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THE LONG-TERM EFFECTS OF TILLAGE AND RESIDUE MANAGEMENT ON THE SOIL PHYSICAL ENVIRONMENT AND ON BARLEY GROWTH

BY

© BALDEV SINGH

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled THE LONG-TERM EFFECTS OF TILLAGE AND RESIDUE MANAGEMENT ON THE SOIL PHYSICAL ENVIRONMENT AND ON BARLEY GROWTH submitted by BALDEV SINGH in partial fulfillment of the requirements for the degree of DOCTOR OF PHILOSOPHY in SOIL PHYSICS.

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Date: Nov 16, 1990

DEDICATION

I dedicate this thesis to my parents Mrs. Saran Kaur and Dr. Harbax Singh, and to my wife Swarnjit, and my children Rajbir and Ravijot. They have always provided me encouragement and loving support.

ABSTRACT

The soil physical response to reduced and no-tillage systems is generally unquantified on the Canadian prairies. This study quantified the effects of three long-term tillage-residue systems on the soil environment and barley growth during the 9th and 10th year after treatment initiation on a fine-textured, well-aggregated and well-drained Typic Cryoboroll (Black Chernozemic) at Ellerslie, Alberta (subhumid, cryoboreal). The treatments were: no-tillage with surface straw; rototillage to a 10-cm depth with straw incorporated; and rototillage to a 10-cm depth after straw was removed.

The no till+straw treatment provided the highest residue cover, and had a more stable though lower surface roughness, larger average aggregate size (dry and water-stable), and higher organic-C content (0-5-cm depth) compared with the tilled treatments. Surface soil of the till+no straw treatment contained the most wind-erodible and water-slakable aggregates. The till+straw treatment generally had properties intermediate to those of the other two treatments. Soil bulk density (Db) was affected by treatments to approximately 10-cm depth and penetration resistance (PR) to 45 cm. Average Db and PR were greatest in the top 10 cm of the no-till treatment, but in the subsoil PR was generally greatest in the till+no straw treatment.

Plant available water capacity of the 0-15-cm depth was the lowest in the no-till treatment. Infiltration rate and saturated hydraulic conductivity (0-7.5-cm depth) were in the order: no till+straw >till+straw >till+no straw. The treatments affected the soil water content to a 100-cm depth, but seasonal evapotranspiration did not differ among treatments.

For the study period, seedling emergence was delayed and the yield lowest in the no till+straw treatment. Shoot growth was the best in till+straw. Total root mass and length in the 0-50 cm depth were unaffected by treatments; however, root length density and specific root length in 0-15 cm interval were the greatest in till+no straw. The till+straw treatment seemed to be the best from a crop production standpoint, although from a soil and water conservation perspective, the no till+straw treatment was best.

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INTRODUCTION

1.1 Background

Recent years have witnessed major changes in agricultural practices in many parts of the world as the impact of science has been brought to bear on the 'art' of farming. Much of the progress has been crop-oriented and soil-related, yet many of the developments have been at the expense of soil and water resources (Sprague, 1986). Tillage (mis)management has often been blamed for soil deterioration and reduced crop yields on a long-term basis.

The primary objectives of tillage are: control of weeds and pests; incorporation of crop residues, fertilizers and other soil amendments; alteration of soil structure to provide a better seedbed environment for germination and root growth; and possibly conservation of soil water by effects on infiltration, runoff and evaporation processes (Hillel, 1980; Phillips, 1984). But excessive tillage, facilitated by farm mechanization, has led to the loss of topsoil, structure and organic matter through wind and water erosion in many parts of the world, and has also created other management problems like soil compaction, with crop productivity greatly reduced. Thus emphasis on developing alternatives to excessive use of tillage has been growing globally.

With improvements in seeding equipment, fertilizer application methods, crop residue management and chemical weed and pest control methods, the need for tillage in modern farming has greatly reduced. The objective of the thrust towards reduced tillage is to limit mechanical disturbance of the soil to that required for seed placement (Sprague, 1986). Another goal is to leave much of the crop residue on the soil surface. This approach has been utilized to develop innovative 'conservation tillage' methods variously termed: zero or no-tillage, minimum tillage, reduced or limited tillage, direct-drill, stubble mulching, etc. The purpose is to control soil erosion, conserve water, avoid soil compaction and to use energy more efficiently with accompanied decreases in costs of machinery, fuel and labor.

Reduced disturbance of the soil matrix and the presence of dead and decaying mulch of crop residues on the soil surface under conservation tillage systems result in a soil environment and microclimate which are different than those under conventional tillage systems. The modified environments influence crop growth patterns both directly and indirectly in many ways.

1.2 Changes in soil physical environment and crop response

Soil surface conditions and soil physical properties and processes that may be altered by tillage-residue methods include surface residue cover, surface roughness and reflectance, organic matter, aggregation, bulk density, aeration, soil strength, soil water retention and transmission characteristics, soil water and temperature regimes, etc.

Different tillage systems and crop species provide a variable degree of residue cover (Sloneker and Moldenhauer, 1977; Erbach, 1982) which protects the soil surface against erosive rain and wind. It affects radiation balance, changing the thermal and water regimes. Infiltration, runoff and erosion are also directly affected by residue cover. Changes in surface roughness or microrelief with tillage method affect exposed surface area, air currents, and radiation balance (Currence and Lovely, 1970) and also directly affect depressional storage and runoff.

The content and distribution of soil organic matter will be altered after several years in a reduced tillage system (Blevins et al., 1983; Dick, 1983) due to differences in amount of residue returned and possibly in root growth patterns, biological activity and soil water and temperature regimes. Improvements in aggregation after several years of direct drilling or reduced tillage are generally reported (Anderson, 1971; Lal, 1976; Hamblin, 1980; Carter and Kunelius, 1986; Kladivko et al., 1986). In contrast, continuous cereal cultivation and/or residue removal generally lead to organic matter decline, structural deterioration and accelerated soil erosion (Adu and Oades, 1978; Coleman and Hendrix, 1988). The extent of change in organic matter content and aggregation depends on their initial levels in the soil.

Typically, tilled soils have lower bulk densities within the tilled layer than do untilled soils, but the effects can be modified by other management practices and environmental factors such as rainfall and freeze-thaw cycles (Kay et al., 1985; Benoit and Lindstrom, 1987). Excessive tillage may lead to formation of a tillage-pan of high bulk density (Db) and soil strength in the sub-surface which can impede water movement and root growth. Conversely, increased Db of surface soil in no-till systems may or may not be root-restricting since density at which plant rooting is significantly reduced depends on soil texture, structure, soil water, drainage and possibly other environmental factors. The Db of the surface few cm of soil is very important from a hydrological standpoint. In a tilled soil, Db of surface soil may soon increase due to rainfall and lower aggregate stability and this may result in reduced infiltration and increased runoff. Soil strength, which is generally considered a more sensitive indicator of tillage-induced changes in soil behavior and root response than Db (Pidgeon and Soane, 1977; Bauder et al., 1981), is also variously affected by tillage-residue systems.

Different conditions of soil surface, size distribution and continuity of pores, size distribution and stability of aggregates, macrofaunal activity, etc. under various tillage systems affect soil water retention and movement (surface and subsurface) differently which, in turn, affect the soil water balance and the water regime. Higher soil water contents under no-till and reduced-till systems are often reported (e.g. Chavalier and Ciha, 1986; Culley et al., 1987), but may or may not mean greater plant water availability (Van Ouwerkerk and Boone, 1970; Negi et al., 1981). Other factors and processes of soil environment including soil strength, soil water conductivity, soil temperature, microbial activity and various chemical and biochemical reactions may, however, be influenced, thus affecting plant growth indirectly.

Reported effects of tillage systems on various factors and processes of the soil physical environment are often contradictory in that the extent and even direction of change may be different. Soil and climatic conditions including antecedent values of soil properties, time and method of measurement, cropping patterns, type of tillage equipment used, depth of tillage, other cultural practices employed, etc., all modify the tillage-induced response in the soil environment to various degrees. Duration for which a tillage system has been prevalent controls the achievement of 'equilibrium' conditions, if any. The situation is further complicated by where in the plot, in-row or between-rows, sampling is done. Temporal variability of many properties warrants caution in selecting times of measurement. The depth resolution of measurements is also an important consideration because some of the treatment effects may get masked by taking larger depth intervals, particularly in reduced or no-till systems which tend to cause stratification of soil properties somewhat resembling natural ecosystems.

The field variability of soil physical properties is usually large (Warrick and Nielsen, 1980) which may affect statistical inferences. In the range of process-limiting values, statistically insignificant changes in a certain factor, e.g. porosity, may have a large effect, for instance on soil aeration; such results are important and need closer scrutiny (Soane and Boone, 1986).

The changed soil and crop environments interact in a complex manner to affect crop growth through varied effects on seedling emergence, root growth patterns, tillering, leaf area development, crop phenology, and various yield-contributing factors. Crop response to a given tillage system is largely species-specific and is further modified by length of growing season, amount and distribution of rainfall, other meteorological conditions as well as antecedent soil properties. Thus, effects of changes in soil properties due to tillage practices must be interpreted differently for climatic regions, localities within a region, and often for soils on a farm, when they differ appreciably in texture, drainage, depth, topographic characteristics, etc. (Griffith et al., 1986). Variable crop response to tillage methods has often been observed in different years even at the same site, making the task of interpretation even more challenging. Consequently, tillage methods developed in one location may not be suitable for another location (Hillel, 1980).

1.3 Study objectives

Conservation tillage systems, including no-tillage, have a great potential on the Canadian prairies where problems generally associated with conventional tillage systems (wind and water erosion, compaction, organic matter decline, soil water deficiency, reduced crop yields, etc.) are becoming common. Scientific research into the long-term effects of tillage-residue systems on soil physical environments and barley (*Hordeum vulgare* L.) growth under the agroclimatic and soil conditions of Central Alberta (cool temperate, Cryoboreal subhumid environment, inherently well-aggregated soil with high organic matter content) is scant. However, such information is vital for understanding system behavior as well as in assessing the relative suitability of different management systems in this region, especially considering the site-specificity associated with such systems. Such information is also essential in developing and validating process-oriented crop growth models with a view to understand and predict the soil and crop responses to tillage and residue management in an agroecological perspective. The information will also be useful in understanding the response of other components of the soil environment (soil fertility, soil biological, etc.) to these tillage-residue systems.

A comprehensive field study was initiated to quantify many of the factors and processes of the soil physical environment as influenced by three tillage-residue systems namely: no-tillage with straw retained on the surface, rototillage to a 10-cm depth with straw incorporated, and rototillage after the straw had been removed. Weeds were controlled chemically. The study was conducted 9 and 10 years after establishment of the treatments in Central Alberta on a well-drained Typic Cryoboroll (Black Chernozemic) with relatively few management problems otherwise.

The results of the study are presented in five chapters in this dissertation, each with its own specific objectives. These objectives are summarized as follows.

To determine the long-term effects of three tillage-residue management systems:

1. On the degree of residue cover, surface roughness, aggregate size distribution and stability, organic matter content and some other soil properties (Chapter 2).

2. On soil bulk density, soil strength and porosity, with emphasis on their temporal and spatial variation and with consideration of implications for plant growth (Chapter 3).

3. On soil water retention, pore size distribution, plant available water capacity, infiltration characteristics and saturated hydraulic conductivity, with consideration to seasonal changes in the latter two variables (Chapter 4).

4. On spatial and temporal variation of soil water during each of the two growing seasons in relation to the modified soil physical properties and meteorological conditions (Chapter 5).

5. On shoot and root growth, yield and water use patterns of barley in relation to the soil environments modified by these tillage-residue treatments as well as the growing season meteorological conditions (Chapter 6).

The last Chapter (7) includes a synthesis of the results reported in Chapters 2 through 6 along with conclusions derived from the study.

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Chapter 2

TILLAGE AND RESIDUE MANAGEMENT EFFECTS ON RESIDUE COVER, SURFACE ROUGHNESS, AGGREGATION AND SOME OTHER PROPERTIES OF A TYPIC CRYOBOROLL UNDER CONTINUOUS BARLEY IN CENTRAL ALBERTA

2.1 INTRODUCTION

Tillage has been used for weed control, incorporation of crop residues, fertilizers and other soil amendments, as well as to provide seed-bed conditions favorable for crop germination, emergence and root growth. With the development of improved seeding equipment and chemical weed control methods, tillage may often be reduced or even eliminated with a view to soil and water conservation and for economic considerations including reduced energy inputs and timeliness. Less disturbance of the soil matrix under these conservation tillage systems may result in a soil physical, chemical and biological environment which is different than that under conventional tillage systems.

The extent and direction of the change in soil environment, however, depends largely on several factors including antecedent soil characteristics, cropping patterns, other cultural practices employed besides tillage, type of machinery used for various operations, prevailing agroclimatic conditions, as well as the duration a given tillage treatment has been prevalent. Therefore, under a given soil-water-plant-environment-machine-time setup, changes brought about by tillage practices may prove inhibitory, conducive or neutral to plant growth and development and so should be interpreted in relation to all these factors.

Responses to tillage systems which leave crop residues on the surface or where the residue is incorporated into the surface soil might be different than those to systems where the residue is removed. Further, the straw left on the surface or incorporated into the surface soil may change the structural condition of the soil differently, thus variably affecting soil bulk density, soil strength, pore-size distribution, etc. Residue cover protects the soil surface against raindrop impact and strong winds. It also affects partitioning of solar energy at the soil surface and soil evaporation, affecting the soil's hydrothermal regime. The biological activity in soil is also directly influenced by the placement and amount of organic material. Thus it is important to quantify the amount and distribution of crop residues on and near the soil surface.

Another important soil surface condition which is greatly affected by tillage is surface roughness, also referred to as soil microrelief. Changes in surface roughness, in turn, affect the exposed surface area, air currents and partitioning of radiation which indirectly influence the moisture, temperature and aeration regime of the soil (Currence and Lovely, 1970). Surface or depressional storage and movement of water (i.e. runoff) and, therefore, rate and amount of soil erosion, are also related to the degree of surface roughness. In addition to being affected by tillage, residue-burying operations and surface smoothing practices, soil surface roughness is markedly affected by natural degradation processes like raindrop impact, soil freezing and thawing and wetting and drying cycles (Unger and McCalla, 1980; Onstad and Voorhees, 1987). Therefore, repeated measurements of surface roughness may help in describing some of the tillage-induced changes in soil conditions.

The content and depth distribution of organic matter as well as soil pH are expected to be differently affected by tillage and residue management practices because of minimal soil disturbance in a no-tillage system and fertilizers and other amendments being applied mostly on the soil surface in no-till systems but mixed into surface soil in the tilled systems. Any changes in the soil water retention and movement characteristics, soil thermal and aeration regimes, root growth and distribution as well as biological activity among different tillage systems are also likely to affect soil organic matter and pH differently.

Improvement in the structural condition (i.e. aggregate size and stability) of a range of soil types has been reported after several years of continuous direct-drilling in cool temperate environments (Ellis et al., 1977; Hamblin, 1980; Kladivko et al., 1986) as well as in wet tropical environments (Lal, 1976). The results were variously attributed to increased surface organic matter, prolific rooting in the surface zone and greater faunal activity, suggesting that the origin of increased aggregate stability lies mainly in the bonding of mineral particles by organic substrates.

Conversely, when continuous cereal cultivations are practised, or where crop residues are removed, organic matter decline as well as structural deterioration are generally noted (Adu and Oades, 1978; Tisdall and Oades, 1980; Haynes and Swift, 1990) as the aggregates are exposed frequently to physical disruption by rapid wetting and raindrop impact as well as shearing by implements. The rate and extent of these structural changes may be modified by environmental conditions like rainfall patterns, freeze-thaw cycles, soil temperatures, cropping patterns, etc.

Not much scientific information is available on the long-term impact of various tillage and residue management practices on soil properties under the soil and agroclimatic conditions of Central Alberta. This soil has good natural aggregation and high organic matter content and the environment is Cryoboreal-Subhumid. How such conditions modify the tillage-residue effects on soil properties is not clearly known.

The objectives of this study were to determine the effects of three tillage-residue management systems on (1) degree of residue cover provided and soil surface roughness created at various times over a growing season, (2) size-distribution and water-stability of soil aggregates, and (3) selected soil characteristics including organic carbon, pH, and particle-size distribution of a Typic Cryoboroll (Black Chernozem) under continuous spring barley (*Hordeum vulgare* L.) production for nine years in Central Alberta. The research reported in this chapter is a part of a broader study to quantify the factors and processes of the soil environment as influenced by tillage and residue management.

2.2 MATERIALS AND METHODS

2.2.1 *Site and soil description*

The study site is located near Edmonton at the Ellerslie Research Station of the University of Alberta. It is situated at 53^{o} 25' N latitude, 113^{o} 33' W longitude with an elevation of 694 m above mean sea level. The local topography is gently rolling to rolling morainal plain with slopes rarely exceeding 2% (Crown and Greenlee, 1978).

The soil at the site was developed from fine-textured lacustrine deposits of the Proglacial Lake Edmonton and belongs to the Malmo series. It has a clay loam texture (39% clay, 41% silt and 20% sand) in the 0–15-cm depth. It is classified as a fine loamy, mixed, Typic Cryoboroll according to Soil Taxonomy (Soil Survey Staff, 1975; D.J. Pluth, Personal Comm., 1990) and a Black Chernozemic according to the Canadian System of Soil Classification (Crown and Greenlee, 1978). This soil is characterized by a black surface horizon approximately 20 cm in depth, very dark-brown clay from 20 to 40 cm depth and dark grayish-brown from 40 to 100 cm depth. It has good internal drainage with the ground water table fluctuating between 1.5 and 3.0 m during the year. The predominant clay mineral is montmorillonite which imparts a moderate swell-shrink potential to the soil.

The climate of the Edmonton area is between dry and moist subhumid, characterized by relatively warm summers and cold winters (Bowser et al., 1962). The 30-year (1951-1980) average annual daily air temperature is 1.7 ^{o}C with January the coldest month (-17 ^{o}C) and July the warmest month (16 ^{o}C) (Environment Canada, 1982). The average daily maximum and minimum air temperatures are: 7.6 and -4.1 ^{o}C (whole year), 22.4 and 9.6 ^{o}C (July) and -11.5 and -21.7 ^{o}C (January). The average annual precipitation is 452 mm, of which 339 mm (75%) occurs as rain and the rest as snow. Approximately 60% of the total precipitation (274 mm) occurs during the growing season extending from May to August with July the wettest month (85 mm). Ellerslie has an average 109 frost-free days per year and number of degree-days >5 °C is 1230. A large portion of the region is under mixed cereal cultivation with barley the most popular grain crop.

2.2.2 *Tillage-residue treatments*

Ten tillage, residue and nitrogen management systems were established in fall 1979 to investigate the long-term effects of these systems on soil environment and crop growth. Three of these were selected for the present study: (1) no-tillage, straw retained on the surface; (2) conventional tillage, straw retained and incorporated; and (3) conventional tillage, straw removed.

Conventional tillage consisted of late fall cultivation using a rotocultivator (John Deere Model 448, weighing 140 kg with a rotor speed of 185 rpm) towed behind a 13.2 kW tractor (John Deere Model 750, mass 680 kg, wheelbase 155 cm and width 113.2 cm), followed by similar spring cultivation at the time of seeding. The tillage depth was approximately 10 cm. In the no-till treatment, the crop was seeded directly without tillage. The only disturbance of soil in this treatment was the motor-driven seed-drill (mass approximately 700 kg, 6 wheels on the back and 4 in the front, each 12.5-cm wide) which is equipped with four hoe-openers at 22.5 cm spacing, and a small reaper-binder (mass 114 kg, width 130 cm).

The crop was harvested at a height of approximately 10 cm. Threshed straw from each plot in treatments (1) and (2) was returned to the corresponding plot and uniformly spread before fall tillage. In treatment (3), all straw and most of the stubble were removed before tillage. All treatments were replicated four times in a randomized complete block design. Each individual plot measured 6.8 x 2.7 m.

The tillage and residue management treatments were repeated annually. The plots were seeded to spring grain barley (*Hordeum vulgare* L.) at 90 kg ha^{-1} each year. The cultivar was 'Empress' in 1988 and 'Heartland' in 1989. The seeding depth was 5 cm. Nitrogen (56 kg ha^{-1}) was applied as urea at the time of seeding. It was broadcast in no-till plots and incorporated into surface soil with tillage in other treatments. Phosphorus (17 kg ha^{-1}) as triple superphosphate was drilled with the seed. The crop rows, 22.5 cm apart, were located in approximately the same position each year. Grassy and broad leaf weeds were controlled with a mixture of 'Glean' or chlorsulfuron (2-chlor-N[(4-methoxy-6 methyl-1,3,5-triazin-2-yl) aminocarbonyl] benzenesulfonamide) at 15.6 g ha^{-1} a.i., plus 'Hoegrass 284' or diclofop-methyl (methyl 2-[4-(2,4-dichlorophenoxy) phenoxy] propanoate) at 2.75 L ha^{-1} sprayed post-emergence at 100 L ha^{-1} using a backpack sprayer. Dates of relevant field operations for the duration of the present study (1988 and 1989) are given in Table 2.1.

2.2.3 *Measurements and analyses*

2.2.3.1 *Residue cover*

The proportion of soil surface covered with crop residue was estimated using a line-intersect method (Sloneker and Moldenhauer, 1977). A nylon string marked at 15-cm intervals (total 30 marks) and tied to metallic spikes at each end, was laid diagonally to the tillage direction. Marks that touched or were directly over a piece of residue at least 1 cm in length were counted. Four to five sets of measurements were made in each plot. Residue cover was calculated by expressing the number of marks touching the straw as a percent of total number of marks.

2.2.3.2 *Soil surface roughness*

Two locally manufactured, 1.8 or 0.9 m wide, microrelief meters (rillmeters) were used to measure the soil surface elevations (distances from a level datum to the soil surface). The rillmeter was always positioned perpendicular to the tillage direction. The rillmeters were placed on two side supports, and the equal-length measuring pins, each 12.5 mm apart, were gently lowered until all pins rested on the soil surface. The positions of upper ends of the measuring pins corresponded to the natural configuration of the soil.

They were marked on tracing paper taped to the plexiglass back (which also guided the movement of pins), using the shadows of the pins as a guide. Reference points were determined for each trace, taken as equal heights above the soil surface for the vertical sides of the rillmeter frame. Several (2 to 4) random transects were measured in each plot, before and after tillage and seeding operations and after harvest. In the laboratory, point elevations were measured from the reference plane.

Height measurements followed a normal distribution according to the Univariate procedure of SAS statistical package (SAS Institute, Inc., 1985), so transformation (as advocated, for example, by Burwell et al. (1963) was deemed unnecessary. Currence and Lovely (1970) also showed that conversion to logarithms is not always necessary. No adjustment for slope was made because the field plots were almost level. No abnormally large or small heights were detected. Surface roughness (SR) was computed as standard deviation of all the measured heights.

2.2.3.3 *Particle size distribution and particle density*

Particle size analysis of the 2-mm ground and sieved soil was determined on bulk soil samples taken during fall 1988 from depths of 0–5, 5–10, 10–15 (all treatments), and 15 to 105-cm depth in 15-cm intervals (only till+no straw treatment). The hydrometer method (Gee and Bauder, 1986) using a standard ASTM No. 152H hydrometer was used for silt and clay fractions. The 0 to 30-cm soil was pretreated with hydrogen peroxide to remove organic matter. Only the 75 to 105-cm soil was pretreated with HCl to remove carbonates. The sand fraction (0.05 to 2 mm) was separated directly by sieving the dispersed soil and was further divided into coarse, medium and fine sand fractions using a sonic sifter (Model L3P, Allen- Bradley Company, Wisconsin). In calculating particle size at various times of hydrometer readings, corrections were applied to solution density and viscosity for Na-hexametaphosphate concentration in the soil suspension (Gee and Bauder, 1986).

Particle density of soil including its organic matter was determined using the pycnometer method (Blake and Hartge, 1986).

2.2.3.4 *Organic carbon, pH and electrical conductivity*

Total carbon of soil samples collected in fall 1988 was determined by dry oxidation followed by infrared detection using LECO CR12 carbon analyzer (LECO Corporation, St. Joseph, MI 49085, USA). There were negligible carbonates in the 0 to 75-cm soil, therefore total C was taken as organic-C. For the 75–105-cm depth, carbonate content was determined by acid neutralization and back titration (Bundy and Bremner, 1972) and its amount (inorganic-C) subtracted from total C to give organic-C. A 1:2 soil:water suspension was used to determine soil pH using Model 630 Fisher Accumet® pH meter (Fisher Scientific Co., U.S.A.) and electrical conductivity using Model 31 Conductivity Bridge (Yellow Springs Instrument Co., Inc., Ohio, U.S.A) following McKeague (1978).

2.2.3.5 *Soil aggregate analysis*

Before fall tillage 1988 (i.e. on 14 October), bulk soil samples were collected from 0–5-cm depth within the interrow spacings in each plot using a rectangular trough (15 cm x17.5 cm). The field-moist soil was allowed to air-dry (6% average mass moisture content). For dry aggregate size distribution analysis, the samples were manually shaken through a nest of sieves having rectangular holes with equivalent diameters of 19, 16, 12.5, 8, 4, 2, 1, 0.5 and 0.25 mm and a pan underneath. The fraction retained on each sieve or pan was oven-dried (105 ^{o}C), weighed, and expressed as a percentage of total dry soil mass.

For determining the water-stable aggregate-size distribution, air-dried (3.5% average mass moisture content) samples of the 0–5-cm soil were passed through an 8-mm sieve. Some of the larger aggregates had to be gently pushed through the sieve with a rubber stopper. Triplicate 50-g sub-samples of this soil were wet-sieved (modified from Kemper and Chepil, 1965) through a nest of sieves for 30 minutes after letting the soil moisten by capillarity for two minutes on the top sieve. Tap water at 20 °C and having an average EC of 0.28 dS m^{-1} was used for wet-sieving in a Yoder-type apparatus. The sieve stack was oscillated through an amplitude of 3.75 cm at a rate of 30 min^{-1}. The sieves in the nest had equivalent diameter of 4, 2, 1, 0.5, 0.25 and 0.125 mm. The soil mass retained on each sieve was oven-dried (105 °C) and weighed. Each fraction was further corrected for unaggregated sand by stirring the retained aggregate mass in about 15 ml of 5% Na-hexametaphosphate solution plus 200 ml distilled water in an electric shaker for 5 minutes and then passing it through the same sieve with a spray of water. The sand left on the sieve was oven-dried and its mass subtracted from the corresponding uncorrected mass.

The results of dry- and wet-sieving analyses were expressed as percent aggregate size distribution as well as mean weight diameter (MWD) (van Bavel, 1950; Youker and McGuiness, 1956) and geometric mean diameter (GMD) (Gardner, 1956; Kemper and Chepil, 1965). The aggregate size distributions were also used to compute a dry-aggregation index (DAI), a water-stable aggregation index (WAI) and a water-stability index (WSI) according to the method of Dobrazanski et al. (1975). Each aggregate fraction was assigned a weighting value (0 to 10) representing the agronomic significance of that fraction. The aggregation index (dry or water-stable) was calculated as:

$$\text{DAI (or WAI)} = \sum P_i Q_i$$

where P_i = percent content (w/w) of aggregate fraction i

Q_i = weight factor assigned to aggregate fraction i

The Q values used in the present study were: $Q_{<0.25\ mm} = 0$, $Q_{0.25-0.5} = 3$, $Q_{0.5-1} = 5$, $Q_{1-2} = 10$, $Q_{2-4} = 9$, $Q_{4-8} = 3$, $Q_{8-12.5} = 1$, $Q_{>12.5} = 0$. The highest values were given to soil aggregates of 1-4 mm size because a soil containing aggregates of this size usually possesses the most favorable air-water relationships for the growth and development of cereal crops (Dobrazanski et al.,1975; Braunack and Dexter, 1989). The water-stability index (WSI) was calculated as the ratio of WAI to DAI.

2.2.3.6 *Statistical analyses*

The experimental variables were subjected to analysis of variance using either UANOVA procedure developed at the University of Alberta (T. Taerum, Personal Comm., 1990) of the SPSS^x statistical program, or ANOVA procedure of the SAS statistical package (SAS Institute, Inc., 1985). The data were tested for fulfillment of the assumptions of analysis of variance (homogeneity of variances, normal distribution, etc.), and analyzed (except for aggregates) as a split-plot model with tillage system as whole plots and depth or time of measurement as subplot treatments. Aggregate size data were analyzed as a randomized complete block design for each size fraction. The MWD and GMD data were analyzed similarly. Least significant difference or Duncan's Multiple Range (DMR) tests ($P \leq 0.05$) were performed for means separation of those main effects and interactions which showed significant F-values in the analysis of variance.

2.3 RESULTS AND DISCUSSION

2.3.1 *Residue Cover*

The surface residue cover was in the order: no till+straw >till+straw >till+no straw; the differences among treatments being significant at all times of measurement (Table 2.2). Residue cover on no-till plots varied from 70 to 79% at start of the growing season and from 95 to 99% over the non-growing period (fall, winter and early spring). Seeding, which was the only soil disturbance in this treatment in the spring, caused some redistribution of the surface residue, significantly reducing the proportion of soil surface covered by straw material by 25%. (Note that all percentage numbers mentioned in this section are absolute values).

In the till+straw treatment, one roto-cultivation during the fall caused a significant reduction of 14 and 38% in the cover in 1988 and 1989, while a second cultivation plus seeding in 1989 further reduced the cover remaining over winter by 39% (significant).

Thus this tillage system had a residue cover of approximately 40% remaining after spring tillage and seeding operations. Conversely, about 60% of the residue produced during the previous growing season was incorporated into the tilled layer (0–10 cm depth) with combined fall and spring tillage plus seeding operations. In the till+no straw treatment, a small cover (6 to 16%) was still provided by straw pieces, awns, etc., left in place during the harvesting and combining operations. Sloneker and Moldenhauer (1977) observed similar effects of various tillage operations on oat residue cover.

Straw cover values can exhibit considerable year to year variability. For example, in the till+straw treatment after fall cultivation, cover was 85% in 1988 and 61% in 1989. This was mainly ascribed to different amounts of residue produced in the two years (4554 kg ha^{-1} in 1988 and 3772 kg ha^{-1} in 1989). Dickey et al. (1984), Carter et al. (1988) and Yonts et al. (1989) also observed different amounts of residue produced and surface cover provided in different years with the same tillage system. Another reason may be variable distribution of straw by the cultivator. Condition of residue (Kladivko et al., 1986) and soil moisture condition at tillage may also contribute to differential distribution (incorporated vs. that left on surface) of the crop residue. The observed increase in cover from 11 to 16% in till+no straw treatment between fall tillage 1988 and spring tillage 1989 might be due to trapping of wind-blown residue from the adjacent treatments which showed a 4–5% decline in residue cover during the same period.

2.3.2 *Soil surface roughness*

After spring or fall tillage, both the tilled treatments showed significantly greater surface roughness (SR) compared with the no-till treatment (Table 2.3). There was no significant difference between the two tilled treatments at any time of measurement, although the till+straw treatment tended to have greater roughness than the till+no straw treatment. Crop residues in the till+straw treatment, which were partly buried and partly on the surface, gave the soil surface a rougher configuration than in the till+no straw treatment.

Fall tillage during 1988 increased the SR of till+straw treatment from 0.60 to 1.03 (73%) while that of the till+no straw treatment increased from 0.59 to 0.87 (48%). Both the increases were significant as compared with the pre-tillage values. Similar were the effects of spring tillage-cum-seeding operations in 1989. Notably, in the no-till treatment a seeding operation alone increased the SR (June 8, 1989) significantly (35%) compared with the pre-seeding value.

Between spring tillage-cum-seeding and harvest times, there was a significant reduction in surface roughness in all three treatments in both years. However, the reduction was much greater in the tilled treatments (61 to 34%) than in no-till treatment (44 to 21%). This is associated with greater initial SR values in tilled treatments and greater potential efficacy of seasonal rainfall in reducing the SR by soil disruption in these treatments having low surface residue cover (Table 2.2). In the no-till treatment, greater residue cover would be expected to dissipate most of the kinetic energy of falling rain. Further in all treatments, the reductions in SR were greater in 1988 than in 1989 which is associated with greater rainfall amounts in 1988 and different distributions during the two years (data not given).

The no-till treatment generally had the smallest roughness except after harvest in 1988 when it was nonsignificantly greater than the other two treatments. This resulted from much greater reduction of SR in the tilled treatments. In a recent review, Zobeck and Onstad (1987) also observed that tillage and rainfall had the greatest effects on soil surface roughness.

An unusual observation is that there was a nonsignificant increase in SR of all treatments between fall tillage 1988 and spring 1989. The increase was greater in the till+no straw treatment (22%) than in the other two treatments (4-11%).

Although the no-till treatment had a lower surface roughness than the tilled treatments, its greater residue cover is expected to provide more effective and sustained runoff and erosion control than the tilled treatments. Although initially a rougher surface of tilled soil would tend to reduce runoff by increasing the surface depression storage and also by increasing infiltration capacity due to loose surface soil, this beneficial effect would last for a shorter period, particularly in till+ no straw treatment where surface roughness can decrease quickly due to impact of intense rains. A surface crust/seal can also form in such conditions, considerably reducing the infiltration rate.

A no-till system, on the other hand, is expected to maintain a greater infiltration rate by (1) reducing the velocity of overland flow, if any, due to its greater residue cover, (2) having greater biochannel production (data not reported) as well as continuity of pores, and (3) by having more water stable aggregates. Also a greater residue cover in no-till system dissipates much of the rainfall energy, reducing soil detachment and particle breakdown.

2.3.3 *Soil particle size distribution*

The texture of soil in the 0–5-, 5–10- and 10–15-cm depth was silty clay loam, clay loam and clay, respectively, and it was unaffected by the tillage-straw treatments (Table 2.4). The clay content increased and silt content decreased with depth. In the 0–5-cm depth, silt and fine silt content was somewhat lower and sand content higher in the no till+straw treatment as compared with tilled treatments. The trends were reversed in the 5–10-cm and 10–15-cm depths but the differences were very small. Further, 70% of the sand fraction was fine sand in all three layers.

Different soil texture in the three layers even in the tilled treatments and lack of any major difference from the untilled treatment shows that the cultivation was probably not intense enough to cause a uniform particle size distribution in the tilled zone (0–10 cm).

Predominance of silt and fine sand particles in a soil can significantly affect soil behavior (Carter, 1987). In Australia, red-brown earth soils with more than 10% silt and a ratio of fine to coarse sand greater than 3 are subject to slaking and breakdown of soil structure (Greenland, 1971). Other studies have shown that soils with relatively high contents of silt and fine sand have a tendency for structural instability and compaction (Batey and Davies, 1971) especially if soil organic carbon levels are low (Hamblin and Davies, 1977). Although the soil in this research fulfills the above criteria of high silt and fine sand contents as well as a >3 ratio of fine to coarse sand in all three depths and treatments (Table 2.4), the high organic-C content of this soil (Table 2.5) would be expected to mitigate the potential for soil structure deterioration. Greenland (1971) also showed that soils with high silt and fine sand contents often demonstrate a positive relationship between soil structure and organic matter.

2.3.4 *Soil organic carbon*

The till+no straw treatment showed the lowest organic-C content for all 5-cm layers to 15 cm (Table 2.5). In the 0–5-cm depth, the no till+straw treatment had the greatest content of organic-C which was significantly (P=0.05) different from the tilled treatments. The relative increases were 4.1 and 14.1% over the till+straw and till+no straw treatments, respectively. The difference between till+straw and till+no straw was also significant in this depth.

In the 5–10-cm depth interval, the trend changed in that till+straw treatment had the highest organic-C content which was significantly greater (6.1%) than that of till+no straw but similar to that of the no till+straw treatment. There were no significant differences among the three treatments in the 10–15-cm depth. Thus the distribution of organic matter with soil depth differed considerably among treatments. This could have implications in soil structural characteristics including aggregate size distribution and aggregate stability. Carter et al. (1988) observed similar depth effects of direct drilling and mouldboard plowing on organic-C content of a fine sandy-loam (Orthic Podzol) in Atlantic Canada.

Blevins et al. (1977, 1983) found only small differences in organic matter content of no-till and conventional tillage treatments below 5-cm depth.

Averaged over the 0–15-cm depth interval, the two straw treatments had a similar organic-C content which was significantly greater (by a relative amount of 6.4%) than that of the no-straw treatment. Apparently smaller depth intervals are needed to discern differences among treatments. The results imply that the rate of decomposition of organic matter was probably similar in the two straw treatments, and that the observed different vertical distribution of carbon in these treatments was the result of tillage or lack thereof. Some other studies have shown that plant residues decompose faster when buried than when left on the surface (Brown and Dickey, 1970; Sain and Broadbent, 1977). Blevins et al. (1977, 1983) found greater organic-C under no-till than under conventional tillage for a silt loam (Typic Paleudalf). Lal (1976) observed similar results for Alfisols in Western Nigeria. Dormaar et al. (1979), Rasmussen et al. (1980) and Skidmore et al. (1986) observed higher organic matter contents of soils where residues were incorporated compared with soils where residue was removed by burning or hauling away.

Averaged over all the treatments, the organic-C content significantly decreased with each increment of 5 cm to 15-cm depth. The greatest decrease (18%) occurred in the no-till treatment. The organic-C content of the 0-5 and 5-10-cm soil layers in each of the tilled treatments was statistically the same but it was different from that of the 10-15-cm layer. This is ascribed to the fact that roto-cultivation, which was about 10 cm deep, caused considerable mixing of soil in the tilled zone. On the other hand in the no-till treatment, the soil remained largely undisturbed for 9 years, such that organic matter concentration could increase at the surface. This also explains why there were no significant differences among treatments in the soil just below the depth of tillage (i.e. in the 10–15 cm depth).

Soil mixing was perhaps more complete in the tillage treatment where straw was removed than where it was retained and incorporated. This is indicated by the differences in organic-C content of 0–5 and 5–10-cm layers in these two treatments wherein there was some decline in the 5–10-cm depth in the till+straw treatment. This may also have been caused by a non-uniform vertical incorporation of residue during tillage in this treatment (Dick and Daniel, 1987). Relatively less effective soil mixing in the till+straw treatment compared with the till+no straw one was also indicated by a generally greater surface roughness in the former (Table 2.3).

2.3.5 *Soil particle density*

Average particle density of 0-15 cm soil was low (2.48 Mg m^{-3}) which is mainly ascribed to high organic matter content of this soil. Particle density of 0–5 cm soil was significantly lower in the no-till treatment compared with till+no straw treatment but was similar to that of till+straw (Table 2.5). The treatment differences for 5–10 and 10–15 cm depth intervals were nonsignificant. Further, particle density tended to increase with depth although the only significant difference found was between 0–5 cm and other depths of no-till treatment. The trends in soil particle density largely correspond with those in organic-C content.

2.3.6 *Soil pH*

As in the case of organic-C, tillage system effects on soil pH also varied with depth as indicated by a significant tillage x depth interaction. However, averaged over all the depths, tillage effects were non-significant (P=0.05) (Table 2.5). In the 0–5 cm depth, the no till+straw treatment showed the lowest pH which was significantly different (by 0.14 of a unit) than the till+no straw treatment having the highest pH. However, in the 5-10 and 10-15-cm depths, the till+straw treatment had the minimum pH. Shear and Moschler (1969) and Mahler and Harder (1984) also observed that untilled soils were more acidic in the surface 7.5 cm and less acidic in deeper layers than ploughed soils.

In the no till+straw treatment, pH significantly increased with each increment of 5-cm depth. In the two tilled treatments, however, pH of 0–5 and 5–10-cm layers was statistically not different (again the effect of soil mixing with cultivation). In the next layer (10–15-cm), pH increased in both the tilled treatments, significantly in the till+straw treatment and non-significantly in till+no straw treatment. Averaged over all the treatments, pH increased significantly with each increment of 5 cm to 15-cm depth.

The extent of change in pH from 0–5 to 10–15-cm depth (0.33, 0.12 and 0.10 units in the no till+straw, till+straw and till+no straw treatments, respectively) shows, as in case of organic-C content, the effects of soil disturbance as well as mode of disposal of straw (surface placement, incorporation and removal) on soil pH. Blevins et al. (1983) for a silt loam Alfisol in Kentucky after 10 years of corn production and Dalal (1989) for a Vertisol in Queensland, Australia after 13 years of wheat/barley production, observed significantly lower pH under no-tillage than under conventional tillage systems in the 0–30-cm depth. However, Carter and Kunelius (1986) observed higher pH (and lower organic-C) in direct drill than under cultivated fine sandy loam soil at 0-5-cm depth after 3 years of Italian ryegrass establishment in Prince Edward Island, Canada.

Increased organic-C under no-tillage system might at least be partially responsible for acidifying the surface soil (through release of organic acids by microbial decomposition of plant residues) more than that under conventional tillage system. Further, the nitrogen fertilizer (urea) was always surface applied in the no-till plots, and it was mixed into surface soil (0–10 cm) in the tilled plots. This might also have resulted in differential response of pH to tillage treatments as nitrogenous fertilizers have an acidifying effect on soil through release of protons during the nitrification process (Blevins et al., 1983).

Increased acidity in the no-till plots does not seem to be an immediate problem, although it may become a concern on a long-term basis because if it increases further, it can cause nutrient imbalances in the soil and plants (loss of exchangeable Ca, excess of exchangeable Al, etc).

2.3.7 *Electrical conductivity*

Electrical conductivity (EC) of soil in the 0–5, 5–10 and 10–15 cm layers was significantly greater (15-17%) in no till+straw treatment compared with till+no straw (Table 2.5). In 0–5 cm depth, no-till EC was significantly greater than that of even till+straw treatment, while in other depths they were similar. The results indicate that undisturbed surface soil in the no-till treatment accumulated greater concentrations of ions than tilled soil, possibly by an increase in exchange sites due to its increased organic matter content. These results are opposite to those of Dalal (1989) who observed lower EC in no-till compared with conventional-till throughout the soil profile.

2.3.8 *Aggregate size distribution and stability*

2.3.8.1 *Dry aggregate size distribution*

The 0–5-cm soil of the no till+straw treatment showed the highest proportion (9.6%) of large (>16 mm) dry aggregates which was significantly greater than the till+no straw treatment (1%) and nonsignificantly greater than the till+straw treatment (4.9%) (Fig. 2.1). Similar trends were observed for the aggregate sizes between 16 mm and 2 mm with no till+straw treatment having 52% of all aggregates in this size-range, followed by till+straw with 48%. The till+no straw with only 32% of the aggregates in this size-range was significantly smaller than the other two treatments. A transition in trends occurred at the 2- to 1-mm size range with till+no straw starting to have the largest proportion of < 2 mm aggregates (66%) compared with 29% for no till+straw and 42% for till+straw treatment.

Considering aggregates <1 mm as wind-erodible (some workers including Chepil, 1955; Siddoway, 1963 and Skidmore et al., 1986, considered < 0.84 mm size as wind-erodible), the no-till soil had a considerably smaller fraction of the aggregates (16%) in the wind-erodible range compared with that from till+no straw (49%). The till+straw treatment was intermediate with 29%.

When the results of dry aggregate size analysis were calculated as mean weight diameter (MWD) and geometric mean diameter (GMD), the treatments were again significantly different (Table 2.6). The MWD of the no till+straw soil was 36% greater than that of the till+straw (nonsignificant) and 173% greater than of the till+no straw treatment (significant at P=0.05). GMD is considered a more sensitive parameter than MWD to detect changes in aggregate size distribution caused by tillage operations (Hadas et al., 1978). GMD was 66 and 284% greater with no-till system compared with till+straw and till+no straw systems, respectively. Increase of GMD in till+straw over till+no straw (132%) was also significant.

The median aggregate size (D_{50}, aggregate diameter corresponding to 50% of the cumulative percentage) was derived from the cumulative aggregate size-distribution curves (not presented). The average D_{50} was 4.7, 2.9 and 1.0 mm for the no till+straw, till+straw and till+no straw treatment, respectively. This again demonstrates better aggregation status of the straw-involving treatments, with untilled soil having the best aggregation state of the 0-5-cm soil.

Other researchers (e.g. Chepil, 1955; McCalla, 1945; Miller and Kemper, 1962; Siddoway, 1963) also observed greater advantage for aggregation from leaving the residue on the surface rather than incorporating it into soil. The residue placed on the surface probably continues to replenish the soil-binding cementing products over a longer period. Also surface residue protects the topsoil against rain-drop impact. Further over the winter period, the almost 100% residue cover on the soil surface in the no till+straw treatment (Table 2.2) would probably help keep the surface soil warmer than the other treatments having no or partial cover, and thus likely reduce the effect of freeze-drying which can be especially destructive of soil aggregates (Skidmore, 1975).

