COMPARATIVE RESPONSE OF CANOLA, FIELD PEA AND WHEAT TO ZERO TILLAGE

by

Sylvia Poppe

A Thesis
Submitted to the Faculty of Graduate Studies
in Partial Fulfilment of the Requirements
for the Degree of

MASTER OF SCIENCE

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Abstract

The comparative response of canola, field pea and wheat to zero tillage.

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Knowledge of the relative responses of different crop species to zero tillage is important for rotation planning in conservation farming systems. The performance of Katepwa wheat, Westar canola, and Victoria field pea was investigated under zero and conventional tillage on a sandy loam at Carman, MB, and on a clay loam soil at Portage la Prairie, MB, in 1989 and 1990. Parameters under investigation included dry matter accumulation, crop development, evapotranspiration (ET), soil water extraction, water use efficiency (WUE), plant water stress, yield, and quality. An additional study was done at Portage in 1990 examining the response of field pea and canola to zero tillage under simulated early season drought.

Effects of zero tillage on establishment, growth, yield, yield components and grain quality of these crops were limited. For grain yield, location and year were more important than tillage regime.

Differences in ET among crop species in response to zero tillage was greater in 1989, a dry year, than in 1990, a relatively wet year. The trends for ET were reflected in soil water depletion trends. In 1989, canola extracted more water at all depths under zero tillage compared with conventional tillage. However, zero tillage increased soil water extraction below 50 cm in field pea, and above 50 cm in wheat, compared to conventional tillage. At both sites in 1990 the trend was for less water

depletion below 90 cm under zero tillage. Higher WUE under zero tillage occurred three of 16 times and was attributed to a higher transpiration:ET ratio. A reduction in tillage enhanced WUE in field pea more frequently than in canola or wheat.

Relative water content measurements indicated that tillage affected the water status of canola and field pea more often than wheat. For canopy and leaf temperature measurements positive responses to zero tillage were more frequent at Carman than at Portage, possibly due to the sandier soil at Carman. Only one response to tillage was observed for leaf conductance. It can be concluded that these crops are all well adapted to production under a zero tillage system.

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List of Abbreviations

NS	Nonsignificant
T	Tillage
S	Species
TS	Tillage by species interaction
ET	Evapotranspiration
WUE	Water use efficiency
RWC	Relative water content
Portage	Portage la Prairie, Manitoba

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1.0 Introduction

The amount of agricultural land available on this earth is limited and most of it is presently in production. Degradation of this land base decreases it's potential for crop productivity and the efficiency with which crops can be produced. Soils on the prairies have been degrading rapidly ever since the beginning of intensive cultivation. With about 29% of the improved land on the Canadian prairies subject to moderate and severe wind or water erosion, and with cultivated soils on the prairies having lost 50 to 60% of their original organic matter (Dumanski, 1986), the productivity of the prairie land base is seriously threatened. In the past, when productivity decreases occurred for similar reasons in other parts of the world, people sometimes had the option of moving to new land to make a new start (Carter and Dale, 1974). However, now there is no new land. Therefore, it is imperative that presently productive agricultural land is carefully managed so that long-term productivity can be maintained. An important step in improving long-term sustainability of agriculture in western Canada is reducing the amount of tillage used in crop production. Zero tillage systems which maintain crop residue at, or near the soil surface are also effective in conserving water, increasing crop water use efficiency and in reducing energy usage (Unger, 1990).

To develop effective conservation tillage systems we must understand how the different crops that prairie farmers grow in their rotations respond to zero tillage. A considerable amount of research has been done in the United States to determine the effects of zero tillage systems on the productivity of crops such as corn *(Zea mays* L.), soybeans *(Glycine* *max* L.), sorghum *(Sorghum bicolor* L.) and winter wheat *(Triticum aestivum* L.). On the Canadian prairies, studies of crop response to zero tillage have focused mainly on cereals. Less research has been conducted on special crops such as field pea and canola, which are commonly grown in rotation with wheat in the Black soil zone of western Canada. In the past, most studies have concentrated on the effects of zero tillage on final yield. However, more information on the physiological consequences of zero tillage is required in order to more fully understand the effects of conservation tillage on the internal processes of plants.

The present study was initiated to compare the response of wheat *(Triticum aestivum* L.), canola *(Brassica napus* L.), and field pea *(Pisum sativum* L.) to a reduction in tillage. The first objective was to compare the growth, development, evapotranspiration, water use efficiency, grain yield, yield components and grain quality of these crops under zero and conventional tillage. A further objective was to determine the influence of zero tillage on soil water availability and on plant water status. Field experiments were conducted in two years and on two soil types, sandy and silty clay soils, to determine whether soil type and environmental conditions may modify the effect of zero tillage on these crops. The hypothesis of the present study was that zero tillage has no effect on the performance of these three crops.

2.0 Literature Review

Zero tillage in this discussion is defined as any crop production system which does not use tillage as a means of seedbed preparation, and in which the seeding operation is carried out with minimal soil disturbance.

2.1 Environmental Factors

Tillage systems can strongly affect the soil environment, including both soil temperature and soil water content (Unger, 1990). Therefore, observed differences in crop performance among tillage systems are often due to differences in soil environment. At times, conditions in the aerial environment exert a stronger effect on crop performance than tillage, thereby masking the effect of tillage. The effect of soil temperature, soil water availability, precipitation and air temperature on crop response to zero tillage will be examined in greater detail.

2.1.1 Soil Temperature

Zero tillage often reduces soil temperatures, especially during the spring when soils are warming up (Gauer et al., 1982; Wall and Stobbe, 1984; Gupta et al., 1988; Johnson and Lowrey, 1985; Potter, 1985). There are a number of reasons why soil temperatures under zero tillage are lower than those under conventional tillage. Spring soil temperatures are very closely related to the amount of soil residue cover since residue decreases thermal admittance and total heat inputs to the soil profile (Johnson and Lowrey, 1985; Potter et al., 1985). Soils under zero tillage are often wetter and, despite a higher heat diffusivity, require more heat to warm up than those under conventional tillage since water has a higher heat capacity than soil. For these reasons, maximum spring soil temperatures in northern regions such as the Canadian prairies may be 1 to 5°C lower under zero tillage than under conventional tillage (Carter and Rennie, 1985).

2.1.2 Soil Water Availability

Another modification of the soil environment that often occurs with zero tillage is an increase in available soil water (Gauer et al., 1982; Lafond and Loeppky, 1988; Wilhelm et al., 1989). Increased residue cover under zero tillage can increase soil water conservation because surface residues reduce runoff, increase infiltration, reduce evaporation, and increase snow trapping on fields (Smika and Unger, 1986). Wilhelm et al. (1989) showed that soil water content increased with each increase in the amount of surface residue cover. Water storage during the growing season was 30 to 33 mm greater when no residue was removed than when all residue was removed. Much of the increase in available soil water content observed under zero tillage occurs in the surface soil layers (0 to 30 cm) during times of frequent precipitation, although in some cases the water content of the entire soil profile is also increased (Lafond and Loeppky, 1988; Wilhelm et al., 1989).

2.1.3 Precipitation

The amount of precipitation received before and during the growing season is important in determining yield and crop growth responses to zero tillage. Previous studies have shown significantly higher yields for sunflowers (Deibert and Utter, 1989), soybeans and small grains (Baeumer and Bakermans, 1973) grown under zero tillage in dry years but equal or lower yields during wet years when compared to conventional tillage systems. The seasonal distribution of precipitation is also important in determining the amount of soil water conserved under zero tillage. For example, frequent rainfall events cause the moisture conserving aspect of the crop residue cover to be more effective than infrequent rainfall events (Unger, 1990). During long dry periods the effect of the residue on water conservation becomes less significant.

Rainfall distribution over the growing season is also important in determining crop response to tillage (Edwards et al., 1988). A lack of precipitation at sensitive crop development stages, such as at floral initiation, flowering, or grain filling (Richards and Thurling, 1978b; Entz and Fowler, 1988; Maurer et al., 1968) may mask any previously noticeable growth responses to tillage. Crops also differ in sensitivity to moisture stress at different stages and thus may differ in response to rainfall distribution under different tillage systems (Heath and Hebblethwaite, 1987).

2.1.4 Air Temperature

Air temperature is another environmental factor which can greatly modify crop response to zero tillage systems. While growth under zero tillage may be enhanced due to higher levels of available water, this effect may be masked if high temperatures occur at sensitive development stages. High temperatures at flowering can cause pollen and flower abortion and may affect the development of the fruit, thereby reducing yield (Hardwick, 1985; Nichols et al., 1985; Wilhelm et al., 1989; Jeuffroy et al., 1990). These stresses can have severe effects on crop yields which cannot be overcome by a favorable soil water environment.

2.2 Agronomic Responses to Zero Tillage

2.2.1 Crop Establishment

For maximum yields to be obtained, quick, uniform emergence of vigorous seedlings is desirable. Soil temperature and soil moisture are the factors most important in determining the effect of zero tillage on crop establishment. Crop residues remaining at or near the soil surface can also negatively affect crop emergence and early growth by shading the plants, by releasing residual herbicides (Klepper and Rickman, 1988) and by producing phytotoxins (Cochran et al., 1977).

The increased available soil water levels under zero tillage compared to conventional tillage can be advantageous to crop establishment especially in dry years when the extra moisture may be critical for germination and emergence. Adequate soil moisture is especially important for the establishment of small-seeded crops such as canola and alfalfa. Wolf and Edmisten (1989) found increased emergence, forage yields, and crop survival of alfalfa with better soil moisture conditions under zero tillage, while Donaghy (1973) found increased canola and flax emergence and establishment under zero tillage. Lafond (1991) found plant stands of field pea and wheat, large-seeded crops, were not affected by a reduction in tillage. Extra soil moisture and residue mulch may also prevent soil crust formation which otherwise decreases the emergence of crops with hypogeal emergence (White and Robson, 1989), such as canola. Field pea, which has an epigeal type of emergence, is also sensitive to surface crusting (Dawkins and McGowan, 1985). Therefore, under dry conditions, zero tillage provides a more favorable soil environment for crop establishment.

Under wet conditions, zero tillage can be detrimental to crop establishment. Soils may become waterlogged resulting in poor aeration, which inhibits germination and emergence (Klepper and Rickman, 1988). Wet soils may also be conducive to the development of diseases such as common root rot *(Cochliobolus sativus)* (Klepper and Rickman, 1988). Plants with root systems which are damaged early in their development often continue to display the effects by having poor growth, an inability to cope with subsequent stresses, and lower productivity (Wilhelm et al., 1989).

Lower spring soil temperatures under zero tillage are beneficial for the initial growth and establishment of corn and soybeans in southern regions where soils are often too hot and dry for good crop establishment under conventional tillage (Doran et al., 1984; Ojeniyi, 1986). However, in temperate regions such as the Canadian prairies, lower spring soil temperatures can significantly delay early crop development resulting in decreased yield and quality. In this region, warm season crops such as corn are often most sensitive to zero tillage (Wall and Stobbe, 1983; Gupta et al., 1988). Emergence and early development of cool season crops such as wheat, canola and field pea are not as sensitive to low soil temperatures as corn. Gauer et al. (1982) and Carter and Rennie (1985) found that spring wheat has a broad temperature tolerance in the germinating phase, while Kondra et al. (1983) found *Brassica napus* cultivars to be relatively insensitive to low temperatures during germination and emergence. In Saskatchewan, Lafond (1991) also found that there were no differences in early plant stand of field pea (70 plants m^{-2}) and wheat (300 plants m^{-2}) under conventional and zero tillage while plant stand of flax was reduced under zero tillage. Low plant populations for flax under zero tillage were attributed to poor seed-soil contact due to interference by crop residues.

Factors affecting crop establishment under zero tillage include soil temperature, soil water content, and crop residue factors, including phytotoxin production, the presence of residual herbicides and excessive shading. Depending on soil type, previous crop, herbicide residues and stubble height and quantity, crop establishment may or may not be affected by a reduction in tillage.

2.2.2 Crop Growth

Crop growth includes both shoot growth and root growth. Shoot growth can be characterized by examining such parameters as aerial dry matter accumulation, crop height, and light interception by the crop canopy. Root growth can be characterized directly by examining root length, weight, and distribution in the soil, or indirectly by examining soil water extraction patterns. Due to its effects on the soil environment, zero tillage can affect both shoot and root growth.

Crop development is a function of temperature (Frank et al., 1987). The ambient temperature will affect how long a crop will remain at a particular growth stage, a factor which will, in turn, affect the potential for growth at that stage.

2.2.2.1 Aerial Dry Matter Accumulation

Plant growth is a function of growth rate and duration (Wilson et al., 1985). Any factor that affects either the growth rate or the duration of that growth will affect the accumulation of dry matter of a crop over the growing season. Factors important for aerial dry matter accumulation over time include photosynthesis, transpiration, and adequate nutrition.

Zero tillage can affect photosynthesis through increased shading and delayed water stress. During early growth, shading by previous crop residues can limit radiation interception by the crop, reducing its growth potential. Although shading is a comparatively minor factor, its effect on early growth may result in reduced grain yield (Klepper and Rickman, 1988; Wilhelm et al., 1989). Zero tillage can also affect photosynthesis by affecting soil water availability. Gas exchange in leaves and stems is controlled to a large extent by soil water availability, as well as by atmospheric demand for water. Therefore higher soil water levels under zero tillage may increase gas exchange and transpiration. In Swift Current, Sask., Campbell et al. (1986) observed that wheat under zero tillage retained its leaves two weeks longer than wheat under conventional tillage. They attributed the delayed senescence to increased soil water under zero tillage.

Zero tillage may also affect plant nutrition (Carter and Rennie, 1982; Varvel et al., 1989). Zero tillage can decrease the efficiency of use of broadcast fertilizers (Mahli and Nyborg, 1989) since nutrients may become immobilized by crop residues at or near the soil surface.

Dry matter accumulation patterns differ with plant development stage. During vegetative growth, dry matter production is mainly in the form of leaves, while after anthesis dry matter production is in the form of seeds and fruits. Factors that affect flowering and seed set will therefore affect postanthesis dry matter accumulation. Entz and Fowler (1989) found that the yield of winter wheat under zero tillage was positively related to dry matter accumulation at flowering and maturity. A strong positive relationship between aerial dry matter at flowering and grain yield was also observed for oilseed rape (Richards and Thurling, 1978b) and field pea (Heath and Hebblethwaite, 1987). These results indicate the importance of vegetative dry matter accumulation for high grain yields. Deibert and Utter (1989) found that vegetative dry matter was higher for sunflower under zero tillage than under conventional tillage in a dry year and that reproductive dry matter was higher under no-till for both dry and wet years. The growth of a crop depends primarily on the timing of soil water deficits in relation to sensitive crop growth stages.

Some studies have shown decreased dry matter accumulation for various crops under zero tillage (Carter and Barnett, 1987; Kaspar et al., 1987; Webber et al., 1987; Klepper and Rickman, 1988; Varvel et al., 1989; Wilhelm et al., 1989). In some cases, reduced early growth was the result of poor seedling establishment. In other cases, poor root growth or low soil temperatures were cited as possible explanations for low aerial growth rates. Studies with pea have shown that dry matter production is positively correlated with rooting depth (Heath and Hebblethwaite, 1987) and negatively correlated with air temperature (Nichols et al., 1985). Studies with wheat have shown that dry matter production was maximized when soil temperature was equal to air temperature, since differences in soil and air temperature affect the movement of water within the plant (Kirkham and Ahring, 1978). In some cases, winter wheat crops have overcome low vegetative dry matter accumulation that occurred due to a reduction in tillage, resulting in similar dry matter levels to those of conventionally tilled crops later in the season (Kaspar et al., 1987; Webber et al., 1987; Wilhelm et al., 1989). These results indicate that some crops grown under zero tillage are able to compensate for their poor initial growth.

2.2.2.2 Crop Height

Measurements of crop height can help characterize crop growth since crop height and dry matter accumulation are often highly correlated (Kirkham and Ahring, 1978; Deibert and Utter, 1989). Crop height is affected by crop canopy factors such as leaf area and planting density, as well as by soil water availability, rooting depth and root density. Shading by previous crop residue might also affect plant height early in the growing season by causing etiolation of seedlings.

The effect of zero tillage on crop height has been examined for corn (Lal, 1974; Ojeniyi, 1986; Carter and Barnett, 1987; Kaspar et al., 1987), wheat (Carter and Rennie, 1985; Lafond and Loeppky, 1988), soybean (Elmore, 1987), field pea (Lafond and Loeppky, 1988) and sunflower (Diebert and Utter, 1989). In some cases tillage effects were inconsistent; however, in most cases there was either an increase or no change of plant height with zero tillage. Lafond and Loeppky (1988) found that zero tillage increased plant height for both wheat (10 cm) and field pea (4 cm) while Carter and Rennie (1985) found a decrease in wheat plant height under zero tillage. No studies examining crop height for canola under zero tillage were found.

Root development has been shown to be positively correlated with plant height in wheat (Oussible and Crookston, 1987) and pea (Heath and Hebblethwaite, 1987). These studies both indicate that deeper rooting and better root distribution allowed plants to grow taller. As well, Kirkham and Ahring (1978) demonstrated an optimum temperature (20° to 28°C) at which wheat root growth and shoot height were both maximized.

2.2.2.3 Light Interception by the Crop Canopy

Canopy light interception is a major factor affecting the photosynthetic potential of a crop. Therefore, the effect of reduced tillage on canopy and leaf area development can be very useful in determining its effect on crop growth. A number of examples are available which indicate a possible influence of tillage on canopy development. Doran et al. (1984) observed more rapid canopy closure with corn and soybeans under zero compared to conventional tillage. Wilhelm et al. (1989) found a lower leaf area index for winter wheat under zero tillage than under conventional tillage. They attributed the lower leaf area to a decrease in growing degree-day accumulation due to lower soil temperatures under zero tillage. Carter and Rennie (1985) also observed that differences in crop canopy (shoot height), between tillage systems tended to modify soil temperature differences of 1° to 5°C that occurred during the first 30 days of crop growth.

Heath and Hebblethwaite (1985b) found that radiation interception was more efficient but its conversion to dry matter was less efficient for pea under high water stress conditions than under low water stress conditions. Because zero tillage can help to delay water stress due to higher soil water availability, it may extend the time a canopy is active (i.e. delay leaf senescence) (Campbell et al., 1986). Thus, the effect of zero tillage on leaf development, and consequently on light interception, depends on its effect on soil temperature and soil moisture conditions.

2.2.2.4 Root Growth

Root growth has important implications for soil water extraction by crops. Zero tillage can affect soil temperature, soil water content and distribution, soil nutrient distribution, and may increase soil compaction (Gauer et al., 1982; Carter and Rennie, 1985; Unger, 1990). Therefore, zero tillage has the potential to dramatically affect root growth and distribution in the soil profile. In addition, zero tillage affects the incidence of some root diseases and the production of phytotoxins from decaying crop residues (Cochran et al., 1977; Sturz and Bernier, 1987; Klepper and Rickman, 1988). As Heath and Hebblethwaite (1987), Richards and Thurling (1978b), and Chevalier and Ciha (1986) found, root growth is a major factor in determining plant growth, productivity, and grain yield for pea, canola and spring wheat.

Root growth under zero tillage has been examined in a number of studies. Kaspar et al. (1987) found that for the first 20 to 60 days after emergence, corn root dry weight under zero tillage was reduced compared to conventional tillage. Although Newell and Wilhelm (1988) found that surface residue encouraged corn root proliferation near the surface due to the distribution of water and nutrients, they concluded that zero tillage holds a greater potential for delaying the onset of water stress during drought than conventional tillage.

Increased soil compaction, which may occur under zero tillage, can impede root growth and distribution (Dawkins and McGowan, 1985; Dann et al., 1987; Oussible and Crookston, 1987). Under conventional tillage, the loosening of compacted soils by deep tillage may cause the growth of profuse, finer and longer roots which take up water more efficiently (Dann et al., 1987). In this study, oilseed rape, which has a large taproot, was more responsive to this soil loosening than wheat. However, both wheat and oilseed rape were more responsive than pea. Heath and Hebblethwaite (1985a) concluded that pea has a characteristically shallow root system and thus might not even reach compact soil layers deeper in the soil profile. However, Stobbe et al. (1970) found that mechanical impedance was higher under conventional than under zero tillage due to the development of a hard tillage pan under conventional tillage.

The response of root growth to soil temperature has been examined by Ali-Khan et al. (1977) for pea and by Kirkham and Ahring (1978) for wheat. The optimum temperature for root growth for pea was 16°C, while the optimum temperature for wheat ranged from 20 to 28°C for wheat. Lower temperatures were found to hamper the development of a strong root system and, therefore, caused a decrease in shoot growth.

Root growth under zero tillage can also be affected by root pathogens and phytotoxins. Sturz and Bernier (1987) found that cereal crown and root tissues can harbor root pathogens *(Gaeumannomyces graminis* var. *tritici, Cochliobolus sativus, Fusarium culmorum, Fusarium equeseti,* and *Microdochium bolleyi)* under zero tillage. Lukach and Hanson (1989) found that three years of zero tillage caused an increase in the incidence of stubble-borne pathogens and a decrease in incidence of soil-borne pathogens such as *Cochliobolus sativus*. On the other hand, Cherrington and Elliot (1987) examined the production and colonization of inhibitory pseudomonads on grassy and legume crops and found that the two crop types under conventional and zero tillage systems were colonized to the same extent; however, the production of pseudomonads was higher for zero tillage than conventional tillage wheat. Therefore, although it is clear that the potential for adverse effects exists, there is as yet no clear evidence that root pathogens and phytotoxins increase under zero tillage.

2.2.3 Crop Development

Crop development rate is important in determining crop productivity. The length of time that a crop remains at a certain stage, such as floral initiation, anthesis, or seed-filling, can have a very significant effect on seed yield. Crop development is controlled by a number of factors, including temperature, soil fertility, soil water and light conditions. While zero tillage may affect these parameters, sensitivity of crop development to these factors depends on the crop species and cultivar. For example, vegetative development of cereal crops, whose terminal meristem remains below the soil surface during early development stages, can be strongly influenced by soil temperature (Klepper and Rickman, 1988; Wilhelm et al., 1989). On the other hand, development of broad-leaved crops, whose terminal meristem is above the ground after emergence, may be more strongly influenced by air temperature, a factor which may or may not be affected by tillage system. A number of studies have shown that initial development of wheat under zero tillage is slower than under conventional tillage (Carter and Rennie, 1985; Klepper and Rickman, 1988; Wilhelm et al., 1989). Similar trends were observed for corn (Kaspar et al., 1987; Carter and Barnett, 1987). However, other studies have found no effect of zero tillage on either germination and emergence time (Gauer et al., 1982), or on early leaf and tiller development in wheat (Chevalier and Ciha, 1986; Lafond and Loeppky, 1988). In wheat, observed differences in early development due to tillage often disappeared by heading time. In an experiment with corn, days to silking were increased under zero tillage, and in some cases, grain yield was lower compared to conventional tillage (Kaspar et al., 1987).

The length of flowering time in indeterminate crops can be affected by soil moisture content. Under water deficit conditions, which may be more likely to occur under conventional tillage, development rate may be accelerated to the extent that it affects crop yield potential and possibly final yield. For example, low soil water content can signal the pea floral meristem to stop producing more flowers (Hardwick, 1985), causing early senescence and decreased yields. Although the increased soil water content under zero tillage has the potential to increase the length of the flowering time and thus yield potential, Lafond and Loeppky (1988) found no differences in length of flowering time for peas under conventional and zero tillage systems even though differences in final yield were observed.

Although little work has been done on the response of canola to zero tillage, Kondra et al. (1983) found that initial development of *Brassica napus* was not affected by temperature. Richards and Thurling (1978a) showed that time to 50 percent anthesis was not significantly affected by various planting dates, indicating that the preanthesis development rate of *B. napus* was not very sensitive to environment. However, Morrison et al. (1989) concluded that temperature is the most important environmental factor regulating the phenological development of Westar canola above a baseline temperature of 5°C. Also, because it is an indeterminate plant, cessation of floral initiation in canola may be affected by soil moisture (McGregor, 1981) and thus could be affected by a reduction in tillage.

2.2.4 Evapotranspiration

Evapotranspiration (ET) is a function of soil water evaporation and crop transpiration. ET of a crop is calculated by adding the change in soil water content over a period of time to the amount of precipitation received. In many studies measuring ET in dryland crop production, deep drainage (>120 cm), upward movement of deep water and runoff are assumed to be zero. Entz and Fowler (1989) reported ET values of 171 to 315 mm for winter wheat, while Wilson et al. (1985) reported values of 225 to 334 mm for field pea. The amount of ET is also a function of the amount of available water in the soil profile and the root development of the crop. A crop with a poorly developed root system will not be able to make full use of the water present in the soil profile. Both dry matter production and final grain yield were found to be closely related to ET and a function of soil water availability for wheat (Entz and Fowler, 1989) and field pea (Wilson et al., 1985).

ET is strongly positively influenced by free water evaporation (deWit, 1958; Hobbs and Krogman, 1977). Hobbs and Krogman concluded that ET is affected more by evaporation than by crop type. However, ET is dependent on radiation interception, and therefore, crops with poor canopy expansion or duration may use less water (Wilson et al., 1985). ET also varies with crop development. Entz and Fowler (1989) found that the ratio of ET of winter wheat before and after anthesis averaged 1.7:1. For crops such as pea, a high water availability before flowering may lead to excessive vegetative growth and a water deficit during pod filling (Heath and Hebblethwaite, 1985a). Shallow rooting crops such as pea may experience a yield collapse due to excessive vegetative growth, when grown under zero tillage. However, Lafond and Loeppky (1988) did not find this to be the case. In fact, they observed that pea used water deeper in the soil profile (60-120 cm) under reduced than under conventional tillage. This additional ET corresponded with a significantly higher grain yield.

Additional soil water under zero tillage may not necessarily mean an increase in ET. For example, with winter and spring wheat, Varvel et al. (1989) and Chevalier and Ciha (1986) found that the extra available water under zero tillage was not used by the crop. Under conventional tillage, the spring wheat used more water and used it more effectively than under zero tillage. Both authors concluded that full utilization of extra available water under zero tillage was prevented by delayed early growth, and sometimes by smaller root systems of crops under zero tillage. On the other hand, Lafond and Loeppky (1988) working with wheat and field pea, Webber et al. (1987) working with sunflower, and Shanholtz and Lillard (1969) working with corn, found that ET increased with a reduction in tillage. The increase in ET was attributed to additional growth under zero tillage resulting in a higher water requirement than under conventional tillage.

2.2.5 Water Use Efficiency

Water use efficiency (WUE) is calculated by dividing dry matter or grain yield (kg ha^{-1}) by ET (mm). WUE is inversely related to the amount of free water evaporation (deWit, 1958; Fischer and Turner, 1978) and daytime vapor pressure deficit (Wilson et al., 1985). Thus, although WUE is a function of crop species, environmental modification of this parameter is possible (Lafond and Loeppky, 1988; Unger, 1990).

For a given crop cultivar, the most practical way to increase WUE is to increase transpiration as a proportion of total ET. In water-limiting environments, increasing WUE can be accomplished by decreasing water loss from direct soil evaporation. By maintaining residues at the soil surface, evaporation is decreased and a greater proportion of ET is available for transpiration to produce dry matter or grain yield. The importance of decreased evaporation for increased WUE was demonstrated for peas by Wilson et al. (1985).

The response of crop WUE to a reduction in tillage has been studied for a number of crops. Unger (1990) cites various studies which very clearly show that increased surface residues and zero tillage result in increased WUE of grain yield production for winter wheat and grain sorghum. Lafond and Loeppky (1988) report the same trend for spring wheat and field pea with WUE levels of 6.43 and 4.72 kg ha^{-1} mm^{-1}, respectively, under zero tillage compared with 4.92 and 3.64 kg ha^{-1} mm^{-1}, respectively, under conventional tillage. Thus, zero tillage shows promise for increasing crop WUE by decreasing water losses due to evaporation and enhancing growth by providing a more favorable soil environment.

2.2.6 Grain Yield

Crop productivity of most grain crops is ultimately measured in terms of grain yield. Grain yield is an integration of the interacting effects of crop growth, crop ET, and other parameters. Grain yield responses to zero tillage have been examined in numerous studies; however, in most cases, few other parameters were measured.

The most dramatic yield responses to zero tillage usually occur in dry years. Diebert and Utter (1989) found yields of 1680 kg ha^{-1} under conventional tillage and 1825 kg ha^{-1} under zero tillage for sunflower in a dry year. The opposite trend was observed in a wet year. Webber et al. (1987) found soybean yields were increased from an average of 1590 kg ha^{-1} under conventional tillage to 2090 kg ha^{-1} under zero tillage in two dry years, while in a wet year the opposite trend was observed. Higher yields under zero tillage in dry years may be attributed to higher levels of available soil water which can delay or prevent drought stress during sensitive development periods.

Results from other studies indicate a variety of yield responses to tillage. For example, lower yields under zero tillage were observed for corn (Wall and Stobbe, 1983; Carter and Barnett, 1987), and for oilseed rape on sandy soils (Baeumer and Bakermans, 1973). Increased yields under zero tillage were reported for corn by Ojeniyi (1986) and Edwards et al. (1988), and for oilseed rape by Stobbe et al. (1970) and Baeumer and Bakermans, 1973). Lafond (1991) found a yield increase from 1785 kg ha^{-1} under conventional tillage to 1935 kg ha^{-1} under zero tillage for field pea, and from 1558 kg ha^{-1} to 1883 kg ha^{-1} for spring wheat for the years

1987 to 1990. Stobbe (1989) reported yield increases from 1890 kg ha^{-1} under conventional tillage to 2150 kg ha^{-1} under zero tillage for canola and from 2950 kg ha^{-1} to 3190 kg ha^{-1} for wheat for the years 1984 to 1986. Studies with corn (Lal, 1974), winter wheat (Wilhelm et al., 1989), sunflower (Deibert, 1989) and spring wheat, oilseed rape and barley (Donaghy, 1973) have indicated no significant difference in yield due to tillage system. This wide variation in yield responses to zero tillage is not surprising considering the nature and extent of environmental influences, crop growth responses and crop water use responses to zero tillage. In each case there was likely one or more dominant factors such as moisture stress or soil temperature which determined the yield response to the tillage system.

2.2.7 Harvest Index

The ratio of grain yield to total aerial dry matter is referred to as the harvest index. As indicated earlier, there is a strong positive relationship between above ground dry matter production and grain yield for oilseed rape (Richards and Thurling, 1978b), for field pea (Heath and Hebblethwaite, 1987), and for wheat (Entz and Fowler, 1989). Harvest index provides an estimate of the conversion efficiency of this dry matter to grain yield (Donald and Hamblin, 1968).

Harvest index is determined primarily by environmental conditions after flowering. The conversion of the available dry matter to grain yield depends on factors that affect yield formation, including drought and high temperature stress. Richards and Thurling (1978b) found that the harvest index of oilseed rape was strongly affected by drought stress at flowering. High temperatures can cause flower or pod abortion as well as termination of flowering in indeterminate crops, thereby limiting the sink capacity (i.e., the number of seeds per unit area) of the crop. When the sink capacity is limited, benefits of zero tillage in terms of vegetative dry matter, the source, would most likely not be able to compensate for lost yield potential. A limited sink capacity could result in a lower harvest index under zero compared to conventional tillage. However, if the source and sink factors are similarly affected by stresses under both tillage systems, no differences in harvest index between tillage systems would be expected.

2.2.8 Grain Yield Components

Yield component analysis increases our understanding of crop response to tillage. Any factor which affects a component of grain yield will ultimately affect yield potential. For grain crops such as wheat, canola and field pea there are three main components of grain yield: the number of seed bearing pods or spikes per unit area, the number of seeds per pod or spike, and the seed weight. These yield components are determined at different stages in the plant's life cycle and thus may be affected differently by soil and atmospheric environmental modifications under zero tillage.

2.2.8.1 Pod or Spike Density

Pod or spike density is the earliest yield component determined in the plant's life cycle. Pod density is a major component of the yield of oilseed rape (Richards and Thurling, 1978b; McGregor, 1981), while spike density is highly correlated with yield in wheat (Entz and Fowler, 1988). For a cereal crop such as wheat, spike density can be affected by plant population density, soil fertility and soil moisture. Soil fertility and soil moisture will also affect the number of fertile spikes that will develop per unit area (i.e., the proportion of tillers that produce seed-bearing spikes) (Entz and Fowler, 1988). For indeterminately flowering crops such as pea and canola, the number of pods m^{-2} will be influenced by plant population density and soil conditions, as well as by factors that can cause flowering to terminate. Low levels of available soil water and high temperatures can decrease pod density of field pea (Hardwick, 1985; Nichols et al., 1985) and oilseed rape (McGregor, 1981; Dawkins and McGowan, 1985). McGregor (1981) reported that pod density was the yield component most affected by environment in oilseed rape.

Studies with wheat have shown that zero tillage either had no effect on spike density (Chevalier and Ciha, 1986) or that spike density was increased with a reduction in tillage (Lafond and Loeppky, 1988; Wilhelm et al., 1989). As Entz and Fowler (1988) showed, spike density in wheat is strongly influenced by soil moisture. Thus in dry years, spike number per unit area would be expected to be higher under zero tillage than under conventional tillage.

There have been no studies which examined the effect of zero tillage on pod density of pea or oilseed rape. However, studies have shown that pod density can be affected significantly by soil moisture (McGregor, 1981; Hardwick, 1985). Although this might suggest that plants under zero tillage should have a higher pod number per unit area, other environmental parameters such as air temperature may at times mask the effect of tillage on pod density.

