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SOIL WATER AND TEMPERATURE REGIMES IN WINTER WHEAT AS AFFECTED BY CROP ROTATION, TILLAGE AND ROW SPACING

by

Tusheng Ren ©

A thesis submitted to the Faculty of Graduate Studies and Research in partial
fulfillment of the requirements of the degree of Doctor of Philosophy

in

Soil Science

Department of Renewable Resources

Edmonton, Alberta

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ABSTRACT

An integrated management system is vital for successful winter-wheat (*Triticum aestivum* L.) production in the semi-arid Canadian prairies. A 2-y study (1993/94 - 1994/95) was conducted at the Lethbridge Research Centre on a sandy clay loam Dark Brown Chernozem to evaluate the influence of crop rotation, tillage system, and row spacing on soil water and temperature. Winter-wheat performance was also evaluated. The study used plots established in 1984 following a split-split plot design. Treatments studied included combinations of three crop rotations (continuous winter wheat [WW], winter wheat - canola [WC], and winter wheat - fallow [WF]), two tillage systems (conventional [CT] and zero [ZT]), and two row configurations (uniform [UR] and paired [PR]).

Soil water conditions related largely to precipitation patterns and cropping sequence. During the over winter period beginning immediately after seeding, water content decreased on WF plots but partially increased on WC and WW plots. By spring, however, the WF rotation consistently had 40-70 mm more water to 1.5-m depth than the WW and WC rotations. In the WF rotation, ZT conserved more water than CT. The WF rotation generally had warmer soil temperatures during winter but cooler in early spring than those in continuously-cropped rotations. In all crop rotations, ZT soil temperatures were lower than those under CT but recovered later in the growing season. Soil temperature variations related more to crop-residue cover and soil-water content than to soil thermal properties. Row configuration had a minor influence on soil water and temperature.

Crop growth and yield correlated closely with fall soil water content to 1.5 m. In conclusion: a) summer fallow is a viable option in winter-wheat rotations for increasing water reserves, b) continuous winter wheat induced heavy infestations of downy brome and led, in turn, to reduced crop growth, c) a 3-y rotation (fallow - winter wheat - canola) may be the best combination for winter wheat in semi-arid southern Alberta, d) ZT succeeded when weeds could be controlled effectively and economically, e) except under winter wheat after canola, paired-row seeding should not be used in combination with ZT.

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CHAPTER 1

GENERAL INTRODUCTION

Winter wheat (*Triticum aestivum* L.) production in the semi-arid Canadian prairies is limited by low and variable precipitation. Traditionally, summerfallow has been practiced to increase soil water and therefore stabilize crop yield. Summerfallow, however, is very inefficient in storing summer precipitation and often leads to soil erosion, salinity and degradation (de Jong and Steppuhn, 1983). Continuous cropping, therefore, is often recommended to take advantage of seasonal soil water and provide effective erosion control. Lindwall et al. (1995) found that winter wheat in a wheat-barley-fallow rotation yielded on average 4% higher than in the wheat-fallow rotation, while soil water reserves to 1.5-m depth fell to 61% of that under the wheat-fallow rotation. With continuous winter wheat, however, the winter annual grassy weed downy brome (*Bromus tectorum* L.) may become a severe problem within a few years (Blackshaw et al., 1994). As a result, efforts are being made to diversify crop rotations to include annual crops like canola (*Brassica campestris* L.) and flax (*Linum usitatissimum* L.) (Larney and Lindwall 1994, 1995). These crops compete well against downy brome and benefit from the reduction of annual broad-leaved weeds and wild oats following winter wheat.

Soil erosion remains a dominant threat to the long-term sustainability of farming. Conservation tillage is seen by many as one of the few options farmers in western Canada have to assure the long-term sustainability and economic viability of their operations. With the availability of cost-effective herbicides, conservation tillage systems offer the potential for eliminating or reducing the length of the highly inefficient, long fallow periods frequently used in the Canadian Prairies. It has been shown that the benefits of winter wheat in crop rotation can be enhanced with conservation tillage which maintains more crop residue on the soil surface and conserves more available soil water in the root zone (Lindwall and Anderson, 1981; Lafond et al., 1992; Izaurralde et al., 1994; Larney and Lindwall, 1995; Lindwall et al., 1995). Successful adoption of conservation tillage cropping systems, even for a very limited area in Western Canada, has demonstrated that many soils need little, if any, tillage to be productive (Foster and Lindwall, 1986).

Effective seeding is one of the most critical aspects to consider in developing successful systems of conservation tillage. One such system, paired-row seeding, involves the placing of seeds in pairs of rows spaced 10 to 18 cm apart with a spacing of 33 to 40 cm between the next pair instead of the conventional 17 to 20 cm uniform row spacing. Some researchers reported yield advantages and substantial reductions in erosion with paired-row seeding (Krall et al., 1979; Papendick, 1985). Others, however, indicated no agronomic advantage for spring wheat in dryland sites (Benson et al., 1990; Kushnak et al., 1992; Cutforth and Selles, 1992; Larney and Lindwall, 1994). It has been hypothesized that the apparent contradictory findings are due to a poor understanding of the interactive effects of crop, tillage and seeder type on water conservation and crop production.

Successful crop production, regardless of the methods used, requires a careful assembling of numerous components (e.g., rotation, tillage, seeding equipment) into an integrated system (Lindwall et al., 1995). Considerable knowledge gaps still exist today in the understanding on how these systems function. Therefore, in order to advance the knowledge and use of conservation cropping in the semi-arid Canadian prairies, further studies are needed to understand the interactive effects of crop rotation, tillage method, and row configuration.

Soil water dynamics are the result of many soil properties and processes. Soil temperature not only plays an important role in controlling water exchange near the soil surface (e.g., evaporation) but also liquid and vapor movement through the soil profile. Lower soil temperatures decrease the availability of soil water and nutrients to plants and reduce plant root vigor (de Jong and Rennie, 1967). Management practices can be implemented to modify soil water and thermal conditions in order to create a favorable environment for crop growth.

Soil water and temperature regimes are strongly influenced by their spatial and temporal variations. Contradictory results on the effects of management practices on soil properties, especially near the soil surface, have often been reported from comparisons of one-time measurements of dynamic properties (Dao, 1993). It would be misleading, therefore, to attempt to explain the effects of tillage and residue cover on a particular chemical or biological process from only a few observations of maximum and minimum soil temperatures (Gupta et al., 1983).

The objective of this study was to increase the understanding of soil temperature and water regimes under various crop rotation, tillage and row spacing treatments. Such knowledge, especially if mechanistic, would provide a basis for the development of more effective land management systems for successful winter wheat production in the semi-arid Canadian prairies. This dissertation discusses the results from four separate but related studies conducted in the field or laboratory from 1993 to 1995 during winter wheat growing seasons.

Chapter 2, 'Soil water regimes in various crop rotation and tillage systems with different row spacings', compares the overwinter water recharge and spring soil water dynamics between a winter wheat-fallow rotation and continuous cropped rotations and between conventional and zero tillage practices. Influences of row spacing and weather condition on the performance of the crop rotation and tillage treatments are also evaluated.

Chapter 3, 'Soil temperature regimes in various crop rotations and tillage systems with different row spacings', reports the results of seasonal and daily soil temperature variations with different treatments. The relative importance of crop residue, snow depth and soil water conditions on the soil thermal environment at various crop growth stages is discussed.

Chapter 4, 'Modification of soil thermal properties by long-term crop rotation and tillage systems', presents the results of calculated and measured thermal properties of soil as affected by different crop rotation and tillage treatments. Variation of the thermal properties as functions of soil water content, bulk density and water retention characteristics are also discussed.

Chapter 5, 'Influence of crop rotation, tillage and row spacing on winter wheat performance', summarizes the effects of crop rotation, tillage and row spacing on the rate of emergence, early crop growth and final yield. The discussion includes the possible implications of these results to the design and application of new crop rotation and tillage systems.

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CHAPTER 2

SOIL WATER REGIMES IN VARIOUS CROP ROTATION AND TILLAGE SYSTEMS WITH DIFFERENT ROW SPACINGS

2.1 INTRODUCTION

Winter wheat (*Triticum aestivum* L.) production in the semi-arid Canadian prairies is limited by low and variable precipitation. Summerfallow is traditionally practiced to increase soil water content and therefore stabilize crop yield. However, research has shown that the favorable yields on summerfallow land are frequently attributed to the higher available N supply rather than the difference in moisture reserve (Johnson, 1983). In addition, summerfallow has proved to be inefficient in storing summer precipitation and is often advanced as a major cause of soil erosion, salinity and degradation (de Jong and Steppuhn, 1983). Continuous cropping, therefore, is recommended to take greater advantage of seasonal soil water and provide effective erosion control. With continuous winter wheat, however, the winter annual grassy weed downy brome (*Bromus tectorum* L.) may become a severe problem after a few years of continuous cropping (Blackshaw et al. 1994). Consequently, efforts are being made to diversify crop rotations to include annual crops like Polish canola (*Brassica campestris* L.) and flax (*Linum usitatissimum* L.) in the system (Larney and Lindwall 1994, 1995). These crops compete well against downy brome and benefit from the reduction of annual broad-leaved weeds and wild oats following winter wheat.

A question then arises: is available soil water adequate for continuous cropping? Lindwall et al. (1995) found that crop yield and soil water content were significantly lower in continuous winter wheat than in winter wheat-fallow rotation, but reducing the fallow frequency from 50 to 33% (winter wheat-fallow vs. winter wheat-barley-fallow) had a negligible effect on total water reserves. Studies by Larney and Lindwall (1994, 1995) indicated that rotating winter wheat with canola and flax is feasible, provided these crops can be successfully established. Continuous cropping of spring wheat at Lethbridge resulted in 69 mm less available soil water to 120-cm depth at seeding time (Chang et al., 1990). A review by Campbell et al. (1990) concluded that summerfallow continues to play a significant role in the Brown and Dark Brown soils because of unpredictable and variable precipitation. However, its frequency of use has decreased as producers reduce their dependency of mechanical tillage in favor of herbicides for weed control.

Conservation tillage can increase soil water content by (i) increasing infiltration and reducing runoff; (ii) reducing evaporation loss and (iii) trapping and holding snow (McCalla and Army, 1961; Unger and Phillips. 1973; Unger and McCalla, 1980; Smika and Unger, 1986). However, the magnitude of the effect depends on amount of residue cover, infiltration rate of the soil, water storage capacity of the soil and evaporation potential of the climate (Prasad and

Power, 1991) and is closely related to cropping systems and crop rotations, fallow length and types (Unger and Phillips, 1973). On the Canadian Prairies, conservation tillage effects on winter wheat have not been studied thoroughly. Lindwall and Anderson (1981) showed that advantages of winter wheat could be enhanced with zero tillage which was most beneficial when precipitation at fall planting was below normal (Lindwall et al., 1995). Carefoot et al. (1990) observed higher total soil water (0-120 cm depth) and grain yield with zero tillage than with conventional tillage due to increased snow trapping and/or reduced evaporation with zero tillage in the spring. However, Larney and Lindwall (1995) indicated that zero tillage gave higher available water only in the 0 to 15 cm depth during the spring time, and had no effect on precipitation storage efficiency during the fallow year. In central Alberta, Izaurralde et al. (1994) found soil water changes were more closely associated with the kind of crop grown than with the method of tillage used.

Effective seeding is one of the most critical aspects of successful conservation tillage crop production. Paired-row seeding involves placing the seed in pairs of rows spaced 10-18 cm apart with a space of 33-40 cm between the next pair instead of the conventional 17-20 cm uniform row spacing. Some research has shown yield advantages and substantial reductions in erosion with paired-row seeding (Lindwall and Anderson, 1977; Krall et al., 1979; Papendick et al., 1985; Tanaka and Aase, 1987). Other research indicated no agronomic advantage in dryland sites for spring wheat (Benson et al. 1990; Kushnak et al.

1992; Cutforth and Selles, 1992) or winter wheat (Larney and Lindwall, 1994). An important reason for the conflicting findings is the lack of information on the interaction effect of crop, tillage and seeder on soil water regimes.

Successful crop production, regardless of the methods used, requires a careful combination of numerous components (e.g., rotation, tillage, seeding equipment) into an integrated system (Lindwall, et al., 1995). Considerable gaps still exist in the current knowledge of how to manage the system effectively for more efficient soil water conservation and crop production. Furthermore, soil water is characterized by spatial and temporal variations. It may be misleading to explain the effects of crop rotation and tillage on crop growth and production based on only a few measurements of soil water content over time. Therefore, the objectives of this study were: (i) to compare the soil water regimes under different crop rotations and evaluate the feasibility of alternative crop rotations to the winter wheat-fallow; (ii) to investigate the performance of zero tillage and associated row spacing in improving soil water content under different crop rotations and therefore (iii) to provide additional information for the development of more effective land management systems for winter wheat production in the semi-arid Canadian prairies.

2.2 MATERIALS AND METHODS

The study was conducted on winter wheat during the 1993/94 and 1994/95 growing seasons on a Dark Brown Chernozemic soil (Typic Haploboroll) near the Agriculture and Agri-Food Canada Research Center, Lethbridge, Alberta (49°42'N, 112°47'W, elevation 915m). The Ap soil horizon is a sandy clay loam with 34% sand and 38% clay. Organic carbon content is approximately 1.9% in the 0 to 20 cm depth intervals. The mean annual precipitation and pan evaporation are 402 mm and 1192 mm, respectively.

The experiment was established in 1984 as a split-split-plot design (Fig. 2-1). The main treatment was crop rotation, including continuous winter wheat (WW), winter wheat-canola (*Brassica napus*) (WC) and winter wheat-fallow (WF). Winter wheat was seeded in the fall and canola in the spring. The fallow period on the WF rotation has a duration of 13 to 14 months. More details for the management practices are given in Table 2-1.

The sub-treatments were conventional tillage (CT) and zero-tillage (ZT). For CT, the seedbed was prepared with one pass of a tandem disc (10-12 cm working depth), followed by a rodweeder and packers. A rodweeder consists of a horizontally rotating rod operating 5 to 8 cm below the soil surface that pulls or cuts off weeds with minimum surface disturbance. In the fallow phase of the WF rotation, tillage consists of an initial pass of a wide-blade cultivator (6-9 cm depth) followed by a heavy-duty cultivator as required (normally two or three passes in the season) to control weeds. The ZT plots were direct-seeded and herbicides (glyphosate, paraquat, bromoxynil/MCPA and glyphosate/2,4-D) were used at recommended rates.

The sub-sub treatment was row spacing that included uniform-row (UR) and paired-row (PR) seeding. The UR configuration was accomplished by using a conventional high clearance hoe drill with openers 20-cm apart, the PR configuration required the use of a disc drill that had paired openers 13-cm apart with 38-cm between each pair (Fig. 2-2).

During the establishment of winter wheat in the fall and when the plants were actively growing in the spring, gravimetric soil water was determined in four replications in 15-cm increments to a 1.5-m depth using a truck-mounted 2.5-cm diameter, hydraulically-driven sample tube for the crop rotation and tillage treatments (Larney and Lindwall, 1995). Soil water data were converted to a volumetric basis using bulk densities of soil cores taken from six soil profiles on the study sites (Beke, 1989).

In the springtime, volumetric soil water contents were measured in two replications at 5, 10, 20, and 40 cm depths, both at the inter-row and intra-row positions (Fig. 2-2) with a time-domain reflectometry (TDR) instrument (Model 1502C, Tektronix, Beaverton, OR). The TDR probes were installed in the fall soon after winter wheat was seeded. Soil pits (15 cm by 50 cm) were carefully excavated with soil horizons kept separate for backfill. A wooden template with pre-drilled holes was used to mark the positions and depths for the insertion of TDR probes. The TDR probes were then inserted horizontally into the undisturbed soil. Finally, the soil pits were carefully backfilled and displaced residue placed back on the soil surface. Soil water measurements were made twice a day in 1994 and daily in 1995 since no significant difference was found between the two daily measurements in 1994.

The TDR instrument was calibrated in the laboratory. Soil taken from the study site was air dried at room temperature, passed through a 2-mm sieve, and packed uniformly into eight PVC cylinders (10 cm diam. by 30 cm deep) with a bulk density of 1.33 Mg m^{-3}. The soil was moistened to various water contents (dryness to saturation) with an increment of 0.03 m^3 m^{-3}. With each increment of soil water content, TDR measurements were made and the soil and the cylinder were weighted. Finally the apparent dielectric constants (K_a) were calculated and a relationship between soil water content (θ, m^3 m^{-3}) and K_a was established as,

$$\theta = -9.67 \times 10^{-2} + 5.05 \times 10^{-2} K_a - 2.38 \times 10^{-3} K_a^{\,2} + 5.08 \times 10^{-5} K_a^{\,3} \qquad (1)$$

Soil water retention curves were determined at four depth increments: 0 to 5, 5 to 10, 10 to 15, and 15 to 20 cm. For each depth increment, four undisturbed core samples (3.0 cm high and 5.5 cm diam.) were taken manually for each tillage treatment in the paired-row configuration. The soil water retention curves were determined for these cores in the laboratory using the pressure plate method (Klute, 1986) at pressures of 0.003, 0.005, 0.01, 0.03, 0.05, 0.1, 0.5, and 1.5 MPa.

Crop residue left on the soil surface was collected in a 1-m^2 area in two replications for each of the row spacing treatments during the springtime. Dry weights of loose and upright residue were determined separately in the laboratory.

For statistical analysis, means of soil water measurements at each depth were calculated for each replication. Analysis of variance was performed on the measured soil properties by using the General Linear Model (GLM) procedure in SAS (SAS Institute, 1990). Fisher's protected least significant difference method (Steel and Torrie, 1980) was used for comparison of means.

2.3 RESULTS AND DISCUSSION

2.3.1 Meteorological and Soil Surface Conditions

Weather conditions of the two study years were quite different (Fig. 2-3). Precipitation amounted to 356 mm during the growing season of winter wheat from September 1993 to July 1994, a value close to the long term normal of 360 mm. During the September-November period, inclusive, in 1993, 101 mm precipitation fell, or 25% more than long term mean. Precipitation during the period of April to June 1994 was 175 mm, 10% higher than normal. Air temperature in the 1993/94 growing season was close to the long term average. It was therefore concluded that the 1993/94 season was quite favorable for the growth and development of winter wheat.

Although the 1994/95 growing season had 470 mm precipitation, or 30% more than the long term average, the distribution of precipitation in the season was not uniform. Precipitation was higher than normal in October (58 vs. 22 mm) and was close to normal in November (20 vs. 19 mm) 1994. Monthly air temperature was 1.3 to 3.7 °C higher than normal from December 1994 to February 1995 and precipitation in the same period was only 29 mm or 38% of normal. On the other hand, precipitation from April to July 1995 was 286 mm or 80% above normal, making it one of the wettest years on record. Monthly air temperature during the same period was 0.7 °C lower than normal.

The WC rotation with ZT had the highest quantity of residue cover followed by the WW rotation with ZT (Fig. 2-4). However, the former had a lower proportion of upright stubble. Surface crop residue under conventional tillage was similar for WC and WW rotations. In comparison with these rotations, the WF rotation had a smaller amount of crop residue cover under ZT and no crop residue cover under CT.

2.3.2 Water Retention Characteristics

At the 0 to 5 cm depth interval, the amount of water retained was generally lower on the WF rotation than the continuous-cropped rotations under both tillage systems (Fig. 2-5). At matric potentials from 0.3 to 15 MPa, for example, soil water content ranged from 0.19 to 0.27 $m^3 m^{-3}$ for the WF rotation, while it ranged from 0.22 to 0.35 $m^3 m^{-3}$ for the WW rotation. However, at the 10 to 15 cm depth interval, the WF rotation tended to have higher soil water under a given matric pressure than the WC and WW rotations, especially under zero tillage. Soil water retention differences between the WC and WW rotations were generally not significant.

Except for the WW rotation for the 5 to 10 cm depth interval, the CT treatment generally retained a higher amount of water at lower matric pressures but a lower amount of water at greater matric pressures than the ZT treatment. In the 0 to 5 cm depth interval, for example, the CT treatment had 0.06 $m^3 m^{-3}$ more water at 0.03 MPa than the ZT treatment but 0.02 $m^3 m^{-3}$ less at 15 MPa.

2.3.3 Soil Water Regime

2.3.3.1 Overwinter Period

Soil water to a 1.5-m depth was significantly reduced by shifting from fallow cropping to continuous cropping (Table 2-2). After winter wheat seeding in fall, the WF rotation had 70 and 120 mm more water than the continuous-cropped rotations in 1993 and 1994, respectively. The soil water advantages of fallow were also apparent at spring sampling when the WF plots had 40 and 70 mm more water reserves than the continuous-cropped rotations in 1994 and 1995, respectively. The WW rotation showed slightly higher water content than the WC rotation in the 0 to 1.5-m depth, but the differences were generally not statistically significant.

Overwinter change in soil water content as affected by crop rotation was related to soil water status in the fall (Table 2-2). In the 1993/94 season, for example, the WC and WW plots had 16 mm water recharge in the 0 to 1.5-m soil depth while the WF plots lost 12 mm water. The extremely dry soil condition enhanced soil water recharge in the 1994/95 overwinter period and 47 and 35 mm water was conserved on the WC and WW plots respectively. The water loss under WF was probably also related to the more vigorous winter wheat growth on the fallow plots (Larney and Lindwall, 1995).

Many studies on the semi-arid Canadian prairies have shown the benefits of zero tillage on soil water conservation with summerfallow. Lindwall and Anderson (1981) reported that available soil water (to 1.5 m) before seeding was up to 19% higher with ZT than with CT in a spring wheat-fallow rotation in southern Alberta. Tessier et al. (1990) reported that ZT conserved 8% more soil water than conventional fallow systems in Saskatchewan. Also in Saskatchewan, Lafond et al. (1992) found ZT increased soil water (to 1.2 m) by 6% over CT for stubble cropping and by 4% for fallow. They concluded that with the adoption of conservation practices, fallow cropping could be eliminated without necessarily increasing production risks. However, Lindwall et al. (1995) showed that under three different crop rotations (continuous winter wheat, winter wheat-barley-fallow and winter wheat-fallow), the average soil water to 1.5-m was only 3% higher on ZT plots than on CT plots. Studies on continuous-cropped rotations in central and southern Alberta indicated that ZT had little impact on available soil water compared to crop rotation (Izaurralde et al. 1994; Larney and Lindwall, 1995).

This study demonstrated that tillage effects on soil water content under winter wheat varies with crop rotation, soil water status in fall and the time and amount of precipitation in fall and winter. ZT generally prevented soil water from evaporative loss during the 1993/94 overwinter period when greater than normal precipitation was received in fall and winter. Under WF rotation, for example, significantly higher water content was recorded on the CT plots than on the ZT plots after winter wheat seeding (Fig. 2-6). During the overwinter period, however, the CT plots lost 28 mm (6%) water while the ZT plots had a small water recharge. Consequently, winter wheat under the two tillage systems showed similar water contents at spring sampling. Under the WW rotation, there was a 43 mm (11%) water increase on the ZT plots and a 10 mm water loss on the CT plots from fall to spring sampling. Accordingly, total water content to a 1.5-m depth was significantly higher on ZT plots than on CT plots under WW in the spring. The higher water content for CT compared to ZT with WF at fall sampling was probably because the soil under CT plots could hold more water than under ZT at lower matric pressures (Fig. 2-5).

Under the dry conditions of the 1994/95 season, large amounts of soil water were extracted by preceding winter wheat and canola crops on the continuous-cropped plots and consequently any benefits of ZT in soil water conservation were not evident at fall sampling (Fig. 2-6). On the WF rotation, however, the ZT plots had 73 mm (17%) more water to 1.5-m soil depth than the CT plots. Although water content on average was significantly higher on ZT than on CT at spring sampling (Table 2-2), the differences between CT and ZT for individual crop rotation followed a similar pattern to that at fall sampling (Fig. 2-6), indicating that overwinter water recharge was not significantly improved by ZT under the dry winter conditions in the 1994/95 season.

Therefore, it can be concluded that the advantages of ZT on overwinter water content are generally decreased with increasing cropping frequency. With above-normal precipitation in fall and winter, water conservation by ZT on continuous-cropped rotations can be as effective as on fallow cropping. Under dry conditions, however, ZT performs better than CT only on fallow cropping.

In the chinook-dominated area of southern Alberta, overwinter water recharge of soil depends on the infiltration of precipitation during the unfrozen period and moving up of water from deeper profiles to the freezing front (McGinn et al., 1994). In the 1993/94 season, infiltration of precipitation during the unfrozen period played an important role in the recharging process, as indicated by the increases of water contents in most of the soil profiles under ZT (Fig. 2-7). Soil water contents were increased at depths above 80 cm but decreased at depths below 80 cm in the 1994/95 overwinter period (Fig. 2-8). Thus, water deeper in the soil profiles could have been drawn to the freezing front.

2.3.3.2 Spring Period

Crop rotation had the greatest effect on soil water regimes in spring. As shown in Fig. 2-9, the WF rotation consistently showed higher soil water content than the continuous-cropped systems in the 0 to 40-cm depth, under both tillage systems and row spacing treatments in 1994. In early April when the soil was relatively dry, the difference was as high as 8 to 20 mm. The WC and WW rotations showed similar water contents, either under dry conditions or after rainfall events. In comparison with the UR treatment, the PR treatment had slightly more water. However, the influence of row spacing on soil water content was less than that of crop rotation. No significant difference was found between zero tillage and conventional tillage in total water content between 0 to 40 cm depth throughout the period.