2.3.8.2 *Water-stable aggregate size distribution*

The no till+straw treatment showed a much greater proportion (68%) of water-stable aggregates >1 mm size than the till+straw (48%) and till+no straw (27%) treatments (Fig. 2.2). Forty two percent of all aggregates were in the 8–4-mm size range in the no-till treatment, while this amount was 27% in the till+straw and 12% in the till+no straw treatment. The differences among treatments were significant. As in dry aggregate distribution, a transition in trends was evident at the 1–0.5-mm range such that the till+no straw treatment showed higher proportion of smaller (<0.5 mm) aggregates while the no till+straw treatment showed the lowest proportion, the difference being statistically significant. The till+straw treatment behaved intermediate to the other two treatments.

The MWD and GMD of water-stable aggregates were also significantly affected by the treatments, with no till+straw giving as much as 4 times the GMD of till+no straw (Table 2.6). The average D_{50} values for no till+straw, till+straw and till+no straw treatments were 3.0, 1.0 and 0.4 mm, respectively.

Soil aggregates have been divided into two size categories (or hierarchical orders) that appear to depend on different binding agents for their water-stability (Tisdall and Oades, 1982; Oades, 1984; Dexter, 1988). Microaggregates (< 0.250 mm dia) are considered to depend on organo-mineral associations (involving mostly polysaccharides) for stability against disruptive forces caused by rapid wetting and mechanical disturbance. The organic matter which stabilizes microaggregates is incorporated in the small pore spaces between domains and other clusters, and is well protected against microbial attack. The stability of microaggregates, may therefore, be relatively permanent and as such rather insensitive to cropping and management. On the other hand, macroaggregates (>0.250 mm) are mostly formed when soil is enmeshed by living or partially-decomposed roots and fungal hyphae. The organic matter which stabilizes the larger aggregates is, thus, constantly renewed by crop growth and is readily accessible to decomposition. Therefore, the amount and stability of macroaggregates is greatly influenced by cropping and management practices especially tillage and residue disposition.

Based on this criterion (0.250 mm), the proportion of micro- and macro-aggregates was, respectively, 12 and 88% in no till+straw treatment, 23 and 77% in till+straw, and 42 and 58% in till+no straw treatment. These data suggest that soil in the till+no straw treatment is still well aggregated.

The treatment differences with regard to micro- vs. macro-aggregates seem to be associated mainly with differences in tillage. Although the no till+straw treatment significantly increased organic-C content of the 0–5-cm soil (Table 2.5), it appears that in the present case organic matter content has only a limited contribution in causing the treatment differences as it has been reported (Kemper and Koch, 1966) that at about 20 g kg^{-1} or more organic matter contents, aggregate status is much less sensitive to organic matter concentration. The organic matter content (=organic carbon x 1.724) of the 0–5-cm depth was greater than 9% (i.e. 90 g kg^{-1}) in all the treatments in the present research. It is therefore inferred that some phenomenon (other than % C) associated with tillage influenced the distribution between micro- and macro-aggregates. One such phenomenon is physical disturbance.

2.3.8.3 *Aggregation- and water-stability indices*

Values of dry-aggregation index (DAI) did not vary significantly between treatments (Table 2.7). If quality of soil structure in the seedbed is mainly related to its size-distribution of air-dry aggregates (Braunack and Dexter, 1989), then all three tillage-residue systems could be considered to possess a good dry-aggregate composition because DAI exceeded 400 in each case (Dobrazanski et al., 1975; Carter et al., 1990). The no till+straw treatment, however, showed a significantly greater water-stable aggregation index (WAI) compared with the tilled treatments. Thus this system will likely resist water erosion more effectively than the others. The till+no straw system had the smallest WAI, indicating its greater susceptibility to water erosion. The till+straw treatment was between the other two, but it was closer to no till+straw than to till+no straw, again showing the beneficial effect of straw in aggregation process.

The water-stability index (WSI), which characterizes the change in aggregate distribution upon treatment with water, behaved similarly to WAI, but unlike WAI the difference between no till+straw and till+straw was not significant (Table 2.7). A greater than 1 value of WSI indicates an increase in the number of aggregates of more desirable sizes after water treatment. Smaller the value of WSI<1, greater is the destruction of agronomically desirable aggregates. Accordingly, in till+no straw treatment, aggregates underwent pulverization showing their lower stability in water. In the no-till treatment, however, the aggregate size distribution became more favorable to plant growth after the action of water. There was not much change in the case of till+straw treatment.

Enhanced aggregate stability of the topsoil with no-till or direct-drill systems compared with conventional-till systems has been observed for several sandy loam to silty clay loam soils in Indiana (Mannering et al., 1975; Kladivko et al., 1986), silty soils in Germany (Ehlers, 1979) and clay soils in Great Britain (Douglass and Goss, 1982). The improved soil structure was invariably attributed to an increase in soil organic matter and lack of soil disturbance.

2.4 CONCLUSIONS

The studied tillage and residue management systems considerably affected the soil surface conditions and the other measured soil properties. Both degree of surface residue cover and soil surface roughness had a large temporal variation. Residue cover was in the order: no till+straw >till+straw >till+no straw, both after tillage-cum-seeding operations as well as over the non-growing period. The residue cover in the till+no straw treatment was inadequate from a soil conservation perspective. The no till+straw system generally had the minimum soil surface roughness.

Minimal soil disturbance in the no-till system has resulted in some stratification of organic carbon, pH and particle density. Despite this soil having an initially high organic-C content and good aggregation, the no-till treatment significantly increased the soil organic-C and average size of both air-dry and water-stable aggregates in the surface 0–5 cm depth, compared with the till+no straw treatment. The till+straw was usually between the other two treatments. Average per cent organic-C in 0-15-cm layer was, however, not different in the two straw treatments. The top 5 cm soil was significantly more acidic in no-till than in other treatments.

The surface soil in the no till+straw treatment had a considerably lower proportion of wind erodible as well as water-slakable aggregates. This treatment also had a significantly higher wet-aggregation index as well as water-stability index. Behavior of the till+straw treatment was intermediate. The dry-aggregation index was similar among the treatments.

The measured surface conditions and soil characteristics indicated that for the soil-climatic conditions of this study, the no till+straw system had the highest soil quality from a soil conservation perspective.

Table 2.1 Management practices for spring barley over the study period.

Operation	1988	1989
Spring tillage	May 19	May 26
Seeding and fertilization	May 19	May 26
Herbicide application	June 10	June 18
Harvesting	Aug. 29	Sept. 1
Fall tillage	Oct. 21	Oct. 16

Table 2.2 Surface residue cover as affected by tillage and residue management practices and seasonal change.

Tillage-residue System	Residue cover (%)[¶]				
	1988		1989		
	After spring till & seeding (May 27)	After fall tillage (Oct. 23)	Before spring tillage (May 12)	After spring till & seeding (June 4)	After fall tillage (Oct. 21)
No till+straw	79 b[†] A[‡]	99 a A	95 a A	70 c A	99 a A
Till+straw	42 d B	85 a B	80 b B	41 d B	61 c B
Till+no straw	14 a C	11 ab C	16 a C	6 b C	12 a C

¶ Each value in the table is derived from 16-20 sets of measurements.

† Means for a tillage system followed by a common lower case letter are not significantly different (P=0.05) using DMR test.

‡ Means for a time of measurement above a common upper case letter are not significantly different (P=0.05) using DMR test.

Table 2.3 Soil surface roughness as affected by tillage and residue management system and seasonal change.

Tillage-residue System	Soil surface roughness (cm)[¶]					
	1988			1989		
	After spring till & seeding (May 27)	After harvest, before fall till (Oct. 6)	After fall tillage (Oct. 28)	Before spring tillage (May 2)	After spring till & seeding (June 8)	After harvest, before fall till (Sept. 20)
No till+straw	1.137 a[†] A[‡]	0.635 b A	0.635[§] b A	0.703 b A	0.952 a A	0.755 b A
Till+straw	1.418 b B	0.596 d A	1.034 c B	1.081 c B	1.681 a B	1.108 c B
Till+no straw	1.507 a B	0.590 c A	0.873 b B	1.065 b B	1.617 a B	0.959 b B

¶ Each value in the table is derived from 450-900 surface elevation points.

† Means for a tillage system followed by a common lower case letter are not significantly different (P=0.05) using DMR test.

‡ Means for a time of measurement above a common upper case letter are not significantly different (P=0.05) using DMR test.

§ Value assumed same as that on Oct. 6.

Table 2.4 Soil particle size distribution (%, w/w) for three depth intervals.

Tillage-residue System	Clay (<2)†	Silt (2-50)	F.silt (2-5)	Sand (5-2000)	F.sand (50-250)	Fine sand / Coarse sand	Texture class‡
				0-5 cm			
No till+straw	37.7	43.9	10.4	18.5	12.9	6.5	SiCL
Till+straw	37.8	44.5	11.5	17.7	12.3	7.4	SiCL
Till+no straw	37.7	44.4	11.3	18.0	12.5	6.7	SiCL
				5-10 cm			
No till+straw	38.1	40.5	7.6	21.4	15.0	6.6	CL
Till+straw	38.7	40.1	8.7	21.2	14.7	6.4	CL
Till+no straw	38.3	39.5	7.6	22.2	15.4	6.7	CL
				10-15 cm			
No till+straw	40.8	38.6	8.2	20.6	14.6	7.2	C
Till+straw	40.3	39.4	7.5	20.2	14.2	7.2	C
Till+no straw	42.2	34.1	7.3	23.8	16.7	6.7	C

† Numbers in parentheses are particle sizes in µm.

‡ Based on Canada Soil Survey Committee.

SiCL-silty clay loam, CL-clay loam, C-clay

Table 2.5 Soil organic carbon, particle density, pH and electrical conductivity under three tillage-residue systems.

Tillage-residue	Soil depth (cm)							
System	0-5	5-10	10-15	Mean	0-5	5-10	10-15	Mean
	Organic C (%, w/w)				*Particle density (Mg m^{-3})*			
No till+straw	6.30 a† A‡	5.78 b AB	5.34 c A	5.81 A	2.45 b B	2.49 a A	2.49 a A	2.47 A
Till+straw	6.05 a B	5.89 a A	5.44 b A	5.79 A	2.45 a AB	2.47 a A	2.48 a A	2.47 A
Till+no straw	5.52 a C	5.55 a B	5.29 b A	5.45 B	2.49 a A	2.49 a A	2.50 a A	2.49 A
Mean	5.96 a	5.74 b	5.36 c		2.46 b	2.48 ab	2.49 a	
	pH				*EC (dS m^{-1})*			
No till+straw	5.62 c B	5.79 b A	5.95 a A	5.79 A	0.25 a A	0.21 b A	0.22 b A	0.23 A
Till+straw	5.72 b AB	5.73 b A	5.84 a B	5.76 A	0.21 a B	0.23 a A	0.22 a A	0.22 A
Till+no straw	5.76 b A	5.80 ab A	5.86 a AB	5.81 A	0.21 a B	0.18 b B	0.19 ab B	0.20 B
Mean	5.70 c	5.77 b	5.88 a		0.23 a	0.21 b	0.21 ab	

† Means for a tillage system followed by a common lower case letter are not significantly different (P=0.05) using DMR test.

‡ Means for a depth interval above a common upper case letter are not significantly different (P=0.05) using DMR test.

Table 2.6 Tillage and residue management effects on mean weight diameter (MWD, mm) and geometric mean diameter (GMD, mm) of air-dry and water-stable aggregates in the 0-5 cm soil depth.

Tillage-residue System	MWD±SD†	GMD±SD
	Dry aggregates	
No till+straw	7.7±2.2 a‡	4.3±1.3 a
Till+straw	5.6±1.7 a	2.6±0.8 b
Till+no straw	2.8±1.1 b	1.1±0.4 c
	Water-stable aggregates	
No till+straw	3.3±0.6 a	1.8±0.4 a
Till+straw	2.3±0.4 b	1.0±0.2 b
Till+no straw	1.3±0.3 c	0.4±0.1 c

† SD refers to standard deviation of the mean (n=4).

‡ Means in a column followed by a common letter are not significantly different (P=0.05) using LSD test.

The comparisons are valid only within a given aggregate analysis method.

Table 2.7 Dry- and wet-aggregation indices and water-stability index for 0-5 cm soil layer.

Tillage-residue System	DAI†	WAI‡	WSI¶
No till+straw	405 a§	456 a	1.15 a
Till+straw	409 a	392 b	0.97 a
Till+no straw	442 a	302 c	0.68 b

† Dry-aggregation index.
‡ Water-stable aggregation index.
¶ Water-stability index.
§ Means in a column followed by a common letter are not significantly different (P=0.05) using LSD test.

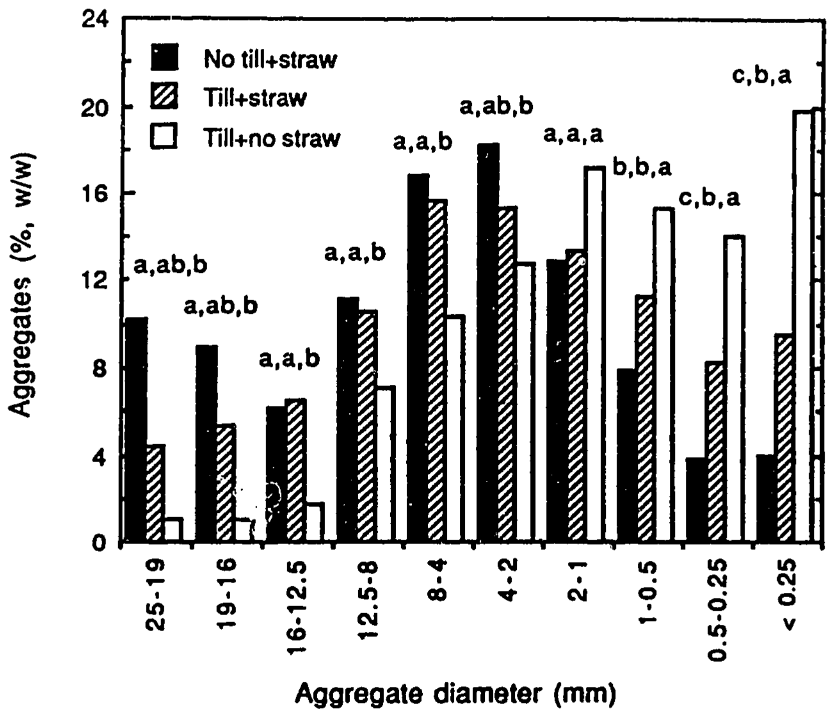

Figure 2.1. Size distribution (mass of aggregates of a given size-range in relation to total mass) of air dry aggregates in the 0-5 cm soil layer. Within a given aggregate size-range, treatment means with the same letters are not significantly different (P=0.05).

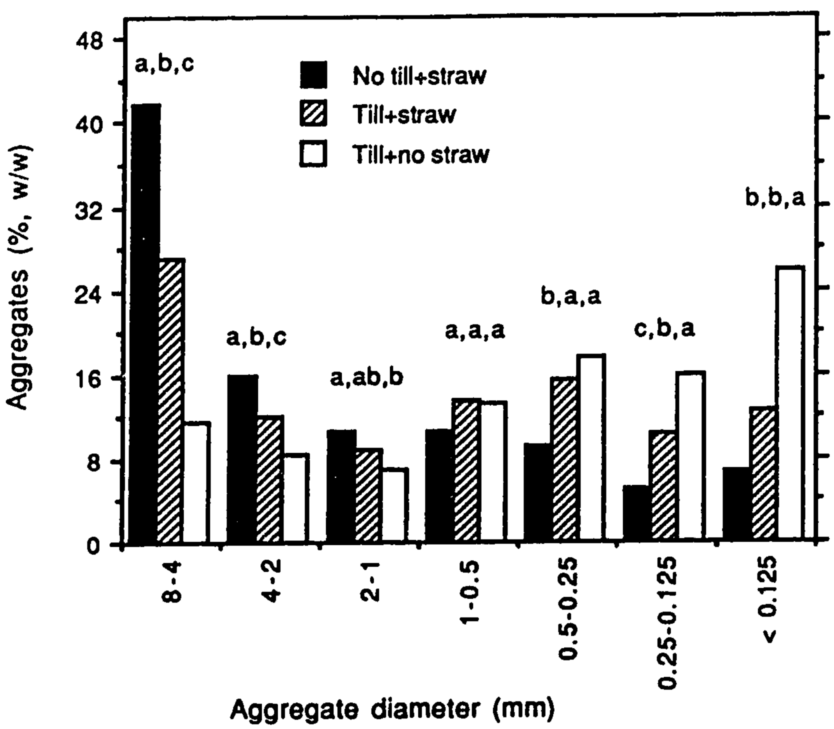

Figure 2.2. Size distribution (mass of aggregates of a given size-range in relation to total mass) of water-stable aggregates in the 0-5 cm soil layer. Within a given aggregate size-range, treatment means with the same letters are not significantly different (P=0.05).

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Chapter 3

LONG-TERM TILLAGE AND RESIDUE MANAGEMENT EFFECTS ON BULK DENSITY, POROS[illegible] SOIL STRENGTH OF A TYPIC CRYOBOROLL UND[illegible]NUOUS SPRING BARLEY

3.1 INTRODUCTION

Soil bulk density and porosity profoundly influence air-water relations and potential productivity of a soil (Blevins et al., 1984). Similarly, soil strength (mechanical impedance) has been reported to influence crop root growth (Voorhees et al., 1975; Ehlers et al., 1983; McAfee et al., 1989). These soil properties (among others) are almost always altered by tillage (or lack thereof) and crop residues. The reported effects of such management practices, particularly no-tillage, are quite variable and often contradictory. A greater bulk density (Db) in no-till or direct-drill than in a conventional tillage system was observed, for example, by Gantzer and Blake (1978) for a clay loam (Aquic Argiudoll) under corn for 6 years in Minnesota, and by Pidgeon and Soane (1977) for sandy loam to clay loam soils cropped to barley for 7 years in Scotland. On a Georgia Hapludult, Nesmith et al. (1987) also measured greater Db and mechanical impedance in the Ap horizons under no-tillage double cropped soybean compared to a moldboard plow-disk system. Hammel (1989) observed a significantly greater Db in a no-till system compared with a moldboard plow system for two silt loam Xerolls under 10 years of winter wheat plus spring rotations in northern Idaho. Van Ouwerkerk and Boone (1970) reported lower total porosity under untilled than under tilled conditions for some Netherland soils.

In contrast, other researchers have not observed a significant difference in bulk density of conventional and no-till systems. Among these are: Shear and Moschler (1969) after 6 years of continuous no-till corn in Virginia; Blevins et al. (1983) after 10 years of continuous corn on an Hapludalf in Kentucky; Hill and Cruse (1985) for a clay loamy Haplaquoll and a loamy Hapludoll under corn for two and eight years in Iowa; Tollner et al. (1984) for an acid soil under wheat-soybean rotation for 7 years in the southern Piedmont.

Soil strength in the upper portion of the soil profile, as measured with a penetrometer, has usually been observed to be greater under no-till or minimum-till systems than under conventional tillage in continuous long-term field studies (Bauder et al., 1981; Lindstrom et al., 1984; Tollner et al., 1984; Hill and Cruse, 1985; Hammel, 1989). Under certain conditions, some soils may also be subject to formation of traffic- or tillage-induced layers with root-restricting soil strength and bulk density (Voorhees et al., 1978; Swan et al., 1987).

Soil penetration resistance (PR) is generally considered a more sensitive indicator of tillage-induced changes in soil behavior and root response than Db (Pidgeon and Soane, 1977; Voorhees et al., 1978; Bauder et al., 1981; Hammel, 1989). Bauder et al. (1981) observed no effect of tillage on moist Db during the 10th year of study, but measured considerably greater PR (>2 MPa) in the near-surface zones of untilled plots. Pidgeon and Soane (1977) reported that PR continued to increase with time although Db in the tillage zone reached an equilibrium value three years after introduction of tillage treatments. Straw disposal methods (removal, incorporation, surface retention, etc.) may also differently affect soil bulk density, moisture content, soil strength, pore-size distribution, etc., thus modifying the effects of tillage on these properties.

Soil strength is considered a strong function of moisture content and Db (e.g. Taylor and Gardner, 1963; Mirreh and Ketcheson, 1972). It is also related in a poorly understood manner to other soil-related factors such as clay mineralogy, texture, structure, and percent organic matter (Cassel, 1982). The site, weather, climate and possibly crop-related factors may further moderate the extent and direction of change in bulk density and soil strength as a result of tillage-residue practices. The usually observed large spatial and temporal variation in these properties, if not properly considered, may mask treatment differences and create problems in interpretation and use of the data (Cassel, 1982).

Scientific information on the effects of various long-term tillage-cum-residue management practices on bulk density and soil strength under the soil and agroclimatic conditions of Central Alberta (subhumid-cryoboreal with annual freeze-thaw cycles) is generally lacking. In the previous chapter, effects of three tillage-residue systems on soil surface conditions, organic matter content, aggregation and some other properties of a naturally well-aggregated Mollisol (Black Chernozemic) under continuous barley (*Hordeum vulgare* L.) production in Central Alberta were examined as part of a broader study. The objective of the research reported in this chapter was to quantify the effects of these practices on soil bulk density, soil strength and total soil porosity. The study monitored these soil characteristics during the course of a growing season in two row positions, in-row and between-row, and at different depths.

3.2 MATERIALS AND METHODS

3.2.1 *Site and soil description*

The research was conducted during the 1988 and 1989 growing seasons on field plots located near Edmonton at the Ellerslie Research Station (53^{o} 25' N, 113^{o} 33' W; 694 m above sea level) of the University of Alberta. The soil of the experimental site was developed from lacustrine deposits and is classified as: fine loamy, mixed, Typic Cryoboroll according to Soil Taxonomy (Soil Survey Staff, 1975) and a Black Chernozemic according to the Canadian System of Soil Classification (Crown and Greenlee, 1978). It has good internal drainage and a moderate swell-shrink potential. Other soil, site and climate details are given in Chapter 2.

3.2.2 *Tillage -residue treatments*

Ten tillage, residue and nitrogen management systems were established in the fall of 1979 to investigate the long-term effects of these systems on soil environment and crop growth. Three of these were selected for the present study: (1) no-tillage, straw retained on the surface, (2) conventional tillage, straw retained and incorporated, and (3) conventional tillage with straw removed.

Conventional tillage consisted of late fall cultivation using a rotovator. followed by similar spring cultivation at the time of seeding. The tillage depth was approximately 10 cm. In the no-till treatment, the crop was seeded directly without tillage. The only disturbance of soil in this treatment was the seed-drill and a small reaper-binder. The crop was harvested approximately 10 cm above the soil surface. In treatments (1) and (2), threshed straw from each plot was returned to the corresponding plot and uniformly spread before fall tillage. In treatment (3), all straw and most of the stubble were removed before tillage. Treatments were replicated four times in a randomized complete block design and repeated annually.

The plots were seeded to spring barley at 5 cm depth each year. The crop rows, 22.5 cm apart, were located in approximately the same position each year. Weeds were controlled chemically. Details regarding the machinery used and other agronomic practices for the two years of the present study are given in Chapter 2.

3.2.3. *Measurements and calculations*

3.2.3.1 *Soil bulk density and porosity*

The (dry) bulk density of soil (Db) was determined using soil cores and a gamma ray attenuation technique (Gardner, 1986). A pre-calibrated surface moisture-density gauge (Model MC-1, Campbell Pacific Nuclear Corp., California) was used to measure the average soil Db in the 0–10-cm depth, both in the in-row and between-row position at two randomly selected locations within each plot. The reading at each depth was repeated after rotating the probe through a 90^0 angle. A moisture-density combination probe (Model 501, Campbell Pacific Nuclear Corp., California), which concurrently measures the wet bulk density and volumetric water content of a given depth interval of soil, was used to determine soil Db below 15 cm at 10-cm increments in the same access tubes (one per plot) as used for moisture measurement with neutron probes. Dry bulk density was calculated as the difference between wet bulk density and fractional volumetric water content.

To provide adequate resolution in measuring tillage-induced changes in Db within surface soil, and to detect any compact layer, 'undisturbed' soil cores 7.6-cm dia. by 7.5-cm length were obtained from the 0-7.5-cm and 7.5-15-cm depths with a modified Uhland core sampler (Blake and Hartge, 1986). Cores were taken only in the interrow spaces at two randomly selected locations within each plot, twice in 1988 (July 11 and September 21) and once in 1989 (September 21). Sampling was done when the soil water was sufficient to facilitate uniform sampling with a minimum of compaction or shattering.

Care was taken during sampling to avoid any visible traffic from field operations; such traffic can have significant effects on soil physical properties (Voorhees et al., 1978), and thereby affect the treatment response. In order to minimize resistances, the inside and outside surfaces of the aluminum cores were completely cleaned before taking each sample. For the 0–7.5-cm depth, the sampler could be usually hand-pushed to the required depth, while for the 7.5–15-cm depth, a few gentle light-hammer blows onto a wooden block placed on top of the sampler were needed. Cores that compacted or shattered during the process were discarded. The 0–7.5-cm and 7.5–15-cm cores were taken from different but adjacent locations because of disturbance caused in taking the first core. For the 1989 sampling, cores were sectioned carefully in the field at 2.5-cm increments with a jewellers saw having a very fine blade. The 1988 cores were stored at 4 ^oC prior to further use to minimize biological activity. Bulk density was calculated on an oven-dry (105 ^oC) basis.

Total soil porosity (f_t, % v/v) was computed using the relation: $f_t = 100(1\text{-Db}/\rho_s)$ where ρ_s is particle density of soil including its organic matter content. Measured values of ρ_s, which varied among treatments and depths (Chapter 2), were used for computations.

3.2.3.2 *Penetration resistance*

Soil resistance to penetration (PR) was measured to 45-cm depth when soil water in the upper soil layers facilitated uniform sampling. As for Db, measurements were made at two row-positions, in the crop row and midway between adjacent rows, at two randomly selected locations in each plot. Further at each location, two penetrations were made approximately 30 cm apart for each position. Thus for a given treatment, position and depth, there were 16 measurements at each time of sampling. However, for the purpose of statistical analysis, the two penetrations at each location were averaged.

In 1988, PR was measured with a manually operated proving-ring cone penetrometer (Model CN-973, SOILTEST, Inc., Illinois, USA) equipped with a 30^o cone having 3.2 cm^2 basal area (20.3 mm dia) and 45-cm extension rod 15.9 mm in diameter. The measurements were made on June 2 (14 days after seeding and tillage) and September 13 (15 days after harvest). The depths sampled were surface (when the base of the cone is flush with the soil surface), 2.5, 5, 7.5, 10, 12.5, 15, 20, 25, 30, 35 and 45 cm. In the second year, PR was measured four times: April 26 (before spring tillage and seeding), June 13 (18 days after tillage and seeding), July 13 (mid-season) and September 5 (4 days after harvest), using a manually operated recording penetrometer equipped with a 30^o cone having a 0.95 cm^2 basal area (11 mm dia) and a 45-cm long extension rod (Model CP-10, RIMIK PTY LTD, Toowoomba, Australia). This penetrometer is preset to measure and record PR readings at 15-mm increments to a maximum depth of 45 cm (30 readings per penetration). With both the penetrometers, it took approximately 15 to 20 seconds for a 45-cm insertion.

Concurrent with PR measurements, soil water content was determined gravimetrically and/or with moisture-density probes and/or a neutron probe, adjacent to penetrometer sampling locations.

3.2.3.3 *Statistical analyses*

The bulk density, porosity and PR data were subjected to analysis of variance using UANOVA procedure of the $SPSS^x$ statistical program. This procedure has been developed at the University of Alberta (T. Taerum, Personal Comm., 1990). Analysis was treated as a modified multi-split plot design (R.T. Hardin, Personal Comm., 1990) with tillage as whole plots, time of measurement (if any) as subplot, row-position (if any) as sub-subplot and soil depth (if any) as sub-sub-subplot treatments. The location effect was calculated separately as sampling error and excluded from the relevant error term. Data were tested for fulfillment of the assumptions of analysis of variance (homogeneity of variances, normal distribution, etc.). These tests showed that PR data needed transformation. A log-transformation, as suggested by some researchers (e.g. Cassel and Nelson, 1979), did not improve the tests for normality and homogeneity of variances to the desired level. The Box-Cox transformation procedure (Sokal and Rohlf, 1981) was used to find the best possible transformation for the current data sets. This transformation is of the form:

$$Y' = (Y^{\lambda} - 1)/\lambda, \qquad (\lambda \neq 0)$$

$$Y' = \ln Y, \qquad (\lambda = 0)$$

where Y and Y' are the original and transformed values, respectively. The value of λ was automatically calculated by the computer program (subroutine BOXCOX of the $SPSS^x$ package) and was 0.5613 and 0.3242 for the first and second year of data. Least significant difference (LSD) or Duncan's Multiple Range (DMR) tests (usually $P \leq 0.05$) were performed for means separation of significant main effects and interactions.

3.3 RESULTS AND DISCUSSION

3.3.1 *Soil bulk density*

3.3.1.1 *Surface bulk density (averaged 0-10 cm)*

Main effects of tillage treatment (T), row-position (P) and time of measurement (t), as well as t x P interaction on the surface (0 to 10-cm depth) soil dry bulk density (Db) were significant (P=0.01) during each year of measurements (Table 3.1).

Averaged over position, the no-till treatment had a significantly greater Db than both the tilled treatments, as measured two weeks after spring tillage and seeding in 1988 (Table 3.2). After this, the two treatments that received straw showed only a negligible increase in average Db, but the till+no straw treatment had a significant compaction resulting in a maximum Db of 1.08 Mg m^{-3} (significantly greater than even the no-till treatment) at the time of harvest. Thus the effect of tillage in decreasing Db of till+no straw treatment had disappeared by the end of the growing season (15 weeks after sowing). Adeoye (1982) observed similar temporal effects on Db of a plowed tropical soil. Tiarks et al. (1974) reported a study in which temporal changes in Db exceeded the differences effected by tillage treatments. In the present study, the minimum Db was observed in the till+straw treatment throughout the growing season.

Fall cultivation reduced Db of the surface 10 cm from 0.99 to 0.92 Mg m^{-3} (7%) in the till+straw and from 1.08 to 0.99 Mg m^{-3} (8%) in the till+no straw treatment, as measured on 2 November, 12 days after cultivation. There was not much change in Db over the winter period in any of the treatments (Tables 3.2 and 3.3). This implies that freeze-thaw cycles probably did not affect the tillage-induced changes in Db. Kay et al. (1985) reported almost similar effects of ground freezing on soil Db under zero and conventional tillage in Ontario. They hypothesized that ice lenses create inherently unstable pores that collapse as the ice melts and the soil drains. As a result, soil quickly reconsolidates upon thawing and returns to near pre-freezing bulk densities prior to spring planting.

The spring tillage and seeding operations in the second year further reduced the average Db of both tilled treatments by 5-8% compared with the pre-seeding values (Table 3.3). In the no-till treatment, the seeding operation caused only a very small decline in soil

Db. At all times of measurement in 1989, Db followed the pattern: no till+straw > till+no straw > till+straw. These trends were generally consistent with those observed in the first year.

Positional differences in soil bulk density varied during a growing season. Db in the between-row (BR) position was greater than that of the in-row (IR) position by 13-18% on June 2, 1988 (Table 3.2). On August 1, the positional differences had disappeared, but on September 13 soil in the BR position was again 3-5% more dense. The positional differences averaged across treatments were significant for the June 2 and September 13 measurements. During 1989, soil in the BR position continued to be significantly denser than that in the IR position for all post-seeding measurements. The differences for various treatments and measurement times varied from 9 to 23%, except that the no-till treatment on June 13 had only a 2% difference. A greater decrease in Db of soil in IR position (9-13%) than that in the BR position (1-4%) in the tilled treatments soon after 1989 sowing might be related with the type of tillage and seeding operations.

Averaged across time of measurement, soil Db was greater in the BR position in each of the three treatments (5-6% in the first year and 6-10% in the second year). This explains the lack of significance for the tillage x position interaction in both years (Table 3.1). Averaged across time of measurement and position, Db of the no-till treatment was the same in both years (1.02 Mg m^{-3}), indicating that the soil in this system has attained an equilibrium bulk density. Pidgeon and Soane (1977) reported that no-till soil (below 6-cm depth) in their study had reached an equilibrium Db after 3 years.

These tillage, position and temporal effects on surface Db can be attributed to the type of tillage and straw management practiced and the seasonal rainfall. Straw retained on the soil surface as mulch (as in the no till+straw treatment) dissipates the energy of rain drops before they reach the soil surface; straw incorporated in surface soil (also providing a partial surface cover) acts as a cushion against the compacting action of rain. Also the straw treatments had a greater number of larger-sized water-stable aggregates than the no-straw treatment (Chapter 2). This would also help resist densification of soil in the straw treatments.

In contrast, an almost bare soil surface in the till+no straw treatment is exposed to the beating action of rain causing soil slumping, and thus together with having predominantly smaller water-stable aggregates and lower water-stability, is more prone to compaction than soil in the straw treatments. This is consistent with the large increase observed in soil Db of the till+no straw treatment from 1 August to 13 September, 1988. During this period, 98 mm of rain was received, and many leaves on the plants had senesced leaving a largely vertically oriented canopy. Note that the crop was harvested on 29 August. More rapid drying of surface soil after each rainfall event in the till+no straw treatment because of its almost bare soil surface would speed settling of soil due to cohesive and adhesive forces (Camp and Gill, 1969). Temporal variation in Db can also result from repeated shrinking and swelling of soil (Berndt and Coughlan, 1976)

3.3.1.2 *Bulk density with depth (0-15 cm , by 2.5 cm intervals)*

The main effects of tillage treatment (T), time of measurement (t) and soil depth (D), as well as the T x D interaction were significant ($P \leq 0.05$) for Db determined on soil cores by volume-mass measurements during 1988. Similarly, the T, D and T x D interaction effects were significant for a single measurement in 1989. Although the time x tillage x depth interaction during 1988 was non-significant at $P=0.05$, preplanned T x D mean comparisons were made for each of the two times of measurement (T. Taerum, personal comm., 1990).

The lowest soil Db was observed in the till+straw treatment in all 2.5-cm layers to 15-cm depth during both years, the only exception being the 0-2.5-cm layer in 1989 (Fig. 3.1). Soil Db was similar in the 0–2.5-cm depth of all three treatments at the middle of the growing season in 1988 (July 11). However, at harvest time in both years, the no till+straw treatment had a significantly lower (7 and 11%) Db in this layer than the till+no straw treatment. A greater compaction of the almost bare surface of the till+no straw plots was likely caused by seasonal rains, whereas accumulation of both decomposed and undecomposed organic matter close to the soil surface in the no-till treatment prevented densification. In the next three 2.5-cm increments (2.5 to 10-cm depth), the no till+straw treatment had the highest soil Db at all times of measurement. The only significant differences found, however, were between the no till+straw and till+straw treatments in the 2.5-5-cm depth in both years and among all three treatments in the 5-7.5-cm depth in the second year. Below 7.5-cm depth the treatment differences were always nonsignificant.

Averaged over all depths in the 0–15-cm zone, the Db in the no till+straw, till+straw and till+no straw plots was, respectively 1.00, 0.96 and 1.00 Mg m^{-3} in 1988 (N=96), and 1.03, 0.97 and 1.01 Mg m^{-3} in 1989 (N=48). In both years, Db of soil in the no till+straw treatment was significantly greater than that in the till+straw treatment, but similar to that of the till+no straw treatment. Surprisingly, a small difference of 0.04 Mg m^{-3} tested significant. Significant tillage x depth interactions point out the necessity of measuring Db at smaller depth intervals within, and for some depths below, the tilled zone in order to discern treatment differences, if any. Similarity of average Db values in different treatments in the two years confirmed the earlier indication (section 3.3.1.1) that soil has probably attained an equilibrium bulk density with the imposed management practices.

3.3.1.3 *Db vs. plant growth considerations*

Bulk density ranges required for optimum plant growth are unknown for most soils (Cassel, 1982). The relations between Db changes induced by tillage and plant growth and yield are also not well understood. Further, the Db values at which root growth ceases or is restricted (critical or limiting bulk density) for a given crop species vary with soil water content, soil texture, and soil structure (Jones, 1983). Pierce et al. (1983) developed criteria for estimating non-limiting, critical and root-limiting soil bulk densities based on basic soil physical properties. According to their estimates, the non-limiting, critical and root-limiting bulk densities for the soil used in this study (fine loamy family texture class) are 1.46, 1.67 and 1.78 Mg m^{-3}, respectively. Assuming validity of the above model for conditions of the present study, none of the bulk densities measured to a depth of 90 cm (data for depths below 15 cm not presented) is expected to adversely affect root growth and proliferation.

3.3.2 *Total soil porosity*

The tillage and depth effects on total soil porosity were quite similar to those on Db. However, the differences became smaller due to variation of particle density values with treatment and depth. In the 0-2.5-cm layer, the no till+straw treatment displayed significantly greater porosity (f_t) than the till+no straw treatment during both years, although differences were rather small (Table 3.4). The two straw-involving treatments were similar in this layer. In the 2.5 to 7.5-cm layer, however, the no-till treatment had the minimum f_t. Below 7.5-cm depth, there were no differences among treatments in both years. The till+straw treatment showed a greater f_t in all the depths. Douglas et al. (1980) and Coote and Malcolm-McGovern (1989) reported a lower average porosity on direct-drilled and no-till plots than the tilled plots, for a clay soil and on two out of three sites, respectively.

Differences detected among treatments were small, though mostly significant. They are not expected to affect significantly the soil hydraulic behavior or plant response because the characteristic porosity as well as infiltration rate and hydraulic conductivity (Chapter 4) of this soil are all high. This will help in maintaining a sufficient air-filled porosity level even in quite wet conditions. The effect of lower porosity in the no-till treatment at the 2.5-7.5-cm depth is offset, at least in part, by a greater number of continuous earthworm channels and biopores created by the roots of the preceding crops (data not presented), which can function as a preferred pathway for water movement (Ehlers, 1975) as well as for root penetration and colonization (Edwards and Lofty, 1980; Ellis and Barnes, 1980; Ehlers et al., 1983).

3.3.3 *Soil penetration resistance*

Results of analyses of variance conducted on the Box-Cox transformed soil penetration resistance (PR) data are given in Table 3.5. The model, which explained 88 and 83% of the total variation in the data for 1988 and 1989 measurements, included main and interaction effects of tillage system, row-position, depth and time of measurement. Because the time x tillage x depth interaction was significant each year, it is important to consider variation in PR with depth for tillage treatments separately for each measurement time. The two years were not compared as such because different penetrometers were used eac: ear.

3.3.3.1 *The 1988 trends*

On June 2 (two weeks after spring tillage and seeding in 1988), PR of the 0-7.5-cm soil (averaged over position) was the highest in the no till+straw treatment while the two tilled treatments were quite similar with the lowest PR in the till+straw (Fig. 3.2A). Increases for the no-till treatment over the till+straw varied from 32 to 101% (all significant) while those over till+no straw varied from 19 to 85% (significant except at 7.5-cm depth). Soil water content in surface 10-cm of the no-till treatment was also greater (by 4 to 5% absolute) than that of the tilled treatments which were similar (Table 3.6). Thus the PR differences in the 0-10-cm depth cannot be attributed to soil water content. Db of this soil layer was, however, somewhat greater in no-till than in the tilled treatments (1.02 vs. 0.96 and 0.99 Mg m^{-3}) and may have caused the observed PR differences.

Below 10 cm to a depth of 45 cm, significantly greater PR was observed in the till+no straw treatment than the other two treatments which were almost identical; this was partially explained by soil water content which was usually less (1 to 4%) in the till+no straw treatment. An increased bearing capacity of soil below tillage depth in the no-till treatment is probably also indicated by these observations (Culley et al., 1987). Soil strength increased with depth; the patterns of increase were somewhat different in the three treatments in the 0-15-cm depth, but the differences did not persist below that depth.

Over the growing season, PR in the 0-2.5 cm layer increased in all three treatments; the largest increase (>6 fold) was in the till+no straw treatment, as measured on 13 September (Figures 3.2B and 3.2A). This is attributed primarily to greater rainfall-induced compaction of the bare soil surface of the tilled+no straw plots than of the other two straw-involving treatments. Except this difference, the trends among treatments were similar to those observed on 2 June. Averaged across time and depth of measurement, PR of the till+no straw soil (1019 kPa) was significantly greater than that of the other two systems which were similar, with no till+straw and till+straw having an average PR of 880 and 825 kPa, respectively.

The effect of row-position varied with tillage system, soil depth and time of measurement. The positional differences were much more pronounced after tillage and seeding than at the end of the growing season. In the no till+straw treatment, PR was significantly greater in the between-row (BR) position only for 0-2.5-cm depth, the difference varying from 22-56% after seeding to 15-17% after harvest (data not shown). In the tilled treatments, however, the in-row (IR) position showed a significantly greater PR in the surface 10-cm depth, the difference usually decreasing with depth. Again the differences were much greater on 2 June (32-195% in till+straw, 12-182% in till+no straw), than on 13 September (0-11% and 1-8%). These positional effects are attributed to the effects of tillage and/or seeding, seasonal rainfall and natural soil subsidence or reconsolidation. A significant time x tillage x position interaction revealed that the effect of row position was significant only for the tilled treatments on June measurement (data not shown).

3.3.3.2 *The 1989 trends*

Of the 30 depths sampled during 1989, only those were selected for mean comparisons which corresponded closely to the depths studied during 1988. On April 26, a month before spring tillage and seeding, PR of the no till+straw treatment was significantly greater (22 to 120%) in the top 7.5-cm soil as compared with both tilled treatments which behaved similarly (Fig. 3.3A). The difference between no-till and till+straw treatments was significant to a 12-cm depth. Soil water content (Table 3.6) as well as Db (Table 3.3) were the highest in the no-till treatment. Below 15 cm, the till+no straw treatment had greater PR than the other two treatments which were similar. These trends correspond closely with those observed in 1988.

Treatment effects were similar on June 13 (after spring tillage and seeding) (Fig. 3.3B), although absolute values of PR were considerably lower than those on April 26. The treatment differences were again explained generally by Db in the surface depths and by moisture content in the lower depths. PR increased more steeply in surface soil of no-till than of the tilled treatments, a pattern evident at all times of measurement. This is perhaps a reflection of the less disturbed soil condition and therefore less uniform soil properties in the surface soil. The till+straw treatment had the lowest PR below 15 cm on July 13 (data not shown), but on June 13 the no-till treatment showed the lowest PR. Trends in soil water were, however, similar on these days with till+straw having the highest moisture (Table 3.7). This again demonstrates that soil water differences alone do not always account for observed PR differences.

At the end of the growing season (i.e. on September 5), PR of the top 15 cm soil was again the highest in the no-till system (Fig. 3.3C) which also had the greatest Db in 0-10 cm depth (Table 3.3) with soil water content less than or similar to other treatments (Table 3.7). From 15 to 30 cm depth, PR as well as the soil water content were similar in the three treatments. Between 30 and 40 cm depths, however, PR was maximum and soil water the minimum in the till+no straw treatment.

The effect of row-position was generally similar to that in 1988 with large temporal variation over the period from pre-seeding to harvest. On 26 April, both the no till+straw and till+straw treatments had a greater PR in the BR position in surface 7.5-cm soil, while till+no straw showed an opposite trend (data not shown). The differences usually decreased with depth. The Db data did not explain these differences. Positional differences increased and even changed trends after tillage and/or seeding operations. No till+straw treatment still had greater PR in the BR position in 0–5-cm depth while till+straw showed considerably greater (21 to 68%) PR in the IR position in 0–12-cm depth. The till+no straw treatment continued to have greater PR in the IR position (66 to 45%) in this depth.

Positional differences in the no-till system increased after seeding because seeding operation loosens the in-row soil to the seeding depth (approximately 5 cm), but has little effect on soil in the between-row position. In the tilled treatments, however, compaction wheels running behind hoe-openers of the seed-drill may be compacting the soil in the IR position relative to the BR position. By harvest time, positional differences were greatly reduced as a result of seasonal rainfall, natural soil settling, root activity, soil faunal (mostly earthworm) activity, etc.

3.3.3.3 *PR vs. root growth considerations*

Although it is difficult to compare soil strength values measured with penetrometers and the forces experienced by extending roots, penetrometer resistance is a valid and valuable parameter to assess changes in soil strength produced by tillage practices (Cassel, 1982). There is, however, lack of information regarding the critical soil penetration resistance for root growth of various plants under different soil conditions. Gerard et al. (1982) reported that critical soil strength at which root elongation stopped was a function of clay content of soil. It was 2.5 MPa in clay soils and 6 to 7 MPa in coarse-textured soils. Taylor et al. (1966) reported 2.0-2.5 MPa as root-restricting PR. Ehlers et al. (1983) reported a root-limiting PR of 3.6 MPa in the tilled Ap horizon but 4.6-5.1 MPa in the untilled one. The difference was attributed to the development of a continuous pore system in untilled soil, created by earthworms and the roots from preceding crops. These biopores of low soil strength can act as pathways and loci for root growth as well as for water movement. A relatively large number of macro-channels were observed in the no-till plots in this study also (data not presented).