2.2.8.2 Seed Number

Seed number per pod or spike is another important component of yield. Seed number in cereal grains is determined between the floral initiation stage when spikelet number is determined, and anthesis, when the number of fertile flowers per spikelet is determined. In indeterminately flowering crops such as oilseed rape and field pea, the number of seeds per pod is determined partly during the time of floral initiation, and partly at flowering when the number of fertile ovules per flower is determined. Few studies were found which measured the effect of a reduction in tillage on seed number.

In wheat, length of the floral meristem development period is determined by soil temperature. Thus, if reduced soil temperatures under zero tillage persist until floral initiation, the potential spikelet numbers may be influenced. However, drought (Frank et al., 1987) and high temperature stress (Fischer and Maurer, 1976) at critical growth stages, such as between tillering and anthesis (Entz and Fowler, 1988), can cause abortion of these spikelets or florets, causing reduced yields regardless of tillage system. The response of this yield component to zero tillage may also depend on the type of environmental stress encountered. For example, if soil moisture is the dominant stress, zero tillage may result in higher seed numbers, as Ojeniyi (1986) found in corn. However, if air temperature is the dominant stress, tillage effects may be masked.

Seed number in pea and canola is determined somewhat differently than in wheat. Flowering in canola and field pea includes the development of numerous ovules within the ovary. If these ovules are not fertilized or if they are aborted during the time shortly after flowering, such as can happen in pea up to five days after full bloom (Hardwick, 1985), seed number may decrease (Jeuffroy et al., 1990). These results indicate that the critical period may extend beyond flowering for some crops. For oilseed rape, drought stress, especially at flowering, will decrease the number of seeds per pod (Richards and Thurling, 1978b). Although not as important as pod number, seed number of oilseed rape is important for determining final grain yield. The effect of zero tillage on seed number per pod is limited to its effect on soil moisture content and availability during the stages which are critical in determining seed number per pod, and to compensatory growth that may occur if stand density is decreased with zero tillage.

2.2.8.3 Seed Weight

While pod or spike number and seed number are yield components which are affected by plant development, seed weight production is a growth process. Environment affects seed weight in the same way as it affects any other plant growth process, namely, by affecting transpiration and photosynthesis. Leaves and other plant organs provide photosynthate during seed growth. During pod fill in canola, most of the leaves fall off and photosynthate is produced by the pods and stems (Clarke, 1978). During pod fill in pea, most of the photosynthate for seed growth comes from the leaves, pods and tendrils located at each particular reproductive node (Pate, 1985). In wheat, much of the photosynthate to fill the kernels is produced either by the flag leaf or by parts of the spike (Simpson, 1968).

Water stress is the factor that can most affect seed growth when comparing reduced and conventional tillage systems. Richards and Thurling (1978b) found that drought and rooting characteristics affected the seed weight of late-flowering rapeseed cultivars. Entz and Fowler (1988) found that the seed weight of winter wheat was dependant on two parameters: prevailing environmental conditions after anthesis, and available soil water in the root zone at anthesis. Nichols et al. (1985) found that pea seed weight was decreased by high temperature stress at any development stage since heat affects both light interception and photosynthesis. Factors other than available soil water can also affect seed weight of oilseed rape (Clarke and Simpson, 1978) and wheat (Entz and Fowler, 1988), thereby modifying the effects of zero tillage.

Seed weight was found to be unaffected by a reduction in tillage for wheat and oilseed rape (Stobbe et al., 1970), field pea (Lafond and Loeppky, 1988) and sunflower (Deibert, 1989). On the other hand, Lafond and Loeppky (1988) found an increase in seed weight of spring wheat with zero tillage, while Wilhelm et al. (1989) found a decrease in seed weight of spring wheat under zero tillage. For soybeans, Edwards et al. (1988) reported an increase in seed size and yield of soybean under zero tillage compared with conventional tillage. Elmore (1987) reported similar results in one of two years, but in the other year he found that soybean seed weight under conventional tillage was higher than that under zero tillage.

The effect of zero tillage on seed weight appears to be related to its effect on factors such as root and shoot growth as well as on soil moisture availability. Lower seed weight may also be related to higher pod number and seeds per pod under zero tillage. Under other conditions, environmental factors such as air temperature may modify these effects, causing conflicting results for different years, locations and crops.

2.2.9 Grain Quality

Grain quality is a measure of the suitability of grain for its end use. Quality factors vary with crop species and uses. In hard red spring wheat, which is mainly used for bread production, protein content is an important quality parameter. Protein content is also a measure of pea quality, whether the peas are to be used for human or animal consumption. The most important quality parameter for canola is oil content. To ensure a good quality oil, seeds must be fully mature and produce an oil low in chlorophyll. Because canola meal is used for animal consumption, a high protein content is also desirable.

Test weight is another important quality parameter. The test weight of grain depends on seed density which is a measure of the accumulation of photosynthate in the seed. Test weight is increased with moisture and nutrients and, therefore, the only possible direct effect of zero tillage on test weight is through changes in soil moisture. Stobbe et al. (1970) found no significant effect of tillage on test weight of wheat, barley, flax, and oilseed rape.

The effect of zero tillage on protein content and protein yield varies with crop species and environmental conditions. Entz and Fowler (1988) found protein content in winter wheat to be negatively related to extractable soil water at stem elongation while protein yield was independent of any soil measurements. In wheat, protein content is also often negatively correlated with grain yield (Partridge and Shaykewich, 1972). Therefore, any yield increases with zero tillage may result in lower grain protein content. This relationship does not hold for pea which is a leguminous crop that can fix its own nitrogen. Zachariassen and Power (1987) found that a soil temperature of 10°C, compared to 20 or 30°C, greatly increased nitrogen fixation of field pea, especially later in the season. Therefore, lower soil temperatures under zero tillage may enhance nitrogen fixation by legumes resulting in a higher seed protein content (Askin et al., 1985).

Oil content and oil yield in canola are determined by the amount of assimilate partitioned into the seeds and metabolized into fatty acids. The effect of zero tillage on this process is not known although Deibert (1989) found that zero tillage had no effect on the oil content or oil yield of sunflower. The effect of tillage on oil quality in canola is not well documented; however, it is known that the chlorophyll content of the oil is related to the process of chlorophyll breakdown during seed ripening (Cenkowski et al., 1989). Therefore, differences in maturity between tillage systems may affect oil quality.

2.3 Crop Water Relations in Response to Zero Tillage

In order to better understand agronomic responses to zero tillage, it is important to look at how a reduction in tillage affects physiological water relations within plants. Studies have indicated that zero tillage or high amounts of surface residues will delay the onset of water stress and decrease the extent of plant water stress in wheat (Stobbe et al., 1970), corn (Lal, 1974; Doran et al., 1984; Newell and Wilhelm, 1988), soybean (Doran et al., 1984; Webber et al., 1987) and sorghum (Doran et al., 1984). In these studies, lower water stress under zero tillage was attributed to an increase in available soil water under zero tillage. Various methods have been used by researchers to characterize plant water stress of field grown plants, including leaf or canopy temperature, leaf conductance and leaf relative water content.

2.3.1 Relative Water Content

Relative water content measures the relative turgidity of leaves and is a direct indicator of plant water content (Turner, 1981). It has been used by many workers to determine the extent of drought stress and the ability of plants to maintain their water content under stress. Richards (1978) found that relative water content was a good indicator of water status in canola and was positively related to leaf area, growth rate and efficient water use in drought resistant canola genotypes. Baeumer and Bakermans (1973) reported that visible wilting of corn and sugar beets was delayed for hours or even days when these crops were grown under zero tillage rather than conventional tillage. A similar observation was made for wheat by Campbell et al. (1986). Sinclair and Ludlow (1985) argued that relative water content is the drought stress indicator which most closely reflects the plant's physiological state.

2.3.2 Leaf or Canopy Temperature

Leaf and canopy temperature are indirect measurements of plant water status. The ability of a plant to maintain a leaf temperature below that of the ambient air indicates its ability to transpire, resulting in leaves cool enough for growth and photosynthesis to occur. Jackson (1982) found that canopy temperature was directly related to ET because as ET increased, canopy temperature decreased. Kirkham and Ahring (1978) concluded that measuring leaf temperature was a useful technique for drought sensitivity screening in wheat breeding programs. Clarke and McCaig (1982) found that at higher drought stress levels, leaf temperature of oilseed rape *(Brassica napus)* was higher, closer to the ambient temperature. Their work indicates the potential usefulness of this technique for measuring drought stress in canola.

Kirkham and Ahring (1978) reported that at low root temperatures, plants had cool leaves, while at high root temperatures the plant's ability to keep leaf temperature below air temperature was impaired.

Doran et al. (1984) found that a reduction in soil temperature, with increasing levels of crop residue, reduced leaf temperature in corn, sorghum, and soybean. Since leaf and canopy temperature are measurements of the same parameter, similar results might be expected with canopy temperature measurements. Based on these observations, it is clear that the combination of increased soil moisture and decreased soil temperatures under zero tillage could strongly reduce plant water stress as measured by shoot temperature.

2.3.3 Leaf Conductance

Conductance of water from leaf surfaces is a practical way to measure transpiration (Bennett et al., 1987) and is, therefore, a good indicator of photosynthetic potential (Turner, 1981). As plants experience drought stress there is a trade-off between maintaining photosynthesis to maintain growth, and limiting transpiration to limit the effects of drought. The response of leaf conductance to increasing drought stress depends on the developmental stage of the plant and whether or not it has been exposed to any previous stress.

Plants that have had previous exposure to drought or high temperature stress respond differently to subsequent stresses than those plants that have not had such preconditioning. For example, the leaf water potential at which leaf conductance decreases due to stomatal closure decreases with preconditioning (Thomas et al., 1976). This reduced stomatal sensitivity to stress is especially noticeable after flowering. Ackerson et al. (1977) found that after flowering of sorghum, leaf conductance remained high, even with low water potentials. Similar observations have been made in winter wheat (Entz and Fowler, 1990). This phenomena allows photosynthetic productivity for grain filling to be maintained at the expense of water conservation. Frank et al. (1973) found that photosynthetic recovery of leaves after stress was related to diffusive resistance for spring wheat at tillering and heading. However during grain filling, photosynthesis did not recover and stress-induced senescence occurred.

The potential usefulness of leaf conductance as a research tool has been demonstrated by a number of workers. For example, Kirkham and Ahring (1978) found that leaf conductance of wheat peaked when root temperature and air temperature were equal, the point at which dry matter production and crop height were also the greatest. Their results indicate that there may be a close connection between maximum conductance and optimum growth conditions for wheat. Both Clarke and McCaig (1982) and Richards (1978) found that leaf conductance in oilseed rape decreased with decreasing soil water content indicating that leaf conductance may be a good measure of the effect of a reduction in tillage on plant productivity potential.

2.4 Conclusions

The effects of zero tillage on crop performance can be measured in various ways. Detailed investigations of the response of different crops to zero tillage increases our understanding of the adaptation of a particular crop to this production system. From the above discussion it becomes clear that there may be both advantages and disadvantages to the use of zero tillage for crop production on the Canadian prairies. Suitability of crops such as canola, field pea and wheat to zero tillage in the Black soil zone of Manitoba will depend on how well these crops respond in terms of growth, yield, grain quality, ET, WUE, and plant water status.

3.0 Agronomic Performance of Canola, Field Pea, and Wheat under Conventional and Zero Tillage.

3.1 Introduction

Currently there is a strong interest among farmers to reduce the amount of tillage used in crop production. To encourage the adoption of zero tillage systems by farmers on the Canadian prairies, we must know how zero tillage affects the growth and productivity of a variety of commonly grown crops. Such information is also useful for rotation planning in conservation tillage systems in the Black soil zone of the Canadian prairies. The objective of the present study was to compare the establishment, growth, yield, yield components and grain quality of three important crops, canola *(Brassica napus* L.), field pea *(Pisum sativum* L.) and wheat *(Triticum aestivum* L.) under zero and conventional tillage.

3.2 Materials and Methods

3.2.1 General

Field plots were established on an Almassippi loamy very fine sand at Carman and on a Fortier silty clay at Portage la Prairie (Portage), Manitoba in 1989 and 1990. In 1989 the previous crop at both sites was wheat, and in 1990 it was barley *(Hordeum vulgare* L.).

The experimental design was a split plot with tillage as the main plot and crop species as the subplot. Tillage treatments included zero and conventional tillage. Zero tillage involved seeding into untilled crop residue, leaving 60 to 90% crop residue cover on the soil surface after seeding. In the 1989 trials, conventional tillage involved two passes with a chisel plow or tandem disc, and harrowing and packing immediately prior to seeding. In the 1990 trials, conventional tillage treatments involved two passes with a chisel plow or tandem disc in the fall of 1989 and one pass with a tandem disc, harrows and packers in the spring of 1990 immediately prior to seeding. The crop species and cultivars used were Westar canola, Victoria field pea, and Katepwa wheat. Experiments at Carman were replicated six times while experiments at Portage were replicated four times. Main plot size was 12.9 x 7 m at Portage in 1989 and 18.6 x 7 m at all other sites. Subplot size was 4.3 x 7 m at Portage in 1989 and 6.2 x 7 m at the remaining sites.

3.2.2. Crop Management

Trials were seeded using a Noble Model 2000 hoe drill. Seeding depth was set at 1 cm for canola and 2.5 cm for field pea and wheat. A row spacing of 20.3 cm was used in all trials. Seeding rates and seed lots did not vary between sites or years except in 1990 when a new seed lot of Katepwa wheat was required due to poor germination of the 1989 seed lot in 1990. Recommended rates of certified seed were used in all trials: 8 kg ha^{-1} (200 viable seeds m^{-2}) for canola, 160 kg ha^{-1} (130 viable seeds m^{-2}) for field pea, and 100 kg ha^{-1} (300 viable seeds m^{-2}) for wheat (Anonymous, 1988). Seed viability was determined immediately prior to seeding using a standard germination test at 20°C. All seed was treated with fungicide (Table 3.1) and pea seed was inoculated with *Rhizobium* spp immediately prior to seeding. In 1989, seeding was done on May 11 at Carman and on May 16 at Portage while in 1990, seeding was done on May 10 at Carman and on May 31 at Portage.

Fertilizer was applied according to soil test results (Appendix 1). Seed-placed fertilization was the same for all three crops in both years: 20 kg ha^{-1} P_2O_5 and 5 kg ha^{-1} nitrogen (N). At Carman, an additional 100 kg ha^{-1} N, 70 kg ha^{-1} K_2O, and 20 kg ha^{-1} SO_4 was broadcast after seeding while at Portage an additional 75 kg ha^{-1} N was broadcast.

Weeds were controlled using herbicides at recommended rates (Table 3.2). A severe weed infestation at Carman in 1989 required repeated herbicide applications. Insects were controlled with insecticides applied at recommended rates (Table 3.3). The main insect pests were flea beetles *(Phyllotreta cruciferae* (Goeze)), grasshoppers *(Camnula pellucida* (Scudder), *Melanoplus sanquinipes* (Fabricius) and *Melanoplus bivittatus* (Say)), blister beetles *(Lytta* spp. and *Epicauta* spp.) and aphids *(Sitobion avenae* and *Acyrthosiphon pisum* (Harris)). Preventative disease control measures were followed, including the use of seed treatments for the control of seedling diseases and the use of foliar fungicides for the control of leaf diseases in wheat, including septoria leaf spot *(Septoria tritici)*, tanspot *(Pyrenophora trichostoma)*, leaf rust *(Puccinia recondita)* and stem rust *(Puccinia graminis)*, and sclerotinia stem rot *(Sclerotinia sclerotiorum)* in canola (Table 3.1).

Table 3.1 Fungicides applied to wheat, canola and field pea grown under zero and conventional tillage during 1989 and 1990 at Carman and Portage la Prairie, Manitoba.

Year	Location	Date(s)	Crop	Fungicide	Rate(kg a.i./ha)
Both	Both	Seeding	Wheat	carbathiin	0.0552
		Seeding	Canola	carbathiin	0.0081
				thiram	0.0162
		Seeding	Pea	carbathiin	0.064
				thiram	0.064
1989	Carman	June 29	Canola	benomyl	0.75
		July 3	Wheat	propiconazole	0.125
1989	Portage	July 4	Canola	benomyl	0.75
		July 4	Wheat	propiconazole	0.125
1990	Carman	June 30	Canola	benomyl	0.75
		June 30	Wheat	propiconazole	0.125
1990	Portage	July 10	Canola	benomyl	0.75
		July 10	Wheat	propiconazole	0.125

Table 3.2 Herbicides applied to wheat, canola and field pea grown under zero and conventional tillage during 1989 and 1990 at Carman and Portage la Prairie, Manitoba.

Year	Location	Date(s)	Crop	Herbicide	Rate(kg a.i./ha)
1989	Carman	May 15	All	glyphosate	1.78
		May 31 and June 10,23	Wheat	diclofop methyl + bromoxynil	0.792 0.280
		May 31 and June 21	Pea and canola	sethoxydim	0.350
		June 10,27	Pea	bentazon	1.08
		May 31	Canola	TokRM	1.34
		June 23	Canola	clopyralid + Muster[1]	0.200 0.015
1989	Portage	May 18	All	glyphosate	1.78
		May 20	All	glufonsinate ammonium	1.30
		June 8	Wheat	diclofop methyl + bromoxynil	0.792 0.280
		June 8	Pea	sethoxydim	0.350
		June 8	Canola	sethoydim + clopyralid	0.350 0.300
		June 23	Wheat	bromoxynil + MCPA amine	0.280 0.420
		June 23	Pea	bentazon	1.08
		June 23	Canola	clopyralid + Muster[1]	0.200 0.015
1990	Carman	May 15	All	glyphosate	1.78
		June 9	Wheat	diclofop methyl + bromoxynil	0.792 0.280
		June 9	Pea and canola	sethoxydim	0.350
		June 12	Pea	bentazon	1.08
1990	Portage	May 29	All	glyphosate	1.78
		June 22	Pea	bentazon	1.08
		June 23	Wheat	diclofop methyl + bromoxynil	0.792 0.280
		June 23	Canola	sethoxydim + clopyralid + Muster[1]	0.350 0.200 0.015

[1] 2(((((4-ethoxy-6-(methylamino)-1,3,5-triazin-2-yl)amino)carbonyl) amino)sulfonyl)benzoate.

Table 3.3 Insecticides applied to wheat, canola and field pea grown under zero and conventional tillage during 1989 and 1990 at Carman and Portage la Prairie, Manitoba.

Year	Location	Date(s)	Crop	Insecticide	Rate(kg a.i./ha)
All	All	Seeding	Canola	lindane	0.122
1989	Carman	May 22 and June 8	All	carbofuran	0.134
		June 21	All	deltamethrin	0.0075
		July 10	All	malathion	0.800
1989	Portage	June 9	All	carbofuran	0.134
		June 19	All	deltamethrin	0.0075
		July 4	Pea	malathion	0.700
1990	Carman	June 5,16,26, July 11 and August 2	All	carbofuran	0.134
		May 29	All	deltamethrin	0.0075
		June 12	Canola	deltamethrin	0.0075
		July 25	All	dimethoate	0.210
1990	Portage	June 11	All	deltamethrin	0.0075
		June 22	All	carbofuran	0.134
		July 14	Pea	malathion	0.700
		July 30	All	malathion	0.700

3.2.3 Measurements

3.2.3.1 Residue Cover

Crop residue cover (%) for each tillage treatment was determined immediately after seeding using the line transect method as described by Richards et al. (1984). Three samples were taken in each main plot. In 1990, additional straw was applied to zero tillage plots at Carman where required for even residue coverage.

3.2.3.2 Environment

Precipitation was monitored throughout the growing season at all sites. At all sites except Portage in 1989, manual rain gauges were used. At Portage in 1989, a rainbucket connected to a Licor Model L1000 weather station (Licor, Inc., Lincoln, Nebraska) was used. Daily maximum, minimum and mean air temperatures were recorded at the Portage Plant Science Research Station in 1989 and at the Canadian Forces Base at Portage in 1990.

Daily maximum, minimum and mean soil temperatures were monitored at Portage in 1989 and 1990 and at Carman in 1990 using Campbell Scientific Model CR-10 dataloggers equipped with Model 107 temperature sensors (Campbell Scientific Inc., Logan, Utah). At Portage in 1989, soil temperatures were monitored at 2, 10 and 20 cm in wheat under both zero and conventional tillage. In 1990, soil temperatures were monitored at 5 and 10 cm depths at Portage and at a 10 cm depth at Carman for each tillage-crop species treatment combination. Soil temperature observations were taken from shortly after seeding to well after flowering. Due to a shortage of dataloggers, only one replicate per site was monitored.

3.2.3.3 Establishment

Crop establishment was determined by counting the number of plants in three adjacent 1-m sections of row in each subplot two to three weeks after seeding. As well, actual seeding depth was determined for each treatment combination at Portage in 1989 and 1990 and at Carman in 1990. Seedlings were excavated from the soil two to three weeks after seeding and the length of the portion of the stem that was without chlorophyll was measured. Five seedlings per subplot were examined.

3.2.3.4 Crop Growth

Crop growth was determined by measuring dry matter accumulation, plant height, and light interception by the crop canopy. Aerial dry matter accumulation was determined at one to two week intervals in 1989 and at two week intervals in 1990. Plant material from three adjacent, randomly selected, 1-m sections of row from each subplot was removed and dried at 80°C for at least 48 hours before being weighed. Crop height was determined by measuring the height of four plants randomly selected in each subplot. Light interception by the crop canopy was determined using a Licor Model LI-185B quantum meter with a line quantum sensor (1 m long) at solar noon. The quantum flux ($\mu E\ m^{-2}\ sec^{-1}$) was determined by placing the sensor at ground level beneath the crop canopy perpendicular to the crop rows. A second reading was taken above the crop canopy at the same orientation to sun. Percentage interception of photosynthetically active radiation by the crop canopy was then calculated as:

$$\%\ \text{light interception} = \frac{\text{quantum flux above} - \text{quantum flux below}}{\text{quantum flux above the canopy}} \qquad (3.1)$$

Two sets of light interception readings were done per subplot. For each location, plant height, light interception and dry matter accumulation measurements were all taken on the same day.

3.2.3.5 Crop Development

Crop developmental stages were determined at intervals throughout the growing season. The Zadoks-Chang-Kondak scale (Zadoks et al., 1974) was used for wheat, the Harper-Berkenkamp scale, slightly revised, (Harper and Berkenkamp, 1975) was used for canola, and the Knott scale (Knott, 1987) was used for field pea. In 1989, measurements were taken for each subplot but in 1990 they were only taken for each crop species treatment or each crop species-tillage treatment combination. Measurements were taken in conjunction with crop growth measurements (Appendix 2).

3.2.3.6 Grain Yield

Grain yield was determined for all subplots by harvesting an area of 10 m^2 in 1989 and 25 m^2 in 1990. Canola was cut at Harper-Berkenkamp stage 5.4, bagged and dried with forced hot air in 1989. In 1990, the canola was cut and bagged or cut and left in a swath, and allowed to dry down naturally. Field peas were cut at Knott stage 303, bagged and dried with forced hot air in 1989, but dried naturally in 1990. Both canola and field peas were threshed using a Hege Model 125 small plot combine. Wheat was straight combined at Zadoks stage 92 using the same small plot combine. Samples from all crops were weighed and moisture content determined using a Labtronics Model 3.5 grain moisture meter. Yields were corrected to 14.5% moisture content for wheat and field pea and to 10% for canola since these are the moisture contents at which the respective crops are considered to be dry. Harvest index was calculated using grain yield and final dry matter measurements:

$$\text{Harvest Index} = \frac{\text{grain yield (kg/ha)}}{\text{dry matter yield (kg/ha)}}. \qquad (3.2)$$

3.2.3.7 Yield Components

Seed weight was determined by measuring the weight of 200 to 1000 seeds per subplot. Pod number per plant for field pea and canola was determined on 10 randomly selected plants per subplot. Plant stand at harvest was also determined for these crops so that pods per m^2 could be calculated. Spikes per m^2 of wheat was determined immediately prior to harvest on three adjacent 1-m sections of row in each subplot.

Seeds per spike or pod were calculated for all crops and sites except for field pea in 1989, in which case seeds per pod were counted on the 10 plants used for pod counts.

3.2.3.8 Grain Quality

Protein content was determined from grain subsamples for all three crops using the Kjeldahl method. Protein yield was calculated as:

$$\text{Protein Yield (kg ha}^{-1}\text{)} = \text{protein content(\%) x yield(kg ha}^{-1}\text{)}. \qquad (3.3)$$

Oil and chlorophyll content of canola were determined using the near infrared method (Campbell, 1984). Oil yield was calculated as:

$$\text{Oil Yield (kg ha}^{-1}\text{)} = \text{oil content (\%) x yield (kg ha}^{-1}\text{)}. \qquad (3.4)$$

All oil and chlorophyll measurements were conducted at the Canadian Grain Commission Oilseeds Laboratory.

Hectolitre weights of grain samples were also determined using a funnel, roller and 0.5 litre cup manufactured for this specific purpose.

3.2.3.9 Statistical Analysis

All data collected from samplings, as well as all parameters calculated from the data, were subjected to analysis of variance (Statistical Analysis Systems Institute, 1986). Differences with $P<0.05$ were considered to be significant. Combined analysis was conducted for parameters common to the four sites using the model described in Appendix 5. Homogeneity of error variances for site-years was verified using a maximum F test (Rohlf and Sokal, 1969). Differences between crop species were only discussed when the tillage by species or site-year by species interactions were significant.

3.3 **Results and Discussion**

3.3.1 Environmental Factors

3.3.1.1 Soil Temperature

Soil temperature measurements are presented for Portage in 1989 (Figure 3.1) and for Carman and Portage in 1990 (Figures 3.2 to 3.4). Measurements at Portage in both years characterized the soil temperature response to tillage at different depths (Figures 3.1, 3.3 and 3.4). Measurements in 1990 at both sites characterized soil temperature response to tillage for each crop species (Figures 3.2, 3.3 and 3.4). Heat inputs into a zero tillage system might be expected to be lower than those into a conventional tillage system due to lower absorption of incoming radiation by straw and standing stubble under zero tillage compared with bare black soil under conventional tillage. Results of the present study indicate that, although in some instances soil temperatures were lower under zero tillage, in other cases they were higher or no differences were observed.

Johnson and Lowrey (1985) found that temperature differences between zero and conventional tillage were greater at 5 cm than at 10 or 15 cm. However, results from Portage in 1989 indicated a smaller temperature difference between tillage systems at 2 cm than at 10 or 20 cm (Figure 3.1). On the other hand, no noticeable differences in soil temperature were observed at either 5 or 10 cm soil depths at Portage in 1990 (Figures 3.3 and 3.4, respectively). At Portage in 1989 and 1990, daily soil temperatures under both zero and conventional tillage appeared to fluctuate less as soil depth increased (Figure 3.1, 3.3 and 3.4).

Temperature differences between tillage systems at Portage in 1989 and at Carman in 1990 early in the season ranged from 0 to 2°C. These temperature differences were similar to the 0.5 to 2°C temperature decrease for zero tillage compared to conventional tillage observed by Gauer et al. (1982) at 5 cm depth. However, contrary to previous studies where few postanthesis soil temperature differences were observed (Gauer et al., 1982; Carter and Rennie, 1985), soil temperatures under zero tillage ranged from 0 to 7°C lower than under conventional tillage (Figures 3.1, 3.2, 3.3 and 3.4). One reason for reduced heat inputs under zero tillage after anthesis may be the higher level of previous crop residue under zero tillage (Table 3.4).

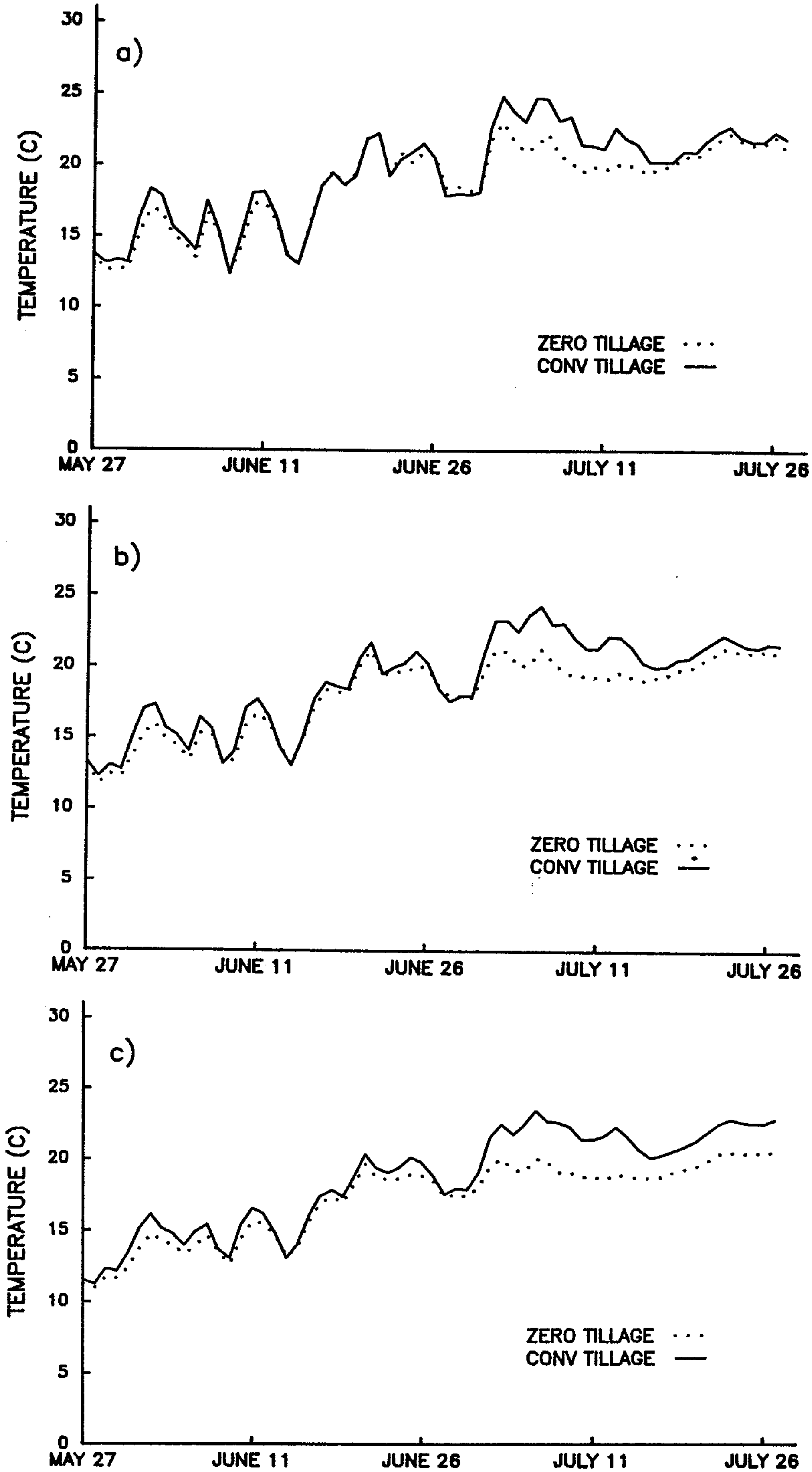


Figure 3.1
Mean daily soil temperatures at a) 2 cm, b) 10 cm and c) 20 cm for wheat at Portage in 1989.

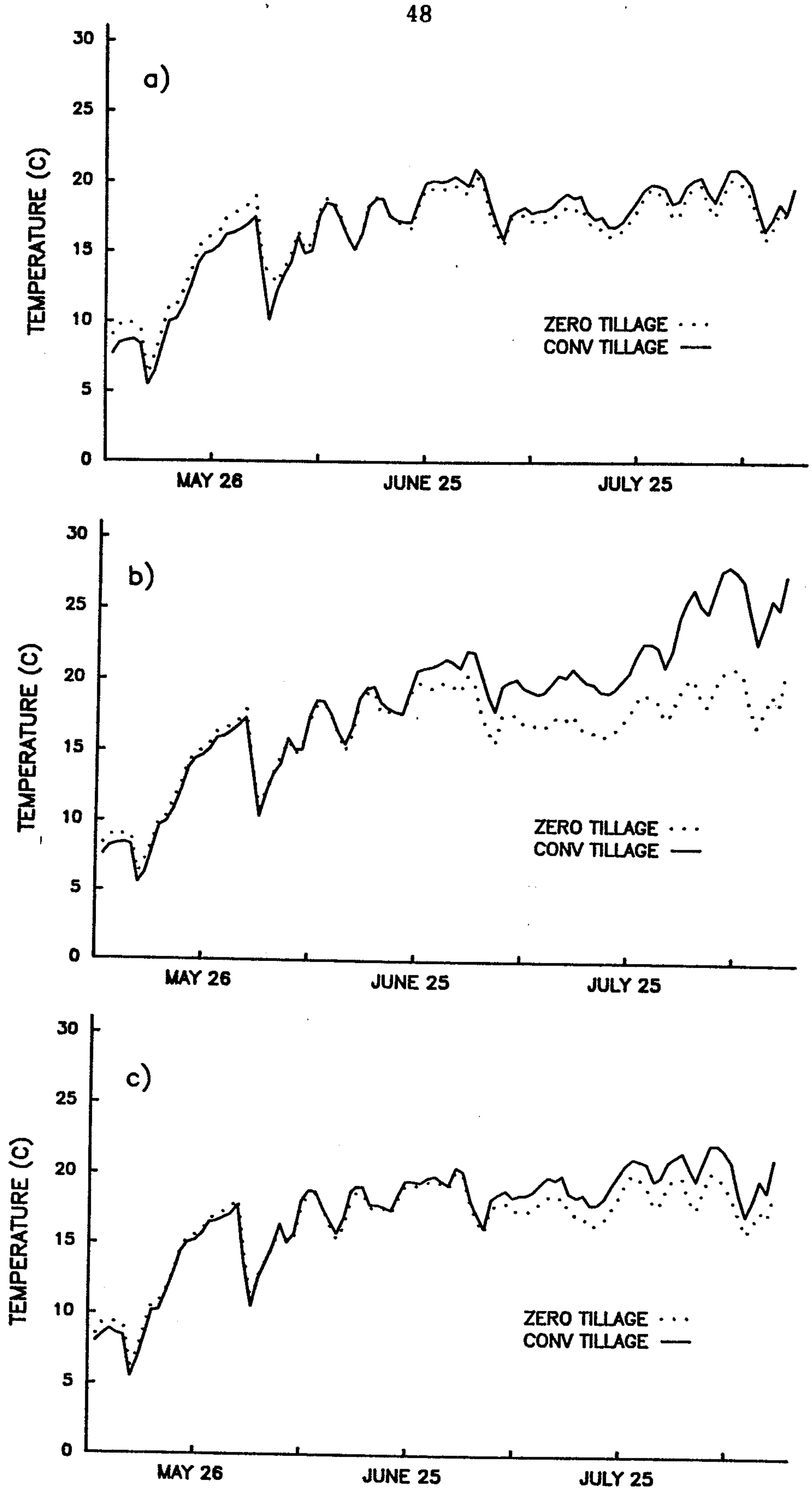


Figure 3.2
Mean daily soil temperatures at 10 cm for a) canola, b) field pea and c) spring wheat at Carman in 1990.