Change in soil water content during and after a rainfall event was monitored to examine the effects of treatments on processes of soil water recharge and depletion. From May 17 to 21, 57.8 mm rainfall was received and soil water content in the 0 to 40 cm depth interval reached the highest level of the season. Soil water recharge during this period was linearly correlated to water content preceding the rain: the driest rotation treatment, WC, had the greatest gain and the wettest rotation treatment, WF, the least (Fig. 2-10). During the rainfall period, evaporation losses from all the plots could be assumed equal, transpiration losses on the WF plots were no less than on WC and WW plots since winter wheat on the WF plots had more vigorous early growth (Larney and Lindwall, 1994). Furthermore, there was no significant runoff during the rainfall period. This evidence would lead to the conclusion that there was more water at soil depths below 40 cm on the WF rotation than on the continuous-cropped rotations. This could be expected because the WF rotation had the highest soil water content preceding the rain (Figs. 2-10 and 2-11) and therefore higher unsaturated hydraulic conductivity than the WC and WW rotations during the early rainfall period. In comparison with crop rotation, tillage and row spacing treatments showed less influence on soil water recharge in the 0 to 40 cm depth interval (Tables 2-3 and 2-4).

Soil drying from May 21 to May 26 was not significantly affected by crop rotation or row spacing treatments (Tables 2-3 and 2-4). Tillage treatment effects were evident only at 5 cm on the WW rotation. The ZT treatment maintained the highest water content among all treatment combinations following the rain but lost more water than the CT treatment, possibly because of greater evaporation (Unger and Phillips, 1973) and/or deeper drainage from the 40-cm zone.

From May 26 to 31, soil water losses under CT were in the order of WC > WW >WF (Table 2-3). On May 26, for instance, soil water content of the WF plots was significantly higher than that of the WC and WW plots at 40 cm (Fig. 2-11). On May 31, the WF plots showed significantly higher water contents than the WC and WW plots at depths of 5, 10, and 40 cm. The differences were most likely due to the higher water content at soil depths below 20 cm on the WF plots and, therefore, evaporative water loss could have been compensated by the upward movement of water from deeper soil layers. Since the crop canopy had been well established at this stage, the ZT treatment did not show greater advantages over CT in reducing evaporation. As a result, soil water contents were approximately the same for both tillage treatments except that the CT plots showed higher water contents at 40 cm under the WF rotation (Fig. 2-11). The row spacing treatment did not significantly affect the soil drying process (Table 2-4). However, soil water content under PR was generally higher than that under UR at the four depths (Fig. 2-12), probably because of the poor canopy establishment with PR (Larney and Lindwall, 1994).

Differences in soil water between the treatments were generally not significant in the spring of 1995 because of above-normal precipitation. Later in the season, the WF and WW rotations were seriously infested by downy brome. Therefore, soil water dynamics in the spring of 1995 were not assessed.

2.4 SUMMARY AND CONCLUSIONS

Soil water conditions are more related to crop rotation than to tillage or row spacing for the soil and climate in southern Alberta. During the study period, the WF rotation contained 70 to 120 mm more water at fall seeding time and 40 to 70 mm more water in spring than the continuous-cropped rotations. During the overwinter period, however, water losses occurred on the WF plots while the WC and WW rotations was partially recharged. Soil water contents and overwinter recharge were similar for the WC and WW rotations. During the springtime, higher water contents on the WF plots enhanced movement of precipitation water to the deeper soil profiles.

Compared to conventional tillage, zero tillage generally retained more water at higher matric pressures and less water at higher matric pressures.

Under field conditions, however, tillage effects on soil water content under winter wheat varied with crop rotation, soil water status in fall and the time and amount of precipitation in fall and winter. The advantages of ZT over CT for water conservation were generally decreased with increasing cropping frequency but increased with improved soil water conditions. Under wet conditions (1993/94), water conservation with ZT on continuous-cropped rotations was as effective as on fallow cropping mainly because of increased infiltration and reduced evaporation. Under dry conditions (1994/95), ZT had 17% more water to a 1.5-m soil depth after winter wheat seeding in fall. This effect, however, was only observed with fallow cropping.

Although higher soil water contents were observed with PR seeding than with UR seeding, the differences were largely attributed to the poor canopy establishment on the PR plots. Appropriate seeding equipment with proper adjustment for seedbed conditions to obtain adequate stand establishment appeared to be a more important factor than row configuration.

In semi-arid southern Alberta, successful weed (e.g., downy brome) control is as important as soil water conservation and erosion control in determining appropriate management practices for winter wheat production. It appears that unless adequate chemical control of downy brome is achieved, having alternative crops (e.g., canola) in winter wheat rotations is vital. Also, maintaining fallow in the crop rotation with a reduced frequency (e.g., every third year rather than every second year) can reduce soil degradation, suppress weeds, give good erosion control, and help maintain more stable crop production. Zero tillage can be successfully used in winter wheat production for erosion control and improve water conservation. However, the benefits of zero tillage with respect to water conservation are very dependent on the precipitation patterns and potential confounding effects from weed infestation.

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Table 2-1. Selected management practices for winter wheat and canola during the study period.

Crop	Year	Variety	Seeding date	Harvest date	N	P_2O_5
					kg ha^{-1}	
Wheat	1993/94	AC Readymade	3 Oct	15 Aug	27b + 34c1	28b
Wheat	1994/95	AC Readymade	14 Sep	22-23 Aug	27b + 34c1	28b
Canola	1993/94	Tobin	4 May	10 Aug	9b + 34c2	40b
Canola	1994/95	Tobin	24 May	11 Sep	9b + 34c2	40b

b banding application at seeding time.

c1 broadcasting application in the following spring.

c2 broadcasting application before seeding.

Table 2-2. Total soil water to a 1.5-m depth in fall and spring during the study period.

Treatment	1993/94 Oct. 28	1993/94 Apr. 27	1993/94 Change	1994/95 Sep. 28	1994/95 Apr. 21	1994/95 Change
	mm					
Crop rotation						
WC	362 b	378 b	16 a	276 b	323 a	47 a
WF	443 a	431 a	-12 b	401 a	391 a	-10 b
WW	383 b	399 ab	16 a	292 b	327 a	35 a
Tillage						
CT	401 a	393 a	-8 a	309 a	327 b	18 a
ZT	391 a	413 a	22 a	337 a	367 a	30 a

† WC = winter wheat - canola, WF = winter wheat - fallow, WW = continuous winter wheat, CT = conventional tillage, and ZT = zero tillage.

‡ For a given treatment, means followed by the same letter in the same column within a treatment do not differ significantly at $P \leq 0.05$.

Table 2-3. Changes in volumetric soil water content under different crop rotation and tillage treatments from May 17 to 31, 1994.

Soil depth	Tillage	Crop Rotation	Change in soil water content		
			May 17-21	May 21-26	May 26-31
cm			%		
5	CT†	WC	9.6 ± 0.9a‡	-4.6 ± 0.6ab	-2.3 ± 0.3ab
		WF	5.0 ± 0.6b	-4.2 ± 0.5ab	-1.0 ± 0.3b
		WW	8.3 ± 0.7a	-3.1± 0.9b	-1.2 ± 0.5b
	ZT	WC	9.3 ± 0.5a	-5.5 ± 0.2a	-1.5 ± 0.5ab
		WF	5.3 ± 1.1b	-3.8 ± 0.7ab	-1.4 ± 0.4ab
		WW	8.0 ± 0.3a	-5.3 ± 0.6a	-2.8 ± 0.1a
10	CT	WC	7.3 ± 0.7a	-3.7 ± 0.4a	-2.5 ± 0.4ab
		WF	3.8 ± 0.5b	-3.6 ± 0.3a	-1.0 ± 0.3c
		WW	5.7 ± 0.6ab	-3.6 ± 0.5a	-1.4 ± 0.4bc
	ZT	WC	7.5 ± 0.6a	-4.6 ± 0.5a	-1.8 ± 0.2abc
		WF	4.3 ± 0.7b	-3.3 ± 0.5a	-1.5 ± 0.3abc
		WW	5.8 ± 0.2ab	-4.1 ± 0.4a	-2.7 ± 0.4a
20	CT	WC	6.9 ± 0.6a	-3.2 ± 0.3a	-2.9 ± 0.6a
		WF	3.0 ± 0.7d	-2.5 ± 0.4a	-1.1 ± 0.2c
		WW	5.4 ± 0.5b	-3.1 ± 0.4a	-1.7 ± 0.5b
	ZT	WC	6.0 ± 0.4ab	-2.7 ± 0.3a	-2.2 ± 0.2ab
		WF	3.8 ± 0.4cd	-2.4 ± 0.4a	-2.0 ± 0.4abc
		WW	4.2 ± 0.2c	-2.3 ± 0.1a	-1.6 ± 0.4b
40	CT	WC	4.9 ± 0.1a	-1.8 ± 0.4a	-2.1 ± 0.3a
		WF	2.6 ± 0.7b	-1.6 ± 0.5a	-0.3 ± 0.3c
		WW	3.6 ± 0.4b	-2.0 ± 0.3a	-0.8 ± 0.4b
	ZT	WC	4.4 ± 0.4a	-1.6 ± 0.1a	-1.7 ± 0.5ab
		WF	3.0 ± 0.0b	-2.0 ± 0.2a	-1.2 ± 0.1ab
		WW	3.5 ± 0.4b	-1.7 ± 0.2a	-1.2 ± 0.1ab

† WC = winter wheat - canola, WF = winter wheat - fallow, WW = continuous winter wheat, CT = conventional tillage, and ZT = zero tillage.

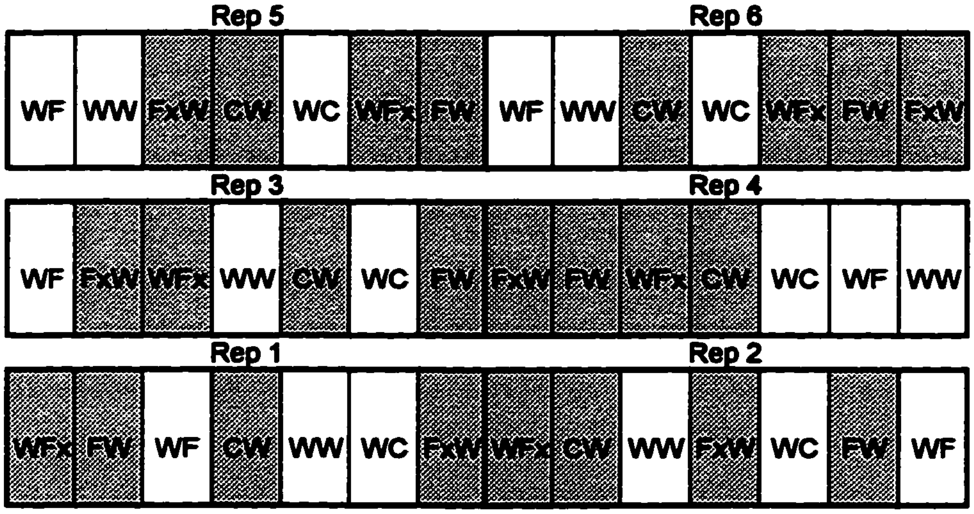
‡ Means followed by the same letter in the same column at a given depth do not differ significantly at P ≤ 0.05.

Table 2-4. Changes in volumetric soil water content under different crop rotation and row spacing treatments from May 17 to 31, 1994.

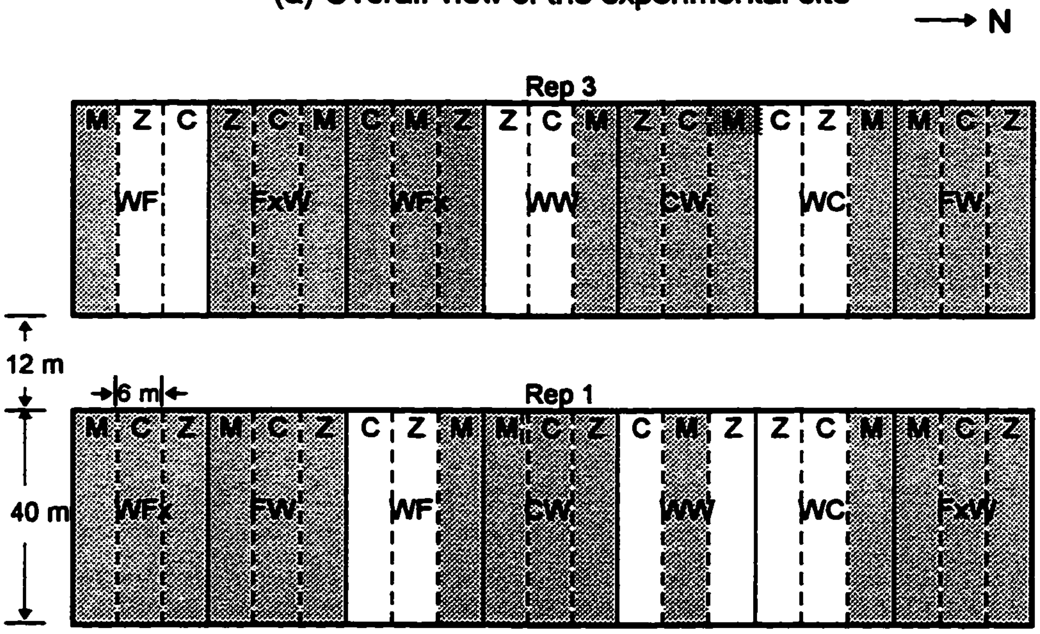
Soil depth	Row spacing	Crop Rotation	Change in soil water content		
			May 17-21	May 21-26	May 26-31
cm			%		
5	PR†	WC	8.7 ± 0.8a‡	4.4 ± 0.5a	2.3 ± 0.5a
		WF	5.7 ± 1.1b	4.3 ± 0.7a	1.2 ± 0.3a
		WW	7.9 ± 0.1a	3.7 ± 0.7a	1.8 ± 0.7a
	UR	WC	10.3 ± 0.2a	5.7 ± 0.3a	1.5 ± 0.4a
		WF	4.5 ± 0.1b	3.7 ± 0.4a	1.2 ± 0.4a
		WW	8.4 ± 0.7a	4.6 ± 1.1a	2.1 ± 0.3a
10	PR	WC	6.7 ± 0.4a	3.8 ± 0.4a	2.1 ± 0.4a
		WF	4.2 ± 0.8b	3.8 ± 0.5a	1.3 ± 0.4a
		WW	5.7 ± 0.3ab	3.8 ± 0.4a	1.8 ± 0.4a
	UR	WC	8.1 ± 0.5a	4.5 ± 0.6a	2.3 ± 0.4a
		WF	3.9 ± 0.5b	3.2 ± 0.2a	1.2 ± 0.2a
		WW	5.8 ± 0.6ab	3.9 ± 0.5a	2.3 ± 0.6a
20	PR	WC	5.8 ± 0.3b	2.7 ± 0.3a	2.2 ± 0.4a
		WF	3.8 ± 0.6cd	2.8 ± 0.4a	1.9 ± 0.5bc
		WW	4.3 ± 0.2c	2.4 ± 0.1a	1.0 ± 0.2c
	UR	WC	7.2 ± 0.5a	3.1 ± 0.4a	2.9 ± 0.5a
		WF	3.0 ± 0.7d	2.1 ± 0.2a	1.2 ± 0.1c
		WW	5.3 ± 0.6b	3.1 ± 0.4a	2.3 ± 0.3a
40	PR	WC	4.8 ± 0.4a	1.8 ± 0.3a	1.6 ± 0.5ab
		WF	2.8 ± 0.6b	2.0 ± 0.5a	0.5 ± 0.3b
		WW	3.8 ± 0.3ab	2.1 ± 0.4a	0.6 ± 0.2b
	UR	WC	4.5 ± 0.2a	1.5 ± 0.2a	2.3 ± 0.2a
		WF	2.8 ± 0.3b	1.5 ± 0.2a	1.0 ± 0.3b
		WW	3.4 ± 0.4b	1.7 ± 0.2a	1.3 ± 0.2ab

† WC = winter wheat - canola, WF = winter wheat - fallow, WW = continuous winter wheat, PR = paired-row, and UR = uniform-row.

‡ Means followed by the same letter in the same column at a given depth do not differ significantly at $P \leq 0.05$.



(a) Overall view of the experimental site



(b) Plots for installation of thermocouple and TDR probes

Fig. 2-1. Field layout of the experiment in 1994/95. Each tillage plot was split into paired-row seeding and uniform-row seeding. Shadowed plots were not included in the study.

WF = wheat-fallow
WC = wheat-canola
WFx = wheat-flax
WW = continuous wheat
M = minimum tillage

FW = fallow-wheat
CW = canola- wheat
FxW = flax-wheat
C = conventional tillage
Z = zero tillage

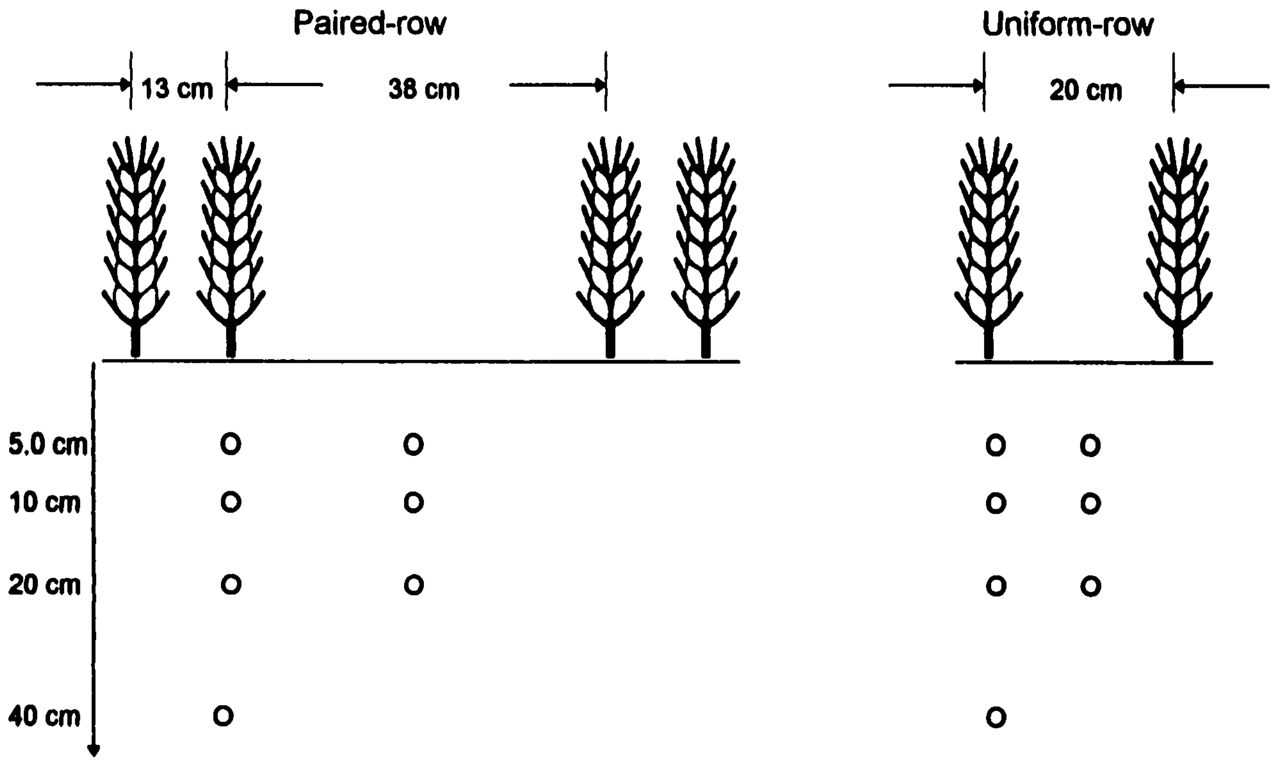


Fig. 2-2. Schematic view of the TDR moisture probe locations (o) in the soil profile.

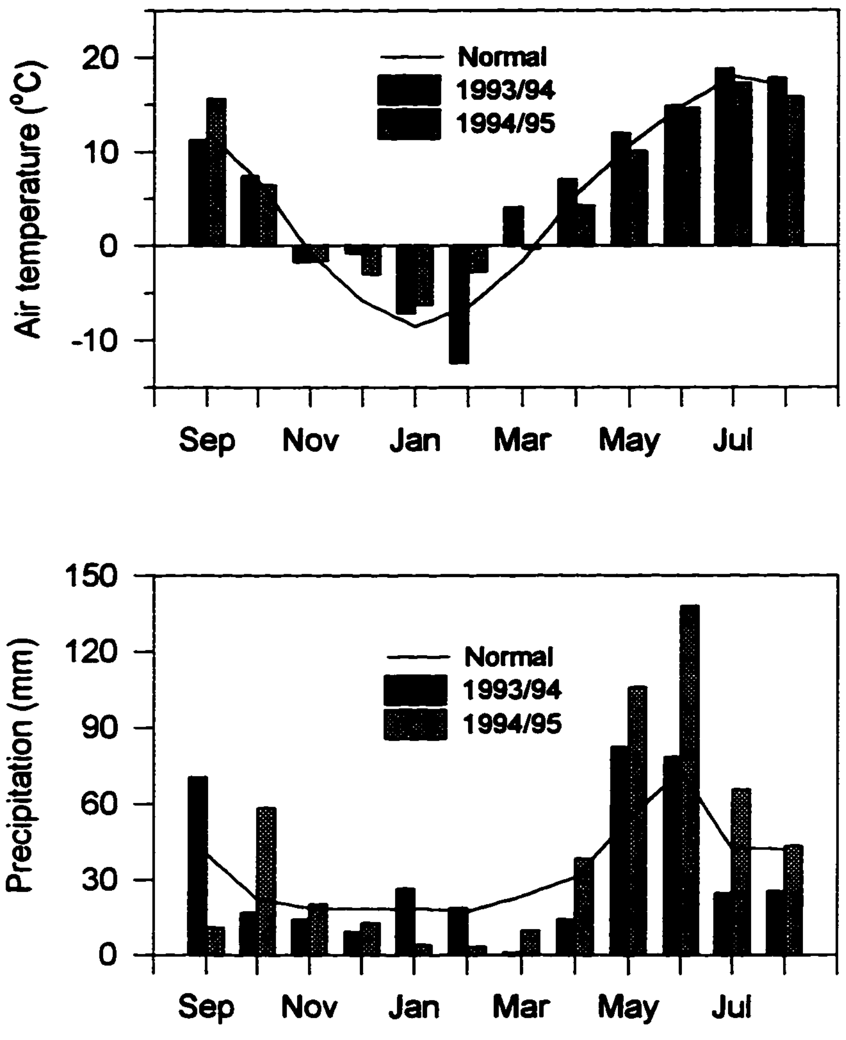


Fig. 2-3. Air temperature and precipitation during the study period, compared to the long term normal in Lethbridge.

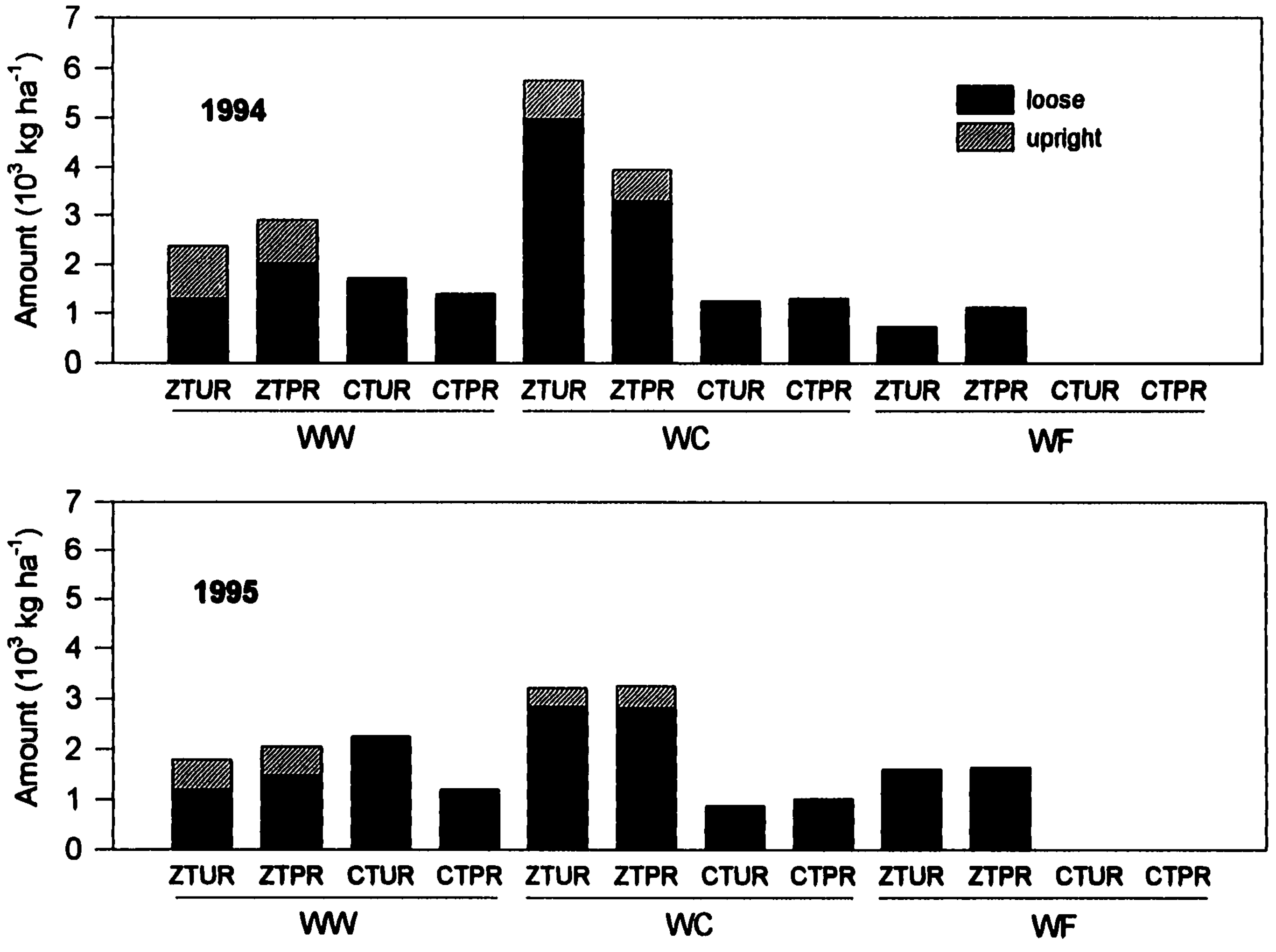


Fig. 2-4. Surface crop residue characteristics under various treatments in the springs of 1994 and 1995.

