EFFECT OF NITROGEN APPLICATION ON WINTER WHEAT UNDER ZERO TILLAGE AND SPRING WHEAT UNDER ZERO AND CONVENTIONAL TILLAGE

BY

BRANDON JAMES GREEN

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

MASTER OF SCIENCE

Department of Soil Science
University of Manitoba
Winnipeg, Manitoba

ISBN 0-315-63389-1

EFFECT OF NITROGEN APPLICATION ON WINTER WHEAT UNDER ZERO TILLAGE AND SPRING WHEAT UNDER ZERO AND CONVENTIONAL TILLAGE

BY

BRANDON JAMES GREEN

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

MASTER OF SCIENCE

ABSTRACT

A 2 year field study was conducted to evaluate the effect of N application on winter wheat under zero tillage, spring wheat under zero tillage and spring wheat under conventional tillage at 1 site in Manitoba. Grain yield, straw yield, protein content of the grain, N content of the straw, N uptake by grain plus straw, water use efficiency based on grain yield and water use efficiency based on yield of grain plus straw of each wheat-tillage regime were increased by N application. Recovery of applied-N by the grain plus straw of each wheat-tillage regime was decreased by increasing rates of N application. However, levelling-off of each yield parameter occurred as rates of N application increased.

Grain yield and water use efficiency based on grain yield were greatest for the winter wheat. Grain yield of spring wheat under zero tillage was higher than that for spring wheat under conventional tillage in the first crop year, but was similar in the second crop year. However, water use efficiency based on grain yield was higher for the spring wheat under zero tillage in both crop years. Protein content of the grain was the same for spring wheat under zero tillage and spring wheat under conventional tillage,

however, protein content of the grain of winter wheat was substantially lower than that for the spring wheats. Thus the winter wheat outyielded and used water more efficiently than the spring wheat. At comparable rates of applied-N, however, protein content of the grain of winter wheat was inferior to that of spring wheat. Zero tillage provided for a more efficient use of water and yields equal to or greater than with conventional tillage. Protein content of the grain was not affected by tillage.

ACKNOWLEDGEMENTS

I would like to thank my parents, George and Donna Green, for their years of love and patience and for their encouragement to enter university and make my career a productive one.

I would like to thank the staff of the University of Manitoba Department of Soil Science and in particular Professor A. O. Ridley for their teachings, the non-academic as well as the academic. I would also like to thank ERDAF for their funding of this project.

Finally and most importantly I would like to express my deepest gratitude to my wife, Lori, who helped me, encouraged me and loved me throughout my B.S.A. and M.Sc. degrees.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

Spring wheat is the traditional variety of wheat produced over most of the Canadian prairies. In the Chinook region of SW Saskatchewan and SE Alberta, however, winter wheat has commonly been grown (Fowler, 1983). These crops have traditionally been produced using conventional tillage practices. Relatively recent technological advances in machinery and herbicides, however, have made wheat production by zero tillage possible.

Winter wheat has been reported to substantially outyield spring wheat and to use water more efficiently than spring wheat, although the protein content of the grain of winter wheat has also been reported to be much lower than that for spring wheat (Fowler, 1983). Most of the prairies experience winter temperatures too severe for the survival of winter wheat under conventional tillage. With a zero tillage cropping system stubble of the previous crop is left standing, thus trapping snow. Snow cover has been found to moderate soil temperature during the winter, by forming an insulating barrier (Gusta et al., 1983). Winter wheat has been found to be a viable crop over a much greater portion of the prairies, when using zero tillage (Fowler, 1983).

The snow trapped by standing stubble has also been found to increase the spring soil moisture content (Staple et al., 1960; Smika and Whitfield, 1966; Aase and Siddoway, 1980). Furthermore, standing stubble has been reported to decrease the evaporative loss of soil moisture prior to crop canopy development in the spring (Brun, 1985). On the Canadian prairies this conservation of soil moisture is usually conducive to increased crop growth and yield. Zero tillage crop production has also proved to be an effective means of reducing wind and water erosion, thereby conserving the soil. However, yield comparisons between crops under zero and conventional tillage have not provided consistent results.

An understanding of the response to rate of N application by a crop is essential for determining both crop potential and crop management. The response to applied-N and the effect of soil moisture on this response by winter and spring wheat under conventional tillage, are relatively well documented. However, winter wheat and crop production by zero tillage are relatively new in Manitoba and most of Manitoba is generally less arid than those areas where much of the research has been conducted. Therefore, little is known on how winter wheat compares with spring wheat and degree to which moisture conservation and zero tillage will affect wheat yield, quality and water use efficiency, on the eastern prairies.

This project was initiated to study and compare the response to rate of N application by winter wheat under zero tillage and spring wheat under zero and conventional tillage, on the eastern Canadian prairies. The data reported within is part of a larger study consisting of two sites over three years.