Table 3.4 Crop residue cover (%) under zero and conventional tillage systems, 1989 and 1990.

Location	Year	Residue Cover (%) Conventional Tillage	Zero Tillage
Carman	1989	42	62
	1990	27	88
Portage	1989	36	81
	1990	20	76

A reduction in soil temperature after anthesis under zero tillage at Carman in 1990 was greatest for field pea and least for canola (Figure 3.2). One reason for the temperature reduction may have been differences in crop canopy between these two crops under zero compared with conventional tillage. For example, canopy light interception after anthesis was 3 to 7% higher for field pea and 2 to 3% for canola under zero compared with conventional tillage at Carman in 1990. However, after anthesis the field pea canopy was lodged and therefore had its dry matter much more densely arranged near the soil surface compared to the upright, almost leafless canola canopy, resulting in a greater decrease in heat inputs for field pea than canola under greater crop canopy cover with zero tillage (Figure 3.2a, b). The decreases in soil temperature under zero tillage for wheat (1.5 to 3°C) after anthesis were consistent between the two sites where this trend was observed (Figures 3.1b, 3.2c) and the magnitude of the differences was intermediate to those of field pea and canola.

In conclusion, while it was not possible to test soil temperature differences between tillage systems statistically, the response of soil

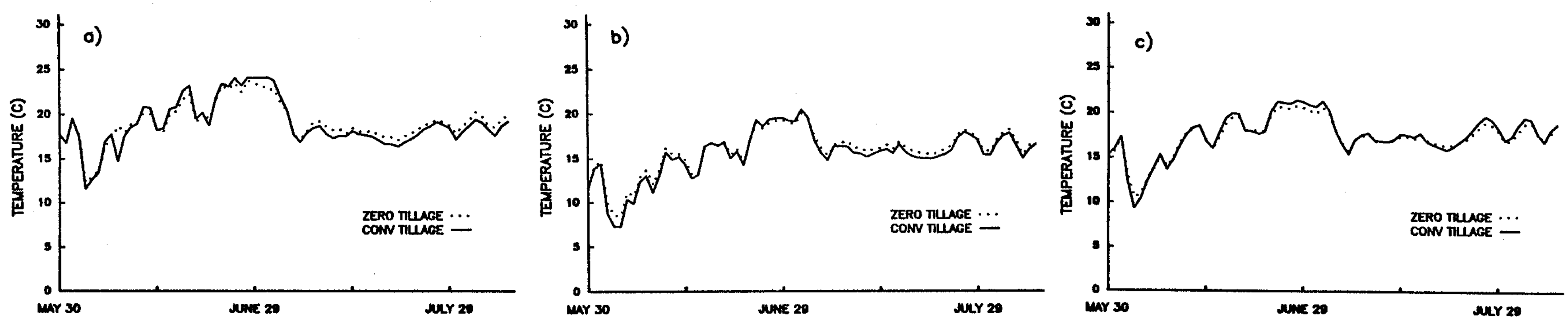


Figure 3.3
Mean daily soil temperatures at 5 cm for a) canola, b) field pea and c) spring wheat at Portage in 1990.

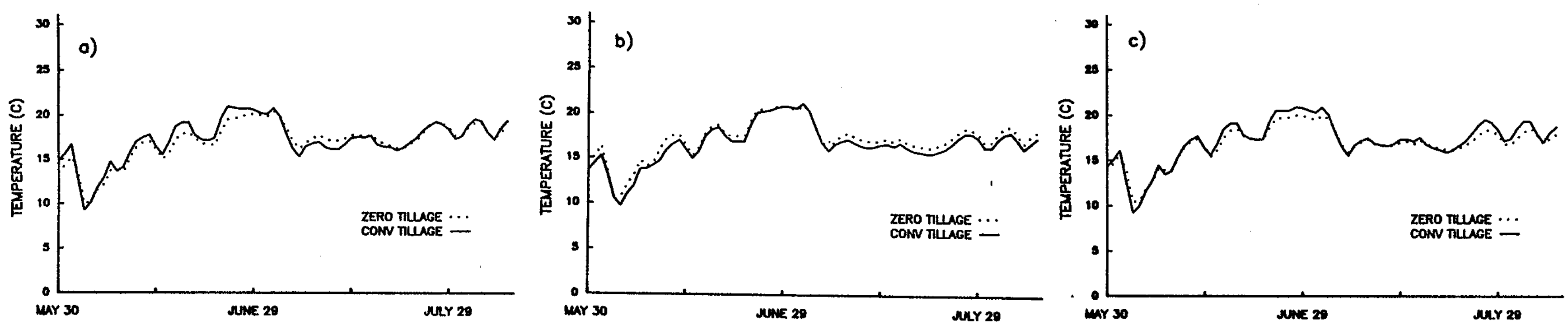


Figure 3.4
Mean daily soil temperatures at 10 cm for a) canola, b) field pea and c) spring wheat at Portage in 1990.

temperature to zero tillage in the present study was not always as expected. Early season temperatures under zero tillage were not noticeably lower than those under conventional tillage at any site. In several instances, temperatures were higher under zero than under conventional tillage early in the season (Figure 3.2). Thus, detrimental effects of zero tillage on early growth, which are often attributed to reduced spring temperatures under zero compared to conventional tillage (Gauer et al.,1982; Wilhelm et al., 1989) may not have been an important factor in this study.

Soil temperatures after anthesis were lower under zero than conventional tillage at Portage in 1989 and at Carman in 1990. Because soil temperature can affect root distribution in the soil profile (Kirkham and Ahring, 1978), this difference in soil temperature at critical stages of growth such as anthesis and grain filling, may have a detrimental effect on yield potentials of crops under zero tillage. At these critical stages, limited root distribution may limit water availability and therefore the plant's ability to cope with high evaporative demands, possibly masking previous growth advantages due to increased available water under zero tillage.

3.3.1.2 Air Temperature

Air temperature at Stevenson screen height (1.5 m) was measured in both years at Portage. Air temperatures in 1989 were above average in May and July, while temperatures in 1990 were above average during the months of June and August (Table 3.5). Average monthly temperatures in 1989 and 1990 were never below the long term average. Temperatures in excess of

29°C can be detrimental to flowering and seed formation (Frank et al., 1987; Morrison et al., 1989; Jeuffroy, et al., 1990). In 1989, there were 22 days with temperatures in excess of 29°C between late June and early August (i.e., during flowering and grain-filling). The entire month of July in 1989 was hot (Figure 3.5) and daily maximum temperatures averaged 5.5°C above normal (Table 3.5). Air temperatures were close to the long-term average for the month of July, 1990 (Table 3.5) when most of the crops were flowering at Carman, but somewhat higher than normal in late July and early August when crops were flowering at Portage (Figure 3.6). In 1990, there were only 13 days in excess of 29°C between June 24 and August 8. Thus temperature stress at flowering differed between the two years and may have been a factor affecting crop yields.

Table 3.5 Long-term average and actual monthly temperature and precipitation at Portage in 1989 and 1990.

Month	Year	Temperature (°C)			Precipitation
		Maximum	Minimum	Mean	Total(mm)
May	Normal[1]	17.0	4.6	10.8	31.0
	1989	22.1	5.3	13.9	24.0
	1990	17.5	2.8	10.2	42.7
June	Normal	22.9	10.6	16.8	81.0
	1989	23.3	9.8	16.5	124.0
	1990	24.4	11.5	18.0	133.6
July	Normal	25.6	13.5	19.6	77.4
	1989	31.1	15.1	21.8	32.0
	1990	25.4	13.0	19.2	53.6
August	Normal	24.7	12.0	18.4	80.0
	1989	26.7	11.7	18.8	65.0
	1990	26.8	13.0	19.9	42.6

[1] Long-term average temperatures at Portage (Environment Canada).

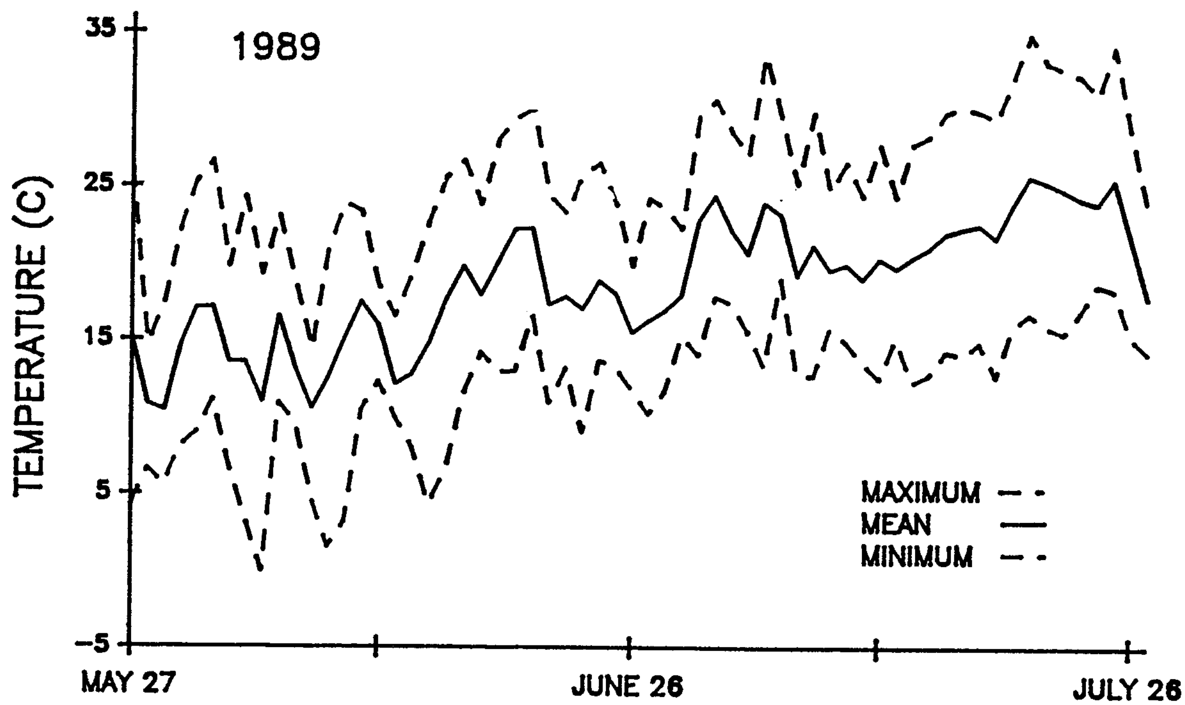


Figure 3.5
Air temperatures at Stevenson screen height, Portage la Prairie, 1989.

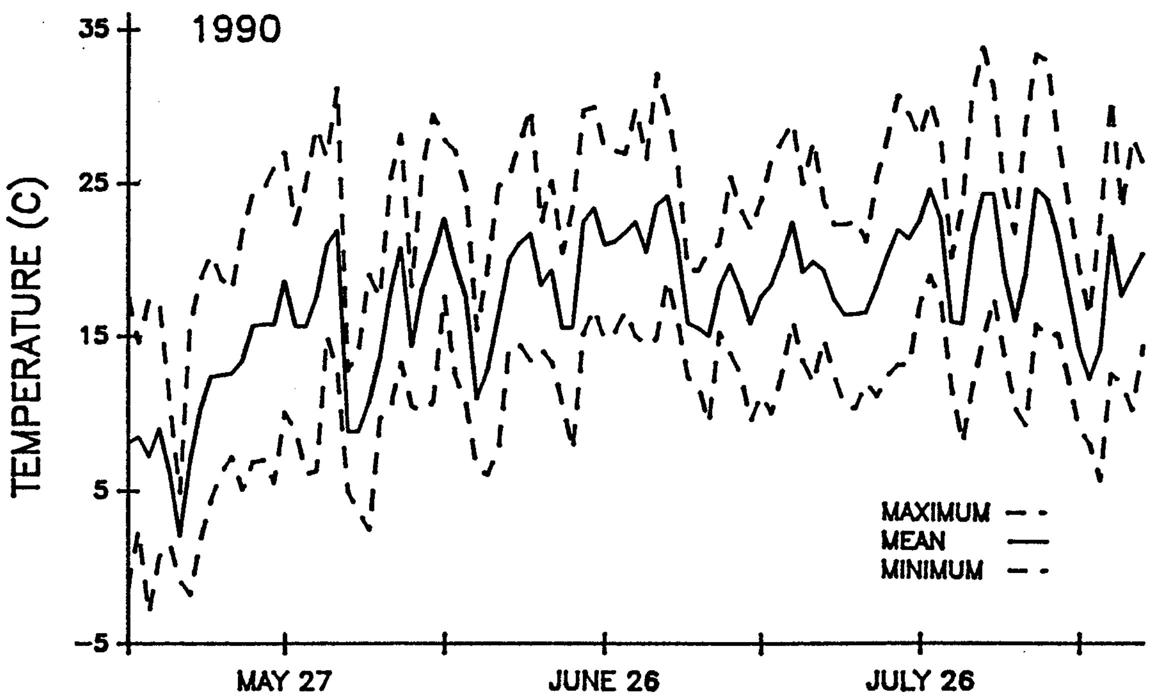


Figure 3.6
Air temperatures at Stevenson screen height, Portage la Prairie, 1990.

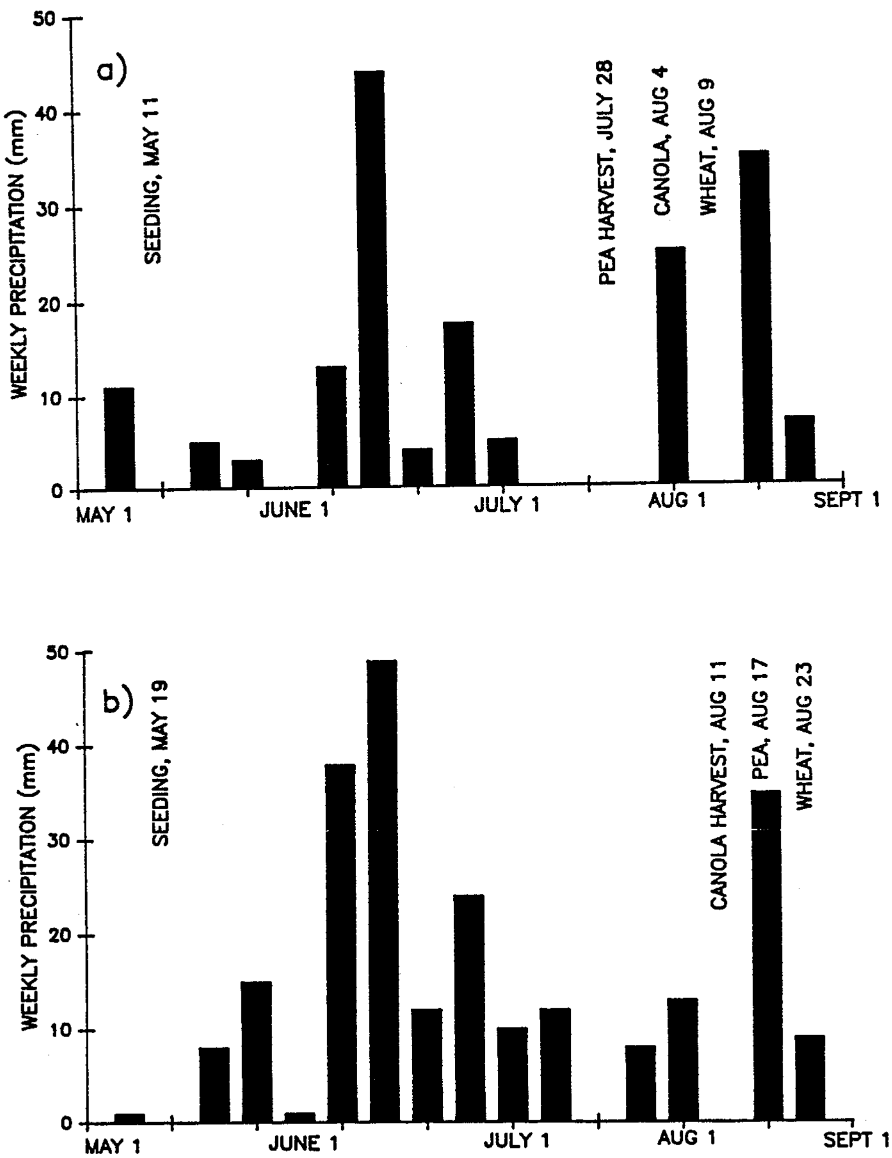
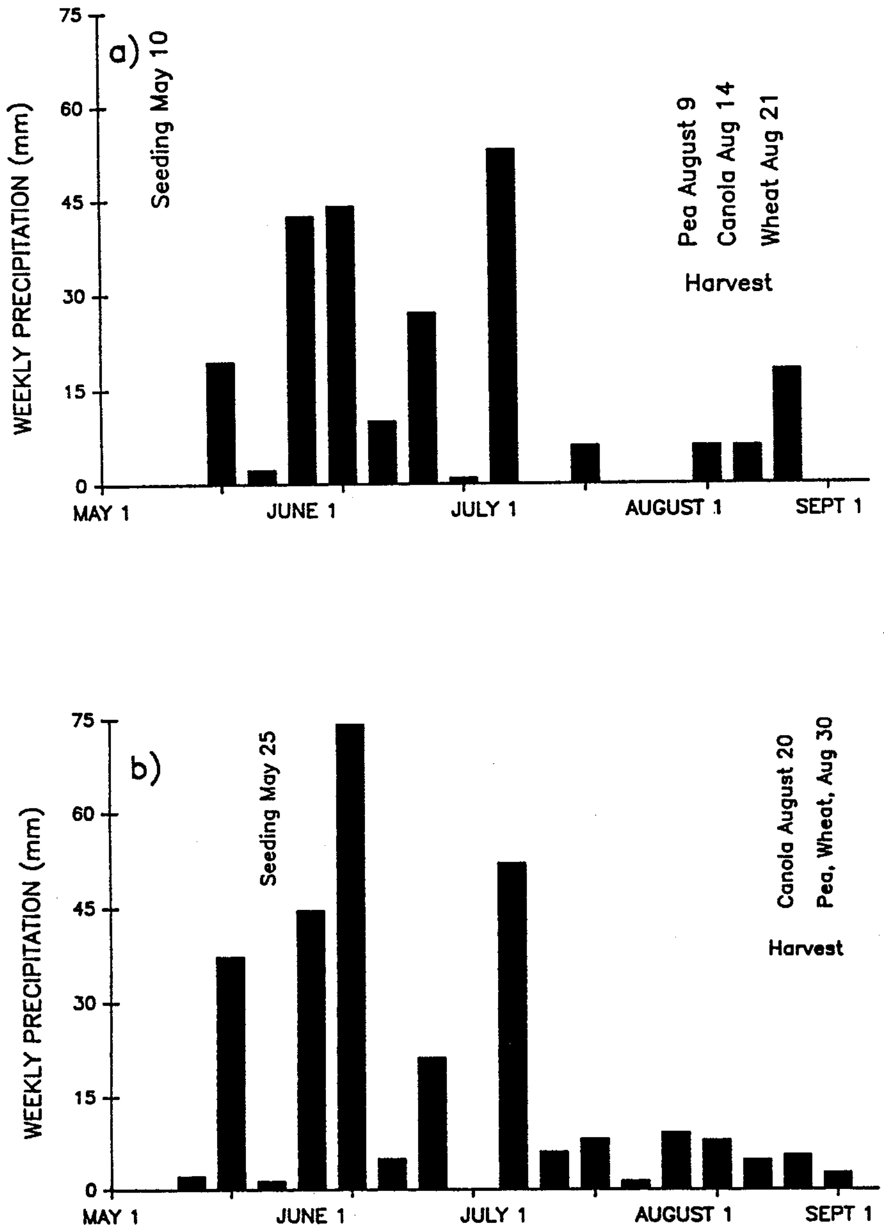


Figure 3.7
Weekly precipitation during the growing season in 1989 at a) Carman and b) Portage la Prairie, Manitoba.



Figures 3.8
Weekly precipitation during the growing season in 1990 at a) Carman and b) Portage la Prairie, Manitoba.

3.3.1.3 Precipitation

Precipitation levels varied greatly between sites and years. Growing season precipitation in 1989 was 91.5 mm at Carman and 190 mm at Portage (Figures 3.7 and 3.8). The combination of a drought in 1988 (data not shown), low growing season precipitation and a low soil water-holding capacity caused drought stress to be especially severe at Carman in 1989. Although June and early July were very wet in 1990, the precipitation for the later part of the season was well below average (Table 3.5). In 1990, growing season precipitation was 220 mm at Carman and was 242 mm at Portage. However, prior to seeding, Portage received an additional 37 mm of precipitation. This, together with later precipitation, resulted in very wet conditions for much of the growing season at this site. Precipitation was more similar between the two sites in 1990 than in 1989 (Figures 3.7 and 3.8).

3.3.2 Crop Establishment

Crop establishment was determined by measuring plant stand after total emergence. Crop establishment was not significantly ($P<0.05$) affected by tillage except at Carman in 1990 (Table 3.7; Appendix 3, Table A3.1) where establishment of wheat was better under zero tillage but establishment of canola was better under conventional tillage. Establishment of field pea was not affected by tillage at this site. Lower establishment of canola under zero tillage could not be attributed to differences in seeding depth (Table 3.6). However, the higher residue cover under zero tillage (Table 3.4) may have increased the distance seedlings had to go to reach sufficient light for growth and thus may have caused the lower emergence for canola. White and Robson (1989) found that seedlings of species with small seeds and an epigeal type of emergence, such as canola, are less able to emerge under stress than other species with larger seeds and different emergence mechanisms, such as field pea and wheat.

Table 3.6 Average seeding depth (mm) of canola, field pea and wheat under zero and conventional tillage.

Tillage(T)	Species(S)	Carman	Portage	
		1990	1989	1990
Conventional	Canola	16 ± 5[1]	21 ± 20	11 ± 5
	Field Pea	39 ± 4	37 ± 26	55 ± 14
	Wheat	40 ± 8	49 ± 15	54 ± 7
Zero	Canola	16 ± 11	23 ± 10	12 ± 7
	Field Pea	32 ± 4	27 ± 16	51 ± 9
	Wheat	29 ± 12	36 ± 25	48 ± 6

[1] ± standard deviation.

Table 3.7 Plant stands (plants m^{-2}) of canola, field pea and wheat under zero and conventional tillage.

Tillage(T)	Species(S)	Carman		Portage	
		1989	1990	1989	1990
Conventional	Canola	63	200	135	135
	Field Pea	53	106	116	89
	Wheat	131	271	248	295
Zero	Canola	58	165	102	117
	Field Pea	52	113	114	84
	Wheat	127	307	268	262
			TS*		

*, ** significant at the 0.05 and 0.01 probability levels, respectively.

Lafond and Loeppky (1988) found no effect of zero tillage on the establishment of field pea or wheat. Baeumer and Bakermans (1973) concluded that the response of seedling establishment to tillage varied between soil types; however, no evidence for soil type differences was found in the present study. Poor establishment of all crops at Carman in 1989 (Table 3.7) was attributed to drought, while poor emergence of field pea at Portage in 1990 was attributed to very wet soils in spring. Other studies (Doran et al., 1984; Ojeniyi, 1986; Carter and Barnett, 1987; Wolf and Edmisten, 1989) indicated that soil conditions under zero tillage were more conducive to crop establishment than those under conventional tillage, especially in dry years. Lack of a tillage response at the driest site in the present study (Carman in 1989) was attributed to the relatively small difference in residue cover (20% vs. 56% difference at Portage in 1990) on zero compared with conventional tillage plots (Table 3.4). In conclusion, crop establishment was not strongly affected by tillage in most of these trials.

3.3.3 Crop Growth

3.3.3.1 Aerial Dry Matter Accumulation

Dry matter accumulation for canola, field pea and wheat responded similarly to zero tillage in most instances in this study (Figures 3.9, 3.10, 3.11, and 3.12). While many significant differences in dry matter accumulation between species were observed, only one significant tillage effect and one significant tillage by species interaction was recorded over the 26 sampling dates (Appendix 3, Tables A3.2 to A3.5). While Lal

(1974) also found no significant effect of zero tillage on dry matter accumulation, other studies have shown a decrease in dry matter production for spring wheat (Chevalier and Ciha, 1986), winter wheat (Baeumer and Bakermans, 1973; Klepper and Rickman, 1988; Wilhelm et al., 1989), soybean (Webber et al., 1987), and corn (Baeumer and Bakermans, 1973; Carter and Barnett, 1987; Kaspar et al., 1987) under zero compared to conventional tillage. On the other hand, Diebert and Utter (1989) reported that sunflowers had a higher dry matter production under zero than under conventional tillage throughout the season. Results of the present study clearly indicate that dry matter accumulation of these crops was not affected by the tillage systems.

In some cases, the decrease in dry matter production reported in the literature was confined to the early part of the growing season with total dry matter levels converging by anthesis (Webber et al., 1987; Wilhelm et al., 1989). The only instance where tillage affected early season dry matter accumulation in this study was at Carman in 1990, where a significant tillage by species interaction occurred on the first sampling date for the season (June 4). On this date, wheat showed very little response to the tillage system, while canola showed a positive response and pea showed a negative response to zero tillage (Table 3.8). A severe flea beetle *(Phyllotreta cruciferae* (Goeze)) infestation appeared to have caused more damage to canola under conventional tillage than under zero tillage, and therefore, may have been one reason for lower canola dry matter under conventional tillage. It was interesting to note that the poorer emergence of canola under zero tillage at this site (Table 3.7) had no detrimental effect on it's growth under zero tillage. Lower dry matter

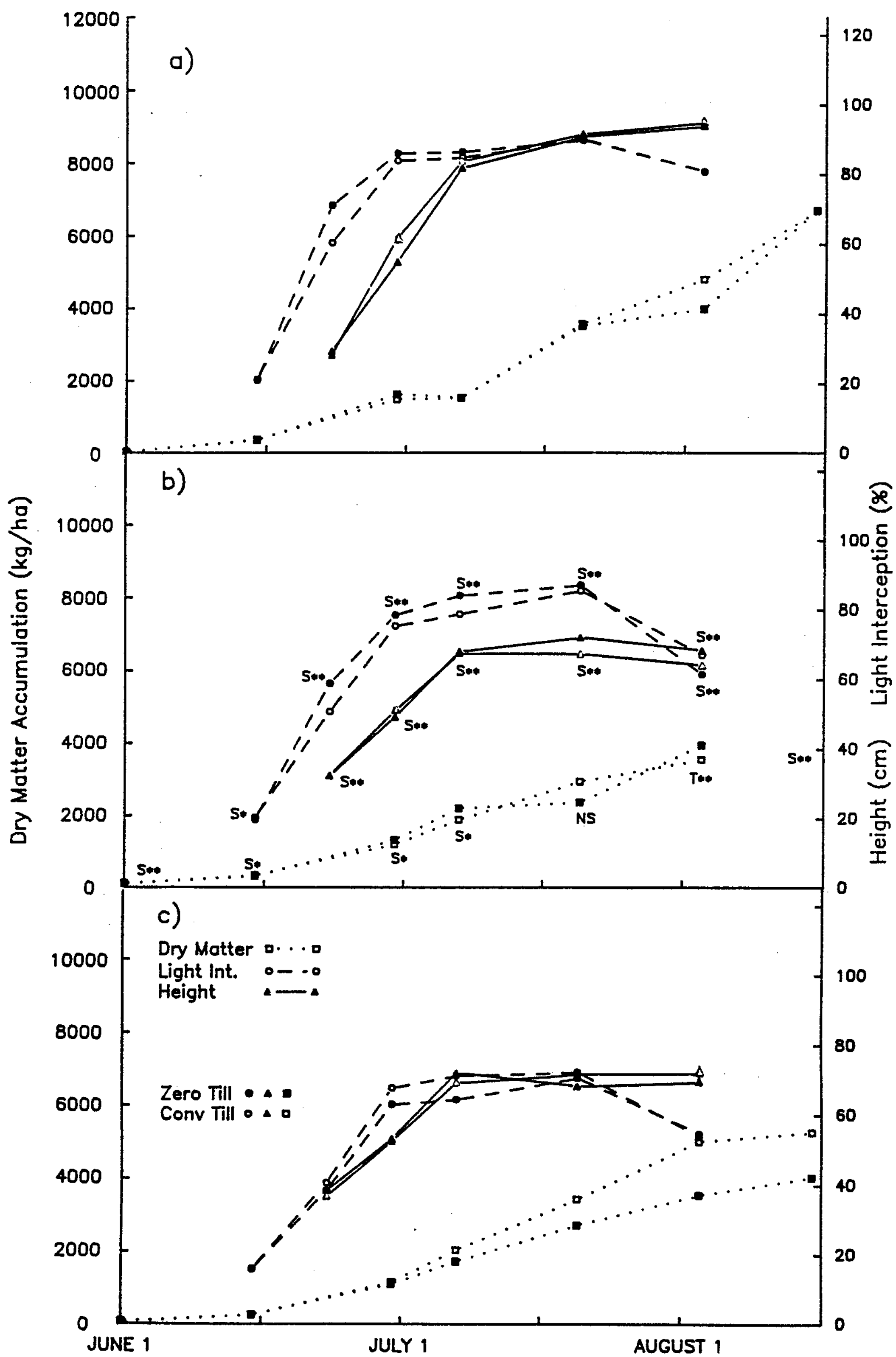


Figure 3.9
Seasonal dry matter accumulation, light interception by the crop canopy, and crop height for a) canola, b) field pea and c) wheat under zero and conventional tillage at Carman in 1989. * and ** indicate significance of tillage (T) or species (S) at the 0.05 and 0.01 probability levels, respectively.

for field pea under zero tillage may have been caused by the heavier trash cover under zero tillage (Table 3.4).

Table 3.8 Dry matter accumulation (kg ha^{-1}) of canola, field pea and wheat under zero and conventional tillage, Carman, June 4, 1990.

Tillage(T)	Species(S)	Dry Matter Accumulation (kg ha^{-1})	
Conventional	Canola	33.0	
	Field Pea	104.2	
	Wheat	109.8	
			TS**
Zero	Canola	49.1	
	Field Pea	82.0	
	Wheat	102.3	

*, ** significant at the 0.05 and 0.01 probability levels, respectively.

The other significant ($P<0.05$) effect of tillage on dry matter production occurred on July 26, 1989 at Carman, shortly before harvest (Figure 3.9). On this date, conventional tillage crops had higher dry matter than zero tillage crops. However, differential response of crops to a reduction in tillage on this date was significant at $P=0.0686$. This was due to the lower dry matter production for wheat and canola under zero than under conventional tillage, while dry matter for field pea was slightly higher under zero tillage.

Lack of significant tillage effects on preanthesis dry matter accumulation in this study indicates that there were no differences in the photosynthetic capacity of the crops for flowering and seed production.