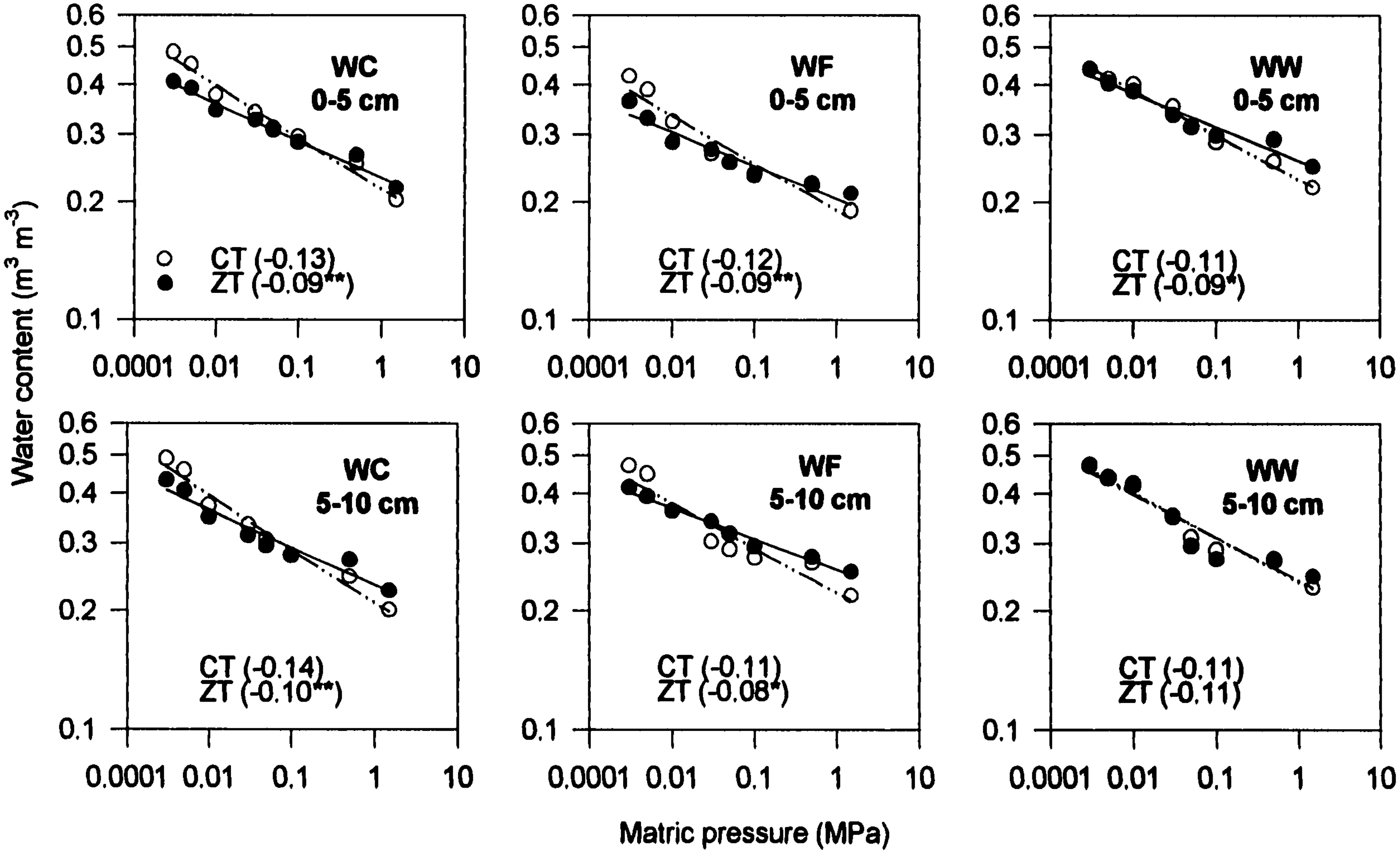


Fig. 2-5. Soil water retention characteristics under CT and ZT with various crop rotation treatments. Line slopes are in parentheses. *, ** Significant at 0.05 and 0.01 level, respectively.

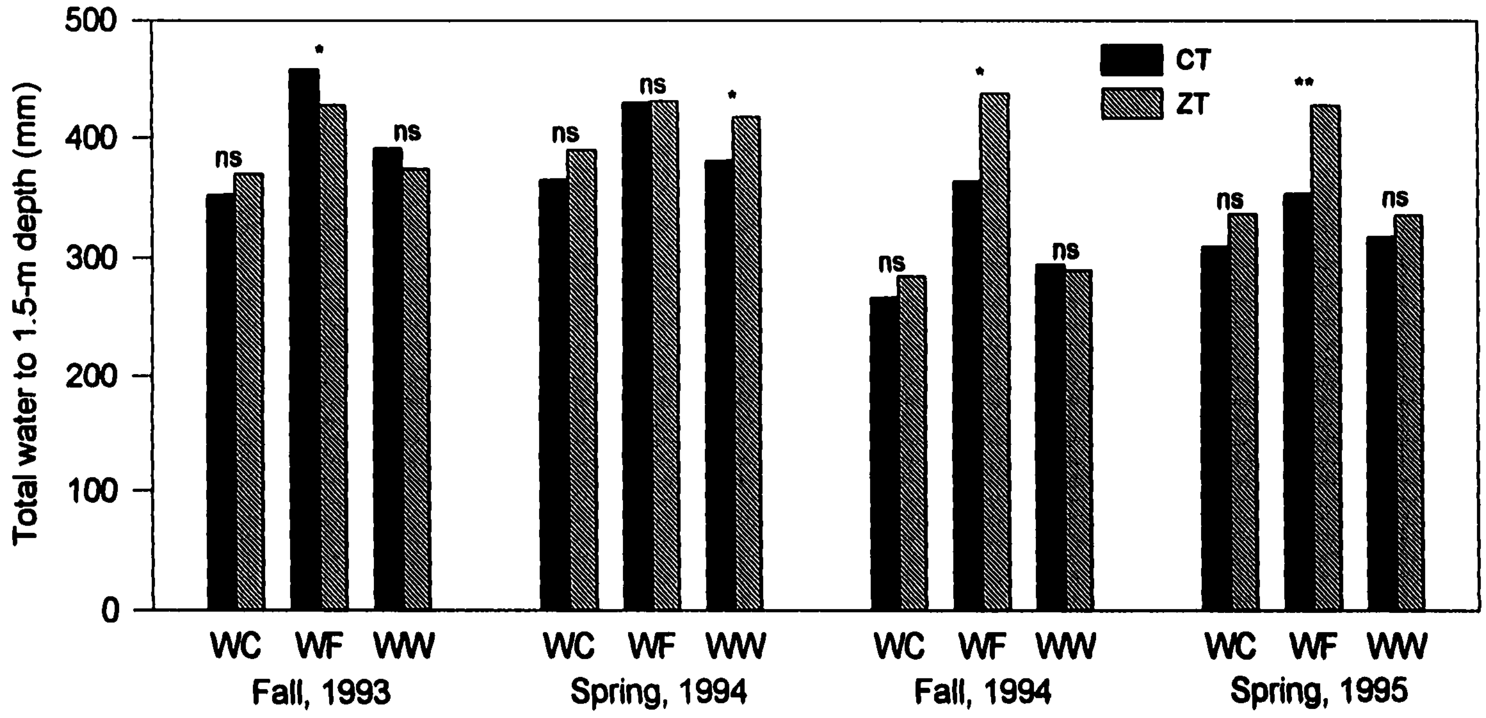


Fig. 2-6. Total soil water to 1.5-m depth as affected by tillage methods under various crop rotations for winter wheat in fall and spring. *, ** Significant at 0.1 and 0.01 level (within a rotation) respectively; ns = nonsignificant.

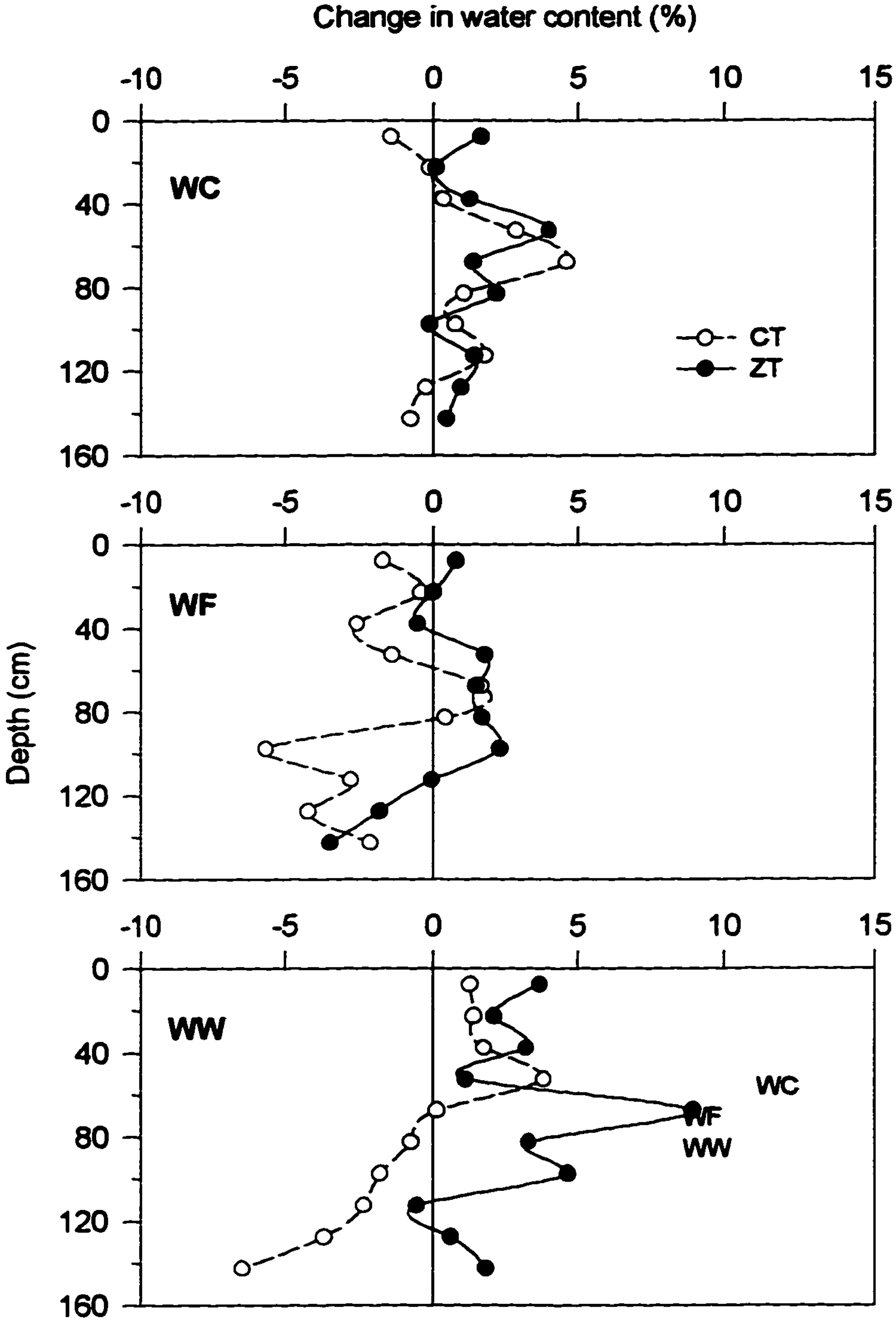


Fig. 2-7. Change in soil water content between Oct. 28, 1993 and Apr. 27, 1994.

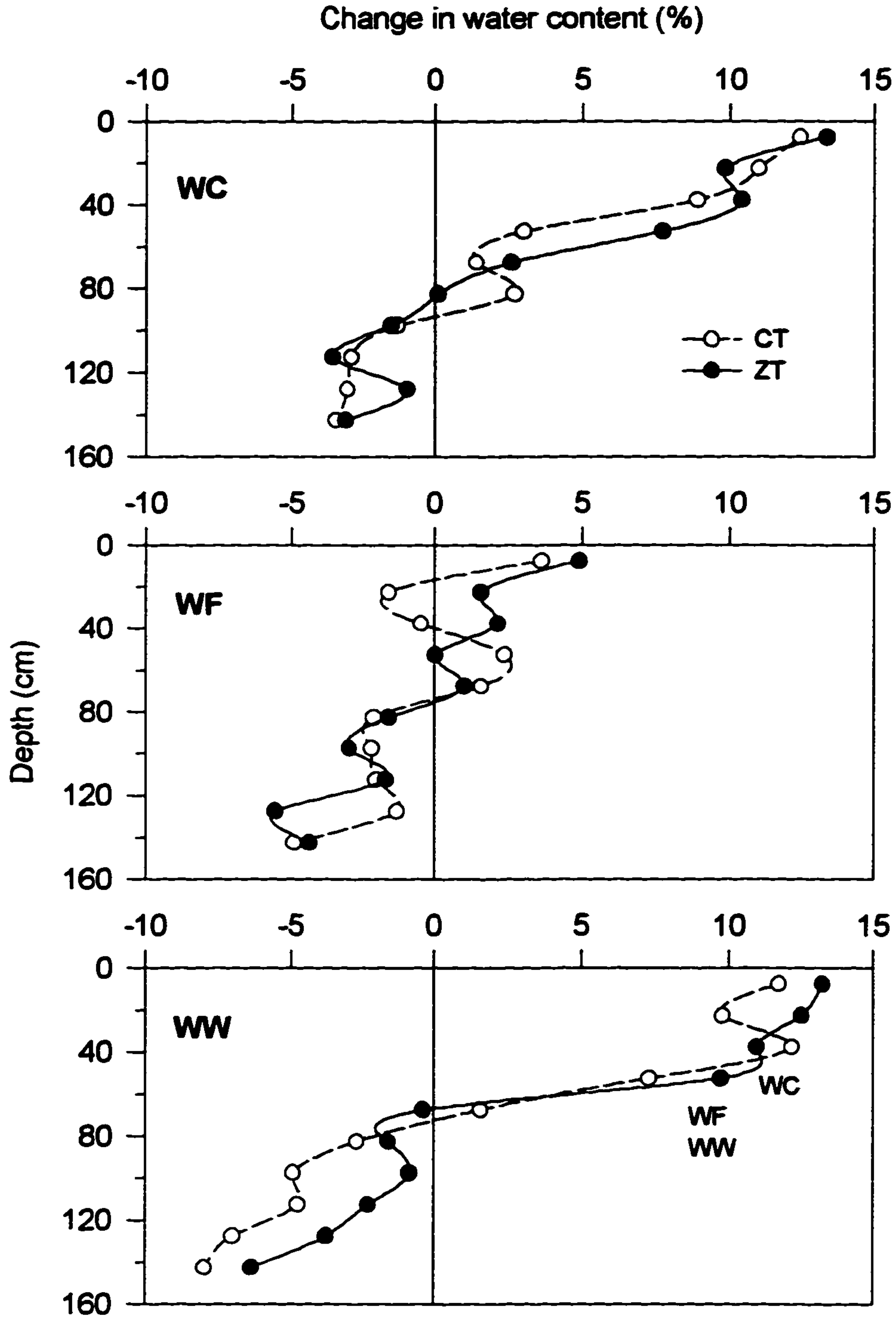


Fig. 2-8. Change in soil water content between Sep. 28, 1994 and Apr. 21, 1995.

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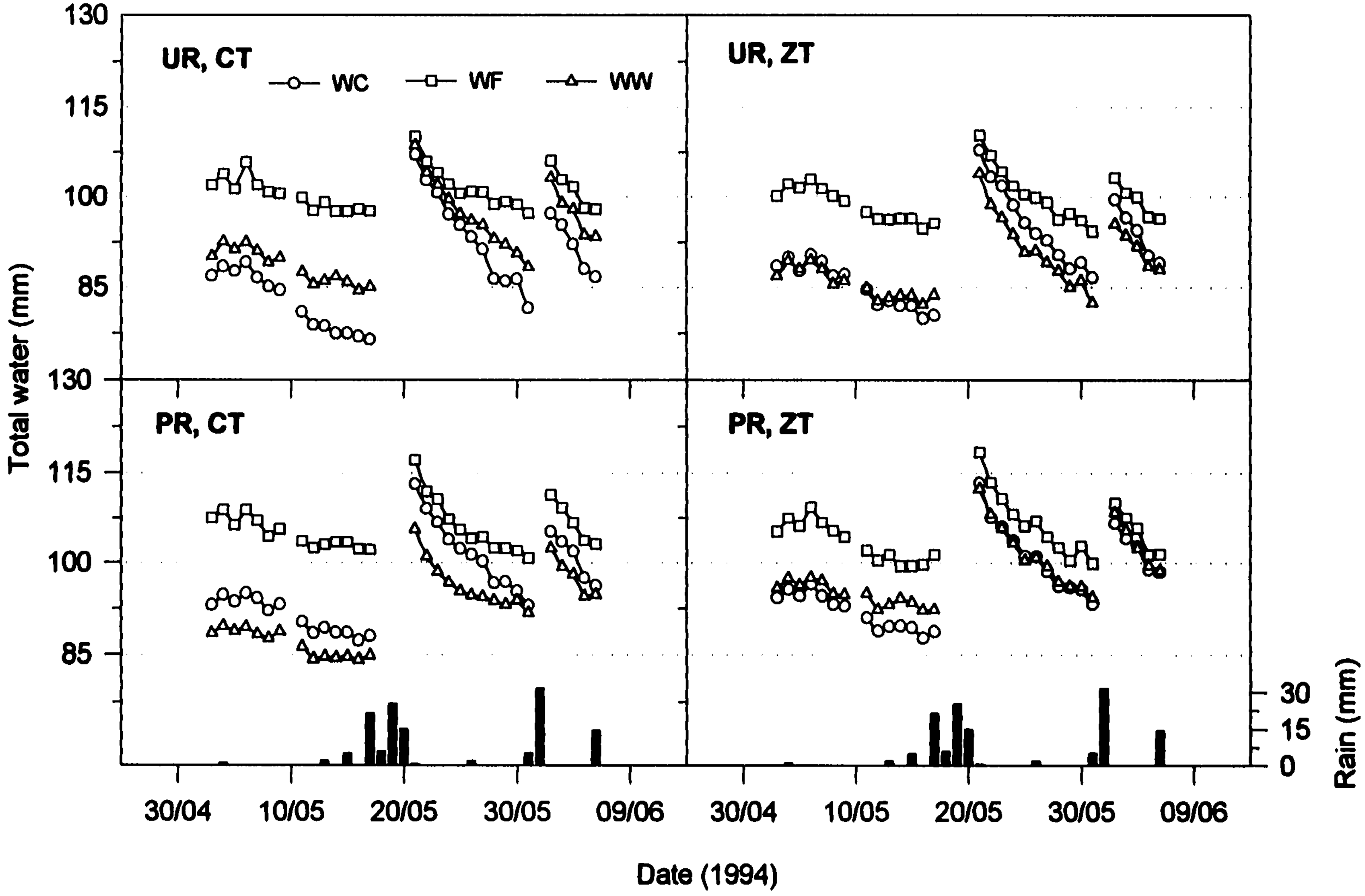

Fig. 2-9. Precipitation and total soil water in 0-40 cm under different treatments in the spring of 1994.

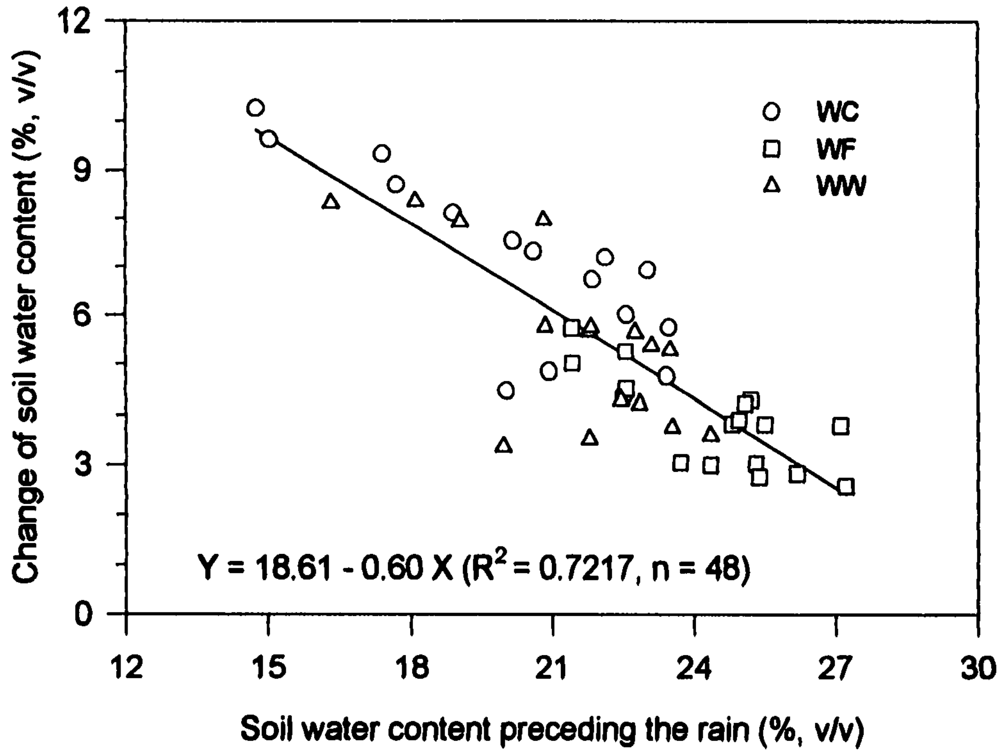

Fig. 2-10. Soil water recharge in 0-40 cm depth with 57.8 mm rainfall from May 17 to May 21, 1994 as affected by soil water content preceding the rain.

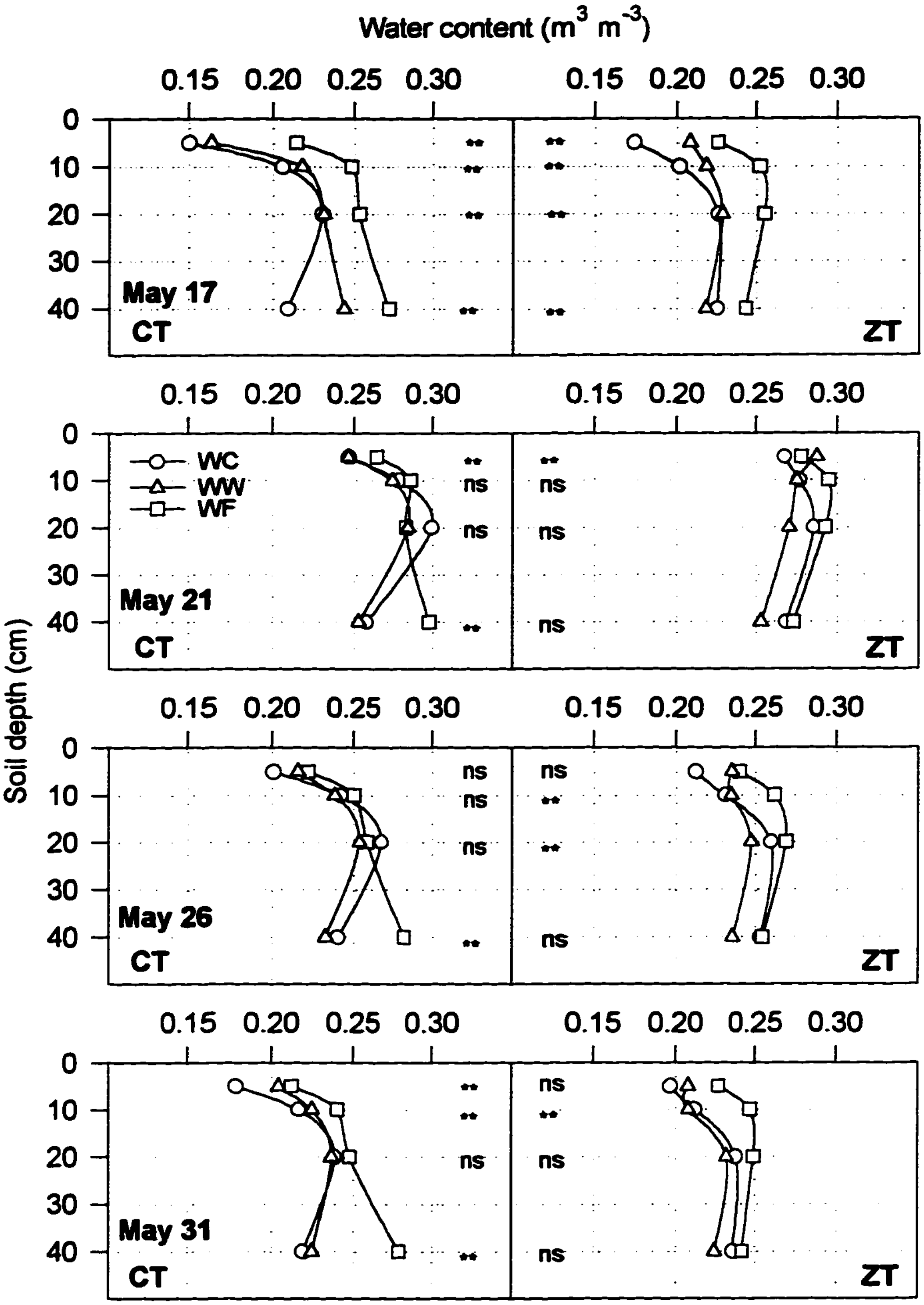

Fig. 2-11. Changes of soil water content in 0-40 cm under CT and ZT with a rainfall event (57.8 mm from May 17 to 21) in 1994. ns and ** indicate not significant and significant at 0.05 level, respectively.