2. LITERATURE REVIEW

2.1 Water Supply, Moisture Stress and Wheat Growth.

"Water makes up more than half of all living tissue and more than 90 percent of most plant tissues."[1] However, most of the water that enters the plant is subsequently transpired, and in effect the plant acts as an intermediary in the dynamic movement of water between soil (source) and atmosphere (sink) (Gardner, 1960). The movement of water between soil and atmosphere, via plants, is known as transpiration and the rate at which water vapour diffuses into the atmosphere is known as the transpiration rate. Transpiration rate is dependent upon the magnitude of the sink or evaporative demand, the ability of the soil to act as the source of water, and the subsequent plant response (Tanner, 1957).

Transpiration rate is directly proportional to evaporative demand, and evaporative demand is directly proportional to the incoming solar radiation (Russell, 1973). The evaporative demand is defined by humidity and wind speed such that as humidity and windspeed increase

[1] Raven, P. H., Evert, R. F. and Curtis, H. 1976. Biology of Plants, second edition, p. 515. Worth Publishers, Inc., New York, New York.

the transpiration rate decreases and increases, respectively. Soil water content also affects transpiration rate. As soil water content decreases, the plant begins to close its stomata to maintain relative turgidity. If soil water content continues to decrease, however, a point is reached where soil water flux to the plant can not meet the evaporative demand, and the plant wilts (Hillel, 1971).

Intensity, duration and timing of moisture stress affect wheat growth and yield parameters. Dubetz (1961) grew wheat on loam and loamy sand soils re-wetted to field capacity at 3/4, 1/2 and 1/4 of field capacity, and found grain and straw yields and N uptake decreased as the moisture stress regime became greater. Campbell and Davidson (1979) found the grain yield of wheat remained unchanged when moisture stress applied between tillering and last leaf visible growth stages was increased (0 to -1, -15 and -40 atm). However, when moisture stress was applied between last leaf visible and anthesis growth stages, grain yield decreased as moisture stress increased. Spratt and Gasser (1970) allowed wheat to wilt severely during the tillering, stem extension and heading growth stages, and not at all. Grain and straw yields and N uptakes by grain and straw were highest when no stress was applied. Grain yield was least affected when stress was applied at tillering and most affected when stress was applied at stem extension.

Straw yield and nitrogen uptake by the grain were least affected when stress was applied at heading and most affected when stress was applied at stem extension. Nitrogen uptake by the straw was decreased least when stress was applied at heading and most when applied at tillering. Campbell et al. (1981) grew wheat on a loam soil maintained at -0.3 atm soil moisture from tillering to maturity, and at -15 and -40 atm from tillering, booting and flowering growth stages to maturity. At 174 kg applied-N ha^{-1}, the highest grain yield and lowest protein content of grain occurred when the soil was maintained at low moisture stress (-0.3 atm). Otherwise, grain yield decreased and protein content increased as stress was applied at flowering, tillering and booting stages, respectively. Furthermore, grain yield decreased and protein content increased as moisture stress increased from -15 to -40 atm.

Although the physiological explanation of these results is beyond this discussion, attention can be drawn to the basic plant yield responses. Firstly, yield and N uptake by grain and straw decrease, and N content of grain and straw increase as moisture stress is increased, regardless of plant growth stage. Secondly, the flowering stage of wheat development appears to be the most critical growth stage with respect to moisture stress. Yield and N uptake were lowest and protein content highest when moisture stress was applied at, or just prior to, the flowering growth stage. The results of Hobbs and Krogman (1967) and Campbell et al. (1977a) help explain this phenomenon. Their work showed that evaporative demand and the daily rate of water use by wheat are greatest at approximately the flowering stage of growth. Therefore, soil moisture deficiency during this period produces greater stress on the plant than when applied at earlier or later growth stages.

Yield of grain is most often the main measure of crop productivity. To quantitatively compare crop productivity and the effect of management practices on crop productivity, under the infinite number of soil-plant-air moisture regimes, the measure 'water use efficiency' can be used. deJong and Rennie (1969) reported water use efficiency as shown by the equation:

$$\text{Water use efficiency} = \text{Yield} / (\text{SSM} + \text{P} - \text{HSM})$$

where yield is yield of grain, SSM is spring soil moisture content, P is growing season precipitation, HSM is harvest soil moisture content, and (SSM + P - HSM) is consumptive water use. In a similar equation, Viets (1962) used yield of grain plus straw for the yield term and calculated evaporative demand in place of consumptive water use. These equations also indicate that water use efficiency can be increased by those factors that increase crop yield and/or decrease consumptive water use and/or increase spring soil moisture content.