3.3.3.2 Crop Height

Reduction in tillage significantly affected crop height in a number of instances (Figures 3.9 to 3.12; Appendix 3, Tables A3.6 to A3.9). At

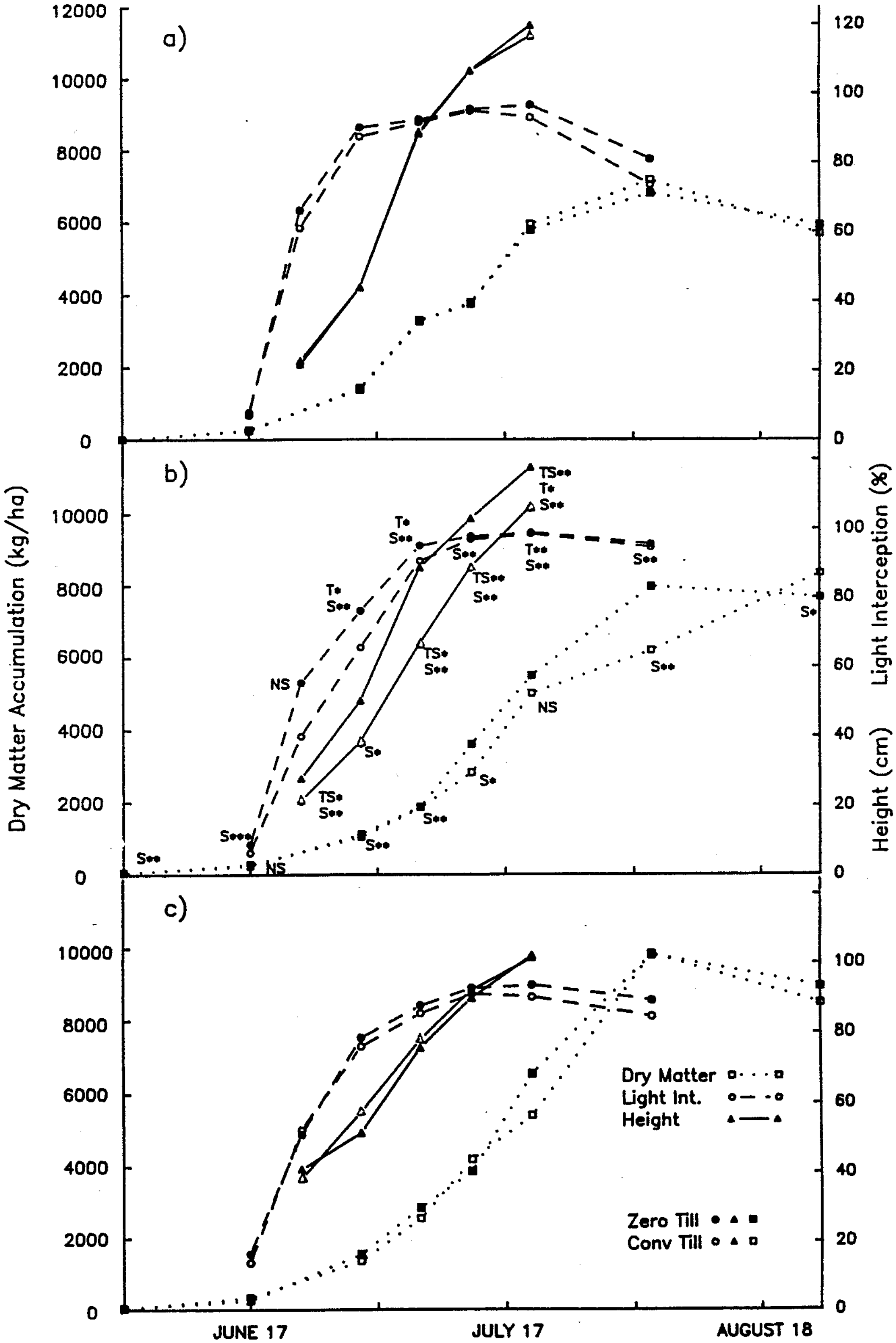


Figure 3.10
Seasonal dry matter accumulation, light interception by the crop canopy, and crop height for a) canola, b) field pea and c) wheat under zero and conventional tillage at Portage in 1989. * and ** indicate significance of tillage (T) or species (S) at the 0.05 and 0.01 probability levels, respectively.

Portage in 1989, significant ($P<0.05$) tillage by species interactions were recorded on four of the five sampling dates (Figure 3.10), indicating that the three crops responded differently to tillage. The basis for the significant interactions was the fact that field pea was consistently 7 to 12 cm taller under zero than under conventional tillage while wheat and canola were unaffected. This positive effect of zero tillage on field pea height was maintained for much of the growing season. A significant effect of zero tillage on crop height was observed for all crops on July 4, 1990 at Carman (Figure 3.11).

Other researchers also have observed that crop height was affected by zero tillage. For example, Lafond and Loeppky (1988) found that zero tillage increased height of wheat (10 cm) and field pea (4 cm), while Carter and Rennie (1985) found that wheat height was higher under conventional than under zero tillage. Doran et al. (1984), Kaspar et al. (1987), Lal (1974), Ojeniyi (1986), and Carter and Barnett (1987) reported a variable response of corn height to zero tillage. Doran et al. (1984) reported that height of corn increased with the decreasing soil temperature and the increasing soil water content resulting from high crop residue levels. Kirkham and Ahring (1978) reported that plant height in wheat was greatest when root temperature equalled that of the air.

Differences in the soil environment under zero and conventional tillage may also have played a role in determining height differences in the present study. For example, taller crops under zero tillage at Carman in 1990 and at Portage in 1989 may have been due to lower soil temperatures which were closer to the optimum for crop growth (Figures 3.1 and 3.2, respectively). Soil temperature differences between tillage

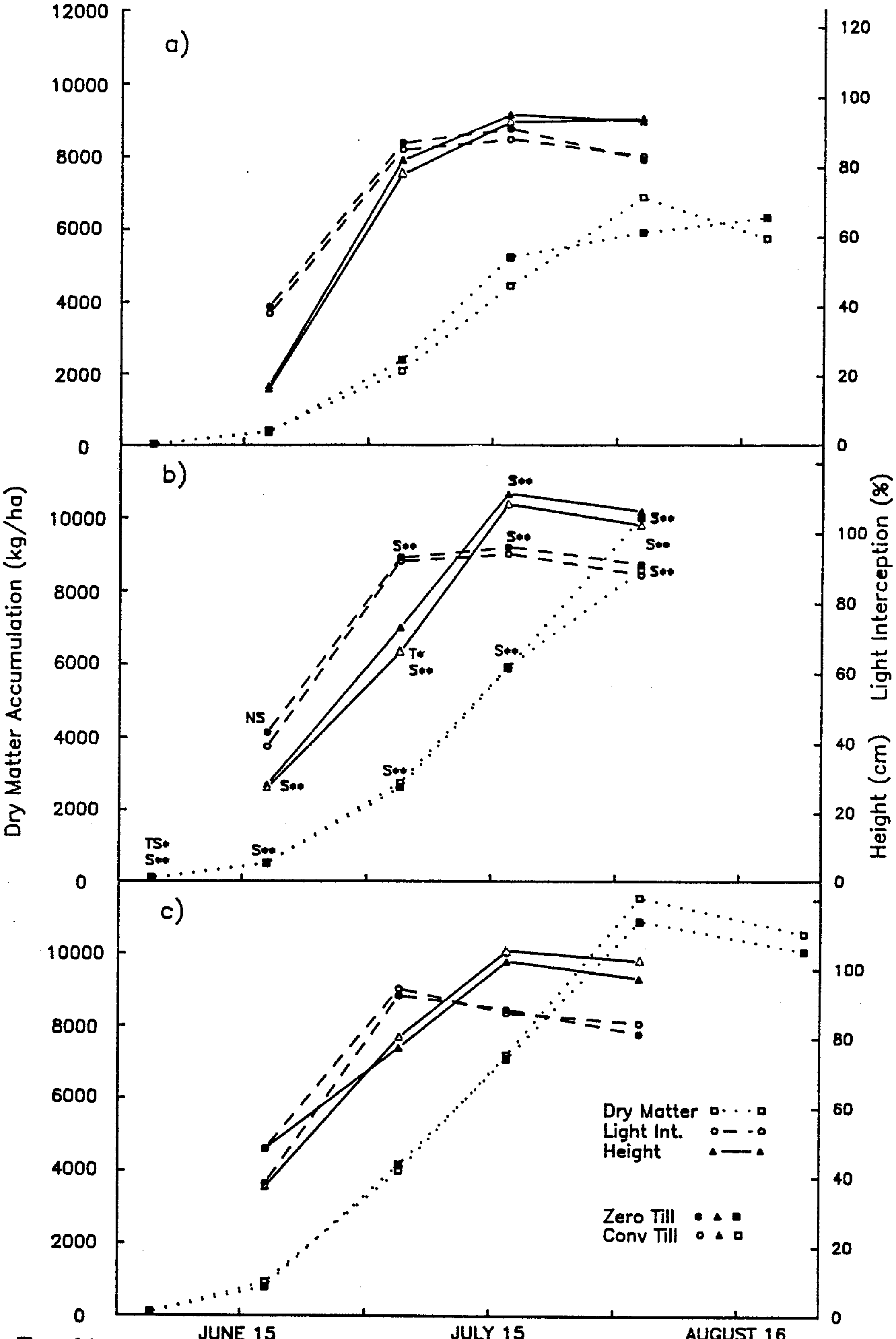


Figure 3.11
Seasonal dry matter accumulation, light interception by the crop canopy, and crop height for a) canola, b) field pea and c) wheat under zero and conventional tillage at Carman in 1990. * and ** indicate significance of tillage (T) or species (S) at the 0.05 and 0.01 probability levels, respectively.

treatments were negligible at Portage in 1990 which may have been a factor contributing to the lack of any tillage effects on crop height at that site.

3.3.3.3 Light Interception by the Crop Canopy

Canopy light interception was consistently different ($P<0.05$) among the three crop species (Figures 3.9 to 3.12; Appendix 3, Tables A3.10 to A3.13). However, significant tillage responses were only found for three of the seven sampling dates at Portage in 1989 and for one of the three sampling dates at Portage in 1990. In 1989, light interception by the crop canopy was greater under zero tillage, however in 1990, light interception was highest ($P<0.05$) for the conventional tillage plots. The lack of any significant tillage by species interactions for light interception (Figures 3.9, 3.10, 3.11 and 3.12) suggests that where differences occurred, all three crops responded similarly to zero tillage.

Although it does not appear that any previous studies have examined the effect of tillage on crop light interception, some have examined similar parameters such as leaf area index. Wilhelm et al. (1989) working with winter wheat, found that the leaf area index was decreased under zero tillage. On the other hand, Doran et al. (1984), found that the reduced stress levels under high residue cover (100% to 150% of residue produced by the previous crop) allowed earlier and more complete canopy closure than under low residue cover (0 to 50%) for corn and soybean. It is possible that reduced stress levels were also a factor contributing to higher canopy light interception for field pea, canola and wheat at

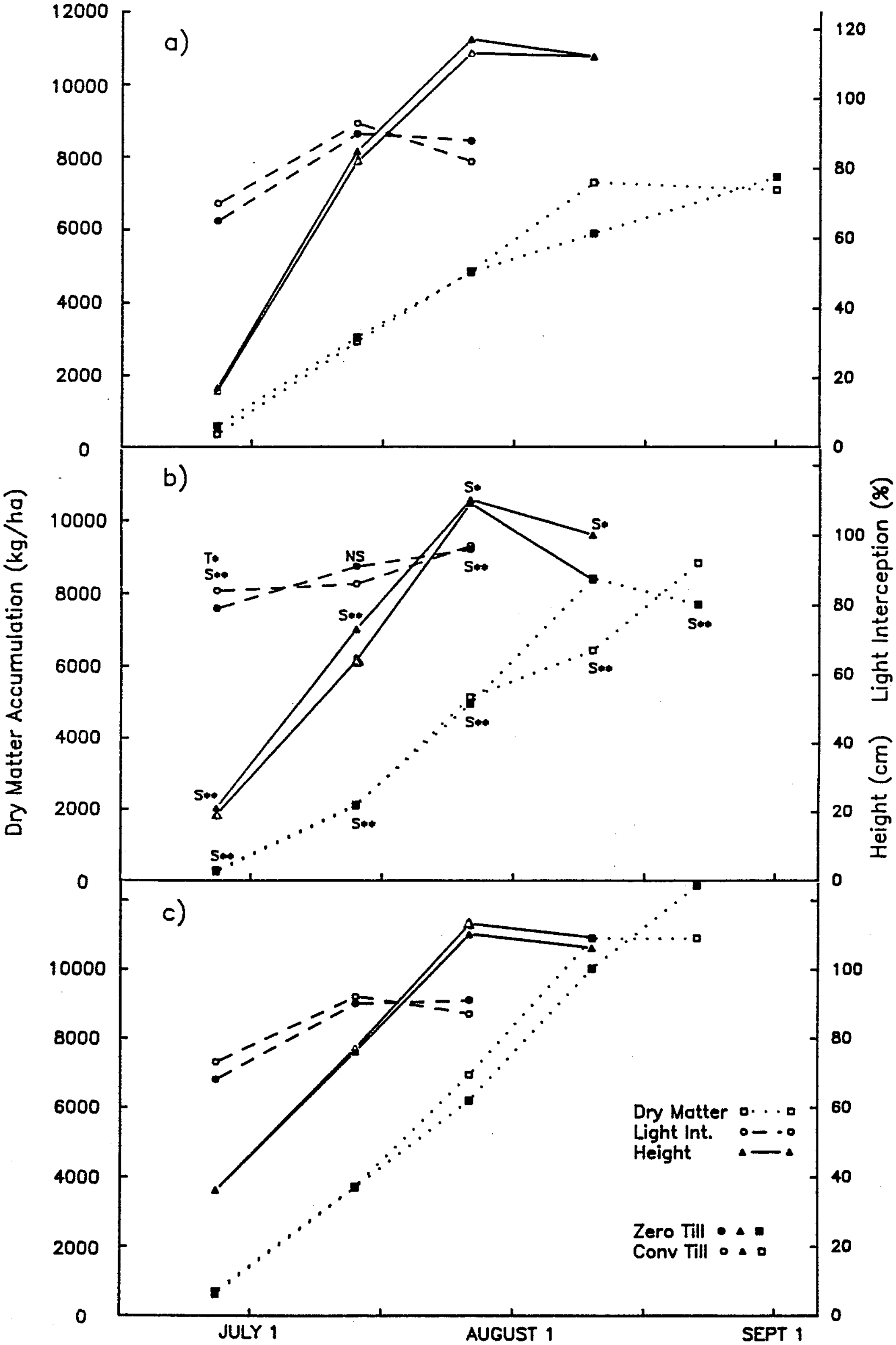


Figure 3.12
Seasonal dry matter accumulation, light interception by the crop canopy, and crop height for a) canola, b) field pea and c) wheat under zero and conventional tillage at Portage in 1990. * and ** indicate significance of tillage (T) or species (S) at the 0.05 and 0.01 probability levels, respectively.

Portage in 1989. Because 1989 was drier and hotter than 1990, water stress effects would be expected to have been greatest in 1989. Lack of a positive response at Carman in 1989 may have been due to the low level of residue cover in the zero tillage plots (Table 3.4). Therefore, moisture conserving and stress reducing characteristics of zero tillage may have been less.

A significant tillage response occurred on June 26, 1990 at Portage (Figure 3.12) with crops under conventional tillage having greater canopy light interception than those under zero tillage. Standing stubble under zero tillage may have shaded the crops, thereby limiting light interception and reducing growth. Altered growth due to shading may have affected the spatial distribution of the crop canopy since there were no significant differences in dry matter production. The spring of 1990 was very wet (Figure 3.8) and cool (Figure 3.6). These conditions may have contributed to poorer canopy development under zero tillage, which was the opposite of the trend in 1989 at Portage where conditions were warmer and drier.

Light interception by the crop canopy, both as a measure of canopy fullness and as a measure of photosynthetic capacity, is a useful parameter characterizing crop growth potential. Differences in crop canopy development between tillage systems often vary within a season. Both Carter and Rennie (1985) and Wilhelm et al. (1989) have shown that crop canopies can affect soil temperature and thus subsequent growth of wheat. Their observation of poorer early season canopy development under zero tillage was attributed to lower soil temperatures under zero tillage compared to conventional tillage. However, the thinner crop canopy resulted in greater light penetration to the soil causing soils to warm up more under zero than under conventional tillage. These authors found that soil temperature differences had a profound effect on plant growth, causing differences to be equalized between tillage systems by heading. In the present study there were few crop canopy and preanthesis soil temperature differences between tillage systems. Where differences were found, light interception by the crop canopy was most often increased under zero tillage.

3.3.4 Grain Yield

Tillage did not significantly affect grain yield at any of the four sites (Table 3.9; Appendix 3, Table A3.14). When results from all sites were analyzed in a combined analysis there was a significant species effect and a site by species interaction; however, there was still no significant effect of tillage (Table 3.9). In addition, no significant tillage by species by site interactions were observed. This indicates that the three crop species reacted similarly to zero tillage at all sites.

The lack of significant tillage effects on grain yield in the present study indicates that some of the advantages under zero tillage recorded earlier in the growing season (i.e., dry matter production, crop height, and light interception; Figures 3.9 to 3.12), especially for field pea, were not expressed in final yield. In 1989, there were 22 days between June 24 and August 8 on which air temperatures exceeded 29°C. In 1990 there were only 13 days in excess of 29°C during the same time

Table 3.9 Grain yield (kg ha^{-1}) of canola, field pea and wheat under zero and conventional tillage.

Tillage(T)	Species(S)	Carman 1989	Carman 1990	Portage 1989	Portage 1990
Conventional	Canola	1996	2272	2000	2252
	Field Pea	1962	3781	3741	3403
	Wheat	2056	4221	3046	3881
Zero	Canola	1835	2180	1908	2049
	Field Pea	2010	4129	3371	3469
	Wheat	1807	4054	3203	3880
		NS	NS	NS	NS

Combined analysis: Site-year**, Site-year x Species**.

*, ** significant at the 0.05 and 0.01 probability levels, respectively.

period. This time period included anthesis and part of the grain-filling time at all sites. The high temperatures may have been a factor in preventing field pea and wheat from being able to take the full advantage of any improved soil water conditions under zero tillage. Therefore, while the potential for improved yields appeared to exist under zero tillage, significant yield improvement did not occur because conditions were not suitable. The lack of a significant yield response to tillage holds other relevance as well. For example, zero tillage did not appear to have a detrimental effect on yields of canola, field pea or wheat. Therefore, it appears that zero tillage is a practical alternative to conventional tillage for farmers growing these crops in their rotations.

Nonsignificant effects of tillage on final yield have also been reported by others. For example, Stobbe et al. (1970) reported a non-significant yield increase for oilseed rape under zero tillage at one of two sites while wheat was not significantly affected. Similarly, Donaghy (1973) reported a yield increase of oilseed rape under zero tillage for only one of eight sites while no significant yield differences between tillage systems were found for wheat at the same eight sites. Wilhelm et al. (1989) found yield decreases for wheat under zero tillage but Lafond and Loeppky (1988) found a significant yield increase for wheat with a reduction in tillage. Lafond and Loeppky (1988) also found that field pea yielded significantly more under zero tillage than under conventional tillage. However, these results differ from those in the present study. Their yields averaged from 1785 kg ha^{-1} under conventional tillage to 1935 kg ha^{-1} under zero tillage while those in the present study were more than double these values at three of the four sites. Therefore, comparisons between these two studies may be of limited value.

Similar variable responses to zero tillage were also observed in other crops, including corn (Lal, 1974; Edwards et al., 1988), soybean (Elmore, 1987; Edwards et al., 1988; Webber et al., 1989), and sunflower (Diebert, 1989; Diebert and Utter, 1989). Some of these reports showed that the greatest benefits from zero tillage occurred in dry years.

A significant site by species interaction was recorded for grain yield in this study (Table 3.9). The basis for this significant interaction appeared to be differences in the yield trends between sites for canola compared with those of the other two crops, especially in 1989. For example, at the driest site (Carman, 1989), all crops yielded between 1807 and 2056 kg ha^{-1}. Under higher precipitation at Portage in 1989, wheat and field pea yielded over 3000 kg ha^{-1} while the yield for canola remained at about 1900 kg ha^{-1}. Although the level of available soil water at anthesis for canola was similar for Carman and Portage (136 mm and 146 mm, respectively, for the 130 cm profile), preanthesis ET was higher at Portage (Figures 4.1 and 4.2). These results suggest that wheat and field pea were able to develop a larger sink and thus were able to yield higher, while canola did not. One explanation for the different responses by the three crops may be that air temperature, which was varied less between the two sites than precipitation, affected canola yields more than soil water availability, and that canola is more sensitive to air temperature than the other crops. Air temperatures above 25°C at or shortly after flowering are especially damaging to flowering and pod set in Westar canola (Morrison et al., 1989). In 1990, yields of canola were similar to those in 1989, varying only 100 kg ha^{-1} between sites, despite greater ET and available water at anthesis (242 mm at Carman and 235 mm at Portage), again supporting the observation that air temperature may affect canola yields more than soil water does. Wheat and field pea were much more responsive to increases in ET and thus yielded better at Portage in 1989 and at Portage and Carman in 1990 compared with at Carman in 1989.

3.3.5 Harvest Index

Harvest index was not significantly affected by tillage at any site (Table 3.10), indicating that tillage regime did not affect the conversion of dry matter to grain yield in any of the trials. Combined analysis of all sites indicated that the main factor in affecting harvest index was crop species. However, environmental conditions can also cause considerable variation in harvest index values. As Wilson et al. (1985)

noted, seed weight of field pea can vary from 40 to 60% of the total final crop dry weight. Richards and Thurling (1978b) found that the harvest index of oilseed rape was most affected by drought stress at flowering. Any stress after vegetative growth stages have been completed could be expected to have a significant effect on harvest index since it would affect the plant's ability to convert its dry matter into grain yield. Higher air temperatures and lower precipitation after anthesis in 1989 may have been the cause for the lower harvest index of all crops in 1989 compared with 1990 (Table 3.10).

Table 3.10 Harvest index of canola, field pea and wheat under zero and conventional tillage.

Tillage(T)	Species(S)	Carman		Portage	
		1989	1990	1989	1990
Conventional	Canola	.23	.40	.26	.32
	Field Pea	.36	.44	.31	.42
	Wheat	.28	.40	.26	.36
Zero	Canola	.22	.35	.24	.28
	Field Pea	.34	.43	.32	.45
	Wheat	.31	.41	.27	.32
		NS	NS	NS	NS

Combined analysis: Site-year**.

*, ** significant at the 0.05 and 0.01 probability levels, respectively.

Harvest index is a reflection of environmental conditions during both vegetative and reproductive growth. If both vegetative and reproductive growth periods are favorable for growth, harvest index will be maximized. Therefore a greater effect of tillage on harvest index may have been observed if zero tillage had promoted excessive luxuriant growth early in the season, followed by a yield collapse due to a late-season drought. However, there was no significant yield collapse in the present study.

3.3.6 Yield Components

Few significant tillage responses for yield components were observed in this study (Tables 3.11, 3.12 and 3.13). The only significant tillage by species interaction for pods or spikes m^{-2} occurred at Carman in 1989. The basis for this interaction was a large increase in the number of pods m^{-2} for canola with zero tillage, and a small decrease for field pea. Spikes m^{-2} were only increased slightly in wheat. Lafond and Loeppky (1988) and Wilhelm et al. (1989) also found more spikes m^{-2} for wheat under zero than conventional tillage. Pod number for field pea (Hardwick, 1985) and oilseed rape (McGregor, 1981) has been shown to be strongly influenced by soil moisture conditions. Higher pod number of these crops under zero tillage might have been due to greater available water under zero tillage.

There were no significant tillage responses for pods or spikes m^{-2} at any other site. The lower pod or spike numbers for field pea and wheat at Carman in 1989 and the high pod numbers of canola and field pea in Portage in 1989 compared with other sites, resulted in a significant site by species interaction (Table 3.11).

No significant effect of tillage was observed for seed number per pod or spike (Table 3.12). Since seed number in wheat (Entz and Fowler, 1988) and canola (Richards and Thurling, 1978b) is dependant on conditions

Table 3.11 Pod or spike number (per m^2) of canola, field pea and wheat under zero and conventional tillage.

Tillage(T)	Species(S)	Carman 1989	Carman 1990	Portage 1989	Portage 1990
Conventional	Canola	4661	6003	8585	6536
	Field Pea	681	929	1441	737
	Wheat	336	651	635	701
Zero	Canola	5858	5958	9416	5902
	Field Pea	612	901	1543	866
	Wheat	356	641	646	713
		TS*	NS	NS	NS

Combined analysis: Site-year x Species**.

*, ** significant at the 0.05 and 0.01 probability levels, respectively.

from floral initiation until anthesis, soil water during this period may not have been different between tillage treatments. Ojeniyi (1986) concluded that if soil water was the dominant stress at anthesis for corn, seed number would be favorably affected by a reduction in tillage. However, in the present study other environmental stresses such as high temperature and high evaporative demand may have masked any soil moisture benefits with zero tillage. High seed numbers for wheat at Carman in 1989 and high seed numbers for canola at Portage in 1990 (Table 3.12) resulted in a significant site-year by species interaction.

A differential crop species response of seed weight to tillage was observed in one of the four trials (Table 3.13). At Carman in 1990, seed weight of pea was increased 6 mg with zero tillage, while seed weight of canola was increased slightly and seed weight of wheat was decreased slightly. Differences in seed weight observed in this trial do not appear

Table 3.12 Seed number (per pod or spike) of canola, field pea and wheat under zero and conventional tillage.

Tillage(T)	Species(S)	Carman 1989	Carman 1990	Portage 1989	Portage 1990
Conventional	Canola	9.2	8.1	5.9	11.1
	Field Pea	3.6[1]	2.6	3.4[1]	3.1
	Wheat	24.2	18.1	16.0	16.3
Zero	Canola	6.9	7.5	4.8	11.3
	Field Pea	3.6[1]	2.9	3.0[1]	2.4
	Wheat	20.7	18.0	16.3	15.9
		NS	NS	NS	NS

Combined analysis: Site-year*, Site-year x Species**.

[1] Counted by hand - all others were calculated.
*, ** significant at the 0.05 and 0.01 probability levels, respectively.

Table 3.13 Seed weight (mg) of canola, field pea and wheat under zero and conventional tillage.

Tillage(T)	Species(S)	Carman 1989	Carman 1990	Portage 1989	Portage 1990
Conventional	Canola	4.8	4.8	4.5	3.3
	Field Pea	141.7	159.7	168.1	174.9
	Wheat	25.6	36.0	30.2	34.2
Zero	Canola	4.8	5.0	4.5	3.2
	Field Pea	143.7	165.6	165.1	173.6
	Wheat	24.6	35.3	30.5	34.1
		NS	TS*	NS	NS

Combined analysis: Site-year**, Site-year x Species**, Site-year x Tillage**, Site-year x Tillage x Species**.

*, ** significant at the 0.05 and 0.01 probability levels, respectively.

to be due to compensatory growth, since no tillage or tillage by species interactions were observed for the two earlier yield components at Carman in 1990. Therefore, conditions for grain-filling were more favorable for peas under zero tillage at this trial. These results are different than those reported by Lafond and Loeppky (1988) who found no differences in seed weight of pea due to zero tillage, and Wilhelm et al. (1989) who found a decrease in seed weight of wheat under zero tillage.

3.3.7 Grain Quality

Hectolitre weights of grain samples were not significantly different between tillage systems in any of the trials (Table 3.14), indicating that moisture and growth conditions were not sufficiently different between tillage systems to affect assimilate production by the plants and assimilate accumulation in the seeds. Similar results were found for wheat and oilseed rape by Stobbe et al. (1970) and Donaghy (1973).

There were significant species effects and a site by species interaction for hectolitre weight (Table 3.14). This interaction appeared to be because the hectolitre weight of field pea and wheat was consistently higher in 1990 than in 1989 while this was not always true of canola.

Protein content of the grain was not significantly affected by tillage in any of the trials (Table 3.15). However, protein content was considerably higher at Carman in both years than at Portage. The higher protein content at Carman may have been due to the effect of the 105 kg ha^{-1} N applied at Carman on the sandy loam soil compared to the 80 kg ha^{-1} N

Table 3.14 Hectolitre weight (kg hl^{-1}) of canola, field pea and wheat under zero and conventional tillage.

Tillage(T)	Species(S)	Carman		Portage	
		1989	1990	1989	1990
Conventional	Canola	67.0	67.8	67.9	70.3
	Field Pea	82.9	85.4	82.1	85.4
	Wheat	74.5	76.9	73.4	78.4
Zero	Canola	67.5	67.1	68.2	70.2
	Field Pea	83.2	85.3	82.1	85.7
	Wheat	74.6	77.0	74.6	78.6
		NS	NS	NS	NS

Combined analysis: Site-year**, Site-year x Species**.

*, ** significant at the 0.05 and 0.01 probability levels, respectively.

applied on the clay loam at Portage even though soil tests indicated similar nitrogen levels at the beginning of the season (Appendix 1).

One might have expected a lower protein content under zero tillage if grain yields were increased. Although a negative correlation between yield and protein content for wheat has been documented (Partridge and Shaykewich, 1972), this relationship is not necessarily linear (Shaykewich, personal communication). There were no yield differences and thus no protein content differences due to tillage. However, the considerably lower yields of wheat at Carman in 1989 compared with Portage that same year, resulted in a higher grain protein content (Table 3.15). For field pea one might have expected that lower soil temperatures, especially as measured in 1990 at Carman under zero tillage (Figure 3.2), might have increased atmospheric nitrogen fixation (Zachariassen and Power, 1987). However, if such a response did occur in the present study it was not great enough to result in an increase in protein content of zero tillage peas.

Table 3.15 Protein content (%) of canola, field pea and wheat under zero and conventional tillage.

Tillage(T)	Species(S)	Carman		Portage	
		1989	1990	1989	1990
Conventional	Canola	26.9	26.0	22.3	20.2
	Field Pea	27.1	25.1	26.2	24.4
	Wheat	14.6	16.6	12.9	13.5
Zero	Canola	27.5	25.9	23.1	20.5
	Field Pea	27.0	24.7	26.6	25.3
	Wheat	14.5	16.2	13.0	13.8
		NS	NS	NS	NS

As with protein content there were no significant tillage effects on protein yield (Table 3.16). In most cases, pea had the highest protein yield per ha of all crops. Donaghy (1973) also found that zero tillage had no effect on protein content or yield of oilseed rape or wheat.

Similar protein yields between tillage systems indicate similar levels of nitrogen and water were available for seed formation under both zero and conventional tillage. Similar protein yields also suggest that broadcast fertilizer application of nitrogen was not disadvantaged under zero compared to conventional tillage. The much higher protein yield at Carman in 1990 confirms that there a greater availability of nitrogen at this site. There was a significant site by species interaction for protein yield, similar to that for grain yield. Variation in protein yield of canola over sites was once again minimal compared to that of field pea and wheat.

Table 3.16 Protein yield (kg ha^{-1}) of canola, field pea and wheat under zero and conventional tillage.

Tillage(T)	Species(S)	Carman		Portage	
		1989	1990	1989	1990
Conventional	Canola	536	591	447	454
	Field Pea	529	951	980	831
	Wheat	297	700	385	529
Zero	Canola	504	566	438	418
	Field Pea	542	1021	897	877
	Wheat	260	655	416	534
		NS	NS	NS	NS

Combined analysis: Site-year**, Site-year x Species**.

*, ** significant at the 0.05 and 0.01 probability levels, respectively.

Oil content of canola was statistically significantly affected by tillage at only one of four sites while oil yield was never significantly affected by tillage (Table 3.17). At Carman in 1989, the oil content of canola under zero tillage was 0.2% lower than that under conventional tillage. Although this is statistically different, biologically, a 0.2% difference is not significant. Results were similar to those of Diebert (1989) who found that a reduction in tillage had no effect on oil content or oil yield of sunflower. Donaghy (1973) also found that flax and oilseed rape had similar oil contents under zero and conventional tillage.

Chlorophyll content of canola was not significantly affected by tillage, although at Carman in 1989 the crop under zero tillage would have exceeded the 24.9 ppm limit for the Number 1 canola grade. Canola from

Table 3.17 Quality of canola grown under zero and conventional tillage.

Quality Parameter	Tillage(T)	Carman 1989	Carman 1990	Portage 1989	Portage 1990
Oil Content (%)	Conventional	45.3	48.4	43.7	43.9
	Zero	45.1	48.3	43.1	44.0
		T*	NS	NS	NS
Oil Yield (kg/ha)	Conventional	872	998	905	1087
	Zero	790	958	860	991
		NS	NS	NS	NS
		Combined analysis:		Site-year**.	
Chlorophyll (ppm)	Conventional	23.2	16.0	21.4	10.7
	Zero	30.3	15.2	19.5	13.1
		NS	NS	NS	NS
		Combined analysis:		Site-year**.	

*, ** significant at the 0.05 and 0.01 probability levels, respectively.

this treatment would have been down graded to Number 2 status if sold on the market. High chlorophyll under zero tillage in this trial may have been caused by the rapid dry down procedure used for the canola after harvest in 1989, resulting in insufficient breakdown of the chlorophyll. Slight maturity differences that may have existed between tillage systems may have caused more chlorophyll to become fixed under zero than under conventional tillage. However, these results were not statistically significant and no similar trend was observed at the other three sites. Chlorophyll levels were much lower under field drying conditions in 1990. Thus, it appears that large differences in chlorophyll content of canola should not be expected with a reduction in tillage.

3.4 Conclusions

Although there were numerous isolated cases of tillage responses for various agronomic parameters, tillage had very little effect on the establishment, growth, yield, yield components and grain quality of canola, field pea and wheat. At Portage in 1989 the potential for greater productivity of field pea under zero tillage was demonstrated. However, the greater growth did not result in any yield or quality benefits for zero tillage peas over conventional tillage peas. Lack of expression of these early season advantages may be due to other environmental factors which were not accounted for in this study. Zero tillage did not affect crop productivity, indicating that these crops can be grown as successfully under zero as under conventional tillage systems.

4.0 Water Use and Water Use Efficiency of Canola, Field Pea, and Wheat under Conventional and Zero Tillage.

4.1 Introduction

Since zero tillage can strongly influence soil temperature and soil moisture (Gauer et al., 1982) it may affect soil water use. In the previous paper the effects of a reduction in tillage on aerial plant growth parameters were examined, including dry matter accumulation, crop height and grain yield. Effects of zero tillage on soil water depletion may help explain some of the growth and yield results discussed in the previous paper since soil water extraction by a plant is directly related to aerial growth and yield.

Water use efficiency of grain yield and dry matter production might be expected to improve under zero tillage because less evapotranspiration (ET) is wasted through direct soil evaporation, leaving more available for transpiration and crop production (Unger, 1990). The objective of this study was to compare the ET, soil water depletion and water use efficiency (WUE) of canola, field pea and wheat under zero and conventional tillage.