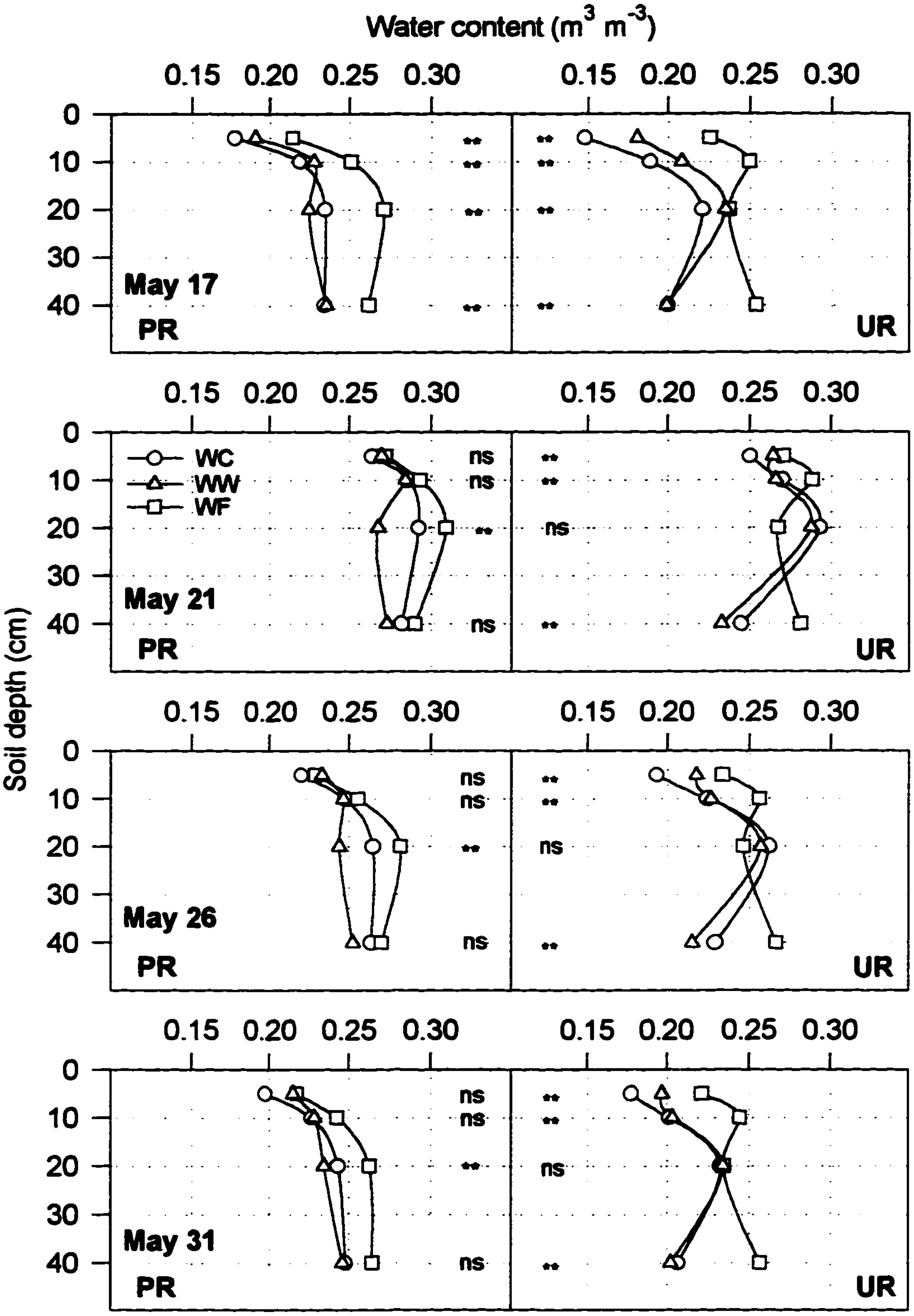

Fig. 2-12. Changes of soil water content in 0-40 cm under PR and UR with a rainfall event (57.8 mm from May 17 to 21) in 1994. ns and ** indicate significant and not significant at 0.05, respectively.

CHAPTER 3

SOIL TEMPERATURE REGIMES IN VARIOUS CROP ROTATION AND TILLAGE SYSTEMS WITH DIFFERENT ROW SPACINGS

3.1 INTRODUCTION

Soil temperature in agricultural land is a function of the heat flux through the soil surface, soil-thermal characteristics, and crop-canopy attributes. Conservation tillage strongly modifies surface conditions (e.g., color, micro relief, structure, water content) and structure of soil and thereby influences the heat exchange across the soil surface, soil thermal properties and, ultimately, the soil temperature regime (McCalla and Army, 1961; Wierenga et al., 1982; Izaurralde et al., 1986; Prasad and Power, 1991).

Influence of conservation tillage on soil temperature depends on residue characteristics such as quantity, geometry, age, height, color and distribution (Unger and McCalla, 1980). Burrows and Larson (1962) noticed that the damping of soil temperature fluctuation increased as the thickness of residue cover increased. In Texas, Unger (1988) found maximum soil temperatures to be highest in winter under no-till with shredded residues but highest on no-till with upright residue in other periods. As straw mulch becomes dark from weathering, the reflection of incoming radiation decreases and so does the insulation effect of mulching (McCalla and Army, 1961). Optimization of mulching benefits has been attempted by partially removing mulch cover on a tropical soil (Bristow and Abrecht, 1989) and in the northern Corn Belt of the USA (Fortin, 1993).

Soil temperature responses to conservation tillage also depend on the extent of mechanical disturbance to soil by tillage implements and time of the tillage operation. Upper-profile soil temperatures were reduced by 1.8, 2.3, 5.9 °C by chisel plowing, till plant and no-till, respectively (Johnson and Lowery, 1985). Wall and Stobbe (1984) found that fall tillage induced lower maximum but higher minimum soil temperatures than spring tillage.

Geographic location and associated climatic environmental differences should be considered when studying the effects of conservation tillage on soil temperature. In the northern Corn Belt of the US where soil temperatures are often too low for optimum germination and seedling growth, residues resulting from the use of conservation tillage usually delay emergence and early crop growth (Allmaras et al., 1964; Al-Darby and Lowery, 1987). Mock and Erbach (1977) reported grain-yield reductions of up to 30% under such conditions. Increased snow accumulation under reduced tillage with upright residue reduced frost occurrence, induced early frost disappearance and produced higher early-spring temperatures (Benoit et al., 1985; Cullum et al., 1990). In tropical areas, use of mulch largely reduced maximum soil temperatures and induced increased plant growth (Abrecht and Bristow, 1990) and grain yield (Lal, 1978).

Soil temperature regimes as affected by tillage systems have not been thoroughly studied in the Canadian Prairie. In Manitoba, Gauer et al. (1982)

investigated how zero and conventional tillage influenced soil temperatures and water content on three soil types. Although soil water in spring was higher under zero than under conventional tillage, soil temperatures were either higher or lower, depending on differences in straw management and seasons. They concluded that soil temperature differences resulting from tillage elimination would not limit cereal production in southern Manitoba. In a study on corn, Wall and Stobbe (1984) reported that zero tillage and crop residue retention tended to depress maximum seedbed soil temperature. In Saskatchewan, Carter and Rennie (1985) observed maximum soil temperatures under zero tillage were 1 to 5 °C lower than under conventional tillage during the first 30 days of spring wheat (*Triticum aestivum* L.) growth. Subsequent differences in crop canopy (shoot height), developed between tillage systems, tend to modify the soil temperature profile. Anderson and Russell (1964) studied the effects of various rates of straw mulch on soil temperature and the performance of spring and winter wheat for 9 years in southern Alberta. Although soil temperatures were depressed with increased straw levels, a quantity of mulch up to 4.5×10^3 kg ha^{-1} could be used without deleterious effects on winter wheat. Other field studies in Alberta have shown zero tillage to benefit soil water conservation (Carefoot et al., 1990; Larney and Lindwall, 1995; Lindwall et al., 1995) but no study has examined soil temperature dynamics in conservation production systems. Further, there is little if any information to compare soil temperatures among crop rotations and row-spacing configurations. The first objective of this study was to compare seasonal and daily soil temperatures of three winter wheat rotations under various tillage systems and row-spacing configurations. The second objective aimed to determine the differences in the soil thermal regime induced by conservation tillage practices and paired-row seeding in traditional and alternate crop rotations in a semi-arid region of the Canadian Prairie. The findings from the investigation may lead to the development of more effective production systems and to improved understanding of tillage effects on microclimatic environments.

3.2 MATERIALS AND METHODS

3.2.1 Site and Experimental Design

The study was conducted during the 1993/94 and 1994/95 winter wheat seasons on a Dark Brown Chernozemic (Typic Haploboroll) (Table 3-1) near the Agriculture and Agri-Food Canada Research Centre, Lethbridge, Alberta (49° 42'N, 112° 47'W, elevation 915 m). The site has a mean annual precipitation of 402 mm and a mean annual temperature of 5.0 °C.

The experiment was established in 1984 as a split-split-plot design (Larney and Lindwall, 1994). The main treatment was crop rotation, including continuous winter wheat (WW), winter wheat-canola (*Brassica napus*) (WC) and winter wheat-fallow (WF). The sub-treatments consisted of conventional tillage (CT) and zero tillage (ZT). The sub-sub treatment was row spacing including uniform-row (UR) and paired-row (PR) seeding. More detailed description of the experimental design and management practices are given in Chapter 2.

3.2.2 Instrumentation and Measurement

Soil temperature was measured with thermocouples at six depths (2.5, 5, 10, 20, 40, and 80 cm) on inter-row and intra-row locations of the east-west oriented seeding rows (Fig. 3-1). The thermocouples were constructed of 24-gauge unshielded copper-constantan wires. The junction was soldered, PVC rinsed, shrouded in heat-shrink tubing and then put into the centre of copper tubing (5.1 mm OD., 10 cm long) filled with epoxy resin. Probes at the 80-cm depth were taped on a wooden dowel and positioned in the soil vertically into a hole excavated with a soil corer. The top of the dowel was about 10 cm below the soil surface. For the other depths, soil pits (15 cm by 50 cm) were carefully excavated with soil horizons kept separate for backfill. Horizontal holes just smaller than the thermocouple probes were then made by pushing a stainless steel rod into the soil. A wooden template with pre-drilled holes was used to guide the insertion of the rod to ensure the holes were at prescribed depths and distances. The thermocouple probes were then inserted into the undisturbed soil through these holes. At least 50 cm of the thermocouple wires were buried 20 cm below the soil surface, thereby minimizing the effects of thermal conduction of lead wires on temperature measurements. Finally, the soil pits were carefully backfilled and displaced crop residue was placed back on the soil surface.

For the 2.5-cm soil depth measurements, the unshielded thermocouple wires (5-7 m) were connected directly with 22-gauge shielded thermocouple wires (30-70 m), which were then connected to a data logger (CR7, Campbell Scientific, Logan, UT). For the other depths, the unshielded thermocouple wires were connected to a multiplexer (AM416, Campbell Scientific Canada Ltd., Edmonton, Alberta) and 22-gauge shielded thermocouple wires were used to run between the multiplexer and the data logger.

Incoming short wave radiation (model Li-200SZ pyranometer, Li-COR, Inc., Lincoln, NE) at 1.5 m, wind speed (Met One 013 anemometer, Campbell Scientific) at 2 m, air temperature and humidity (Model 207, Campbell Scientific) at 1.5 m and rainfall were also measured in an adjacent fallow plot. In the 1994/95 season, air temperature was observed with a 40 gauge copper-constantan thermocouple since errors were found with the Model 207 sensor in 1993/94. The thermocouple was centred between two 2.5 by 2.5 cm stainless steel plates spaced 1 cm apart which, in turn, were centred between two 5 by 5 cm steel plates spaced 3 cm apart, to ensure the thermocouple was shielded and naturally ventilated. All the soil temperature and climatic parameters were recorded by the CR7 data logger at 2-minute intervals and hourly average values were stored, except for the tipping bucket rain gauge whose output was summed to give hourly totals.

Crop residue left on the soil surface was collected in a 1-m^2 area in two replications for each of the row spacing treatments. Dry weights of loose and upright residue were determined separately in the laboratory.

3.2.3 Calculation and Analysis

For statistical analysis, means of soil temperature measurements at each depth were used. Analysis of variance was performed on the measured soil properties by using the General Linear Model (GLM) procedure in SAS (SAS Institute, 1990). Fisher's protected least significant difference method (Steel and Torrie, 1980) was used for mean comparisons.

3.3 RESULTS AND DISCUSSION

3.3.1 Meteorological and Soil Surface Conditions

Precipitation received during the winter wheat growing season amounted to 356 and 470 mm in 1993/94 and 1994/95, respectively. However, the weather conditions in the 1993/94 season were rather favorable for the growth and development of winter wheat because precipitation was evenly distributed in the growing season. On the other hand, it was dry during fall and overwinter periods but wet in the spring period in the 1994/95 season. More detailed information on weather conditions has been reported in Chapter 2.

The quantity of crop residue left on the soil surface was presented in (Fig. 2-3). Under ZT, surface crop residue on the WF rotation amounted to only 19% of that on the WC rotation and 35% of that on the WW rotation. Under CT treatment, the WC and WW rotations had similar quantities of surface residue but there was negligible amount of surface residue on the WF plots.

3.3.2 Seasonal Variation

Figs. 3-2 and 3-3 summarize the general soil thermal regimes during the study period. In 1993/94, cooling of the soil began in November while the freezing front (0°C isotherm) descended to a depth of 75 cm in mid-January. Soil cooling continued until the end of February but then the trend rapidly reversed towards mid-March when soil warming began.

Soil water content and surface residue were the main factors determining overwinter soil temperature variations. Crop residues can reduce frost depth by insulating the soil surface and trapping snow (Rickerl and Smolik, 1990). In changing between ice, water and water vapor, latent heat is taken up or liberated and as a result the energy and water balances become enmeshed (Oke, 1987). Furthermore, water has a heat capacity higher than other soil components. Therefore, soil water acts as a buffering medium of soil temperature. During the winter of 1993/94, the WF rotation showed higher water content (Chapter 2) and a warmer soil profile than the other two rotations under CT (Fig. 3-2). The -5 °C isotherm reached a maximum depth of 25 cm on WF plots but penetrated to a depth of 37 cm on WW plots and 40 cm on WC plots. Thus the shredded residues on continuous-cropped rotations had a limited insulating effect on soil temperature for CT compared to the buffering effect of soil water. Under ZT, the maximum penetration depth of the -5 °C isotherm was

22 cm on WW plots, 32 cm on WC plots, and 29 cm on WF plots. Hence, crop residues on continuous-cropped rotations, especially WW, reduced frost penetration depth. Although WF plots under ZT had less surface residues than WC plots, temperature of the soil profile was higher in the former than in the latter. The paired-row and uniform-row configurations showed similar seasonal temperature patterns.

Soil cooling was faster and frost depth was greater in the winter of 1994/95 than in the winter of 1993/94 (Figs. 3-2 and 3-3), in spite of higher average air temperatures recorded during the winter of 1994/95. Extremely dry soil conditions during the winter of 1994/95 likely contributed to these results. Nevertheless, crop rotation and tillage effects on overwinter soil temperatures during 1994/95 were similar to those during 1993/94.

Soil water content also controlled and therefore induced differences in spring thawing among treatments. For example, thawing occurred simultaneously under WW, WC, and WF in the upper 25 cm, but there was a one week delay in 1994 at deeper zones under WF (Fig. 3-2). Zero tillage on WC and WW rotations delayed soil warming, but this effect was minimal on plots of the WF rotation.

The snow trapping ability of upright residue under zero tillage and the subsequent effect in soil temperature was investigated on January 16, 1995. Snow depths and soil temperatures at a 2.5-cm depth on WW and WC treatments were higher under ZT than under CT (Fig. 3-4). However, the increase in soil temperature was not proportional to snow depth. For example, soil temperature under CT in the WW treatment was 0.6°C higher than under ZT in the WC rotation, but it had 0.7 cm less snow than ZT in the WC treatment. Adjacent to the north side of the WF rotation were the fallow plots (i.e., with no winter wheat seeded) which had large amounts of upright residue and snow cover. Therefore, snow accumulated on the WF plots as a result of strong northwest winds. In the WF rotation, however, the thicker snow depth observed on ZT than CT did not elevate soil temperatures.

Gauer et al. (1982) reported complete winter-kill of winter wheat under conventional tillage due to lack of snow cover and thus extremely low seedbed temperature (-17 °C). In this study, the extreme minimum soil temperature during the two study years was only -10 to -12 °C and no apparent winter-kill was observed.

3.3.3 Daily Variation in the Spring

Four clear days in March, April, May and June 1994 were selected for examining diurnal variations of soil temperature under different treatments (Fig. 3-5, Tables 3-2 and 3-3). The season-to-season and soil depth variations in daily soil temperature depended largely on soil water content and surface residue conditions. At the beginning of soil warming when evaporation was very small, differences in soil temperature arose mostly from the amount of solar radiation reaching soil surface as well as the amount and albedo characteristics of the surface residue cover. On March 8, for example, the WF rotation under ZT had higher daily maximum soil temperatures (DMST) throughout the soil profile than the other two rotations due to less and darker surface residues (Fig. 3-5, Table 3-2). WF plots under CT had similar DMST to WC and WW plots at depths less than 20 cm but higher at depths greater than 20 cm. Later as the intensity of latent heat transfer increased, soil temperature differences among treatments arose from differences in surface residue levels and soil water content. On April 8, for example, soil in the WF rotation under CT had lower DMST at most depths than did soil in the other two rotations, because of its higher soil water content. Under ZT, the WF rotation had higher DMST than the WC or WW rotation at 2.5 cm, but there were no differences between rotations at any other depth. These trends continued until late May when the crop canopy covered the soil surface and differences in soil water contents became the main factor determining changes in soil temperature. The WF plots thereafter had a DMST equal to or lower than the WC and WW plots for both tillage systems.

Changes in soil temperature under ZT were related to the level of surface residue and, therefore, to crop rotation. The WC and WW rotations under ZT had lower soil temperatures than under CT except on March 8 when the soil was frozen and soil temperatures on ZT plots were similar to or higher than those of CT plots (Fig. 3-5, Table 3-2). However, ZT and CT did not show significant differences in DMST on the WF rotation because small amounts of surface residues under ZT had been partly decomposed and mixed with the soil by spring (Table 3-2). Depression of soil temperature by zero tillage was more pronounced on PR than on UR (data not shown).

Anderson and Russell (1964) found delayed emergence, poorer crop growth and reduced yield of winter wheat with heavy straw covered plots compared with bare plots. In this study, the depression of soil temperature under ZT with WW and WC probably resulted in delayed emergence of plants and reduced early crop growth in comparison to CT. However, the amounts of crop residue in our plots were well below the critical level (4.5 x 10^3 kg ha^{-1}) as described by Anderson and Russell (1964) except in one case (5.8 x 10^3 kg ha^{-1} with ZT+WC+UR in 1994/95). Consequently, no significant yield reductions on ZT plots were expected as a result of the decreases of soil temperatures.

The influence of ZT on soil temperature varied throughout the day and was soil-depth dependent. In agreement with Burrows and Larson (1961), differences between CT and ZT treatments in the WC and WW rotations were greatest for the soil temperature maxima but smallest for the minima (Fig. 3-5). As depth increased, the difference in maximum soil temperature between CT and ZT decreased and converged towards 0°C; differences in minimum soil temperature increased with soil depth above 20 cm but converged towards 0°C below 20 cm (Fig. 3-6). Maximum or minimum temperature differences between CT and ZT were greatest under WW, followed by WC, and least on WF.

Bristow (1988) and Horton et al. (1994) showed that soil water was the dominant factor in energy exchange at soil surface and soil surface temperature.

Daily maximum soil temperatures in vertical and horizontal mulches as well as in bare soil were found to converge on wetting but diverge on drying. Minimum soil surface temperatures responded in a manner opposite to that of the maximum temperature. The variation of differences in soil temperature at 2.5 cm between CT and ZT during a rainfall period were examined (Fig. 3-7). The differences in DMST between CT and ZT followed the pattern as described as Bristow (1988) and Horton et al. (1994) - 7.9°C on May 11 (dry), 0.9°C on May 17 (wet) and 6.6°C on May 22 (drying). It was found, however, that the differences in minimum soil temperatures between CT and ZT depended on the degree of soil saturation. For example, the difference was -0.1°C under dry conditions on May 11 and increased to -1.5 °C on May 15 with rain occurring on May 13. Additional precipitation from May 17 to 19 saturated the surface layer and consequently, the differences in minimum soil temperatures decreased (-0.2 °C on May 19). While the DMST difference started to increase rapidly from May 20 onwards with soil drying, the difference in minimum temperature increased again until May 23 when it began to increase with further drying of the soil. At the 5-cm depth, the differences in DMST between CT and ZT also converged on wetting and diverged on drying, but no significant changes were noticed for the differences in minimum soil temperatures between the two tillage systems.

In comparison, row configuration treatments induced more attenuated DMST differences than did crop rotation and tillage treatments (Table 3-3). Of the four days selected, the PR configuration showed higher DMST than the UR configuration on WC and WW treatments only and not at all soil depths.

Differences in soil temperature among treatments were generally small in the spring of 1995 because of above normal precipitation and thus higher soil water content. Later in the season, a high infestation of downy brome (*Bromus tectorum* L.) on WF and WW treatments masked any treatment effect on soil temperature dynamics (data not shown).

3.4 SUMMARY AND CONCLUSIONS

In the semi-arid Canadian Prairies, crop rotation and tillage interactively determine the soil temperature regime with soil water content and crop residue cover as the main factors controlling the variation. The WF rotation showed the highest overwinter temperature on both tillage systems in the drier soil condition (1994/95) and on CT in the wetter soil condition (1993/94), due to its higher soil water content. Crop residue (especially upright residue) effects on overwinter soil temperature were significant in the wetter year with the WW rotation where ZT had the highest overwinter soil temperature.

During early soil warm-up, crop residue level dominated the processes and its importance became less as the season progressed. When the crop canopy was fully established, soil water content was the determining factor. As a result, soil temperature with WF rotation could be higher than, similar to or lower than that of the continuous-cropped rotations, depending on tillage treatment, soil depth and crop growth stages.

Zero tillage significantly changed soil temperature on the continuous-cropped rotations. Under WW and WC rotations, overwinter soil temperature was higher and spring soil temperature was lower on ZT than on CT. Variations of the differences in daily maximum/minimum soil temperature with soil depth and wetting and drying of the soil were also noted. Row configuration had less effect on soil temperature in comparison to the crop rotation and tillage treatments. The depression of soil temperature under ZT probably delayed emergence of plants and reduced early crop growth compared with the CT treatment. However, significant yield reductions with ZT were neither expected nor observed as a result of soil temperature reductions since the quantities of crop residue in this study were well below critical levels.

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Table 3-1. Selected soil properties at the study site (values are the overall treatment means).

Depth interval	Sand	Clay	Organic carbon	Bulk density	Field capacity	Wilting point
cm		%		Mg m^{-3}	m^3 m^{-3} x 100	
0-5	34.1	38.0	2.07	1.23	31.7	21.5
5-10	34.0	38.5	1.95	1.36	33.2	23.0
10-20	32.9	38.4	1.74	1.33	30.8	21.1

Table 3-2. Maximum soil temperature under different crop rotation and tillage treatments on selected days in spring 1994.

			Maximum soil temperature			
Depth	Crop rotation	Tillage	March 8	April 8	May 8	June 8
cm			°C			
2.5	WC	CT	1.6a	11.7a	21.1ab	21.2ab
		ZT	-1.2b	8.7c	17.9c	18.0c
	WF	CT	1.4a	10.0b	20.5b	18.2c
		ZT	0.8ab	10.2b	20.6b	16.7c
	WW	CT	2.4a	12.5a	22.7a	22.0a
		ZT	-0.6b	8.4c	18.8c	20.2b
5	WC	CT	-0.5ab	9.0a	18.7a	18.9a
		ZT	-1.2b	7.4b	16.6c	16.5bc
	WF	CT	0.0a	7.7b	18.1b	16.6bc
		ZT	-0.9b	7.5b	18.0b	15.3c
	WW	CT	-0.2a	9.1a	19.0a	18.7a
		ZT	-1.2b	6.6c	16.7c	17.7ab
10	WC	CT	-1.1ab	7.0a	17.0a	16.5ab
		ZT	-1.2b	5.8b	14.8c	14.9cde
	WF	CT	-0.9a	5.4bc	16.2b	15.2cd
		ZT	-1.1ab	5.5bc	16.2b	14.1e
	WW	CT	-1.0ab	7.1a	16.8ab	16.5a
		ZT	-1.2b	5.0c	14.9c	15.5bc
20	WC	CT	-1.4c	5.0a	14.8a	14.2ab
		ZT	-1.3c	4.5a	12.5bc	13.3bc
	WF	CT	-1.2ab	2.9b	13.7ab	13.4bc
		ZT	-1.2a	3.4b	13.7ab	12.7c
	WW	CT	-1.3c	4.8a	14.2ab	14.4a
		ZT	-1.3bc	2.8b	11.9c	13.2c
40	WC	CT	-1.6d	2.5a	14.3a	11.5a
		ZT	-1.5c	2.3a	9.0c	11.1b
	WF	CT	-1.4ab	-0.3c	10.0b	11.1b
		ZT	-1.3a	0.6bc	10.2b	11.0b
	WW	CT	-1.6d	2.2a	10.3b	11.7a
		ZT	-1.4b	0.7b	9.1c	11.2b
80	WC	CT	-1.6d	1.4ab	11.81a	10.0a
		ZT	-1.3c	1.4ab	6.0c	9.6c
	WF	CT	-0.9a	1.8a	6.6b	9.8bc
		ZT	-1.0b	1.1ab	6.7b	9.8b
	WW	CT	-1.5d	0.9ab	6.8b	10.2a
		ZT	-1.0b	0.2b	6.1c	9.8bc

† CT = conventional tillage, ZT = zero tillage; WC = winter wheat - canola, WF = winter wheat - fallow, and WW = continuous winter wheat.