Assuming validity of these limits for the conditions of the current study, none of the PR values measured in the potential root-zone seemed root-restricting. Nevertheless, in the event of drier soil conditions, soil strength may possibly increase and become root-restricting, particularly in the lower soil depths where PR is already high. A drier surface soil in the no-till system, together with higher Db and increased PR, may also have some deleterious effect on plant growth, especially root growth.

3.4 CONCLUSIONS

The studied tillage-residue systems affected soil bulk density, porosity and penetration resistance which varied temporally and spatially. The effects on Db were mostly confined to the uppermost 7.5 or 10 cm where the till+straw treatment always had the lowest Db. The no till+straw treatment usually had the highest Db (except in the first 2.5-cm depth) which persisted over the growing season. Differences between the no-till and the tilled treatments were generally significant. Db of the till+no straw treatment seemed most dynamic. Soil in the between-row position was usually more dense than that in the in-row position for all the treatments.

Freeze-thaw cycles over the winter period seemed to have negligible effect on the magnitude of and treatment trends in Db. Average (0-15 cm) Db in respective treatments was similar in the two years, indicating attainment of an equilibrium Db. The effects on total porosity were generally similar to those on Db.

Soil penetration resistance (PR) was affected to 45 cm, the lowest depth monitored. In the surface 10 cm, it was the highest in the no till+straw treatment; being usually significantly different from the tilled treatments which were similar. Below 10 to 15 cm, the till+no straw treatment had the highest PR while the other two treatments were similar. Overall trends were similar at different times of measurement although absolute values of PR changed. Treatment differences in the surface soil were mostly attributed to Db; moisture content was likely a major factor in the sub-surface.

The study did not reveal any tillage-induced layer of high Db or PR. Penetration resistance seemed to be a useful and sensitive indicator of tillage and straw-induced changes in soil physical environment. The results support the contention that it is essential to consider temporal and spatial (position and depth) effects on soil physical parameters such as PR and Db.

Table 3.1 Source of variation and level of significance for analysis of variance of soil bulk density (0-10 cm) for the 1988 and 1989 growing seasons.

Source	1988	1989
Tillage (T)	***	***
Time (t)	***	***
T x t	*	NS
Position (P)	***	***
T x P	NS	NS
t x P	***	***
T x t x P	NS	NS

*, **, *** indicate significance at the 0.10, 0.05 and 0.01 level of probability, respectively.

NS = nonsignificance at $P \leq 0.10$.

Table 3.2 Soil bulk density (average 0-10 cm) as affected by tillage treatment, row position and seasonal change during 1988.

Tillage-residue System	Row Position	Bulk density ($Mg\ m^{-3}$) on			
		June 2 (after seeding)	Aug. 1 (before harvest)	Sept. 13 (after harvest)	Nov. 2¶ (after tillage)
No till+straw	IR†	0.93	1.03	1.02	1.03
	BR‡	1.10	1.00	1.05	
Till+straw	IR	0.90	0.97	0.96	0.92
	BR	1.02	0.98	1.01	
Till+no straw	IR	0.92	1.01	1.05	0.99
	BR	1.05	1.02	1.10	

¶ Measurements in tilled treatments made without consideration of position. The data for this measurement was not included in the ANOVA. Fall tillage was on October 21.

† IR refers to the in-row postion.

‡ BR refers to the between-rows position.

Table 3.3 Soil bulk density (average 0-10 cm) as affected by tillage treatment, position and seasonal change during 1989.

Tillage-residue System	Position	Bulk density ($Mg\ m^{-3}$) on April 26 (before seeding)	June 13 (after seeding)	July 13 (mid-season)	Sept. 5 (after harvest)
No till+straw	IR†	1.01	0.99	0.97	0.98
	BR‡	1.03	1.01	1.08	1.09
Till+straw	IR	0.95	0.8[illegible]	0.83	0.91
	BR	0.95	0.91	1.02	1.01
Till+no straw	IR	1.00	0.91	0.90	0.90
	BR	1.00	0.99	1.07	1.03

† IR refers to the in-row postion.
‡ BR refers to the between-rows position.

Table 3.4 Total soil porosity (%, v/v) at different depths as affected by tillage-residue management.

Soil depth (cm)	No till + straw	Till + straw	Till + no straw	Mean
		1988¶		
0-2.5	63.4 a† A‡	64.3 a A	62.1 b A	63.3 A
2.5-5	58.4 b CD	61.2 a B	60.6 a B	60.0 BD
5-7.5	57.8 b C	60.0 a CD	58.8 ab C	58.9 C
7.5-10	60.2 a B	60.9 a BC	60.5 a B	60.5 B
10-12.5	59.2 a BD	59.7 a CD	59.4 a BC	59.4 CD
12.5-15	59.1 a BD	59.1 a D	58.2 a C	58.8 C
Mean (0-15 cm)	59.7 b	60.9 a	59.9 b	
		1989§		
0-2.5	62.9 a A	60.6 ab B	58.8 b A	60.8 A
2.5-5	57.2 b B	63.6 a A	60.2 A	60.3 b A
5-7.5	57.2 c B	63.4 a A	60.3 b A	60.3 A
7.5-10	57.0 a B	59.2 a B	59.5 a A	58.6 B
10-12.5	57.8 a B	58.0 a B	59.0 a A	58.2 B
12.5-15	57.7 a B	58.4 a B	58.9 a A	58.4 B
Mean (0-15 cm)	58.3 b	60.5 a	59.4 ab	

¶ Average of July 11 and September 21 measurements.

§ September 21 measurement.

† Values in a given depth interval followed by different lower case letters indicate significant difference (P = 0.05) betweeen tillage treatments using Duncan's Multiple Range test.

‡ Values in a given tillage system above different capital letters indicate significant difference (P = 0.05) between depth intervals using Duncan's Multiple Range test.

Table 3.5 Sources of variation and level of significance for penetration resistance data for 1988 and 1989 (transformed with Box-Cox transformation).

	1988		1989	
Source	N	Significance	N	Significance
Tillage (T)	768	**	3820	NS
Time (t)	1152	NS	2865	***
T x t	384	NS	955	NS
Position (P)	1152	***	5760	**
T x P	384	***	1920	*
t x P	576	**	1440	***
T x t x P	192	***	480	NS
Depth (D)	192	***	384	***
T x D	64	***	128	***
t x D	96	***	120	***
T x t x D	32	***	32	***
P x D	96	***	192	***
T x P x D	32	***	64	***
t x P x D	48	***	48	NS
T x t x P x D	16	NS	16	NS

*, **, *** indicates significance at the 0.10, 0.05 and 0.01 probability levels, respectively.

Table 3.6 Soil water content at the time of penetration resistance measurements during 1988.

Soil Depth (cm)	Soil Water (%, V/V) No till + straw	Till + straw	Till + no straw
	June 2, 1988		
0-10	27.2	22.9	22.0
15	39.8	38.9	36.4
20	39 9	39.7	35.9
25	37.4	38.7	35.6
30	35.9	36.5	35.1
35	35.7	36.1	33.8
45	33.8	35.8	33.4
	September 13, 1988		
0-10	31.8	31.5	29.9
15	41.2	41.8	40.4
25	41.2	41.6	38.6
35	38.3	39.9	35.7
45	36.5	36.6	34.5

Table 3.7 Percent soil water content at the time of penetration resistance measurements during 1989.

Soil depth (cm)	No till + straw	Till + straw	Till + no straw
		April 26†	
0-5	35.6	32.4	25.3
5-10	36.1	36.2	32.9
[illegible]	37.4	35.9	33.5
		June 13‡	
0-5	32.4	29.3	27.0
5-10	34.5	34.7	32.8
10-15	36.3	35.8	34.0
10-20	37.8	38.4	36.1
20-30	36.9	37.6	35.6
30-40	33.8	34.6	33.2
		September 5¶	
0-2.5	43.6	40.7	38.5
2.5-5	38.2	40.1	38.2
5-7.5	36.0	38.1	37.9
7.5-10	35.4	36.8	37.0
10-12.5	35.6	35.2	36.0
12.5-15	36.0	35.8	35.0
10-20	36.9	36.5	36.1
20-30	34.7	35.1	33.9
30-40	31.3	30.8	28.2
40-50	29.4	28.0	26.4

† Mass water content.
‡ Mass water content for first 3 layers, volumetric water below.
¶ Mass water content for first 6 layers, volumetric water below.

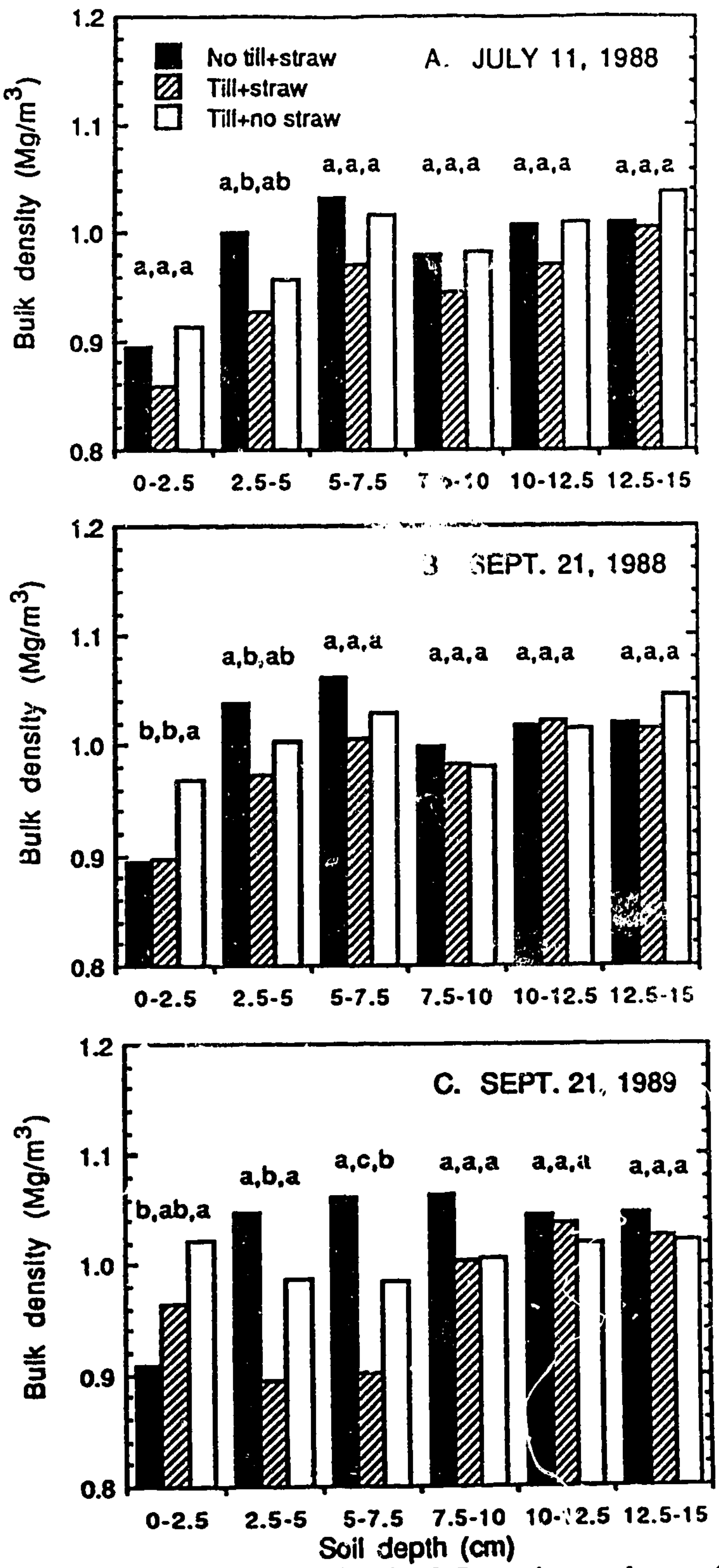

Figure 3.1. Soil bulk density in 2.5-cm intervals on (A) July 11 and (B) September 21, 1988, and (C) September 21, 1989. Within a given depth interval, treatment means with the same letters are not significantly different (P=0.05).

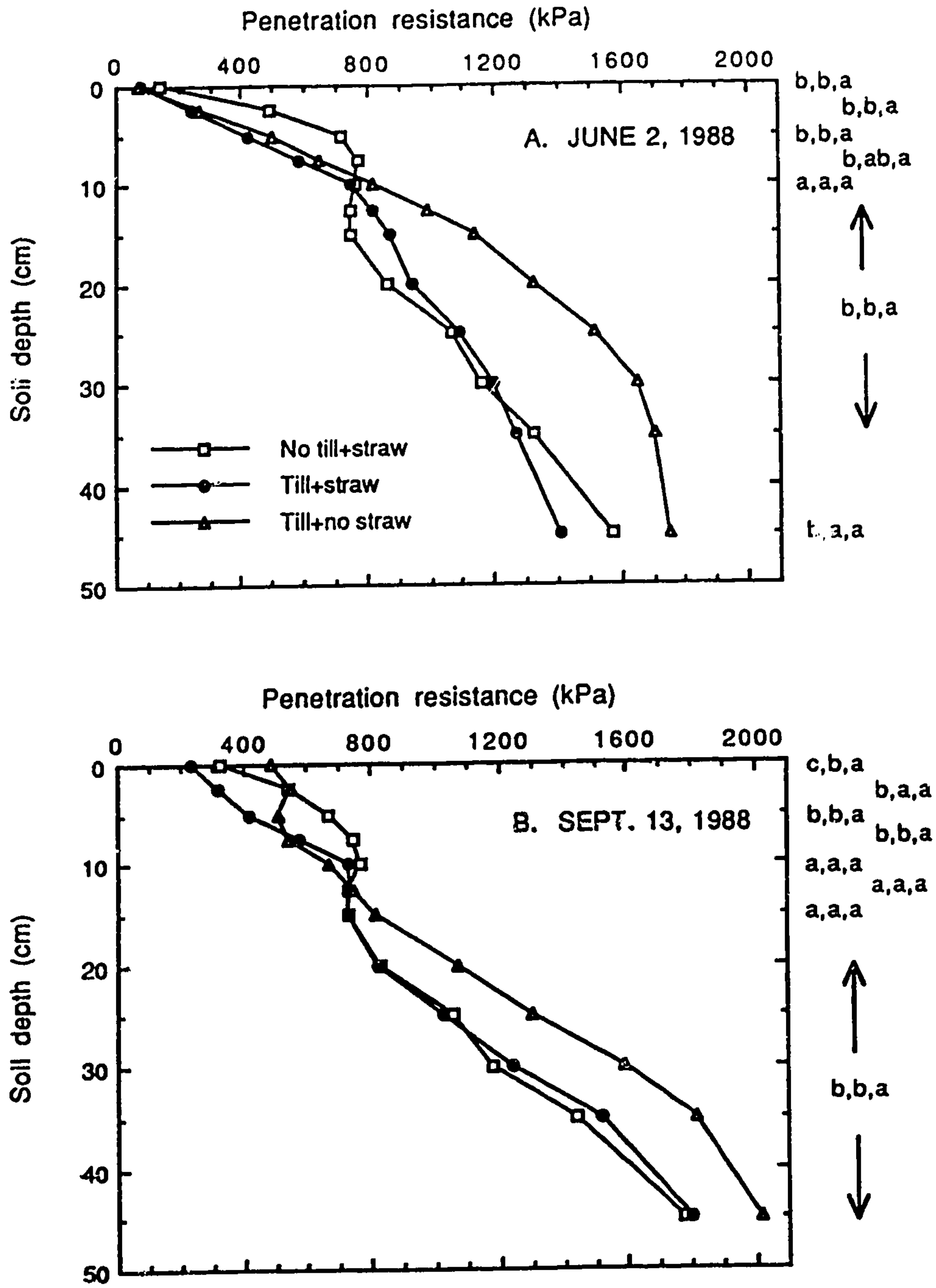

Figure 3.2. Soil penetration resistance (averaged over position) on (A) June 2 and (B) September 13, 1988. Within a given depth interval, treatment means with the same letters are not significantly different (P=0.05). The letters are in the same sequence in which treatments appear in the curves.

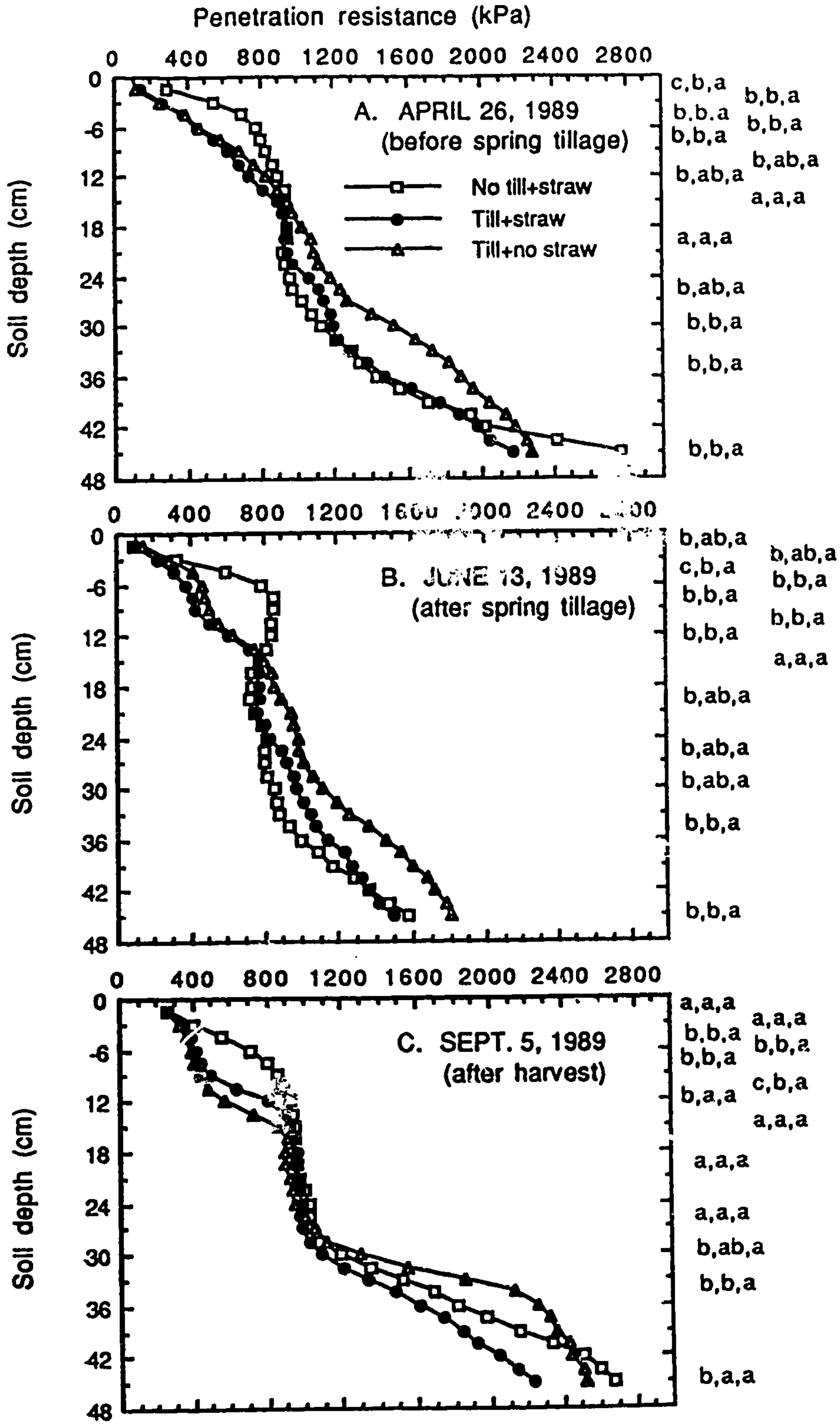

Figure 3.3. Soil penetration resistance (averaged over position) on (A) April 26, (B) June 13 and (C) September 5, 1989. Within a given depth interval, treatment means with the same letters are not significantly different (P=0.05).

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Chapter 4

SOIL HYDRAULIC CHARACTERISTICS OF A TYPIC CRYOBOROLL AS INFLUENCED BY THREE LONG-TERM TILLAGE AND RESIDUE MANAGEMENT SYSTEMS

4.1 INTRODUCTION

The soil water regime is partly determined by soil hydraulic properties related to retention and transmission of water; other controlling factors include evapotranspiration, internal drainage, and runoff. Soil hydraulic properties vary greatly with pore geometry which, in turn, is modified or rearranged by tillage (Klute, 1982), and residue management. Therefore, changes in soil water regime produced by various tillage-residue systems can be understood only if the effects on water retention and transmission properties of the soil are known.

Soil water content is normally greater under reduced tillage systems than under conventional tillage (Blevins et al., 1971; Gantzer and Blake, 1978; Negi et al., 1981; Lindstrom et al.; 1984; Tollner et al., 1984; Johnson et al., 1984). Jones et al. (1968) and Blevins et al. (1971) attributed higher soil water content to reduced evaporation (mainly due to a greater residue cover) and greater ability to store water under no-tillage. Van Ouwerkerk and Boone (1970) hypothesized that no-tillage not only reduces total pore space, but also radically changes the pore size distribution with larger pores disappearing and finer pores predominating. Hill et al. (1985) observed that soil under conventional tillage had a larger proportion of its pore volume in larger pores (>15-μm radii) than the soil under conservation tillage. Allmaras et al. (1982), on the other hand, showed that in the upper 40-cm layer, cultivation produced small pores at the expense of large pores.

Higher soil water content under no tillage may or may not actually benefit plant growth. Tollner et al. (1984) observed significantly less plant available water in surface soil of no-tillage than of the conventional tillage plots in the southern Piedmont, although total water in top 60 cm soil was generally greater in the no-till system. Van Ouwerkerk and Boone (1970) reported that although soil water retention was greater under no-tillage, the amount of plant available water was the same. Hill et al. (1985) also observed no significant differences in soil water retention properties between no-till and conventional-till systems. In contrast, Negi et al. (1981) reported that for the conditions of a growing season, plant available water at 30-cm depth was twice as much in untilled plots as in conventionally tilled plots.

The changes in soil water conducting properties associated with tillage, which may affect infiltration, runoff, internal drainage and evaporation, have not been well documented and often are contradictory. Bouma et al. (1975) observed that long-term cultivation changed water transmission characteristics in two different soil pedons in Wisconsin. In Minnesota, Gantzer and Black (1978) and Lindstrom and Onstad (1984) reported lower porosity and lower saturated hydraulic conductivity (Ksat) in no-till than in conventional tillage for the 7.5-15 cm depth of a clay loam (Aquic Argiudoll) and for 0-15 cm depth of a loam (Udic Haploboroll), respectively. The latter authors reported greater runoff and greater soil loss with the no-till system even under normal rainfall conditions.

In contrast, another study on a well-structured Typic Haplaquoll in Minnesota reported higher Ksat in untracked interrows of no-till than of plowed plots (Culley et al, 1987a,b). Blevins et al. (1983) also reported greater Ksat of a silt loam (Typic Paleudalf) under no-till after 10 years of the treatments. Goss et al. (1978) observed rapid infiltration of water to a depth between 0.5 and 1.0 m in direct-drilled cereal-cropped soil, whereas in plowed soil movement was restricted to the tilled zone. Gantzer and Blake (1978) observed Ksat of 7.5-15 cm depth soil cores to be four times greater in September than in May in the untilled plots, but no difference was found in plowed plots. Burch et al. (1986) also reported seasonal variation in infiltration rate and Ksat.

Minimal disturbance of soil under no tillage may promote continuity and persistence of macropores. Also greater residue cover in no-tillage system may increase earthworm populations and channels (Barnes and Ellis, 1979; Zachmann et al., 1987). The earthworm channels and other biopores can act as important conduits for movement of water through the soil profile during infiltration events with or without ponding (Ehlers, 1975; Beven and Germann, 1982; Bouma et al., 1982, Kladivko et al., 1986), and can thus greatly affect the soil water regime.

Apparently, the direction and magnitude of the tillage and residue management effects on soil hydraulic properties vary with soil type, antecedent soil properties, type and depth of tillage, prevailing agro-ecological conditions, etc. The effects also depend on the duration a tillage system has been used. Consequently, the results obtained elsewhere may not be universally applicable (Papendick and Miller, 1977; Hillel, 1980).

In view of their soil and water conservation effects and economic benefits, conservation tillage (reduced-till or no-till) systems hold a great potential on the Canadian prairies. But scientific information on the long-term effects of such practices on soil quality, including soil hydraulic environment and hydrological implications, under the soil and agroclimatic conditions of Central Alberta is very limited. It was previously reported (Chapters 2 and 3) that three tillage-residue management systems studied in these conditions affected degree of residue cover, surface roughness, organic matter content, aggregate size and stability, bulk density and porosity of a fine-textured and naturally well-aggregated Typic Cryoboroll (Black Chernozemic), continuously cropped to spring barley for 9 years. The objective of the research reported in this chapter was to quantify the effects of these same tillage-residue systems on soil water retention, pore-size distribution and soil water transmission characteristics. An additional objective was to investigate seasonal changes in the water transmission properties, i.e. infiltration characteristics and hydraulic conductivity of the soil.

4.2 MATERIALS AND METHODS

4.2.1 *Site and soil description*

The research was conducted during the 1988 and 1989 growing seasons on field plots located near Edmonton at the Ellerslie Research Station (53° 25' N, 113° 33' W; 694 m above sea level) of the University of Alberta. The soil of the experimental site was developed from lacustrine deposits of the Proglacial Lake Edmonton. It is classified as: fine loamy, mixed, Typic Cryoboroll according to Soil Taxonomy, and a Black Chernozemic according to the Canadian System of Soil Classification. It has good internal drainage and a moderate swell-shrink potential. Other soil and climate details are given in Chapter 2.

4.2.2 *Tillage-residue treatments*

Ten tillage, residue and nitrogen management systems were established in the fall of 1979 to investigate the long-term effects of these systems on soil environment and crop growth. Three treatments were selected for the present study: (1) no-tillage, straw retained on the surface, (2) conventional tillage, straw retained and incorporated, and (3) conventional tillage, straw removed.

Conventional tillage consisted of late fall cultivation using a rotovator, followed by similar spring cultivation at the time of seeding. The tillage depth was approximately 10 cm. In the no-till treatment, the crop was seeded directly without tillage. The only disturbance of soil in this treatment was the seed-drill and a small reaper-binder. The crop was harvested at a height of approximately 10 cm. In treatments (1) and (2), threshed straw from each plot was returned to the corresponding plot and uniformly spread before fall tillage. In treatment (3), all straw and most of the stubble were removed before tillage. Treatments were replicated four times in a randomized complete block design and repeated annually.

The plots were seeded to spring barley at 5 cm depth each year. The crop rows, 22.5 cm apart, were located in approximately the same position each year. Weeds were controlled chemically. Details regarding the machinery used and other agronomic practices for the two years of the present study are given in Chapter 2.

4.2.3 *Measurements and computations*

4.2.3.1 *Soil water desorption characteristics*

4.2.3.1a *Sampling*

Undisturbed soil cores 7.6 cm in diameter by 7.5 cm in length were obtained with a modified double cylinder coring device from the 0-7.5- and 7.5-15 cm depths in July, 1988 (7 weeks after sowing the crop). All cores were taken from the interrow spaces, taking care not to sample areas with visible traffic. The soil cores were sealed and refrigerated (4 ^{0}C) prior to use to minimize biological activity. More details about the sampling procedure are given in Chapter 3.

Each 7.5-cm soil core was subsequently transferred into a stack of three 2.5-cm long aluminum rings using specially designed equipment, and sectioned into three subcores using a fine-blade saw, causing as little soil disturbance as possible. The core sectioning was carried out at a high soil water content. The volume of each subcore was approximately 113 cm^3. Soil water desorption characteristics (SWDC) for the matric potential (Ψ) range 0 to -1500 kPa were determined on these subcores.

4.2.3.1b *The SWDC for 0 to -10 kPa*

This was measured using fritted glass funnels with hanging water columns. The technique was a modification of that used by Baker et al. (1974) and Kooistra et al. (1984), which was derived from the method described by Vomocil (1965). The procedure uses a closed porous cup (to minimize evaporation), which allows measurement of outflow from a single sample as a function of soil water matric potential. The modification was to replace the rubber stopper by a 0.2 mm thick pure rubber sheet to keep the funnel vapor-tight.

A soil core was saturated by capillary rise on the porous fritted disc of the Buchner funnel, having pores of 10-20 μm diameter which supported water suction in the 150-300 cm range. Starting from saturation, water outflow during successive Ψ decrements (-1, -2, -4, -6 and -10 kPa) was measured by observing water levels in a burette connected to the Buchner funnel. The apparatus was pre-calibrated for plate discharge and tube collapse at each suction value. This technique was used for only 2.5-5 and 10-12.5-cm subcores.

4.2.3.1c *The SWDC for -10 to -1500 kPa*

All subcores of a 7.5-cm core were used to determine soil water retention at -10, -20, -33.3, -60, -100, -200, -500 and -1500 kPa, using a pressure-plate apparatus (Klute, 1986). Because of the limited number of available cores, each subcore was used sequentially to obtain equilibrium water content at each of the fore-mentioned Ψ values. Care was taken to ensure hydraulic contact between the soil and the porous plate after each equilibrium. It took 3 to 7 days depending on pressure to achieve equilibrium. After taking the wet mass at the final potential (-1500 kPa), the saturation water content (assumed to represent 0 kPa condition), was determined by fastening a piece of coarse cloth to the lower end of the sample ring with a rubber band, saturating the soil core for approximately 48 h by wetting from the bottom, and then determining the wet and oven-dry (105 ^{o}C) masses. Soil water content at each equilibrium water potential was expressed on a volumetric basis using bulk densities of individual subcores for conversion.

4.2.3.1d *Plant available water capacity*

Reported soil water potentials at in situ field capacity in most soils are near -10 kPa (Cassel and Nielsen, 1986; Hamblin, 1987; Marshall and Holmes, 1988). Therefore, plant available water capacity (PAWC) was calculated as the difference between soil water retained at -10 kPa and -1500 kPa. Hill et al. (1985), Culley et al. (1987) and Wagger and Denton (1989), among others, also used -10 kPa to represent in situ field capacity.

4.2.3.2 *Pore size distribution*

Soil pore-size distribution was computed from the soil water retention data for Ψ range of 0 to -1500 kPa, using the approach of Vomocil (1965). This approach depends upon the theoretical relation between soil water characteristic and distribution of pore sizes. Capillary theory is used to estimate effective pore size from pore suction (Marshall and Holmes, 1988):

$$h = 2\,\gamma \cos \alpha / r\, g\, \rho \qquad (1)$$

where h is soil water suction, γ the surface tension between water and air, α the air-water contact angle, r the effective pore radius, g the acceleration due to gravity, and ρ the density of water. Using $\alpha=0$, the equivalent pore diameter (EPD) of the smallest pore (in µm) drained at a water suction of h kPa is given by 300/h (Marshall and Holmes, 1988). Pore size distribution was expressed as pore volume occurring within a given size interval per unit soil (total) volume. The volume of pores drained between 0 and -1 kPa (EPD >300 µm) was taken as an estimate of macropores (Greenland, 1981), whereas that between -1 and -10 kPa (EPD of 300-30 µm) of transmission pores through which water moves freely under gravity.

4.2.3.3 *Saturated hydraulic conductivity*

4.2.3.3a *Using undisturbed soil cores*

Undisturbed soil cores 7.6 cm diameter x 7.5 cm height, obtained in aluminum cylinders in mid-July and late September (after harvest, before fall tillage) of first year, were used to measure saturated hydraulic conductivity (Ksat) by a constant head and/or a falling head method (modified from Klute and Dirksen, 1986), using locally developed equipment. These cores were different from those used for soil water desorption characteristics, but the method of sampling was the same. The depths sampled were 0-7.5 cm and 7.5-15 cm; different, but adjacent, locations being sampled for the two depths. The soil cores with a piece of coarse cloth and nylon wire-mesh fastened to the bottom with a rubber band were saturated in distilled water by capillary rise, slowly raising the water level over a 2-3 day period to ensure minimum air entrapment and maximum saturation. Ksat values were expressed at 20 ^{o}C using the relation: $K_{20} = K_T.\upsilon_T/\upsilon_{20}$, where T = water temperature (^{o}C), υ = absolute viscosity of water.

4.2.3.3b *In situ saturated hydraulic conductivity*

Saturated hydraulic conductivity of 0-7.5 cm soil was also measured in situ using a modified air-entry permeameter (Topp and Binns, 1976) based on the method of Bouwer (1966). An infiltration cylinder (25 cm i.d.) was driven into the soil to approximately 10 cm and a lid with rubber gasket clamped onto it. Tap water was supplied to the soil surface from a reservoir under positive head. Rate of fall of water (or infiltration rate) was measured until the wetting front reached 7.5 cm as determined by a fast response small diameter tensiometer probe. The probe was allowed to equilibrate with the prevailing soil moisture before starting the water supply. Ksat and air-entry potential were calculated from the measured water intake rate, vacuum gauge reading, water head when the wetting front reached 7.5 cm, and dimensions of the water reservoir and infiltration cylinder (Topp and Binns, 1976). The tests were conducted between harvest and fall tillage (late September) during both study years.

4.2.3.4 *Infiltration characteristics*

The double ring infiltrometer technique (Bouwer, 1986) was used to measure ponded infiltration characteristics of soil. Infiltration tests were carried out 4 times over the study period: after harvest in each year, just after fall tillage the first year and one month before seeding in the second year. The inner and outer rings were 30 and 55 cm in diameter, respectively. Both rings were 25 cm in height and were installed to a depth of 10 cm. During installation, care was taken to keep the disturbance of soil and its residue cover to the minimum. Rate of fall of the water level was recorded with a graduated float. Tap water was used in the test which was continued until a steady infiltration rate was achieved or for one hour, which ever occurred later.

The infiltration data were analyzed using two models:

Philip (1957) model:

$$I = St^{1/2} + At \qquad (2)$$

where I = cumulative infiltration (cm); t = time from start of the infiltration run (min); S= soil water sorptivity (cm $min^{-1/2}$); A = transmissivity (cm min^{-1}). The model parameters S and A were estimated by fitting a non-linear regression model (equation 2) to data from each infiltration run, using NLIN procedure of SAS statistical package (SAS Inc, 1985).

Kostiakov (1932) model:

$$I = at^{b} \qquad (3)$$

$$i = dI/dt = a't^{b'} \qquad (4)$$

where I = cumulative infiltration (cm); t = time (min); a, a', b, b' = empirically determined constants; i = infiltration rate (mm h^{-1}). The model was fitted to measured infiltration data (I and i), using a non-linear regression method, and model parameters computed.

Just before each infiltration run, water content and bulk density of the surface soil were determined using either a moisture-density combination probe (Model MC1, CPN Corp.), or by taking undistributed soil cores with a double-cylinder coring device. The water-filled pore space, WFPS (also called saturation %, degree of saturation or relative saturation) was calculated as:

WFPS= 100 (fractional volumetric water content/fractional total porosity).

Total soil porosity (n) was calculated from measured bulk density (Db) and particle density (ρ_s) as: $n=1-(Db/\rho_s)$. Air-filled porosity = total porosity – volumetric water content. Particle density was obtained from Chapter 2.

4.2.4 *Statistical analyses*

The experimental variables were subjected to statistical analyses using either procedure UANOVA (developed at the University of Alberta) of the SPSS^x statistical software, or procedure ANOVA/ GLM of the SAS statistical program (SAS Inc., 1985). Tests were conducted for fulfillment of the assumptions of analysis of variance. The statistical model for analysis of soil water retention data was a split-split plot design with tillage-residue treatments as main effects, soil depth as split plot and soil matric potential as split-split plot (Drs. R. Weingardt and T. Taerum, personal comm., 1989). Because of soil disturbance during sampling, different locations were sampled for different depths; thus, depth was considered a randomized factor in the analysis. Hill et al. (1985) and Culley et al. (1987a) used similar statistical models.

Analyses of pore size distribution (each pore interval considered separately) and available water capacity were considered a randomized complete block design (RBD). Hydraulic conductivity (Ksat) determined on soil cores was analyzed as a split-plot model (tillage as main effect, soil depth as split-plot effect). Ksat determined with the air-entry permeameter (one depth only), steady state infiltration rate, cumulative water intake at 1 h and infiltration rates at selected times after ponding were analyzed as an RBD. Analysis of Ksat was performed on both the original and the log transformed data. Parameters of infiltration models (S, A, a, b, a', b') were also analyzed using an RBD since the experimental errors were found to be normally distributed (R. T. Hardin, personal comm., 1990). Burch et al. (1986) and Lal et al. (1989b) analyzed parameters of infiltration equations similarly. Least significant difference (LSD) or Duncan's Multiple Range (DMR) tests ($P \leq 0.10$) were performed for means separation of significant main effects and interactions.

4.3 RESULTS AND DISCUSSION

4.3.1 *Soil water desorption characteristics*

Soil water desorption characteristics were measured on all 2.5 cm thick cores to 15 cm depth, but data are presented only for 2.5-5 cm and 10-12.5 cm intervals as representative of conditions in the tilled zone and just below it. Analysis of variance indicated that except for the main effects of tillage and depth, all other main and interaction effects were significant ($P \leq 0.05$) (Table 4.1).

In the 2.5-5 cm depth, soil under the no till+straw treatment retained significantly smaller amounts of water at 0 (saturation), -1 and -2 kPa compared with the till+straw treatment, but the three treatments were similar at -4, -6 and -10 kPa (Fig. 4.1A). Opposite treatment trends were observed for potentials below -10 kPa, the order being: no till+straw >till+straw > till+no straw. The two tilled treatments were not statistically different at any matric potential excepting -500 kPa. Tollner et al. (1984) observed greater water retention in conventional tillage than in no-tillage at $\Psi \geq -80$ kPa. At $\Psi = -10$ kPa, assumed to represent in situ field capacity of this soil (see section 4.2.3.1d), the volumetric water content (Øv) was 0.403, 0.393 and 0.386 $m^3 m^{-3}$ in the no till+straw, till+straw and till+no straw treatments, while at $\Psi = -1500$ kPa, the respective Øv values were 0.250, 0.223 and 0.211 $m^3 m^{-3}$.

The treatments were not statistically different in the amount of water retained in 10-12.5 cm depth (just below the depth of tillage in this study) at all Ψ values except -1 and -2 kPa (Fig. 4.1B). Averaged over all Ψs, two depth intervals were not statistically different but significant Ψ x depth interaction revealed that soil in the 2.5-5 cm interval retained significantly greater water than in the 10-12.5 cm interval for 0 to -2 kPa range, below which range the depth effect was non-significant (data not shown). A significant matric potential effect on water retention indicates a well-spread soil pore size distribution, i.e. a range of pore sizes (Hill et al., 1985).

The relationship between soil water matric potential (Ψ) and volumetric water content (Øv) was also represented as pF curves [$pF = \log_{10}(h)$, $h = -\Psi$ in cm]. These plots had a high linear coefficient of determination ($R^2 > 0.97$) (Fig. 4.2). Observed treatment differences in water retention started at pF 1.8, beyond which the till+no straw treatment was associated with lowest values of Øv; and no till+straw was associated with highest Øv. Hamblin and Tennant (1981) also observed a reversal around this suction for a sandy loam, but the direction of their treatment effects was opposite to that observed in the present study (i.e. no till >conventional till for h≤ approximately 60 cm suction). Allmaras et al. (1977) observed no effect of tillage treatments on soil water desorption characteristic of a silt loam Haploxeroll at matric potentials > -8 kPa, but found a greater Øv in the untilled treatment at < - 8 kPa potential, compared with the chiseled treatment.

4.3.2 *Saturation, field capacity, permanent wilting point and plant available water capacity*

The measured values of saturated water content (SWC) were not different among treatments in any 2.5-cm layer to 15 cm, excepting in the 2.5-7.5 cm interval in which the tillage+straw treatment had a significantly greater SWC than the no-till treatment, probably due to incorporation of straw (data not given).

The till+no straw treatment had a greater plant available water capacity (PAWC) in all 2.5 cm layers to 15 cm depth, as compared with the other two treatments (Table 4.2). The treatment effects were, however, significant only for the 0-2.5-cm interval where no-tillage treatment had significantly lower (5-8% absolute) PAWC compared with the tilled treatments. The two straw treatments were the same below a 7.5-cm depth.

The soil water content at -10 kPa varied little among treatments. In contrast, water retained at -1500 kPa followed the trend: no till+straw >till+straw >till+no straw; the difference between the no-till treatment and till+no straw being significant for all layers in the 0-10 cm zone. The two tilled treatments were not significantly different in any soil layer. The observed differences in the PAWC were, thus, mainly associated with differences in wilting point, an uncommon observation.

Averaged over the 0-15 cm soil zone, PAWC of the no-till treatment was significantly (P=0.10) lower (by 16% relative value or 4 mm water/15 cm soil depth) than that of the till+no straw treatment, with till+straw intermediate to the other two treatments. Tollner et al. (1984) also observed a significantly lower PAWC of no-till than conventional till in the surface soil. Lal et al. (1989) found no effects of tillage methods (including no-tillage) on PAWC of a clayey Alfisol in Ohio.

4.3.3 *Porosity and pore size distribution*

Total porosity of the no till+straw treatment (0.619) was significantly (P=0.10) lower than of the till+straw treatment (0.643) in the 2.5-5 cm layer, but was not different from that of the till+no straw treatment (0.629) (Fig 4.1A). There was no treatment effect on total porosity of the 10-12.5 cm layer (Fig. 4.1B).

Mean pore volume as a fraction of total soil volume, occurring between equivalent pore diameter (EPD) of ∞ to 0.2 μm (i.e. porosity for $\Psi > -1500$ kPa) for the no till+straw, till+straw and till+no straw treatments was, respectively, 0.369, 0.419, and 0.417 $m^3 m^{-3}$ for 2.5-5 cm depth and 0.384, 0.380 and 0.383 $m^3 m^{-3}$ for 10-12.5 cm depth. Thus, compared with the tilled treatments, no-tillage reduced the non-residual porosity only in the 2.5-5-cm layer.

Total pore volume was partitioned into several pore diameter intervals (Fig. 4.3). Analysis of variance indicated a significant (P=0.05) effect of tillage-residue systems on relative pore volume of only 150-30 μm and <0.2 μm EPD intervals for 2.5-5 cm depth, and >300 μm for 10-12.5 cm depth. There was considerable variance in the data with coefficient of variation ranging from 7 to 41%. The CV was notably small (7-9%) for <0.2 μm porosity probably because water retention at low potentials is considered mainly a textural effect rather than a structural one.

The amount of macroporosity (EPD > 300 μm, or porosity drained between 0 and -1 kPa) was not statistically different (average 0.097 $m^3 m^{-3}$) among the three treatments in 2.5-5 cm layer (Fig. 4.3A). When expressed as % of total porosity, the three treatments were 17, 16 and 14% for the no till, till+straw and till+no straw treatments, respectively.

The average macroporosity of 10-12.5 cm interval was similar to that of 2.5-5 cm layer, but the no till+straw treatment had a significantly greater porosity compared with till+no straw (0.110 vs. 0.084 $m^3 m^{-3}$) (Fig. 4.3B). Macroporosity accounted for 18, 17 and 14% of the total porosity in this layer for the three treatments.

Carter and Kunelius (1986) reported similar macroporosity (> 300 μm EPD) values in direct-drill and cultivated surface soil. Culley et al. (1987a) observed that in no-till surface soil (0-10 cm), macroporosity (> 600 μm EPD) accounted for about 5% of total porosity while such porosity was absent in conventional till. The reported effects of tillage systems on macroporosity seem to depend on soil type, texture, structure, soil depth, antecedent soil characteristics, macrofaunal activity, etc., besides type and intensity of tillage and length of time the soil has been under such practices.

Both tilled treatments had a greater transmission porosity (300-30 μm EPD or pore space drained when Ψ is reduced from -1 to -10 kPa), TP, of the 2.5-5 cm soil compared with the no-till treatment (0.15 vs. 0.11 $m^3 m^{-3}$), but differences were nonsignificant. The 150-30 μm portion of TP was, however, significantly greater in the till+no straw treatment than the no-till treatment (Fig. 4.3A). Transmission porosity accounted for 18, 23 and 24% of the total porosity in the no till+straw, till+straw and till+no straw treatments, respectively. Treatment effects were nonsignificant at 10-12.5 cm depth; average TP (0.11 $m^3 m^{-3}$) accounting for approximately 19% of total porosity. Douglas et al. (1980) also observed less volume of transmission pores under direct-drilling on a clay soil.