2.1.1 Effect of zero tillage on stored soil moisture and wheat growth.

Soil moisture stored during the non-growing season is of major importance to crop growth on the prairies. Long-term (1931 to 1960) climatic data indicates that most prairie cropland experiences, to some degree, a seasonal (May to September) water deficit (Baier, 1976). Shaykewich (1974) determined that all of southern Manitoba experienced, to some degree, a soil water deficit by August 13th (assuming soil moisture at field capacity, approximately 10 cm of stored available water, at the beginning of the growing season). Therefore, unless fall precipitation was high, crop yields would be expected to increase with increased over-winter storage of soil moisture. In the central and northern Great Plains of the United States this has been shown to occur. Holt et al. (1964) found the grain yield of corn in western Minnesota and eastern South Dakota increased with over-winter storage of soil moisture. Smika and Whitfield (1966) found the same trend for winter wheat and grain sorghum at North Platte, Nebraska. Young et al.

(1967) amassed data from 64 sites of spring wheat and 2 sites of barley located across North Dakota and found a highly significant correlation ($r = 0.59^{**}$) existed between grain yield and stored available soil moisture at seeding, to 122 cm depth or a dry zone. Similarly, Kachanoski et al. (1985) found grain yield of spring wheat increased with increased spring soil moisture content (mean of 6 Saskatchewan sites).

Standing stubble has been shown to be an effective means of trapping snow and increasing the over-winter storage of soil moisture at several locations across the northern Great Plains of North America (Staple et al., 1960; Smika and Whitfield, 1966; Schneider, 1979; Aase and Siddoway, 1980; Rennie et al., 1983; Campbell et al., 1984; Malhi et al., 1984; Rennie et al., 1984; Campbell et al., 1985). One to 5 cm more water was stored by standing stubble treatments than by non-stubble treatments, depending on soil and climatic factors. Standing stubble has also been found to decrease the evaporative loss of soil moisture prior to crop canopy development in the spring, by reducing wind speed near the soil surface (Aase and Siddoway, 1980; Brun, 1985). The soil moisture advantage of zero-tilled land can last well into the growing season. Near Sydney, Montana, Aase and Siddoway (1980) found standing stubble treatments retained 1 to 3 cm more soil moisture to the 180 cm depth than the bare treatment, throughout the growing season. Gauer et al. (1982) near Homewood, Manitoba, found a higher soil moisture content (to the 5 cm depth) with zero tillage than with conventional tillage. This soil moisture difference lasted until mid-July.

Prairie soils usually experience a soil water deficit by late summer. Although soil moisture conservation is greater with standing stubble and crop yields usually increase with increased soil moisture in the spring, zero-tilled wheat has not consistently outyield conventionally-tilled wheat. Bradley and Donaghy (1977) reported that spring wheat under conventional tillage outyielded spring wheat under zero tillage at 2 sites near Hartney and Hargrave, Manitoba, whereas spring wheat under zero tillage outyielded spring wheat under conventional tillage at 1 site near Virden. Nowatzki (1980) reported comparing zero-tilled spring wheat with spring wheat on land that had been chisel plowed or plowed in the fall, at Langdon, North Dakota. In 1977, the fall chisel plowed wheat slightly outyielded the zero-tilled wheat which slightly outyielded the fall plowed wheat. In 1978, however, the zero-tilled wheat yielded least and significantly less than the fall plowed wheat. In 1979, the zero-tilled wheat slightly outyielded the fall chisel plowed wheat but was significantly less than the fall plowed wheat. Jan and Bowren (1984) reported comparing spring wheat under zero and conventional tillage at 0, 56, 112, and 168 kg applied-N ha^{-1} for 4 years near Melfort, Saskatchewan. They found mean grain yield of spring wheat under conventional tillage was substantially higher than that for zero tillage, at each rate of applied-N. Toly (1984) reported on 3 years of spring wheat-tillage study near Stavely, Alberta. In 1981 the growing season precipitation was 267 mm. Neepawa spring wheat under minimum tillage yielded 2805 kg ha^{-1} whereas that under zero tillage yielded only 2482 kg ha^{-1}. Yields of wheat were equal in 1982 (1452 kg ha^{-1}) with a growing-season precipitation of 102 mm. In 1983 the growing-season precipitation was 114 mm and the minimum tilled wheat (2020 kg ha^{-1}) slightly outyielded the zero-tilled wheat (1954 kg ha^{-1}). Deibert et al. (1986) and Deibert et al. (1985) reported similar studies comparing spring wheat under zero tillage, spring plowing, and spring cultivation at Williston and Minot, North Dakota, respectively. In both studies (Williston lasting for 3 years and Minot lasting for 4), no consistent yield difference between tillage systems was observed. Similar results were reported by Lindwall et al. (1984) for 5 years of study at 6 sites in southern Alberta. At Casselton, North Dakota, Spilde and Deibert (1986) found spring wheat under zero tillage significantly outyielded spring wheat under conventional tillage in 1980. However, in 1981 and 1982 there was no significant difference between tillage systems. The inability of zero-tilled wheat to consistently outyield conventionally tilled wheat is evidence that wheat yields are influenced by several factors. Although it is beyond this discussion to investigate all the parameters that affect wheat yield, some of those which are pertinent to this discussion need to be addressed.