‡ Means followed by the same letter in the same column at a given depth do not differ significantly at $P \leq 0.05$.

Table 3-3. Maximum soil temperature under different crop rotation and row spacing treatments on selected days in spring 1994.

Depth	Crop rotation	Row spacing	Maximum soil temperature			
			March 8	April 8	May 8	June 8
cm			°C			
2.5	WC†	PR	0.5ab‡	10.9a	20.3abc	19.8bc
		UR	-0.1b	9.5b	18.8c	19.4bc
	WF	PR	1.5ab	10.6ab	21.3ab	18.1cd
		UR	0.8ab	9.6b	19.8bc	16.8d
	WW	PR	1.7a	11.3a	21.5a	22.1a
		UR	0.0ab	9.6b	20.0abc	20.1b
5	WC	PR	-0.8ab	8.5a	18.1ab	17.9ab
		UR	-0.9ab	7.9bc	17.2c	17.6ab
	WF	PR	-0.6ab	7.4c	17.8ab	16.2bc
		UR	-0.4ab	7.8bc	18.3a	15.7c
	WW	PR	-0.2a	8.2ab	18.0ab	18.8a
		UR	-1.1b	7.6c	17.7bc	17.6ab
10	WC	PR	-1.1ab	6.7a	16.0a	15.8ab
		UR	-1.2b	6.1ab	15.8a	15.5bc
	WF	PR	-1.0ab	5.2c	15.9a	14.7cd
		UR	-1.0a	5.6bc	16.5a	14.5d
	WW	PR	-1.0ab	6.1ab	15.9a	16.5a
		UR	-1.1ab	5.9b	15.8a	15.5bc
20	WC	PR	-1.3b	5.0a	13.4a	14.0ab
		UR	-1.4c	4.5ab	13.9a	13.6abc
	WF	PR	-1.2ab	2.8d	13.5a	13.1bc
		UR	-1.2a	3.4cd	14.0a	13.0c
	WW	PR	-1.4bc	3.7bc	13.0a	14.1a
		UR	-1.3b	3.9bc	13.2a	13.5abc
40	WC	PR	-1.6c	2.5a	11.9a	11.3b
		UR	-1.6c	2.3ab	11.3a	11.3b
	WF	PR	-1.4a	-0.2d	9.9b	11.1b
		UR	-1.3a	0.6cd	10.3b	11.1b
	WW	PR	-1.6c	1.5ab	9.7b	11.7a
		UR	-1.5b	1.4bc	9.6b	11.3b
80	WC	PR	-1.4cd	1.5a	9.0a	9.9b
		UR	-1.5d	1.4a	8.8a	9.8b
	WF	PR	-0.9a	2.0a	6.5b	9.8b
		UR	-1.0a	0.9a	6.7b	9.8b
	WW	PR	-1.3bc	0.5a	6.5b	10.1a
		UR	-1.2b	0.6a	6.4b	10.0b

† WC = winter wheat - canola, WF = winter wheat - fallow, and WW = continuous winter wheat; PR = paired-row, UR = uniform-row.

‡ Means followed by the same letter in the same column at a given depth do not differ significantly at $P \leq 0.05$.

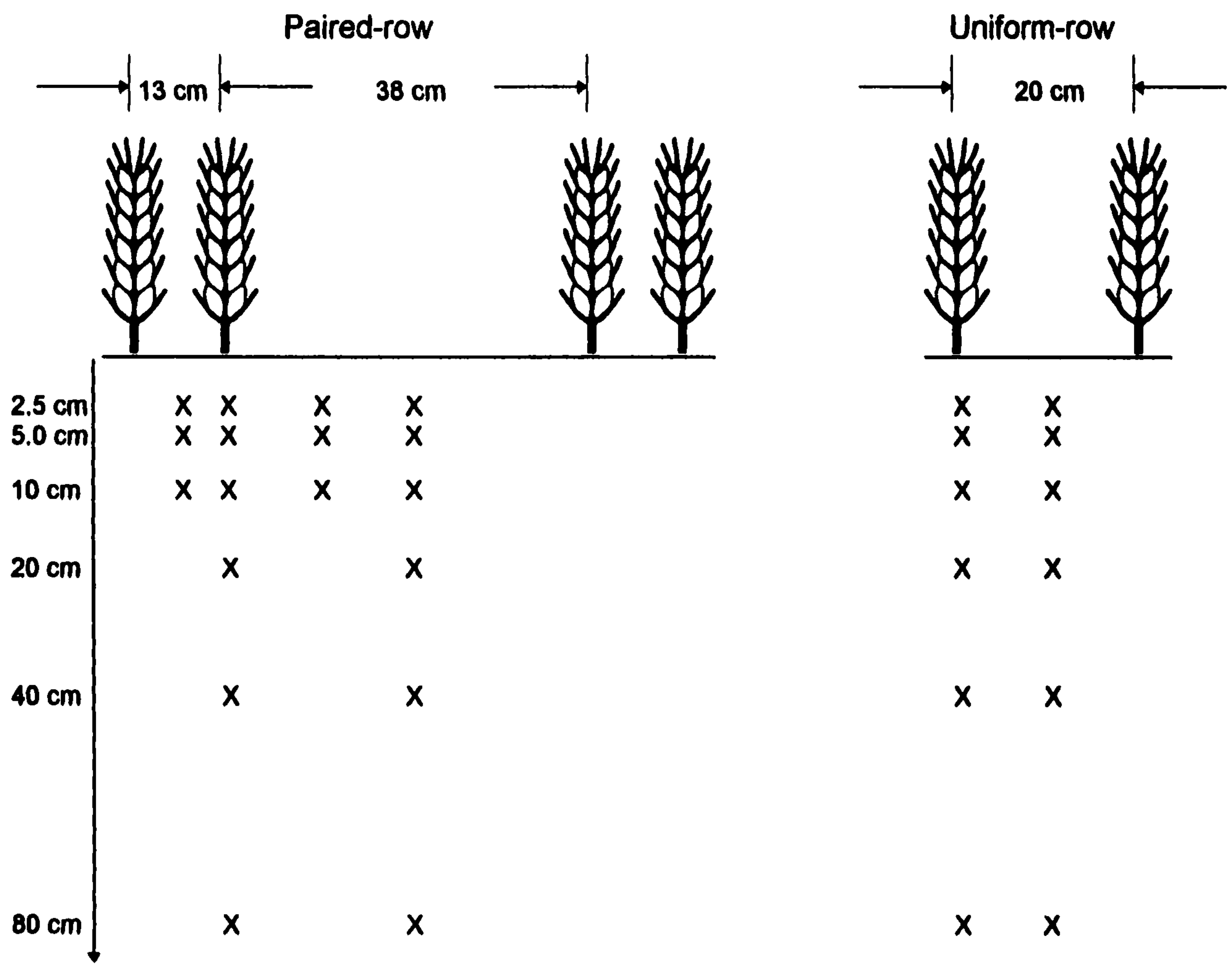

Fig. 3-1. Schematic view of the thermocouple probe locations (x) in the soil profile.

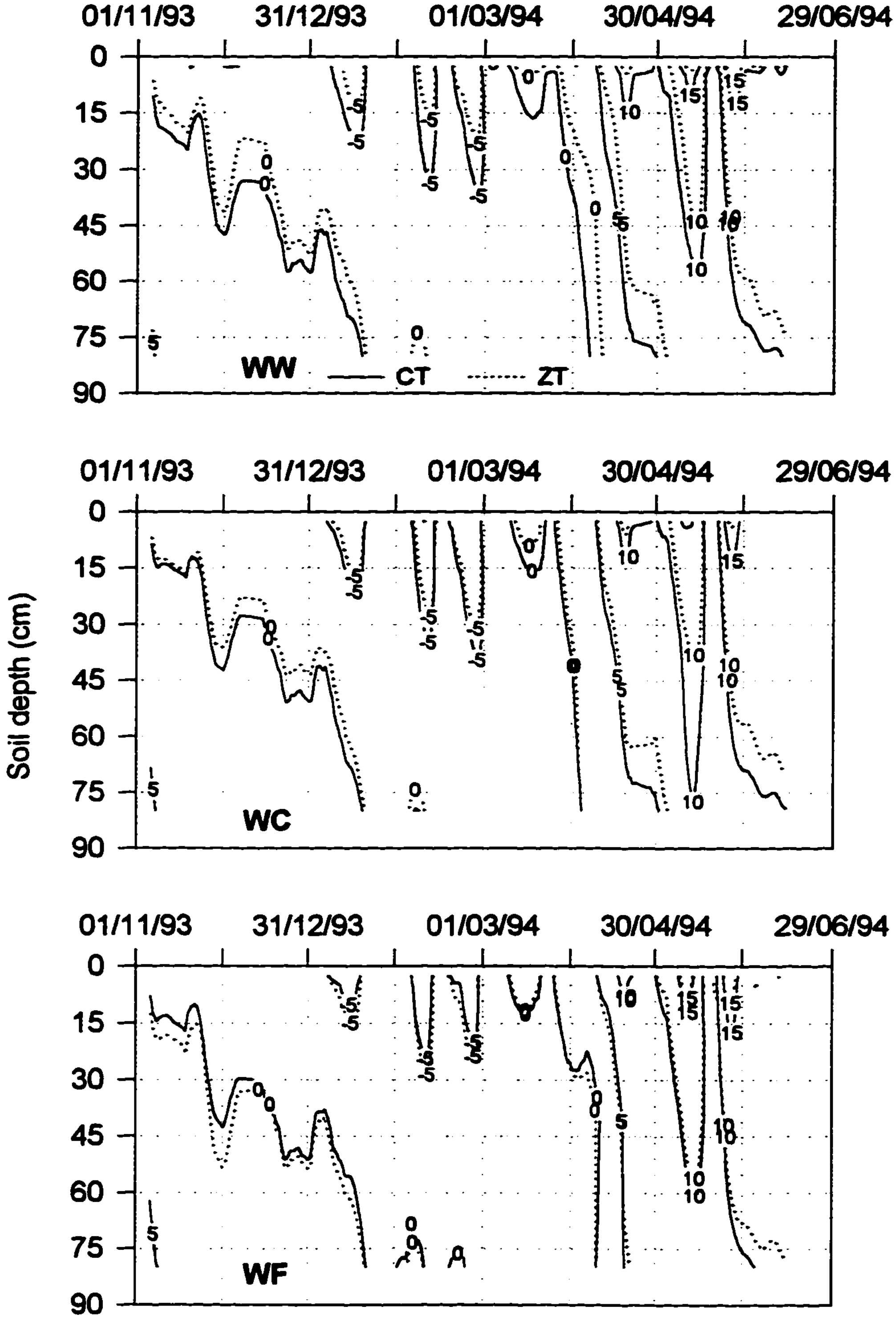

Fig. 3-2. Seasonal temperature distribution in the soil profile during the 1993/94 winter wheat growing season. Data are the five-day moving averages of daily average temperatures.

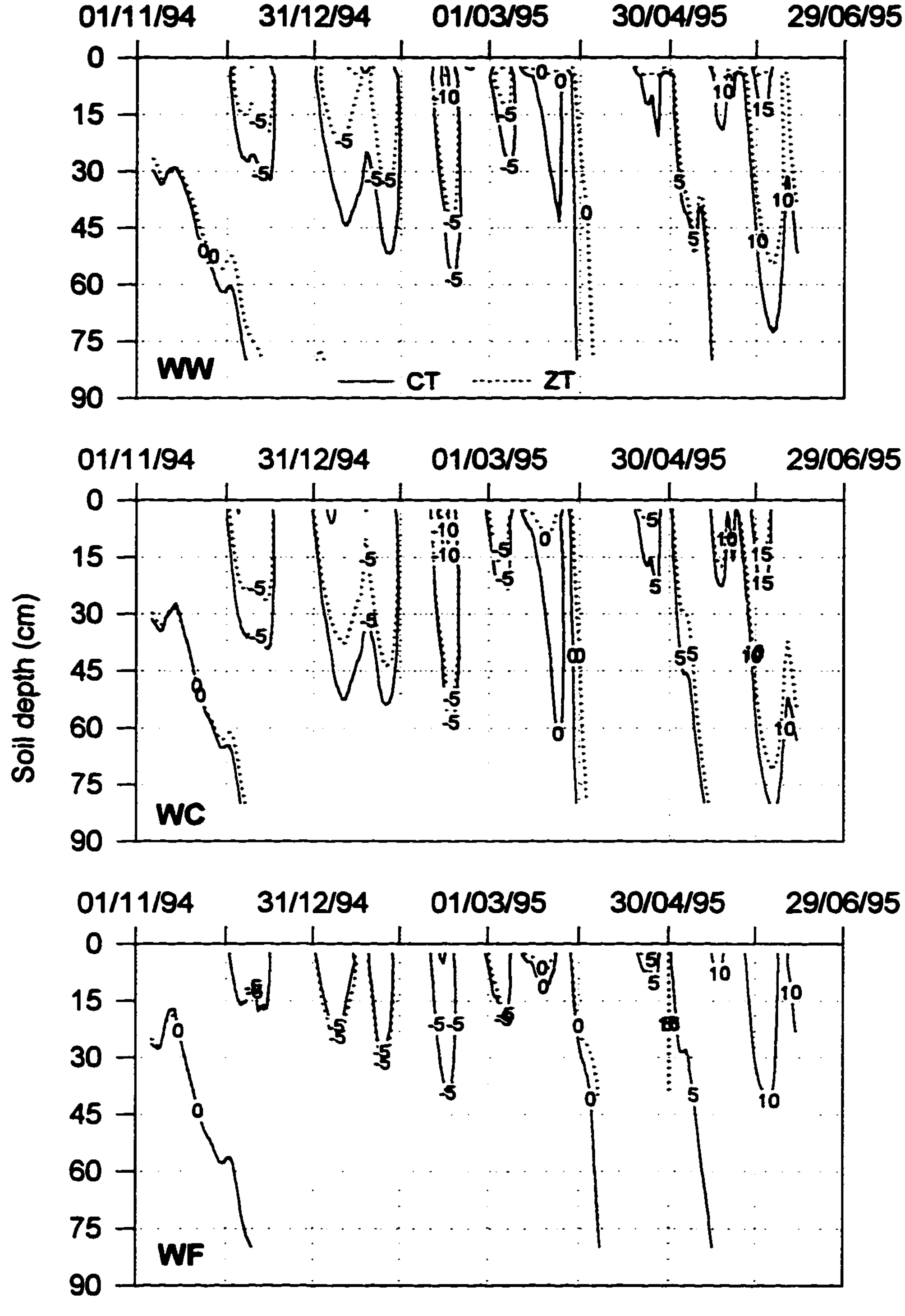

Fig. 3-3. Seasonal temperature distribution in the soil profile during the 1994/95 growing season. Data are the five-day moving average of daily averages temperatures. There are missing values in WF with ZT due to equipment failure.

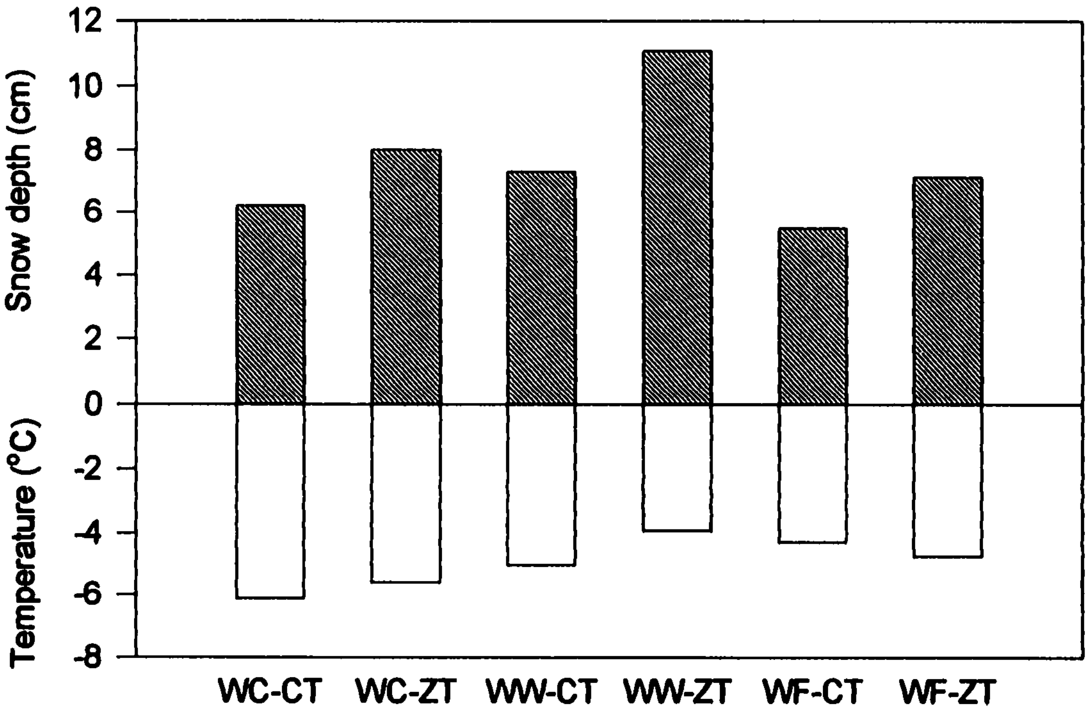

Fig. 3-4. Soil temperature at 2.5-cm depth as affected by snow depth under different crop rotation and tillage treatments on January 16, 1995.

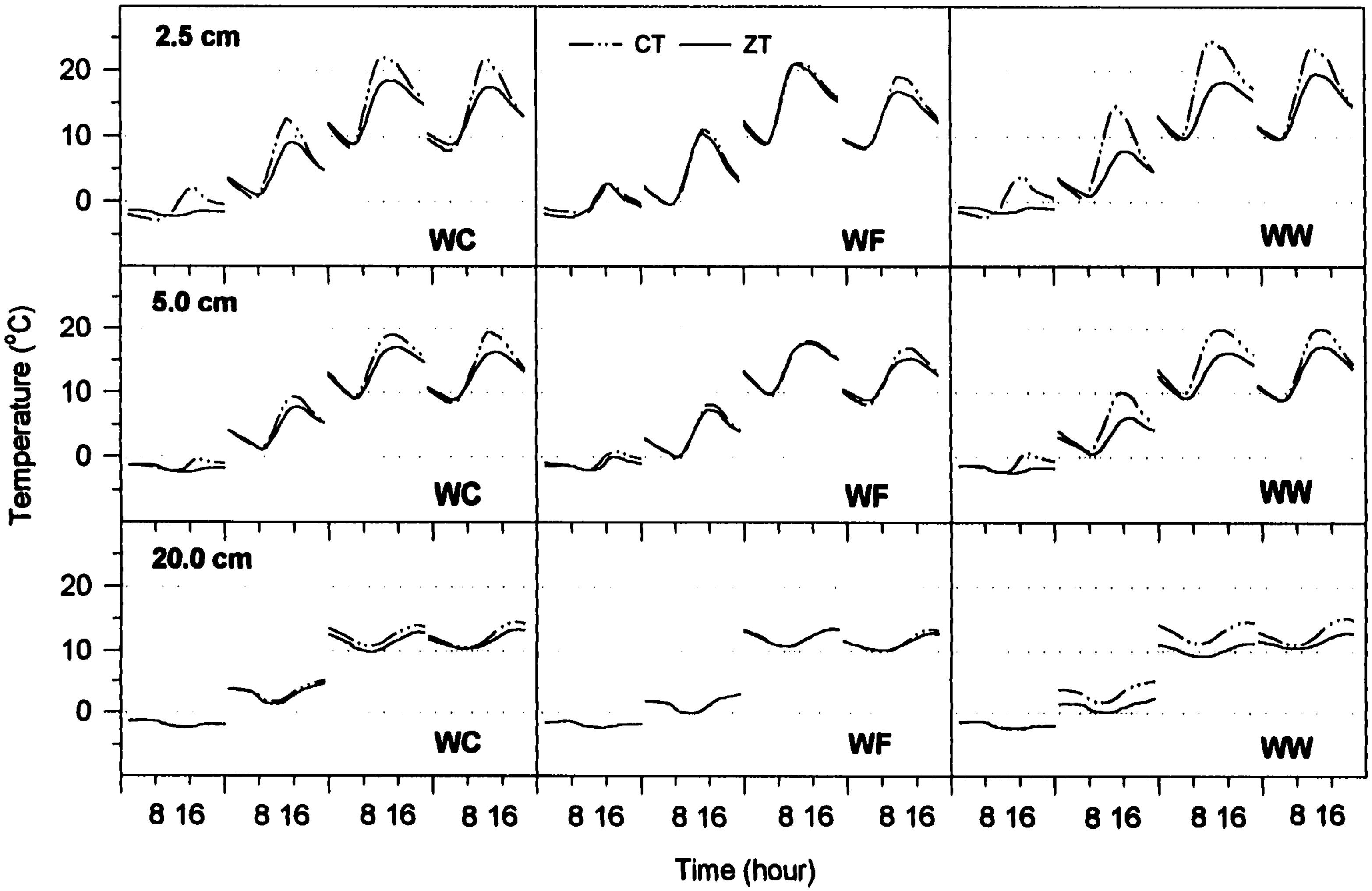

Fig. 3-5. Daily fluctuation of soil temperature under paired-row configuration on March 8, April 8, May 8 and June 8 (from left to right) in 1994.

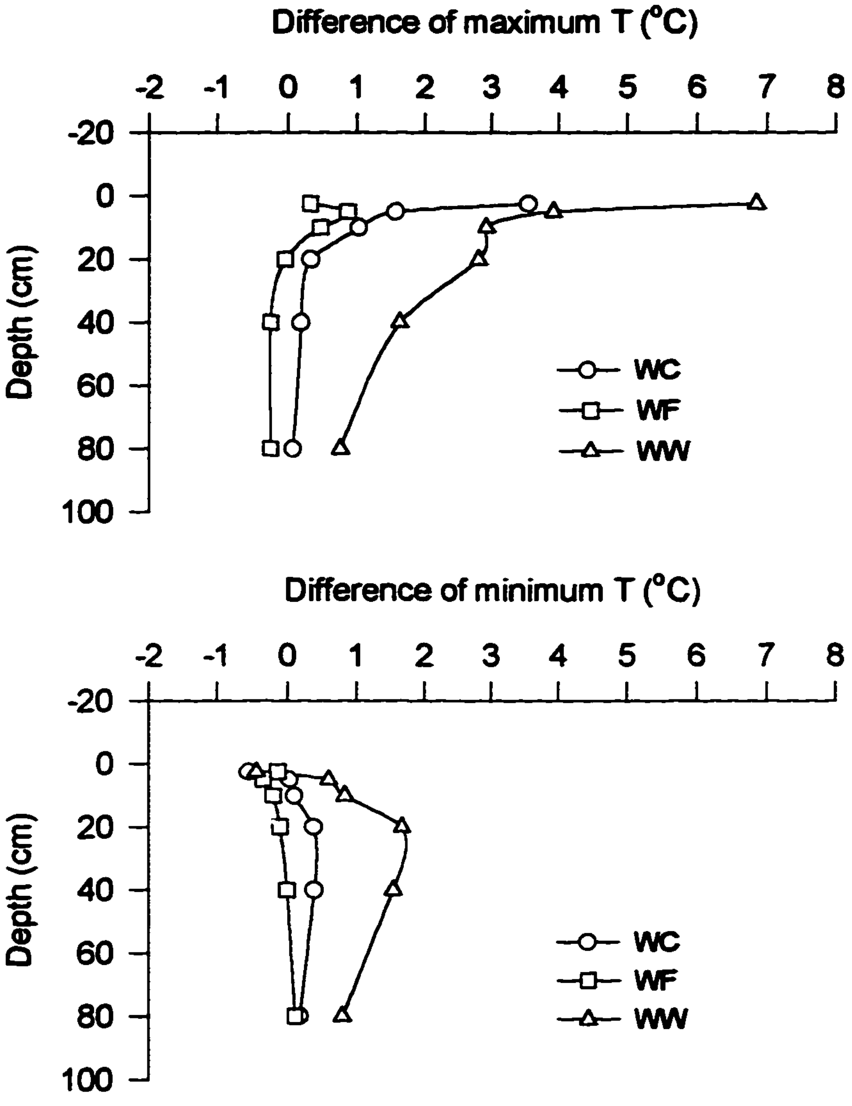

Fig. 3-6. Differences between CT and ZT in daily maximum and minimum soil temperatures under various crop rotations on April 8, 1994.