4.2 Materials and Methods

4.2.1 General

Details of the four field trials are described in the previous paper (Section 3.2). There were four replicates at Portage la Prairie (Portage) and six at Carman. Soil water content in these trials was determined for the 0 to 130 cm depth at one or two week intervals in 1989 and two week intervals in 1990 (Table 4.1). Aluminum neutron access tubes were placed between the rows in the centre of each subplot 2 m from the front of the plot. Volumetric soil water content (cm^3 cm^{-3}, expressed as %) from 10 to 130 cm was determined using Troxler Model 3222 and Model 4300 neutron probes (Troxler Laboratories, Triangle Park, N.C.) to measure soil water at 20 cm increments. Soil water content in the 0 to 10 cm increment was determined gravimetrically using four samples per subplot. The samples were weighed, dried at 100°C for at least 48 hours, and weighed again. Bulk densities for 0 to 10 cm depth were determined for both tillage treatments at each trial and used to calculate volumetric water content for the 0 to 10 cm depth. Water table depths were monitored (Table 4.2) using solid access tubes in 1989 and perforated tubes in 1990. Only soil water values above the level of the water table were used in the analysis. In some cases, neutron access tubes had water in them and measurements could not be taken below the water level in the tubes.

Table 4.1 Soil water sampling dates.

Location	Year	Dates
Carman	1989	May 19, June 1, 14, 29, July 6, 13, 26, August 8 (wheat and canola only)
Portage	1989	May 31, June 15, 28, July 5, 11, 18, August 2, 22
Carman	1990	May 19, June 4, 18, July 4, 17, August 2, 17 (canola only), 21 (wheat only)
Portage	1990	May 31, June 26, July 12, 25, August 8, 20 (canola), 29 (wheat), 30 (pea)

Table 4.2 Water table levels during the growing season at Carman and Portage in 1989 and 1990.

Year	Location	Date	Level (cm)	Year	Location	Date	Level (cm)
1989	Carman	June 14	179	1989	Portage[1]	June 15	121
		June 30	181			June 28	132
		July 6	197			July 5	132
		July 26	198			July 18	133
1990	Carman	July 4	157	1990	Portage	June 26	90
		August 2	>160			July 25	135
						August 8	>140

[1]Water level in neutron access tubes was used.

4.2.2 Available Soil Water

Permanent wilting point was determined for soil from different depths in the soil profile. Westar canola was grown in the soil in one litre pots. When plants reached the rosette stage, water was withheld from plants and leaf length and breadth were measured daily using a ruler. When leaf expansion ceased, the soil was removed and the water content determined gravimetrically. Using bulk density data, volumetric water content was determined for the permanent wilting point. Because bulk density data was not available for Portage below 10 cm the 0 to 10 cm bulk density was used to calculate volumetric permanent wilting point. Volumetric permanent wilting points (%) to 30 cm are presented in Table 4.3. The water content of soils below this depth did not fall below the permanent wilting point in the present study. These values are similar to the range of 6 to 8% for a fine sandy loam and 18 to 23% for a clay soil presented by Unger et al. (1988).

Table 4.3 Permanent wilting point (% volumetric water content) of soils at Carman and Portage as determined using Westar canola plants.

Location	Depth (cm)	% Permanent Wilting Point	Soil Texture
Carman	0-30	8.17	very fine
	30-70	7.31	sandy loam
Portage	0-10	26.8	silty clay
	10-30	28.0	

4.2.3 Evapotranspiration

Evapotranspiration (ET) was calculated as:

$$ET\ (mm) = \Delta soil\ water + precipitation. \qquad (4.1)$$

ET was calculated for the entire growing season and between individual sampling dates.

4.2.4 Soil Water Depletion by Depth

Soil water depletion patterns for each 20 cm depth increment were determined by calculating the amount of soil water depleted between successive sampling dates. The amount of soil water depleted in different soil depth increments was calculated for the periods between emergence and anthesis, anthesis and harvest and emergence and harvest. Upward movement of water was assumed to be negligible.

4.2.5 Water Use Efficiency

Water use efficiency (WUE) was calculated as:

$$WUE = \frac{\text{aerial dry matter or grain yield (kg ha}^{-1}\text{)}}{\text{evapotranspiration (mm)}}. \qquad (4.2)$$

WUE of dry matter production was calculated for the preanthesis period, the postanthesis period and for the entire growing season.

4.2.6 Statistical Analysis

All data collected from samplings, as well as parameters calculated from the data, was subjected to analysis of variance (Statistical Analysis Systems Institute, 1986). Differences with $P<0.05$ were considered to be significant. Differences between crop species were only discussed when the tillage by species or site-year by species interactions were significant.

4.3 **Results and Discussion**

4.3.1 Evapotranspiration

Seasonal cumulative ET for the four sites is shown in Figures 4.1, 4.2, 4.3, and 4.4. At Carman in 1989 (Figure 4.1; Appendix 4, Table A4.1), there was one significant tillage by species interaction on August 8. In this case canola had a higher ET level under zero tillage while wheat had a higher ET level under conventional tillage. Chevalier and Ciha (1986) also found a higher ET for wheat under conventional tillage compared with zero tillage. Field peas were not included in this analysis since they were already harvested.

At Portage in 1989, only the top 90 cm of the soil profile was used in ET calculations because for a time there was water in the neutron tubes below this level. Significant ($P<0.05$) tillage by species interactions

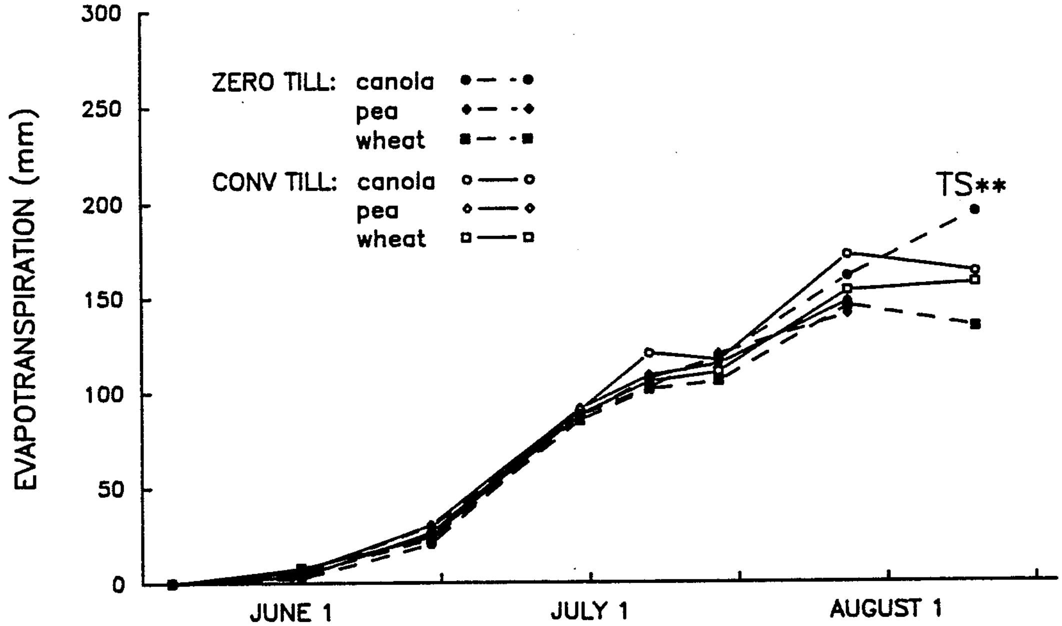


Figure 4.1
Seasonal cumulative evapotranspiration (mm) of canola, field pea and wheat under zero and conventional tillage at Carman in 1989. * and ** indicate significance of tillage (T) or species (S) at the 0.05 and 0.01 probability levels, respectively.

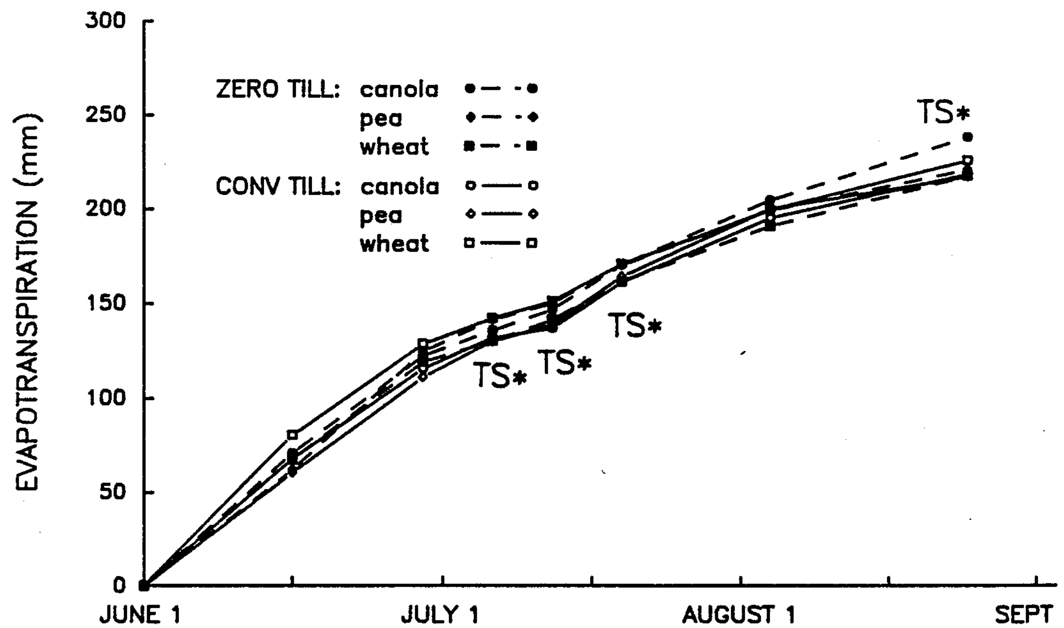


Figure 4.2
Seasonal cumulative evapotranspiration (mm) of canola, field pea and wheat under zero and conventional tillage at Portage in 1989. * and ** indicate significance of tillage (T) or species (S) at the 0.05 and 0.01 probability levels, respectively.

were observed on four of the seven sampling dates (Figure 4.2; Appendix 4, Table A4.2), indicating a strong differential response of canola, field pea and wheat to zero tillage. In each case the trend was the same. Canola and field pea had a higher ET under zero tillage while wheat, just like at Carman in 1989, had a higher ET under conventional tillage. Results for wheat at this site once again support the observations by Chevalier and Ciha (1986). On the other hand, Lafond and Loeppky (1988) found a higher ET (to 120 cm) of wheat under zero tillage. Lafond and Loeppky (1988) found that field pea had a higher ET under zero tillage to 120 cm, supporting similar observations in the present study.

Results for Carman in 1990 were very different from those observed at both sites in the previous year (Figure 4.3; Appendix 4, Table A4.3). Significant ($P<0.05$) tillage responses at five of six sampling dates were due to less ET under zero tillage than under conventional tillage. One reason for lower total ET early in the growing season under zero tillage may be a reduction in evaporation as a fraction of ET due to the higher residue cover of the soil (Table 3.4). Such observations have been made by Wilhelm et al. (1989). Significantly less ET under zero tillage after anthesis may also have been due to the crop canopy as well as previous crop residue. For example, field pea and canola had greater plant height (T*, July 4) and slightly greater canopy light interception (NS) under zero tillage (Figure 3.11) which, in combination with the higher residue still present, may have reduced ET. However, correlation analysis over all crops showed no relationship between light interception and ET (r = 0.06-0.1) for Carman in 1990.

Another reason for less ET under zero tillage may have been less

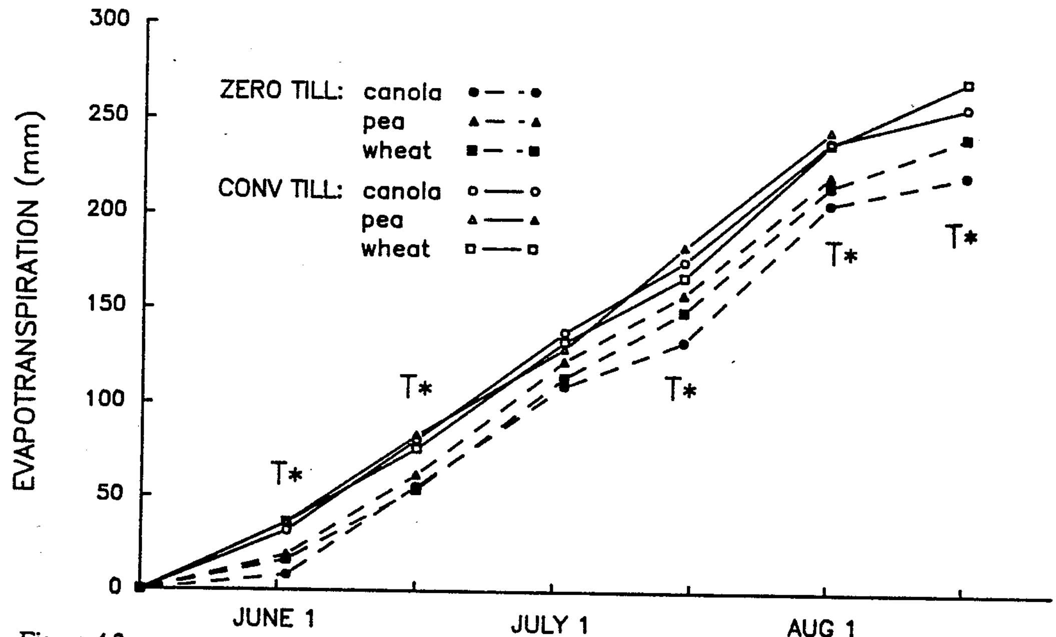


Figure 4.3
Seasonal cumulative evapotranspiration (mm) of canola, field pea and wheat under zero and conventional tillage at Carman in 1990. * and ** indicate significance of tillage (T) or species (S) at the 0.05 and 0.01 probability levels, respectively.

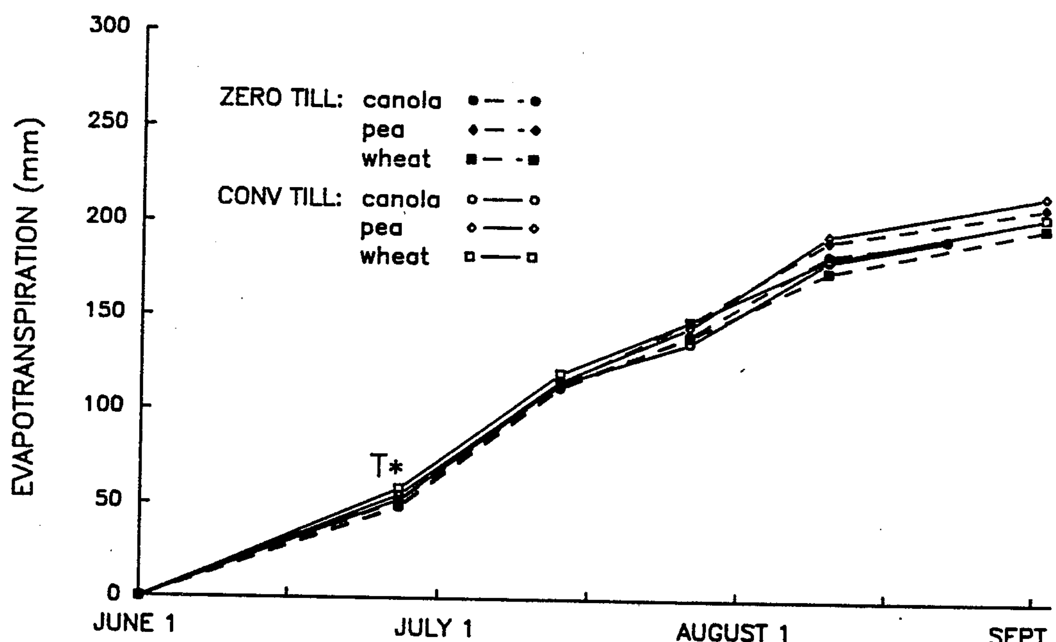


Figure 4.4
Seasonal cumulative evapotranspiration (mm) of canola, field pea and wheat under zero and conventional tillage at Portage in 1990. * and ** indicate significance of tillage (T) or species (S) at the 0.05 and 0.01 probability levels, respectively.

soil water extraction (i.e. less crop transpiration). Varvel et al. (1989) and Chevalier and Ciha (1986) working with wheat concluded that either poor early growth or a smaller root system under zero tillage might prevent crops from making adequate use of available water. However, since transpiration - yield relationships are relatively stable within crop species (Fischer and Turner, 1978), and since no significant differences in grain yield were observed in the present study, it appears that the reduction in ET may have been due more to reduced soil evaporation than reduced transpiration.

Results at Portage in 1990 were similar to those at Carman in 1990. However, although ET of all crops was lower throughout the season for zero tillage, differences were only significant on June 26 (Figure 4.4; Appendix 4, Table A4.4). Lower ET under zero tillage may once again have been due to higher residue cover in the zero tillage plots (Table 3.4) which may have reduced soil evaporation losses, thereby reducing total ET. Wilhelm et al. (1989), working with winter wheat, and Doran et al. (1984), working with corn, sorghum and soybean, found an increase in water storage and less water use by crops grown with increasingly higher residue covers.

Total growing season ET in the present study ranged from 134 to 257 mm (Figures 4.1 to 4.4). These values are in agreement with those in the literature. For example, Wilson et al. (1985) reported total ET values from 270 to 365 mm with irrigation and 225 to 334 mm without irrigation for field pea. Entz and Fowler (1989) reported ET values for winter wheat of 171 to 315 mm without irrigation and 210 to 364 mm with irrigation. Lafond and Loeppky (1988) found the ET of field pea and spring wheat under zero tillage to be 122 % and 144 %, respectively, of that under conventional tillage.

Tillage significantly affected total growing season ET at three of four sites. At Portage in 1990, only species differences were significant. At Carman in 1990, lower seasonal ET under zero tillage carried through until the end of the growing season (Figure 4.3). The lack of a significant tillage by species interaction in this trial indicates that the three crops responded similarly under zero and conventional tillage.

In 1989, significant tillage by crop species interactions were observed at both sites for total ET (Figures 4.1 and 4.2). In both instances the basis of these interactions appeared to be a higher ET for canola under zero compared with conventional tillage (32 mm at Carman and 20 mm at Portage). No effect on ET for field pea was observed. ET for wheat was decreased 9 mm by zero compared with conventional tillage at Portage and was decreased 24 mm at Carman. Higher ET for canola under zero tillage in 1989 cannot be attributed to better early growth under zero tillage. Less ET for wheat under zero tillage at Carman in 1989 may be due to root rot which was present and may have been more severe under zero tillage (Sturz and Bernier, 1987).

In 1989, tillage by species interactions for ET were significant on one of the seven sampling dates at Carman and on four of the seven sampling dates at Portage. In 1990, tillage significantly affected ET on five of six sampling dates at Carman and on one of five sampling dates at Portage. Differences between crop species response to zero tillage appeared greater in a dry year like 1989 than in a wet year such as 1990.

4.3.2 Soil Water Depletion by Depth

Water depletion from the soil profile by a growing crop is dependent on both crop canopy development, which determines the demand for soil water, and on root development, which determines the ability of the plant to extract soil water. Soil water depletion will vary with soil depth depending on soil surface evaporation as well as soil water extraction by plant roots. Figures 4.5, 4.6, 4.7, and 4.8 illustrate soil water at seeding, anthesis and harvest at the four sites in this study. Differences in soil water levels between these development stages represent the soil water extracted during the preanthesis and postanthesis periods. Differences in soil water depletion may reflect differences in rooting depth and activity since soil water extraction and root growth are closely correlated (Cholick et al., 1977; Entz and Fowler, 1988).

At Carman in 1989, there were very few tillage effects on soil water depletion down the soil profile (Table 4.4). There was a significant ($P<0.05$) tillage response for water extracted between June 14 and June 29 at the 0 to 10 cm depth with more water being used under zero than under conventional tillage. When soil water depletion for the entire preanthesis and postanthesis periods was considered, only one significant tillage by species interaction was observed (Table 4.4). Less water was extracted by canola and wheat in the 110 to 130 cm depth under zero compared with conventional tillage during the preanthesis period (Figure 4.5). Water extraction by field pea at this depth was not affected by tillage. These results indicate less effective water depletion for canola and wheat at this depth although ET measurements did not indicate lower

Table 4.4 Significance of tillage (T) and species (S) on soil water depletion at Carman, 1989.

Date	Soil Depth (cm)						
	0-10	10-30	30-50	50-70	70-90	90-110	110-130
May 19-June 1	NS	NS	NS	NS	NS	NS	NS
June 14-29	T*	NS	NS	NS	NS	NS	NS
Preanthesis	NS	NS	NS	NS	NS	NS	TS*,T*
Postanthesis	NS	NS	NS	NS	NS	NS	NS
Growing season	NS	NS	NS	NS	NS	NS	NS

*, ** significant at the 0.05 and 0.01 probability level, respectively.

soil water depletion from the soil profile for this time period (Figure 4.1). In each case canola depleted the most water below 30 cm and the least between 0 to 30 cm. These results indicate more postanthesis root activity in canola compared to wheat and field pea (Figure 4.5).

Numerous significant tillage by species interactions and several significant tillage effects were observed for soil water depletion from different depths and different time intervals at Portage in 1989 (Table 4.5; Figure 4.6). Significantly more water was used under zero than under conventional tillage between May 31 and June 15 at the 10 to 30 cm depth increment and between June 15 and 28 at the 0 to 10 cm depth (data not shown), indicating possibly more intense rooting at these shallow depths under zero than conventional tillage.

Significantly more water was depleted by canola and wheat and less by field pea under zero compared with conventional tillage during the

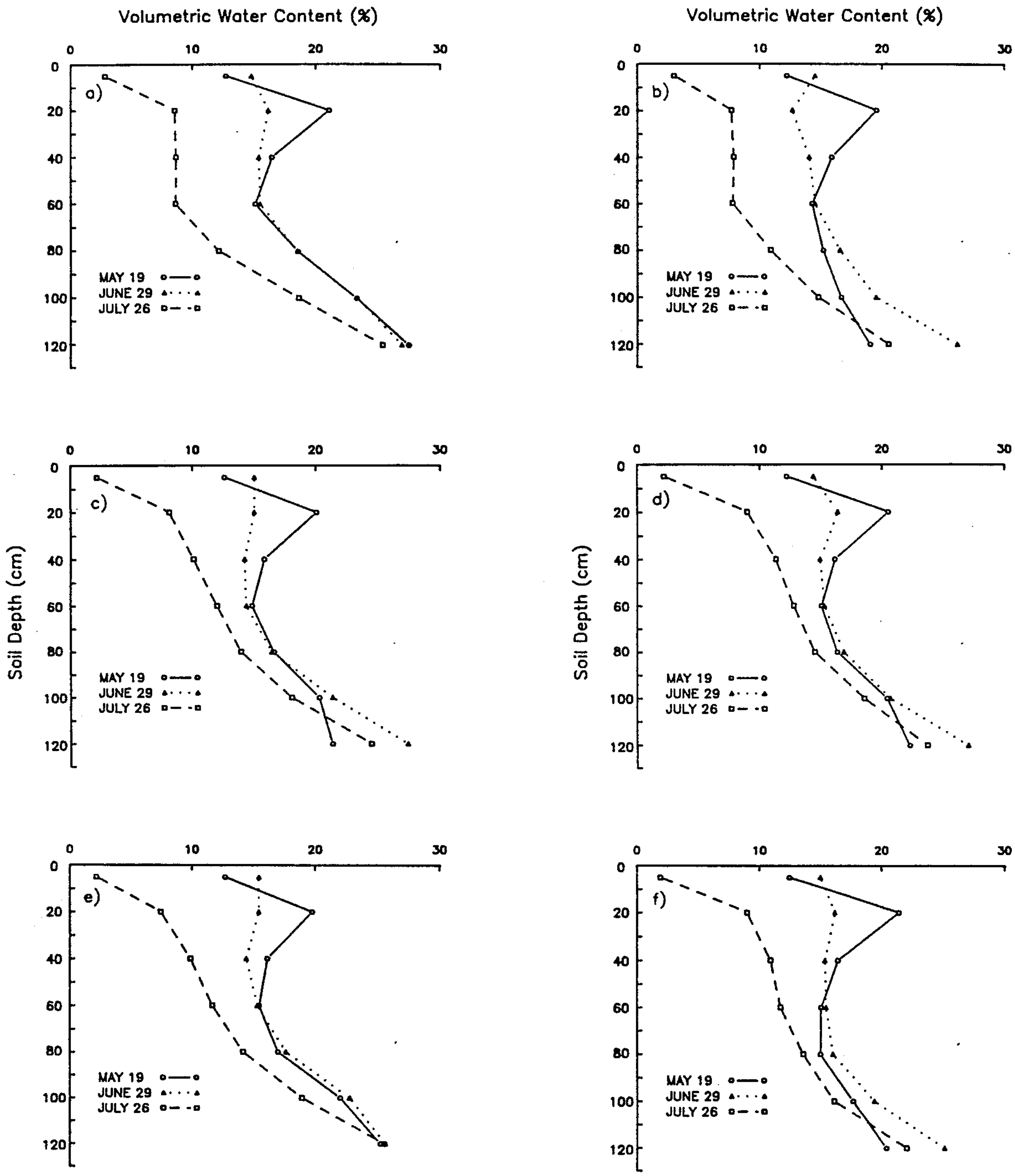


Figure 4.5
Soil water content (0 - 130 cm) at seeding (May 19), anthesis (June 29) and harvest (July 26) for canola (a,b), field pea (c,d) and wheat (e,f), grown under zero (b,d,f) and conventional tillage (a,c,e) at Carman in 1989.

Table 4.5 Significance of tillage (T) and species (S) on soil water depletion at Portage la Prairie, 1989.

Date	Soil Depth (cm)						
	0-10	10-30	30-50	50-70	70-90	90-110	110-130
May 31-June 15	NS	T*	NS	NS	NS	NS	NS
Preanthesis	NS	NS	NS	NS	TS*	NS	NS
Postanthesis	NS	TS*	NS	NS	NS	NS	NS
Growing season	TS*	NS	TS*	TS**	TS*	NS	NS

*, ** significant at the 0.05 and 0.01 probability level, respectively.

postanthesis period at 10 to 30 cm and over the growing season at 0 to 10 cm (Table 4.5). It may have been that the pea canopy, being lodged, was more dense than that of wheat or canola, thereby reducing evaporation from the surface soil and increasing water storage. This effect would be similar to that of the pea canopy on soil temperatures at Carman in 1990 compared with wheat and canola (Figure 3.2). Crop growth data (Figure 3.10) supports these results, showing that both light interception by the crop canopy and crop height were increased more for field pea by zero tillage than for canola or wheat. As Kirkham and Ahring (1978) found for wheat, plant height may be a direct reflection of root growth.

A number of other tillage by species interactions for soil water depletion were also observed. For example, soil water depletion over the growing season between 50 and 70 cm and between 70 and 90 cm was reduced significantly ($P<0.01$) more for wheat than for canola or field pea (Table 4.5, Figure 4.6) with a reduction in tillage. Lower soil temperatures

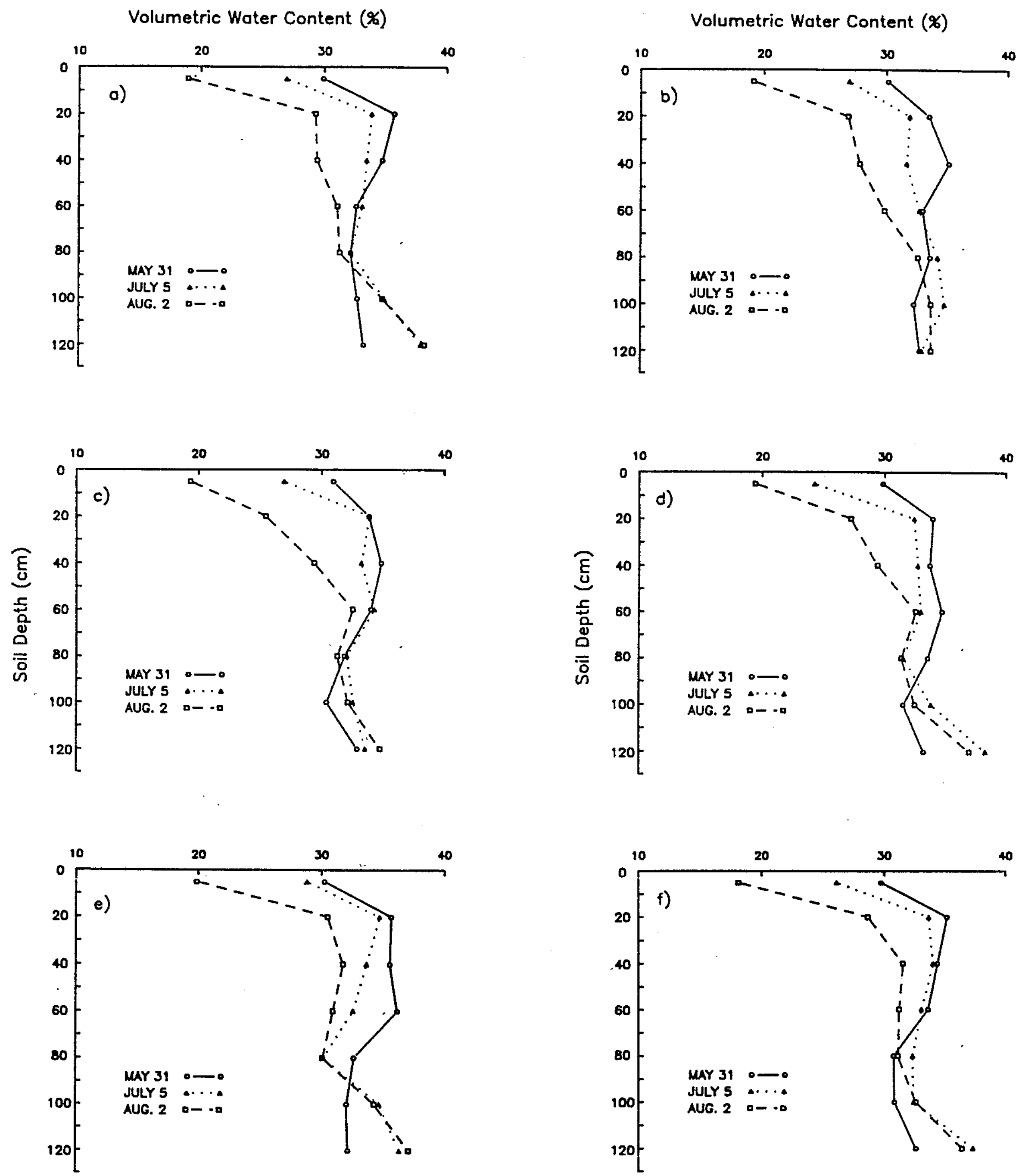


Figure 4.6
Soil water content (0 - 130 cm) at seeding (May 31), anthesis (July 5) and just before harvest (August 2) for canola (a,b), field pea (c.d) and wheat (e,f) grown under zero (b,d,f) and conventional (a,c,e) tillage at Portage in 1989.

(Figure 3.1) may have been a factor affecting soil water extraction by wheat below 50 cm at Portage in 1989.

However, unlike the activity below 50 cm, wheat extracted more water under zero tillage at shallower depths in response to zero tillage compared to the other two crops (postanthesis, 10 to 30 cm and growing season, 0 to 10 cm; Table 4.5; Figure 4.6). Similar results found by Baeumer and Bakermans (1973) indicated that root growth of wheat was more shallow and intense under zero tillage, probably due to a greater concentration of water and nutrients at shallow depths under zero than conventional tillage.

Results for field pea at Portage in 1989 were opposite to those for wheat. For example, growing season water depletion by field pea at shallow depths was significantly decreased by zero tillage, while at greater depths (50 to 90 cm) it was significantly increased (Table 4.5, Figure 4.6). Lafond and Loeppky (1988) also observed greater water extraction between 60 and 120 cm for field pea under zero compared with conventional tillage.

Every tillage by species interaction for soil water depletion by depth indicated that canola extracted more water under zero than under conventional tillage (Figure 4.6a, b). Soil water extraction was increased under zero tillage to the extent that total ET for canola was significantly higher (Figure 4.3) compared to conventional tillage. Higher ET indicates that the soil environmental conditions were more conducive to water extraction by the canola crop under zero than conventional tillage at Portage in 1989. In summary, the effect of zero tillage at Portage in 1989 was higher soil water depletion by canola at all depths, less surface depletion but greater depletion at depth (>50 cm) by field pea and greater surface depletion but less depletion at depth (>50 cm) by wheat.

Table 4.6 Significance of tillage (T) and species (S) on soil water depletion at Carman, 1990.

Date	Soil Depth (cm)						
	0-10	10-30	30-50	50-70	70-90	90-110	110-130
May 19-June 4	NS	NS	NS	T*,TS*	T*	NS	T*
August 2 - Harvest[2]	T*	NS	NS	NS	NS	T*	T*
Preanthesis	NS	NS	NS	TS*	NS	NS	NS
Postanthesis	T**	NS	NS	NS	NS	NS	NS
Growing season	T*	NS	NS	NS	NS	T*	T*

[1] Harvest: canola, August 17; field pea, August 2; wheat, August 21.
*, ** significant at the 0.05 and 0.01 probability level, respectively.