Soil temperature in the spring has been found to be cooler with zero tillage than with conventional tillage (Evenson and Olson, 1970; Gauer et al., 1982; Gupta et al., 1983). Midseason dry matter yield of wheat; nutrient uptake by wheat; and nutrient content of wheat are reduced by cool soil temperature (Evenson, 1970; Boatwright et al., 1976). Jan and Bowren (1984) compared spring wheat under zero tillage with that under conventional tillage near Melfort, Saskatchewan, and found grain yields (mean of four years of study) of spring wheat under conventional tillage surpassed those of spring wheat under zero tillage, at all rates of applied-N. The zero-tilled soil was found to have a lower mean temperature (by 2 to 3 degrees Celsius) than conventional tilled soil for several weeks in the spring. The authors considered this the reason for the lower yields with zero tillage.

The effect of stored soil moisture on yield can be modified by growing season precipitation. In western Minnesota and eastern South Dakota, Holt et al. (1964) found above-average rainfall during the critical growth period minimized the effect of stored soil moisture on grain yield of corn. Therefore, if this occurred while comparing zero-tilled spring wheat with conventionally tilled spring wheat, greater yield from zero-tilled spring wheat could not be expected.

Excess soil moisture can also cause a reduction in yield rather than an increase. On a Regina clay soil near Regina, Saskatchewan, Rennie et al. (1983) found the grain yield of spring wheat increased with increased stored soil moisture up to 58 cm per 130 cm depth of soil, and then decreased as the stored soil moisture continued to increase. Thus, the conservation of moisture could be detrimental to crop yield if levels of precipitation push the soil moisture levels so high that an anaerobic soil environment is created. However, this is unlikely on most Prairie soils except for the heavy-textured lacustrine clays or soils with impeded drainage in areas of high precipitation.

The data of Donaghy (1973) suggested that low N supply could be a reason why spring wheat under zero tillage often yields less than spring wheat under conventional tillage. At two sites near Carman, Manitoba, he found the grain yield of spring wheat under conventional tillage was greatest at low rates of applied-N, whereas the grain yield of spring wheat under zero tillage was greatest at high rates of applied-N. In a review of literature on the subject, Harapiak et al. (1986) concluded that considerably more applied-N is lost from zero-tilled fields than from conventionally tilled fields, especially when broadcast-applied and especially when the N source is urea. Spilde and Deibert (1986) measured soil NO_3-N levels to 60 and 120 cm depths after zero and conventionally tilled crops. They found greater NO_3-N with conventional tillage at both depths in both years of study and attributed this to reduced mineralization under newly zero-tilled land. Therefore, Donaghy's spring wheat under zero tillage was likely more N deficient than the spring wheat under conventional tillage at low rates of applied-N, and thus the spring wheat under conventional tillage outyielded the spring wheat under zero tillage. Conversely, at high rates of applied-N where N supply did not limit yield, the soil moisture advantage of zero tillage provided for greater yields from zero-tilled spring wheat than from conventionally tilled spring wheat. This suggested that zero-tilled spring wheat requires greater amounts of applied-N to maximize its potential. It also suggested the results of Nowatzki (1980), Lindwall et al. (1984), and Bradley and Donaghy (1977) might have been different had the comparisons been made at a higher rate of applied-N.

Winter wheat may benefit more than spring wheat from the greater soil moisture conservation with zero tillage. Researchers in Saskatchewan (Fowler, 1983) and in Manitoba (Rourke and Stobbe, 1984; Rourke et al., 1983) have reported that winter wheat outyields spring wheat. Winter wheat is actively growing earlier in the spring than spring wheat and this is considered by some researchers to allow for more timely use of soil moisture during the spring (Brown and Black, 1983; Fowler, 1983; Rourke and Stobbe, 1984; Rourke et al., 1983). In Saskatchewan, Gross et al. (1987) found that winter wheat rooted deeper and more extensively than spring wheat up until the flowering stage of spring wheat development; at which point in time spring wheat caught up with winter wheat. However, by the flowering stage of spring wheat growth the soil had lost much of its water reserves. Thus, because of its early growth habit winter wheat is a more efficient user of spring soil moisture.

2.2 Nitrogen Supply and Wheat Growth.

Nitrogen is naturally added to the soil by biological N_2 fixation and by precipitation containing combined N.