In the 2.5-5 cm interval, the amount of macroporosity plus transmission porosity (EPD>30 μm, may be called 'drainable porosity') was somewhat smaller in no till (0.216±0.013 $m^3 m^{-3}$) compared with till+straw (0.250±0.018) and till+no straw (0.240±0.011), but the differences were nonsignificant. No treatment differences were observed in the 10-12.5 cm layer. Hill et al. (1985) observed similar tillage effects on porosity with > 30 μm EPD.

The amount of plant-available water storage porosity (30-0.2 μm EPD) accounted for only 25 to 29% of the total porosity, with no significant differences between treatments and depths. The no-till surface (2.5-5 cm) soil contained significantly greater (by 4%) amount of residual pores (EPD <0.2 μm, pores retaining water below -1500 kPa) compared with the till+no straw treatment (Fig. 4.3A). The residual porosity was large, constituting 41, 35 and 34% of the total porosity in the no till+straw, till+straw and till+no straw treatments, respectively. Average proportion of residual porosity in 10-12.5 cm depth was 38%, with no difference among treatments.

It can be inferred that in the no-till surface soil, even if total soil water is greater than in the tilled treatments (due mainly to reduction in evaporation by surface residues), the plant available water may or may not be higher, and sometimes may even be less.

Cumulative pore size distribution curves could be described in the form (Fig. 4.4):

$$y = a+b \log x$$

where y = porosity of pores smaller than a given size ($m^3 \, m^{-3}$); x = pore diameter (μm); a,b = parameters of the equation. The above model fitted the measured data very well ($R^2 > 0.96$).

4.3.4. *Saturated hydraulic conductivity (Ksat)*

Results of Ksat measurements on undisturbed soil cores and in the field are presented in Tables 4.3 and 4.4. Analyses of variance were performed on both original and log transformed values. The statistical interpretation was changed in some cases after the transformation. For the core-determined Ksat, depth and depth x tillage interaction were significant at each time of measurement.

Ksat (core) of the 0-7.5 cm depth was always in the order: no till+straw > till+straw > till+no straw (Table 4.3). Midway during the 1988 growing season, the mean (arithmetic) Ksat of the no tillage treatment was 1.5 and 7.2 times that of the till+straw and till+no straw treatment, respectively. The respective ratios in September (after harvest) were 2.2 and 3.6. The difference between no till+straw and till+no straw was always significant (P =0.05). The till+straw treatment was similar to no till+straw in July and to till+no straw in September. However, at the 10% probably level, all three treatments were always significantly different from each other.

There was a sharp reduction (5.5 and 3.6 fold in July and September, respectively) in Ksat of the no-till treatment from 0-7.5 cm to 7.5-15 cm depth. In the till+straw treatment, the decreases were 1.8 fold in both July and September. In the till+no straw treatment, Ksat of the second depth was lower than that of the first depth by only 28% in both July and September. Treatment differences in the second depth were not generally significant. The general persistence of treatment trends from July to September confirms the existence of real effects of tillage and residue management on Ksat.

Saturated hydraulic conductivity is a combined measure of size and continuity of pores. Greater Ksat in untilled soil is an indication of better pore continuity and/or presence of large pores and biochannels in this system. The pore-size distribution data indicated a somewhat greater macroporosity (>300 μm pore diameter) in no-tillage. Earthworm activity was also visually observed to be greater in the no-till plots. Transmission porosity (300-30 μm dia pores) was, however, somewhat lower under no tillage. A greater pore continuity, possibly as a result of minimal soil disturbance, is thus indicated in the no-till system. Greater water-stability of aggregates in the no-till treatment (Chapter 2) probably also contributed to its higher Ksat.

A much larger Ksat of the no-till treatment in 0-7.5-cm layer than the 7.5-15-cm layer suggests a more vigorous macro-faunal activity and pore-continuity in the surface layer. Douglas et al. (1980) similarly observed lower total porosity and transmission porosity but increased infiltration and earthworm activity on a clay soil. Ehlers (1975), Blevins et al. (1983), Culley et al. (1987a), and Coote and Malcolm-McGovern (1989) also observed a greater Ksat under no-till. In contrast, Lindstrom and Onstad (1984), Carter and Kunelius (1986) and Heard et al. (1988) found a reduced Ksat under no-till.

The coefficient of variation (CV) for Ksat varied from 22 to 74% for original data, and was reduced to between 6 and 32% by log transformation. There did not seem to be a consistent trend in CV values among treatments over time, but the trends among treatments were the same for both depths at each time of measurement. CV values exceeding 200 for Ksat measurements have often been reported (Warrick and Nielsen, 1980; Culley et al., 1987; Heard et al., 1988).

In situ measurement of Ksat using an air-entry permeameter (AEP) revealed treatment trends which were generally similar to those obtained with cores (Table 4.4). Comparing Ksat of the 0-7.5 cm depth measured by the two methods in September 1988, the only notable difference was in the Ksat of the no till+straw treatment which was 82.6 and 50.8 $\mu m\ s^{-1}$ by core and AEP, respectively. A lower in situ measured Ksat is possible since the AEP may average vertical and horizontal Ksat values. Thus, if vertically oriented continuous macropores were more prevalent under no-till than under tilled treatments, and if tillage treatments did not affect the relative contribution of interfacial flow in cores (i.e. flow between sample holder and soil matrix), if any, a lower value of AEP-determined Ksat in the no-till treatment will be the result (Culley et al., 1987a). The AEP-determined Ksat is probably more representative of the actual conditions since the AEP tested a much larger volume of soil (3682 cm^3) compared with the core (340 cm^3). Also the soil is minimally disturbed in the field method.

Treatment trends in Ksat (AEP) were different in September 1989 than those in September 1988 in that the Ksat of the till+straw treatment was the same as that of the no till+straw. The Ksat values were greater in all treatments in 1989 than in 1988. Year- to-year and seasonal variation in Ksat values can arise due to differences in soil structural characteristics, bulk densities, porosities, biological activity, seasonal rainfall characteristics, etc.

Ksat of the till+no straw treatment, though much lower than that of the no-till treatment, seems to permit adequate hydrological conditions in the soil profile. This also suggests a good continuity of pores even in the tilled treatments.

4.3.5 *Infiltration characteristics of soil*

Infiltration characteristics in different treatments were measured four times over the two growing seasons in order to assess seasonal change, effect of a tillage operation, etc. These results are presented as infiltration rate and cumulative infiltration curves. The infiltration data were also used to fit two infiltration models.

4.3.5.1 *Infiltration rate*

On 1 September 1988 (3 days after harvest), infiltration rate (IR) was in the order: no till+straw > till+straw > till+no straw, at all times after ponding of water (Fig. 4.5.1A). Infiltration rate at 1 minute dropped to almost half of the 0.5 minute reading, a result observed also for other tests in this study.

Analyses of variance conducted for IR at selected times within a run indicate that IR of the no till+straw treatment was always significantly greater than that of the till+no straw. The two straw treatments were always nonsignificantly different. For example, 1 minute after ponding, IR was 930, 810 and 450 mm h^{-1} in the no till+straw, till+straw and till+no straw treatments, respectively. At 5 minutes, the respective rates were 615, 472 and 225 mm h^{-1}. Thus in the first 5 minutes, there was a steeper reduction in IR of the till+no straw treatment (2.0 fold) than in no-till (1.5 fold) and till+straw (1.7 fold). This is perhaps a reflection of more stable soil aggregate structure in the straw treatments (particularly in the no-till) than in the no-straw treatment. Water stability of aggregates measured in these plots followed the trend: no till+straw > till+straw > till+no straw (Chapter 2).

The no-till treatment had a higher initial infiltration rate despite its greater water-filled pore space (WFPS) and smaller air-filled porosity (AFP) in the 0-10 cm depth, compared with the other two treatments (Table 4.5). At 30 minutes, IR was 420, 339 and 174 mm h^{-1} in the usual treatment order, and the ratio of IR at 1 min to that at 30 min was 2.2, 2.4 and 2.6.

The infiltration rate started approaching an equilibrium (or steady) value sooner (approximately 15-20 minutes after start of the run) in the till+no straw treatment than in other two treatments (about 40 minutes). This is perhaps indicative of a relatively smaller pore heterogeneity in the no-straw system than in the straw-involving systems. The steady-state or final infiltration rate was 373, 269 and 164 mm h^{-1} in no till+straw, till+straw and till+no straw treatments, respectively (Table 4.6). Steady-state IR was therefore 2.3 times greater (significant at P=0.10) in the no-till treatment compared with till+no straw.

On November 2, 1988 (12 days after fall tillage), general treatment trends were similar to those on September 1, except during the first minute or so when the two tilled treatments had a greater IR compared with the no-till treatment (Fig. 4.5.1B). The IRs at 0.5 minute were 1520, 1960 and 1840 mm hr^{-1}, and at 1 minute 820, 1060 and 840 mm hr^{-1}, in the no till+straw, till+straw and till+no straw treatment, respectively.

A reason for greater initial IR in tilled treatments on 2 November is their reduced Db and increased porosity following tillage on 21 October, as well as a 5-10% lower surface soil water content compared with no-till, which resulted in a 12 to 19% lower WFPS and 9 to 12% greater AFP in tilled treatments than in the untilled one (Table 4.5). Treatment differences were, however, not significant at any time including the steady-state rate. The steady-rate of the tilled treatments did not change at all from the pre-tillage (September) values. It is inferred that the initial infiltration rate of a freshly tilled soil may increase but the equilibrium rate may be unaffected. Surprisingly, steady-state rate of the no-till treatment decreased from 373 to 280 mm h^{-1} over this period.

Infiltration was also measured in late April 1989 to evaluate effects of freeze-thaw cycles and soil subsidence occurring over the winter and early spring period on the tillage-induced changes. The WFPS and AFP did not differ much from the November values (Table 4.5), but infiltration rates at almost all times of measurement in all treatments were considerably lower in April (Fig. 4.5.2A). For example, compared with the pre-freezing values, the steady-state rate was reduced by 44 and 46% in the two straw-involving treatments and by 32% in the no-straw treatment (Table 4.6). Probably cryoturbation of the soil matrix over the winter reduced the continuity of soil pores, because otherwise total porosity, water-filled porosity and air-filled porosity changed little over this period. Freeze-thaw cycles have been reported to reduce soil aggregate size generally (Benoit, 1973). The steady-state IR of the untilled treatment was still significantly greater than that of the till+no straw treatment.

Treatment trends in IR measured on September 21, 1989 (after harvest) were similar to those observed after harvest in 1988, but differences were generally nonsignificant (Fig. 4.5.2B). Coefficient of variation ranged from 7 to 58%. The steady state infiltration rates almost doubled from the April values in all the treatments (Table 4.6) despite a higher WFPS and a lower AFP in September than in April (Table 4.5). It appears that a significant macro-faunal (mainly earthworm) activity plus root activity over the crop growing period increased the size and number of continuous biopores, increasing the infiltration capacity of the soil in all treatments. It is inferred that infiltration rate of soil can have a considerable temporal variation.

Overall higher steady state infiltration rate of the no-till treatment is attributed to a larger number of bigger water-stable aggregates and a higher organic matter content of the surface soil (Chapter 2), and possibly a greater number of large, continuous biochannels (Ehlers, 1975; Edwards and Norton, 1986; Zachmann et al., 1987). The latter effect was observed when sectioning soil cores obtained for measuring root growth in July 1988 (data not shown). In case of an intense rainfall event, greater residue cover of the no-till treatment (Chapter 2) will reduce overland flow. On the other hand, a smaller or no residue cover in the tilled treatments together with lower water-stability of aggregates, can increase soil particle detachment and help form a surface seal, effectively reducing the infiltration rate.

4.3.5.2 *Cumulative infiltration*

The overall treatment trends in cumulative water infiltration (CI) vs. time after ponding were similar at all times of measurement for different runs, the usual order being: no till+straw > till+straw > till+no straw (Figures 4.6.1 and 4.6.2). Statistical analyses were conducted only for measurements at 5, 10, 30 and 60 minutes after ponding; they revealed generally significant (P=0.10) differences between no till+straw and till+no straw treatments. The two straw treatments were never statistically different.

Taking cumulative infiltration at 1 hour for till+no straw treatment as 100, the relative CI values for the no till+straw and till+straw treatments were: 238 and 186 in September 1988, 162 and 152 in November 1988, 137 and 126 in April 1989, and 173 and 154 in September 1989, respectively (computed from Table 4.7). Although the infiltration values (rates and amounts) can be considered high even in the till+no straw treatment, further higher values in the treatments (untilled or tilled) that retained straw will preclude any possibility of runoff and soil erosion resulting from highly intense rainfall events.

4.3.5.3 *Infiltration models*

The computed values of sorptivity (S) and transmissivity (A) parameters of Philip's (1957) model and 'a' and 'b' constants of Kostiakov (1932) model are given in Table 4.8. The value of parameter S is indicative of a soil's capacity to absorb water, and thus controls the infiltration rate during the first few minutes of ponding (3-10 minutes according to Marshall and Holmes, 1988). At larger 't', the second term 'At' in equation (2) predominantly governs the infiltration process, and therefore the steady-state infiltration rate.

The coefficients of determination (R^2) of the regression equations were high (between 0.84 and 0.99) and similar for the two models, indicating that both the models applied equally well to the measured data. Generally significantly lower values of S for the till+no straw treatment indicate its lower initial infiltration rates. Larger S values of the tilled treatments than the untilled one for the November measurement also reflect higher initial infiltration rates (for about 1 minute only) in the recently tilled treatments. Such trends in initial IR were actually observed (see the sub-section 4.3.4.1). Reduced sorptivity in till+no straw treatment, combined with its bare soil surface and a lower water-stability of aggregates can, at least theoretically, produce some runoff from highly intense rains. The transmissivity coefficient (A) was also generally lower in the till+no straw treatment as compared with the other two. This parameter generally reflected the magnitude of steady-state infiltration rate and the field-measured saturated hydraulic conductivity, except perhaps for the April measurement.

Like sorptivity S, the constant 'a' in the Kostiakov model is indicative of the initial infiltration process whereas constant 'b' represents the rate of increase in cumulative infiltration with time. For the current data sets, the constant 'a' actually behaved similarly to sorptivity in terms of the treatment trends at different times of measurement (Table 4.8). Constant 'b' behaved differently at different measurements, and was not that good in reflecting treatment trends in cumulative infiltration.

4.4 CONCLUSIONS

The study revealed that the three tillage-residue systems in effect for 9 years had produced some changes in the hydraulic characteristics of this fine-textured and good-structured Mollisol subject to annual freeze-thaw cycles. Treatment differences were small in soil water retention properties but were considerable in water transmission properties.

Plant available water capacity was the highest in the till+no straw treatment for all 2.5-cm layers to 15 cm and it was lowest in the no till+straw treatment in the surface 7.5

cm. The treatment differences were mainly associated with water retention at -1500 kPa rather than that at -10 kPa (field capacity).

Pore size partitioning revealed a relatively high macroporosity (14 to 18% of total porosity) of this soil, with no treatment differences in 2.5-5-cm depth; but no-till had significantly higher macroporosity in the 10-12.5 cm layer compared with till+no straw.

All three treatments seemed to have adequate water conduction from an hydrological point of view. Saturated hydraulic conductivity (Ksat), infiltration rate and cumulative infiltration at 1 hour followed the trend: no till+straw >till+straw >till+no straw. Ksat of the 0-7.5-cm depth was 1.5 to 7.2 times greater in the no-till treatment than in the tilled treatments with much smaller treatment differences in the 7.5-15 cm interval. Infiltration characteristics and hydraulic conductivity had considerable temporal variation. There is a further need to quantify the contribution of biochannels to water flow in this soil.

Although the infiltration rates were quite high even in the till+no straw treatment, even higher rates in the straw treatments (untilled or tilled) will preclude any possibility of runoff and soil erosion resulting from highly intense rainfall events.

Table 4.1 Significance of the effects of tillage treatment, soil water matric potential (Ψm) and soil depth on soil water retention characteristics.

Source	df	F – Statistic significance
Tillage	2	NS†
Ψm	12	***
Ψm x tillage	24	***
Depth	1	NS
Tillage x depth	2	**
Ψm x depth	12	***
Tillage x Ψm x depth	24	***

† NS = nonsignificance at $P \leq 0.05$
, * indicates significance at the 0.05 and 0.01 probability level, respectively.

Table 4.2 Soil water retention properties and plant available water capacity (PAWC) as affected by tillage-residue system and soil depth.

	Soil water (%, v/v) at						PAWC (%, v/v)		
	-10 kPa¶			-1500 kPa					
Soil depth (cm)	No till + straw	Till + straw	Till + no straw	No till + straw	Till + straw	Till + no straw	No till + straw	Till + straw	Till + no straw
0-2.5	35.3	34.9	36.2	25.0 a	19.3 b	18.0 b	10.3 b†	15.6 a	18.2 a
2.5-5	40.4	39.3	38.7	25.0 a	22.4 ab	21.2 b	15.4 a	16.9 a	17.5 a
5-7.5	39.3	38.8	38.0	25.7 a	24.7 ab	23.2 b	13.6 a	14.1 a	14.8 a
7.5-10	38.1	36.2	37.7	24.1 a	22.3 ab	21.2 b	14.0 a	13.9 a	16.5 a
10-12.5	39.7	39.3	40.4	23.2 a	23.1 a	22.9 a	16.5 a	16.2 a	17.5 a
12.5-15	39.2	39.0	40.0	24.0 a	23.4 a	23.6 a	15.2 a	15.6 a	16.4 a
Mean (0-15cm)	38.7 A	37.9 A	38.5 A	24.5 a A	22.5 b B	21.7 b B	14.2 a B‡	15.4 a AB	16.8 a A

¶ Only significant difference found was between no till+straw and till+straw in 7.5-10 cm depth (P=0.10).

† Means in a row followed by different small letters are significantly different at P=0.05, using DMR test.

‡ Means in a row above different capital letters are significantly different at P=0.10, using DMR test.

Table 4.3 Saturated hydraulic conductivity (Ksat¶) of the 0-7.5 and 7.5-15 cm undisturbed soil cores. The associated coefficients of variation (CV) are also included.

Tillage-Residue System	July 1988 (n=4) Ksat, a† Mean ±SE	July 1988 (n=4) Ksat, a† CV %	July 1988 (n=4) Ksat, g‡ Mean ±SE	July 1988 (n=4) Ksat, g‡ CV	Sept. 1988 (n=8) Ksat, a Mean ±SE	Sept. 1988 (n=8) Ksat, a CV	Sept. 1988 (n=8) Ksat, g Mean ±SE	Sept. 1988 (n=8) Ksat, g CV
0-7.5 cm								
No till+straw	92.1 a, A ±23.3	50	4.4 a, A ±0.4	18	82.6 a, A ±10.0	34	4.4 a, A ±0.1	8
Till+straw	61.2 a, B ±6.8	22	4.1 a, A ±0.1	6	38.2 b, B ±7.6	57	3.5 b, B ±0.2	15
Till+no straw	11.3 b, C ±2.5	45	2.4 b, B ±0.2	18	22.8 b, C ±4.7	59	3.0 b, C ±0.2	23
7.5-15 cm								
No till+straw	16.6 a, A ±4.1	49	2.7 b, B ±0.2	18	23.2 a, A ±4.3	52	3.0 a, A ±0.2	16
Till+straw	34.0 a, A ±3.9	23	3.5 a, A ±0.1	6	21.6 a, A ±4.6	61	2.9 a, A ±0.3	24
Till+no straw	8.7 a, A ±1.5	35	2.1 b, C ±0.2	19	18.1 a, A ±4.8	74	2.6 a, A ±0.3	32

¶ Units for Ksat are $\mu m\ s^{-1}$.
† Arithmtic means.
‡ Geometric means.

Note: Means in a column followed by different small and capital letters are significantly different at P = 0.05 and P = 0.10, respectively, using LSD test. Comparisons are permitted only in a given depth interval.

Table 4.4 Saturated hydraulic conductivity (Ksat¶) of 0-7.5 cm soil measured *in situ* with an air-entry permeameter.

Tillage-Residue System	Ksat, a† ±SE	CV	Ksat, g‡	CV	Air-entry Potential (-cm)	CV
			September 30, 1988			
No till+straw	50.8 a, A ±10.3	40	3.9 a, A ±0.2	11	12 a, A ±5	94
Till+straw	39.8 a, AB ±4.2	21	3.7 a, AB ±0.1	6	10 a, A ±5	105
Till+no straw	28.7 a, B ±5.7	39	3.3 a, B ±0.2	14	6 a, A ±3	82
			September 26, 1989			
No till+straw	86.9 a, A ±16.7	39	4.4 a, A ±0.2	12	21 a, A ±1	14
Till+straw	89.9 a, A ±13.2	29	4.5 a, A ±0.1	6	22 a, A ±3	23
Till+no straw	39.0 b, B ±6.0	28	3.6 b, B ±0.1	7	21 a, A ±2	20

¶ Units of Ksat are $\mu m\ s^{-1}$.

† Arithmetic mean.

‡ Geometric mean.

Note: Means in a column, followed by different small and capital letters are significantly different at P = 0.05 and P = 0.10, respectively, using LSD test. Comparisons are permitted only within a date of measurement.

Table 4.5 Water filled pore space (WFPS)¶ and air filled porosity† of 0-10 cm soil layer at the time of infiltration measurements.

Tillage-residue System	Sept. 1, 88	Nov. 2, 88	April 27, 89	Sept. 21, 89
		Water filled pore space (%, v/v)		
No till+straw	53.3±1.2‡	56.5±1.8	53.8±1.5	61.2±0.9
Till+straw	49.9±1.6	45.0±5.0	41.7±0.4	51.0±1.9
Till+no straw	49.1±2.0	37.9±1.1	38.0±1.0	53.7±1.3
		Air-filled porosity (%, v/v)		
No till+straw	27.5±0.9	25.6±1.4	27.4±1.1	23.0±0.7
Till+straw	30.2±1.2	34.4±4.0	36.2±0.7	30.6±1.5
Till+no straw	29.2±1.4	38.0±0.6	37.2±0.8	27.8±0.9

¶ $\text{WFPS} = \frac{\text{fractional volumetric water content}}{\text{fractional total porosity}} \times 100$

† Air-filled porosity = total porosity - volumetric θ

‡ Means are followed by ± SEmean.

Table 4.6 Steady-state infiltration rate at different times in a growing season.

Tillage-residue System	Steady-state infiltration rate (mm h^{-1})			
	Sept. 1, 1988 (after harvest)	Nov. 2, 1988 (after tillage)	April 27, 1989 (before seeding)	Sept. 21, 1989 (after harvest)
No till+straw	373±79 a¶	280±14 a	158±11 a	331±43 a
Till+straw	269±29 ab	261±44 a	140±26 ab	284±17 a
Till+no straw	164±24 b	166±42 a	113±16 b	210±58 a

¶ Means in a column followed by different letters are significantly different (P = 0.10) using least significant difference test.

Note: Each mean value in the table is followed by ± SEmean.

Table 4.7 Cumulative water intake at the end of 1 hour ponded infiltration.

Tillage-residue System	Water intake (mm)			
	Sept. 1, 1988 (after harvest)	Nov. 2, 1988 (after tillage)	April 27, 1989 (before seeding)	Sept. 21, 1989 (after harvest)
No till+straw	455±94 a¶, A	348±20 a, A	214±13 a, A	477±59 a, A
Till+straw	356±35 ab, A	326±53 a, AB	196±29 a, AB	425±18 a, AB
Till+no straw	191±27 b, B	215±47 a, B	156±15 a, B	276±70 a, B

¶ Means in a column followed by different letters are significantly different at P = 0.05 (lower case letters) and P = 0.10 (uppercase letters), using LSD test.

Note: Each mean value in the table is followed by ± SEmean.

Table 4.8 Parameters of Philip and Kostiakov infiltration models.

Tillage-Residue System	Philip model			Kostiakov model		
	S	A	R^2	a	b	R^2
			September 1, 1988			
No till+straw	1.93 a¶	0.52 a	0.89	1.91 a	0.77 a	0.89
Till+straw	1.85 a	0.37 ab	0.97	1.76 a	0.74 a	0.97
Till+no straw	0.80 b	0.21 b	0.94	0.78 b	0.77 a	0.94
			November 2, 1988			
No till+straw	1.53 a	0.39 a	0.99	1.49 a	0.77 a	0.99
Till+straw	1.72 a	0.32 ab	0.95	1.61 a	0.73 ab	0.95
Till+no straw	1.70 a	0.14 b	0.93	1.65 a	0.61 b	0.92
			April 27, 1989			
No till+straw	1.86 a	0.12 a	0.99	1.72 a	0.62 b	0.99
Till+straw	1.74 a	0.10 a	0.94	1.63 a	0.60 b	0.94
Till+no straw	1.01 b	0.13 a	0.97	0.92 b	0.70 a	0.97
			September 21, 1989			
No till+straw	2.80 a	0.43 a	0.96	2.50 a	0.72 a	0.96
Till+straw	2.43 a	0.39 a	0.99	2.18 a	0.73 a	0.99
Till+no straw	1.45 b	0.27 a	0.84	1.30 b	0.74 a	0.84

¶ Means in a column followed by different letters are significantly different at P = 0.10 using LSD test. Comparisons are valid only within a time of measurement.

$I = St^{0.5} + At$ (Philip)

$I = at^b$ (Kostiakov)

I = cumulative infiltration (cm); t = time (min).

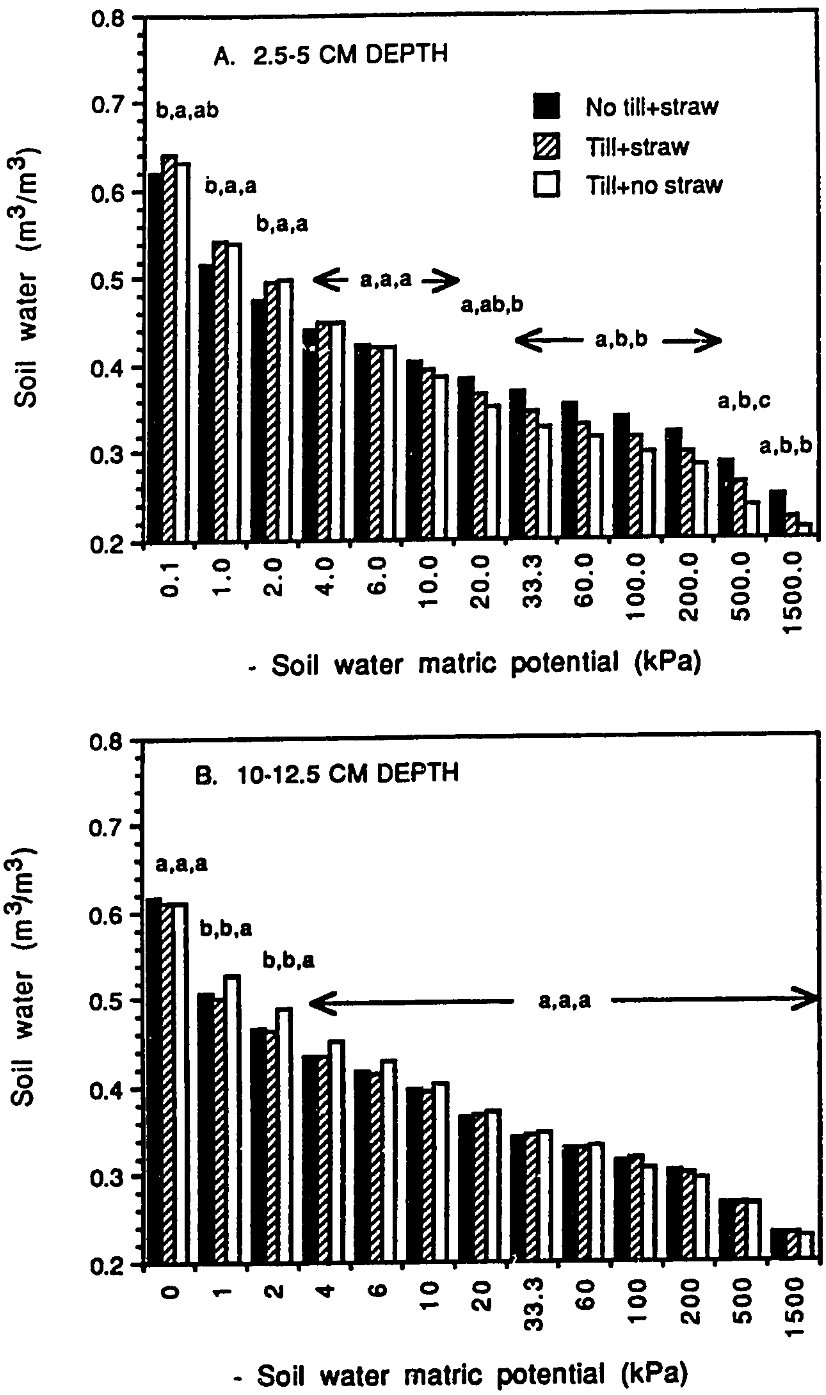

Figure 4.1. Soil water retention for (A) 2.5-5 cm and (B) 10.5-12.5 cm depth intervals. For a given matric potential, treatment means with the same letters are not significantly different (P=0.05).

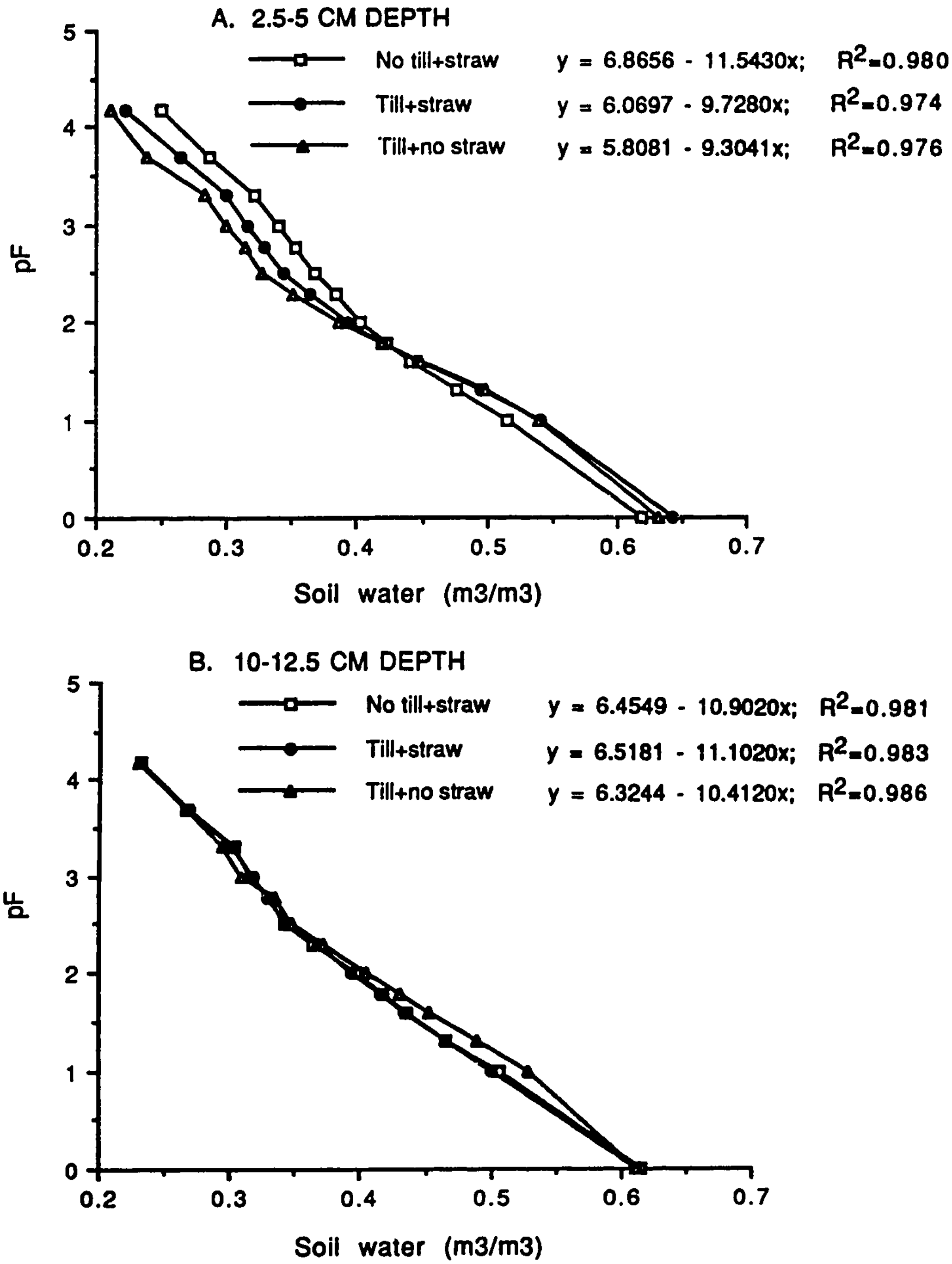

Figure 4.2. Soil water retention (or pF) curves for (A) 2.5-5 cm and (B) 10-12.5 cm depth intervals.

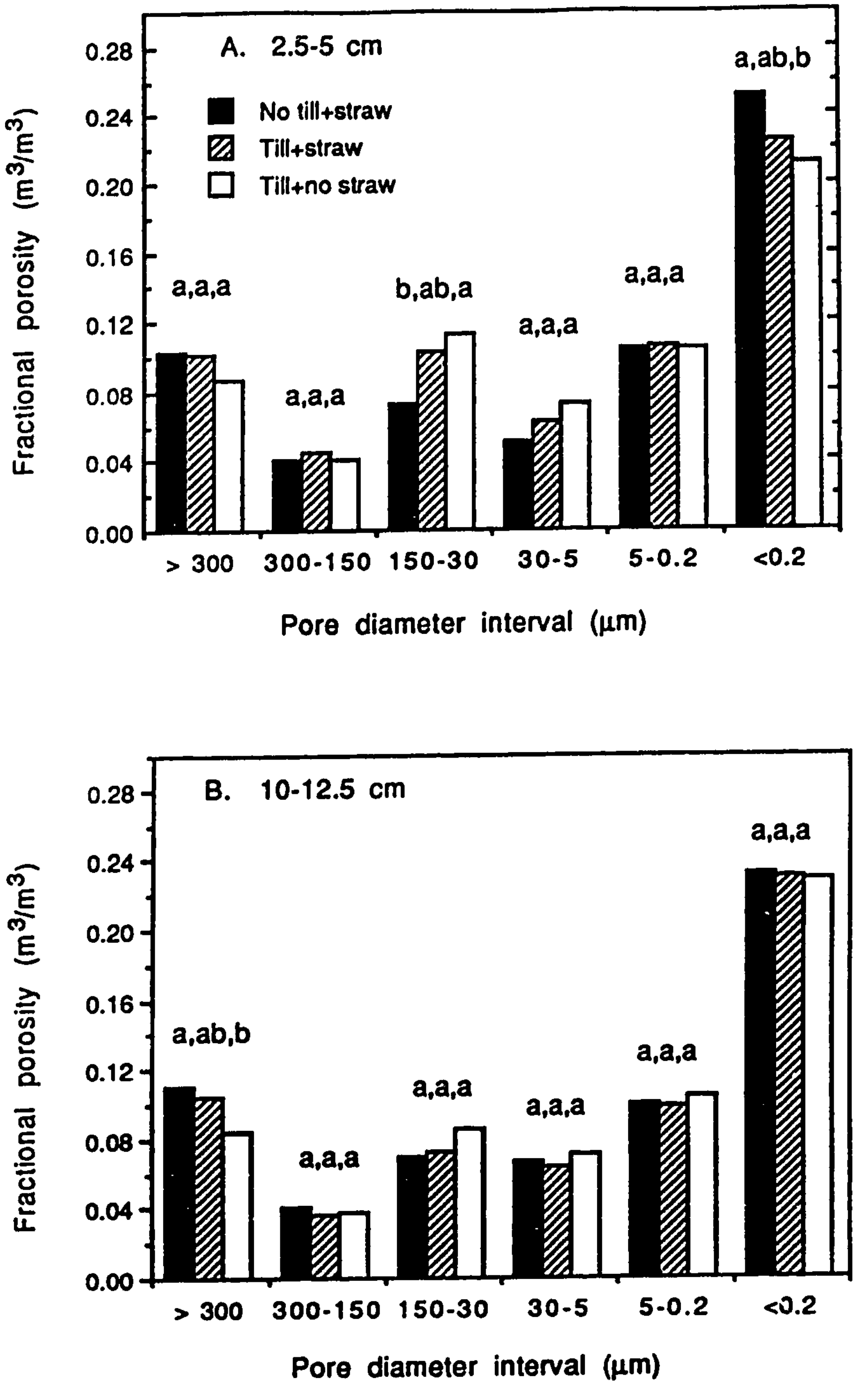

Figure 4.3. Pore size distribution (volume of pores in a given size interval as a fraction of total soil volume) for the (A) 2.5-5 cm and (B) 10-12.5 cm soil layers. Within a given pore-size interval, treatment means with the same letters are not significantly different (P=0.05).

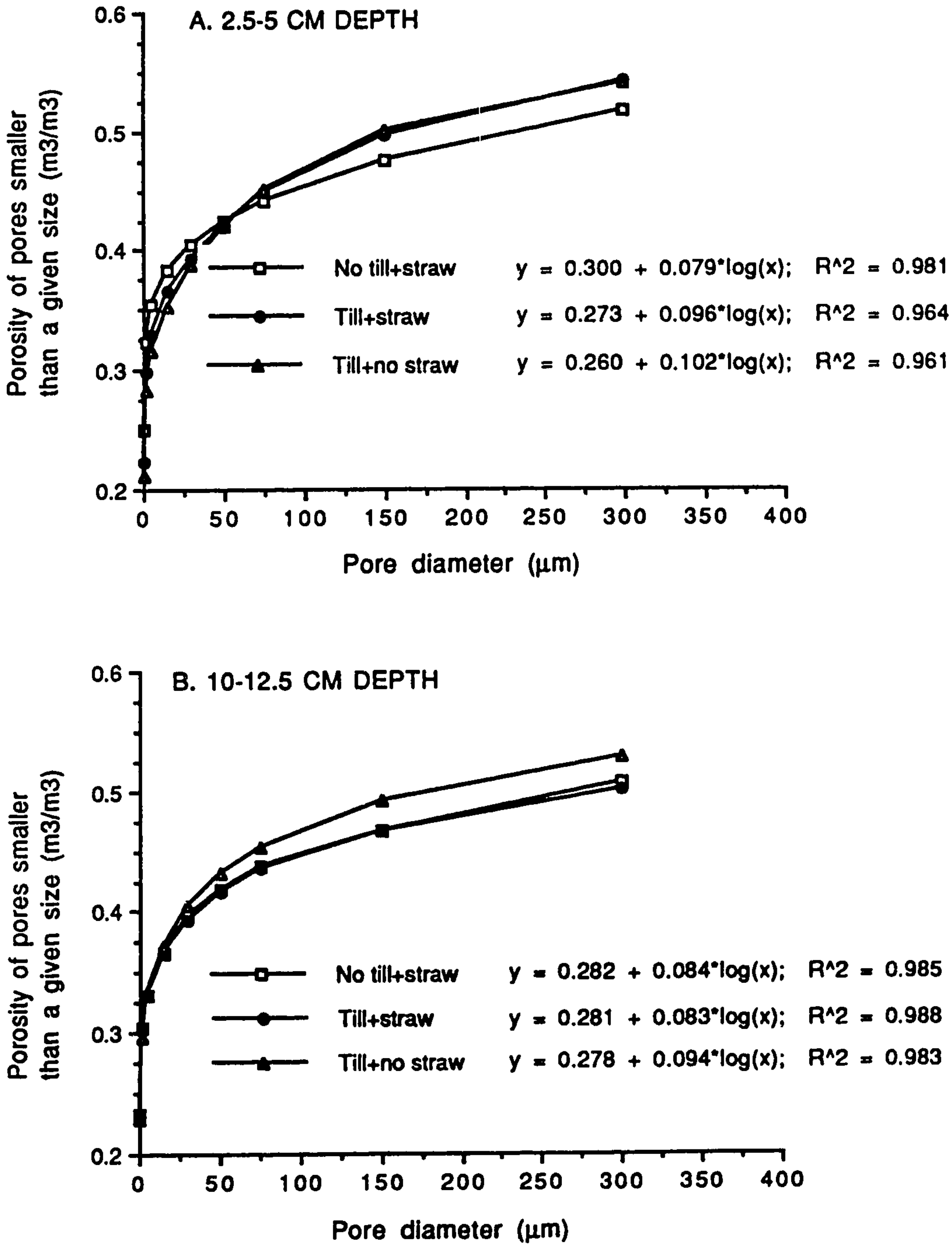

Figure 4.4. Cumulative pore size distribution (equivalent pore diameter ≤ 300 µm) for the (A) 2.5-5 cm and (B) 10-12.5 cm soil layers.

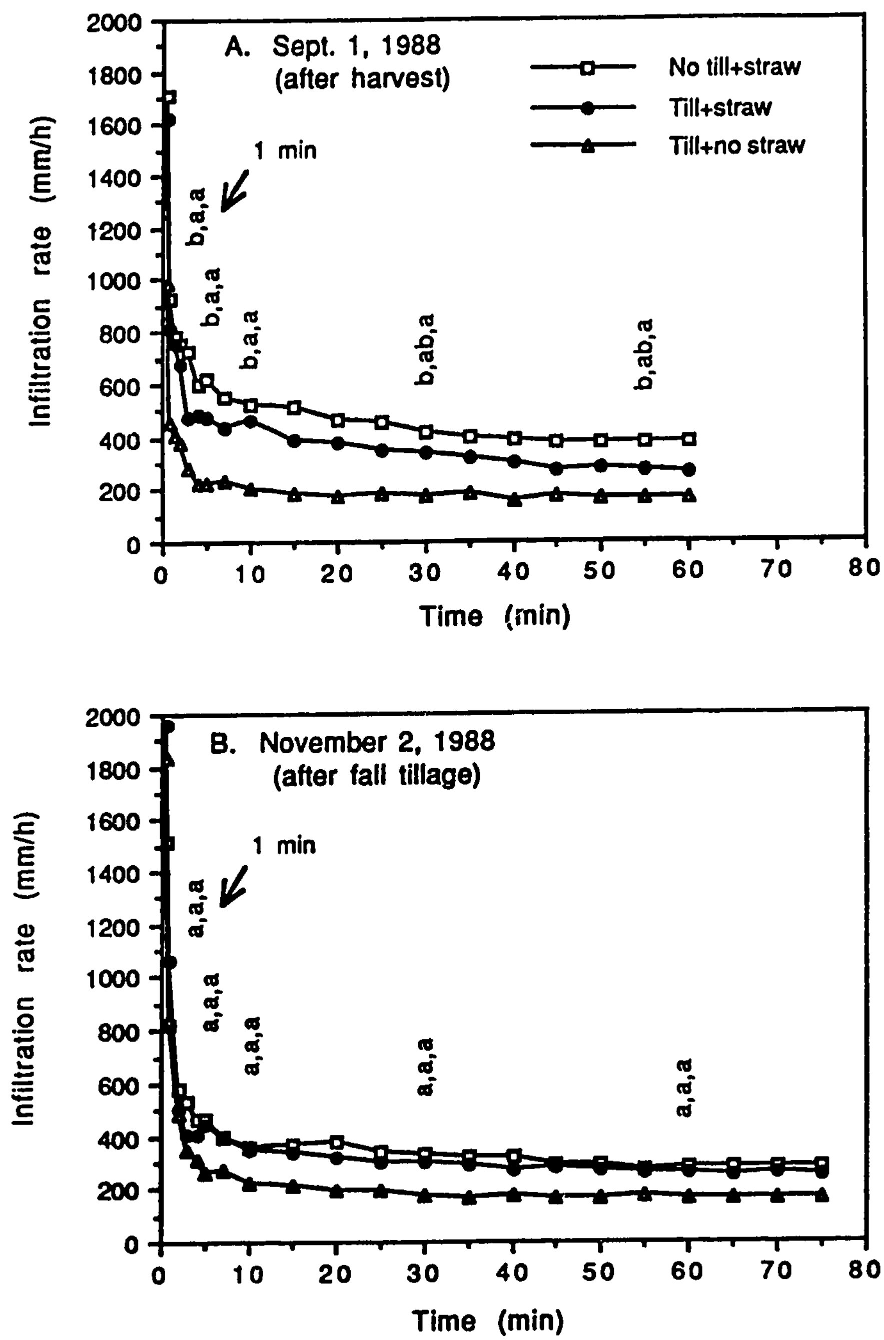

Figure 4.5.1. Infiltration rate on (A) September 1 and (B) November 2, 1988. For a given time after ponding, treatment means with the same letters are not significantly different (P=0.05). The letters are in the same sequence in which treatments appear in the curves.