The most significant factor affecting soil water depletion at Carman in 1990 was tillage (Table 4.6). As with ET at this site (Figure 4.3), soil water depletion by depth over the growing season was often significantly lower for zero than conventional tillage. This trend was especially evident below 50 cm (Figure 4.7). Less water extraction under zero tillage in this trial may have been due to the negative effects of zero tillage on rooting patterns. Baeumer and Bakermans (1973), Chevalier and Ciha (1986), and Varvel et al. (1989) all found that crops under zero tillage have smaller root systems than under conventional tillage due to slower early season growth and development. Smaller root systems under zero tillage in this trial may have been the result of lower soil temperatures. As indicated in section 3.3.1.1, soil temperatures at this

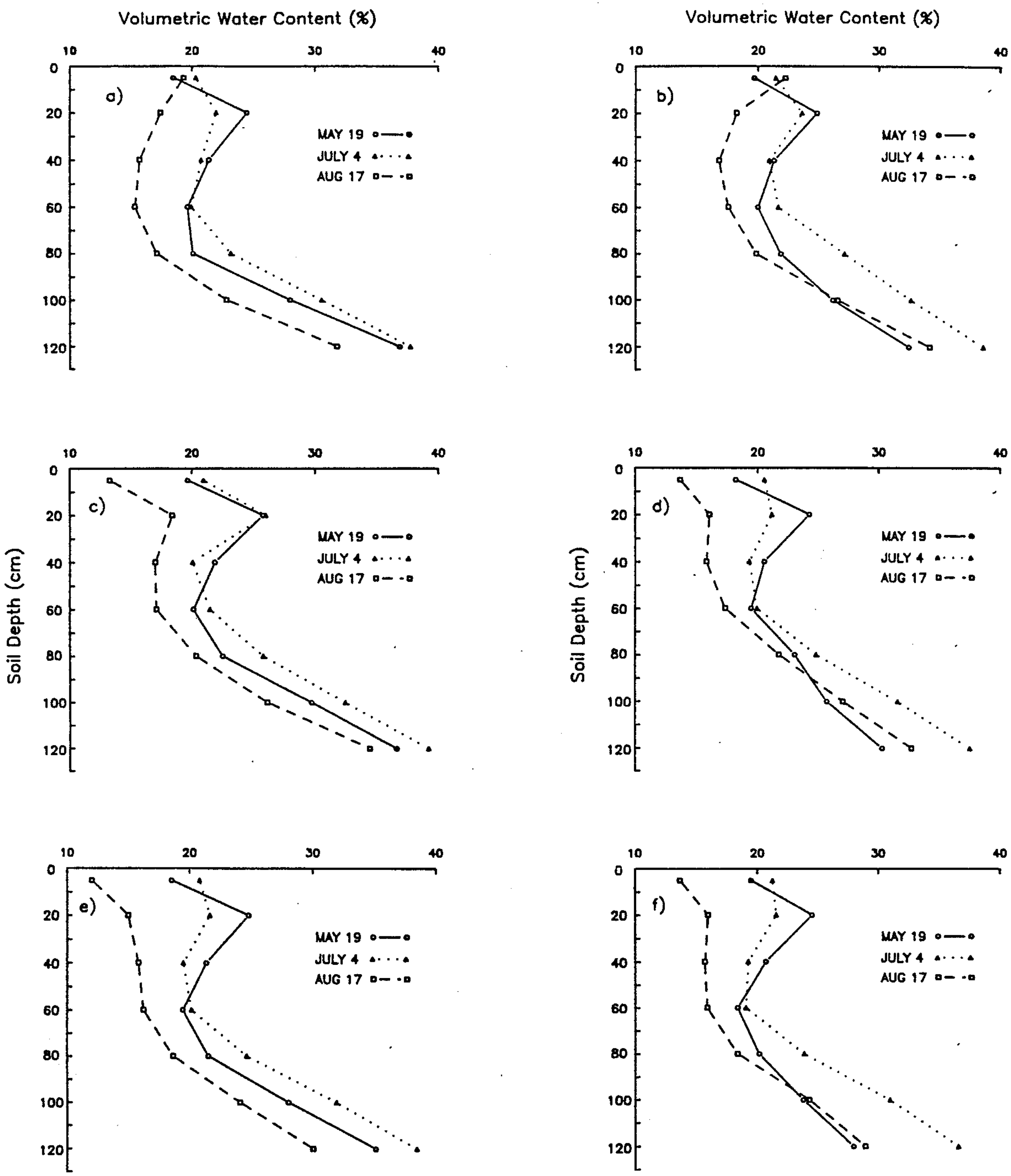


Figure 4.7
Soil water content (0 - 130 cm) at seeding (May 19), anthesis (July 4) and harvest (August 17) for canola (a,b), field pea (c,d) and wheat (e,f) grown under zero (b,d,f) and conventional tillage (a,c,e) at Carman in 1990.

site were considerably reduced (up to 7°C at 10 cm depth) under zero compared with conventional tillage, especially later in the season (Figure 3.2). Temperature differences in the present study were found to increase with increasing depth (Figure 3.1). Therefore, soil temperatures below 80 or 90 cm may have been too cold to allow normal root activity at Carman in 1990. Lower soil temperatures could also have resulted in decreased soil evaporation thus decreasing water depletion under zero tillage.

A significant tillage by species interaction during the preanthesis period at Carman in 1990 indicated that while all three crops used more water under zero than conventional tillage between 50 and 70 cm, the effect was greatest for canola (Figure 4.7). However, despite one significant tillage by species interactions at this site, the dominant trend was a similar response to tillage by all three species (Table 4.6; Figure 4.7). These results are completely the opposite of those of Lafond and Loeppky (1988) who found that water use of pea and wheat at various depths was increased with a reduction in tillage. However, these results for wheat at Carman in 1990 are similar to those reported by Chevalier and Ciha (1986) and Varvel et al. (1989).

A significant tillage response for the postanthesis period and the entire season at this site indicated that more water was depleted under conventional tillage than zero tillage at 0 to 10 cm, leaving the surface soil wetter at harvest time under zero tillage. The extra surface soil water can be important in a crop rotation, ensuring that fall-seeded crops or under-seeded forage crops are able to germinate quickly and become well established.

Although only one significant tillage response was observed for seasonal ET at Portage in 1990 (Figure 4.4), numerous tillage responses were observed for soil water depletion at different depths (Table 4.7). Similar to results for Carman in 1990, the trend was for decreased water depletion under zero tillage (Figure 4.8).

On May 31 in the 0 to 10 cm increment the level of available soil water was significantly ($P<0.01$) higher under zero compared with conventional tillage (by 3 mm) since greater residue cover under zero tillage lead to less evaporation from the soil surface (Unger, 1990). However, soil water content in spring was significantly ($P<0.05$) greater under conventional compared with zero tillage for all other depth increments between 10 and 110 cm (analysis not shown). Several factors may account for this observation which is contrary to the observations of Gauer et al. (1982), Lafond and Loeppky (1988), and Wilhelm et al. (1989). Infiltration of water into the heavy clay soil at this site may have been increased when the soil was disturbed through tillage, leading to a greater accumulation of water between the spring of 1989 and the spring of 1990 under conventional compared with zero tillage. Zero tillage soils may have remained frozen longer in the spring and thus had less infiltration of spring snow melt. Also, soil cracking was quite prevalent in the dry summer and fall of 1989. Tillage in the conventional tillage plots may have sealed these deep cracks at the soil surface, thereby preventing evaporation. Under zero tillage, however, cracks may have remained open and evaporation from deep in the profile may have continued. As well, evaporation from soils under conventional tillage may have been greater than under zero tillage, and thus caused greater upward movement of water from the very shallow water table (Table 4.2). The greater

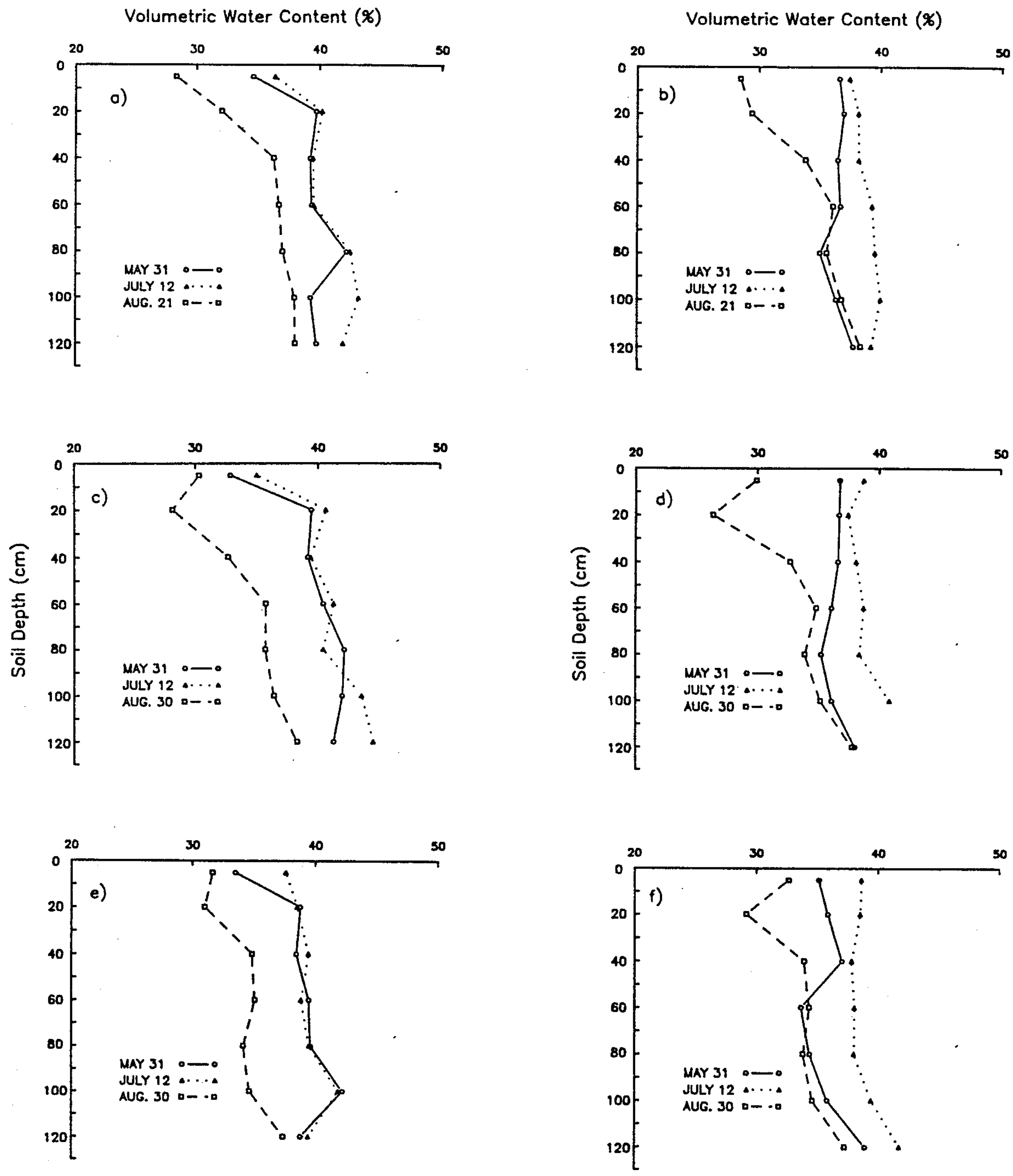


Figure 4.8
Soil water content (0 - 130 cm) at seeding (May 31), anthesis (July 12), and harvest (August 21,30) for canola (a,b), field pea (c,d) and wheat (e,f) grown under zero (b,d,f) and conventional (a,c,e) tillage at Portage in 1990.

upward movement may have increased the soil water content under conventional tillage and provided for increased soil water depletion as occurred under conventional compared with zero tillage (Table 4.7).

Table 4.7 Significance of tillage (T) and species (S) on soil water depletion at Portage la Prairie, 1990.

Date	Soil Depth (cm)						
	0-10	10-30	30-50	50-70	70-90	90-110	110-130
May 31-June 26	NS	T*	T**	T*	T*	NS	--
Preanthesis	NS	TS*	NS	T*	T**	NS	--
Postanthesis	T*	NS	NS	NS	NS	NS	--
Growing season	NS	NS	NS	T*	T*	TS*	NS

*, ** significant at the 0.05 and 0.01 probability level, respectively.

Unger (1990) found that treatments with a higher soil water content at planting (usually zero tillage in the studies he reviewed) resulted in greater ET by the crop. This relationship was also observed in the present study. For example, from May 31 to June 26 significantly more water was depleted between 10 and 90 cm and between 0 and 130 cm from conventional tillage plots than from zero tillage plots at Portage in 1990 (Table 4.7). The same trend was evident between 50 and 90 cm and between 0 and 130 cm during the preanthesis period. There was a significant tillage by species interaction at 10 to 30 cm (Table 4.7), where wheat had used more water under zero than conventional tillage while canola and pea were hardly affected.

Only one significant response to tillage was observed after anthesis in this trial. Crops under zero tillage depleted more water between 0 and 10 cm than under conventional tillage, possibly reflecting more shallow and intense rooting (Baeumer and Bakermans, 1973). For the entire growing season, tillage effects were significant between 50 and 90 cm and trends were the same as those prior to anthesis. These trends were also similar to those at Carman in 1990, with all crops using less water deeper down in the soil profile under zero tillage (Figure 4.8). Greater water depletion by all crops under conventional tillage also occurred between 90 and 110 cm (P=0.0592) for the entire growing season. In this instance, only field pea and wheat depleted significantly less water under zero tillage than conventional tillage (Figure 4.8; Table 4.7).

Both shoot growth, root growth and soil water availability can affect soil water depletion patterns. Shoot growth and canopy development can affect evaporation from the soil as well as transpiration by plants. The effect of crop canopy on evaporation was observed at Portage in 1989 for field pea when water use near the surface was decreased under zero compared with conventional tillage after anthesis and crop height, dry matter accumulation and light interception by the crop canopy were all increased (Figure 3.10). Soil temperature most likely affected root growth of all crops (Kramer, 1969), especially in 1990, causing decreased soil water extraction under zero tillage compared to conventional tillage at greater depths; however, after anthesis at Portage in 1990, soil water depletion was increased under zero tillage at shallow depths. Because plant growth and yield were not significantly adversely affected by this apparent reduction in root growth under zero tillage, it may not be a liability. Results in 1989 indicated that, under drier conditions, a reduction in tillage can actually increase water extraction below 50 cm. Wet soils, as in 1990, which stay cooler longer in the spring might be expected to have greater temperature gradients with depth than drier soils, as in 1989, and may therefore, have a greater effect on depth of soil water depletion by plants.

In conclusion, soil water depletion patterns gave trends similar to those observed for ET and were useful in explaining the nature of decreases in evapotranspiration under zero tillage compared with conventional tillage. From the 1990 results, it appears that the soil water depletion ability of all three crops at greater depths is decreased under zero tillage, explaining why ET for all crops was generally lower under zero than conventional tillage. However, these results occurred in a year when early season precipitation was well above normal while late season precipitation was much below normal. Conditions were much drier in 1989. Drier conditions allowed for the expression of differential soil water depletion responses of species to tillage (Proffitt, 1985) resulting in significant tillage by species interactions similar to those for total ET in 1989.

4.3.3 Water Use Efficiency

Water use efficiency (WUE) was calculated for incremental dry matter production throughout the season, for dry matter production during the preanthesis and postanthesis periods, and for grain yield. Because of the large amount of error involved in the calculations for smaller time increments (C.V. from 24 to 1742%), few significant effects or interactions were observed and therefore only preanthesis, postanthesis and growing season data will be discussed. WUE is dependent on two factors, dry matter or grain yield production, and ET. Depending on the relationship between these two factors, WUE may or may not be affected by a reduction in tillage. Dry matter production or grain yield may be affected by air temperature, evaporative demand, and ET, while ET may be affected by plant growth, and soil environmental conditions such as soil temperature and soil water content.

No significant tillage effects or tillage by species interactions for WUE of seasonal dry matter or grain yield were observed at Carman in 1989 (Figure 4.9). High stress conditions due to low precipitation and high temperatures might have been expected to differentiate between tillage systems and between crop species responses to tillage. However, because there was only a 20% difference in residue cover between tillage treatments (Table 3.4), there was no significant response of WUE to a reduction in tillage at this site.

At Portage in 1989, there were no significant ($P<0.05$) effects or interactions for either WUE of dry matter production or grain yield (Figure 4.10). However, the tillage by species interaction for WUE of postanthesis dry matter production was significant at $P=0.0563$. In this case, wheat and canola were slightly adversely affected by a reduction in tillage while WUE for field pea was greatly increased (Figure 4.10b). At this site, dry matter production, height and light interception by the crop canopy were significantly greater for field pea under zero tillage while canola and wheat were much less affected (Figure 3.10). Thus, the increased growth of pea, partly due to the increase in ET (Figure 4.2),

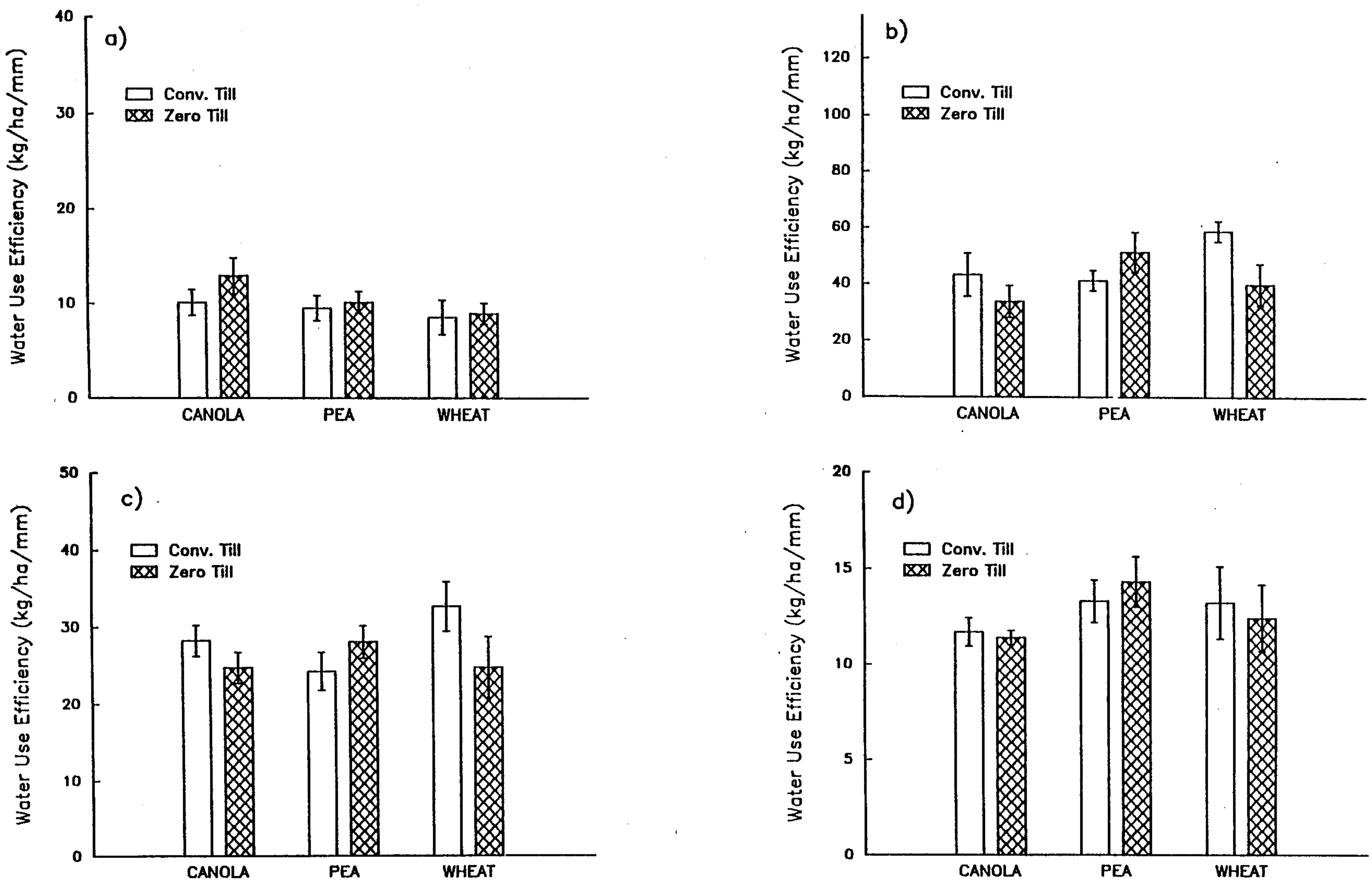


Figure 4.9
Water use efficiency of a) preanthesis dry matter production (ns), b) postanthesis dry matter production (ns), c) growing season dry matter production (ns), and d) grain yield (ns) for canola, field pea, and wheat grown under zero and conventional tillage at Carman in 1989. Bars indicate standard error.

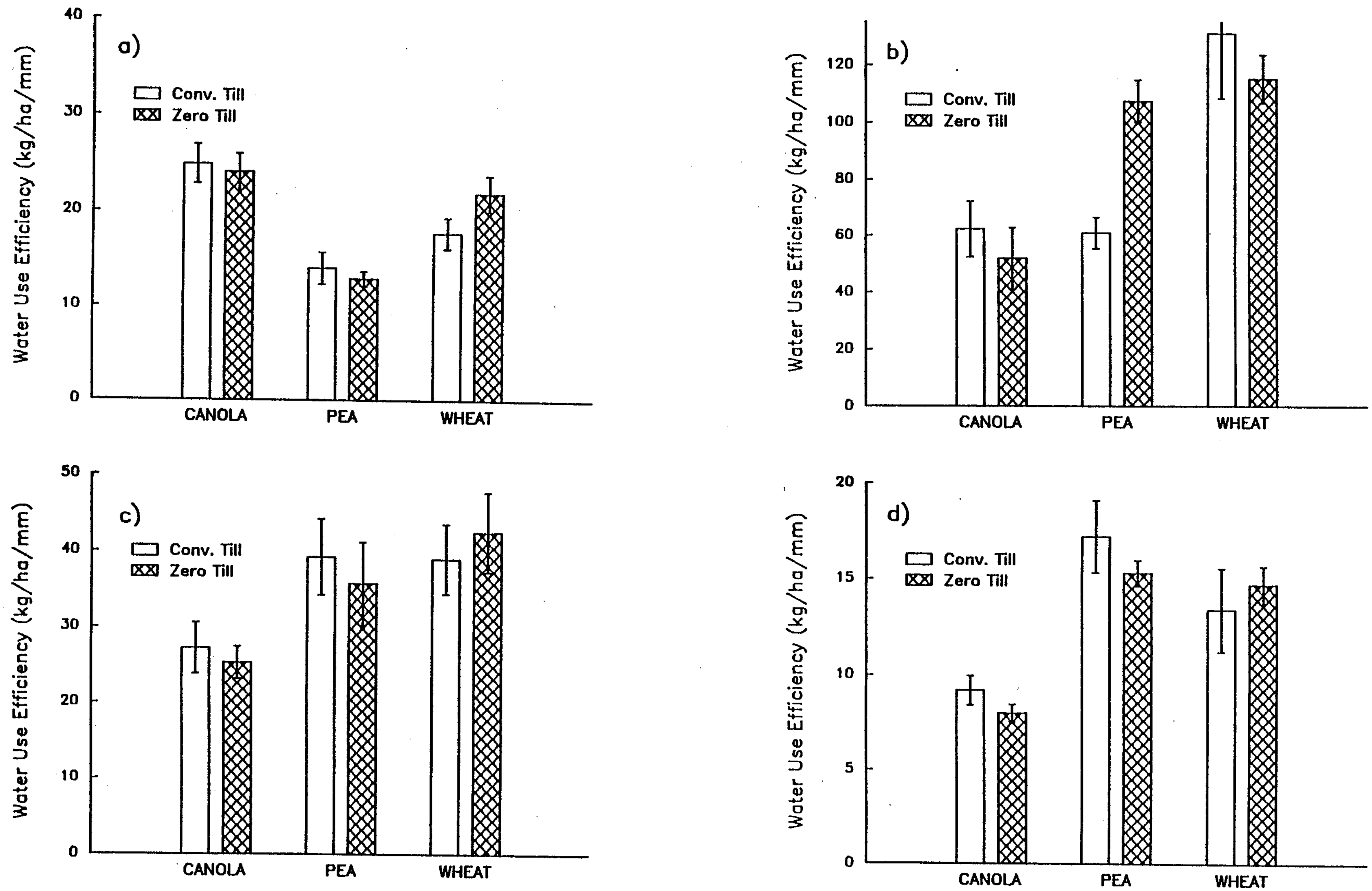


Figure 4.10
Water use efficiency of a) preanthesis dry matter production (S), b) postanthesis dry matter production (S**,TS(p=.0563)), c) growing season dry matter production (S*) and d) grain yield (S*) for canola, field pea and wheat grown under zero and conventional tillage at Portage in 1989. Bars indicate standard error.**

resulted in more efficient use of available water under zero than conventional tillage. While canola also had a higher ET under zero tillage (Figure 4.2), dry matter production was not increased under zero tillage probably because air temperature limited flowering and seed set. Therefore, WUE for canola at Portage in 1989 was lower under zero than conventional tillage. Similar to the results for field pea, Lafond and Loeppky (1988) found that zero tillage increased WUE for grain yield of field pea as well as both ET and grain yield, indicating increased efficiency of production under zero tillage. However, water use efficiencies reported by Lafond and Loeppky (1988) were much lower than those in the present study (for wheat, 6.43 and 4.72 kg ha^{-1} mm^{-1}, and for pea, 4.92 and 3.64 kg ha^{-1} mm^{-1}, respectively for zero and conventional tillage) since their yields were lower.

Significant tillage by species interactions for WUE of postanthesis dry matter production ($P<0.05$) and grain yield ($P=0.0689$) at Carman in 1990 indicated that WUE of field pea was higher under zero tillage than under conventional tillage while WUE of canola and wheat were not affected (Figure 4.11). WUE of dry matter production for the entire season was significantly ($P<0.05$) less for conventional tillage than for zero tillage; however, the lack of a significant tillage by species interaction indicated that all three crops were affected similarly. Once again the trend is definitely there for greater WUE under zero tillage than conventional tillage.

No significant tillage effects or interactions for WUE for preanthesis, postanthesis and growing season dry matter production were observed at Portage in 1990 (Figure 4.12). However, for the first month

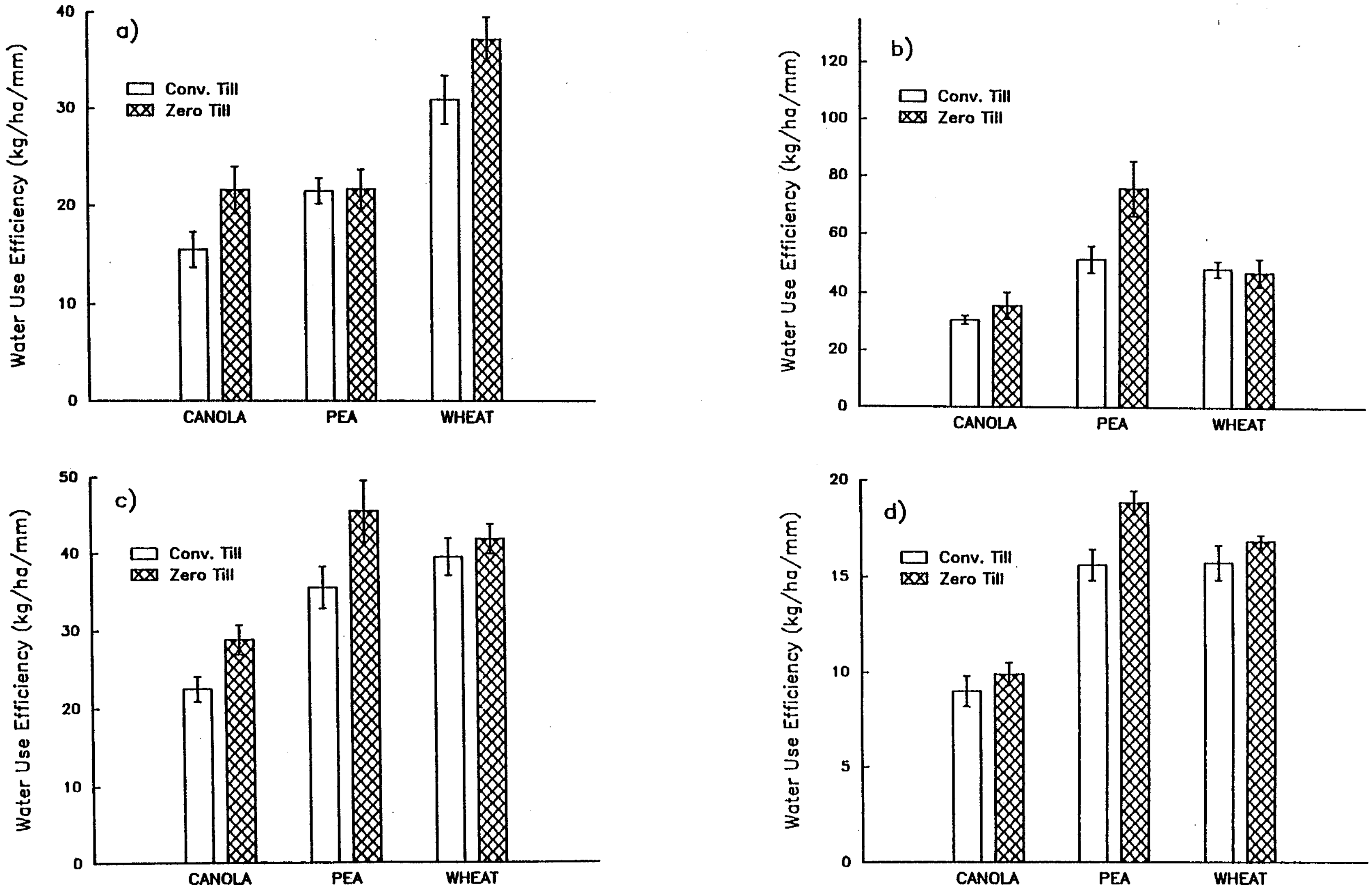


Figure 4.11
Water use efficiency of a) preanthesis dry matter production (S**), b) postanthesis dry matter production (S**, TS**), c) growing season dry matter production (T*, S**) and d) grain yield (S**, T(p=0.0689)) for canola, field pea and wheat grown under zero and conventional tillage at Carman in 1990. Bars indicate standard error.

of the growing season, May 31 to June 26, WUE of dry matter production was significantly ($P<0.05$) higher under zero tillage (3.8 kg ha^{-1} mm^{-1} under zero tillage and 3.1 kg ha^{-1} mm^{-1} under conventional tillage). Because dry matter production was not affected by tillage system (Figure 3.12), this observation suggests higher WUE was due to less direct soil evaporation under zero tillage early in the growing season. Thus the extra soil water present under conventional tillage at this site (Figure 4.8) was not responsible for extra production of dry matter or improved WUE under conventional tillage compared with zero tillage.

In 13 of 16 cases where WUE of grain yield or dry matter production was measured in the present study, no significant ($P<0.05$) effect of zero tillage was observed (Figures 4.9 to 4.12). However, in those cases where WUE was significantly affected by tillage, the general trend was for an increase in WUE under zero compared to conventional tillage. When interactions with crop species occurred, field pea was found to respond much more favorably to a reduction in tillage than canola. Wheat appeared to be least favourably affected by zero tillage. Lafond and Loeppky (1988) also found an increase in WUE of pea and wheat under zero tillage compared to conventional tillage.

As Unger (1990) showed, numerous studies have found that WUE was increased with a reduction in tillage along with increases in both yield and ET. Higher surface residues under zero tillage provided for increases in soil water content and yield with only small increases in ET. In these studies, higher WUE was attributed to less soil evaporation and more transpiration by the crop. Such an explanation for improved WUE under zero tillage appears to apply to this study as well. For example,

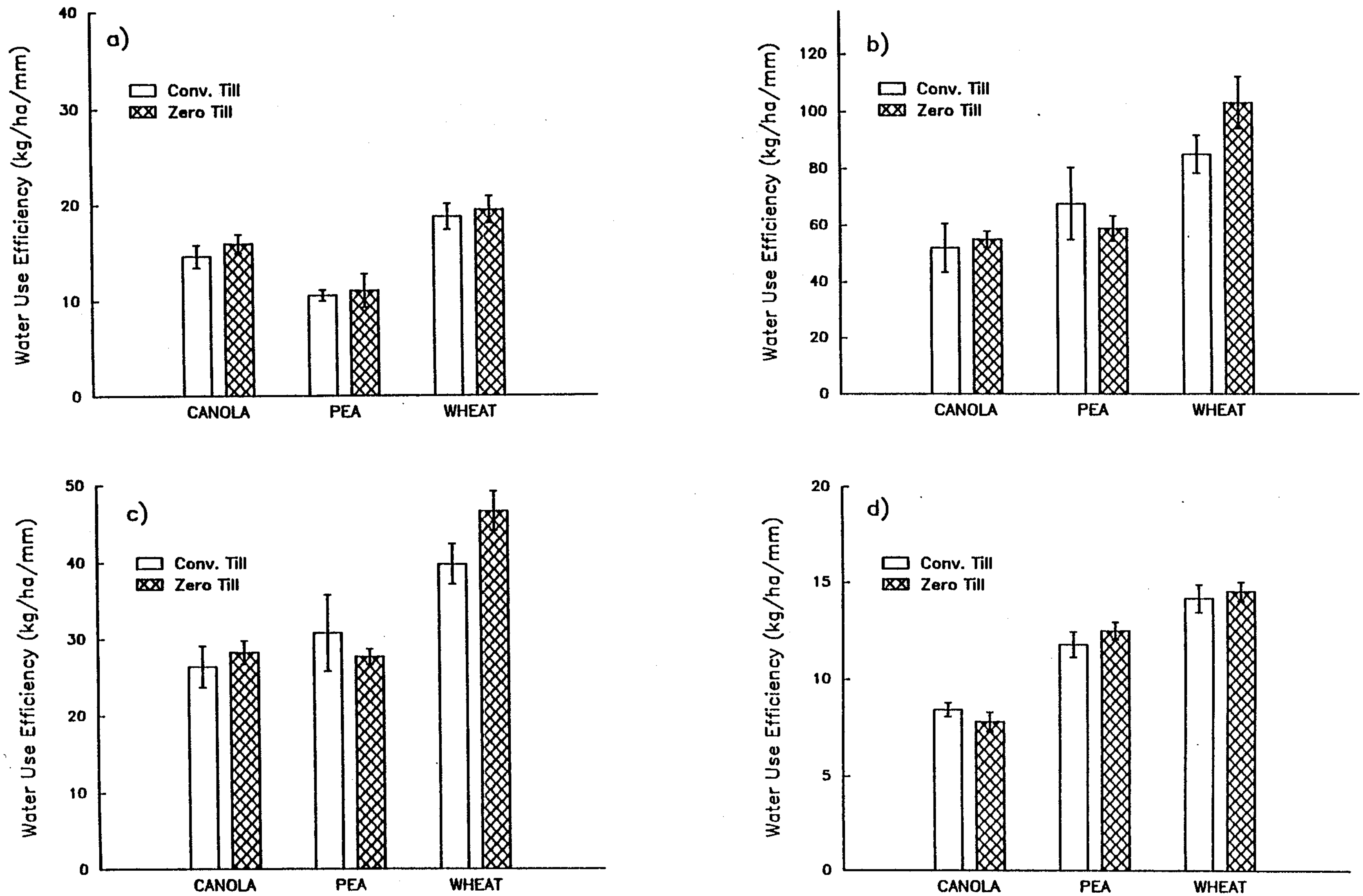


Figure 4.12
Water use efficiency of a) preanthesis dry matter production (S**), b) postanthesis dry matter production (S**), c) growing season dry matter production (S**) and d) grain yield (S**) for canola, field pea and wheat grown under zero and conventional tillage at Portage in 1990. Bars indicate standard error.

although crops at Carman in 1990 (Figure 4.3) used significantly less water under zero tillage, productivity and final grain yield were not different between tillage systems (Table 3.9). The lack of differences in productivity despite differences in ET suggests that much of the extra water used under conventional tillage may have been lost as evaporation from the soil. Within a species the yield:transpiration ratio is relatively constant, varying only with potential evaporation (Wilson et al., 1985; Unger et al., 1988). Therefore, changes in crop management systems, such as zero tillage, can ultimately only affect the evaporation:ET ratio, resulting in increases in WUE by decreased evaporation. However, by increasing soil water content, zero tillage systems can also increase growth and allow for more efficient use of the water that is received as precipitation.