Soil loses N by volatilization, leeching, and biological and chemical denitrification (Stevenson, 1982). Soil N is more plant available or less plant available according to the dominance of mineralization or immobilization, respectively (Jannson and Persson, 1982). Nitrogen is found in the soil in inorganic and organic forms. Nitrogen enters the plant mainly as NO_3-N because chemical and biological processes occurring in the soil make it the most prevalent ionic species of N in well-drained root zones. Many crops, however, also readily absorb NH_4^+-N when this ionic species is dominant. Since the attraction between NO_3^- and soil colloids is negligible, NO_3^- is readily carried within the mass flow of water to plant roots. Conversely, the attraction between NH_4^+ and soil colloids is substantial and thus NH_4^+ movement by mass flow is minimal. However, when potential uptake exceeds N supply from mass flow, the concentration of N at the root surface decreases and diffusion of N also occurs (Olson and Kurtz, 1982).

Nitrogen is an essential nutrient for plant growth. The plant requires N: as a component of the chlorophyll molecule; as a component of amino acids and thus proteins; to utilize carbohydrates; as a component of enzymes; to stimulate root development and activity; and, to assist in the uptake of other nutrients (Olson and Kurtz, 1982). Plant growth and N uptake are integrally related. Campbell et al. (1977b) showed that the accumulation of N in the wheat plant is almost directly proportional to dry matter production. Spratt and Gasser (1970) monitored dry matter production and N uptake by wheat over the course of the growing season. Whether drought was imposed during tillering, stem extension, heading, or not at all, N uptake increased correspondingly with increased dry matter production.

Plant growth and N uptake are functions of N supply. In a growth chamber study, Davidson and Campbell (1984) showed that increased N application increased the dry matter accumulation and N-uptake by wheat, throughout the growing season. Grain and straw yields increase with increased N supply until maximum response is achieved, and then decrease with greater N supply (Russell, 1973). With data collected from 118 sites throughout Nebraska over seven years, Olson et al. (1976) showed that the grain yield of winter wheat was increased with increased residual soil NO_3-N and applied-N. Similar results were reported for Neepawa spring wheat in southern Manitoba by Alkier et al. (1972). They showed grain yield was increased with increased residual soil NO_3-N and applied-N until maximum response was achieved. Alternatively, protein content of the grain continued to increase with increased N supply, although the initial 34 kg N ha^{-1} that was applied decreased protein content when wheat was grown on low residual NO_3-N soils. The drop in protein content at low N rates of applied-N was accompanied by a large yield increase, and thus it was attributed to the biological dilution of plant protein.

2.2.1 Applied-N effects on wheat.

Considerable field research has been done on the effect of applied-N on wheat. Grain yield of wheat increases with increased rates of applied-N, until maximum response is achieved. Alkier et al. (1972) studied the effect of N application rate on Neepawa spring wheat under conventional tillage, on non-fallowed land in southern Manitoba. They found grain yield (mean of five site-years) was increased by N application to the maximum rate applied (403 kg N ha^{-1}). Racz (1974) reported similar results for conventionally-tilled spring wheat (c. Neepawa) on non-fallowed land in southern Manitoba. He found grain yield (mean of 12 site-years) was increased by N fertilization up to the maximum rate applied, 269 kg N ha^{-1}. At two sites near Carman, Manitoba, Donaghy (1973) found grain yield of spring wheat under zero tillage was increased by the application of N up to 202 kg N ha^{-1}, but decreased slightly when 269 kg N ha^{-1} was applied. Field trials of zero-tilled winter wheat in the Parkland region of Saskatchewan found grain yield increased with increased available-N up to the maximum, 250 kg ha^{-1}, in years of normal or below normal precipitation (Fowler, 1983). At Melfort, Saskatchewan, Jan and Bowren (1984) found the grain yield of winter wheat under zero tillage (mean of five years of study) was increased by applied-N up to the maximum rate of application, 168 kg N ha^{-1}. Near Minnedosa, Manitoba, Grant (1982) found the grain yield of zero-tilled winter wheat was increased by N application up to 240 kg N ha^{-1}, during both years of study.

The protein content (%) of wheat grain is affected by N fertilization such that protein content is generally increased by increased N application. Alkier et al. (1972) measured protein content of the grain of conventionally-tilled spring wheat on non-fallowed land in southern Manitoba. They found protein content (mean of five site-years of study) remained relatively constant with rates of applied-N up to 67 kg ha^{-1}. However, protein content then increased with increased rates of application greater than 67 kg ha^{-1}, up to the maximum rate (403 kg ha^{-1}). Racz (1974) reported similar results for 12 site-years of conventionally-tilled Neepawa spring wheat on non-fallowed land in southern Manitoba. Protein content of the grain remained relatively constant with rates of applied-N up to 67 kg ha^{-1} and then increased as application rate was increased up to the maximum rate (269 kg ha^{-1}). These authors attributed the lack of response to the initial applications of N (with respect to protein content) to the influence of large yield increases, i.e. the biological dilution of plant protein. Donaghy (1973) reported similar results for spring wheat under zero tillage at one site near Carman, Manitoba. At the second site, however, the biological dilution was not apparent. Field trials of zero-tilled winter wheat in the Parkland region of Saskatchewan found mean protein content of the grain increased with increased available-N up to 300 kg N ha^{-1} in years of normal precipitation and up to 420 kg N ha^{-1} in years of below normal precipitation (Fowler, 1983). At Melfort, Saskatchewan, Jan and Bowren (1984) found the protein content of the grain of winter wheat under zero tillage (mean of five years of study) was increased by N application up to the maximum rate applied (168 kg ha^{-1}). Grant (1982) found protein content of the grain of winter wheat under zero tillage was initially constant (due to the biological dilution of plant protein) but then increased with increased rate of N application up to the maximum (240 and 300 kg N ha^{-1} during the 1979-80 and 1980-81 crop years, respectively) near Minnedosa, Manitoba.

