4
September 11	93.0	16.0	13.9	12.1	11.9	15.9	13.8	12.1	11.9	26.7	17.0	20.8
September 14	96.0	14.7	13.5	12.6	12.8	14.8	13.4	12.6	12.7	19.6	19.5	17.8
September 18	100.0	11.8	10.9	10.3	10.9	11.9	10.8	10.4	10.9	13.7	13.0	20.1
September 21	103.0	12.6	12.1	11.7	11.8	12.8	12.2	11.8	11.8	12.6	23.5	17.2
September 25	106.0	16.4	14.7	12.9	12.2	16.3	14.5	12.9	12.1	26.6	21.5	16.3
September 28	109.0	10.4	9.1	8.4	9.5	10.5	9.1	8.5	9.4	14.1	8.0	14.6
October 2	113.0	15.4	13.4	11.6	11.0	15.5	13.2	11.5	10.9	27.0	24.5	16.4
October 5	116.0	14.6	13.1	11.8	11.4	14.5	12.9	11.7	11.2	21.7	24.0	14.4

Appendix D. Daily and cumulative precipitation (mm) recorded at the research site near Brunkild in 1992.

Date	Days since seeding	Precipitation	
		Daily	Cumulative
June 9	0	0	0
June 10	1	0	0
June 11	2	0	0
June 12	3	0	0
June 13	4	0	0
June 14	5	0	0
June 15	6	7	7
June 16	7	24	31
June 17	8	0	31
June 18	9	0	31
June 19	10	0	31
June 20	11	0	31
June 21	12	0	31
June 22	13	3	35
June 23	14	7	42
June 24	15	0	42
June 25	16	0	42
June 26	17	0	42
June 27	18	4	42
June 28	19	0	42
June 29	20	0	42
June 30	21	11	57
July 1	22	1	58
July 2	23	12	70
July 3	24	3	73
July 4	25	0	73
July 5	26	0	73
July 6	27	0	73
July 7	28	0	73
July 8	29	0	73
July 9	30	0	73
July 10	31	1	74
July 11	32	0	74
July 12	33	0	74
July 13	34	4	78
July 14	35	0	78
July 15	36	0	78

Appendix D (cont). Daily and cumulative precipitation (mm) recorded at the research site near Brunkild in 1992.

Date	Days since seeding	Precipitation	
		Daily	Cumulative
July 16	37	10	88
July 17	38	0	88
July 18	39	0	88
July 19	40	0	88
July 20	41	0	88
July 21	42	0	88
July 22	43	0	88
July 23	44	0	88
July 24	45	1	89
July 25	46	0	89
July 26	47	11	100
July 27	48	1	101
July 28	49	0	101
July 29	50	0	101
July 30	51	1	102
July 31	52	0	102
August 1	53	1	103
August 2	54	6	109
August 3	55	0	109
August 4	56	0	109
August 5	57	0	109
August 6	58	0	109
August 7	59	0	109
August 8	60	0	109
August 9	61	36	145
August 10	62	0	145
August 11	63	0	145
August 12	64	0	145
August 13	65	0	145
August 14	66	0	145
August 15	67	0	145
August 16	68	0	145
August 17	69	0	145
August 18	70	0	145
August 19	71	0	145
August 20	72	0	145
August 21	73	0	145

Appendix D (cont). Daily and cumulative precipitation (mm) recorded at the research site near Brunkild in 1992.