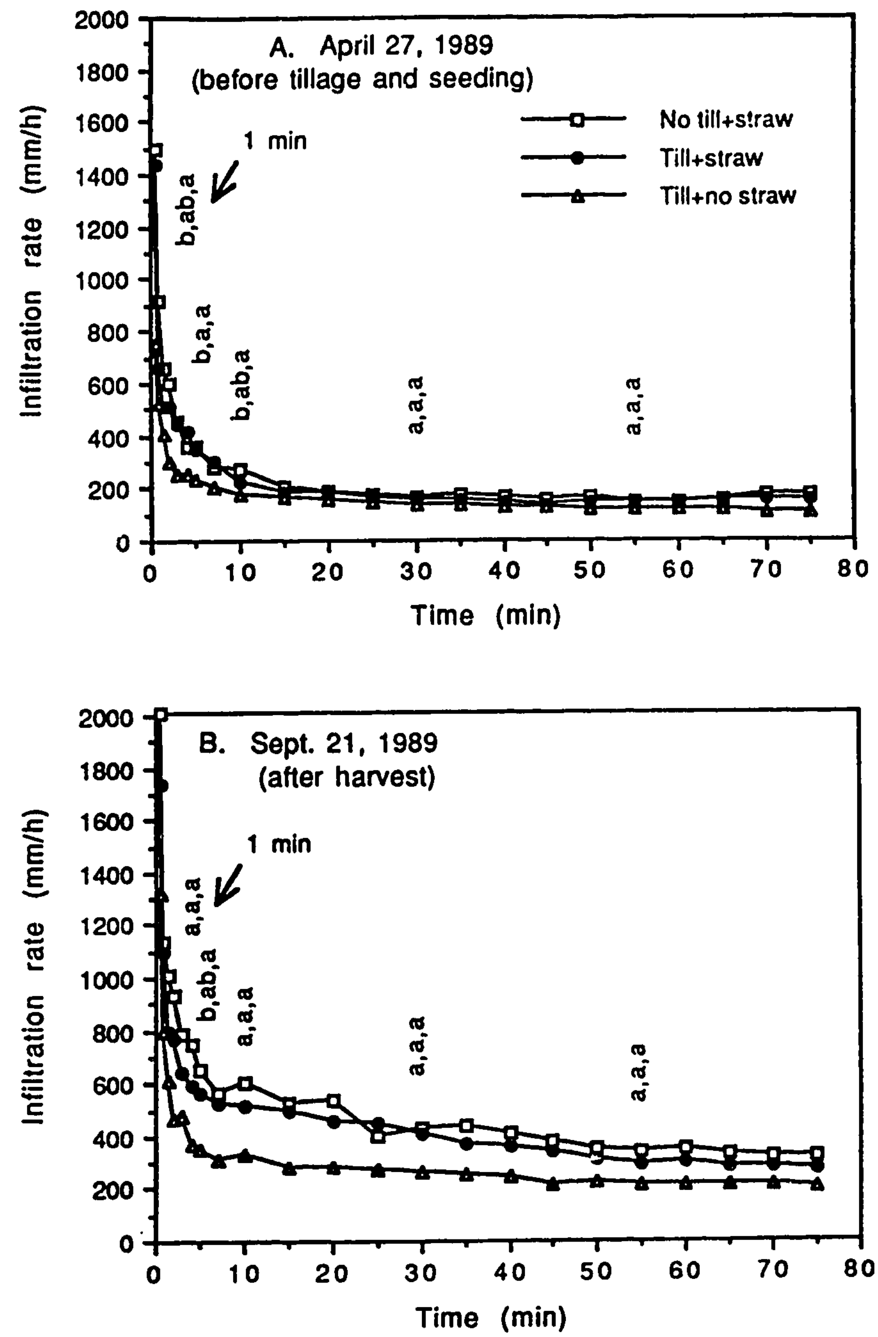

Figure 4.5.2. Infiltration rate on (A) April 27 and (B) September 21, 1989. For a given time after ponding, treatment means with the same letters are not significantly different (P=0.05). The letters are in the same sequence in which treatments appear in the curves.

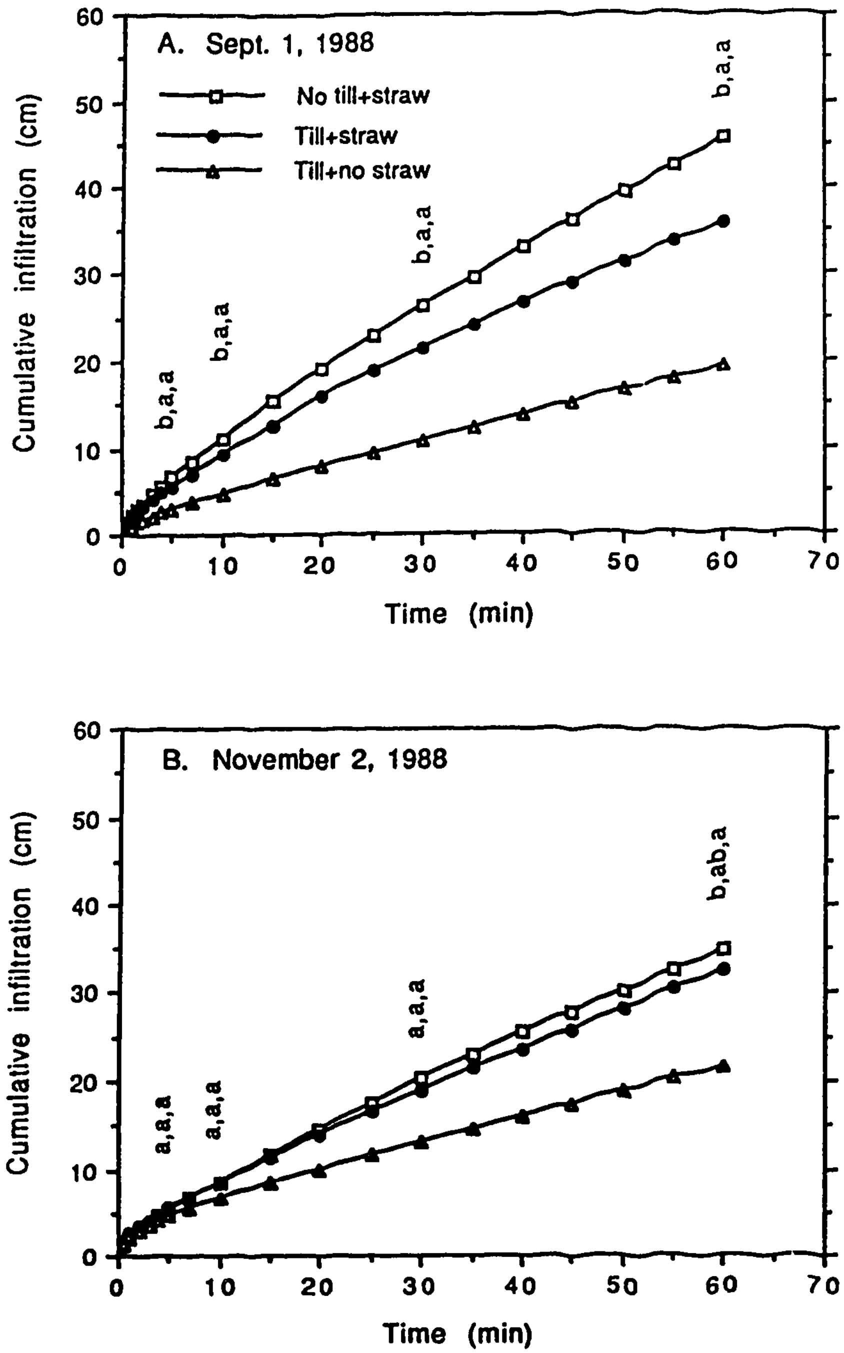

Figure 4.6.1. Cumulative infiltration on (A) September 1 and (B) November 2, 1988. For a given time after ponding, treatment means with the same letters are not significantly different (P=0.05). The letters are in the same sequence in which treatments appear in the curves.

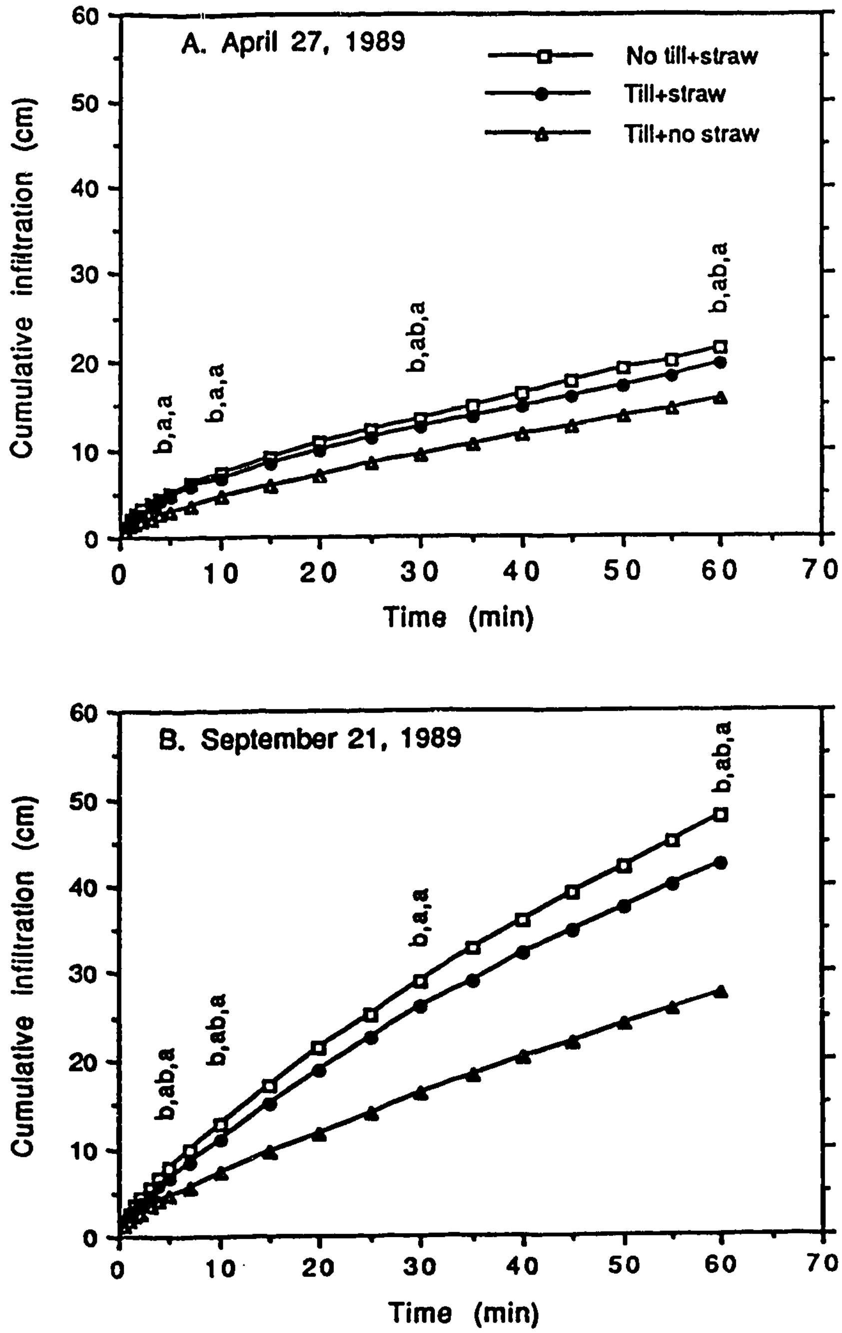

Figure 4.6.2. Cumulative infiltration on (A) April 27 and (B)September 21, 1989. For a given time after ponding, treatment means with the same letters are not significantly different (P=0.05). The letters are in the same sequence in which treatments appear in the curves.

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Chapter 5

INFLUENCE OF LONG-TERM TILLAGE AND RESIDUE MANAGEMENT PRACTICES ON SOIL WATER REGIME OF A TYPIC CRYOBOROLL UNDER CONTINUOUS SPRING BARLEY

5.1 INTRODUCTION

The soil water regime is very dynamic, being a result of complex interactions of many variables related to current and past occurrences of weather, soil properties, cropping patterns and agricultural management practices (De Jong and Bootsma, 1988). In the absence of irrigation, such as over a major part of the Canadian prairies, success of a crop largely depends on the amount of soil water at seeding, and on the growing-season precipitation and efficiency of its storage in the soil profile. Thus, it is imperative to develop and utilize management practices that help maintain a favorable soil water regime for optimal crop growth and development.

The soil water regime is greatly affected by evaporation, transpiration, infiltration, runoff and internal drainage. These processes are controlled, in part, by the water retention and transmission properties of soil. Tillage-residue management systems variably affect these soil hydraulic properties, and thus the soil water regime. No-tillage systems maintain a substantial crop residue cover on the soil, which reduces water runoff and increases infiltration. In addition, residue cover reduces evaporation and can increase snow trapping (Moody et al., 1963; Gauer et al., 1982; Smika and Unger, 1986). Thus, no-tillage systems generally result in a more efficient storage of precipitation. Through their effects on root and shoot growth, however, tillage-residue systems can differentially affect plant water uptake and, thus, indirectly modify the soil water regime.

Many studies reported greater soil water under conservation tillage systems (with surface residues) than under conventional tillage, both in drier (arid and semiarid) and wetter (subhumid and humid) regions (e.g. Jones et al., 1969; Blevins et al., 1971; Phillips, 1974; Bennett, 1977; Gantzer and Blake, 1978; Gauer et al., 1982; Grevers et al., 1986; Heer and Krenzer, Jr., 1989). For a silt loam in Kentucky (a relatively humid location), evaporation from May through September was 2.4 times greater under conventional tillage than under no-tillage (Phillips, 1984). This difference provided 18% more water for transpiration by no-tillage corn than for conventional tillage corn during the growing season. Whether the increased soil water under conservation tillage systems actually benefits crop growth depends on prevailing micrometeorological conditions, crop growth stage, water holding capacity of the soil, other conditions in the soil environment that may limit plant growth, etc.

Not much is known regarding the soil water dynamics as affected by long-term tillage-residue management under the soil, site and agroclimatic conditions of Central Alberta. As part of a broader study carried out on a well-drained and fine-textured Typic Cryoboroll in Central Alberta, it was reported in the previous chapters that a no-till system maintained a greater surface residue cover, had a better aggregation status, and an increased water transmission, compared with the tilled (with or without straw) treatments. Small changes in pore-size distribution and water retention were also measured. The objective of the present research was to quantify the soil water regime during a crop (barley) growing season, under the same three long-term tillage and residue management systems. An additional objective was to discover if the soil water during the growing season was adequate for crop growth under these management systems.

5.2 MATERIALS AND METHODS

5.2.1 *Tillage-residue treatments*

Ten tillage, residue and nitrogen management systems were established on a near-level, well-drained, fine loamy, mixed, Typic Cryoboroll (Black Chernozemic) at the

Ellerslie Research Station (53^{o} 25' N, 113^{o} 33' W, 686 m a.s.l.) of the University of Alberta in the fall of 1979 to investigate the long-term effects of these systems on soil environment and crop growth. Of these, three systems were selected for the purpose of the present study: (1) no-tillage, straw retained on the surface; (2) conventional tillage (roto-tillage to 10-cm depth), straw retained and incorporated into the surface soil; and (3) conventional tillage, all straw and most of the stubble removed. In the no-tillage treatment, crop was seeded directly at 5 cm. The conventional tillage involved roto-tillage in fall and at seeding. The treatments were repeated each year. The plots were continuously cropped to spring barley (*Hordeum vulgare* L.). The growing season extended from May 19 to August 29 in 1988 and from May 26 to September 1 in 1989. Weeds were mainly controlled with herbicides. Greater details regarding soil, site, climate, treatments and cultural operations are given in Chapter 2 .

5.2.2 *Measurements and calculations*

5.2.2.1 *Soil water*

Soil water was measured at seeding, harvest and at approximately weekly intervals in all the plots, using a neutron scatter technique (Gardner, 1986). One open-ended neutron probe access tube (Aluminum, 50 mm i.d.) was installed in each plot with a hydraulic coring unit. Soil water was measured in each tube with a pre-calibrated neutron probe depth moisture gauge (Model 503 Hydroprobe, Campbell Pacific Nuclear Corp., Martinez, CA). Readings were taken in 10-cm increments from 15 to 95 cm below the soil surface. Two 16-s readings were taken at each depth. The reading at 15 cm was used as a measure of soil water in the 7.5 to 20-cm depth. For all other readings, a 10-cm diameter sphere of influence was used. Surface (0-7.5 cm) soil water content was measured on 4 locations adjacent to an access tube using another neutron probe in conjunction with an hydrogenous shield (Chanasyk and Naeth, 1988).

Profile soil water was calculated as:

$$PSW_z = \sum_{i=1}^{n} \O_{vi} \cdot T_i$$

where PSW_z = amount of water (mm) present in depth z (mm) of the soil; $z=\sum_{i=1}^{n} T_i$; T_i = thickness (mm) of soil layer i; $\O_{vi}$ = volumetric water content ($m^3\ m^{-3}$) of soil layer i; n = number of layers in the considered soil profile.

Rainfall and air temperature were measured during the growing season within 50 m of the research site. Long-term records of these data for the site were obtained from Environment Canada (1982).

5.2.3 *Statistical analyses*

For each time that water measurements were made, soil water content at selected depths (7.5, 15, 45 and 85 cm) was statistically analyzed using a completely randomized block design (RBD). Profile soil water computed for 0-20, 0-50 and 0-100 cm depth, was similarly analyzed. Data were tested for homogeneity of variance using Cochran and Bartlett- Box tests. The UANOVA procedure of the $SPSS^x$ statistical program was used for analysis of variance. The least square means were computed and used when an observation was missing. The F-test (Steel and Torrie, 1980) was used to determine significant tillage effects, and the least significant difference test was used to separate treatment means at 5% level of significance.

5.3 RESULTS AND DISCUSSION

5.3.1 *Growing season precipitation and air temperature*

Daily rainfall was better distributed during 1989 than during 1988 season (Figures 5.1A and 5.1B). There were two distinct rainless periods in 1988 season, one of 10 days immediately after sowing and a second of 18 days from July 19 to August 5. Total precipitation for the 1988 and 1989 growing seasons was 315 and 243 mm, respectively. The May to August precipitation was 18% more and 7% more than the 1951-80 average in 1988 and 1989, respectively (Table 5.1). The 1989 growing season was relatively milder in air temperature than the 1988 season (Table 5.2). The month of May in 1988 was particularly warm; average temperature being 4.2 ^{o}C greater than the long-term average. Only 17 mm rain was received in this month as compared with the long-term average of 45 mm. June and August 1988 also had above-normal temperatures as well as rainfall. The 1989 season had closer to average temperatures as well as precipitation.

5.3.2 *Soil water content with time*

Volumetric water content of the 0-7.5-cm depth was the most dynamic (Fig. 5.2). It was generally significantly greater under the no till+straw treatment compared with the till+no straw treatment in both years. The two straw treatments were generally not different during the 1988 season but were so during the 1989 season. The till+no straw treatment was the driest except during the latter part of the 1988 season.

Water content of the 0-7.5 cm depth generally followed the rainfall pattern. After an appreciable rain the differences among treatments were reduced, whereas with continued dry conditions, the no till+straw treatment showed appreciably higher water content than the till+no straw treatment, the difference on absolute value basis reaching as high as 8%. This is apparently a result of reduced evaporation due to a substantial residue cover in the no-till treatment (Chapter 2). Higher water content of the till+straw treatment compared with till+no straw is also ascribed to a partial straw cover (approximately 40%) in the former treatment.

Unger and McCalla (1980) and Smika and Unger (1986), after a review of literature, concluded that effects of various tillage systems on soil water were primarily associated with effects of residue cover provided by these systems on evaporation and infiltration. In the present study, the infiltration rate of soil was quite high in all the treatments (Chapter 4);

therefore infiltration and runoff might only be small factors in the observed treatment differences in soil water content. Blevins et al. (1971) attributed higher moisture under conservation tillage systems to reduced evaporation due to residue cover, and also to a greater ability to store water under no-tillage due to rearrangement of the pore size distribution. In the present study, treatment differences in soil water retention, particularly near the 'field capacity' range, were very small (Chapter 4). Phillips et al. (1980) also attributed higher soil water content under the no-tillage system to reduction of evaporation losses due to mulch on the surface.

The water conserving effect of the no-tillage system was evident even after development of a full crop canopy in 1989, as demonstrated by a measurement 77 days after seeding (Fig. 5.2B). Such an effect was not apparent in 1988. Treatment differences were generally greater in 1989 due to lower though better distributed rainfall than in 1988. Because both growing seasons experienced above-average rainfall, it is implied that in a drier year with greater evaporative potential the treatment differences could be even greater.

The -1500 kPa volumetric water content of soil in the 0-7.5 cm depth was 25.2, 22.1 and 20.8% in the no till+straw, till+straw and till+no straw treatments, respectively (Chapter 4). Measured soil water content of 0-7.5-cm depth was close to or below these limits on several occasions in both years (in all treatments in 1988 and in tilled treatments in 1989). However, no permanent wilting of the crop was observed although plant water status was not measured. This means that either the plants were extracting water below -1500 kPa potential in the 0-7.5 cm layer (approximately 50% of the total root mass and 43% of the total root length at grain formation stage in 1988 were present in this zone-Chapter 6), or/and the soil below 7.5-cm depth was able to supply water to the plants at a rate sufficient to meet the evapotranspiration requirement, or/and the plants were stressed only temporarily. Root water extraction below -1500 kPa has been observed in several instances (Marshall and Holmes, 1988).

Water content at 15-cm depth, representing soil water status of the 7.5-20-cm layer, was always the lowest in till+no straw treatment in both years, being generally significantly different than the other two treatments which normally did not differ (Fig. 5.3). Volumetric water content at -1500 kPa for 7.5-15-cm depth was 23.8, 22.9 and 22.6% for the no till+straw, till+straw and till+no straw treatments, respectively (Chapter 4). Only once in each year, and in tilled treatments only, did the water content approach this lower limit of plant water availability. In both years, the till+straw treatment generally had the highest water content at 15-cm depth up to about mid-season after which it was mostly between the other two treatments. A more vigorous crop in the till+straw system (Chapter 6) probably extracted more water for transpiration in the later stages of crop growth.

In both years, the till+no straw treatment had the lowest water content even at deeper depths of 45 cm and 85 cm, the difference between no till+straw and till+no straw generally varying from 0 to 3% absolute values (data not shown). Nevertheless, the treatment differences were non-significant at all times for the 85-cm depth in both years, and at all but 3 times in 1988 and one time in 1989 at the 45-cm depth.

5.3.3 *Soil water storage with time*

The no till+straw treatment had significantly greater total water in 0-20-cm depth interval compared to the till+no straw treatment at all measurement times in both years, except near harvest in 1988 (Fig. 5.4). The difference varied between 3 mm (6%) and 9 mm (18%) in 1988 and between 2 mm (3%) and 12 mm (26%) in 1989. Note that percentage values in the brackets are relative differences. The till+straw treatment was intermediate, usually closer to no till+straw up to nearly mid-season, and to the till+no straw treatment afterwards. Thus early in the season straw appeared to be the main factor, later tillage was paramount.

The results for total water to 50-cm depth were generally similar to those for 0-20-cm depth. The values ranged from 131 to 187 mm and 137 to 189 mm in the no till+straw, 121 to 185 mm and 126 to 190 mm in the till+straw, and 117 to 175 mm and 121 to 176 mm in the till+no straw treatment, during the first and second year, respectively (Fig. 5.5). The difference between the no till+straw and till+no straw treatments was generally significant, for more number of times in 1989, and varied from 6 to 16 mm (4 to 12%) in 1988 (except the last two measurements), and 4 to 18 mm (2 to 12%) in 1989.

General treatment trends of total soil water in the 0-100-cm profile were remarkably similar to those of 0-20 and 0-50-cm depths (Fig. 5.6), implying that the soil water regime was affected to a 100-cm depth (the lowest depth monitored) by tillage-residue systems. The values ranged from 290 to 369 mm and 287 to 357 mm in the no till+straw, 276 to 369 mm and 272 to 353 mm in the till+straw, and 267 to 354 mm and 259 to 331 mm in the till+no straw system, during 1988 and 1989 growing season, respectively. The treatment differences were again significant for a greater number of measurements in 1989 than in 1988, a general reflection of different rainfall amounts and distribution in the two years (Fig. 5.1). Other micrometeorological parameters such as total solar and net radiation, air temperature, relative humidity and wind speed might also have contributed to the observed differences through their influence on evapotranspiration.

In 1988, only 34 mm of rain fell during July 17 to August 17. During this period, the no till+straw treatment had generally significantly greater (13 to 26 mm or 5 to 9%) total water to 100-cm depth compared to both tilled treatments (Fig. 5.6A). In 1989, difference between the no till+straw and till+no straw treatments was significant 9 times out of 13 and varied from 12 to 28 mm (4 to 11%) whereas the two straw treatments were mostly non-significantly different.

5.3.4 *Soil water profiles*

5.3.4.1 *The 1988 growing season*

Soil water distribution with depth as affected by tillage-residue systems is reported for selected measurement times over the two growing seasons (Figures 5.7 and 5.8).

One day after spring tillage-cum-seeding in 1988 (i.e. on 20 May), the till+no straw treatment had the lowest soil water at all depths to 100 cm (Fig. 5.7.1A). At and below 15-cm depth, the two straw treatments were very close; with till+straw being somewhat wetter. This latter trend continued to show until the measurement on 16 July. These treatment differences at the beginning of the growing season indicate different storage efficiencies/capacities and/or different evaporation rates among the treatments over the winter period as well as the snow-melt to seeding period. Differential snow trapping may also be a factor. At several locations on Canadian prairies, Grevers et al. (1986) observed a greater soil water gain in zero-till compared to conventional-till during autumn to seeding period, ascribed primarily to reduced soil evaporation under residue-covered zero-till system during snow-melt to seeding.

The depletion of soil water during the period from seeding (19 May) to 4 June was similar among treatments; being 8.3, 8.8 and 8.5 mm for 0-20-cm depth in the no till+straw, till+straw and till+no straw treatments, respectively. During this period, the crop extraction of soil water can be assumed very small, compared to soil evaporation. This period was also relatively hot and dry (22.4 ^{o}C average maximum temperature, 9.8 mm rain). Similarity of water loss in the three treatments, therefore, suggests that while in the no-till treatment a substantial straw cover may have reduced evaporation (see discussion in section 5.3.2), it is possible that formation of a drier surface layer ('soil mulch') due to recent tillage probably curtailed evaporation in the tilled treatments. Willis and Bond (1971) reported that longer-term soil evaporation decreased with shallow tillage.

The period June 5 to 15 received 71 mm of rainfall. The overall increase in 0-100-cm profile-stored water during this period was the same in the three treatments (58, 58 and 60 mm in the usual order), indicating similar general hydrologic conditions of all treatments. However, distribution of rain water within the soil profile varied between treatments. The increase in 0-7.5 cm soil water content was 12.5, 6.8 and 8.5% in the no till+straw, till+straw and till+no straw treatments, respectively (Figures 5.7.1B and 5.7.2A). At 15 and 25-cm depths, the respective increases were 5.9, 7.0 and 9.3%, and 7.2, 8.2 and 8.8%. Gains at other depths were similar among treatments; nevertheless, the till+no straw treatment continued to have lowest water content throughout the profile.

Greater water content of the surface soil in the no till+straw treatment under wetter conditions prevailing in this period is again attributed mainly to lower evaporation in this system. Greater water retention in no-tillage at matric potentials corresponding to soil water contents measured on 15 June (refer to soil water desorption curves given in Fig. 4.2A, Chapter 4) may be another reason. Larger gain of water in the 7.5-30-cm depth than 0-7.5-cm depth in the tilled treatments, a trend opposite to that observed in no-tillage, suggests that water probably moved deeper in the tilled treatments. It is difficult to explain this behavior.

Midway during the 1988 growing season (i.e. on 16 July, 58 days after seeding), general trends in soil water profiles were similar to those on 15 June (Fig. 5.7.2B). The period 16 July to 5 August was very droughty with only 1.6 mm rain. This was also the period of active reproductive growth (Chapter 6). Overall water loss from the 0-100-cm profile from 16 July to 2 August was 50, 65 and 65 mm in the no till+straw, till+straw and till+no straw treatments, respectively. The no till+straw treatment still had the highest water content at all depths below 7.5 cm (Fig. 5.7.3A). This again shows the water conserving effect of the no till+straw treatment, although somewhat greater soil water extraction by a more vigorous crop of the tilled treatments cannot be discounted.

The effect of dry weather on soil water profiles is clearly visible from measurements on 2 August (Fig. 5.7.3A). The moisture content gradients at all depths in all treatments were directed upwards, indicating a large evapotranspiration requirement of the aerial environment. Water was lost from the entire soil profile, with the maximum extraction occurring from approximately the top 60 cm (Figures 5.7.2B and 5.7.3A). This indicates that the potential rooting depth of barley in the experimental soil was around 60 cm.

After 16 July, the two straw treatments changed trends in that water content in the till+straw treatment now generally remained lower than that in the no-till treatment in most of the profile. This was likely due to greater soil water extraction during this active reproductive growth period by a somewhat larger crop (greater green leaf area index and greater shoot dry matter- Chapter 6) in this treatment. Also after 24 July, the soil in the no-till treatment was not the wettest in 0-7.5 cm depth.

From 2 August till harvest (29 August), 77 mm rain fell, increasing the water content at all depths but mostly in the top 60 cm (Fig. 5.7.3B). The increases in total soil water for 0-100-cm profile were 43, 56 and 50 mm in no till+straw, till+straw and till+no straw treatments, respectively. Towards crop maturity, transpiration becomes very small. Evaporation loss is also small because of canopy shading. Thus, differential evapotranspiration might only be a small factor in the observed treatment differences. Possibility is that some rain water drained below 100 cm in the no till+straw treatment because soil infiltrability and hydraulic conductivity were the highest in this treatment (Chapter 4). Some of the 45-mm rain from 18 to 21 August might have been lost by this process. Phillips (1984) also reported more drainage of soil water below the rooting depth under no-tillage than under conventional tillage.

5.3.4.2 *The 1989 growing season*

Rainfall in 1989 was more frequent and better distributed though smaller in amount than in 1988 (Figures 5.1A and 5.1B). It rained on 58 days during the 99-day growing season in 1989 compared with 35 days during the 103-day growing season in 1988.

The soil water profiles at seeding in 1989 (31 May) were remarkably similar to those in 1988 (Figures 5.8.1A and 5.7.1A). Trends in the water profiles on June 7, 17 and 25 (not shown) were similar to those at seeding. There was almost daily rain from 19 June to 11 July for a total of 112 mm (Fig. 5.1B). Consequently, the water profiles on 9 July were all directed downwards (Fig. 5.8.1B). Even in these very wet soil conditions, the till+no straw treatment still had the lowest water content throughout the soil profile excepting the surface 7.5-cm depth.

The period 9 to 31 July was one of vigorous crop growth with 53 mm rainfall. The soil water profiles on July 15, 23 and 31 were generally similar in trends. On 31 July, for example, the water content at all depths was in the order: no till+straw >till+straw >till+no straw (Fig. 5.8.2A). During this period, water loss from 0-20-cm depth was 5 mm greater in the tilled treatments compared to the no-tilled one. This indicates that the no-till treatment was effective in decreasing evaporation even in a full crop canopy, although a differential crop removal of soil water may also be a contributing factor.

On 20 August, 10 days before harvest, soil water gradients in the top 40-cm depth were directed downwards (Fig. 5.8.2B) because 35 mm of rain fell during 5 days preceding this measurement. The treatment trends for measurements after 31 July until harvest continued to be consistently similar, with the no-till treatment showing the maximum water content at all depths whereas till+no straw generally had the lowest water content.

The measured soil water profiles showed that the tillage-residue treatments had produced changes in soil water regime throughout the 1.0-m profile in both study years. Heer et al. (1989) on a silt loam Argiustoll in Oklahoma, and Gauer et al. (1982) on four soils varying from sandy loam to clay in southern Manitoba, also reported consistently greater water content throughout the 1.2- and 1.35-m profile with no-till as compared with conventional tillage system. In contrast, Blevins et al. (1971) observed effects of tillage system on soil water content only to a depth of 60 cm of a silt loam in Kentucky.

5.4 CONCLUSIONS

The study demonstrated that the three long-term tillage-residue management systems affected the soil water regime to 100 cm, the greatest depth monitored, despite a relatively low atmospheric evaporative potential at this site. The magnitude of influence varied during the growing season and also between the two study years. The treatment differences were significant even at the beginning of a growing season.

The till+no straw treatment was generally the driest at all depths. The no till+straw treatment had the highest soil water in 0-7.5-cm depth for most of the growing season. Total soil water to a depth of 50 cm was generally significantly lower in the till+no straw treatment compared with the no till+straw treatment. The two straw treatments were not generally different for 0-50 and 0-100-cm profile water storage.

The soil water seemed adequate for plant growth except on a few occasions. Possibility exists that in relatively drier years, soil water of 0-15-cm depth can go below the -1500 kPa water content, particularly in the tilled treatments.

The water conserving effect of the no till+straw treatment was evident during both dry and wet conditions, and also after development of a full crop canopy. It implies that the no till+straw system would possibly carry the crop through short-term drought conditions. During excessively wet conditions, however, this treatment might induce anaerobic conditions in the surface soil and also experience greater percolation losses.

Table 5.1 Monthly and total rainfall during the growing season (May–August) of 1988 and 1989, and the 30-year average for the same months, at Ellerslie, Alberta.

	Precipitation (mm)		
Month	1988	1989	Average (1951-80)
May	17†	53‡	45
June	110	61	78
July	118	110	84
August	78	69	67
Total	323	293	274

† 9 mm after seeding.
‡ 3 mm after seeding.

Table 5.2 Air temperature (°C) during May to August in 1988 and 1989, and the 30-year average for the same months at Ellerslie, Alberta.

	1988			1989			1951-80 Average		
Month	Max.	Min.	Avg.	Max.	Min.	Avg.	Max.	Min.	Avg.
May	21.2 ±4.9	5.2 ±3.5	14.7 ±3.1	17.1 ±6.0	3.0 ±3.4	10.5 ±4.4	17.2	3.4	10.3
June	22.3 ±3.6	10.2 ±3.2	16.7 ±2.6	21.2 ±3.3	8.5 ±2.7	15.0 ±2.4	20.3	7.6	14.0
July	22.7 ±3.9	9.5 ±2.6	16.4 ±2.7	23.9 ±3.6	10.8 ±2.4	17.5 ±2.5	22.4	9.6	16.0
August	22.0 ±3.8	8.7 ±2.1	15.7 ±2.3	21.3 ±5.0	9.6 ±4.0	15.5 ±4.1	21.2	8.5	14.9
Avg. (May-Aug)	22.0 ±4.1	8.5 ±3.4	15.9 ±2.7	20.9 5.2	8.0 ±4.4	14.6 ±4.3	20.3	7.3	13.8
Growing Season¶	22.4 ±4.0	9.0 ±3.1	16.2 ±2.6	21.8 ±4.3	9.1 ±3.8	15.6 ±3.5			

¶ 1988: May 19 to August 29; 1989: May 26 to September 1.

Note: Means are followed by ± standard deviation.

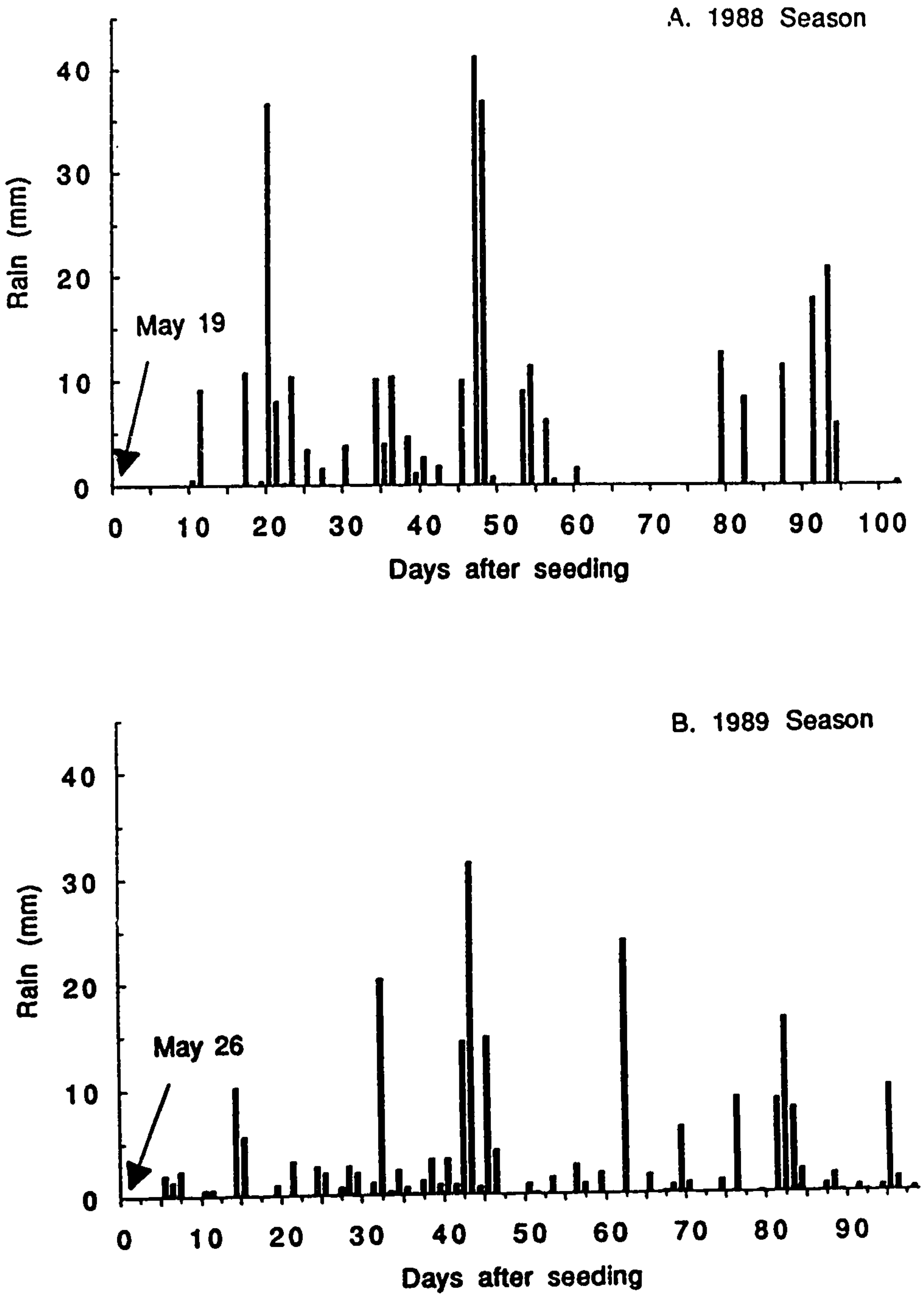


Figure 5.1. Daily rainfall distribution during the (A) 1988 and (B) 1989 growing seasons.

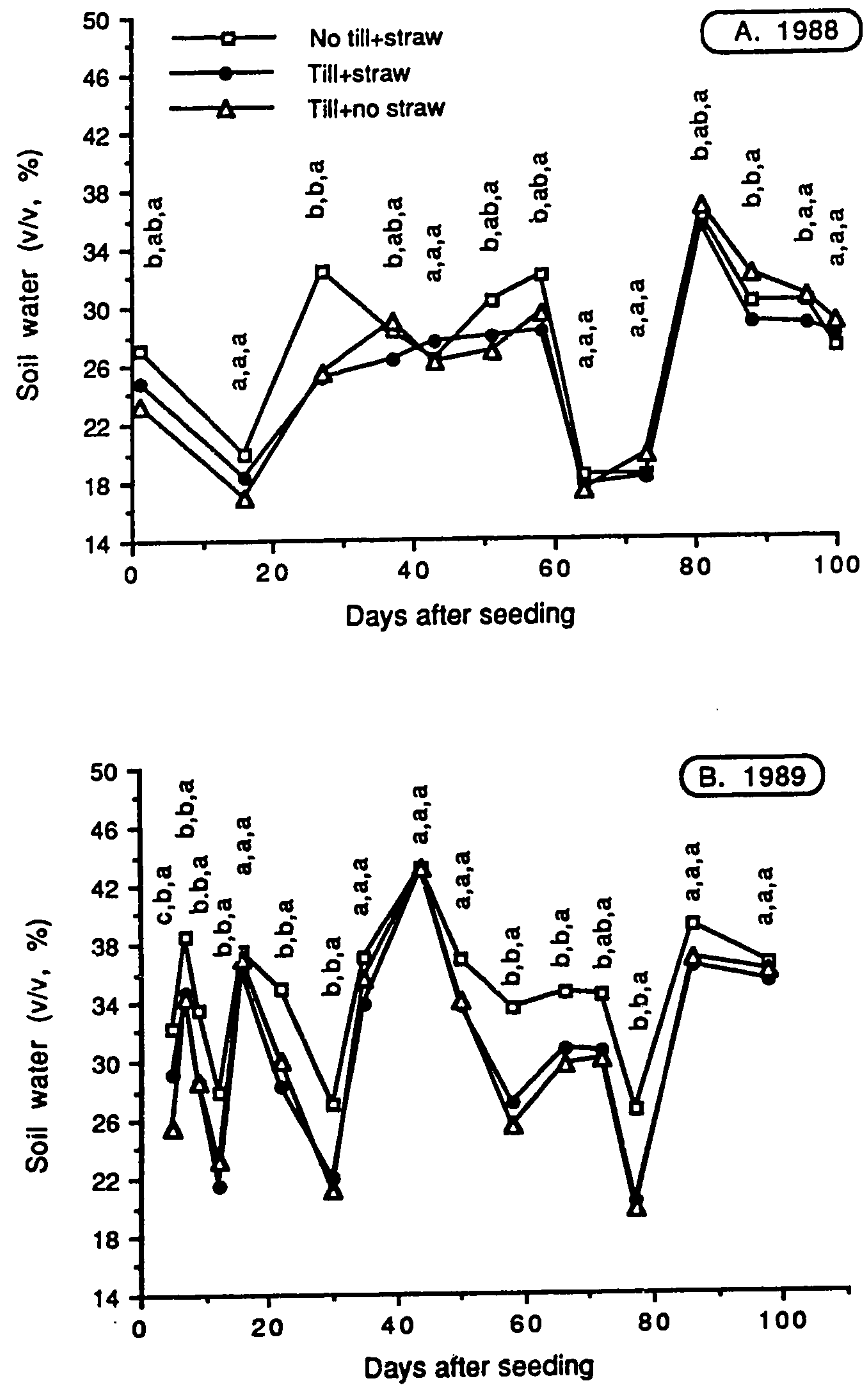


Figure 5.2. Volumetric water content of the 0-7.5 cm soil layer during the (A) 1988 and (B) 1989 growing seasons. For a given day, treatment means with the same letters are not significantly different (P=0.05). Seeded on May 19, 1988 and May 26, 1989.