Yield and N content (%) of straw and N uptake (kg N ha^{-1}) by the above-ground portion of wheat are also affected by N fertilization. Yield and N content of straw and N uptake are increased by N application, although N content of straw is often relatively constant with the initial increments of N application due to biological dilution of plant protein. McNeal et al. (1971) compared five varieties of spring wheat under conventional tillage at five rates of applied-N near Belgrade, Montana. They found mean straw yield and total N uptake were increased with N application up to the maximum rate applied (89.7 kg ha^{-1}). They also found the mean N content of straw remained relatively constant up to 44.8 kg applied-N ha^{-1}, and then was increased with increased N application up to the maximum rate applied. Ramig and Rhoades (1963) compared conventionally tilled winter wheat at four rates of applied-N and four levels of preplanting soil moisture for three years near North Platte, Nebraska. They found straw yield and total N uptake were increased by increased N application up to the maximum rate (88 kg ha^{-1}) at each level of preplanting available soil moisture. They also found N content of straw remained relatively constant with rates of applied-N up to 44 kg ha^{-1} and then increased with 88 kg applied-N ha^{-1}, when preplanting available soil moisture was greater than zero. When preplanting available soil moisture was zero, N content of straw was increased by each rate of applied-N up to the maximum.

Recovery of applied-N (%) by the above ground portion of wheat, is also affected by N fertilization. However, unlike previously discussed parameters, recovery of applied-N generally decreases with increased rates of applied-N. Near Swift Current, Saskatchewan, Campbell and Paul (1978) measured the effect of seven rates of applied-N (up to 164 kg ha^{-1}) and two moisture regimes (precipitation only, and precipitation plus supplemental irrigation) on spring wheat grown in lysimeters. They found recovery of applied-N by the above-ground portion of the crop was increased slightly with increased rates of applied-N up to 62 kg ha^{-1} for the precipitation only treatment, and up to 82 kg ha^{-1} for the irrigated treatment. With the precipitation only treatment, recovery decreased markedly with further applications of N. With the irrigated treatment, recovery was similar for the 125 kg applied-N ha^{-1} rate but markedly lower for the 164 kg applied-N ha^{-1} rate. Grant (1982) reported similar results for winter wheat under zero tillage near Minnedosa, Manitoba. Recovery of applied-N by grain plus straw was increased slightly with rates of applied-N up to 90 kg N ha^{-1}. Recovery then decreased as N application was increased up to the maximum rate applied (300 kg N ha^{-1}).

The water use efficiency of wheat generally increases with the increased application of N, if soil N is limiting. Campbell et al. (1977a) found the water use efficiency (based on yield of grain plus straw) of spring wheat grown in lysimeters with precipitation only, was increased with increased rates of applied-N up to 62 kg N ha^{-1}, and then remained constant up to the maximum applied (164 kg N ha^{-1}). With irrigation the water use efficiency increased with increased rates of applied-N up to 41 kg N ha^{-1}, and then remained constant up to the maximum rate of applied-N. Using data from the same study, Campbell et al. (1977b) found water use efficiency based on the yield of grain only, increased rapidly with increased rates of applied-N up to 41 kg N ha^{-1} and then remained constant with further applications, for the irrigation treatment. Conversely, water use efficiency based on yield of grain for the precipitation only treatment increased at a slower rate, not reaching the level attained by the wet treatment until 164 kg N ha^{-1} was applied. Working with winter wheat under conventional tillage near Bozeman, Montana, Brown (1971) found water use efficiency (based on grain yield) was increased from 7.3 to 11.4 kg ha^{-1} mm^{-1} by an initial application of 67 kg N ha^{-1}, but no further increase occurred when the application of 200 kg N ha^{-1} was made.

2.2.2 Nitrogen - water supply interactions.

The effects of N - water supply interactions on the yield parameters of wheat are relatively well understood.