Date	Days since seeding	Precipitation	
		Daily	Cumulative
August 22	74	0	145
August 23	75	0	145
August 24	76	1	146
August 25	77	0	146
August 26	78	0	146
August 27	79	0	146
August 28	80	0	146
August 29	81	0	146
August 30	82	0	146
August 31	83	2	148
September 1	84	28	176
September 2	85	0	176
September 3	86	0	176
September 4	87	3	179
September 5	88	0	179
September 6	89	0	179
September 7	90	3	182
September 8	91	4	186
September 9	92	0	186
September 10	93	0	186
September 11	94	14	200
September 12	95	0	200
September 13	96	0	200
September 14	97	0	200
September 15	98	1	201
September 16	99	2	203
September 17	100	0	203
September 18	101	8	211
September 19	102	0	211
September 20	103	0	211
September 21	104	0	211
September 22	105	0	211
September 23	106	0	211
September 24	107	0	211
September 25	108	0	211
September 26	109	0	211
September 27	110	2	213

Appendix D (cont). Daily and cumulative precipitation (mm) recorded at the research site near Brunkild in 1992.

Date	Days since seeding	Precipitation	
		Daily	Cumulative
September 28	111	0	213
September 29	112	0	213
September 30	113	0	213
October 1	114	0	213
October 2	115	0	213
October 3	116	0	213
October 4	117	0	213
October 5	118	1	214
October 6	119	0	214

Appendix E. Pore size distribution (% of core volume) at the 5.0, 10.0 and 20.0 cm soil depth for conventionally and zero tilled soils.

Pore volume at various water potentials (suction) as a percent of core volume[1] at the 5.0 cm soil depth for conventionally and zero tilled soils.

Suction (KPa)	Tillage Treatments		CV	P Value
	Conventional	Zero		
0.1 - 1.0	3.6	3.3	26.7	0.431
1.0 - 2.5	4.3	4.0	45.3	0.617
2.5 - 4.9	2.5	2.6	66.0	0.876
4.9 -9.8	3.4	3.7	25.5	0.451
9.8 - 33.3	6.1	5.6	13.0	0.140
33.3 - 49.9	2.7	2.5	22.9	0.552
49.9 - 99.8	4.0	4.2	10.7	0.821
99.8 - 1497.7	16.5	16.2	5.7	0.561
1497.7 - Oven Dry	30.9	33.8	34.5	0.667
Total	73.9	76.1	16.18	0.813

1 core volume = 19.11 ml

Pore volume at various water potentials (suction) as a percent of core volume[1] at the 10.0 cm soil depth for conventionally and zero tilled soils.

Suction (KPa)	Tillage Treatments		CV	P Value
	Conventional	Zero		
0.1 - 1.0	3.2	3.4	24.0	0.623
1.0 - 2.5	2.7	3.1	34.1	0.457
2.5 - 4.9	1.4	1.4	38.7	0.981
4.9 -9.8	2.6	2.5	28.3	0.704
9.8 - 33.3	4.8	4.5	16.7	0.365
33.3 - 49.9	2.6	2.5	29.7	0.749
49.9 - 99.8	3.4	3.8	23.8	0.440
99.8 - 1497.7	14.5	15.3	9.3	0.305
1497.7 - Oven Dry	33.2	34.7	19.9	0.674
Total	68.6	71.1	9.19	0.454

1 core volume = 19.11 ml

Appendix E (cont). Pore size distribution (% of core volume) at the 5.0, 10.0 and 20.0 cm soil depth for conventionally and zero tilled soils.

Pore volume at various water potentials (suction) as a percent of core volume[1] at the 20.0 cm soil depth for conventionally and zero tilled soils.

Suction (KPa)	Tillage Treatments		CV	P Value
	Conventional	Zero		
0.1 - 1.0	3.3	3.3	26.6	0.954
1.0 - 2.5	3.0	2.8	13.1	0.399
2.5 - 4.9	1.7	1.4	17.9	0.094
4.9 -9.8	2.5	2.7	24.3	0.523
9.8 - 33.3	4.2	3.9	15.3	0.433
33.3 - 49.9	2.7	2.3	24.5	0.273
49.9 - 99.8	3.9	3.6	11.7	0.167
99.8 - 1497.7	13.0	12.3	9.4	0.403
1497.7 - Oven Dry	40.5	34.5	26.3	0.273
Total	74.7	67.6	14.31	0.231

1 core volume = 19.11 ml

Appendix F. Soil strength (MPa) for on and off tire tracks for conventionally and zero tilled soils at tillering, anthesis, and harvest in 1992.