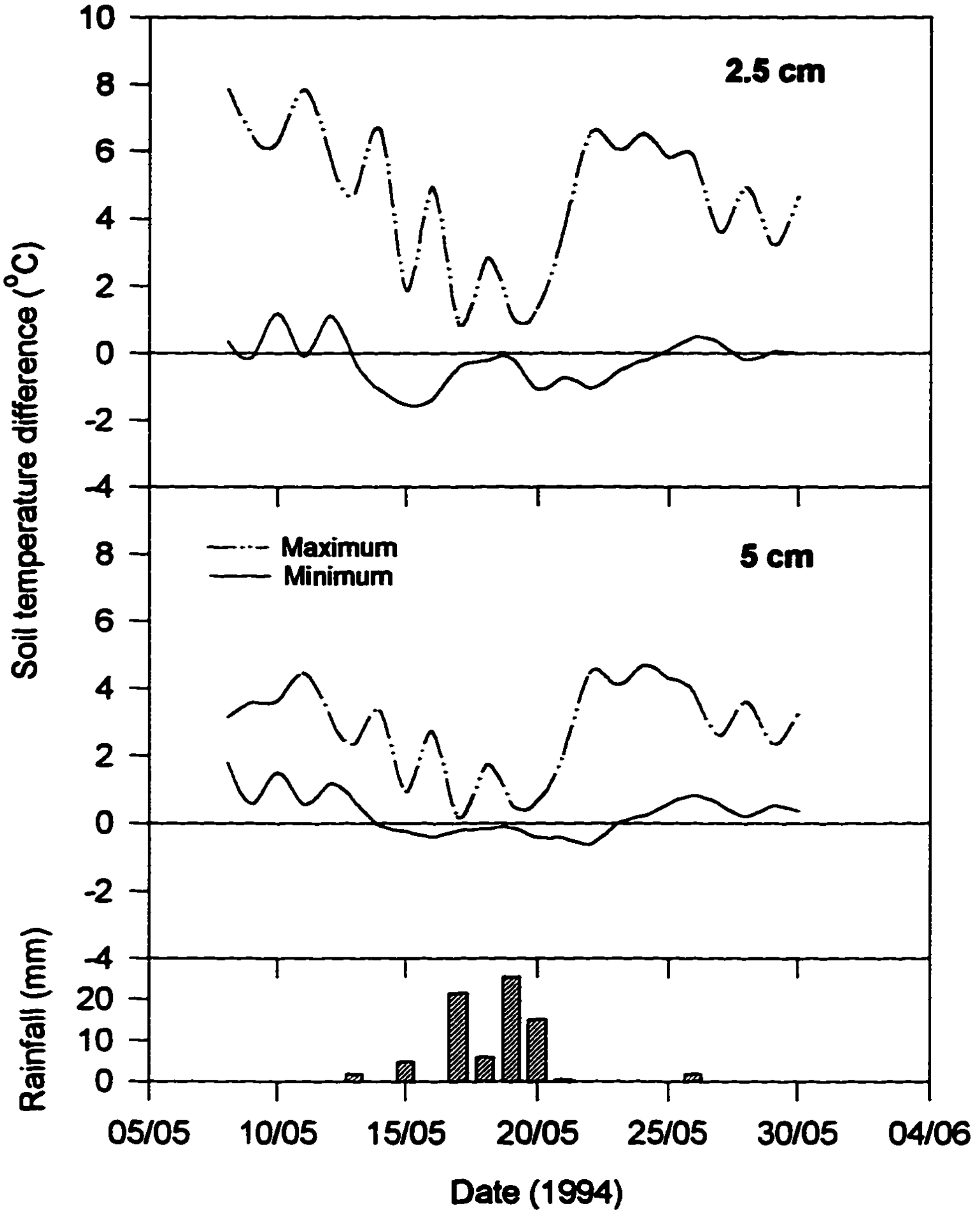

Fig. 3-7. Differences in maximum and minimum soil temperatures at 2.5- and 5.0-cm depths between conventional and zero tillage under continuous winter wheat with a rainfall event (64.5 mm rain from May 13 to May 21, 1994).

CHAPTER 4

MODIFICATION OF SOIL THERMAL PROPERTIES BY LONG-TERM CROP ROTATION AND TILLAGE SYSTEMS

4.1 INTRODUCTION

Heat flow through soil is controlled by soil thermal properties and temperature gradients. Thermal conductivity and volumetric heat capacity are two of the basic thermal properties of soil. While the former determines the rate of heat transfer under a constant temperature gradient, the latter controls the temperature response to a given amount of added heat. Soil thermal diffusivity, the ratio between soil thermal conductivity and volumetric heat capacity, is an index to express temperature changes with time and depth. These thermal properties are functions of the soil's mineral composition, texture, pore size distribution and especially, water content. In a moist soil, some heat transfer is non-linearly associated with mass movement of both water and vapor and with latent heat storage. Therefore the terms apparent thermal conductivity (λ) and apparent thermal diffusivity (α) are introduced to characterize soil heat transfer in moist soils.

Tillage may influence soil thermal properties by altering soil bulk density, pore size distribution and soil water content. The impact of tillage on soil thermal properties, however, has been reported in only a few field studies. Allmaras et al. (1977) reported tillage practices that induced increased porosity had reduced values of λ and α. In Scotland, Hay et al. (1978) reported that direct-drilled soil under barley had a higher α than ploughed soil and attributed this result to the greater bulk density measured in the direct-drilled field. Potter et al. (1985) observed that under similar soil bulk density and volumetric water contents, λ and α in a zero till system were greater than in conventional and chisel plow tillage systems. They suggested that tillage operations induced a different pore-size distribution and/or soil matrix arrangement from that under zero tillage. It was also found that increased soil water storage under long-term zero tillage produced a greater thermal contact area and, consequently greater λ under zero tillage than conventional tillage (Azooz and Arshad, 1995). There were no reported investigations on how crop sequence may influence soil thermal properties.

In the semi-arid Canadian prairies, growing attention is being paid to zero tillage for controlling soil erosion, trapping and holding snow, increasing infiltration and reducing evaporation loss. Soil temperatures, however, are often below optimum for plant growth in the early spring and this undesirable condition may be more pronounced with zero tillage. The objective of this study, therefore, was to evaluate (i) how tillage practices influenced soil thermal properties on a long-term established experiment and (ii) if changes in soil thermal properties induced by tillage treatment are crop-rotation dependent.

4.2 THEORETICAL BACKGROUND

4.2.1 The de Vries Model

Considering soil as a medium of either water or air with ellipsoids of air and solids dispersed in it, the thermal conductivity λ of the soil can be expressed as (de Vries, 1963):

$$\lambda = \sum_{i=0}^{n} k_i X_i \lambda_i / \sum_{i=0}^{n} k_i X_i \qquad (1)$$

where n is the number of different kinds of particles, X_i is the volume fraction of the i-th particle, λ_i is the thermal conductivity of the i-th particle (W m^{-1} K^{-1}), i = 0 refers to the continuous medium (water for moist soil or air for dry soil) and k_i is the coefficient of the i-th particle which equals to the ratio of average temperature gradient in the particular soil component to average temperature gradient in the continuous medium, or

$$k_i = 1/3 \sum_{j=1}^{3} [1 + (\frac{\lambda_i}{\lambda_0} - 1) g_i]^{-1} \qquad (2)$$

where g_i is the shape factor of the i-th particle, $g_1 + g_2 + g_3 = 1$.

In moist soils, the apparent thermal conductivity of air (λ_a) is introduced to account for latent heat transfer:

$$\lambda_a = \lambda_{ad} + \lambda_v \qquad (3)$$

$$\lambda_v = h \lambda_v^s \qquad (4)$$

$$\lambda_v^s = \frac{LD}{R_v T} \frac{P}{(P - P_v^s)} \frac{\partial P_v^s}{\partial T} \qquad (5)$$

where λ_{ad} is thermal conductivity of dry air, λ_v is the thermal conductivity of moist air in saturated soil pores, h is the relative humidity of soil air (fractional), λ_v^* is λ_v for saturated vapor, P_v^* is saturated partial vapor pressure in air (Pa), P is the atmospheric or barometric pressure (Pa), L is the latent heat of vaporization (J kg^{-1}), D is the diffusion coefficient of water vapor in the air ($m^2\ s^{-1}$), R_v is the gas constant for water vapor (460 J $kg^{-1}\ K^{-1}$) and T is the absolute temperature (K).

de Vries (1963) also provided the following equation for calculation of the volumetric heat capacity of soils:

$$C_v = 1.93X_m + 2.51X_o + 4.18\theta \qquad (6)$$

where C_v is the volumetric heat capacity of soil (MJ $m^{-3}\ K^{-1}$), X_m and X_o are the volumetric fraction of soil minerals and soil organic matter, respectively, and θ is the volumetric soil water content.

4.2.2 The Line Source Heat Probe Method

The line source heat probe is used on undisturbed soil cores to determine soil thermal conductivity. This method approximates the infinite line source of heat by a long electrically heated wire enclosed in a cylindrical probe. The probe is introduced into the material, heating current is supplied to the wire, and the temperature rise is measured with a thermocouple placed next to the wire. The apparent thermal conductivity of soil is then calculated according to

$$\lambda = \frac{Q}{4\pi(T_1 - T_2)}\ln(t_2 / t_1) \qquad (7)$$

where t_1 and t_2 are starting and ending time of heating (s), respectively, T_2-T_1 is the temperature increase (°C) of the heat probe from t_1 to t_2 and Q is the heating rate (W m^{-1}).

4.3 MATERIALS AND METHODS

4.3.1 Site and Experimental Design

The study was conducted during the 1993/94 and 1994/95 winter wheat seasons on a Dark Brown Chernozemic soil (Typic Haploboroll) near the Agriculture and Agri-Food Canada Research Center, Lethbridge, Alberta (49°42'N, 112°47'W, elevation 915 m). The mean annual precipitation is 402 mm. The Ap soil horizon is a sandy clay loam with approximately 1.9% organic carbon.

The experiment was established in 1984 as a split-split-plot design. Crop rotation is the main treatment with tillage as the sub-treatment and row spacing as the sub-sub-treatment. The crop includes continuous winter wheat (WW), winter wheat-canola (*Brassica napus*) (WC) and winter wheat-fallow (WF). The tillage treatments were conventional tillage (CT) and zero-tillage (ZT). The row spacing treatment consisted of uniform-row (UR) and paired-row (PR) seeding. More detailed information about the experiment was given in Chapter 2.

Fertilizer rates for winter wheat were a band application (in-row for the UR and mid-row for the PR) of 27 kg ha^{-1} N and 28 kg ha^{-1} of P_2O_5 below the seed followed by a broadcast application of 34 kg ha^{-1} of N the following spring. The canola received 34 kg ha^{-1} of N broadcast before seeding, and 9 kg ha^{-1} N and 40 kg ha^{-1} of P_2O_5 banded at seeding time.

4.3.2 Bulk Density, Soil Organic Matter and Particle Analysis

Soil bulk densities were determined at four depth increments: 0 to 5, 5 to 10, 10 to 15 and 15 to 20 cm. For each depth increment, four undisturbed core samples (3.0 cm high and 5.5 cm diam.) were taken manually for each tillage treatment. The soil water characteristics were determined in laboratory using the pressure plate method (Klute, 1986) at pressures of 0.003, 0.005, 0.01, 0.03, 0.05, 0.1, 0.5 and 1.5 MPa. Finally the samples were oven dried at 105 °C to determine the soil bulk densities. The particle-size distributions of the different horizons were determined by the Bouyoucos hydrometer method (Bouyoucos, 1962).

Soil organic matter contents were estimated from the measurements of total C and total N contents, which were determined by an automated dry combustion technique (Carlo Erba™, Milan, Italy). It was considered that CO_3^{2-} existed in the total C if the value of total C:total N was greater than or about 12. This particular C:N value was then replaced by the treatment average. Organic carbon was thus calculated as the product of total N and the corresponding value of C:N. Percent soil organic matter was estimated by multiplying soil organic C by 1.724.

4.3.3 Laboratory Measurement of Soil Thermal Conductivity

For laboratory studies, edged plastic tubes (12 cm diam. by 25 cm long) with pre-drilled holes at 2.5, 7.5 and 15 cm were used. In the spring of 1995, the tubes were pushed into soil by a punch truck to collect triplicate sets of undisturbed soil cores to a 20 cm depth at randomly selected sites between two pairs of the paired-row treatment. The soil surface was carefully maintained at the prescribed 0 level on the tube. The cores were brought to the laboratory, saturated by sprinkling water on the soil surface (covered by paper towel) and left at room temperature (about 22 °C) for about 48 h. Soil thermal conductivity measurements began when water content was near field capacity. The line source heat probe (Model TC-20, Soiltronics, Burlington, WA) used was 60 mm long and 0.90 mm in diameter. During the measurements, the probe was inserted into the soil samples horizontally through the pre-drilled holes at each depth. A heating cycle of 100 s using 2.5 V was applied and the probe temperatures were recorded at 1-s intervals using a data logger (CR21X, Campbell Scientific, Logan, UT). The temperature rise registered during the first 6 s was not used in the calculation, as the measurements were considered to be influenced by the probe. Soil water was measured at the same depth with the TDR (Model 1502C, Tektronix, OR) by inserting the waveguide (10 cm long) into the horizontally-drilled holes. The holes were kept sealed except during the measurements. At least five replications of measurements were done under different soil water contents. Volunteer wheat plants were cut off during the measurement process.

Volumetric water content and temperature of the soil were also measured under field conditions (Chapters 2 and 3).

4.3.4 Calculations and Analyses

Analyses of variance were performed on soil texture, organic carbon content and bulk density by using the General Linear Model (GLM) procedure in SAS (SAS Institute, 1990). Fisher's protected least significant difference method (Steel and Torrie, 1980) was used for comparison of means.

To compare the soil water retention characteristics under different treatments, first the relationship between matric pressure (P) and soil water content (θ) was established by using the following equation:

$$\log(\theta) = b + a\log(P) \qquad (8)$$

where a and b are coefficients. Analysis of covariance was then applied to test the heterogeneity of slopes (a) for different treatments by using the GLM procedure in SAS (SAS Institute, 1990). If the slopes were not significantly different, analysis of variance was performed to examine the differences between treatment means.

For θ in the range of 0.75 to 0.40 $m^3 \ m^{-3}$ at 20 °C, soil λ was calculated by using the computerized de Vries model (Tarnawski and Wagner, 1992) and α was determined as the ratio of λ to C_v. A regression was performed on the calculated λ data and the following equation derived:

$$\lambda = d + c(\log(\theta))^2 \qquad (9)$$

where c and d are coefficients. The differences between slopes (c) of Eq. (9) for various treatments were then tested by using the procedures of analysis of covariance. If the slopes were not significantly different, analysis of variance was performed to examine the differences between treatment means.

4.4 RESULTS AND DISCUSSION

4.4.1 Soil Texture, Organic Carbon Content and Bulk Density

Since soil disturbance from conventional tillage was limited to the 0 to 12 cm layer, only the results from 0 to 10 cm are presented. Soil particle-size distribution, organic carbon content and bulk density under different treatments are shown in Table 4-1. Except for a few cases, none of the above soil properties were significantly affected by crop rotation and/or tillage treatments. Soil organic carbon content decreased and soil bulk density increased as soil depth increased. For example, organic carbon content was in the range of 2.0 to 2.2% in the 0 to 5 cm depth interval and 1.8 to 2.0% in the 5 to 10 cm depth interval. Soil bulk density ranged from 1.2 to 1.3 Mg m^{-3} in the 0 to 5 cm depth interval and 1.3 to 1.4 Mg m^{-3} in the 5 to 10 cm depth interval.

4.4.2 Measured Soil Thermal Conductivity

Soil λ values measured with the line source heat probe at 2.5 and 7.5 cm depths are presented in Fig. 4-1. At 2.5 cm, the WF rotation showed slightly lower λ values than the continuous-cropped rotations. With soil water content at 0.2 $m^3 m^{-3}$, for example, λ value for WC, WF, and WW rotation was about 1.2, 0.9, and 1.1 W m^{-1} K^{-1}, respectively. No significant differences in λ were found between the two tillage systems. The λ values at 7.5 cm were generally higher than those at 2.5 cm. However, crop rotation and tillage treatment did not significantly affected soil λ at 7.5 cm.

4.4.3 Predicted Soil Thermal Properties

According to Eq. (6), C_v of the soil is a linear function of soil water content. At a certain water content, therefore, no significant differences were expected among the C_v values of various treatments since properties such as soil organic carbon content and particle-size distribution had not been significantly altered by the crop rotation and tillage treatments. Further, differences in α due to treatments should also follow those of soil λ. Consequently, discussions of crop rotation and tillage effects on soil thermal properties will focus mainly on soil λ.

The λ values of the soil estimated from the de Vries model as a function of the soil water content (θ) under CT and ZT with various crop rotations are presented in Fig. 4-2. At θ less than 0.2 m^3 m^{-3}, water bridges for heat conduction were gradually formed from one grain to another and λ increased rapidly with increasing θ. λ continued to increase with further increases in θ but at slower rates.

Table 4-2 presents the estimated coefficients for Eq. (9) under various crop rotation and tillage treatments at 20 °C with soil water ranging from 0.075 to 0.40 m^3 m^{-3}. The slopes of the fitted lines were equal and therefore the differences of least-square means were tested for all the treatment combinations (Table 4-3). In the case of crop rotation treatment, the WW rotation had the highest λ values at 0 to 5 cm depth interval under both tillage systems. The WC rotation showed higher λ values than the WF rotation under ZT in the 0 to 5 cm depth interval. At 5 to 10 cm depth interval, however, λ values were in the order of WW > WF > WC under CT and WF > WW > WC under ZT, respectively. Change of soil λ by tillage depended on soil depth and crop rotation treatment. In the 0 to 5 cm depth interval, significantly higher λ values on ZT than on CT were evident only under the WC rotation. In the 5 to 10 cm depth interval, however, λ values were increased by ZT on both the WC and WF plots. Soil λ increased with soil depth and the changes were greatest for the WF rotation.

According to de Vries (1963), thermal conductivity of bulk soil should not be influenced by particle size, assuming that sand, silt and clay particles have similar mineralogical properties, i.e., individual grains of similar shapes and packed to the same density should have similar conductivities. Other soil conditions that may affect soil thermal properties are bulk density, age hardening of soil, water release characteristics, heat convection, water content, water vapor diffusion, and convection of water vapor (Kaune et al., 1993).

Influences of soil bulk density on soil thermal conductivity have been well documented (Allmaras et al., 1977, Hay et al., 1978, Hopmans and Dane, 1986, and Kaune et al., 1993). A lower bulk density implies less solid matter per unit volume soil and poorer thermal contacts and therefore, smaller C_v, λ and α values. Treatments with higher bulk densities showed higher λ values indicating a strong linear relationship between soil bulk density and λ at both soil depth intervals (Fig. 4-3). In the 0 to 5 cm depth interval, for example, soil bulk density ranged from 1.20 to 1.31 Mg m^{-3} (Table 4-1) while λ varied from 0.83 to 0.93 W m^{-1} K^{-1} (Table 4-3). The corresponding ranges for the 5 to 10 cm depth interval were 1.30 to 1.41 Mg m^{-3} and 0.92 to 1.04 W m^{-1} K^{-1}.

Soil water retention characteristics with different crop rotation and tillage treatments are presented in Fig. 2-4. Except for the WW rotation at 5 to 10 cm, the CT treatment generally retained a higher amount of water at lower matric pressures but a lower amount of water at greater matric pressures than the ZT treatment. In the 0 to 5 cm depth interval, for example, the CT treatment had 0.06 $m^3 m^{-3}$ more water at 0.03 MPa than the ZT treatment but 0.02 $m^3 m^{-3}$ less at 15 MPa. This suggested that the conventional tilled soil had less water-filled pores than the zero-tilled soil, since soil bulk density was not significantly different between the two systems. The decrease in water-filled pores by the tillage operation probably caused a reduction of λ values in comparison to zero tillage under WC and WF rotations (Fig. 4-3). Nevertheless, other factors probably also contributed to the differences in λ and α values between CT and ZT. With the WF rotation, for example, λ values for the CT and ZT treatments were identical at 0 to 5 cm depth interval, although ZT showed greater water holding capacity than CT at higher matric pressures. Influences of crop rotation treatments on soil pore-size distribution were not significant, as indicated by the similar slopes of the fitted lines among WC, WF, and WW under a given tillage system (Fig. 2-4).

Allmaras et al. (1977) observed that soil α increased about 25% as soil was packed after plowing, primarily due to the decrease of soil porosity. In a study by Johnson and Lowery (1985), α in the 5 to 10 cm zone was 20 to 25% higher in a ZT treatment than in moldboard plowing and chisel plowing treatments. Potter et al. (1985) also reported that under similar soil bulk density and water conditions, soil λ under ZT was at least 20% higher than under CT. In this study, λ values under ZT were 4 to 8% greater than under CT system. In some cases, there were no significant differences in λ between the two tillage systems (e.g., on WW). This was possibly caused by the fact that the soil samples were collected during winter wheat growing season for all the crop rotations and the soil disturbance associated with CT was limited to within a 12-cm soil layer. Furthermore, the residue effects of the soil disturbance by tillage and seeding operations might not have been significant after seven months.

Many researchers have successfully used the de Vries method to predict the λ of soil (Wierenga et al., 1969, Hopmans and Dane, 1986). Hadas (1977) pointed out that the de Vries model underestimated λ under nonsteady state conditions. This study showed good agreement between the predicted and the experimentally determined λ values at lower soil water contents (Fig. 4-4). However, at higher water contents, λ was underestimated by 15 to 20% using the de Vries model. The apparent inconsistency may be attributed to three factors. First, the line source heat probe measured λ at a given soil depth which was assumed to represent the soil layer while the prediction of the de Vries model was based on the average properties of the soil layer. Second, at high water contents, convective flow of liquid water from hot to cold areas of the probe likely occurred during heating of the probe. Consequently λ was increased due to the loss of heat caused by water movement. Finally, latent heat transfer by vapor movement at intermediate water contents probably also contributed to the greater measured values and the underestimations from the de Vries model.

According to the Fourier's law of heat conduction, for a given amount of heat input into the soil, an increase of λ reduces the temperature gradient of the soil. Consequently, the upper profile of the ZT plots would be cooler during the daylight hours and warmer at night than that of the CT plots on a typical summer day. Under field conditions, however, most of the temperature variations were accounted for by factors other than λ (i.e., amounts and distribution of surface residue, albedo, and water content). On May 2, 1994, for example, the gradient of daily average temperature on CT (0.42 °C) was 1.27 times that on ZT (0.33 °C) in the 2.5 to 5-cm depth under WC rotation (Table 4-3). On the other hand, calculated soil λ value of ZT was similar (1.03 times) to that of CT in the 0 to 5-cm depth interval. Therefore, soil heat flux on CT plots was 1.23 times that on ZT plots.

4.5 SUMMARY AND CONCLUSIONS

Estimates of soil thermal properties were obtained for a long-term crop rotation and tillage experiment. At a given soil water content, there were no significant differences in volumetric heat capacity (C_v) among various treatments because of the similarities in particle-size distribution and organic matter content. With the WC and WF rotations, the values of predicted apparent heat conductivity (λ) for the ZT treatment were 4-8 % higher than those of the CT treatment, due to the small differences in soil bulk density and water retention characteristics. Tillage treatment did not change soil λ on the WW rotation. Under similar soil water conditions, variations of λ among crop rotation treatments were mainly due to the differences in soil bulk density. In the 0 to 5 cm zone, λ values tended to be lower with the WF rotation than the continuous-cropped rotations. At the 5 to 10 cm zone, however, λ values were the lowest for the WC rotation. Treatment effects on apparent thermal diffusivity (α) followed the same pattern as λ.

The measured λ values were generally in agreement with those calculated by the de Vries model at lower water contents. However, the measured values were 15 to 20% higher than predicted from the de Vries model, due to inaccuracies in both methods caused by latent heat transfer in both liquid and vapor phases.

Despite the changes of soil λ and α by tillage operations, soil temperature variation between treatments was largely attributed to the differences in the amount and distribution of crop residue on the soil surface.

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Table 4-1. Selected soil properties under different crop rotation and tillage treatments.

Soil depth	Crop rotation	Tillage	Particle-size distribution			Organic C content	Bulk density
			Sand	Silt	Clay		
cm			%				Mg m^{-3}
0-5	WC†	CT	34.5 ± 1.0ab‡	27.8 ± 1.0a	37.8 ± 0.1ab	2.02 ± 0.13a	1.20 ± 0.01a
		ZT	36.7 ± 0.3a	25.5 ± 0.8a	37.9 ± 1.0ab	2.15 ± 0.18a	1.27 ± 0.01a
	WF	CT	34.4 ± 2.9ab	26.4 ± 0.7a	39.3 ± 2.2a	2.00 ± 0.09a	1.20 ± 0.08a
		ZT	33.9 ± 2.4ab	27.6 ± 0.6a	38.6 ± 1.8ab	1.99 ± 0.16a	1.20 ± 0.05a
	WW	CT	32.9 ± 0.7b	29.6 ± 2.5a	37.6 ± 1.8ab	2.14 ± 0.09a	1.31 ± 0.01a
		ZT	31.8 ± 0.4b	29.9 ± 0.1a	37.1 ± 1.3b	2.13 ± 0.24a	1.23 ± 0.06a
5-10	WC	CT	35.0 ± 0.4a	26.8 ± 1.0a	38.3 ± 0.6a	1.98 ± 0.13a	1.30 ± 0.03a
		ZT	33.0 ± 0.5a	28.5 ± 0.4a	38.6 ± 0.8a	2.04 ± 0.20a	1.34 ± 0.07a
	WF	CT	34.9 ± 1.3a	25.5 ± 1.6a	39.6 ± 0.3a	1.93 ± 0.19ab	1.35 ± 0.03a
		ZT	35.9 ± 2.4a	25.5 ± 0.6a	38.6 ± 1.8a	1.81 ± 0.23b	1.41 ± 0.13a
	WW	CT	32.8 ± 1.7a	29.9 ± 2.2a	37.3 ± 0.4a	2.02 ± 0.07a	1.36 ± 0.00a
		ZT	33.3 ± 1.0a	27.9 ± 2.1a	38.9 ± 1.1a	1.94 ± 0.12ab	1.37 ± 0.04a

† WC = winter wheat - canola, WF = winter wheat - fallow, WW = continuous winter wheat, CT = conventional tillage, and ZT = zero tillage.

‡ At a given depth interval, means followed by the same letter in the same column do not differ significantly at $P \leq 0.05$.

Table 4-2. Coefficients for Eq. (9) under various crop rotation and tillage treatments with soil water content ranging from 0.075 to 0.40 $m^3\ m^{-3}$ at 20 °C.