In a recent review of literature on the subject, Henry et al. (1986) reported unpublished data by Henry in Saskatchewan which found grain yield of spring wheat was increased with increased rates of applied-N and applied-water (by irrigation). Maximum yield, however, was greater than the sum of the response to N plus the response to water. The difference was attributed to the interaction of N and water supply. Campbell et al. (1977a), Campbell et al. (1977b), and Campbell and Paul (1978) reported on a study conducted near Swift Current, Saskatchewan, where spring wheat grown in lysimeters on stubble land was subjected to seven rates of applied-N up to 164 kg ha^{-1}, and two moisture regimes (precipitation only, and precipitation plus supplemental irrigation). Under both moisture regimes, these authors found yield and protein content of grain; yield, N content and N uptake of grain plus straw; and, water use efficiency based on yield of grain (only) and grain plus straw were increased by N application. Recovery of applied-N (%) by grain plus straw, however, was generally decreased by increasing N application under both moisture regimes. They also found the response to applied-N was increased by increased moisture supply, for each parameter except N content. In this case the response to applied-N was decreased with increased water supply, thereby indicating the dilution of N content with a yield increase. In Manitoba, similar results were reported by Racz (1974) for Neepawa spring wheat under conventional tillage (mean of 12 site-years) on non-fallowed land with respect to grain yield, and by Grant et al. (1985) for Norstar winter wheat under zero tillage (near Minnedosa, Manitoba) with respect to yield and protein content of grain. Racz (1974), however, had found little or no effect of water supply on N response with respect to protein content of the grain.

The yield parameters of wheat are also affected by N - stored soil moisture interactions. Eck and Tucker (1968) collected data from 104 fertilizer trials on winter wheat in western Oklahoma. They found significant correlation between soil moisture at seeding and grain yield response to applied-N ($r = 0.244^{**}$) and a highly significant correlation between soil moisture in the spring and the grain yield response to applied-N ($r = 0.265^{**}$). Ramig and Rhoades (1963) reported on the effects of soil moisture level (0, 7.4, 15.0 and 20.6 cm to the 183 cm depth) at seeding and rate of applied-N (0, 22, 44 and 88 kg ha^{-1}) on winter wheat, mean of three years of study at North Platte, Nebraska. They found increased soil moisture at seeding increased the response to applied-N with respect to yield of grain and straw, N uptake by grain plus straw, and water use efficiency (based on grain yield). They also found increased soil moisture decreased the response to applied-N with respect to the N content of grain and straw. This was due to a dilution of N content by the increased yield and indicated the maximum rate of N applied was too low. Schneider (1979) determined the effect of level of over-winter stored soil moisture on the response to N by spring wheat under zero tillage. Zero, 25 and 50 kg N ha^{-1} was applied to 0, 18 and 36 cm high stubble treatments that contained 1.4, 2.4 and 4.7 cm (to the 120 cm depth), respectively, of stored soil moisture in the spring. He found increased soil moisture increased grain yield and decreased protein content of the grain, at each rate of applied-N. Campbell et al. (1984) and Campbell et al. (1985) reported results from successive years of a study (near Swift Current, Saskatchewan) investigating the effect of stubble height on the over-winter storage of moisture and the effect of the stored soil moisture on the response to applied-N by spring wheat under zero tillage. The 'tall' stubble treatment provided for greater over-winter storage of soil moisture than the 'short' stubble treatment, in both years of the study. The greater soil moisture of the 'tall' stubble treatment was considered responsible for the significantly greater response to applied-N, with respect to grain yield, on this treatment. In 1984, for example, the 'tall' stubble conserved 24 mm more available water to the 120 cm depth of soil than did the 'short' stubble. This added moisture helped provide for an average of 198 kg ha^{-1} more grain on the 'tall' stubble plots than on the 'short' stubble plots.

3. METHODS AND MATERIALS

The experiment was conducted on a Manitou clay loam soil, near Kaleida, Manitoba, during the 1984-85 and 1985-86 crop years. The soils were determined to be Orthic Black Chernozem developed on non-calcareous shale-clay glacial till (Ellis and Shafer, 1943). Field plots were established on the farm of Keith Forrest (SE 10-2-8W) in the first year and on the farm of George Henderson (NW 9-2-8W) in the second year.

3.1 Treatments.

Land was prepared as necessary to accommodate non-replicated main blocks of conventionally tilled spring wheat, zero tilled spring wheat and zero tilled winter wheat. All subplots received 25 kg P ha^{-1}, as 11-51-0, with the seed. This also provided 12 kg applied-N ha^{-1}. Further N, as 46-0-0, was surface-applied after seeding to create subplot treatments of 12, 60, 180 and 300 kg applied-N ha^{-1} for conventionally tilled spring wheat; and 12, 30, 60, 90, 120, 180, 240 and 300 kg applied-N ha^{-1} for zero tilled spring wheat and zero tilled winter wheat. Six replicates of randomized subplots were set out within each main block.