Soil strength (MPa) for on and off tire tracks for conventionally and zero tilled soils at tillering in 1992.

Depth	Off Tire Tracks		On Tire Tracks		Tillage x Track	
(cm)	Conventional	Zero	Conventional	Zero	CV	P Value
3.5	0.08	0.10	0.09	0.09	20.67	0.509
7.0	0.44	0.93	0.67	0.79	25.12	0.129
10.5	1.01	1.54	1.38	1.58	14.11	0.185
14.0	1.09	1.49	1.42	1.52	26.09	0.465
17.5	0.99	1.30	1.21	1.23	28.41	0.461
21.0	0.91	1.16	1.11	1.07	22.34	0.319
24.5	0.89	1.11	1.04	1.03	15.35	0.235
28.0	0.93	1.05	1.03	1.03	9.92	0.302
31.5	0.95	1.05	1.04	1.05	6.39	0.251
35.0	0.94	1.09	1.04	1.10	4.61	0.153
38.5	0.99	1.13	1.07	1.16	1.98	0.146
42.0	1.02	1.15	1.08	1.17	2.89	0.247
45.5	1.04	1.14	1.09	1.17	4.13	0.618
49.0	1.04	1.16	1.08	1.19	4.29	0.846
52.5	1.10	1.23	1.10	1.20	4.14	0.617

Soil strength (MPa) for on and off tire tracks for both tillage treatments at anthesis in 1992.

Depth	Off Tire Tracks		On Tire Tracks		Tillage x Track	
(cm)	Conventional	Zero	Conventional	Zero	CV	P Value
3.5	0.12	0.10	0.10	0.11	20.67	0.404
7.0	0.61	0.69	0.75	0.78	25.12	0.827
10.5	1.34	1.62	1.70	1.58	14.11	0.432
14.0	1.76	1.82	1.67	1.74	26.09	0.963
17.5	1.78	1.84	1.67	1.83	28.41	0.839
21.0	1.76	1.80	1.56	1.62	22.34	0.945
24.5	1.76	1.79	1.45	1.63	15.35	0.543
28.0	1.73	1.87	1.40	1.62	9.92	0.672
31.5	1.70	1.92	1.37	1.61	6.39	0.961
35.0	1.67	1.93	1.39	1.57	4.61	0.828
38.5	1.60	1.92	1.39	1.55	1.98	0.677
42.0	1.53	1.83	1.36	1.57	2.89	0.818
45.5	1.50	1.75	1.34	1.51	4.13	0.824
49.0	1.50	1.65	1.37	1.41	4.29	0.878
52.5	1.56	1.68	1.38	1.52	4.14	0.956

Appendix F (cont.). Soil strength (MPa) for on and off tire tracks for conventionally and zero tilled soils at tillering, anthesis, and harvest in 1992.

Soil strength (MPa) for on and off tire tracks for both tillage treatments at harvest in 1992.

Depth	Off Tire Tracks		On Tire Tracks		Tillage x Track	
(cm)	Conventional	Zero	Conventional	Zero	CV	P Value
3.5	0.14	0.18	0.15	0.16	14.24	0.219
7.0	0.44	0.66	0.54	0.54	18.22	0.119
10.5	0.65	0.88	0.74	0.89	47.96	0.492
14.0	0.81	0.97	0.82	0.98	8.18	0.905
17.5	0.94	1.02	0.89	1.02	8.56	0.648
21.0	0.98	1.05	0.88	1.04	8.52	0.412
24.5	1.02	1.08	0.91	1.09	10.05	0.384
28.0	1.08	1.16	0.95	1.12	13.35	0.570
31.5	1.10	1.26	1.00	1.19	16.11	0.909
35.0	1.12	1.35	1.04	1.24	16.32	0.899
38.5	1.14	1.40	1.07	1.27	13.35	0.765
42.0	1.14	1.40	1.09	1.28	9.81	0.600
45.5	1.17	1.40	1.13	1.31	9.83	0.664
49.0	1.17	1.38	1.13	1.28	11.72	0.694
52.5	1.18	1.34	1.14	1.29	10.14	0.911

Appendix G. Oxygen diffusion rate ($\mu g \cdot cm^{-2} \cdot min^{-1}$) for conventionally and zero tilled soils, on and off tire tracks at tillering and harvest in 1992.