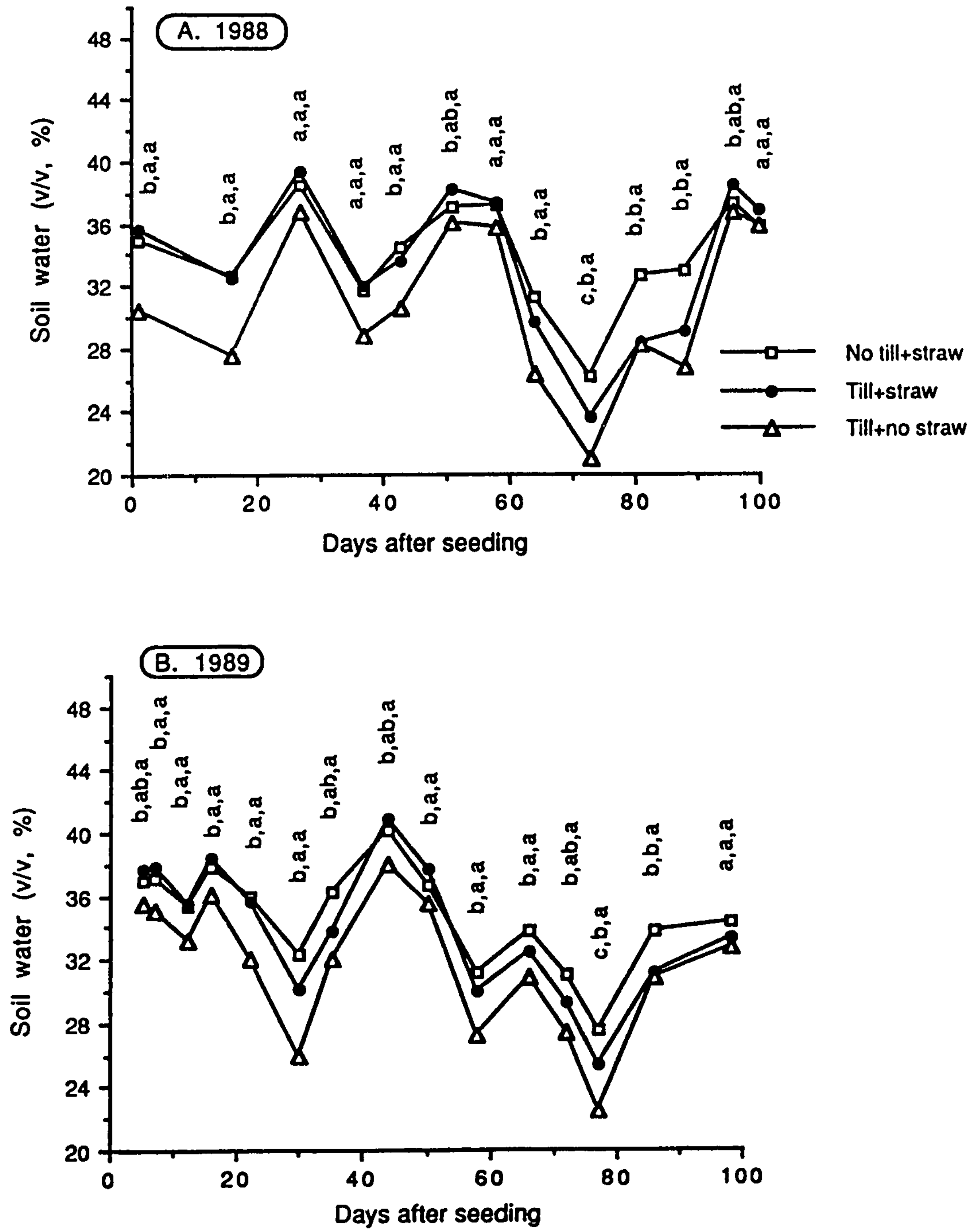


Figure 5.3. Volumetric water content at the 15-cm depth during the (A) 1988 and (B) 1989 growing seasons. For a given day, treatment means with the same letters are not significantly different (P=0.05). Seeded on May 19, 1988 and May 26, 1989.

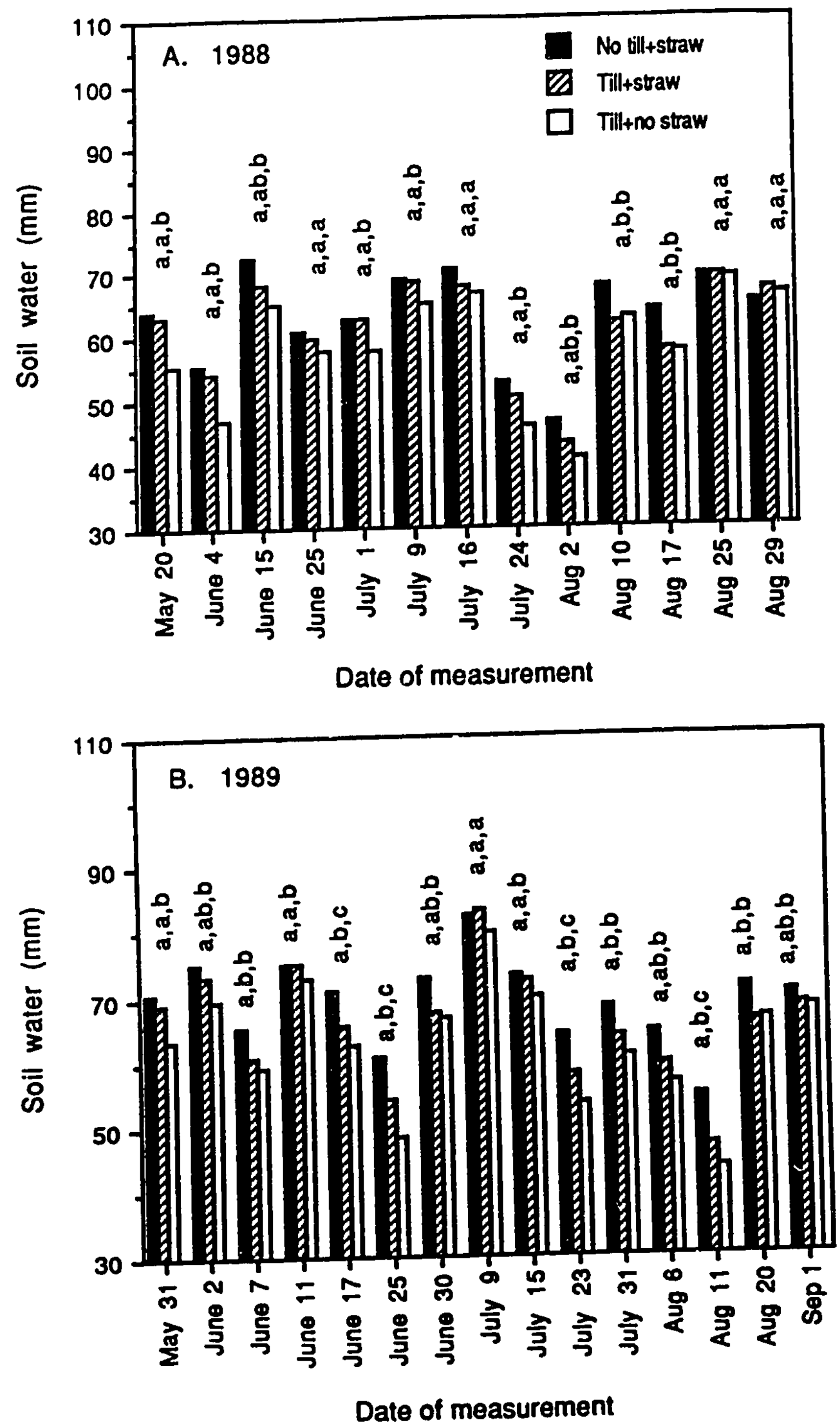


Figure 5.4. Total soil water in the 0-20 cm depth interval during the (A) 1988 and (B) 1989 growing seasons. Within a given day, treatment means with the same letters are not significantly different (P=0.05). The letters are in the same sequence in which treatments appear in the bars.

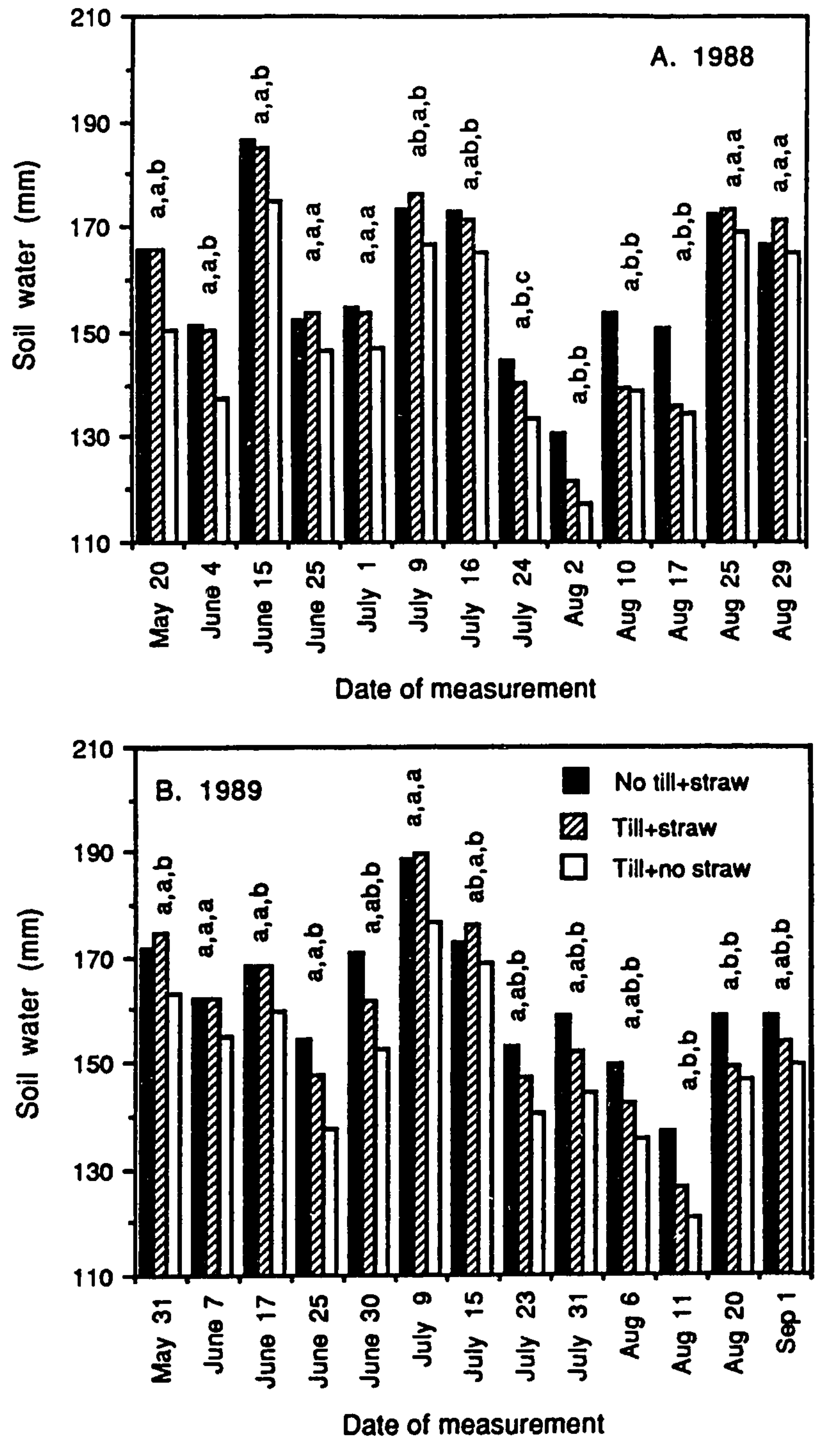


Figure 5.5. Total soil water in the 0-50 cm depth interval during the (A) 1988 and (B) 1989 growing seasons. Within a given day, treatment means with the same letters are not significantly different (P=0.05).

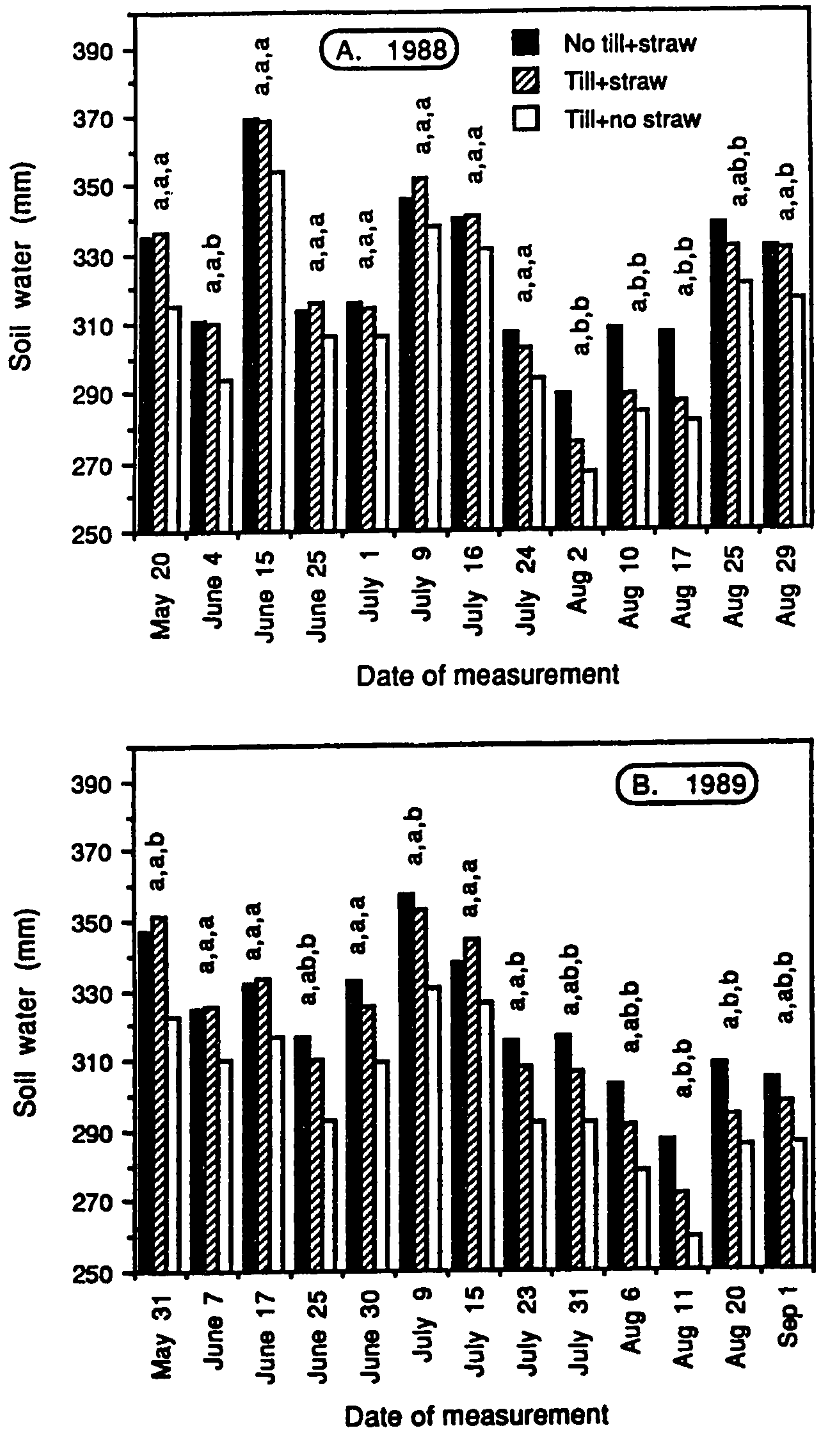
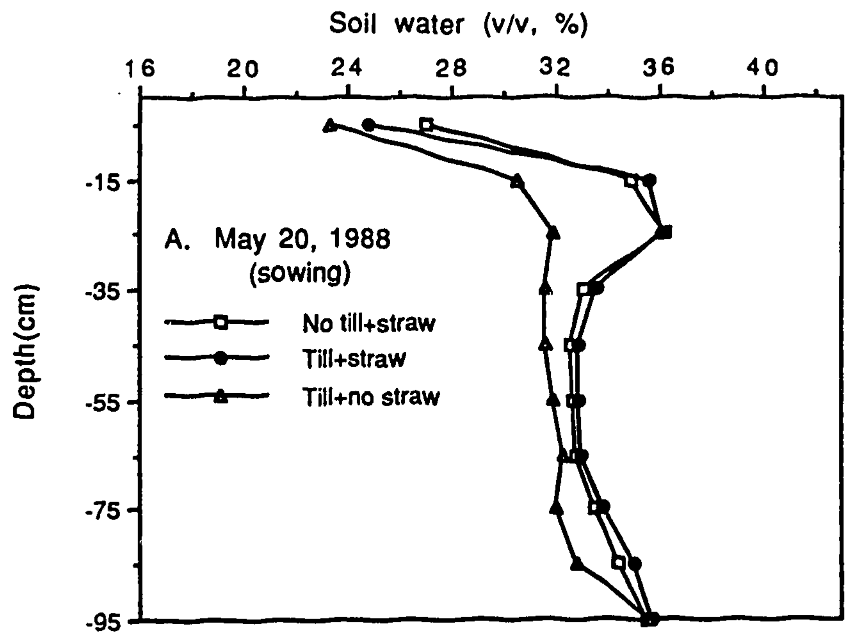


Figure 5.6. Total soil water in the 0-100 cm depth interval during the (A) 1988 and (B) 1989 growing seasons. Within a given day, treatment means with the same letters are not significantly different (P=0.05).



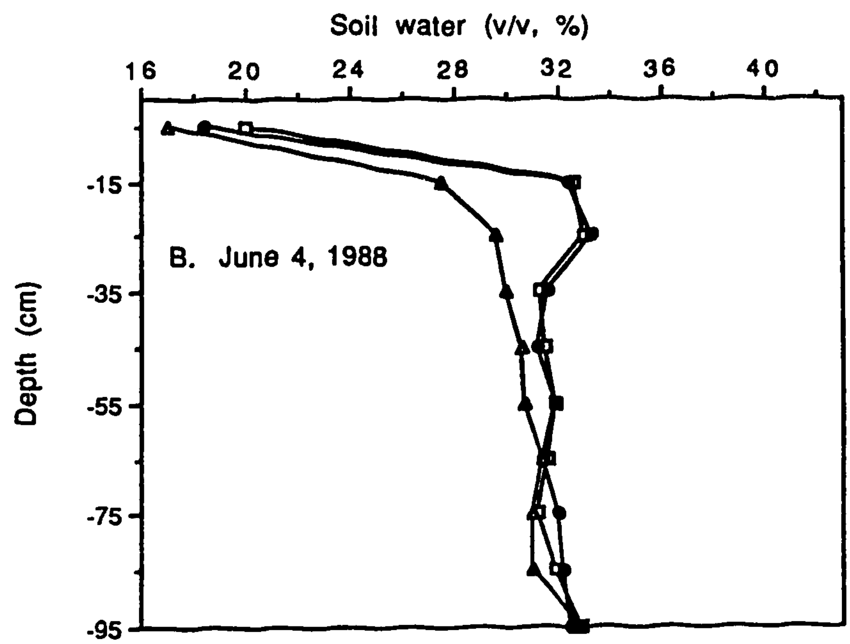


Figure 5.7.1. Soil water profiles on (A) May 20 and (B) June 4, 1988.

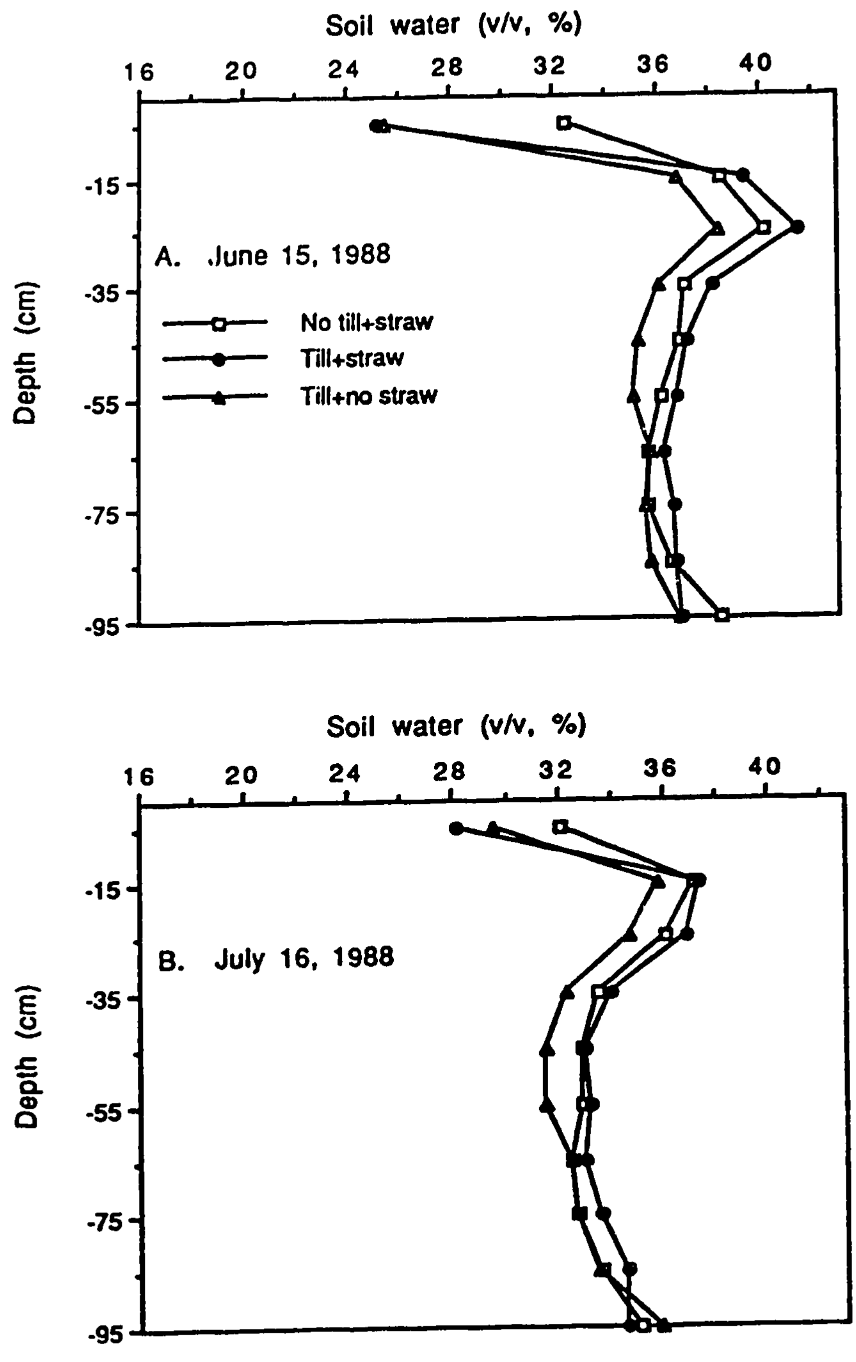


Figure 5.7.2. Soil water profiles on (A) June 15 and (B) July 16, 1988.

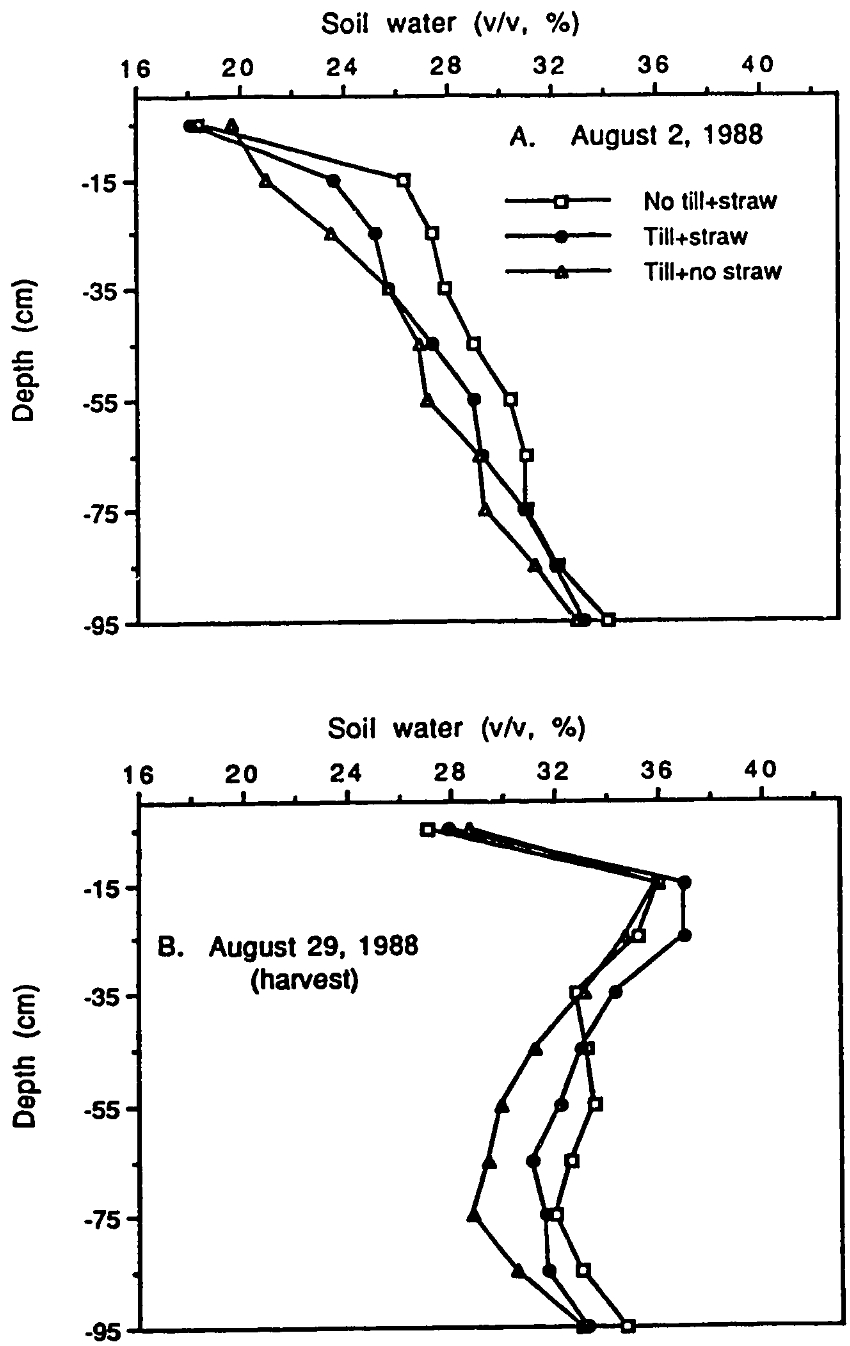


Figure 5.7.3. Soil water profiles on (A) August 2 and (B) August 29, 1988.

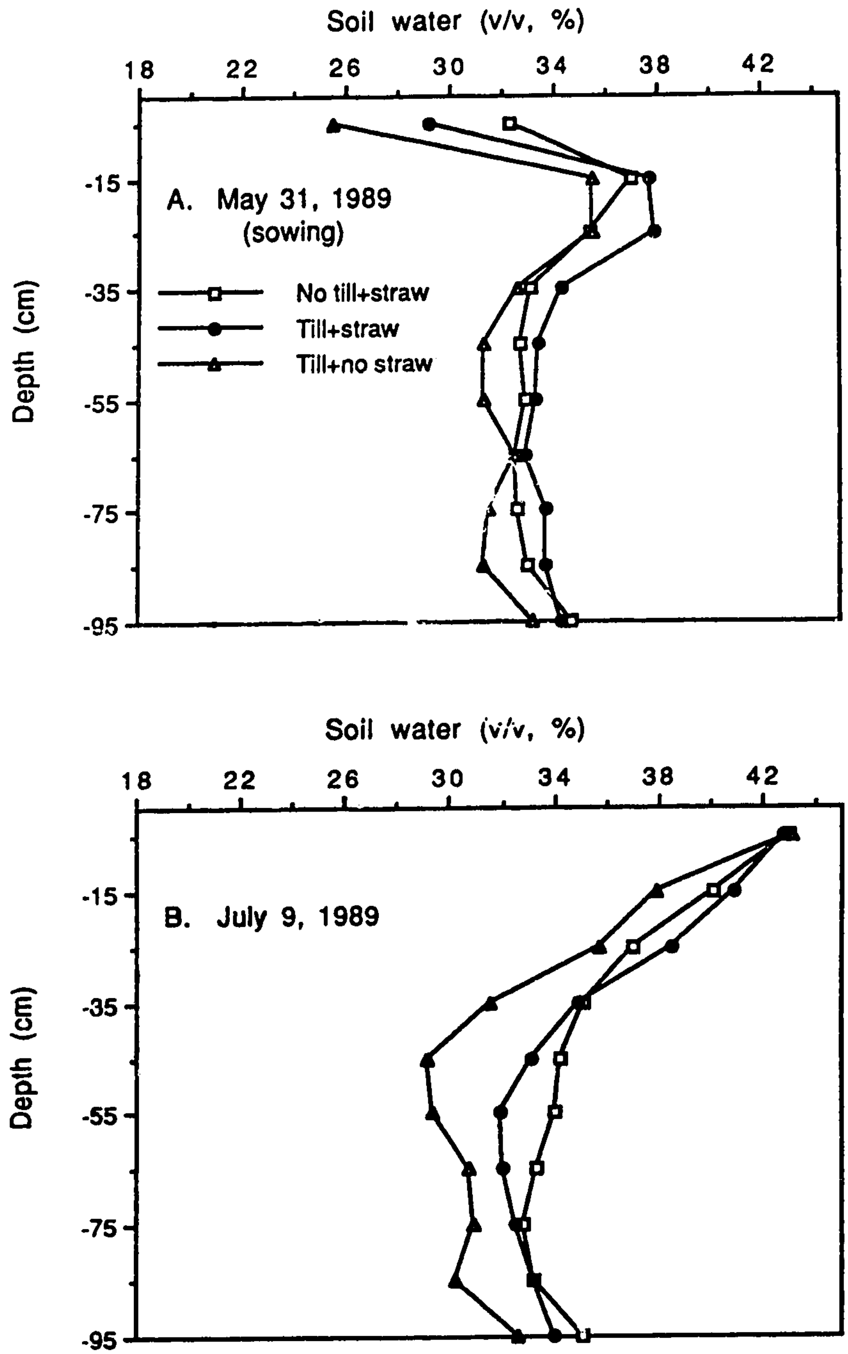


Figure 5.8.1. Soil water profiles on (A) May 31 and (B) July 9, 1989.

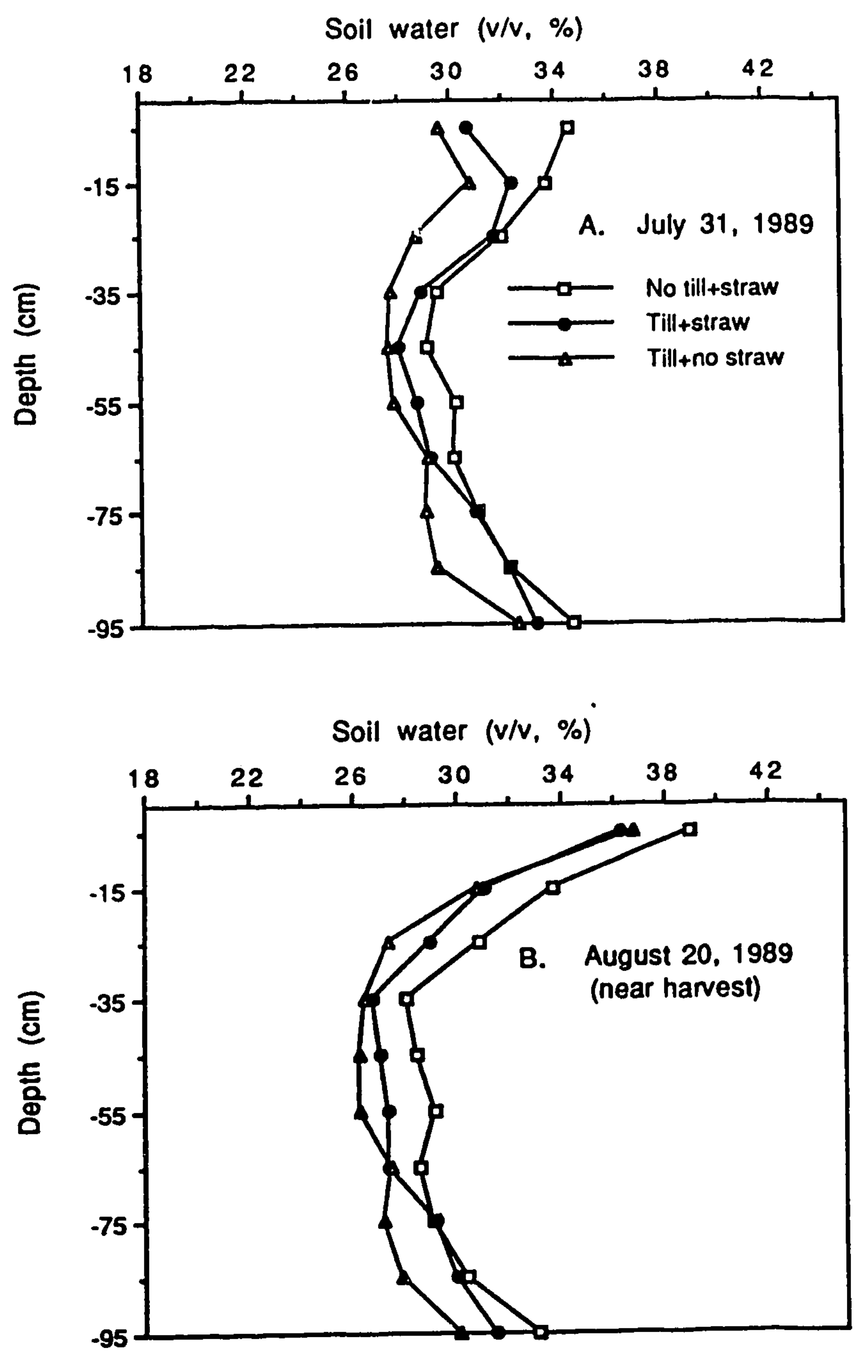


Figure 5.8.2. Soil water profiles on (A) July 31 and (B) August 20, 1989.

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Chapter 6

GROWTH RESPONSE AND WATER USE OF SPRING BARLEY IN RELATION TO LONG-TERM TILLAGE AND RESIDUE MANAGEMENT IN CENTRAL ALBERTA

6.1 INTRODUCTION

Conservation tillage practices such as no-tillage are being intensively researched because of their potential in reducing soil erosion, conserving soil water, and lowering production costs by saving time, labor, machinery and fuel costs. The success of such practices, however, largely depends upon the maintenance of high or optimal levels of crop production on a sustained basis (Griffith et al., 1977)

When soil tillage is reduced or eliminated, marked changes in the soil environment may occur. The soil physical parameters that are often altered include soil bulk density, soil strength, aggregation, pore size distribution, soil hydraulic characteristics including water retention and transmission, soil water and thermal regimes, aeration regime, organic matter, etc. The extent and direction of change in these factors and processes largely depend upon soil type, antecedent soil characteristics, short and long-term agroclimatic conditions, type of machinery used, soil water condition at tillage, cropping patterns, as well as the duration these tillage practices have been prevalent. No-tillage systems usually leave large amounts of crop residue on the soil which may further modify the surface characteristics and soil and micrometeorological environments.

Crops respond to the changed environments in a complex manner through varied effects on seedling emergence and growth, root growth, tillering, leaf area development, crop phenology, and various yield-contributing factors. Crop water use is also expected to be affected. Interpreting the effect of changes in soil physical properties due to reduced tillage on crop response is, however, not a simple process (Griffith et al., 1986).

Quite variable response to tillage-residue practices, even within regions, has been reported in field studies. These apparent inconsistencies in performance of conservation tillage systems are mostly associated with differences in soil types, climatic conditions, drainage, geographical location, position on the landscape, temporal variability of tillage-induced changes in soil parameters, etc. (Benoit and Lindstrom, 1987).

In general, grain yields were little affected by tillage practices under conditions of adequate soil water, favorable precipitation and good drainage, provided other factors such as soil fertility, weed control and plant populations were equal (Amemiya, 1977; Bennett, 1977; Elliot et al., 1977; Griffith et al., 1977; Johnson, 1977; Reicosky et al.,1977; Unger et al., 1977; Lal et al., 1978). Negative yield responses to conservation tillage systems leaving large amounts of crop residue on the soil surface have been reported on poorly drained, fine-textured soils (Griffith et al., 1973). Under conditions of limited soil water and limited soil precipitation or irrigation, crop yields were equal and often significantly higher with reduced and no-tillage systems than with conventional tillage (Amemiya, 1977; Fenster, 1977; Unger et al, 1977; Unger and Wiese, 1979; Tanaka, 1989). Higher yields with these conservation tillage systems generally were attributed to increased soil water contents resulting from increased infiltration, decreased runoff and possibly decreased evaporation.

The crop response to tillage methods also seems to vary somewhat with crop species, but the effects are not clear due to interactions with other factors that affect crop growth. Hallauer and Colvin (1985) observed higher corn yields under autumn plowing or spring disking than under reduced or no-tillage in Central Iowa. Elmore (1987) in central Nebraska reported that soybean yields under conservation tillage were greater than under conventional tillage when a water deficit existed at planting in dry years. Chevalier and Ciha (1986) observed reduced rates of tillering and leaf production of spring wheat with no-tillage. In contrast, significant grain yield increases for no-till spring wheat compared to conventional tillage were observed in the central Great Plains and Pacific Northwest even though no-till soils warmed slower than conventionally tilled soils (Fenster and Peterson, 1979; Ciha, 1982). Cochran et al. (1982) found no difference in grain yield of winter wheat between no-till and conventional tillage treatments.

O'Sullivan and Ball (1982) reported that grain yield of spring barley on a sandy loam soil in Scotland 4 years after start was significantly higher with mouldboard ploughing to 25-cm depth than with direct drilling. Rotary cultivation also yielded more than direct drilling. Ears m^{-2} were significantly lower in the direct drilling treatment compared with conventional ploughing.

Through their effects on various factors of soil structure, soil strength, bulk density, and soil hydraulic and thermal environments, tillage-residue systems variably affect the root growth patterns including amount and size of roots. Despite their greater soil bulk density, no-tillage (or direct-drilled) plus crop residue systems tended to accumulate barley, corn or oat roots near the soil surface (top 7.5 or 10 cm) compared to clean or conventional tillage (Ellis et al., 1977; Griffith et al.,1977, Ehlers et al., 1983). Also corn roots in the surface were larger in diameter with no-tillage which caused them to have less absorbing surface for water and nutrient uptake per unit mass of roots (Griffith et al.,1977). Barber (1971) observed similar effects of no-tillage on corn root length density and diameter in the top 10 cm of soil. NaNagara et al. (1976) reported much greater corn root length density in 0-15-cm depth for no-tillage than for conventional tillage, with opposite trends in the 15-30-cm depth. No report about tillage effects on barley root diameter was found.

The effect of differences in root growth due to tillage methods on grain yield largely depends on the availability of water and nutrients in the root zone (Voorhees, 1977). When residue cover resulted in adequate water near the soil surface, crop yield was not well correlated with root mass or rooting depth in tillage studies (Griffith et al., 1977).

Canada is the third largest barley (*Hordeum vulgare* L.) producer in the world with Alberta alone contributing 50% (5.5 million tonnes) of the total Canadian production (Alberta Agriculture, 1984). In North-Central Alberta, it is grown during May through

August under rainfed conditions. Under the soil and agroclimatic conditions of this region (Cryoboreal, subhumid), a no-tillage system with residue from previous crop left on the soil may delay soil warming, and together with generally greater soil water in the surface (Chapter 5) may delay seedling emergence and vigor and subsequent crop growth. These early season conditions, however, vary from year to year and largely depend on snow accumulation over the winter, weather conditions during spring-melt period, and rainfall and temperature regime from spring-melt to seeding, etc. Meteorological conditions during the growing season, especially the rainfall amount and distribution and solar irradiance, also greatly contribute to yearly variations in crop response.

In the previous chapters, three long-term tillage-residue systems studied at Ellerslie, in Central Alberta, were reported to have affected degree of residue cover, soil microrelief, organic matter content, soil aggregation, soil bulk density, penetration resistance, pore size distribution, soil water retention, hydraulic conductivity and infiltration, soil water content, etc.

Information about growth and water use by barley in relation to various factors of soil environment is relatively scant under the soil and agroclimatic conditions of Central Alberta, but is vital for assessing the relative suitability of different management practices in this region. This information is also necessary to develop and validate process-oriented crop growth models. The objective of the research reported in this chapter was to quantify the growth response and water use patterns of spring barley in relation to the soil physical environment induced by the same three long-term tillage-residue management practices as mentioned before.

6.2 MATERIALS AND METHODS

6.2.1 *Site and soil description*

The research was conducted during the 1988 and 1989 growing seasons on field plots located near Edmonton at the Ellerslie Research Station (53° 25' N, 113° 33' W; 694 m above sea level) of the University of Alberta. The soil of the experimental site was developed from lacustrine deposits of the Proglacial Lake Edmonton. It is classified as: fine loamy, mixed, Typic Cryoboroll according to Soil Taxonomy, and a Black Chernozemic according to the Canadian System of Soil Classification. It has good internal drainage and a moderate swell-shrink potential.

The climate of the Edmonton area is between dry and moist sub-humid, characterized by relatively warm summers and cold winters. The average daily maximum and minimum air temperatures are: 7.6 and -4.1 °C (whole year), 22.4 and 9.6 °C (July) and -11.5 and -21.7 °C (January). The average annual precipitation is 452 mm, of which approximately 60% (274 mm) occurs during the growing season extending from May to August with July the wettest month (85 mm). Ellerslie has an average 109 frost-free days per year and number of degree-days >5 °C is 1230. Other soil and climate details are given in Chapter 2.

6.2.2 *Tillage-residue treatments*

Ten tillage, residue and nitrogen management systems were established in the fall of 1979 to investigate the long-term effects of these systems on soil environment and crop growth. Three treatments were selected for the present study: (1) no-tillage, straw retained on the surface, (2) conventional tillage, straw retained and incorporated, and (3) conventional tillage, straw removed.

Conventional tillage consisted of late fall cultivation using a rotovator, followed by similar spring cultivation at the time of seeding. The tillage depth was approximately 10 cm. In the no-till treatment, the crop was seeded directly without tillage. The only disturbance of soil in this treatment was the seed-drill and a small reaper-binder. The crop was harvested at a height of approximately 10 cm. In treatments (1) and (2), threshed straw from each plot was returned to the corresponding plot and uniformly spread before fall tillage. In treatment (3), all straw and most of the stubble were removed before tillage. Treatments were replicated four times in a randomized complete block design and repeated annually. Each individual plot measured 6.8 x 2.7 m.

The plots were seeded to grain barley (*Hordeum vulgare* L.) at 90 kg ha^{-1} each year. The cultivar was 'Empress' in 1988 and 'Heartland' in 1989. The seeding depth was 5 cm. Nitrogen (56 kg ha^{-1}) was applied as urea at seeding. It was broadcast in no-till plots and incorporated into surface soil with tillage in other treatments. Phosphorus (17 kg ha^{-1}) as triple superphosphate was drilled with the seed. The crop rows, 22.5 cm apart, were located in approximately the same position each year. Grassy and broadleaf weeds were controlled with a mixture of 'Glean' or chlorsulfuron (2-chlor-N[(4-methoxy-6 methyl-1,3,5-triazin-2-yl) aminocarbonyl] benzenesulfonamide) at 15.6 g ha^{-1} a.i., plus 'Hoegrass 284' or diclofop-methyl (methyl 2-[4-(2,4-dichlorophenoxy) phenoxy] propanoate) at 2.75 L ha^{-1} sprayed post-emergence at 100 L ha^{-1} using a backpack sprayer. Some hand weeding was also performed. Details regarding the machinery used and other agronomic practices for the two years of the present study are given in Chapter 2.

6.2.3 *Observations, measurements and calculations*

6.2.3.1 *Crop phenology*

Frequent observations were made on the phenological development of the crop including initiation and completion of various growth stages. These stages were identified on the basis of Feekes scale (Large, 1954) in which stages, based on morphological change, are numbered from 1 to 11 in the order of appearance progressing from seedling emergence through grain ripening. The ripening stages are based on 'feel' rather than on visual observation. Initiation and completion dates of a growth stage were based on occurrence of that stage on at least 75% of the plot area. The Feekes scale is probably the best known and most widely used of all scales (Bauer et al., 1983).

6.2.3.2 *Seedling emergence and tiller production*

Seedling emergence was recorded on the same 1-m row length on two locations per plot until complete emergence. Afterwards, tillers were counted periodically in 30 to 50 cm row lengths on two locations per plot.

6.2.3.3 *Plant height*

Height of the same 20 plants at 2 randomly assigned locations within each plot was measured several times over each growing season. After ear emergence, plant height included the ears.

6.2.3.4 *Dry matter production*

Several times over the two growing seasons, all plants from a 30 to 50 cm row length at two randomly selected locations in each experimental plot were harvested at ground level with a sickle, immediately sealed in polyethylene bags and refrigerated (4 °C) before further analysis. In the laboratory, various plant organs (green leaves, dead leaves, stems and ears) were carefully separated, dried in an oven at 70 °C for 4-5 days and weighed. 'Green' leaves also included those which were partially green. Any senesced leaf material was collected and included in the 'dead leaf' matter.

6.2.3.5 *Leaf area index*

Leaf area (one leaf side only) was measured three times during 1988 growing season (at completion of tillering, heading, and early grain ripening stage), and two times during 1989 growing season (at completion of stem extension and early grain formation stage), using a leaf area meter (Model 3100 Area Meter, LI-COR, Inc., Lincoln, NE). Plant samples used were those taken for dry matter production. Projected area of green stems was also measured separately. Green leaf area index (LAI) was computed as the ratio of total area of green leaves to the ground area sampled.