Crop rotation	Tillage	0-5 cm			5-10 cm		
		Slope (c)	Intercept (d)	R^2	Slope (c)	Intercept (d)	R^2
WC	CT	-0.13	1.18	0.9946	-0.14	1.30	0.9965
	ZT	-0.14	1.27	0.9955	-0.15	1.34	0.9955
WF	CT	-0.14	1.18	0.9938	-0.15	1.35	0.9957
	ZT	-0.13	1.18	0.9927	-0.15	1.43	0.9966
WW	CT	-0.14	1.30	0.9964	-0.15	1.36	0.9966
	ZT	-0.14	1.29	0.9956	-0.15	1.37	0.9961

† WC = winter wheat - canola, WF = winter wheat - fallow, WW = continuous winter wheat, CT = conventional tillage, and ZT = zero tillage.

Table 4-3. Apparent soil thermal conductivity (λ) calculated using the de Vries model as affected by various crop rotation and tillage treatments at 20 °C. λ values are the means with θ ranging from 0.075 to 0.40 $m^3 m^{-3}$.

Crop rotation	Tillage	λ 0-5 cm	λ 5-10 cm
		$W m^{-1} K^{-1}$	$W m^{-1} K^{-1}$
WC†	CT	0.83 c‡	0.92 d
	ZT	0.90 b	0.96 c
WF	CT	0.83 c	0.96 c
	ZT	0.83 c	1.04 a
WW	CT	0.93 a	0.98 b
	ZT	0.92 a	0.99 b

† WC = winter wheat - canola, WF = winter wheat - fallow, WW = continuous winter wheat, CT = conventional tillage, and ZT = zero tillage.

‡ Means followed by the same letter in the same column do not differ significantly at $P \leq 0.05$.

Table 4-4. Water content (θ), apparent thermal conductivity (λ) and temperature of the soil in the 0 to 5-cm zone for CT and ZT under WC on May 2, 1994.

Treatment	θ	λ	Temperature 2.5-cm	 5.0-cm
	$m^3\ m^{-3}$	$W\ m^{-1}\ K^{-1}$	°C	
CT†	0.19	0.81	10.23	9.81
ZT	0.21	0.84	9.12	8.79

† CT = conventional tillage and ZT = zero tillage.

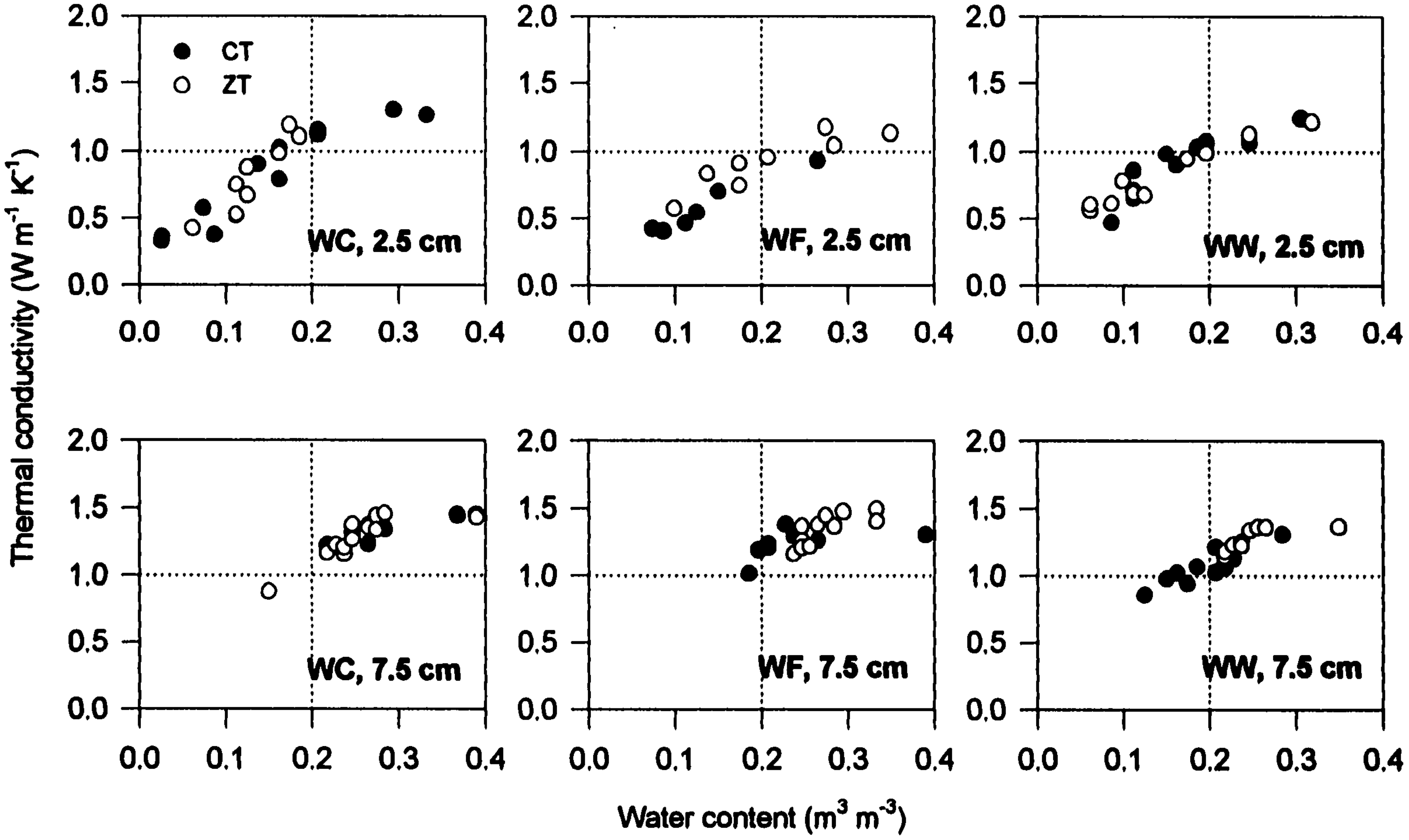

Fig. 4-1. Apparent thermal conductivity of the soil measured by using the line source heat probe method.

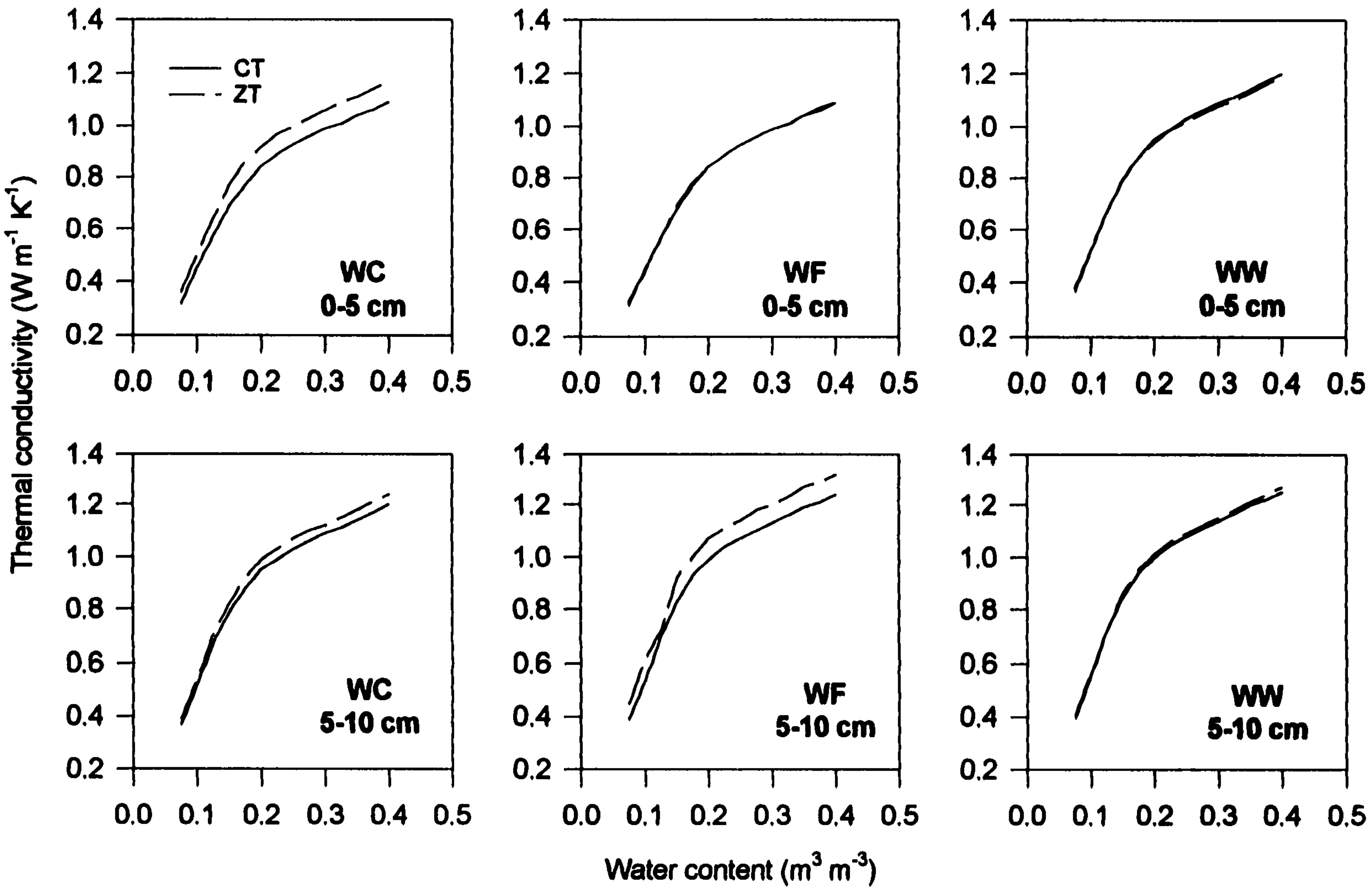

Fig. 4-2. Apparent thermal conductivity as affected by soil water content under CT and ZT with different crop rotation treatments at 0 to 5 cm and 5 to 10 cm with temperature at 20 °C.

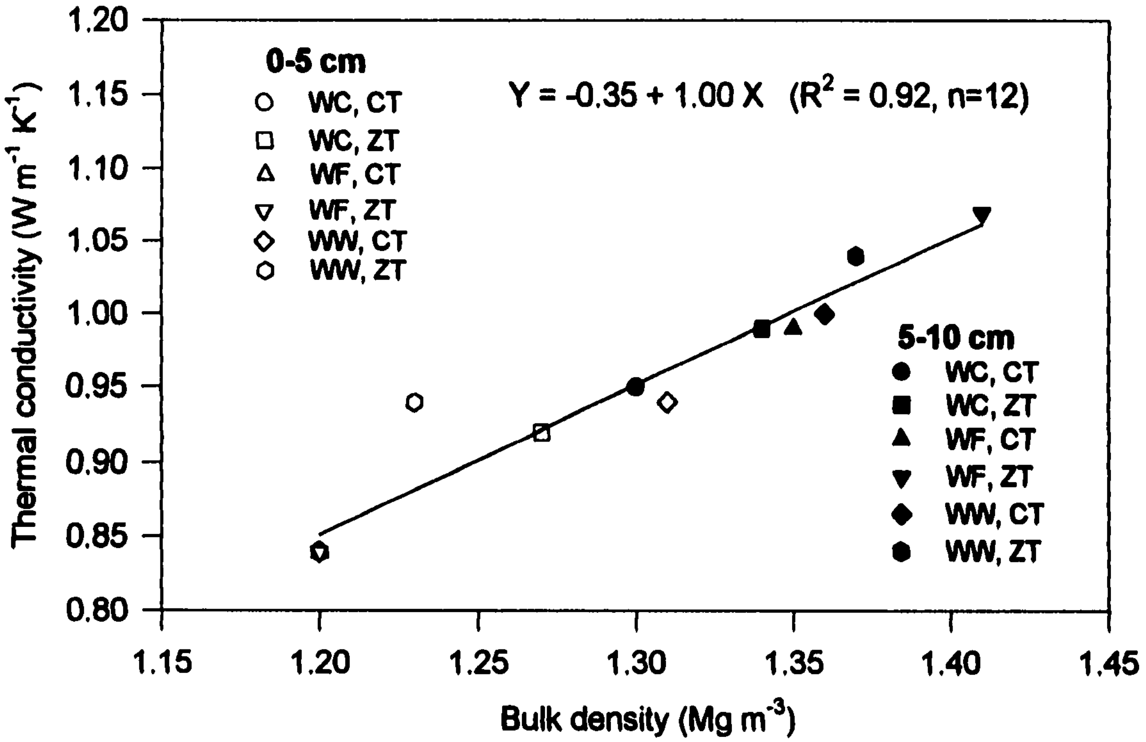

Fig. 4-3. Apparent thermal conductivity as affected by soil bulk density at 20 °C with soil water content at 0.2 m^3 m^{-3}.

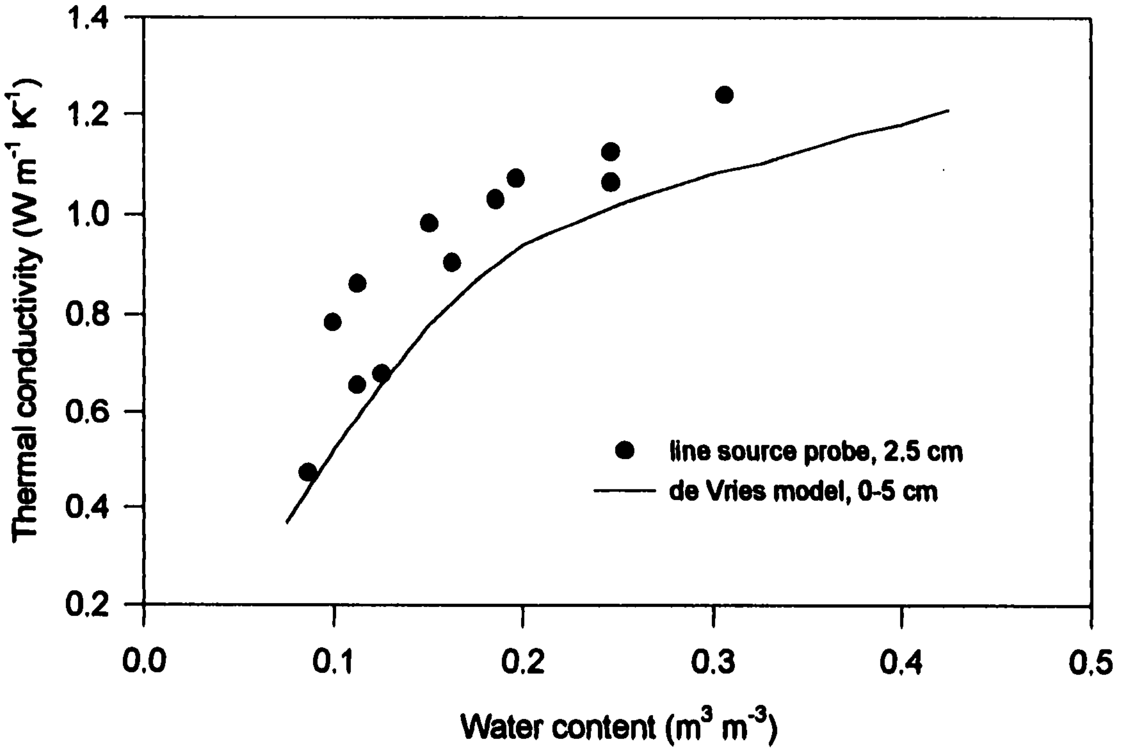

Fig. 4-4. Comparison of measured (line source heat probe method) and estimated (de Vries model) apparent thermal conductivity of the soil for WW under CT.

CHAPTER 5

INFLUENCES OF CROP ROTATION, TILLAGE, AND ROW SPACING ON WINTER WHEAT PERFORMANCE

5.1 INTRODUCTION

Conservation tillage can modify soil temperature and soil water regimes and therefore modify plant growth (McCalla and Army, 1961; Unger and Phillips. 1973; Unger and McCalla, 1980; Smika and Unger, 1986). However, the extent of the effects depend on amount of residue cover, infiltration rate of the soil, water storage capacity of the soil and evaporation potential of the climate (Prasad and Power, 1991) and are closely related to cropping systems and crop rotations, fallow length and types (Unger and Phillips, 1973). In the semi-arid regions of the Canadian Prairies, Lindwall and Anderson (1981) showed that crop production could be enhanced with zero tillage. Carter and Rennie (1982) observed improved surface (0-5 cm) soil water regimes under zero tillage, although there was no differences in total soil water conserved. Carefoot et al. (1990) observed higher total soil water (0-120 cm) and grain yield with zero tillage than with conventional tillage due to increased snow trapping and/or reduced evaporation with zero tillage in the spring.

However, those results have generally been limited to spring wheat and in a single crop rotation. Little information exists for the performance of winter wheat in conservation tillage systems with various crop rotations. A study by

Lindwall et al. (1995) concluded that a management system which incorporates zero tillage into a 3-y rotation (wheat-barley-fallow) is best suited for winter wheat production in southern Alberta. Other studies indicated that soil water changes and production of winter wheat were more closely associated with crop rotation than with the method of tillage used (Larney and Lindwall, 1994, 1995). Izaurralde et al. (1994) reached similar conclusions for three annual crops/cropping systems in central Alberta.

Seed drill performance is another factor affecting the adoption of conservation tillage by winter wheat producers. Generally the paired-row seeding (disc drill) performs well under ideal seedbed moisture while the uniform-row seeding (hoe-drill) provided more effective seed placement than the paired-row seeding under drier soil conditions (Tessier et al., 1991, Lindwall et al., 1994, Larney and Lindwall, 1994).

The challenge therefore remains to develop an integrated management system which uses appropriate crop sequence and tillage methods along with effective seeding techniques for winter wheat production. The objectives of this study were to evaluate the establishment, early growth and crop yield of winter under management systems involving various crop rotations, tillage methods and row spacings. Effects of soil thermal and water conditions associated with different management practices on winter wheat production were also discussed.

5.2 MATERIALS AND METHODS

The study was conducted during the 1993/94 and 1994/95 winter wheat seasons on an Orthic Dark Brown Chemozemic soil (Typic Haploboroll) near the Agriculture and Agri-Food Canada Research Center, Lethbridge, Alberta (49°42'N, 112°47'W, elevation 915m). The Ap soil horizon is a sandy clay loam with 34% sand and 38% clay. Organic carbon content is approximately 1.9% in the 0-20 cm depth. The mean annual precipitation is 402 mm.

The experiment was initiated in 1984 as a split-split-plot design (Larney and Lindwall, 1994). The main treatment was crop rotation, including continuous winter wheat, winter wheat-canola and winter wheat-fallow. The sub-treatments were conventional tillage (CT) and zero-tillage (ZT). The sub-sub treatment was row spacing that included uniform-row (UR) and paired-row (PR) seeding.

Fall band application fertilizer rates for winter wheat was 27 kg ha^{-1} N and 28 kg ha^{-1} of P_2O_5 below the seed followed by a broadcast application of 34 kg ha^{-1} of N the following spring. The canola received 34 kg ha^{-1} of N broadcast before seeding, and 9 kg ha^{-1} N and 40 kg ha^{-1} of P_2O_5 applied at seeding time. Chapter 2 gave the more detailed description of the experimental design and management practices.

During the establishment of winter wheat in the fall and when the plants were actively growing in the spring, gravimetric soil water contents were determined on four replications at 15-cm increments to the 1.5-m depth. Gravimetric soil water data were converted to a volumetric basis using bulk densities of soil cores taken from six soil profiles on the study sites (Beke, 1989). In the spring time, volumetric soil water contents were measured in two replications at 5, 10, 20, and 40 cm depths, both at the inter-row and intra-row positions (Fig. 2-1) with a TDR instrument (Model 1502C, Tektronix, OR). More information on TDR soil water measurements were given in Chapter 2.

Soil temperature was measured with thermocouples at six depths (2.5, 5, 10, 20, 40, and 80 cm) on inter-row and intra-row locations (Fig. 3-1). Incoming short wave radiation and air temperature and humidity at 1.5 m, wind speed at 2 m, rainfall were also measured in an adjacent fallow plot. Soil temperature and weather data were recorded with a data logger (CR7, Campbell Scientific, Logan, UT) in 2-minute intervals. Hourly average values were stored for all the variables, except for the tipping bucket rain gauge whose output was summed to give hourly totals.

Two repeated plant-density measurements (plants m^{-2}) per plot were made in the spring. In 1995, plant height (10 plants per plot) was recorded weekly from May to July. Winter wheat was harvested from a 57-m^2 area of the uniform-row plots and from a 61-m^2 area of the paired-row plots during late July/early August each year using a small plot combine.

Growing degree-days (GDD) were calculated with the following equation,

$$GDD = \sum_{i=1}^{N}((T^i_{max} + T^i_{min})/2 - T_b) \qquad (1)$$

where T^i_{max} and T^i_{min} respectively is the daily maximum and minimum soil temperatures at 2.5-cm depth for the i-th day, T_b (0 °C) is the base temperature and N is the number of days. The daily maximum and minimum temperatures are obtained from the hourly average temperature data. The starting date of GDD calculation was March 1 for 1994 and March 15 for 1995 when the daily average temperature at 2.5 cm was consistently above 0 °C.

Data analyses were conducted using the General Linear Model (GLM) procedure in SAS (SAS Institute, 1990). Fisher's protected least significant difference method (Steel and Torrie, 1980) was used for comparison of means.

5.3 RESULTS AND DISCUSSION

5.3.1 Weather and Soil Surface Conditions

The detailed weather conditions during the study period have been reported in Chapter 2. Basically the 1993/94 season was rather favorable for the growth and development of winter wheat and the 1994/95 season had very dry fall and overwinter periods.

The quantity of crop residue left on the soil surface was presented in Fig. 2-3. Under ZT, surface crop residue on the WF rotation amounted to only 19% of that on the WC rotation and 35% of that on the WW rotation. Under CT treatment, the WC and WW rotations had similar quantities of surface residue but there was negligible amount of surface residue on the WF plots.

5.3.2 Seedling Establishment

Delayed emergence and poorer establishment of winter wheat under zero tillage is often a major concern to producers in southern Alberta. Some researchers have reported crop establishment under ZT to be similar to that under CT, dependent on the moisture status at seeding time (Carefoot et al., 1990). In this study, there was a negative impact of ZT on plant density (Table 5-1). In 1994 and 1995, the CT system had 12 and 25 more plants per m^2 than the ZT system, respectively. Visual observation made after seeding revealed that the drills were not able to effectively penetrate the soil under ZT due to a thick and sometimes uneven distribution of crop residues, especially in the continuous-cropped rotations. No significant differences in plant density were found among crop rotation treatments and between PR and UR seeding methods.

Significant rotation by tillage interaction occurred in the 1994/95 season. The ZT treatment on WF rotation had 91 plants m^{-2} while the CT treatment on WW rotation had 105 plants m^{-2}. However, plant density differences between CT and ZT on the WF rotation were not significant during the same period.

Although the tillage by row spacing interaction was not significant, it appeared that PR performed poorly under zero tillage. On average, plant density with PR seeding were 20 and 9 greater under CT than under ZT in 1994 and 1995, respectively.

5.3.3 GDD and Crop Development

The relationships of plant growth to soil temperature are usually indicated by growing degree-days (GDD), the energy absorbed by soil over a given period of time. Zero tillage significantly reduced the values of GDD in the two study years (Table 5-2). On June 16, 1994 when crop canopy was completely established, the CT system had accumulated on average 90 more degree-days than the ZT system. GDD differences among crop rotation treatments were not statistically significant ($P \leq 0.05$). However, the WW rotation tended to accumulate more GDD than the other two rotations. PR seeding improved soil thermal conditions over UR seeding. During the period of April 15 to June 15, 1994, the PR seeding system accumulated 15-30 more GDD than the UR system. The observed differences of GDD (5-20) between the PR and UR systems in 1995 was not statistically significant.

In 1995, plants under the WF rotation were significantly taller than those in the continuous-cropped rotations (Table 5-3). Differences were small in earlier stages but became larger as the crop established full canopy (about 24 cm on June 9). Further canopy development reduced the difference between WF and the continuous-cropped rotations but WC showed higher plant heights than WW due to the infestation of WW plots by downy brome. On average, the CT system has taller plants than the ZT system, but the differences (maximum 5 cm) were much smaller than those between crop rotations. Differences in plant height due to row spacing were minimal and not statistically significant.

Notably, the variations in plant heights observed among crop rotation treatments did not appear to have been induced by soil temperature or GDD differences (Fig. 5-1). For example, at the time when plants were 80 cm tall, cumulative GDD on the WF, WC and WW plots were 540, 740, and 815 degree-days, respectively. Further examination revealed that changes in plant height as affected by crop rotation to be more related to soil water content to a 1.5-m depth in fall than to spring soil temperature (Fig. 5-2). On average, the WF rotation conserved 117 mm more water to a 1.5 m depth in fall 1994 and accordingly the plant height was 16 cm greater on July 5 than the continuous cropped rotations. Lack of water on the WC and WW rotations reduced crop growth and therefore, plant height.

For a given crop rotation, tillage treatment affected early crop growth by modifying soil temperature and the amount of GDD. For example, plants on the CT plots were 2 to 5 cm taller than those on the ZT plots from May 11 to June 22. However, the differences in plant growth disappeared later in the growing season.

5.3.4 Crop Yield

Crop rotation affected winter wheat yield differently in the two study years. The WF rotation produced significantly higher yield than the WC and WW rotations in 1994 (Fig. 5-3). This expected result was attributed to the greater soil water conservation on WF plots. In comparison with the WC treatment, the infestation of downy brome on the WW plots obviously reduced crop yields. In 1995, both the WW and WF rotations were seriously infested by downy brome later in the season and consequently, the WC rotation produced about 600 and 1000 kg ha^{-1} more than the WF and WW rotations, respectively.