Oxygen diffusion rate ($\mu g \cdot cm^{-2} \cdot min^{-1}$) for conventionally and zero tilled soils, on and off tire tracks at tillering in 1992.

Depth	Off Tire Tracks		On Tire Tracks		Tillage x Track	
(cm)	Conventional	Zero	Conventional	Zero		P Value
2.5	0.31(34)[1]	0.31(35)	0.03(38)	0.28(37)	12.05	0.519
5.0	0.21(37)	0.25(32)	0.16(38)	0.24(38)	25.49	0.504
10.0	0.10(38)	0.14(35)	0.09(40)	0.08(37)	45.24	0.401
20.0	0.14(38)	0.13(36)	0.11(37)	0.10(36)	8.24	0.293

1Values within parenthesis are percent gravimetric water content

Oxygen diffusion rate ($\mu g \cdot cm^{-2} \cdot min^{-1}$) for conventionally and zero tilled soils, on and off tire tracks at harvest in 1992.

Depth	Off Tire Tracks		On Tire Tracks		Tillage x Track	
(cm)	Conventional	Zero	Conventional	Zero		P Value
2.5	0.38(43.8)[1]	0.42(46.7)	0.40(42.8)	0.40(46.1)	17.00	0.534
5.0	0.27(47.9)	0.14(46.9)	0.23(47.9)	0.20(47.0)	46.18	0.330
10.0	0.11(44.0)	0.07(43.6)	0.06(44.4)	0.08(44.8)	24.21	0.233
20.0	0.06(41.1)	0.06(39.7)	0.05(39.5)	0.05(41.1)	26.45	0.863

Appendix H. Number of barley plants, tillers, and dry matter yield for conventionally and zero tilled soils, on and off tire tracks at tillering in 1992.

	Off Tire Tracks		On Tire Tracks		Tillage x Track	
	Conventional	Zero	Conventional	Zero	CV	P Value
Number of plants (m^{-2})	344.6	325.5	251.9	313.7	14.96	0.178
Tillers/Plant	1.80	1.72	1.50	1.24	18.79	0.574
Plant Weight (gm^{-2})	333.7	291.0	132.7	161.8	16.71	0.158

Appendix I. Number of barley spikes and dry matter yield for conventionally and zero tilled soils, on and off tire tracks at anthesis in 1992.

	Off Tire Tracks		On Tire Tracks		Tillage x Track	
	Conventional	Zero	Conventional	Zero	CV	P Value
Number of Spikes (m^{-2})	277.3	344.1	230.9	273.2	19.47	0.685
Plant Weight (gm^{-2})	395.5	854.7	246.0	352.2	32.14	0.098

Appendix J. Barley straw yield, grain yield, total dry matter yield and numbers of spikes for conventionally and zero tilled soils, on and off tire tracks at harvest in 1992.

	Off Tire Tracks		On Tire Tracks		Tillage x Track	
	Conventional	Zero	Conventional	Zero	CV	P Value
Number of Spikes (m^{-2})	295.9	277.8	262.7	233.6	8.83	0.676
Grain Weight (gm^{-2})	206.7	163.3	123.0	110.8	18.35	0.344
Straw Weight (gm^{-2})	316.5	276.5	193.5	190.5	22.85	0.555
1000 kernel weight (g)	31.7	30.8	30.8	29.3	5.39	0.396