6.2.3.6 *Root growth analyses*

6.2.3.6a *Root sampling and washing*

After the completion of ear emergence and during early grain formation stage (approximate stage 10.5.2 of Feekes scale) in 1988 (20 July), root samples were taken by the core method (Böhm, 1979), using a special hand-operated root sampler with a hammering and a sample extraction device (Model J-199A, Equipment for Soil Research B.V. Eijkelkamp, The Netherlands). The cores were 8.0 cm in diameter and were taken from 0-7.5, 7.5-15, 15-22.5, 22.5-30, 30-40 and 40–50-cm depth intervals at 2 row positions: in-the-row (after harvesting the plants), and between-rows, in each of the experimental plots. In one replication, samples were also taken from the 50-60-cm depth. The samples were sealed in polyethylene bags and stored in a freezer (-20 ^{o}C) before further analysis.

Soil was removed from the roots using a locally manufactured (University of Alberta Technical Services) automatic root-wash machine based on a Hydropneumatic Elutriation System (Smucker et al., 1982). This system combines the kinetic energy of pressurized water spray jets and the low energy of air floatation to separate roots and other biological materials from soil, without losing finer roots. The method is efficient, quick and quantitative. Water in each elutriation chamber carrying finer soil particles and organic material including roots, overflowed onto a fine sieve arrangement which retained the roots and other organic debris.

After the overflowing water was relatively clean, the water supply to the washing chamber was stopped and the sieve arrangement removed. The material retained on the sieve was transferred to a beaker with a jet of water and remaining soil particles, coarser charcoal pieces, etc., separated by floatation. Stones and coarse sand too heavy to float, remained behind in the wash chamber. This material was emptied into a fine sieve placed over a vessel. The material was suspended in water and checked for any roots but rarely was any significant root material found. Samples from greater depths (below 30 cm) were so coherent that they had to be pre-dispersed (Böhm, 1979) with 4% Na-hexa-metaphosphate solution overnight before they could be washed in the machine. The washed roots were sealed with some water in plastic bags and kept frozen at -20 ^{o}C (Shuurman and Goedewaagen, 1971) before the next step of hand cleaning.

To separate living roots from other debris (straw pieces, other plant debris, charcoal pieces, bigger dead roots, etc.), the washed root samples were put in a series of containers and living roots separated by floatation, stirring and skimming, picking the roots with tweezers. A piece of wire mesh made into a 'spoon' also helped in skimming off smaller fragments floating along the sides of the container. The cleaned roots were stored in freezer bags at -20 ^{o}C before root length and mass were determined.

Root sampling was repeated after harvest of the crop, but roots could not be analyzed.

6.2.3.6b *Determination of root parameters*

The root samples were used to determine root length, root dry mass and root volume.

Root length was measured with a digital image analysis technique using the line intersection method (Newman, 1966; Tennant, 1975). An IBM-PC computer with a 512 K memory board, a frame grabber or analogue to digital convertor board (Matrix PIP-EZ 1024B board) and a video receiver-monitor (Sony trinitron Model CVM-1271) were used as the hardware of the digitizing system. An analogue image of the roots was transferred to the digitizing system by a video camera (Hitachi CCTV Camera, Model HV-720C). The captured image was digitized and displayed on the video monitor and a grid (we used a 5x5 mm grid) imposed on the image. The computer then counted the intersections of the roots with vertical and horizontal lines of the grid. A software program developed at the Alberta Environmental Centre, Vegreville, Alberta (T.B. Kazamierczak, Personal Comm., 1989) controlled the digitizing process and subsequent processing of the data. An algorithm in the software computed the root length from the number of intersections and the grid size as follows (Tennant, 1975):

$$\text{Root length (cm)} = (11/14) \times N \times \text{grid unit}$$

where N = total number of horizontal and vertical intersections.

The root sample was placed in a flat glass dish containing a thin layer of water, and with the help of forceps and needles the roots were evenly spread and arranged in a single layer as far as possible (so they did not overlap). Most root samples, particularly those from 0-30-cm depth, had to be subdivided and length measured on each sub-sample. The dish containing the roots was placed under the video camera and root length measured by the procedure described earlier.

Before the actual root length measurement, the procedure was standardized and equipment calibrated using threads of different sizes (length and diameter) and colors. Also real roots were then used in calibration. The thickness of water film in the dish, grid size, threshold level, light level, exposure time, etc., were standardized. A calibration equation relating the actual length (La, mm) and computer-measured length (Lc, mm) was developed using the method of least squares:

$$La = 1.7921 + 1.0327\, Lc + 0.0004\, Lc^2, \quad R^2 = 0.99$$

After length measurement, the roots were blotted dry and their volume measured by the water displacement technique (Böhm, 1979). Roots were then dried in an oven at 50 °C for 4-5 days and their dry weight taken. Average diameter (d) of roots in a sample was calculated from the volume (V) and length (L) of the roots as: $d = 2\,(V/\pi L)^{0.5}$. Specific root length (SRL) for a given soil depth interval was computed as: SRL = Root length (m root/m^2 soil area)/root dry mass (g root/m^2 soil area). Root/shoot ratio was calculated on a mass per unit soil area basis.

6.2.3.7 *Crop yields and yield parameters*

Grain and straw yields were determined by hand-harvesting the crop from a central 2.3 m^2 area in each plot. Grain yield was expressed on oven-dry basis and straw yield on air-dry basis. Unit grain mass was determined by weighing 500 grains after oven drying. Number of ears m^{-2} and unit ear mass at harvest were determined by separating and counting all ears in a 1-m row length, and taking oven-dry mass. Harvest index was calculated as the ratio of grain yield to total biomass at harvest.

6.2.3.8 *Water use and water use efficiency*

Soil water content at different depths to 100 cm was determined at seeding, harvesting and periodically during the growing season in both study years, using a neutron scatter technique; the relevant details are given in Chapter 5. Rainfall was measured at a meteorological station located 50 m from the plots. Soil profile water use for a given period was computed as the difference in total profile water storage at the beginning and end of that period. Crop water use (equated to evapotranspiration) for a given period was computed from the general soil water balance equation:

$$P + I = ET + R + D + \Delta S$$

where P= precipitation, I= irrigation, ET= evapotranspiration, R= runoff, D= drainage beyond the root zone, ΔS=soil water depletion or accretion over the period.

There was no irrigation, so I=0. Considering that the plots were almost level, the very high infiltration rate of this soil (Chapter 4), and the low rainfall intensities, runoff losses were assumed nil. Verma and Toogood (1969) also ruled out runoff from maximum rainfall intensities at Ellerslie unless surface sealing occurs. In the absence of measurement, deep drainage was assumed negligible. Water use or evapotranspiration for a given period was, therefore, computed as the sum of soil water depletion and precipitation over that period.

Water use efficiency was calculated as the mass (kg) of grain or dry matter produced per unit land area (ha) per unit water use (mm). Dry matter at harvest was taken as the sum of grain and straw yields.

6.2.4 *Statistical analyses*

The experimental variables were subjected to statistical analyses using either UANOVA subroutine (developed at the University of Alberta) of the SPSS^{X} statistical package, or ANOVA procedure of the SAS statistical program (SAS Institute, Inc., 1985). The statistical model for analysis of plant growth, crop yields and yield parameters, total root mass and length, water use and water use efficiency, etc., was a randomized complete block (RBD) design. Wherever soil depth was involved (e.g. root mass/length distribution with depth), the analysis was considered a split-plot design with tillage-residue treatments as main effects and soil depth as split-plot effects. The location effect was calculated separately as sampling error and excluded from the relevant error term.

Tests were conducted for fulfillment of the assumptions of analysis of variance (homogeneity of variances, normal distribution, etc.). These tests revealed that data on root mass/length density as a function of soil depth needed transformation before the analysis of variance could be performed. The Box-Cox transformation procedure (Sokal and Rohlf, 1981; Chapter 3) was used to find the best possible transformation and the analysis of variance conducted on the transformed data. Mean comparisons were made using least significant difference procedure or Duncan's multiple range test (Steel and Torrie, 1980). All comparisons are reported at the 5% probability level.

6.3 RESULTS AND DISCUSSION

6.3.1 *Meteorological conditions*

The seasonal rainfall and air temperature data are reported in Chapter 5 and are discussed at various places in the current chapter.

6.3.2 *Phenological observations*

Dates of initiation and completion of various phenological stages based on the Feekes scale are given in Table 6.1. These dates are averages for the three treatments. In both years, the no till+straw treatment lagged behind the tilled treatments by 3-5 days in initiation and completion of various growth stages up to approximately anthesis and early grain formation, after which the no-till crop matured faster than the tilled treatments.

6.3.3 *Seedling emergence*

Seedling emergence was completed in 15-16 days after seeding (Table 6.2). Emergence was slower in the no till+straw treatment both years as indicated by a significantly lower emergence count 8 and 9 days after seeding in 1988 and 1989, respectively. However, when all the seedlings had emerged, no significant differences among treatments were found, although in 1989 final count was still lower in the no-till treatment. The two tilled treatments were similar in emergence counts. Complete emergence in no-till was delayed by 3-4 days and seedlings appeared weaker compared with those in the tilled treatments. Early differences in seedling emergence are attributed primarily to lower (3-8 ^{o}C) maximum soil temperature at seeding depth (5 cm) in the no-till treatment (data not presented). Substantial residue cover (Chapter 2) lowered soil temperature and increased surface soil water content (Chapter 5) in this treatment.

Seeding was followed by a rainless period of 10 and 5 days in 1988 and 1989, respectively. This resulted in relatively faster and greater drying of surface soil in the tilled treatments compared with that in the no till+straw treatment. Slower emergence in the no-till treatment seems mainly the result of lower (sub-optimal) soil temperature, although less availability of water to the germinating seeds due to poor seed-soil contact arising from bigger aggregates in the no-till system (Chapter 2) may also be a factor responsible for delayed emergence in this treatment.

6.3.4 *Tiller production*

In 1988, the number of tillers m^{-1} row was always the highest in till+straw treatment (Table 6.2). Trends in the other two treatments changed over the growing season. At harvest, the number of effective tillers (those bearing ears) was the lowest in the no-till treatment, being significantly lower compared with the till+straw treatment. Tiller density was the lowest in no-till treatment throughout the 1989 season but treatment differences were much smaller. The tiller density reached its maximum value approximately one month after seeding each year, coinciding with completion of tillering i.e. stage 5 of the Feekes scale (Table 6.1), and then starting decreasing.

6.3.5 *Plant height*

Plant height continued to increase up to approximately 60 days after seeding (Tables 6.3 and 6.4), which coincided with completion of ear emergence (heading) stage and a little into anthesis and grain formation (Table 6.1). In 1988, plants in the till+straw treatment were the tallest up to completion of ear emergence stage, after which plant height did not differ between treatments (Table 6.3). Compared with the other two treatments, plants in the till+straw treatment were significantly taller by 10-12% and 7-8%, 43 and 52 days after seeding, respectively.

Treatment differences in plant height were more subtle during 1989 (Table 6.4). As in 1988, till+straw treatment showed the greatest plant height, but unlike 1988, treatment differences were significant and persisted throughout the growing season. Plants in no-till treatment were the shortest up to the stem extension stage (48 days after seeding); after this till+no straw treatment had the shortest plants. Differences between the no till+straw and till+no straw treatments were generally non-significant. The difference in plant height between till+straw and no till+straw was 20, 29, 23, 6 and 5% at the completion of seedling emergence, tillering, stem extension, heading and ripening stage, respectively. Ciha (1982) in Pullman, Washington, observed that no-tillage significantly reduced the barley plant height.

Maximum increase in plant height occurred during late tillering through heading stages (i.e. 30 to 52 days after seeding in 1988, and 34 to 59 days after seeding in 1989) (Table 6.5 and 6.6). In both years, growth rate was higher in the till+straw treatment during early part of the growing season, but was higher in no-till treatment during later stages. This again indicates that all growth stages were delayed by a few days (3-5) in the no-till treatment.

6.3.6 *Leaf area index (LAI)*

At the completion of tillering in 1988 (37 days after seeding), the till+straw treatment had the highest LAI (Table 6.7), significantly greater (28%) than till+no straw and nonsignificantly greater (19%) than no till+straw treatment. Differences in LAI were mainly associated with those in tiller production, i.e. leaf numbers. By the end of heading stage (55 days after seeding) green LAI was similar among treatments.

During the period between 37 and 55 days after seeding, while LAI increased in the no till+straw and till+no straw treatments, it decreased in the till+straw treatment. This indicates differential phenological development in the three treatments, i.e. the time to maximum leaf area development was different in the three treatments. Hamblin (1984) in western Australia observed smaller and delayed achievement of maximum leaf area of spring wheat in a disc ploughed compared with a zero-till system on a Xeralfic Alfisol, a result exactly opposite to ours. An early achievement of maximum leaf area in the till+straw treatment will probably leave greater carbohydrate reserves for an extended reproductive growth period, resulting in the observed greater grain yield in this treatment (see later Table 6.12).

A significantly lower green LAI of the no-till treatment compared with the tilled treatments on August 3 (early grain ripening stage), indicates early drying-up and probably early senescence in the no-till treatment. Field observation also indicated an early (approximately 5-7 days) maturity of the crop in the no-till treatment, reducing the period of reproductive growth. Reduced availability and uptake of nitrogen in the no-till treatment may be a possible cause, and warrants further investigation.

In 1989, the till+straw treatment again showed the greatest LAI on both July 13 (completion of stem extension) and July 24 (early grain formation stage), but the treatment differences were non-significant (Table 6.7).

6.3.7 *Shoot dry matter*

At the completion of tillering in 1988 (i.e. on 25 June), the till+straw treatment had the greatest total shoot dry matter which was significantly greater (30%) than that of till+no straw treatment (Table 6.8). Difference between till+straw and no till+straw was also substantial (18%), but non-significant. Dry matter accumulation in both green leaves and stems followed similar trends, with leaves contributing more to total dry matter than the stems. Green leaf dry matter (LDM, g m^{-2}) and green LAI (m^2 m^{-2}) were significantly correlated:

$$LAI = 1.7669 \times 10^{-4} + 3.5951 \times 10^{-2}\ LDM ; \quad R^2=0.879$$

Treatment differences corresponded with those in tiller production.

On July 13, at the end of heading stage, green leaf matter was similar in the three treatments, but the dead (or dry) leaf matter was significantly higher in the till+straw treatment. Stem and ear dry matter was the highest in no till+straw and the lowest in till+no straw treatment. Differences in total dry matter were non-significant.

Trends in treatment effects changed between July 13 and August 3 (early grain ripening stage) in that the no till+straw treatment now showed the lowest dry matter of each green plant part (leaves, stems and ears) but highest amount of dead leaves, again indicating early ripening in no-till. Ears formed the bulk (approximately 50%) of the total above-ground dry matter.

Just prior to harvest (i.e. on 27 August), total dry matter of the no-till treatment was significantly lower than that of the tilled treatments which were similar. Thus, the three treatments behaved differently in partitioning of dry matter among different plant organs during the period 3 to 27 August. In this grain ripening period, the stem mass decreased and ear mass increased in all the treatments, indicating some translocation of carbohydrates from the stems into the reproductive organs. The increase in ear dry matter over this period was large in the tilled treatments, being 35 and 42% in till+straw and till+no straw treatments, while in the no-till treatment it was only 11%. Surprisingly, total dry matter in the no-till treatment decreased over this period while it increased in the tilled treatments.

During early growing season of 1989 (June 18 and 29), total dry matter was significantly lower (average 38% on June 18 and 40% on June 29) in the no till+straw treatment compared with the tilled treatments which were similar with till+no straw having the highest dry matter (Table 6.9). These trends are different than those from 1988. Both leaf matter and stem matter were significantly lower in the no-till crop, reflecting both lower emergence as well as tillering (Table 6.2) and lower plant height in this treatment (Table 6.4). Similar trends were observed on July 13, but differences were non-significant. Dry matter accumulation over the period June 29 to July 13 (stem extension stage) was the highest in the no-till, confirming the phenological observation that early growth stages (emergence, tillering, leaf sheath lengthening, stem extension, boot, anthesis) were delayed by several days (3 to 5 days) in this treatment.

During the heading stage (July 13 to July 24), trends started changing in that the growth rate in the till+no straw treatment was smaller than in the other two treatments; the increase in its dry matter after 13 July was 105% compared with 129 and 121% in no till+straw and till+straw, respectively. During the grain formation and early ripening stages (i.e. from July 24 to August 11) the dry matter increase was the highest (54%) in till+straw; it was 45% each in the other two treatments. This difference was later reflected in the yields. At this stage, ears constituted, on average, 58% of the total dry matter, as compared with 50% in 1988.

At the time of physiological maturity (24 August), the till+straw treatment had the highest dry matter accumulation in all plant parts. Total dry matter was similar for the other two treatments, being 13% lower than the till+straw treatment. Average aerial dry matter measured at harvest time was similar (962 and 992 g m^{-2}) in the two study years.

6.3.8 *Root growth*

6.3.8.1 *Total root mass, total root length and root/shoot ratio*

Total root mass to 50-cm depth, measured just after completion of ear emergence in 1988 (55 days after seeding), was not significantly affected by tillage-residue treatments (Table 6.10). Similarly, total root length (km m^{-2}), which is the sum of root length at each sampled depth, was unaffected. Averaged over the treatments, total root mass was 111 g m^{-2} (or 1110 kg ha^{-1}) and total root length was 20.7 km m^{-2}. These values probably represent the maximum root growth for this cultivar and environment.

On a Black Solod with compact Bnt horizon in Beaverlodge, northwestern Alberta, Soon (1988) observed maximum root mass (to 90-cm depth) of 92 g m^{-2} and root length of approximately 15 km m^{-2}, 80 days after seeding barley (cv. 'Galt') in 23-cm rows. On an irrigated clay loam (thermic Vertic Torrifluvent) in New Maxico, Lugg et al. (1988) observed average maximum root mass of 394 g m^{-2} and root length of 22 km m^{-2} near anthesis of spring barley (cv. 'Briggs') sown in 18-cm rows. Biscoe et al. (1975) and Welbank and Williams (1968) found that total root mass of barley peaked at or just before ear emergence or anthesis.

Lack of significant effects of tillage-residue system on total root mass and length implies that the measured differences in bulk density and soil strength among treatments (Chapter 3), as well as changes in other physical factors and processes of soil environment, were probably not large enough to affect root growth overall. Probably this also means that the inherent values of these soil characteristics are in such a range that they can absorb the treatment-induced changes without exceeding the critical limits for root growth of barley.

Root/shoot ratio on this day, expressed on a mass basis, also did not differ significantly among treatments; the average value was 0.209 (Table 10). For spring barley, Biscoe et al. (1975) reported a root/shoot ratio of 0.353 before ear emergence to 0.143 at maturity. Kirby and Rackham (1971) reported a root/shoot ratio as small as 0.082 at crop maturity. The magnitudes of standard error indicate a greater variability in both root mass and length measurements of straw-involving treatments.

6.3.8.2 *Root mass density profiles*

The tillage x depth interaction for root mass density (g m $^{-2}$) was highly significant (P=0.006). Root mass density (RMD) was the greatest in the 0-7.5-cm depth interval and decreased almost exponentially with depth (Fig.6.1). In this interval, RMD was not significantly different among treatments, although no till+straw had the highest value (61.2 g m^{-2}) and the till+straw the lowest (51.4 g m^{-2}), a difference of 19.1%. In this layer, Db and soil strength were, however, the highest in the no till+straw and the lowest in till+straw treatment (Chapter 3). Ellis et al. (1977) and Ehlers et al. (1983) also observed greater root growth of barley and oats in surface layer of minimum or no- tillage system despite higher soil Db of this layer.

In the 7.5-15-cm depth interval, the no-tillage treatment had the smallest RMD which was significantly lower (30.0%) than that of the till+no straw treatment, although in the former treatment Db was similar to and penetration resistance lower than the others. No till+straw was smaller than till+straw by 13.0%. In all layers below 15 cm, RMD was consistently greater in the no-till treatment compared with the tilled treatments. The difference between no till+straw and till+straw was 9.2, 29.3, 31.7 and 6.2%, and that between no till+straw and till+no straw was 33.0, 24.5 , 66.2 and 27.3%, for 15-22.5, 22.5-30, 30-40 and 40-50-cm depths, respectively. Ellis and Barnes (1980) also reported consistently greater quantity of wheat roots at deeper depths of direct-drilled than on plowed clay soil. When root mass was expressed on a per unit volume basis (Fig. 6.2), trends were similar to those on mass/area basis up to 30-cm depth, but values were reduced in the 30 to 40 and 40 to 50-cm depth intervals.

These differences in RMD are consistent with penetration resistance data (Chapter 3). PR of the soil below 12-15-cm depth was consistently and significantly greater in the till+no straw treatment, with no-till generally showing the minimum PR. Volumetric soil water was also greater in the no till+straw treatment throughout the soil profile (Chapter 5). Profile distribution of roots is strongly influenced by available soil water. When water is not limiting, a very high proportion of roots of cereal crops generally occurs in the surface soil layer (Bloodworth et al., 1958; Gregory et al., 1978). However, Lugg et al. (1988) observed only approximately 30% of total root mass of irrigated barley in 0-15-cm depth interval. Soon (1988) observed only 30% of total root length of unirrigated spring barley in 0-15-cm layer.

In this study, profile soil water was almost always adequate. More than 50% of the total root mass and 43% of total root length was in the surface 0-7.5-cm depth interval (Table 6.11). For the 0-15-cm layer, the percentages of root mass and length were 67 and 62, respectively. Root distribution with depth below 15 cm was fairly uniform with last sampled depth (40-50 cm) contributing 6 to 9% of the total root mass or length.

6.3.8.3 *Root length density (RLD) profiles*

The tillage x depth interaction for RLD (cm cm^{-3}) was highly significant (P=0.001). The overall trends were generally similar to those in root mass density (Figures 6.3 and 6.1). Nevertheless, a distinct difference in trends was observed in the 0-7.5-cm depth interval where the no till+straw treatment showed a lower RLD (11.7 cm cm^{-3}) compared with till+no straw (13.2 cm cm^{-3}). The difference (11.4%) was, however, not significant at the 5% level. This trend was opposite to that in RMD which was 5.3% greater in the no-till treatment compared with till+no straw. Also in 7.5-15-cm layer, the difference between no till+straw and till+no straw increased to 36.8% for RLD from 30.0% for RMD. Differences at other depths were small. These differences between RMD and RLD may be due to the roots in the surface soil being thicker (i.e. larger in diameter) in no-till than in the tilled treatments.

6.3.8.4 *Specific root length and root diameter*

Specific root length (SRL), which is the ratio of root length to root mass, is an index of root morphology reflecting the mean diameter of roots (Fitter, 1985). The smaller the thicker the roots. SRL as a function of soil depth is shown in Fig. 6.4. gn differences were not significant, the no-tillage treatment had the lowest SRL in all depths to 30 cm except 7.5-15 cm layer, implying that roots in this system were coarser or larger in diameter. In the 0-7.5-cm depth, SRL was 151.0 and 173.6 m g^{-1} in the no till+straw and till+no straw treatment, respectively, a difference of 13.0%. Corresponding values for 7.5-15-cm depth were 204.6 and 233.4 m g^{-1}, a difference of 12.3%. Difference between the two straw treatments was small. Visual observations on roots also supported these results. Barber (1971) in Indiana, reported that no-tillage corn roots were larger in diameter in the top 10 cm soil than roots with plowing or chiseling, with no difference below that depth. But Anderson (1987) reported no consistent effect of minimum tillage on corn root diameter. No report on tillage effects on barley root diameter was available for comparison.

Finer roots are considered more desirable since they contact more soil surface and thus provide greater access for nutrient and water uptake (Griffith et al., 1986). Therefore, in the 0-15-cm depth interval of the till+no straw treatment, roots were probably more desirable from a root morphological point of view. Higher mechanical impedance and bulk density increase root diameter (Glinski and Lipiec, 1990). Collis-George and Yoganathan (1985) and Boone and Veen (1982) observed that roots of wheat and maize were thicker under higher soil mechanical impedance. In the present study, the no till+straw treatment had the highest bulk density and penetration resistance in the top 10 cm depth compared with the tilled treatments (Chapter 3). These observations are thus consistent with the relatively thicker roots (or lower SRL) observed in the surface soil of the no-till treatment. But the lowest Db in the till+straw treatment did not produce the finest roots.

Averaged over all the depths, SRL was 201.7, 200.3 and 211.8 m g^{-1} in the no till+straw, till+straw and till+no straw treatment, respectively; the differences being non-significant. Averaged over the treatments, SRL of 0-7.5-cm depth interval was the smallest (160.3 m g^{-1}) and that of 30-40-cm depth interval the largest (234.1 m g^{-1}). Each of these values was significantly different than all others which were similar (198.8 to 211.6 m g^{-1}). Thus, excepting the 30-40 cm layer, the root thickness did not change much with depth below 7.5 cm.

Root diameter, estimated from root length and volume measurements, was on average 0.25, 0.25 and 0.23 mm for the 0-7.5-cm soil layer of the no till+straw, till+straw and till+no straw treatments, respectively (data not shown). The respective values for the other depths were: 0.25, 0.24 and 0.21 mm for the 7.5-15-cm layer; 0.18, 0.18 and 0.20 for the 15-22.5-cm layer; and 0.17, 0.19 and 0.17 mm for the 22.5-30-cm layer. These results also indicate somewhat finer roots in the 0-15-cm depth of the till+no straw treatment, although the differences were not statistically significant. Averaged over the tillage treatments, the in-row position contained significantly thicker roots than the between-rows position (0.28 mm vs. 0.21 mm) for the 0-7.5-cm depth. Positional effect was negligible at 7.5-15-cm depth.

6.3.8.5 *Cumulative root distribution with soil depth*

Cumulative percentages of total root mass (Pm) and total root length (Pl) showed strong curvilinear relationships with soil depth (Sd) for each of the three treatments (Figures 6.5A and 6.5B). The coefficient of determination ranged from 0.98 to 1.00. Treatment differences for root length curves were more pronounced than those for root mass curves. For example, the percentage of total root length in the 0-15-cm layer was 56.5, 59.0 and 69.0 in the no till+straw, till+straw and till+no straw treatment, respectively. Respective values for the 0-30 cm depth interval were 76.5, 79.0 and 85.5%. Root mass values for 0-30-cm soil depth were 82.0, 83.0 and 86.4% for the three treatments.

Since the uptake of water and nutrients by roots is more closely related to surface area or total length than to mass of roots (Barley, 1970), greater root length of till+no straw treatment in the potential rooting zone (0-30 cm) might be an advantage for this system.

6.3.9 *Grain and straw yields, grain/straw ratio and harvest index*

Grain yield was significantly affected by tillage-residue treatments in 1988 but not in 1989 (Table 6.12). In 1988, grain yield under the no till+straw treatment (3264 kg ha^{-1}) was significantly lower by 21.1 and 23.3% than under till+straw (4137 kg ha^{-1}) and till+no straw (4257 kg ha^{-1}), respectively. In 1989, grain yields of no till+straw and till+no straw treatments were similar with the former treatment being 13.3% lower (non-significant at P=0.05) than the till+straw treatment.

Bartholomew et al. (1977) found an average yield reduction of 21% for spring barley under no-tillage when compared to plowing across three environments in Northern Ireland, but under suitable conditions grain yield was equal to or greater than that in conventional tillage. In Great Britain, Elliott et al. (1977) and Ellis et al. (1979) observed similar or increased yield of spring barley with direct drilling compared to plowing. On three silt loam Mollisols in Washington, Ciha (1982) observed consistently greater grain yields of spring barley under no-tillage with standing stubble than under conventional tillage (fall plow and spring disk), although differences were non-significant. On a coarse-textured soil in Western Australia, the conventionally ploughed wheat yielded nearly 20% more than the direct-drilled crop (Hamblin et al., 1982). Obviously, the yield response to tillage system can vary even at the same site.

As with grain yield, straw yield was also the lowest in no-till treatment in both years; the effect being significant in 1989 (Table 6.12). Treatment trends were also somewhat different than those observed in grain yields. For example, grain yield in 1988 was the highest in till+no straw, but straw yield was the highest in till+straw. Also in 1989, till+no straw treatment produced proportionately more straw than the other treatments. These effects were reflected in grain/straw ratio which varied from 0.73 to 0.99 among treatments and years.

Harvest index (HI), which is the proportion of the aerial dry matter which is grain, varied from 0.44 to 0.49 in 1988 and from 0.42 to 0.44 in 1989. The treatment differences in both these indices were non-significant. Although grain/straw ratio and HI for no till+straw treatment were the same in the two years, values of these indices in the tilled treatments were considerably reduced in 1989 compared with 1988.

Averaged over the treatments, grain and straw yields were 30.2 and 18.3% lower in 1989 than in 1988. Apparently, a dry spell of 10 days following seeding in 1988 did not adversely affect the crop, although volumetric soil water (Øv) in the 0-7.5-cm layer 16 days after sowing was 4-5% (absolute values) below the -1500 kPa water content (permanent wilting point , PWP) in all treatments (Chapter 5). Another long dry spell of 18 days from 19 July to 5 August, which coincided with the period of peak reproductive growth (anthesis, grain filling and early ripening), does not seem to have adversely affected the crop yield in the tilled treatments in which Øv of 0-7.5-cm depth on 2 August was 1 to 4% (absolute) below PWP (Chapter 5). However, soil water of 0-7.5-cm layer in the no till+straw treatment was 7% (absolute) lower than its PWP. This probably resulted in some detrimental plant water stress in the no-till crop.

Plant water content determined from measurements of fresh and dry matter on 3 August was 160, 180 and 168% in the total shoot, and 151, 189 and 189% in the green leaves, for the no till+straw, till+straw and till+no straw treatments, respectively. This confirms some water stress in the no-till crop on this day.

Soil water of 7.5-15-cm layer was also close to PWP, but only in the till+no straw treatment was it actually below PWP (by nearly 2%). In all other depths to 50-60 cm (the potential rooting zone), soil water was a few percentage points above PWP on this day.

Somewhat lower soil temperature in the upper root-zone of the no-till treatment during most of the growing season may be partly responsible for its poorer crop growth. Maximum soil temperature generally followed the trend: till+no straw >till+straw >no till+straw (data not shown), the differences being large early in the season.

6.3.10 *Yield components*

In 1988, ear density (number m^{-2}) was unaffected by treatments, but mass per ear was 22 to 27% less (significant) in the no till+straw treatment compared with both tilled treatments (Table 6.13). Unit grain mass, however, was significantly greater in the no till+straw treatment compared with till+no straw, meaning production of bolder grains in the untilled crop. Mass per ear is controlled by number of grains per ear and mass per grain. Thus, a low mass per ear and high mass per grain in the no-till treatment implies a substantially lower number of grains per ear. On the other hand, a greater ear mass and a smaller grain mass in till+no straw means a larger number of grains per ear. In other words, average size of ears in the no-till crop was considerably smaller than in the tilled crop; this was also confirmed by visual observation.

In 1989, overall trends in ear density were similar to those in 1988. But unlike 1988, till+no straw produced significantly fewer ears per unit area as compared with till+straw. Unit ear and grain weights were not significantly affected. Using the earlier logic, number of grains per ear (i.e. ear size) was again the smallest in the no-till treatment. Number of grains per ear was not directly determined.

Mass per ear (implying number of grains per ear) accounted for most of the treatment differences in grain yield each year, while mass per grain had an almost inverse relation with grain yield. These results are somewhat contrary to those of Ciha (1982) in Washington who concluded that barley grain yield in his tillage treatments were mainly affected by kernel test weight and number of heads/m^2, both of which were significantly higher under no-tillage than under conventional tillage. Elliott et al. (1977) and Ellis et al. (1979) found that a reduced 1000-kernel weight in no-tillage was a compensation for a greater ear density observed under this system. In the present study, yield loss in the no-till system due to a smaller mass per ear (and hence a smaller number of grains per ear) could not be fully compensated for by bolder (or heavier) grains.

Average grain yield was 3886 and 2712 kg ha^{-1} in 1988 and 1989, respectively; a decrease of 30.2% in the second year. This decrease is not explained by ear density at harvest, which was actually 14.7% higher in the second year. A smaller (8.2%) average ear mass in 1989 partly accounted for lower yield. If a smaller mass per ear in the second year can be considered to be compensated by a larger ear density, then the yield parameter which explained most of the yield reduction was the mass per grain which was an average 33.7% smaller in the second year. Grains in the second year were very shrivelled. A frost for several days during the late maturity period perhaps caused this. The crop variety used in the second year was also different, and though considered higher yielding it is prone to lodging which could have caused some yield loss. Considerable lodging was evident during maturity period. At no stage in 1989 did the crop show any visible sign of water stress. The soil water seemed adequate throughout the growing season (Chapter 5).

6.3.11 *Water use and water use efficiency*

6.3.11.1 *Seasonal water use*

Seasonal water use or evapotranspiration, computed from the general soil water balance equation, was not significantly affected by the tillage-residue system in both years (Table 6.14). Average seasonal water use was 317 mm in 1988 and 281 mm in 1989. Seasonal use of profile-stored water was also not significantly different among treatments, although till+straw showed greater values in each year. Average profile water use or depletion was 2.0 and 38.0 mm in 1988 and 1989, respectively.

6.3.11.2 *Water use efficiency*

Grain yield water use efficiency, WUEg, in 1988 was significantly lower (21.9%) in no till+straw compared with till+no straw treatment which had the highest WUEg of 13.7 kg ha^{-1} mm^{-1} (Table 6.14). WUEg values for the two tilled treatments were not different. In 1989, WUEg was not significantly affected by the treatments. In both years, trends in WUEg were generally a reflection of those in grain yield since seasonal water use was not much affected by the treatments.

Trends in dry matter water use efficiency, WUEd, at harvest were generally similar to those in WUEg in both years. In 1988, WUEd of no till+straw treatment was significantly lower (average 14.8%) than both the tilled treatments. In 1989, a reduction in the no-till treatment (average 10.6%) was non-significant. Hamblin (1984) also reported lower grain yield and water use efficiency of spring wheat for zero-tilled than for disc-plowed system [illegible] poorly structured Alfisol in Western Australia. Average WUEg and WUEd were 12.4 and [illegible] kg ha^{-1} mm^{-1} in 1988 and 9.6 and 22.2 kg ha^{-1} mm^{-1} in 1989. Lower values in 1989 are ascribed mainly to lower grain and straw yields in 1989 than in 1988.

6.3.11.3 *Cumulative water use patterns*

Cumulative water use (CWU) patterns over the two growing seasons are given in Figures 6.6A and 6.6B. There were only small differences among treatments at any given time. In 1988, CWU was the smallest in till+no straw up to 64 days after sowing (grain formation stage). The till+straw treatment generally had the maximum water use throughout the growing season, attributed mainly to a larger crop (i.e. dry matter production, Table 6.8).

In 1989 also the till+straw treatment maintained the highest CWU throughout the growing season. The no till+straw treatment generally had the lowest water use except between 44 and 50 days when it had the largest water use, 38.8 mm compared with 28.8 mm in till+straw and 24.7 mm in till+no straw (Fig. 6.6B). A likely explanation is that the soil profile on the 44th day (July 9, 1989) was very wet (Fig. 5.9B, Chapter 5) due to almost daily rain for the previous 20 days with a total of 89 mm (Fig. 5.1B, Chapter 5). Therefore, it is likely that in the no-till treatment, most of the 20 mm rain during 44-50 days after seeding, together with [illegible] water from the initially wet soil profile, was lost by deep drainage below the last sampled depth (100 cm), because saturated hydraulic conductivity and infiltration capacity of this treatment was much higher than of the other two treatments (Chapter 4). This at least partially contributed to the greatest estimated water use in the no-till treatment during 44 to 50 days after seeding. Phillips (1984) also reported more drainage of soil water below the rooting depth under no-tillage than under conventional tillage.

6.3.11.4 *Daily water use rate*

Daily water use rates calculated for various phenological stages are presented in Tables 6.15 and 6.16. The treatments do not seem to follow a consistent trend at different growth stages and between years. Average daily water use rate was the highest during heading stage in both years; it was 6.1 mm d^{-1} in 1988 and 4.8 mm d^{-1} in 1989. During the grain formation stage each year, no till+straw treatment had the smallest and till+straw the greatest water use rate, the differences being significant in 1988. This could have somewhat affected the yields. Among all growth stages, average water use rate was the smallest during grain filling and ripening stage each year.

Average water use rate for the whole growing season was not significantly different among treatments and averaged 3.14 mm d^{-1} in 1988 and 3.03 mm d^{-1} in 1989. Somewhat lower water use in 1989 than in 1988 might be due to better rainfall distribution, more cloudiness, and somewhat milder temperatures, particularly in May and June of 1989 (Chapter 5). In 1988, two long dry spells, one immediately following seeding and another during grain filling stage, with possible greater evaporative potential, probably resulted in greater water use.

6.4 CONCLUSIONS

The two-year study demonstrated that in the no till+straw treatment, the seedling emergence and subsequent growth of barley were delayed up to approximately anthesis. Growth characters like tiller density, plant height, leaf area index and dry matter production were generally the greatest in the till+straw treatment and the smallest in the no-till treatment.

Total root mass and length, measured at the early grain formation stage in the first year, were not significantly different among the treatments. Nevertheless, roots in the top 30-cm soil profile were somewhat coarser in the no-till treatment than in the tilled treatments. Approximately 65% of the total (0-50-cm depth) roots (mass or length) were present in the 0-15-cm depth interval. Root growth in the lower (below 12-15 cm) depths seemed to be related to penetration resistance as well as soil water content.

Grain yield response to the treatments varied year-to-year. Grain yield was the lowest in the no till+straw treatment both years. In the first year, both tilled treatments yielded similarly, but in the second year till+straw was the highest and till+no straw similar to no till+straw treatment. Yield variation among the treatments was explained mostly by mass per ear (or number of grains per ear) and that between the years by mass per grain. The total seasonal water use was similar among the treatments. The efficiency of water use for grain production followed the trends in grain yield. Overall, the till+straw system seemed to perform better than the other treatments from a crop production point of view.

Table 6.1 Phenological stages in barley growth during the two growing seasons.

Main growing season segment	Feekes growth stage number	Dates of occurrence	
		1988	1989
Sowing to completion of tillering	1 to 5	19 May-25 June (0-37)¶	26 May-2 July (0-37)
Stem extension	6 to 10	25 June-2 July (37-44)	3 July-12 July (37-47)
Heading	10.1 to 10.5	2 July-13 July (44-55)	12 July-22 July (47-57)
Anthesis and grain formation	10.5.1 to 10.5.4	14 July-24 July (56-66)	22 July-27 July (57-62)
Grain filling and ripening	11.1 to 11.4	24 July-25 August (66-98)	28 July-25 August (63-91)

¶ Numbers in parentheses are days after seeding.

Table 6.2 Emergence and tiller counts (number m^{-1} row length) during the two growing seasons.

1988

Tillage-residue System	May 27 (8)¶	June 3 (15)	June 18 (30)	July 1 (43)	Aug. 3 (76)	Aug. 28† (101)
	emergence		tillers			
No till+straw	27 B‡	80 A	156 AB	144 B	120 AB	98 B
Till+straw	40 A	72 A	169 A	173 A	127 A	113 A
Till+no straw	41 A	75 A	145 B	157 AB	112 B	105 AB

1989

Tillage-residue System	June 4 (9)	June 6 (11)	June 7 (12)	June 11 (16)	June 18 (23)	June 29 (34)	July 15 (50)	July 25 (60)	Aug. 24 † (90)
	emergence				tillers				
No till+straw	30 B	54 A	58 B	63 A	60 A	158 B	119 A	113 A	106 A
Till+straw	45 AB	64 A	66 AB	69 A	70 A	194 A	121 A	114 A	110 A
Till+no straw	51 A	66 A	69 A	70 A	69 A	186 A	126 A	116 A	111 A

¶ Numbers in parentheses are the days after seeding.
† Effective tillers.
‡ Means in a date of measurement followed by a common letter are not significantly different at P=0.05.

Table 6.3 Plant height (cm) during the 1988 growing season.

Tillage-residue System	June 3 (15)¶	June 18 (30)	July 1 (43)	July 10 (52)	July 20 (62)	August 3 (76)	August 24 (97)
No till+straw	11.2 A†	27.3 A	62.9 B	87.2 B	98.1 A	99.2 A	97.2 A
Till+straw	11.2 A	29.5 A	69.4 A	93.0 A	99.2 A	98.9 A	97.6 A
Till+no straw	10.8 A	27.1 A	62.2 B	86.1 B	96.1 A	98.3 A	97.1 A

Table 6.4 Plant height (cm) during the 1989 growing season.

Tillage-residue System	June 13 (18)¶	June 17 (22)	June 29 (34)	July 9 (44)	July 13 (48)	July 24 (59)	August 4 (70)	August 18 (84)	August 23 (89)
No till+straw	11.3 A†	14.5 B	25.3 C	45.0 C	57.1 B	90.8 B	90.5 B	92.3 B	89.9 B
Till+straw	13.5 A	17.8 A	32.7 A	57.2 A	70.0 A	95.9 A	96.0 A	96.9 A	94.8 A
Till+no straw	12.8 A	16.6 AB	29.9 B	51.0 B	61.8 B	89.2 B	88.0 B	89.8 B	87.2 B

¶ Numbers in parentheses are the days after seeding.
† Means in a time of measurement followed by a common letter are not significantly different at P=0.05.

Table 6.5 Growth rate¶ (mm/day) during the 1988 growing season.

Tillage-residue System	Sowing-June 3	June 3-18	June 18-July 1	July 1-10	July 10-20
No till+straw	7.5 A‡	10.8 A	27.3 B	27.1 A	10.9 A
Till+straw	7.5 A	12.2 A	30.7 A	26.2 A	6.1 B
Till+no straw	7.2 A	10.9 A	27.0 B	26.5 A	10.0 A

Table 6.6 Growth rate¶ (mm/day) during the 1989 growing season.

Tillage-residue System	Sowing - June 13	June 13-17	June 17-29	June 29-July 9	July 9-July 13	July 13-July 24
No till+straw	6.3 A ‡	8.0 B	9.1 C	19.6 B	30.3 A	30.6 A
Till+straw	7.5 A	10.9 A	12.4 A	24.5 A	32.2 A	23.5 B
Till+no straw	7.1 A	9.6 AB	11.1 B	21.1 AB	27.1 A	24.9 B

¶ Calculated from plant height.
‡ Means in a time of measurement followed by a common letter are not significantly different at P=0.05.

Table 6.7 Green leaf area index ($cm^2\ cm^{-2}$) during the two growing seasons.

	1988			1989	
Tillage-residue System	June 25 (37)¶	July 13 (55)	August 3 (76)	July 13 (48)	July 24 (59)
No till+straw	3.52 AB†	3.79 A	0.54 B	4.16 A	2.82 A
Till+straw	4.18 A	3.69 A	0.82 A	4.39 A	2.88 A
Till+no straw	3.26 B	3.67 A	0.77 A	4.27 A	2.66 A

¶ Numbers in parenthesis are the days after sowing.
† Means in a date of measurement followed by a common letter are not significantly different at P=0.05.

Table 6.8 Shoot dry matter partitioning during the 1988 growing season.

Tillage-residue System	Dry matter ($g\ m^{-2}$) Green leaves	Dead leaves	Stems	Ears	Total
			June 25 (37 DAS)‡		
No till+straw	96.7 AB†	–	61.6 A	–	158.3 A
Till+straw	112.7 A	–	74.6 A	–	187.3 A
Till+no straw	92.1 B	–	51.7 A	–	143.8 B
			July 13 (55 DAS)¶		
No till+straw	119.6 A	27.6 B	317.6 A	103.7 A	568.5 A
Till+straw	115.2 A	36.1 A	302.2 A	97.7 A	551.3 A
Till+no straw	116.4 A	24.0 B	269.1 A	89.4 A	498.8 A
			August 3 (76 DAS)§		
No till+straw	22.2 B	84.5 A	320.5 A	433.7 A	860.9 A
Till+straw	31.0 A	82.2 A	353.9 A	461.4 A	928.4 A
Till+no straw	29.7 AB	78.2 A	334.1 A	453.8 A	895.8 A
			August 27 (100 DAS)¥		
No till+straw	–	79.8 A	259.1 B	480.5 B	819.4 B
Till+straw	–	87.7 A	325.2 A	620.6 A	1033.6 A
Till+no straw	–	80.4 A	305.3 A	646.9 A	1032.5 A

† Means in a column within a date of measurement followed by a common letter are not significantly different at P=0.05.
‡ Tillering completed (Stage 5 of Feekes scale).
¶ Heading completed (Stage 10.5 of Feekes scale).
§ Milky to mealy ripe (Stage 11.1 or 11.2 of Feekes scale).
¥ Ripe or mature (Stage 11.4 of Feekes scale).

Note: DAS refers to days after seeding.

Table 6.9 Shoot dry matter partitioning during the 1989 growing season.