Larney and Lindwall (1994) reported that ZT produced yields at least 5% higher than CT in 27 of 40 comparisons. This study, however, showed that ZT resulted in significantly lower crop yields than CT in 1994 and 1995 (Fig. 5-3). This was probably caused by the poor crop establishment (Table 5-1) and the earlier and dense infestation of downy brome resulting in water and nutrient depletion on the ZT plots, especially under the WW rotation.

Further investigation indicated that crop rotation, tillage and row spacing interactions were significant ($P < 0.1$) in both years. Analyses of variance were therefore performed within each crop rotation to evaluate the effects of tillage and row spacing treatments on crop production (Table 5-4). Crop yields under ZT were generally similar to (sometimes higher than) that under CT if winter wheat was seeded after canola or fallow. Under the WW rotation, however, crop yield with ZT was decreased by 12 to 17% in 1994 and 28 to 37% in 1995.

On average, winter wheat seeded with PR produced 6% less yield than that seeded with UR in 1994 and no significant differences were found between the two row spacing treatments in 1995 (Fig. 5-3). However, the performance of PR was closely related to crop rotation and tillage treatments (Table 5-4). Comparing to UR seeding, PR seeding decreased crop yield by about 10% on CT and 15 to 21% on ZT under the WW rotation. For the WF rotation, yield reduction with PR were 10 and 19% on ZT in 1994 and 1995, respectively. Under CT, however, crop yield was increased by 13% with PR seeding in 1994.

No consistent yield differences were found between PR seeding and UR seeding under the WC rotation.

Crop production of winter wheat was largely determined by soil water content at seeding time. In the 1993/94 season, for example, water content to a 1.5-m soil depth in fall explained 49% of the yield variation (Fig. 5-4). An 80 kg ha^{-1} yield increase of winter wheat is achieved with each additional 1 cm of water content at seeding time. The relationship between crop yield and soil water content to a 1.5-m depth was not clear in the 1994/95 season due to the confounding effects of downy brome.

5.4 SUMMARY AND CONCLUSIONS

Crop production of winter wheat in semi-arid southern Alberta was mainly determined by the amount of water in the soil profile at seeding. In 1994, an 80 kg ha^{-1} yield increase of winter wheat was achieved with each additional 1 cm of water in fall. High and consistent reserves of water to a 1.5-m depth at seeding time were observed in the WF rotation, which ensured good crop development and high grain yield, although soil thermal conditions under WF were not favorable during earlier plant growth. Therefore, summerfallow may remain as a necessary option in crop rotations for producers. Yet there is still a risk of downy brome infestations for WF rotations (e. g., in 1995). Continuous cropping winter wheat, with low soil water content and high probability of downy brome infestation, resulted in poor crop yields and should not be adopted in this region.

Inclusion of canola in winter wheat rotation systems could be recommended due to the favorable crop production (3588 and 4453 kg ha^{-1} in 1994 and 1995, respectively) and resistance to downy brome invasion. However, yield reduction may be expected with WC under drier than normal weather conditions (Larney and Lindwall, 1994). Unless downy brome is effectively controlled, a 3-y crop rotation, winter wheat-canola-fallow, may be best suited for winter wheat production in semi-arid southern Alberta.

Significant yield reduction with ZT was observed under the WW rotation, due to poor plant establishment and the infestation of downy brome. Crop yields with ZT compared favorably to CT under WC and WF rotations during the study period. With the additional advantages of protecting soil against wind erosion and enhancing soil water conservation, ZT is recommended for WC and WF rotations.

PR seeding performed poorly on the WW rotation. Heavier crop residue and poorer seed placement with the disc drill were significant factors. Moreover, PR seeded plots were more easily infested by downy brome than UR seeded plots under zero tillage. On the WF rotation, PR seeding outyielded UR seeding with CT in 1994, but not with ZT in both years. Yield differences between PR and UR treatments on the WC rotation were inconsistent. PR seeding may also be suitable under conditions when soil temperature is a limiting factor to plant growth since the operation produced a warmer environment than did UR seeding.

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Table 5-1. Seedling establishment with different crop rotation, tillage and row spacing treatments during the study period.

Treatment		Plant population	
		1994	1995
		plants m^{-2}	
Crop rotation	WC†	105a‡	115a
	WF	98a	111a
	WW	112a	141a
Tillage	CT	111a	135a
	ZT	99b	110b
Row spacing	PR	100a	114a
	UR	110a	131a

† WC = winter wheat - canola, WF = winter wheat - fallow, and WW = continuous winter wheat; CT = conventional tillage, ZT = zero tillage; and PR = paired-row and UR = uniform-row.

‡ For a given treatment, means followed by the same letter in the same column do not differ significantly at $P \leq 0.05$.

Table 5-2. Growing degree-days (> 0 °C) on selected days during the study period. Calculation was based on soil temperature at 2.5-cm depth.

Treatment		Growing degree-days					
		15/04/94	15/05/94	15/06/94	15/04/95	15/05/95	15/06/95
		degree-days					
Crop rotation	WC†	111a‡	414a	817a	84a	280a	696a
	WF	111a	427a	819a	63a	248a	647a
	WW	125a	446a	889a	93a	305a	724a
Tillage	CT	133a	461a	887a	95a	303a	717a
	ZT	98b	396b	796b	66b	260b	671b
Row spacing	PR	123a	441a	856a	82a	292a	723a
	UR	108b	416b	827b	78a	271a	664a

† WC = winter wheat - canola, WF = winter wheat - fallow, WW = continuous winter wheat; CT = conventional tillage, ZT = zero tillage; PR = paired-row, and UR = uniform-row.

‡ For a given treatment, means followed by the same letter in the same column do not differ significantly at $P \leq 0.05$.

Table 5-3. Plant height with different crop rotation, tillage and row spacing treatments in the 1995 growing season.

Treatment		Plant height							
		May 11	May 18	May 26	Jun 1	Jun 9	Jun 15	Jun 22	Jul 5
		cm							
Crop rotation	WC†	19.6b‡	29.2b	36.6b	49.9b	61.0b	72.7b	85.5b	102.8b
	WF	26.1a	39.0a	48.8a	67.5a	84.3a	95.8a	101.1a	114.1a
	WW	20.8b	29.2b	36.5b	51.1b	61.0b	72.0b	82.4b	93.9c
Tillage	CT	22.6a	33.4a	42.6a	58.4a	70.7a	82.7a	92.8a	103.0a
	ZT	21.7a	31.5b	38.7b	53.8b	66.8b	77.6b	86.6b	104.1a
Row spacing	PR	22.2a	32.4a	40.9a	55.6a	68.7a	80.1a	89.9a	103.0a
	UR	22.1a	32.5a	40.4a	56.7a	68.8a	80.3a	89.4a	104.2a

† WC = winter wheat - canola, WF = winter wheat - fallow, WW = continuous winter wheat; CT = conventional tillage, ZT = zero tillage; PR = paired-row, and UR = uniform-row.

‡ For a given treatment, means followed by the same letter in the same column do not differ significantly at $P \le 0.05$.

Table 5-4. Winter wheat yields as affected by crop rotation, tillage, and row spacing treatments during the study period.

Crop rotation	Tillage	Row spacing	1993/94	1994/95
			10^3 kg ha^{-1}	
WC†	CT	PR	3.55b‡	4.69a
		UR	3.61b	4.64a
	ZT	PR	3.30b	4.56a
		UR	3.89a	3.92b
WF	CT	PR	4.33a	3.56b
		UR	3.75b	3.52b
	ZT	PR	3.76b	3.65b
		UR	4.19a	4.53a
WW	CT	PR	3.01a	3.86a
		UR	3.34a	4.27a
	ZT	PR	2.50b	2.45c
		UR	2.95a	3.09b

† WC = winter wheat - canola, WF = winter wheat - fallow, WW = continuous winter wheat; CT = conventional tillage, ZT = zero tillage; PR = paired-row, and UR = uniform-row.

‡ Within each crop rotation, means followed by the same letter in the same column do not differ significantly at $P \leq 0.05$.

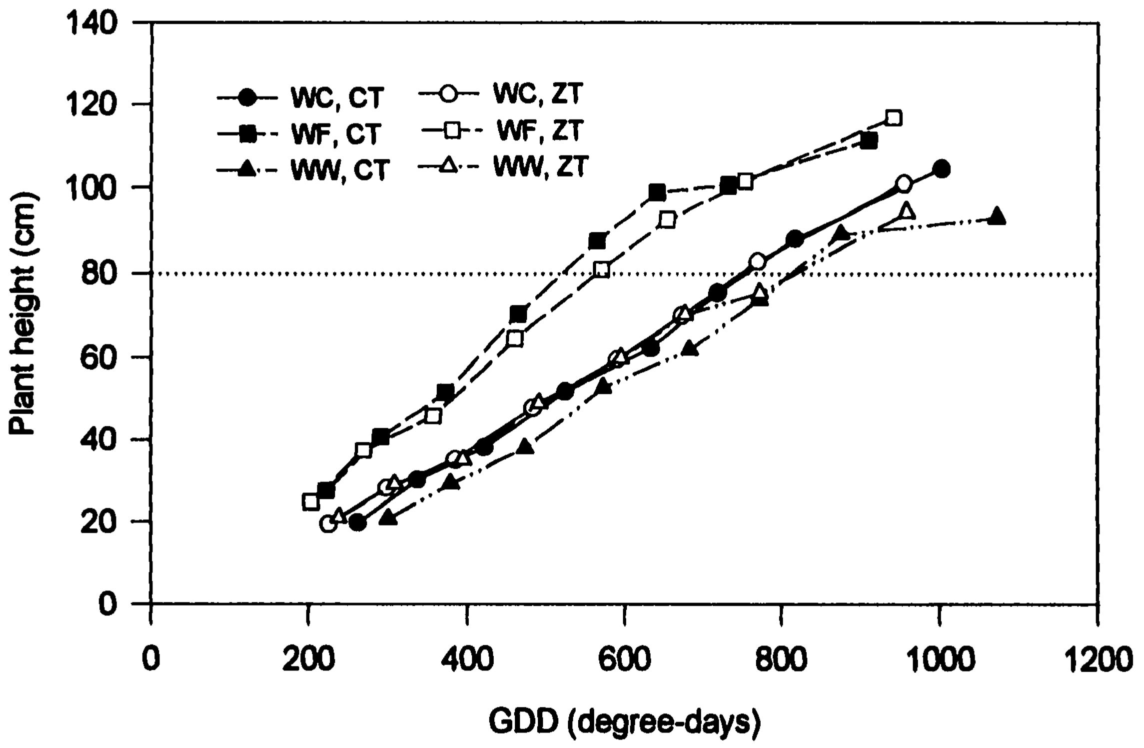

Fig. 5-1. Relationships between growing degree-days (GDD) and plant height as affected by crop rotation and tillage treatments in 1995.

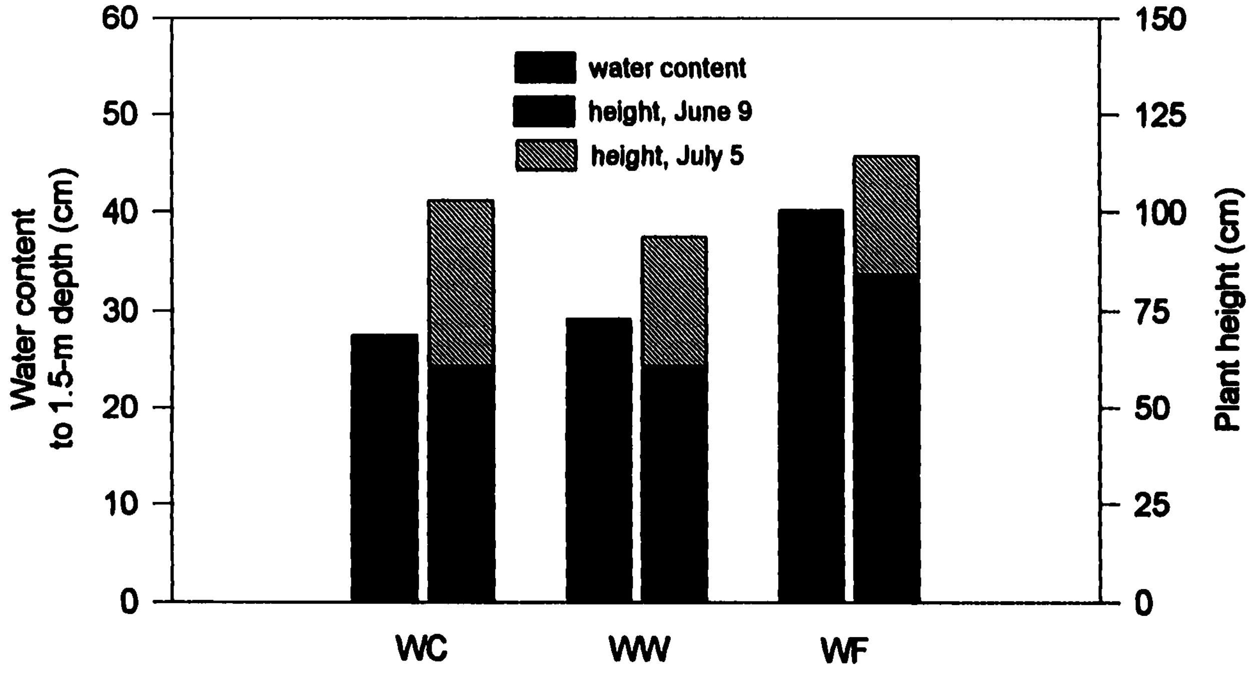

Fig. 5-2. Effect of soil water content to 1.5-m depth in fall 1994 on plant height measured on June 9 and July 5, 1995.

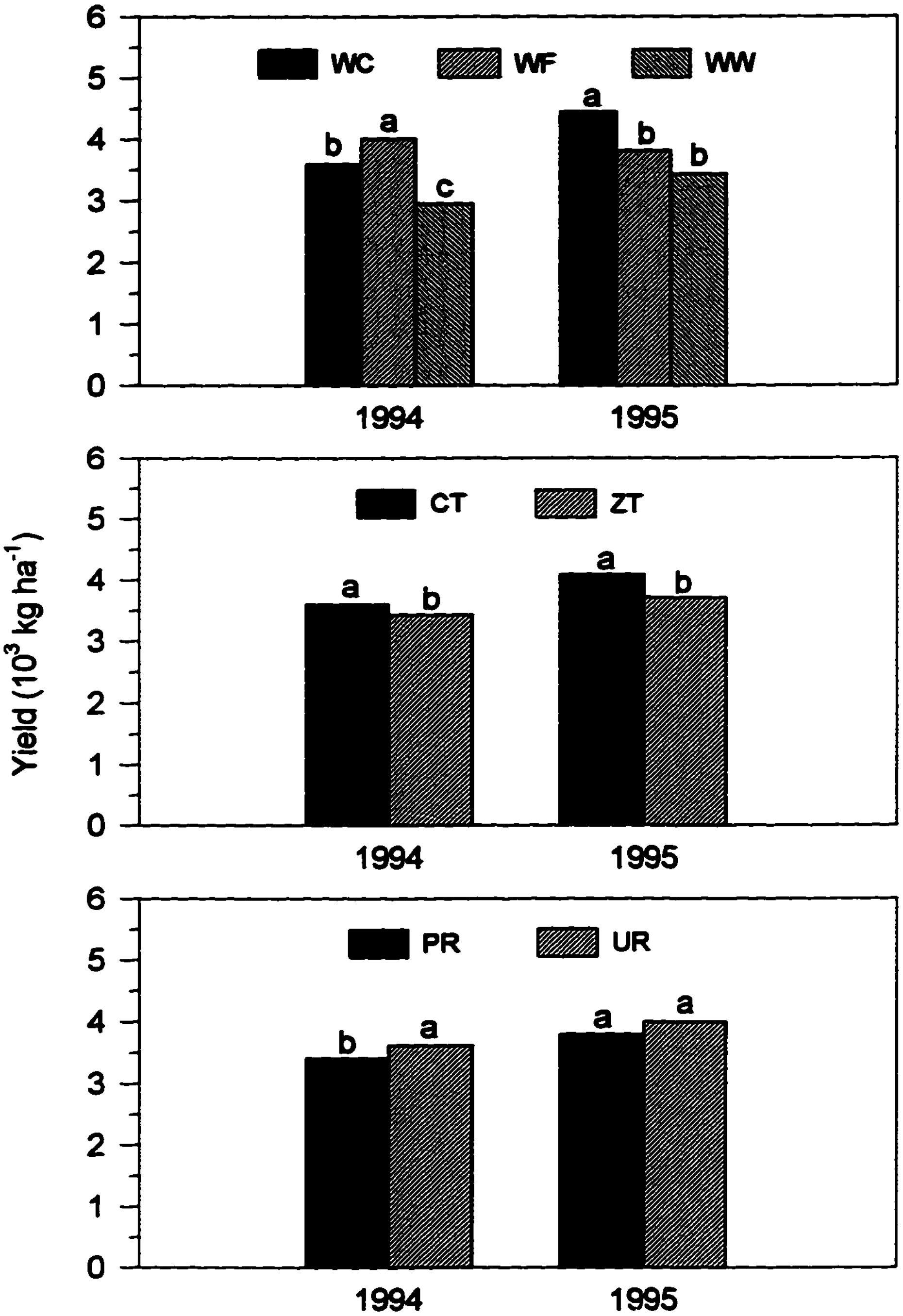

Fig. 5-3. Average crop yield of winter wheat for various treatments in 1994 and 1995. Same letters over bars indicate no significant differences between means ($P < 0.05$).

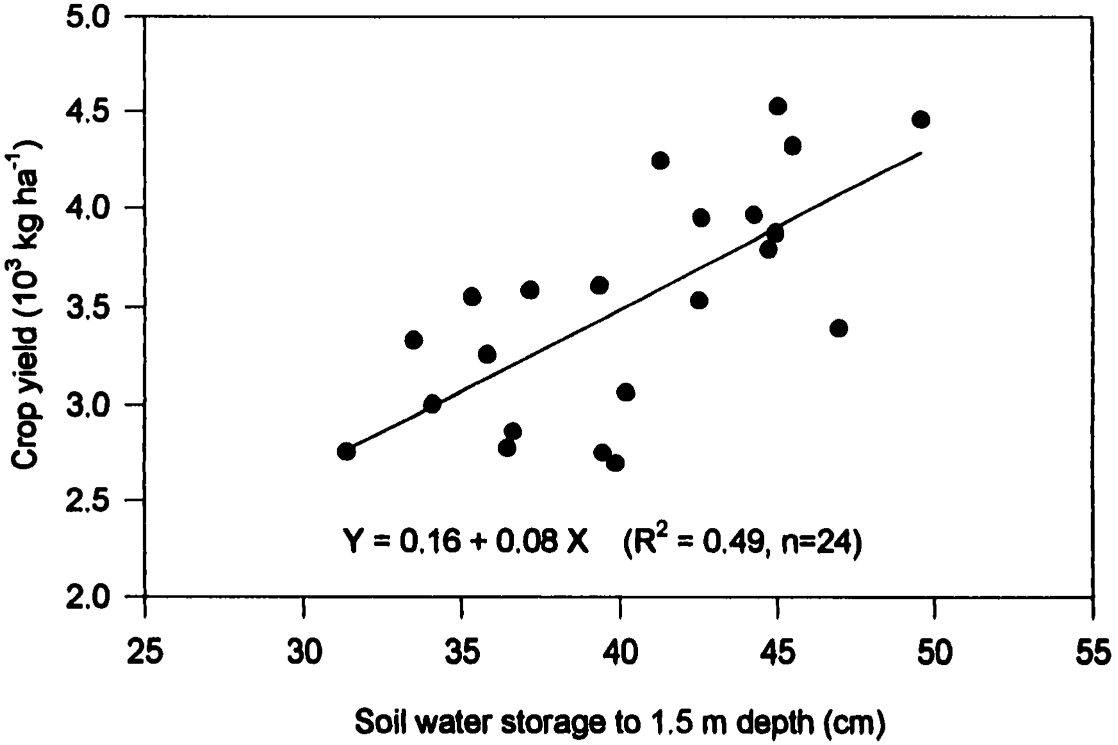

Fig. 5-4. Winter wheat yield as a function of fall soil water to 1.5-m depth for the 1993/94 growing season.

CHAPTER 6

GENERAL DISCUSSION AND CONCLUSIONS

A field study was conducted at Lethbridge, Alberta for 2 y to assess the effects of crop rotation, tillage, and row spacing on soil water and temperature regimes, early crop growth and grain yield of winter wheat. In the semiarid Canadian prairie, soil moisture conditions were largely related to precipitation patterns and crop sequence. In fall, winter wheat plots of the winter wheat-fallow (WF) rotation had between 70 and 120 mm more water to a 1.5-m depth than plots of the other two rotations (continuous winter wheat [WW] and winter wheat-canola [WC]. Corresponding differences in spring ranged from 40 to 70 mm. The favorable soil water condition with WF in the spring enhanced water movement deeper into the soil profile. During the overwinter period, however, the WF plots lost water while the WC and WW plots were partially recharged.

Zero tillage (ZT) seemed to be most effective in storing additional soil water on the WF rotation. During the overwinter period, soil water contents to 1.5-m depth on the ZT plots with WF rotation were almost constant at 450 mm, under both wet (1993/94) or dry (1994/95) conditions. With the continuous-cropped rotation, however, the benefits of ZT were very dependent on weather conditions. When soil water was replenished in the fall and precipitation was near normal over winter, ZT increased overwinter water content by increasing infiltration and decreasing evaporation. ZT did not show any advantage over conventional tillage (CT) with dry soil profiles in fall and less than normal precipitation over winter.

Crop rotation and tillage management interactively determined soil temperature regimes, mainly by modifying soil water content and surface conditions. In the 1993-94 season, the -5 °C isotherm on the WC plots was 15 cm deeper than on the WF plots, due to the low soil water contents. On the continuous-cropped rotations, ZT increased overwinter soil temperature and depressed temperature variations by leaving crop residue, reducing wind speed and maintaining snow cover on the soil surface. Contrary to studies in other areas of the Canadian prairies (Gauer et al., 1982), no winter-kill was observed in this study.

Three stages were identified in spring soil temperature variations as affected by different treatments. Early in the year as the soil was warming-up, differences in soil surface characteristics (e.g., crop residue cover) controlled the differences in soil temperature among treatments. Soil temperature depression by ZT was most obvious at this stage. With increased thawing and intense latent heat transfer, the interactions of tillage and crop rotation became apparent since soil temperature was concurrently determined by surface residue cover and soil water content. Later in the season when a crop canopy covered the soil surface, crop rotation seemed dominated soil temperature differences. These trends, however, were often soil depth and weather (e.g., precipitation events) dependent.

Crop rotation and tillage treatments also affected the apparent heat conductivity (λ) of the soil. The ZT treatment had greater λ values than the CT treatment on the WC and WF rotations, due to the differences in soil bulk density and water retention characteristics. Assuming similar soil water conditions, variations of λ among crop rotation treatments were mainly caused by the change in soil bulk density. For the 0 to 5 cm zone, λ values tended to be lower with the WF rotation than in the continuous-cropped rotations. However, the WC rotation showed the lowest λ values for the 5 to 10 cm zone. Treatment effects on apparent thermal diffusivity (α) followed a similar pattern as observed with λ. In spite of the increases of soil λ and α with zero tillage, soil temperature variation between treatments was largely attributed to the amount and distribution of crop residue on the soil surface.

In comparison to the crop rotation and tillage treatments, row spacing configuration showed minor influence on soil water and temperature regimes. The poor crop establishment with the paired-row seeding probably contributed to the higher soil water contents compared to the uniform-row seeding, particularly in the WW rotation.

Analysis of crop growth and yield data indicated that successful winter wheat production in semi-arid southern Alberta was mainly determined by the amount of soil water content in fall. Consistent high water reserves to 1.5 m depth and minimum weed problems in the WF rotation ensured good crop development and high grain yield, although soil thermal conditions were sometimes not favorable during earlier plant growth. Therefore, summer fallow may still be a necessary option in crop rotations for producers. However, there continues to be a risk of downy brome weed infestations for WF rotations (e.g., in 1995). Continuous cropping of winter wheat, with low soil water content and high probability of downy brome infestation, resulted in poor crop yields and should not be recommended in this region. Inclusion of canola in winter wheat rotation systems could be recommended due to the favorable crop production and resistance to downy brome invasion. However, yield reduction may be expected with WC under drier than normal weather conditions as observed in other studies (Larney and Lindwall, 1994). A rotation that includes one year of fallow followed by winter wheat and then canola, may be best suited for winter wheat production in semi-arid southern Alberta.

ZT showed greater advantages in total water content in fall over CT under the WF rotation, yet no significant temperature reduction was observed. Therefore, producers using fallow in their crop rotation should consider ZT if weeds can be controlled economically. Seeding with uniform-row can enhance the advantages of ZT on WF rotation. Under the WC rotation, ZT has the advantages of protecting soil against wind erosion and enhancing soil water conservation. ZT should not be considered for continuous winter wheat due to the weed problem.

With the benefits of less soil disturbance and leaving more standing stubble for erosion protection and snow trapping (Tanaka and Aase, 1987), PR seeding can be used for winter wheat on WC rotation, with either conventional or zero tillage system, and on WF rotation with conventional tillage.

This two year study demonstrated that the effects of management practices on soil water and temperature regimes were highly complex and interactive. Interactions existed not only among the treatments (crop rotation, tillage, and row spacing), but also between soil water and temperature. Moreover, the dynamic nature of the soil surface (e.g., albedo, amount and color of residue) and weather conditions increased the complexity. Nevertheless, the outcomes of this study provide an impetus toward development of guidelines for integrated management practices (e.g., crop rotation, tillage, and row spacing) for winter wheat production in the semi-arid Canadian prairies. The results are also applicable in models for predicting soil water and temperature relationships as affected by various crop rotation and tillage systems.

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