4.4 Conclusions

Significant differences in ET, soil water depletion and WUE between crops and tillage systems were observed in only a limited number of cases. However, precipitation patterns, especially in 1990, may have had an overriding effect on crop growth and soil water extraction, masking potential differences between crop species responses to tillage systems. Other authors have found the soil water and crop productivity differences due to zero tillage to be more pronounced in drier years than in relatively wet years such like 1990 (Baeumer and Bakermans, 1973; Edwards et al., 1988; Diebert and Utter, 1989). Because soil water was a less limiting factor in determining crop productivity in 1990 than 1989, other factors, such as soil and air temperature and evaporative demand may have modified differences resulting from a reduction in tillage. Conditions in 1989 were much drier resulting in a greater benefit from zero tillage, especially for field pea.

Even with relatively few differences in ET, WUE was improved under zero tillage compared to conventional tillage for some crops at several of the sites. The improved WUE indicates that, although soil water may not necessarily be more available under zero tillage than conventional tillage, especially when zero tillage is just introduced to a field, soil water may be used more efficiently by crops grown under zero than conventional tillage. Although the present study did not represent conditions under a long-term zero tillage system, short-term benefits of zero tillage were evident, including decreases in ET and increases in WUE.

5.0 Plant Water Status of Canola, Field Pea, and Wheat under Conventional and Zero Tillage

5.1 Introduction

The increases in available soil water (Baeumer and Bakermans, 1973; Unger, 1990) can reduce plant water stress levels under zero tillage for wheat (Stobbe et al., 1970), corn (Lal, 1974; Doran et al., 1984; Newell and Wilhelm, 1988), soybean (Doran et al., 1984; Webber et al., 1987) and sorghum (Doran et al., 1984). During drought stress, plants may function more effectively and survive more easily when grown under zero compared with conventional tillage (Campbell et al., 1986). Decreased plant stress levels would be very useful, especially for drought susceptible crops such as field pea and canola. The objective of the present study was to compare the effect of zero tillage on the water stress levels of canola, field pea and wheat.

5.2 Materials and Methods

5.2.1 General

Three of the four trials described in section 3.2 were used in this part of the study. In 1989, only the Portage site was used while in 1990 both Carman and Portage (Portage 1990a) sites were used.

In addition, a fifth trial was initiated at Portage (Portage 1990b) in 1990 to study the plant water stress responses of Westar canola and

Victoria field pea to zero tillage under simulated preanthesis drought. The experimental design was split plot with tillage as the main plot and crop species as the subplot factor. The experiment was replicated four times. Rain shelters were placed over plots to cover 2.5 x 3.0 m of each subplot area immediately after seeding (May 24) and removed when both crops were flowering (July 10). Rain shelters (Photo 1) were constructed of clear plastic and were approximately 2 m in height. The side panels rolled up (Photo 2) to allow free air movement under the shelters when there was no threat of rain. When rain was imminent, side panels were rolled down (Photo 1). Plots received 37 mm of rain in the several weeks prior to seeding (Figure 3.16b). Air temperature was measured under and outside the shelters using thermometers shaded from the sun but with free air movement. Air temperature was slightly elevated under the rain shelters (average 1.8°C) but since all plots were covered to the same extent at all times, this was not a confounding factor in the experiment.

Stress measurements were taken at Portage in 1989 and at Carman and Portage (1990a and 1990b) in 1990 on various dates (Table 5.1).

5.2.2 Relative Water Content

Leaf relative water content (RWC) was determined by excising one new, fully expanded leaf per plot, rolling it loosely, and placing it into a sealed, preweighed tube (or ziplock bag when canola leaves were too large for the tubes) (Turner, 1981). The weight of the leaf and container (tube or bag) was determined four to eight hours after sampling to an accuracy of 0.001 g or 0.0001 g. The leaf was then placed, with the cut

Photo 1
Rainshelters with side panels closed due to threat of rain.

Photo 2
Rainshelters with side panels open to allow free air movement.

end down and with approximately 30 % of the leaf submerged, into a test tube filled with distilled water and allowed to fully hydrate in the dark for twelve to sixteen hours. The hydrated leaf was blotted dry, immediately weighed, and dried at 80°C for 48 hours. The dried leaf was weighed and the RWC calculated:

$$RWC(\%) = \frac{\text{fresh weight (g)} - \text{dry weight (g)}}{\text{hydrated weight (g)} - \text{dry weight (g)}} \times 100. \quad (5.1)$$

Leaves were collected for all subplots either two or three times daily, usually at 8:00, 12:00 and/or 16:00 hours (Table 5.1).

Table 5.1 Plant stress measurement sampling dates.

Parameter	Location	Year	Sampling Dates[1]
RWC	Portage	1989	June 16(3), 28(1), July 5(3), July 11(3)
	Carman	1990	June 15(1), 25(4), July 10(2), July 13(3), 23(3), 31(3)
	Portage	1990a	July 24(3), August 7(3)
	Portage	1990b	June 21(3), 28(2), July 6(2), July 26(1), 30(3)
Canopy Temperature(1)	Carman	1990	June 25, July 10, 23, 31
	Portage	1990a	July 12, 24, August 7
Leaf Temperature and Conductance	Carman	1990	June 25(2), July 10(1), 13(1), July 23(2), 31(2)
	Portage	1990a	July 12(1), 24(2), August 7(2)
	Portage	1990b	June 21(1), 28(1), July 6(2), July 26(1), 30(2)

[1] (1),(2),(3),(4) indicate the number of times per day measurements were taken.

5.2.3 Crop Canopy Temperature

Crop canopy temperature (°C) was determined using an Everest Interscience Model 112 infrared thermometer. Measurements were taken at approximately 16:00 hours on the same day as other plant stress measurements were taken (Table 5.1). Three readings were taken per subplot from an approximately 3 m distance from the edge of the plot. The thermometer was aimed at the crop canopy at an approximately 30° angle and a reading taken. Care was taken to ensure that canopy temperature was not measured in plot areas where the canopy had been removed for dry matter determination.

5.2.4 Leaf Conductance and Leaf Temperature

Leaf conductance and leaf temperature were determined using a Licor Model LI-1600 (Licor Inc. Lincoln, Nebraska) steady state porometer. Leaf temperature (°C) and leaf diffusive resistance (s cm^{-1}) were measured for the abaxial surface of three new fully expanded leaves per subplot. The area measured on each leaf was one cm^2. Leaf conductance (cm s^{-1}) was calculated as the reciprocal of diffusivity resistance measurements (Turner, 1981). Measurements were taken either once per day, 12:00 hours, or twice per day, at 9:00 and 14:00 hours (Table 5.1). Average humidity in the cuvette was set to the level within the canopy and was not altered within replicates. Leaf temperature was measured with a thermocouple located within the cuvette of the porometer.

5.2.5 Statistical Analysis

All data collected from samplings, as well as parameters calculated from the data, was subjected to analysis of variance (Statistical Analysis Systems Institute, 1986). Differences with $P<0.05$ were considered to be significant. Differences between crop species were only discussed when the tillage by species or site-year by species interactions were significant.

5.3 **Results and Discussion**

5.3.1 Relative Water Content

At Portage in 1989, seasonal levels of RWC averaged from 75.4 to 95.6% for canola, from 67.8 to 92.5% for field pea and from 88.7 to 105.7% for wheat. In most cases, differences between species were significant. On any one sampling date, field pea usually had the lowest RWC, while wheat had the highest. Only one significant ($P<0.05$) tillage effect and one significant tillage by species interaction were observed for the 10 sampling times in this study. At 12:00 on July 5, 1989 at Portage, the RWC of plants grown under conventional tillage exceeded ($P<0.05$) that of plants under zero tillage (92.8% vs 91.5%). A plant's ability to maintain a high RWC depends on its ability to extract sufficient soil water to keep up with atmospheric demand. However, differences in RWC here could not be explained by differences in soil water extraction between tillage systems (Figure 4.6).

A significant tillage by species interaction ($P<0.01$) at Portage in 1989 at 16:30 hours on July 11 indicated that crops did not always respond the same to zero tillage. At this site, the RWC of wheat and canola was only very slightly affected by zero tillage; however, RWC of field pea was 75.5% under zero tillage, compared with 67.8% under conventional tillage (Figure 5.1). This difference could not be explained by differences in soil water extraction. In fact, a significant tillage by species interaction for soil water depletion between July 5 and 11 (data not shown) indicated less water use by pea under zero tillage at 50 to 70 cm.

Seasonal RWC values ranged from 75.3 to 114.5% for canola, 42.4 to 128.6% for field pea and 49.4 to 120.9% for wheat at Carman in 1990. The explanation for the very high (>100 %) RWC values observed in some instances is as follows: the combination of low water stress levels and high soil water contents on certain days resulted in nearly fully hydrated leaves. Consequently, differences between hydrated and fresh weights of the leaves were very small, and, therefore, any errors in measurement were magnified in the calculation of RWC. Increasing the number of samples per plot may have reduced the level of error. However, the present RWC values are still useful for comparisons between treatments.

No significant effects of tillage on RWC were observed at Carman in 1990. A significant tillage by species interaction was observed only one of 15 sampling times (Figure 5.2). On this date, RWC for wheat and canola increased slightly in zero tillage plots, while RWC for field pea decreased with zero tillage. One reason for the negative effect of zero tillage on RWC of field pea on this date could have been the shallower root activity of peas under zero tillage at Carman in 1990 (as indicated

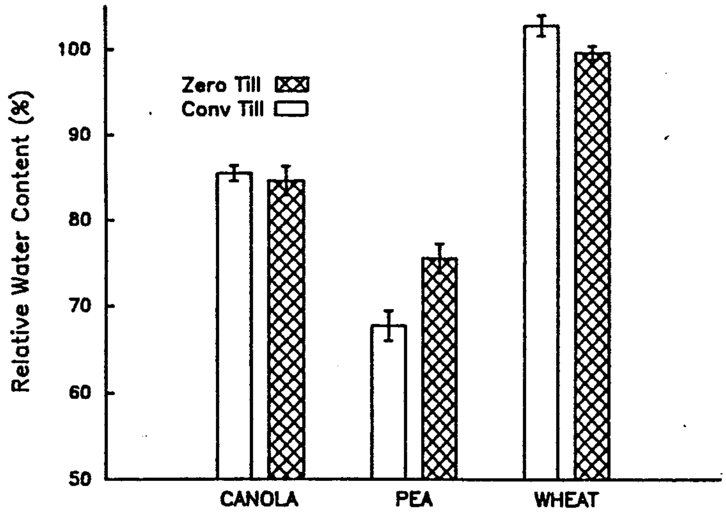


Figure 5.1
Relative water content of leaves of canola, field pea and wheat grown under zero and conventional tillage at Portage, July 11, 1989, 16:00 hours (TS**, S**). Bars indicate standard error.

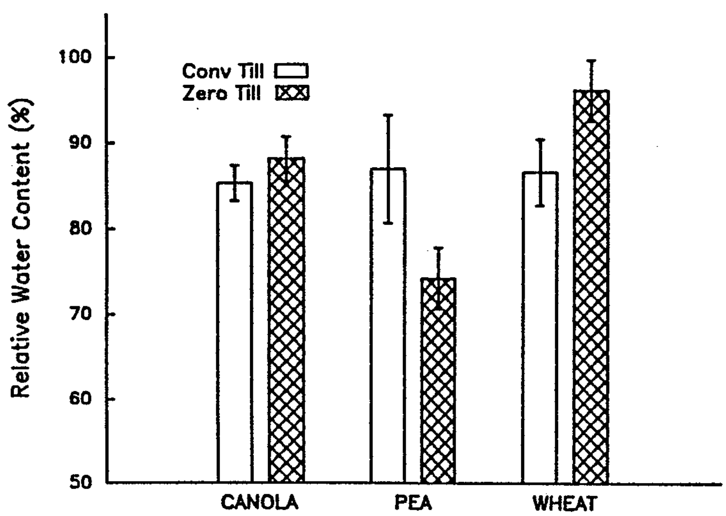


Figure 5.2
Relative water content of leaves of canola, field pea and wheat grown under zero and conventional tillage at Carman, July 13, 1990, 12:00 hours (TS**, S*). Bars indicate standard error.

by soil water extraction Figure 4.7) which may have left the crop more susceptible to temporary stresses imposed by high atmospheric demand for water. Wheat and canola had higher RWC levels under zero tillage on July 13 at Carman (Figure 5.2), despite significantly less soil water extraction under zero tillage (P<0.01), especially between 50 and 90 cm (Figure 4.7).

Levels of soil water were high throughout the season at Portage in 1990(a) (Figure 4.8). RWC values ranged between 88.2 and 132.9% for canola, between 68.9 and 162.8% for field pea and between 91.3 and 139.5% for wheat. Once again, RWC values were frequently above 100%. Significant responses to tillage were observed for two of the six sampling times at this site. At 16:00 hours on July 24, there was a significant tillage response in which the RWC averaged 90.8% for zero tillage crops compared with 85.3% for conventional tillage crops. A significant tillage by species interaction was observed at 8:00 hours on August 7, a day when there was little water stress (RWC was over 100% for all treatments). Again RWC of canola and pea crops was higher under zero than under conventional tillage, but RWC for wheat was lower under zero tillage. No significant differences in soil water occurred in correspondence with these observations.

Average levels of RWC under the rain shelters (Portage 1990b), ranged from 62.3 to 104.8% for canola and from 37.3 to 102.2% for field pea. Lower average values here compared with Portage 1990a indicated that some degree of drought stress had been imposed by the rain shelters. No significant tillage effects or tillage by species interactions for RWC or soil water content were found on any of the 11 sampling times. The lack of tillage effects, even under drought conditions, was attributed to a number of factors. First, tillage treatments were imposed immediately prior to seeding in the spring of 1990, so that initial soil water contents between tillage treatments should have been similar. Second, 37 mm of rain was received the week prior to seeding (Figure 3.8). Under these conditions, the water depletion under the two tillage systems was not different enough to cause any significant differences in soil water content (data not shown) or RWC.

Although Baeumer and Bakermans (1973) reported that visible wilting of corn and sugar beets was delayed with zero compared to conventional tillage, such dramatic responses were not seen in the present study (where wilting was quantitatively measured using RWC). Baeumer and Bakermans (1973) attributed their observation to enhanced soil water depletion, although, as the present study showed, soil water depletion is not always enhanced under zero compared to conventional tillage. However, field pea, which was the most drought sensitive of the three crops (in terms of RWC), showed an improvement in water status under zero tillage in some cases. Had water stress been more of a problem at the sites where RWC was measured, more significant effects due to tillage might have been observed. However, despite the low frequency of significant effects on RWC, results of this study did indicate that RWC can be affected by tillage and that canola and field pea were affected more than wheat.

5.3.2 Crop Canopy Temperature and Leaf Temperature

Excess heat energy from the sun is dissipated through the evaporation of water from stomates. When plants are under water stress stomates close, resulting in reduced transpiration and higher leaf temperatures. Therefore, crop canopy and leaf temperature are indirect measures of plant stress (Kirkham and Ahring, 1978; Jackson, 1982; Clarke and McCaig, 1982).

Temperature values in the present study ranged between 20.5° and 32.7°C for canola, between 19.7° and 32.8°C for field pea and between 19.0° and 32.6°C for wheat. At Carman in 1990, canopy or leaf temperature were significantly affected by tillage two of twelve sampling times and by an interaction between tillage and crop species three of twelve sampling times. On June 25, canopy temperature of all three crops was significantly lower under zero than conventional tillage (Figure 5.3); however, the extent of the temperature depression was greater for canola than for pea or wheat. There were also several tillage by species interactions and tillage effects at Carman for leaf temperature as measured by the thermocouple attached to the porometer. On July 13, there was an interaction between tillage and species at P=0.0517. In this case, field pea and canola had lower leaf temperatures under zero than under conventional tillage (0.3°C difference) while leaf temperatures were 0.3°C higher under zero than under conventional tillage in wheat. As Kirkham and Ahring (1978) and Doran et al. (1984) pointed out, soil or root temperatures may have a very direct bearing on a plant's ability to withstand atmospheric heat stress and maintain lower leaf temperatures. Lower soil temperatures may also affect leaf temperature (Doran et al., 1984). Decreased temperatures under canola (2 to 3°C) and field pea (up to 7°C) (Figure 3.2) due to zero tillage compared to only about 1°C under wheat indicates a possible reason why the effect on leaf temperature on

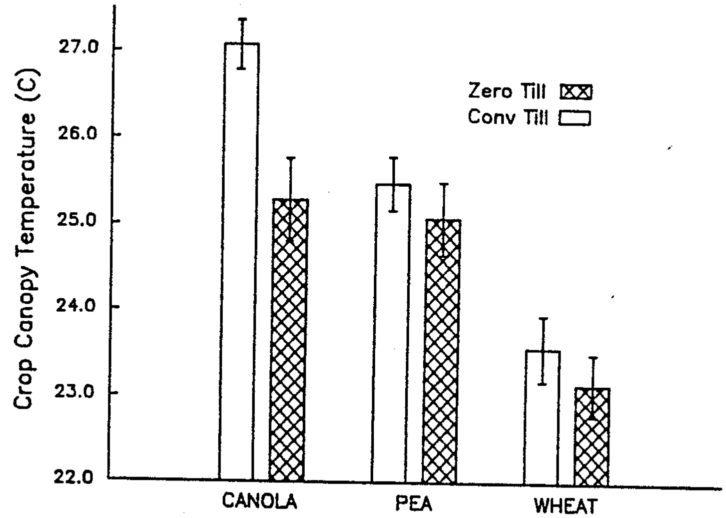


Figure 5.3
Crop canopy temperature of canola, field pea and wheat grown under zero and conventional tillage at Carman, June 25, 1990, 16:00 hours (TS**, T*, S**). Bars indicate standard error.

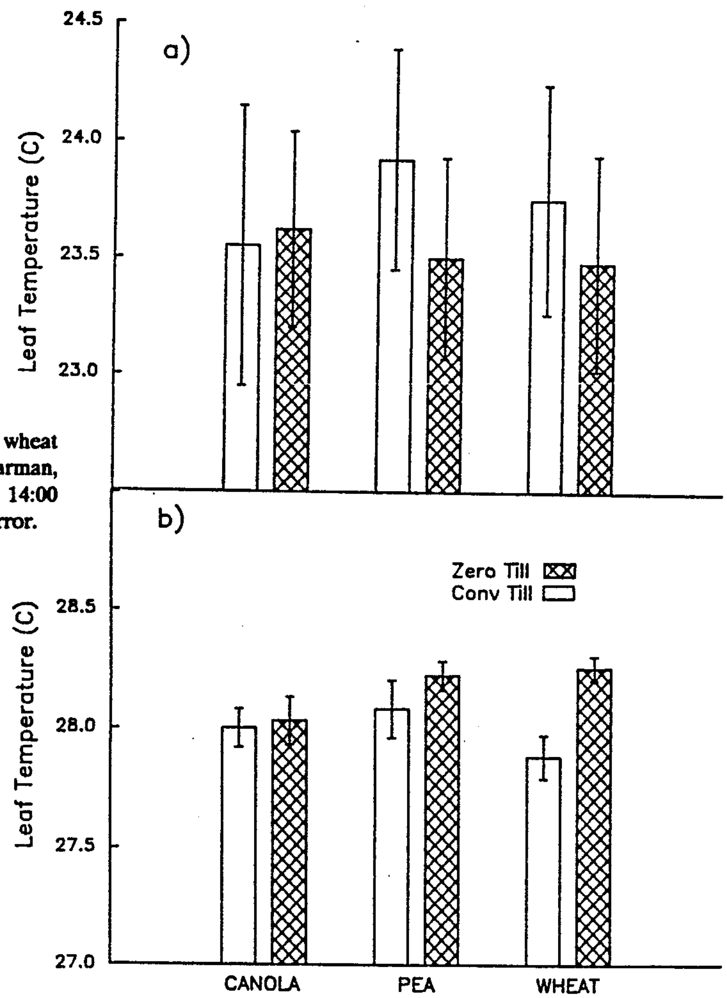


Figure 5.4
Leaf temperature of canola, field pea and wheat grown under zero and conventional tillage at Carman, July 23, 1990 at a) 9:00 hours (TS*) and b) 14:00 hours (TS*,T*, S*). Bars indicate standard error.

wheat was negligible compared to that of field pea and canola.

Two significant tillage by crop species interactions were observed on the July 23 sampling date at Carman. For the 9:00 hours sampling time, field pea and wheat had lower leaf temperatures under zero than conventional tillage, while leaf temperature for canola was not affected (Figure 5.4a). Thus, zero tillage appeared to reduce leaf temperature even at a time of day when water stress is low. However, at 14:00 hours, when average leaf temperatures were 4.4°C higher than at 9:00 (Figure 5.4b), a very different response was observed. In this case, significant tillage and tillage by species interactions indicated that leaf temperatures were higher under zero than conventional tillage, and that the effect was strongest for wheat. Significantly higher leaf temperatures under zero compared to conventional tillage at 14:00 hours may be related to the significantly lower level of soil water depletion (Figure 4.7) and seasonal ET (Figure 4.3) under zero tillage for all crops in this trial. Therefore, lower levels of evapotranspiration may have prevented the plants from maintaining lower leaf temperatures through adequate transpiration, although leaf conductance values, which had very high error (C.V. of 16.4 to 52.4%), did not confirm this (Section 5.3.3). However, this data once again showed water status in wheat to be more negatively affected by a reduction in tillage than that of pea or canola. The greater negative effect of zero tillage on wheat may once again be related to the fact that all crops were seeded on to wheat stubble and that pathogens arising from this stubble may have been higher under zero tillage.

At Portage in 1990(a), temperatures ranged from 22.6° to 33.2°C for

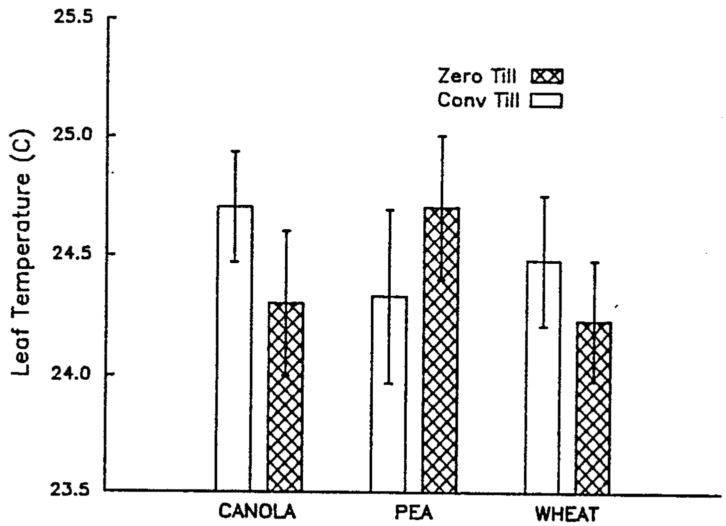


Figure 5.5
Leaf temperature of canola, field pea and wheat grown under zero and conventional tillage at Portage, July 24, 1990 at 10:00 hours (TS*). Bars indicate standard error.

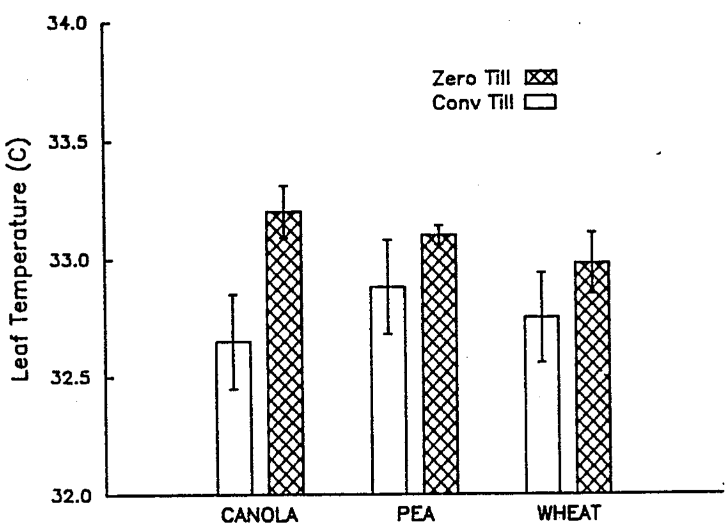


Figure 5.6
Leaf temperature of canola, field pea and wheat grown under zero and conventional tillage at Portage, August 7, 1990 at 14:00 hours (TS*). Bars indicate standard error.

canola, 22.9° to 33.1°C for field pea and 21.5° to 33.0°C for wheat. Canopy temperature was not affected by tillage for any of the three sampling times. However, tillage by species interactions for leaf temperature were found to be significant two of five sampling times. At 10:00 hours on July 24, leaf temperature of canola and wheat were reduced under zero compared to conventional tillage, while the opposite was true for field pea (Figure 5.5).

The second tillage by species interaction occurred at 14:00 hours on August 7 (at average leaf temperature, 32.9°C and maximum air temperature, 33.0°C), where leaf temperature of field pea and wheat was slightly higher under zero than conventional tillage while that of canola was considerably higher (Figure 5.6). It may have been that, although there appeared to be sufficient water (Figure 4.8) for crop growth at this site, under conditions of high atmospheric demand, temporary water deficiencies occurred under zero tillage. A major reason for higher water and temperature stress under zero tillage in this trial could have been the significantly lower ET (Figure 4.4) and lower soil water depletion below 50 cm (Figure 4.8) under zero tillage.

In the rain shelter trial (1990b), the tillage by species interaction for leaf temperature was found to be significant only one of seven sampling times. Average leaf temperatures ranged from 14.3° to 27.6°C for canola and from 14.4° to 27.6°C for field pea. On June 21 the leaf temperature of canola was increased with a reduction in tillage while the opposite was true for field pea (Figure 5.7). Here, pea seemed to benefit more from zero tillage than canola, a result which was also observed for leaf conductance on this date (Section 5.3.3). In this case,

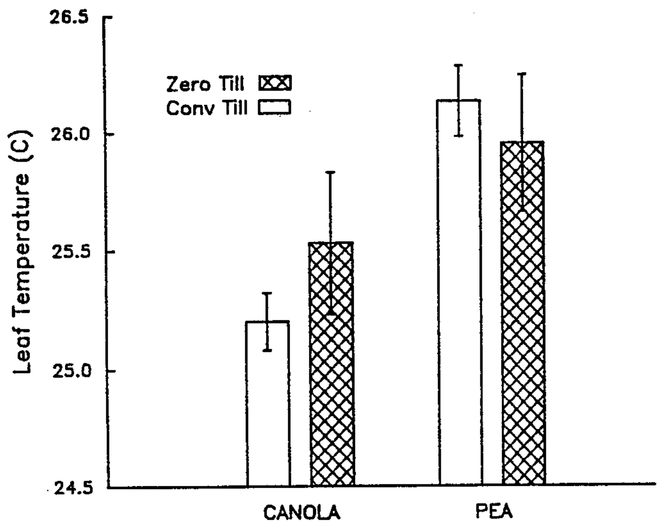


Figure 5.7
Leaf temperature of canola and field pea grown under zero and conventional tillage under rainshelters at Portage, June 21, 1990, 13:00 hours (TS*, S**). Bars indicate standard error.

canola seemed to be responding similarly to a reduction in tillage as it did at Portage, 1990a (Figure 5.6). Since soil water content was not significantly different (P>0.05; data not shown) between tillage systems, less water extraction of canola under zero tillage may have caused it to be under greater stress than under conventional tillage.

Soil water level was relatively high throughout the growing season at both Carman and Portage in 1990 (Figures 4.7, 4.8). At both sites in 1990, ET (Figure 4.3, 4.4) and root activity were restricted under zero compared with conventional tillage. Since water availability was not greater under zero tillage than conventional tillage, and given that water availability is a major factor determining drought stress, it is not surprising that there were only a few decreases in leaf temperature under zero tillage in 1990. In fact, slightly restricted water availability due to less root activity (i.e., less soil water depletion) under zero tillage could have been the cause for the negative responses to tillage observed at both sites.

At Carman, most of the tillage effects were favorable for zero tillage (Figures 5.3, 5.4a and 5.4b), while at Portage plant water status was often decreased with a reduction in tillage (Figures 5.5, 5.6, 5.7). A higher frequency of positive responses to tillage at Carman may be related to the lower soil water holding capacity at Carman compared to Portage. Therefore, instances where soil water availability was insufficient for plants to keep up with atmospheric demand may have occurred with greater frequency at Carman. Negative effects of tillage in 1990a at Portage could have been due to lower soil water content under zero tillage than conventional tillage for the first half of the season.

However, the existence of some positive responses of leaf temperature to zero tillage in a year such as 1990, when moisture was often not limiting, was encouraging since one would not necessarily expect to see a positive response to a reduction in tillage under such conditions.

5.3.3 Leaf Conductance

Leaf conductance was only measured at the three trials in 1990. Leaf conductance for the three crops ranged from 0.25 to 1.69 cm s^{-1} for canola, from 0.17 to 0.87 cm s^{-1} for field pea and from 0.35 to 1.65 cm s^{-1} for wheat at Carman in 1990. At Portage in 1990a, leaf conductance ranged from 0.08 to 1.84 cm s^{-1} for canola, from 0.06 to 0.67 cm s^{-1} for field pea and from 0.39 to 1.85 cm s^{-1} for wheat. No significant responses of leaf conductance to tillage were observed at Carman or Portage (1990a). High variability (C.V. ranging from 16.4 to 52.4% for Carman, 15.9 to 73.4% for Portage 1990a, and 8.2 to 74.8% for Portage 1990b) may have been partially responsible for the lack of significant effects observed. Compared to the variability in the RWC measurements (C.V. from 2.1 to 32.4%, averaging 7.9%) and in the temperature measurements (C.V. from 0.4 to 3.4%, averaging 1.6%), it is not surprising that the detection of significant differences was more frequent for RWC and temperature measurements than for conductance.

However, in the rain shelter trial, a significant tillage by species interaction (C.V. was 9.9%) was observed on July 6 at 9:00 hours (Figure 5.8). Leaf conductance was higher for field pea under zero tillage compared with conventional tillage; however, the opposite trend occurred

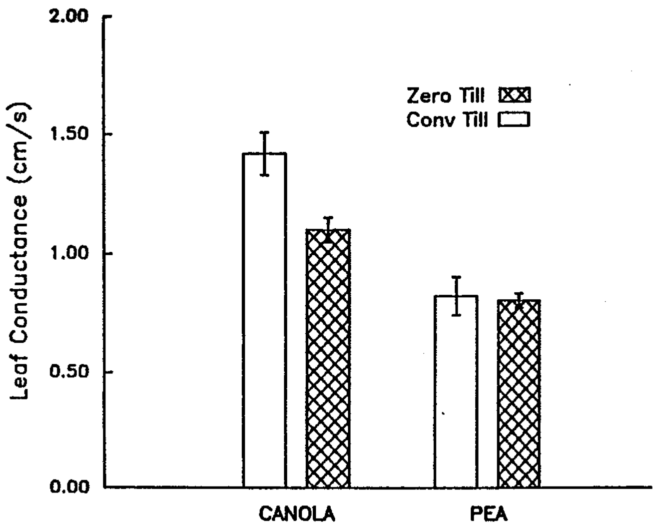


Figure 5.8
Leaf conductance (cm/s) of canola and field pea grown under zero and conventional tillage under rainshelters at Portage, July 6, 1990 at 9:00 hours (TS*, S**). Bars indicate standard error.

with canola. This response was similar to the temperature response on June 21 (Figure 5.7), clearly showing that, on this date, field pea was under less water stress under zero than conventional tillage while the opposite was true for canola. Both Richards (1978) and Clark and McCaig (1982) found that diffusivity resistance increased with increasing soil water deficit for canola. Thus, on this date, the ability of canola to extract water from the soil was inhibited by a reduction in tillage, while no differences were observed for field pea.