Tillage-residue System	Dry matter ($g\ m^{-2}$) Green leaves	Dead leaves	Stems	Ears	Total
			June 18 (23 DAS)‡		
No till+straw					16.3 B†
Till+straw					24.8 A
Till+no straw					27.7 A
			June 29 (34 DAS)¶		
No till+straw	51.5 B	–	21.8 B	–	73.3 B
Till+straw	78.0 A	–	38.2 A	–	116.2 A
Till+no straw	87.0 A	–	38.7 A	–	125.7 A
			July 13 (48 DAS)§		
No till+straw	102.4 A	6.7 A	152.0 A	–	261.1 A
Till+straw	109.2 A	9.8 A	175.2 A	–	294.2 A
Till+no straw	108.1 A	9.5 A	182.6 A	–	300.2 A
			July 24 (59 DAS)¥		
No till+straw	83.7 A	27.5 B	321.4 A	164.0 A	596.7 A
Till+straw	84.5 A	35.2 AB	348.1 A	182.1 A	649.9 A
Till+no straw	83.2 A	35.8 A	320.5 A	174.4 A	613.9 A
			August 11 (77 DAS)=		
No till+straw	12.6 A	70.3 A	289.2 A	492.1 A	864.2 A
Till+straw	8.1 B	85.1 A	334.1 A	575.6 A	1002.8 A
Till+no straw	4.6 B	84.4 A	277.3 A	523.3 A	889.6 A
			August 24 (90 DAS)∞		
No till+straw	–	69.1 C	279.3 B	598.7 A	947.1 A
Till+straw	–	89.4 A	331.9 A	663.0 A	1084.3 A
Till+no straw	–	80.4 B	277.0 B	588.1 A	945.6 A

† Means in a column within a date of measurement followed by a common letter are not significantly different at P=0.05.
‡ Tillering started (Stage 2 of Feekes scale).
¶ Tillering near completion (Stage 4 to 5).
§ Stem extension completed (Stage 10).
¥ Heading completed (Stage 10.5).
= Mealy ripe, kernels soft but dry (Stage 11.2).
∞ Ripe for cutting (Stage 11.4).

Note: DAS refers to days after seeding.

Table 6.10 Total dry root mass, total root length and root/shoot ratio measured on 20 July, 1988 (growth stage 10.5.2 of the Feekes scale). The root mass and length are totals for 0-50-cm depth.

Tillage-residue system	Root mass ($g\ m^{-2}$)	Root length ($km\ m^{-2}$)	Root/shoot ratio ($g\ m^{-2}/g\ m^{-2}$)
No till+straw	118.7 A† (12.5)‡	21.13 A (2.60)	0.210 A (0.021)
Till+straw	104.4 A (11.4)	19.24 A (3.01)	0.191 A (0.025)
Till+no straw	110.2 A (4.5)	21.65 A (0.60)	0.225 A (0.021)

† Means in a column followed by a common letter are not significantly different at P=0.05

‡ Numbers in parentheses are standard error of the means.

Table 6.11 Percentage of total root mass and length of spring barley (0-50 cm depth interval) as a function of soil depth.

Soil Depth (cm)	No till + straw	Till + straw	Till + no straw
		Root mass	
0-7.5	51.5	49.0	52.5
7.5-15	12.5	16.5	19.0
15-22.5	10.0	10.5	8.5
22.5-30	8.0	7.0	6.5
30-40	11.0	9.5	7.5
40-50	7.0	7.5	6.0
		Root length	
0-7.5	41.5	41.5	46.0
7.5-15	15.0	17.5	23.0
15-22.5	11.0	12.0	9.0
22.5-30	9.0	8.0	7.5
30-40	15.0	12.0	8.0
40-50	8.5	9.0	6.5

Table 6.12 Grain and straw yields, grain/straw ratio and harvest index as affected by three tillage-residue treatments.

Tillage-residue System	Grain yield (kg ha^{-1})	Straw yield (kg ha^{-1})	Grain/Straw ratio	Harvest index (kg ha kg^{-1} ha^{-1})
		1988		
No till+straw	3264 B†	4101 A	0.80 A	0.44 A
Till+straw	4137 A	4554 A	0.91 A	0.48 A
Till+no straw	4257 A	4331 A	0.99 A	0.49 A
Mean	3886	4329	0.90	0.47
		1989		
No till+straw	2541 A	3149 B	0.81 A	0.44 A
Till+straw	2932 A	3772 A	0.78 A	0.44 A
Till+no straw	2663 A	3684 A	0.73 A	0.42 A
Mean	2712	3535	0.77	0.43

† Means in a column followed by a common letter are not significantly different at P=0.05. Comparisons are permitted only within years.

Table 6.13 Selected yield components of barley as affected by tillage-residue treatments.

Tillage-residue System	Final ear density (no. m^{-2})	Mass per ear (mg)	Mass per grain (mg)
		1988	
No till+straw	547 A†	886 B	44.2 A
Till+straw	549 A	1130 A	43.9 AB
Till+no straw	533 A	1213 A	41.8 B
Mean	543	1076	43.3
		1989	
No till+straw	614 AB	967 A	29.0 A
Till+straw	661 A	1008 A	28.9 A
Till+no straw	595 B	988 A	28.3 A
Mean	623	988	28.7

† Means in a column followed by a common letter are not significantly different at P=0.05. Comparisons are permitted only within years.

Table 6.14 Seasonal total water use, seasonal profile water use, grain yield water use efficiency, and dry matter† water use efficiency.

Tillage-residue System	Seasonal total water use (mm)	Seasonal profile water use (mm)	Grain WUE ($kg\ ha^{-1}\ mm^{-1}$)	Dry matter WUE ($kg\ ha^{-1}\ mm^{-1}$)
		1988		
No till+straw	317 A‡	2.5 A	10.4 B	23.3 B
Till+straw	320 A	5.1 A	13.0 AB	27.2 A
Till+no straw	313 A	-1.7 A	13.7 A	27.5 A
		1989		
No till+straw	276 A	33.0 A	9.2 A	20.6 A
Till+straw	288 A	44.8 A	10.2 A	23.3 A
Till+no straw	280 A	36.3 A	9.5 A	22.8 A

† Dry matter at harvest = grain plus straw yields.

‡ Means in a column followed by a common letter are not significantly different at P=0.05. Comparisons are permitted only within years.

Table 6.15 Daily water use (mm/day) during various phenological stages (1988).

Tillage-residue System	Seeding to complete tillering (20 May-25 June)	Stem extension (25 June-1 July)	Heading (1 July-16 July)	Grain formation (16 July-24 July)	Grain filling and ripening (24 July-29 Aug.)	Mean for whole growing season
No till+straw	3.64 A¶	1.27 A	6.15 A	4.28 B	1.45 AB	3.14 A
Till+straw	3.61 A	1.94 A	6.00 A	4.98 A	1.35 B	3.17 A
Till+no straw	3.30 A	1.70 A	6.05 A	4.90 A	1.51 A	3.10 A
Mean	3.52	1.64	6.07	4.72	1.44	3.14

¶ Means in a column followed by a common letter are not signficantly different at P=0.05.

Table 6.16 Daily water use (mm/day) during various phenological stages (1989).

Tillage-residue System	Seeding to complete tillering (31 May-30 June)	Stem extension (30 June-9 July)	Heading (9 July-23 July)	Grain formation (23 July-31 July)	Grain filling and ripening (31 July-1 Sept.)	Mean for whole growing season
No till+straw	2.26 B¶	3.65 A	4.79 A	3.29 A	2.57 A	2.97 A
Till+straw	2.66 A	3.24 A	5.04 A	3.72 A	2.46 AB	3.10 A
Till+no straw	2.55 A	3.96 A	4.57 A	3.50 A	2.36 B	3.01 A
Mean	2.49	3.62	4.80	3.50	2.46	3.03

¶ Means in a column followed by a common letter are not signficant'y different at P=0.05.

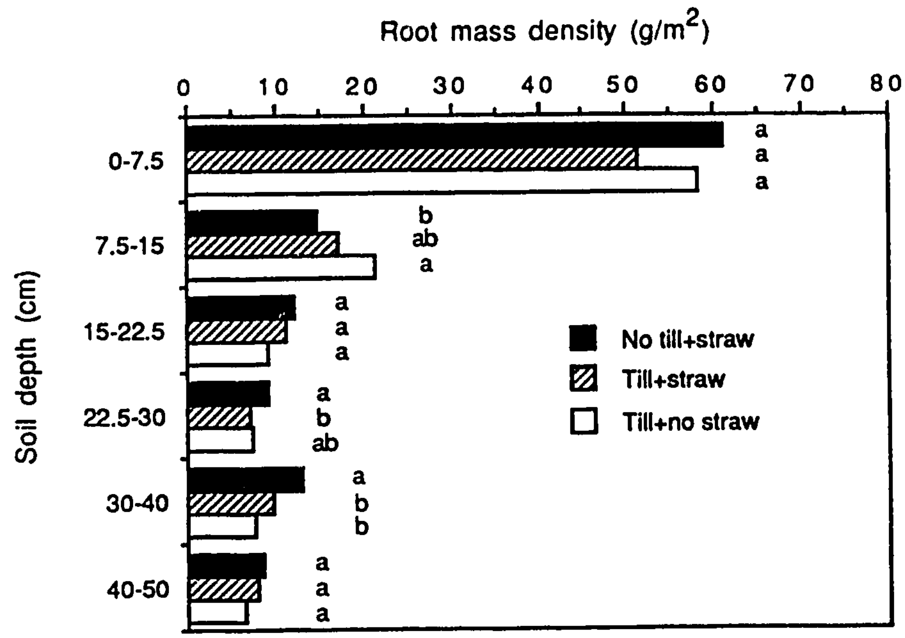

Figure 6.1. Root mass density (g m^{-2}) distribution with soil depth at completion of heading in 1988. Different letters within a given depth interval indicate significant treatment difference at P=0.05. Statistical analysis was conducted on the Box-Cox transformed data.

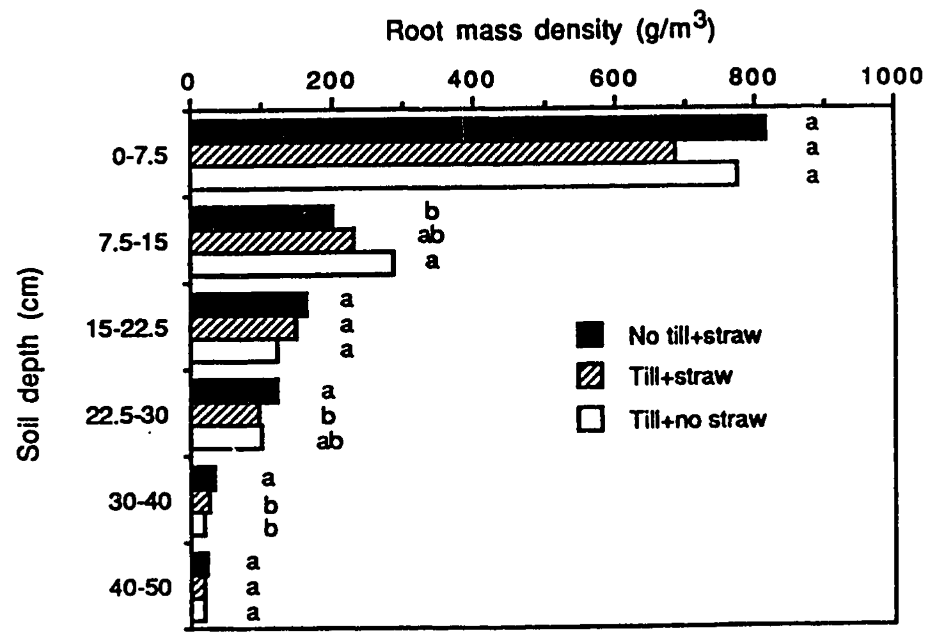

Figure 6.2. Root mass density (g m^{-3}) distribution with soil depth. Different letters within a given depth interval indicate significant treatment difference at P=0.05. Statistical analysis was conducted on the Box-Cox transformed data.

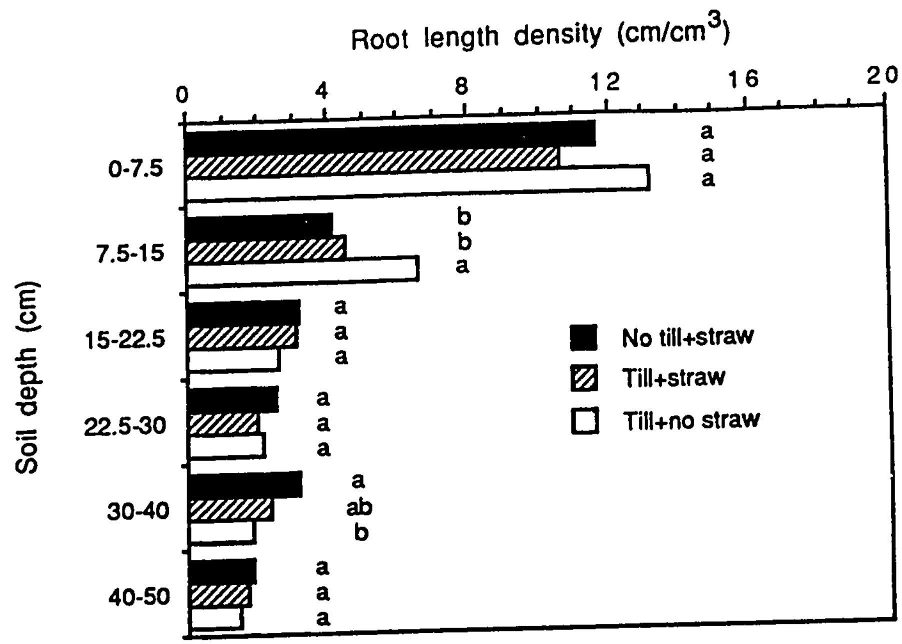

Figure 6.3. Root length density (cm cm^{-3}) distribution with soil depth. Different letters within a given depth interval indicate significant treatment difference at P=0.05. Statistical analysis was conducted on the Box-Cox transformed data.

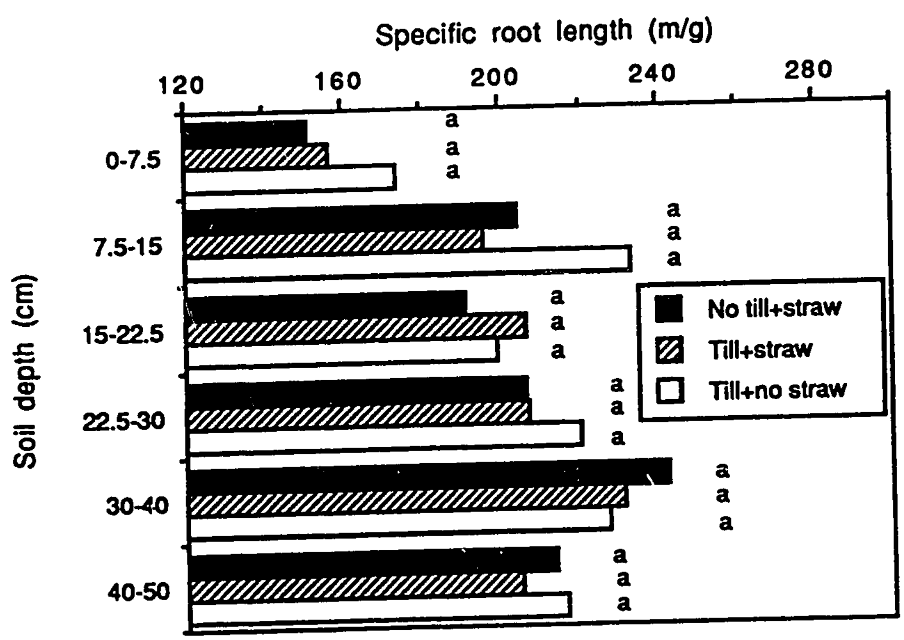

Figure 6.4. Specific root length (m root length per g dry root mass) distribution with soil depth. Different letters within a given depth interval indicate significant treatment difference at P=0.05. Statistical analysis was conducted on the Box-Cox transformed data.

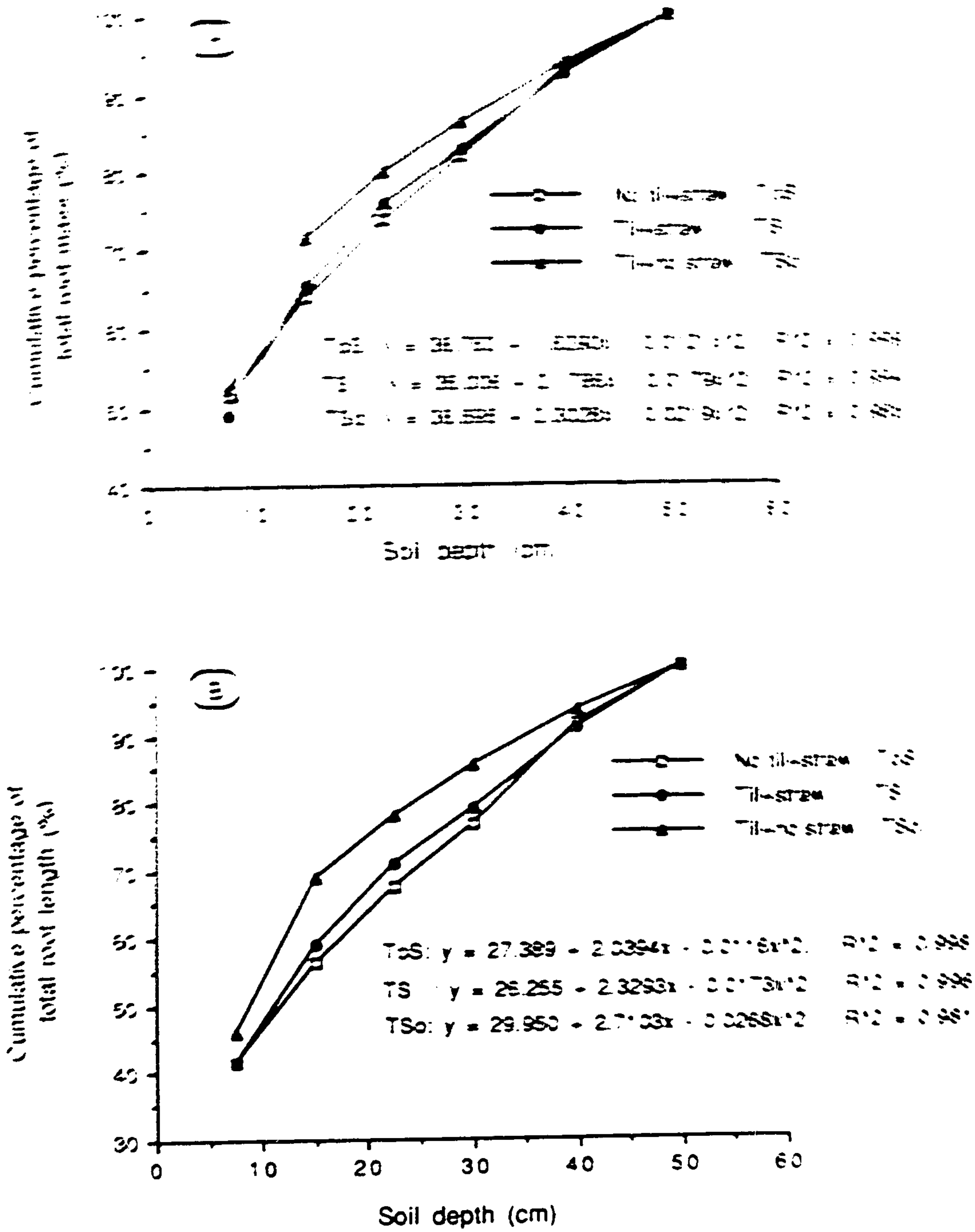

Figure 6.5. Cumulative percentage of the total (0-50 cm interval) (A) root mass and (B) total root length as a function of soil depth.

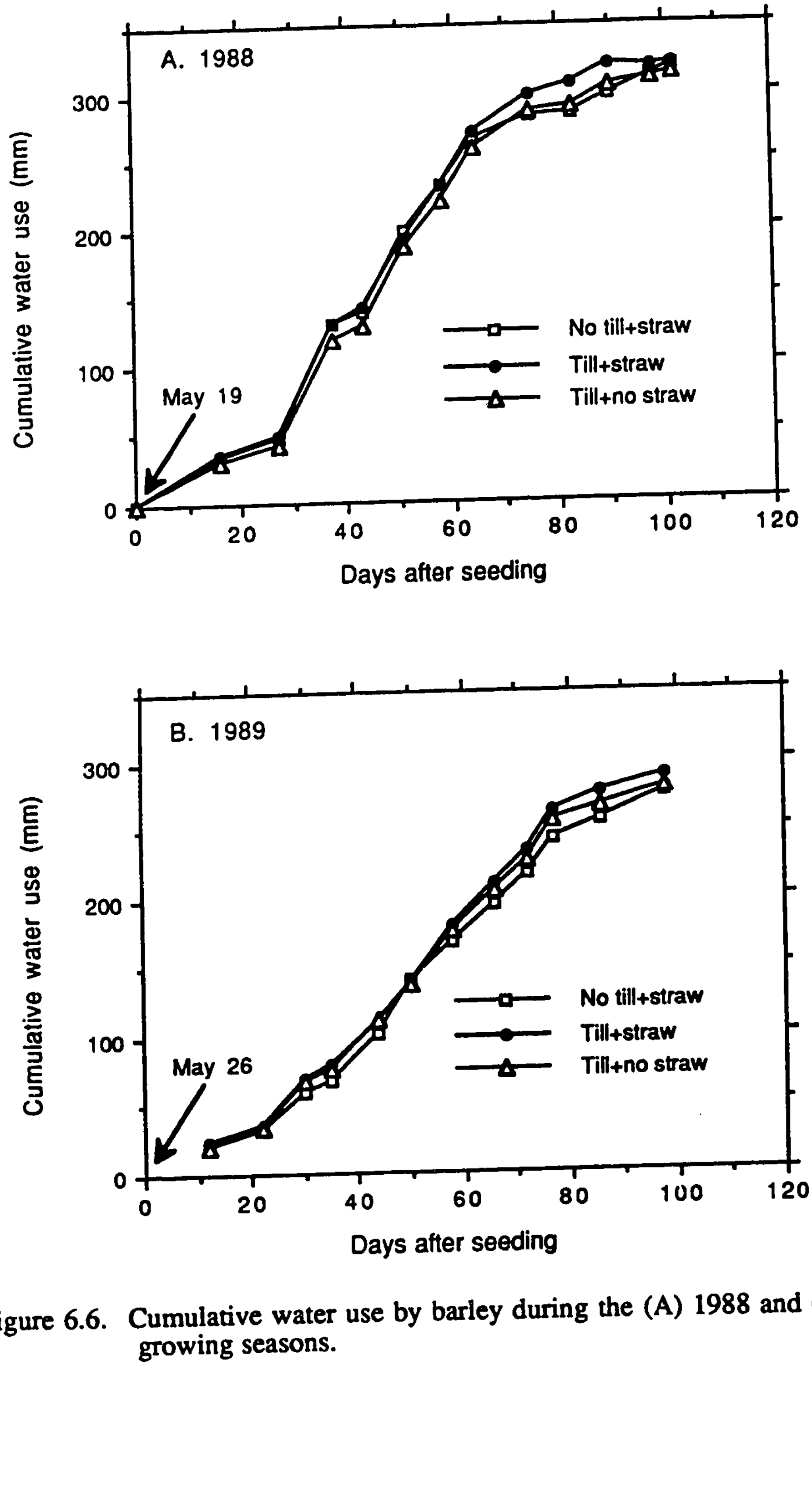

Figure 6.6. Cumulative water use by barley during the (A) 1988 and (B) 1989 growing seasons.

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Chapter 7

SYNTHESIS

7.1 Introduction

Due to their potential in soil and water conservation and in lowering production costs, reduced- or no-tillage systems, in conjunction with different methods of crop residue management, are being intensively researched internationally. The focus of research reported in this dissertation was quantification of changes brought about by long-term tillage-cum-residue management practices in various physical factors and processes of the soil environment, and on the resultant crop response. This section provides a synthesis of the research reported in previous chapters of this dissertation in order to evolve an overall picture of the behavior of the systems studied, and to draw general conclusions. Possible research efforts needed towards further enhancing our understanding of various conservation tillage systems are also included.

7.2 Surface soil conditions, soil structure, bulk density and soil strength

One goal of conservation tillage is to leave enough plant residues on or near the soil surface to control water and wind erosion and to conserve soil water. Modification of the surface configuration (microrelief) with tillage and residue practices also plays a large role in hydrologic and thermal responses.

In this study, the no-tillage system provided 70 to 99% residue cover over the crop growing and the non-growing period compared with 41 to 85% in the till+straw and 6 to 16% in the till+no straw treatment. Although the no-till system had a lower soil surface roughness than the tilled systems throughout a year, it is expected to provide more effective and sustained runoff and erosion control owing to its greater residue cover and a larger number of water-stable aggregates in the surface soil. The proportion of wind-erodible (<1 mm dry) and water-slakable (<0.250 mm water-stable) aggregates was considerably smaller in the surface soil of the no-till treatment. The no-till treatment had significantly higher organic carbon content and lower pH in the 0-5-cm depth compared with the till+no straw treatment whereas the till+straw treatment was intermediate.

This shows that even in this soil (Black Chernozemic or Typic Cryoboroll) with a good natural aggregation and high organic carbon, the no till+straw system had the highest soil quality from a soil conservation perspective. The changed macro- vs. microaggregate distribution and water-stability index among the treatments seem to be mainly related with physical disturbance (or lack thereof) of soil because due to its high level in all the treatments, soil carbon content is expected to play only a small role in aggregation (Kemper and Koch, 1966).

From a plant growth perspective (i.e. soil-air-water relations), the three treatments seemed to be within a desirable range of aggregation. The proportion of dry aggregates <1 mm size was only 16% in the no-till treatment compared with 29% in till+straw and 49% in the till+no straw treatment. From a purely seed-soil contact standpoint, relatively smaller aggregates are preferable (Hadas and Russo, 1974), implying presence of a relatively more desirable seedbed in the tilled treatments. Nevertheless, the 'optimum' aggregate size range varies with soil water conditions, plant growth stage, soil temperature regime, etc., in addition to the crop species (Braunack and Dexter, 1989). In a dry year, smaller aggregates would be more desirable than larger aggregates because the latter can restrict water movement to the roots, thereby limiting plant growth. In an excessively wet period, larger aggregates provide a better aeration regime if drainage is a problem otherwise. Apparently there is a need to determine 'optimum' aggregate sizes for various combinations of soils, crops and climatic conditions.

The increased acidity of surface soil in the no-till system does not seem to be an immediate problem, but may cause nutrient imbalances in the soil and plants on a longer-term basis.

The study did not reveal any tillage-induced compacted soil layer of high bulk density (Db) or soil strength in the tilled treatments. This probably is due to relatively lighter equipment used in the experimental plots. The treatment effects on Db were mostly confined to the uppermost 10 cm where average Db was significantly greater in the no till+straw system. The till+straw treatment always had the lowest Db in this depth interval, attributed primarily to crop residues incorporated in this layer.

The penetration resistance (PR) of the surface soil was significantly greater in the no-till treatment compared to the tilled ones. This was mainly attributed to a higher soil bulk density in the former. Below a depth of 10 to 15 cm, the till+no straw treatment had a considerably higher PR than the other two treatments, and the differences were mainly explained by soil water content. PR seemed to be a better indicator of tillage-induced changes in soil conditions than Db since it combines changes in both Db and soil water content. For example, whereas Db was not affected below approximately a 10-cm depth, PR was clearly different among treatments. This was also reflected in some root growth differences. Differences in PR were, however, not completely explained by differences in Db and soil water content among treatments.

Increased Db and PR and reduced total porosity in the surface soil of the no-till system did not seem to be of a magnitude which could seriously restrict root growth. However, since soil water below a 7.5-cm depth at the time of PR measurements was generally close to field capacity, it appears that in the event of drier soil conditions, soil strength will probably increase and may become root-restricting in the surface for the untilled treatment and in the sub-surface for the till+no straw treatment.

Similarity of average Db values in different treatments in the two study years suggests that the soil has attained an equilibrium Db with the imposed management practices. Db and PR both had considerable temporal and positional variation. A random sampling technique would, therefore, only complicate data interpretation.

Freeze-thaw cycles over the winter affected neither the absolute values nor the treatment differences in bulk density as indicated by similar values before ground freezing and those subsequent to snow-melt. As a result, Db of the surface soil remained persistently higher in the no-till than in the tilled treatments. Kay et al. (1985) reported almost similar effects of ground freezing on soil Db under zero- and conventional tillage in Ontario. They theorized that formation of ice lenses creates pores which are inherently unstable and collapse as the ice melts and the soil drains. As a result, soil quickly reconsolidates upon thawing and returns to near pre-freezing bulk densities prior to spring planting. They further argued that pores created by tillage, on the other hand, are more stable since they are formed by vertical and horizontal displacement of peds. Results from this study seem to support their arguments.

7.3 Soil hydraulic characteristics and soil water regime

The hypotheses tested were that the studied long-term tillage-residue systems have not affected the pore size distribution, soil water retention and transmission characteristics, plant available water capacity, soil water content, and crop water use. The study revealed relatively small treatment differences in soil water retention properties, but soil water transport characteristics were affected to a larger extent. Plant available water capacity (PAWC) made up only 25 to 29% of the total porosity. It was consistently lower in the no till+straw treatment, compared with especially the till+no straw treatment, for all 2.5-cm layers to 15-cm depth. The implication is that the measured greater soil water content in the no-till system may or may not mean a greater availability of soil water for plant growth. The differences in PAWC arose mainly from consistently greater water retention at -1500 kPa in the no-till compared with the tilled treatments since water retention at -10 kPa (assumed 'field capacity' water potential) was similar among the treatments.

The increased 'permanent wilting point' in the no-till treatment is difficult to explain. Actually water retention for all potentials $\leq$ -20 kPa was greater in the no-till treatment.

The amount of water retained at relatively low values of matric suction (say, between 0 and 100 kPa) depends primarily upon the capillary effect and the pore size distribution, and hence is strongly affected by the soil structure (Hillel, 1980). On the other hand, water retention in the higher suction range is due increasingly to adsorption and is thus affected less by structure and more by texture and specific surface of the soil material. Soil particle size distribution was not affected by treatments in this study, thus specific surface was probably not a factor. In the surface soil of the no-till treatment, either water was adsorbed more strongly due to presence of certain chemical substances, or more water was entrapped in the intra-aggregate micropores which do not form a continuous network, but give rise to 'residual porosity' (equivalent pore diameter <0.2 μm). Organic matter can hold a large volume of water but its water content-potential relationships are not clearly known and need investigation. Greater observed water-stability of aggregates in the no-till treatment will probably result in greater residual porosity.

A smaller volume of drainable pores (>30 μm EPD) and larger volume of residual pores in surface soil of the no-till treatment can possibly result in some transitory anaerobic conditions in the event of highly intense rainfall, affecting nutrient availability and water uptake.

All three systems seemed to have an adequate water conduction from an hydrological point of view. Although both saturated hydraulic conductivity (Ksat) of surface soil and steady state infiltration rate of the no till+straw treatment were considerably greater than those of the tilled treatments, the values in tilled treatments were by no means small. Significantly greater values of Ksat and infiltration rate in no-till, together with presence of a substantial residue cover, would likely preclude any possibility of runoff and soil erosion from even the most intense rainfall events.

Ksat and infiltration rate were greater in the no-till treatment even though Db was higher and total porosity was lower in this treatment. Water-filled pore space was also higher in the no-till system at infiltration measurements. These results point to the presence of a larger network of bigger and continuous biochannels (somewhat greater macroporosity in no-till was measured) due primarily to a larger earthworm population, as well as to greater water stability of soil aggregates in the untilled soil. Minimal disturbance of soil in no-till helps in maintaining the continuity of pores and surface residue cover prevents surface sealing.

The till+no straw treatment had the highest initial infiltration rate soon after a tillage operation, but treatment trends in the final rate were unaffected. Surface roughness in tilled treatments also decreased quickly with time after a tillage (due to rainfall and natural subsidence). These conditions, together with a less stable aggregate structure, can soon lead to formation of a surface seal in the tilled treatment with a bare surface, leading to a decreased infiltration rate and an increased possibility of runoff, especially if the land is sloped and rainfall intensity is high. From these considerations, the no till+straw system again seemed better than the tilled treatments from a soil erosion perspective.

The air-entry permeameter provided a quicker estimate of in situ saturated hydraulic conductivity values which were possibly also more representative of field conditions than the core-determined values. A permeameter integrates vertical and horizontal components of hydraulic conductivity and also tests a larger soil volume without disturbing the soil and its surface conditions.

Many soil physical properties which are modified by tillage-residue systems (particularly soil water retention and transmission characteristics, pore geometry and aggregate size distribution), in turn, influence the soil water regime. Residue cover also directly affects the soil water regime by reducing runoff, changing the solar radiation balance and evaporation patterns. In this study, the tillage-residue treatments affected the soil water content to a 100-cm depth, the greatest depth monitored, despite a relatively low atmospheric evaporative potential at this site. Treatment differences even at the beginning of a growing season indicate different storage efficiencies/capacities and/or different evaporation rates among the treatments over the winter period as well as the snow-melt to seeding period. Differential snow trapping may also be a factor.

The till+no straw treatment was almost always the driest at all depths. The no till+straw treatment was the highest in soil water in the 0-7.5-cm depth interval for most of the growing season. The two straw treatments were not generally different for 0-50 and 0-100-cm profile water storage. The treatment differences in soil water were attributed mainly to crop residue cover. A differential water uptake due to differences in the above-ground crop growth in the three treatments might also be a factor, although total root mass and length were similar among the treatments.

The growing-season rainfall during the two study years was above-normal. It means that the treatment differences might be greater in 'normal' and drier years, and soil water in the 0-15-cm depth could go below the -1500 kPa water content, particularly in the tilled treatments. Thus, the no till+straw treatment can be beneficial during drier conditions when its higher water storage can prevent water stress from developing in the plants. But during excessively wet conditions, this treatment may cause anaerobic conditions in the near-surface soil which might adversely affect plant growth. Higher infiltration rate and Ksat in the no-till treatment can be beneficial or detrimental. In case of an initially drier soil profile, water will move into deeper layers where it can be used by the crop later during any drier periods. However, if an intense rain falls on a considerably wet soil profile, greater percolation losses below rooting depth may occur in the no-till system. This situation occurred a few times during the study period.

7.4 Crop growth and water use

Plant growth is the result of a complex interplay of its genetic make-up and its soil and aerial environments. Plant response to modifications in the plant environment due to tillage and crop residue practices is mostly manifested through effects on seedling emergence, development and vigor, root growth, shoot development, phenological development and on various yield-contributing factors. But interpreting the effect on crop growth of changes in soil physical environment induced by tillage practices is not a simple process (Griffith et al., 1986).

The grain and straw yields were the lowest in the no till+straw treatment in each of the two study years. The grain yield of the till+no straw treatment was similar to till+straw in the first year and to no till+straw in the second year. Total root length and mass in the soil profile were not different among treatments. This meant that the changed physical properties (Db, PR, aggregation status, soil hydrothermal regime, etc.) were perhaps within desirable ranges for optimum root growth. (Incidentally, these 'optimum' ranges are presently either not known or are inadequately defined for various combinations of soils, crops and environments). Probably this also means that the inherent values of these soil characteristics are in such a range that they can absorb the treatment-induced changes without exceeding the critical limits for root growth of barley. The question then is how the shoot growth (tiller density, plant height, leaf area, shoot dry mass, etc.) was differently affected by tillage-residue practices. Since in this study, the soil fertility and soil biological aspects were not measured, the discussion is mostly from a soil physical standpoint, and, thus, incomplete.

Unrestricted seedling emergence is essential for healthy plants. In this study, the emergence was delayed by several days in the no till+straw system compared with the tilled systems. This was perhaps mainly due to lower (suboptimal) soil temperature at the seeding depth in the straw-covered untilled plots. There is also a possibility of a poorer seed-soil contact and thus slower seed hydration due to a larger average aggregate size in this treatment. Soil water was otherwise higher in the no-till treatment. Some researchers have attributed poor germination and seedling growth in the no-till systems, particularly when soil is cool and wet, to microbiologically produced phytotoxic organic compounds originating from straw mulches (Blevins et al., 1984). It is hard to say if higher Db and PR measured in the surface soil of the no-till treatment affected the seedling emergence, although a possibility exists. Also direct damage to seedlings from straw residue (shading, etc.) has been reported as a reduction in shoot size or plant stand (Klepper and Rickman, 1988). In this study, tiller density, plant height, leaf area index and above-ground dry matter production were generally the smallest in the no-till and the greatest in the till+straw treatment.

The specific root length as well as direct measurements indicated that roots in the surface soil (0-15 cm) of the till+no straw treatment were finer than in the other two treatments in which straw was retained. This is partially associated with Db and soil strength in the surface depths (Glinski and Lipiec, 1990; Chapter 3). Root length density as well as percentage of total root length in the 0-15-cm layer were also somewhat lower in the no-till treatment. A reduced rate of water and nutrient uptake with smaller root length and thicker roots is another possible reason of smaller shoot size in the no-till system.

Observations and measurements point to an early achievement of maximum leaf area in the till+straw treatment. This perhaps made available greater reserves of photosynthates for an extended reproductive growth period, culminating in the measured large ear size (i.e. number of grains per ear) and grain yield in the till+straw treatment. On the other hand, a shorter grain formation period in no-till (maturity was hastened in this treatment) may have caused greater floret sterility and thus the measured fewer grains per ear. These observations and possibilities need to be investigated further.

Soil water was generally adequate for plant growth in all treatments. However, during a continuous dry spell of 18 days in 1988, which coincided with peak reproductive growth period, soil water in the 0-7.5-cm layer was below permanent wilting point. The decrease below PWP was greater in the no-till than the tilled treatments. The soil water of 7.5-15-cm layer was also close to PWP. Lower available water, together with morphologically less efficient roots for water uptake in the no-till treatment probably caused some water stress in the plants. Lowest water use and plant water content was observed in the no-till treatment in this period. Total seasonal water use was not different among treatments.

Consequently, grain yield water use efficiency of the no-till system was the lowest. This is contrary to generally reported higher water use efficiency in untilled systems.

It should be remembered that 'tillage' in the present study consisted of rotory-cultivation to a depth of approximately 10 cm. This type of tillage is likely to result in a greater degree of soil mixing and pulverization than by the shearing types of tillage equipment. Most of the direct effects of tillage system were observed to approximately 10 cm depth with much less stratification of soil physical properties in the tilled treatments than in the untilled one.

Also to be noted is the fact that the nitrogen fertilizer (urea) was broadcast just before spring tillage and seeding. It got incorporated into the surface soil in both the tilled treatments, but remained on the surface in the no-till plots. In the no-till treatment, which had a substantial residue cover and a generally wetter and cooler surface soil, probably more losses of nitrogen through volatilization and denitrification and less availability due to higher rates of immobilization and lower rates of mineralization compared with the tilled treatments might have affected the crop response. This seems quite possible considering that only a moderate rate of N (56 kg ha^{-1}) was used. Such effects of similar tillage-residue treatments on N dynamics have been reported.

7.5 Conclusions

The following conclusions are drawn in relation to the objectives presented in various papers:

- The three tillage-residue systems created different surface soil conditions. The no-till system had a larger average aggregate size, higher water stability of aggregates and higher organic matter content compared with the tilled treatments. This occurred despite naturally high values of these properties in this soil.

- From a consideration of residue cover, surface roughness, organic matter content, aggregate size distribution, water-stability of aggregates, infiltration characteristics and hydraulic conductivity, etc., the no till+straw system is expected to provide a more effective and sustained runoff and erosion (wind and water) control than the tilled treatments. The tillage+no straw system, on the other hand, seems to have greatest susceptibility to surface crusting and erosion.

- The till+straw system was generally intermediate to the other two treatments in the values of the surface characteristics.

- Treatment effects on soil bulk density (Db) were confined mostly to surface 10-cm depth, but soil penetration resistance (PR) was affected to the lowest monitored depth of 45 cm. Both Db and PR exhibited considerable temporal and positional variation. No tillage-induced or pedogenically compacted soil layer was detected.

- Average Db and PR were higher in the uppermost 10 cm of the no-till treatment compared with the tilled treatments. In the subsoil, PR was generally greatest in the till+no straw treatment.

- Pore-size distribution and soil water retention were affected by tillage treatments to a small extent only. Plant available water capacity of the 0-15-cm depth interval was the lowest in the no till+straw system; differences among treatments arose mainly from permanent wilting point (or residual porosity) rather than field capacity.

- Treatment effects on saturated hydraulic conductivity (0-7.5-cm depth) and infiltration rate were large, with the no till+straw treatment having the highest and till+no straw the lowest water transmissivity. Treatment differences in Ksat were small in the 7.5-15-cm soil layer. Infiltration rate showed some seasonal variation. Both the Philip and Kostiakov infiltration models fitted the measured data well.

- The soil water regime was affected by treatments to the lowest monitored depth of 100 cm. The till+no straw treatment was generally the driest at all depths. The no till+straw treatment had the highest water content in the 0-7.5-cm layer for most of the growing season. The two straw treatments were not generally different for 0-50 and 0-100-cm profile water storage.

- In the no till+straw treatment, seedling emergence and subsequent vegetative growth stages were delayed by several days. Shoot growth (seedling vigor, tiller density, plant height, green leaf area, shoot dry mass) was the best in the till+straw treatment in each study year and was generally poorer in the no till+straw.

- Total root mass and length in the 0-50-cm soil zone was not affected by the treatments; however, distribution of root mass and length with depth was somewhat affected. Root length density and specific root length in the 0-15-cm interval were greatest in till+no straw, suggesting relatively finer roots in this treatment.

- Grain yield was the lowest in the no till+straw treatment in both years. The trends in the other two treatments were different in the two years. Crop water use was not much affected by treatments; thus grain water use efficiency followed the trends in grain yield.

- Overall, the till+straw system seemed better than the other treatments from a crop production point of view, even though no till+straw treatment was the best from a soil and water conservation perspective.

7.6 Some future research efforts

Reasons of lower yield in the no till+straw system, particularly the soil fertility aspects, need to be further explored, so that remedial measures be evolved to achieve yields comparable to those in the tilled systems.

The soil and ambient environments during early crop growth need to be monitored in greater detail since early differences in crop growth seem to be carried over to the later stages.

Criteria need to be developed/improved for evaluating the suitability of soil structure (i.e. aggregate size distribution) produced by different tillage practices for plant growth (different crop species) as well as for erosion control. If the entire aggregate size distribution can be incorporated into a single index, then suitability of different management practices under different soil and agroclimatic conditions can be more effectively assessed.

More work needs to be done on developing and testing critical limits of bulk density and penetration resistance for root (and possibly shoot) growth of different crops under different soil and environment conditions. Soil conditions which can be considered include soil water, texture, structure, initial bulk density, soil mineralogy, etc. Wet bulk density may better represent tillage-induced changes in soil conditions because it combines both dry bulk density and soil water content.

Mathematical relations to relate crop yield with various soil physical properties which are modified by tillage-residue systems need to be developed in order to quantify the contribution of each in determining the yield. This approach might help in determining which of the soil parameters are more important to measure in order to explain tillage-induced changes in the soil environment and resultant crop growth.

More emphasis should be placed on field measurement of hydraulic conductivity since due to a large heterogeneity of pores (i.e. horizontal vs. vertical) in the field, core-measured values may not be that realistic.

Earthworm activity (population and number of biopores) needs to be investigated further in order to explain differences in soil water conduction. Macroporous flow seems to contribute largely to water movement in the untilled soil. Also continuity of pores should be studied.

Higher water retention at -1500 kPa in surface soil of the no-till treatment needs further examination. Soil water retention characteristics as affected by organic matter content should be studied.

Research efforts are required to investigate further the reasons of why bulk density does not change over the winter period despite freeze-thaw cycles in this region.

Evapotranspiration should be partitioned into its components in order to calculate transpiration or plant water uptake. It needs measured or predicted values of hydraulic conductivity as a function of soil water content or potential.

The study indicated that there can be some drainage losses beyond the root zone in case of intense rainfall. It is essential to estimate the drainage component in order to compute accurately the crop water use.

Although a large number of physical factors of the soil environment were measured in this study, the crop response to the studied tillage-residue systems could be only partially explained. The fertility and biological aspects of soil environment, which are also modified by the studied tillage systems, need to be integrated into the soil physical aspects for a thorough understanding of the system behavior. This should be done both through an experimental and a simulation approach.

The viability of different tillage-residue practices should be evaluated from both a soil conservation and a crop production point of view.

7.7 References

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