The effect of the rain shelters was to increase the soil water deficit at Portage 1990b and thus to increase the potential water stress. In fact, greater stress levels occurred in 1990b than in 1990a in terms of available soil water at anthesis (27 mm less water between 0 and 110 cm in 1990b than 1990a) and RWC (range from 37.3 to 104.8% at 1990b and from 68.9 to 162.8% at 1990a). In 1990a, (low water stress) there was no benefit to leaf conductance of either field pea or canola, while in 1990b (higher water stress) there was a positive benefit to leaf conductance for field pea, but not for canola. Therefore, it is possible to say that field pea responds better to a reduction in tillage than canola. Lack of significant responses of leaf conductance to zero tillage in the 1990a trial suggests that leaf conductance may be a less sensitive measure of plant stress than leaf temperature or RWC. Turner (1981) stated that leaf conductance is an index of the effect of water stress on photosynthesis and transpiration and that it is directly related to soil water deficit. It may be more difficult to detect tillage effects on transpiration directly than it is to indirectly detect the effects by measuring leaf RWC or leaf temperature.

5.4 Conclusions

A reduction in tillage did not always affect plant water status as measured in this study by RWC, leaf or canopy temperature and leaf conductance. In most cases where significant effects were observed, canola was not consistently positively or negatively affected, while field pea was usually positively affected and wheat was either unaffected or negatively affected by a reduction in tillage.

Unfortunately, no measures of water stress were taken at the site where the greatest water deficit occurred (i.e., Carman in 1989). Most of the measurements were concentrated in 1990, a year when more than adequate rainfall was received during the first half of the growing season (Figure 3.8; Table 3.4) Therefore the positive benefits of zero tillage reported by other authors (Stobbe et al., 1970; Baeumer and Bakermans, 1973; Lal, 1974; Doran et al., 1984; Webber et al., 1987) were not consistently observed in the present study. Although in many of these previous studies soil water was increased with a reduction in tillage, this was not generally the case in the present study. Consequently, plant stress levels were not always decreased with a reduction in tillage. Had increases in soil water been similar to those reported by Lafond (1991) (2 cm), more positive responses to a reduction in tillage would have been expected.

6.0 General Discussion

Results of this study indicated that canola, field pea and wheat are all well adapted to zero tillage. While, in most cases, these crops responded similarly to a reduction in tillage, significant differences in crop response were observed in a number of cases. These differences tended to be greatest during periods of soil water stress.

Canola yields were similar over sites and tillage systems (Table 3.8; yield range of only 430 kg ha^{-1}), even though levels of ET were very different. Therefore, canola appeared to be affected by factors other than those caused by a reduction in tillage. Morrison et al. (1989) found that Westar canola was very sensitive to air temperature during and after flowering. Therefore, the aerial environment may have affected the yield of canola more than the soil environment in the present study.

Growth parameters for canola were seldom significantly affected by tillage (Figures 3.9 to 3.12). Growth of canola may have been similar between tillage treatments due to its root morphology. Canola, having a tap-root system, may be less affected by previous crop residue (i.e. allelopathy, reduced availability of nutrients) than wheat which has a fibrous root system. Also, since most of the extra soil water accumulated under zero tillage is found in the surface soil layers and canola tends to extract more water from the lower part of the soil profile (Figure 4.5), canola may be less able to benefit from increased soil water under zero tillage.

Field pea, on the other hand, demonstrated a more consistent ability to respond favorably to a reduction in tillage. Parameters that were favourably affected by zero tillage included dry matter accumulation, crop height, light interception by the crop canopy (Figure 3.10), seed weight (Table 3.12), ET (Figure 4.2), WUE (Figure 4.10b, 4.11), RWC (Figure 5.1), canopy temperature (Figure 5.3) and leaf temperature (Figure 5.4a, 5.7). Like canola, field pea is also sensitive to air temperature during reproductive development (Nichols, et al., 1985); however, the yield range between sites (2200 kg ha^{-1}; Table 3.9) was much greater for field pea than for canola. Therefore, although field pea and canola are both drought susceptible crops, field pea may be more sensitive to soil water stress while canola is more sensitive to atmospheric environmental stresses.

Decreased soil temperatures (10° vs. 20° or 30°C) can enhance nitrogen fixation for field pea (Zachariassen and Power, 1987). Lower soil temperature in the present study (Figure 3.2) may be one reason for the favorable responses of field pea to zero tillage.

Wheat showed the least number of favorable responses to zero tillage. Although it had a yield range of 2400 kg ha^{-1} between sites, similar to field pea, there were very few significant responses to zero tillage at any one site. Previous research by Wilhelm et al. (1989) indicated that wheat yields did not respond to a decrease in tillage. They concluded that wheat could not consistently capitalize on the increased soil water under zero tillage. One reason for the decreased response in the present study may be that wheat, being a cereal crop, has the majority of its root system originating from the crown. Therefore, its roots must pass through the surface layers of the soil which are most affected by zero tillage (i.e., increased soil water, phytotoxins, increased nutrients) leading to a root system that is more concentrated in the surface layers of the soil. Therefore, wheat may be more affected than plants with taproots like canola or field pea. Had a different previous crop been used, the results of this study may have been different.

Because of greater concentrations of water and nutrients near the surface under zero tillage, root growth may also be more shallow and intense for wheat under zero tillage. Such a trend has been observed by previous researchers (Carter and Rennie, 1982; Newell and Wilhelm, 1988). Evidence for greater root activity of wheat at shallow depths was especially evident Portage in 1989 (Table 4.6, Figure 4.6). Results of this study also indicated that wheat sometimes did not extract as much water below 50 cm under zero compared with conventional tillage. Such a trend can lead to greater water stress under zero than under conventional tillage (Figure 5.4b). Because of these disadvantages, wheat responded negatively to zero tillage more often than canola and field pea.

Previous research has shown that zero tillage can strongly affect the soil environment (Gauer et al., 1982; Unger, 1990; Lafond, 1991). However, results of this study indicated that there is not necessarily always more water in the soil profile in a short-term zero tillage system compared with a conventional tillage system. Results also suggested that any additional soil water, especially if it is deeper in the soil profile is not always more available to plants. For example, if plants under zero tillage cannot extract water below 80 to 90 cm (Figure 4.7), water present below these depths will be of little use to the crop. If, however, crop productivity is not affected by this decrease in soil water extraction, such as at Carman in 1990, WUE can still be increased by the reduction in tillage (Figure 4.11).

Observed increases in WUE under zero tillage in this study appeared to be the result of decreased soil evaporation and hence a higher transpiration:ET ratio. For example, ET was decreased significantly throughout the growing season at Carman in 1990 under zero tillage (Figure 4.3), yet productivity was not affected (Table 3.9). The only way that WUE can be increased in such a situation (Figure 4.11) is to reduce evaporative water losses. These results support a similar conclusion by Unger (1990).

In this study, soils under zero tillage sometimes had higher levels of available water in the surface soil at harvest (Figure 4.6). Such increases in soil water can enhance the establishment of fall-seeded crops such as winter wheat and fall rye.

Zero tillage can also decrease soil temperatures (Gauer et al., 1982; Figures 3.1 and 3.2). Greater differences in soil temperature with depth (Figure 3.1) may have serious implications for root extension and activity (Kramer, 1969). Crop species differ in the optimum soil temperature for root growth and water absorption (Kramer, 1969). How much effect soil temperatures had on lower soil water extraction under zero tillage, especially at Carman in 1990 (Figures 4.3, 4.7) cannot be determined from the present study. However, it could have been a factor in limiting ET and soil water depletion at depths greater than 90 cm. Limitations in depth of soil water extraction may increase for plant stress levels as indicated by higher leaf temperatures (Figure 5.4b).

All trials in the present study were conducted on cereal stubble. Cereal stubble was chosen because cereals are the highest acreage crops grown in the Black soil zone. However, it was recognized that wheat would be at a disadvantage due to potentially higher stubble-borne disease pressures compared with pea and canola. Wheat and barley residues are also highly reflective, and form a relatively dense mat over the soil surface, and may, therefore, be more effective at reflecting solar radiation and impeding soil evaporation than canola, pea or flax residues. Results may have been different if previous crop types other than cereals had been used.

Trials in this study were conducted using only one cultivar per species. Whether the cultivars used in the present study were representative of their respective species in their response to zero tillage is not known although other authors (Carter and Barnett, 1987; Elmore, 1987; Kaspar et al., 1987; Diebert, 1989; Hall and Cholick, 1989) have found genotypic differences in crop response to zero tillage . A comparison of a number of different genotypes of each species would be necessary to determine this. Further examination of, for example, the tillage response of Victoria field pea, a leafed pea type, compared to that of leafless or semi-leafless pea cultivars would be of interest. A comparison with the work of Lafond (1991), who used a semi-leafless cultivar, indicates similar responses to those in the present study.

The influence of soil type on response to zero tillage was difficult to determine from this study, especially since there were also differences in growing conditions between the two locations. To properly test soil type effects, the sites should have been closer together. However, based on the fact that sandy soils have a lower water holding capacity than clay, one might expect the greatest responses to zero tillage to be on the sandy soil. Unfortunately, at the site which had the combination of low precipitation and sandy soil (Carman, 1989), residue cover differences between tillage systems were very small (Table 3.7).

The greater frequency of tillage by species interactions for crop growth (Figures 3.9 to 3.12) and ET (Figures 4.1 to 4.4) in 1989 than in 1990 support the suggestion (Baeumer and Bakermans, 1973; Diebert and Utter, 1989) that positive responses to zero tillage occur more often in drier years. In a wet year like 1990, when precipitation was generally above average and reasonably well distributed over the growing season, and soil water less limiting, the response of crops to the two tillage systems was more uniform than in 1989. It can be concluded from this that some differences between crop species in response to tillage systems will be masked by a favorable moisture environment.

To encourage adoption of a new farming system, farmers need to be shown that it has both short and long-term benefits. The adoption of zero tillage is advantageous for both soil and water conservation. Although soil water conservation benefits are not always evident in short-term studies such as this one, the long-term goal of soil conservation to protect the prairie soils which have been badly degraded is becoming more and more important. Although yields may not increase under zero tillage, growing crops like field pea and canola as part of a crop rotation should ensure that yields are maintained compared with conventional tillage. Maintenance of yields under a system which conserves soil is a key factor influencing the adoption of such a system by farmers.

Crop rotation is essential in a zero tillage system to reduce the risks of stubble borne diseases (Sturz and Bernier, 1987). Vyn (1988) found that crop rotation was more important than tillage system in maintaining yields in Ontario. The present study provided detailed information on the response of a cereal crop and two alternative rotational crops to zero tillage. Results of this study should encourage farmers to consider growing canola and field pea under zero tillage. To increase cropping options under zero tillage even further, in depth research is also required on the response of crops such as flax, sunflowers, and special crops, such as mustard and lentils, to zero tillage. Also, an examination of the productivity of these crops under zero tillage in an actual rotation is necessary to examine their response to zero tillage on different stubble types and in response to different previous crops.

7.0 Summary and Conclusions

In general, zero tillage had very little effect on the growth and productivity of canola, field pea and wheat under the tillage regimes in the present study. Effects of zero tillage on establishment and growth of these crops were limited. As well, there were no significant yield differences due to a reduction in tillage, and few differences in yield components and grain quality parameters. For grain yield, location and year were more important than tillage regime. Based on these results, it can be concluded that these crops are all well adapted to production under zero tillage.

The effect of zero tillage on soil water extraction varied with crop species and growing conditions. Significant tillage by species interactions for ET in 1989 were generally due to higher ET for canola and lower ET for wheat under zero compared to conventional tillage while ET of field pea was not affected. At Portage in 1989 wheat extracted more water under zero than conventional tillage at shallow depths (0 to 50 cm), while canola extracted more water at all depths, and pea extracted more water at depths greater than 50 cm. In 1990, ET tended to be lower for all crops under zero than conventional tillage. The reason for less ET under zero tillage at both sites in 1990 was less water depletion below 90 cm. However, despite the variable effects of zero tillage on soil water use, its effects on WUE were nonsignificant or positive. Higher WUE under zero tillage in this study was attributed to a higher transpiration:ET ratio (i.e., less soil evaporation).

The effect of zero tillage on plant water status varied. Although there were cases where plant water status was improved under zero tillage there were also cases where it was negatively affected. Tillage affected the water status of canola and field pea more often than wheat and positive responses to zero tillage were more frequent at Carman (sandy soil) than at Portage (clay soil). Overall, the water status of pea was improved more by zero tillage than that of canola or wheat.

In conclusion, measurements taken in this study clearly show the complexity of crop response to zero tillage crop production systems. Response to zero tillage depended on growing conditions and the ability of each crop species to take advantage of the beneficial effects of the respective crop production systems. Although only a few significant agronomic responses to zero tillage were observed, more detailed analysis (water use and plant water status measurements) indicated many subtle effects of zero tillage on these crops. More research is needed to determine the relationship between physiological and agronomic responses to zero tillage.

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APPENDIX 1

Soil Test Results

Table A1.1 Soil test results for Carman and Portage, April, 1989 and 1990.

Location	Year	Depth (cm)	Available Nutrients (kg/ha) NO_3-N	P	K	SO_4-S	pH
Carman	1989	0-15	5.5	24.5	263	6.0	7.6
		15-60	10.0			46.2	
Portage	1989	0-15	5.4	33.5	729	36+	7.8
		15-60	16.1			134+	
Carman	1990	0-15	8.4	14.7	273	3.4	7.1
		15-60	51.8			17.8	
Portage	1990	0-15	7.3	12.7	770	36+	7.7
		15-60	10.1			126+	

APPENDIX 2

Crop Development

Table A2.1 Crop development at Carman in 1989.

Date	Canola[1]	Field Pea[2]	Wheat[3]
June 1	1.0-1.2, 2.1	103-105	13, 21
June 14	2.1-2.3	105-107	15, 21
June 22	3.1-3.2	108-111	23, 33
June 29	4.0-4.2	201-202	43-53
July 6	4.3	204-205	61-69
July 13	4.3-5.1	206-207	69-85
July 26	5.2	210-301	77-85

[1] Harper-Berkenkamp scale (Harper and Berkenkamp, 1975).
[2] Knott scale (Knott, 1987).
[3] Zadoks-Chang-Kondak scale (Zadoks, 1974).

Table A2.2 Crop development at Portage in 1989.

Date	Canola[1]	Field Pea[2]	Wheat[3]
June 15	1.2-2.2	105-107	15, 22
June 21	2.2-2.4	107-109	23, 31-32
June 28	3.2-3.3	109-112	32-33
July 5	4.2	201-202	49-59
July 11	4.3	204-205	65-69
July 18	4.3-5.1	206-207	69-85

[1] Harper-Berkenkamp scale (Harper and Berkenkamp, 1975).
[2] Knott scale (Knott, 1987).
[3] Zadoks-Chang-Kondak scale (Zadoks, 1974).

Table A2.3 Crop development at Carman in 1990.

Date	Canola[1]	Field Pea[2]	Wheat[3]
June 4	1.0-1.2	101-102	12-13
June 18	3.1	108	23-24
June 25	3.2-4.0	110-201	23, 32
July 4	4.2-4.3	205	57-58
July 10	4.3-4.4	205-206	61-67
July 13	4.3-4.4	206-207	65-67
July 17	4.4	207	77-83
July 31	5.2	210-301	85

[1] Harper-Berkenkamp scale (Harper and Berkenkamp, 1975).
[2] Knott scale (Knott, 1987).
[3] Zadoks-Chang-Kondak scale (Zadoks, 1974).

Table A2.4 Crop development at Portage in 1990.

Date	Canola[1]	Field Pea[2]	Wheat[3]
July 12	4.2	203	47-53
July 25	4.3-4.4	205-207	68-72
August 16	5.2-5.3	207-301	86-87

[1] Harper-Berkenkamp scale (Harper and Berkenkamp, 1975).
[2] Knott scale (Knott, 1987).
[3] Zadoks-Chang-Kondak scale (Zadoks, 1974).

APPENDIX 3

Analysis of Variance - Agronomic Responses

Table A3.1 Mean square values for plant stand (plants m^{-2}).

Source	df	Carman 1989	Carman 1990	df	Portage 1989	Portage 1990
Block	5	177.53	232.05	3	355.57	363.55
Tillage(T)	1	106.78	56.25	1	160.17	2053.50
Error a	5	38.18	614.72	3	389.43	1045.94
Species(S)	2	21209.08**	97318.08**	2	53228.66**	82009.54**
T x S	2	12.03	3930.25*	2	1468.67	385.88
Error b	20	144.22	794.50	12	296.40	2302.38

Table A3.2 Mean square values for dry matter accumulation (kg ha^{-1}) at Carman in 1989.

Source	df	June 1	June 14	June 29	July 6
Block	5	935.92	17835.52	609533.32	898779.90
Tillage(T)	1	667.36	1420.03	45724.70	261.36
Error a	5	802.63	5653.05	204225.76	211363.22
Species(S)	2	19411.09**	35213.54*	542406.60*	874727.85*
T x S	2	17.53	441.47	33623.53	304543.53
Error b	20	246.17	7574.38	139369.92	179499.83

Source	df	July 13	July 26	df	August 8[1]
Block	5	1221553.38	2887599.44	5	6162764.20
Tillage(T)	1	1761813.78	3541924.00**	1	2184066.66
Error a	5	1043753.66	193000.33	5	851835.36
Species(S)	2	2346217.33	1407456.33	1	24272770.66**
T x S	2	358685.45	2668732.33	1	2362537.50
Error b	20	1202342.02	868442.55	10	1186299.18

[1]Canola and wheat only.

Table A3.3 Mean square values for dry matter accumulation (kg ha^{-1}) at Portage in 1989.

Source	df	June 2	June 15	June 28	July 5
Block	3	125.15	2718.53	365802.53	175775.82
Tillage(T)	1	2.04	8321.65	38400.00	70092.04
Error a	3	85.82	1482.23	68035.44	24894.82
Species(S)	2	2780.04**	6156.63	380754.50**	4098882.77**
T x S	2	72.79	4136.18	24783.50	58440.67
Error b	12	50.86	2295.18	43454.33	192550.61

Source	df	July 11	July 18	August 2	August 22
Block	3	235353.83	101189.93	925572.11	1656311.44
Tillage(T)	1	171704.17	1491512.04	1340482.67	1350.00
Error a	3	491965.61	1785749.87	1311148.88	4654980.11
Species(S)	2	1423556.20*	1261368.04	20867028.15**	18117383.38*
T x S	2	641216.15	837240.04	2726523.15	723312.13
Error b	12	255765.72	1187433.25	1825468.88	3405469.91

Table A3.4 Mean square values for dry matter accumulation (kg ha^{-1}) at Carman in 1990.

Source	df	June 4	June 18	July 4	July 17
Block	5	673.60	10194.24	161197.49	745715.64
Tillage(T)	1	173.36	27666.78	118680.25	437361.77
Error a	5	340.23	55423.84	120693.85	509699.04
Species(S)	2	14270.26**	788922.50**	11367211.19**	16326671.36**
T x S	2	111.32*	10916.03	151126.58	748750.50
Error b	20	318.17	15507.48	239247.79	1289018.60

Source	df	July 31	Harvest[1]
Block	5	2719292.09	4535469.98
Tillage(T)	1	27944.69	2397852.25
Error a	5	2876859.13	1568606.10
Species(S)	2	72157904.78**	61094419.00**
T x S	2	5151684.78	2805352.33
Error b	20	1643446.78	855434.05

[1]Harvest: canola, August 17; field pea, July 31; wheat, August 21.

Table A3.5 Mean square values for dry matter accumulation (kg ha^{-1}) at Portage in 1990.

Source	df	June 26	July 12	July 25	August 8
Block	3	324.03	175962.00	3173481.90	7836454.15
Tillage(T)	1	24054.00	15810.67	588440.16	51987.04
Error a	3	5152.30	275781.78	1184024.60	949264.37
Species(S)	2	319704.28**	5255073.50**	7174994.04**	33234476.04**
T x S	2	45655.35	9790.04	279099.04	6650982.50
Error b	12	16354.75	292826.80	621962.98	2324627.10

Source	df	Harvest[1]
Block	3	2301138.10
Tillage(T)	1	384053.99
Error a	3	919880.77
Species(S)	2	42793557.11**
T x S	2	3596628.50
Error b	12	3527153.40

[1]Harvest: canola, August 20; field pea, August 30; wheat, August 29.

Table A3.6 Mean square values for crop height (cm) at Carman in 1989.

Source	df	June 22	June 29	July 6	July 13	July 26
Block	5	58.64	106.24	120.71	197.09	93.13
Tillage(T)	1	7.11	64.00	2.78	0.25	0.44
Error a	5	10.31	10.13	102.84	22.12	37.71
Species(S)	2	231.69**	218.36**	774.36**	1834.78**	2764.75**
T x S	2	2.69	43.75	16.36	54.33	36.70
Error b	20	22.73	14.66	63.72	35.36	27.42

Table A3.7 Mean square values for crop height (cm) at Portage in 1989.

Source	df	June 21	June 28	July 5	July 11	July 18
Block	3	2.28	4.71	1.04	3.48	61.16
Tillage(T)	1	66.67	22.04	35.04	92.04	150.00*
Error a	3	11.89	14.38	35.04	33.49	9.67
Species(S)	2	723.38**	291.29*	617.17**	490.29**	550.54**
T x S	2	14.29	163.04	64.67*	155.04**	61.13**
Error b	12	2.17	47.00	13.75	10.61	8.33

Table A3.8 Mean square values for crop height (cm) at Carman in 1990.

Source	df	June 18	July 4	July 17	July 31
Block	5	11.16	25.84	27.63	55.05
Tillage(T)	1	14.69	64.00*	2.25	12.25
Error a	5	7.03	5.33	24.52	58.25
Species(S)	2	1324.78**	426.03**	794.11**	312.33**
T x S	2	0.78	64.75	37.33	61.00
Error b	20	3.71	26.32	23.09	31.27

Table A3.9 Mean square values for crop height (cm) at Portage in 1990.

Source	df	June 26	July 12	July 25	August 8
Block	3	3.20	37.89	67.49	72.72
Tillage(T)	1	5.51	88.16	0.38	66.66
Error a	3	6.74	22.50	98.71	23.22
Species(S)	2	883.21**	450.67**	64.54*	762.13*
T x S	2	2.55	50.17	28.13	136.79
Error b	12	1.35	26.03	14.06	113.35

Table A3.10 Mean square values for light interception by the crop canopy (%) at Carman in 1989.

Source	df	June 14	June 22	June 29	July 6	July 13	July 26
Block	5	28.04	279.95	133.68	249.18	141.31	354.81
Tillage(T)	1	0.93	273.90	0.23	0.01	0.05	21.93
Error a	5	32.44	88.89	53.66	76.54	42.15	91.81
Species(S)	2	92.21*	2132.07**	1186.05**	1064.91**	1155.55**	2178.57**
T x S	2	0.10	138.73	54.06	115.75	8.44	35.18
Error b	20	22.39	84.82	16.98	39.63	43.10	51.96

Table A3.11 Mean square values for light interception by the crop canopy (%) at Portage in 1989.

Source	df	June 15	June 28	July 5	July 18	August 2		
Block	3	31.66	113.57	9.96	0.16	8.00	2.25	58.06
Tillage(T)	1	12.76	248.33	164.33*	6.51	37.50*	27.73**	113.54
Error a	3	13.74	79.67	11.98	5.90	1.18	0.73	13.00
Species(S)	2	152.03**	535.65	649.54**	64.87**	95.86**	86.90**	650.14**
T x S	2	24.89	141.08	43.21	0.76	6.55	5.63	21.36
Error b	12	610.27	90.80	22.74	2.63	7.76	3.35	16.66

Table A3.12 Mean square values for light interception by the crop canopy (%) at Carman in 1990.

Source	df	June 18	July 4	July 17	July 31
Block	5	192.69	33.36	18.19	28.60
Tillage(T)	1	51.36	0.32	14.06	7.20
Error a	5	45.70	12.97	6.97	34.01
Species(S)	2	272.12	186.04**	144.33**	174.76**
T x S	2	13.76	7.99	7.78	20.24
Error b	20	114.82	19.20	11.35	18.12

Table A3.13 Mean square values for light interception by the crop canopy (%) at Portage in 1990.

Source	df	June 26	July 12	July 25
Block	3	15.69	23.35	7.50
Tillage(T)	1	141.14*	0.48	51.92
Error a	3	12.01	14.22	18.60
Species(S)	2	406.13**	26.46	272.78**
T x S	2	0.08	26.16	23.45
Error b	12	41.74	24.50	32.89

Table A3.14 Mean square values for grain yield (kg ha^{-1}).

Source	df	Carman		df	Portage	
		1989	1990		1989	1990
Block	5	1032939	131294	3	366397	280654
Tillage(T)	1	131769	7685	1	62424	12650
Error a	5	129036	99139	3	118020	173500
Species(S)	2	16528	13346577**	2	549738**	6457315**
T x S	2	69312	232127	2	139236	39254
Error b	20	121975	76037	12	437741	88887

Table A3.15 Mean square values for pods or spikes per m^2.

Source	df	Carman		df	Portage	
		1989	1990		1989	1990
Block	5	143860	313568	3	5758920	1420038
Tillage(T)	1	1317139	6779	1	594720	162855
Error a	5	380012	744660	3	907157	668919
Species(S)	2	91021027**	108376814**	2	169327404**	79679251**
T x S	2	1499721*	957	2	403737	338842
Error b	20	326260	548222	12	2739285	1068802

Table A3.16 Mean square values for seeds per pod or spike.

Source	df	Carman 1989	Carman 1990	df	Portage 1989	Portage 1990
Block	5	42.03	0.32	3	3.23	0.84
Tillage(T)	1	32.87	0.12	1	0.84	0.61
Error a	5	24.75	0.82	3	0.11	8.16
Species(S)	2	1161.20**	725.68**	2	383.64**	365.39**
T x S	2	9.30	0.63	2	1.05	0.40
Error b	20	30.72	1.67	12	7.25	5.41

Table A3.17 Mean square values for seed weight (mg).

Source	df	Carman 1989	Carman 1990	d	Portage 1989	Portage 1990
Block	5	28.63	6.32	3	0.64	4.30
Tillage(T)	1	0.85	29.44	1	4.40	4.24
Error a	5	3.42	11.36	3	12.81	5.03
Species(S)	2	66478.28**	83940.62**	2	60699.74**	63351.13**
T x S	2	7.22	37.90*	2	6.69	3.62
Error b	20	7.28	9.77	12	6.14	5.77

Table A3.18 Mean square values for hectolitre weight (kg hl^{-1}).

Source	df	Carman 1989	Carman 1990	df	Portage 1989	Portage 1990
Block	5	2.36	12.89	3	1.69	0.61
Tillage(T)	1	0.75	0.44	1	1.40	1.35
Error a	5	0.56	7.28	3	0.26	0.42
Species(S)	2	753.60**	964.39**	2	399.22**	254.42**
T x S	2	0.09	0.47	2	0.80	0.27
Error b	20	1.30	8.65	12	0.75	0.41

Table A3.19 Mean square values for harvest index.

Source	df	Carman 1989	Carman 1990	df	Portage 1989	Portage 1990
Block	5	0.00024	0.00760	3	0.00016	0.00359
Tillage(T)	1	0.00005	0.00368	1	0.00002	0.00186
Error a	5	0.00067	0.00199	3	0.00165	0.00229
Species(S)	2	0.04672**	0.01314*	2	0.00811	0.03824*
T x S	2	0.00271	0.00240	2	0.00041	0.00428
Error b	20	0.00139	0.00276	12	0.00330	0.00648

Table A3.20 Mean square values for protein content (% dry basis).

Source	df	Carman 1989	Carman 1990	df	Portage 1989	Portage 1990
Block	5	1.65	1.06	3	0.67	0.61
Tillage(T)	1	0.23	0.72	1	1.04	1.35
Error a	5	0.20	0.15	3	0.54	0.42
Species(S)	2	635.11**	332.98**	2	384.26**	254.42**
T x S	2	0.44	0.11	2	0.21	0.27
Error b	20	0.59	0.33	12	0.81	0.41

Table A3.21 Mean square values for protein yield (kg ha^{-1}).

Source	df	Carman 1989	Carman 1990	df	Portage 1989	Portage 1990
Block	5	3301.72	12383.16	3	8256.83	14015.37
Tillage(T)	1	3188.75	0.02	1	2421.49	171.02
Error a	5	4724.66	4497.79	3	9476.41	9518.07
Species(S)	2	249300.86**	541924.95**	2	716180.85**	383057.79**
T x S	2	2237.09	11402.06	2	6759.84	3395.92
Error b	20	3706.71	4774.91	12	17469.93	3956.92

Table A3.22 Mean square values for canola quality.

Source	df	Carman 1989	Carman 1990	df	Portage 1989	Portage 1990
Oil Content (% dry basis)						
Block	5	0.89	1.64	3	0.15	2.27
Tillage(T)	1	1.33*	0.01	1	0.08	0.01
Error a	5	0.15	1.21	3	0.05	0.19
Oil Yield (kg ha-1)						
Block	5	20241.99	30092.36	3	4075.82	563.17
Tillage(T)	1	20324.31	4728.98	1	4015.56	18554.02
Error a	5	6179.38	12557.58	3	25492.10	21608.45
Chlorophyll (ppm)						
Block	5	51.35	28.92	3	28.36	0.49
Tillage(T)	1	11.21	1.92	1	102.96	10.81
Error a	5	32.22	15.64	3	13.07	1.29

APPENDIX 4

Analysis of Variance - Evapotranspiration

Table A4.1 Mean square values for seasonal cumulative evapotranspiration (mm) from May 19, 1989 at Carman.

Source	df	June 1	June 14	June 29	July 6	July 13
Block	5	17.02	21.17	82.59	105.46	192.36
Tillage(T)	1	18.09	60.06	85.13	556.45	3.47
Error a	5	5.86	69.96	159.24	220.73	160.54
Species(S)	2	40.39	158.66*	27.98	349.49	329.27
T x S	2	4.80	23.73	0.44	64.70	76.46
Error b	20	22.36	42.86	125.61	105.83	186.92

Source	df	July 26	Harvest[1]	df	August 8[2]
Block	5	1138.55	2600.97	5	2932.95
Tillage(T)	1	673.80	2.83	1	102.31
Error a	5	184.09	44.52	5	244.88
Species(S)	2	1619.64**	4603.88**	1	6604.09**
T x S	2	16.70	2418.25*	1	4606.83**
Error b	20	176.89	497.86	10	405.13

[1]Harvest: July 26, field pea; August 8, wheat and canola.
[2]Canola and wheat only.

Table A4.2 Mean square values for seasonal cumulative evapotranspiration (mm) from May 31, 1989 at Portage.

Source	df	June 15	June 28	July 5	July 11
Block	3	30.39	145.36	201.25	103.52
Tillage(T)	1	42.41	78.37	3.56	73.89
Error a	3	11.63	125.01	131.33	98.85
Species(S)	2	333.60	81.66	8.09	47.98
T x S	2	153.15	275.44	355.91*	363.44*
Error b	12	257.85	78.92	75.84	58.45

Source	df	July 18	August 2	August 22
Block	3	213.95	252.14	146.24
Tillage(T)	1	27.68	10.06	235.83
Error a	3	94.42	54.58	91.31
Species(S)	2	0.86	36.30	209.17
T x S	2	274.14*	154.49	313.87*
Error b	12	61.73	69.71	60.31

Table A4.3 Mean square values for seasonal cumulative evapotranspiration (mm) from May 19, 1990, at Carman.

Source	df	June 4	June 18	df	July 4
Block	4	143.31	409.75	5	612.54
Tillage(T)	1	3034.28*	4216.92*	1	2890.73
Error a	4	163.87	536.85	5	682.29
Species(S)	2	164.73	86.14	2	23.24
T x S	2	24.92	7.33	2	366.69
Error b	16	60.35	131.89	20	278.52

Source	df	July 17	August 2	Harvest[1]
Block	5	1187.79	517.74	410.18
Tillage(T)	1	7352.36*	6136.24*	7721.28*
Error a	5	775.50	686.65	592.86
Species(S)	2	876.98	306.27	1775.27**
T x S	2	463.21	99.90	111.22
Error b	20	479.99	208.15	172.79

[1]Harvest: July 31, field pea; August 17, canola; August 21, wheat.

Table A4.4 Mean square values for seasonal cumulative evapotranspiration (mm) from May 31, 1990, Portage.

Source	df	June 26	July 12	July 25	August 8	Harvest[1]
Block	3	45.27	125.25	311.52	392.02	470.48
Tillage(T)	1	181.41*	60.99	0.66	29.91	95.44
Error a	3	15.49	27.13	388.22	102.22	227.92
Species(S)	2	42.32	24.90	131.98	444.14*	826.93**
T x S	2	3.43	12.19	97.15	54.03	21.20
Error b	12	16.46	39.30	88.09	78.63	49.60

[1]Harvest: August 20, canola; August 29, wheat; August 30, pea.

APPENDIX 5

Analysis of Variance - Combined Site Analysis Model

Table A5.1 Combined analysis model used for analysis of variance.

Source	Degrees of Freedom[1]	
Tillage	(t-1)	1
Block	(r-1)	5
Error a	(r-1)(t-1)	5
Species	(S-1)	2
Tillage*Species	(S-1)(t-1)	2
Error b	(r-1)(S-1) + (r-1)(S-1)(t-1)	20
Site	(s-1)	3
Site*Tillage	(s-1)(t-1)	3
Site*Species	(s-1)(S-1)	6
Site*Tillage*Species	(s-1)(t-1)(S-1)	6
Error c	(s-1)(r-1) + (s-1)(r-1)(t-1)(S-1)	66
TOTAL		119

[1] where s=4, r=6, t=2, and S=3.