This design of randomized complete blocks within non-replicated main blocks was selected over a split-plot design because of the difficulty in providing environmental buffer zones between crop-tillage regime replicates.

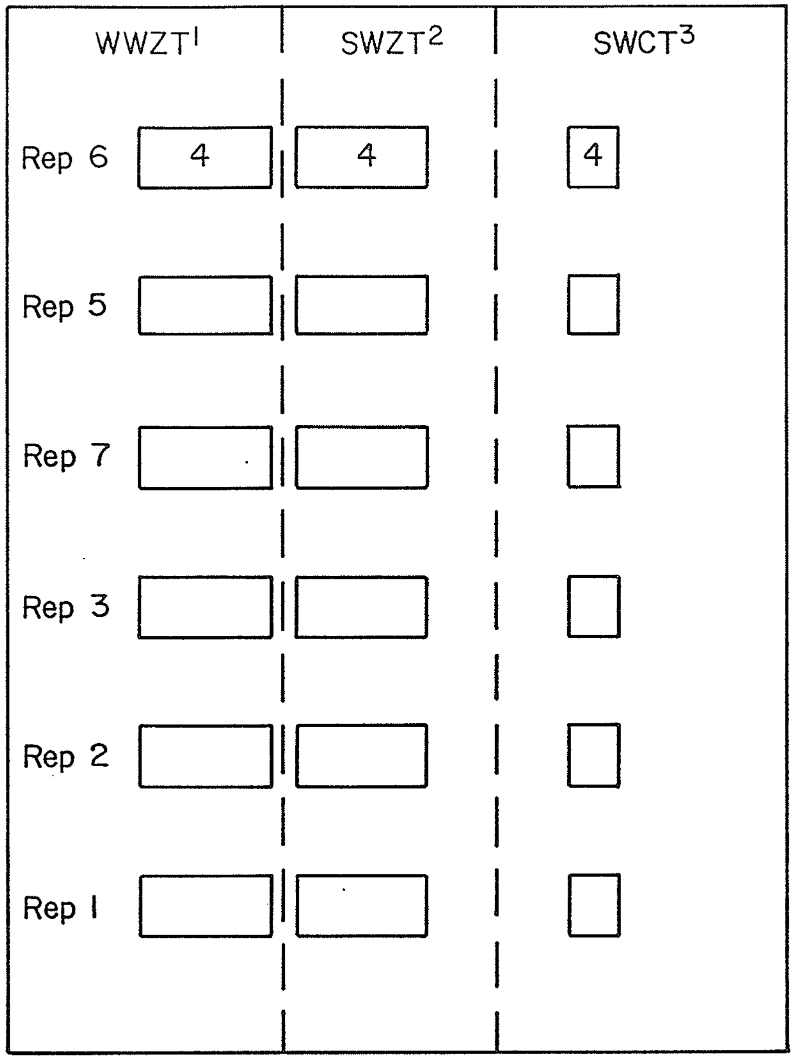
3.2 Land Preparation and Field Procedure.

The plot site was laid out on a field of barley stubble (approximately 20 cm high) in the late summer prior to each crop year (Figure 3.1). The zero tillage main blocks were harrowed to spread straw, and sprayed with 1.10 L ha^{-1} of 356 g L^{-1} Glyphosate plus 0.35 L ha^{-1} of non-ionic surfactant in 112 L ha^{-1} of water the day prior to seeding, to eliminate existing weeds.

The conventional tillage main block was tilled approximately 10 cm deep using a heavy duty cultivator with 30.5 cm shank spacing and 20.5 cm wide shovels, and harrowed, at approximately 6.5 km $hour^{-1}$, in early autumn. In spring it was tandem disced approximately 7 cm deep, and harrowed, at approximately 4.5 km $hour^{-1}$.

After the land in each main block had been appropriately prepared, six replicates of randomized subplots (2 m wide, ie. 1 drill width, by 10 m long) were

Figure 3.1. Plot site map.



1. Winter wheat under zero tillage.
2. Spring wheat under zero tillage.
3. Spring wheat under conventional tillage.
4. N rate subplots.

laid out. The replicates were positioned 15 m apart to facilitate drill manoeuvring. The area between and around replicates was sown to spring wheat and maintained under the appropriate tillage regime to provide for uniform snow entrapment and microclimate within each main block. Three metres of this area outside the perimeter of each replicate, however, was kept mown in 1985 and cultivated in 1986 to allow access for herbicide and fungicide spraying equipment, and plant and soil sampling. Sampling was performed a minimum of 2 m into the subplot to avoid microclimate affects from the access strip. Furthermore, the entire plot site was located at least 30 m and subplots at least 42 m from the edge of the field to avoid the influence of ditches, roadways and grassed borders; to facilitate snow trap; and, to avoid any non-uniformity of the soil fertility level within the plot site. Subplots within each main block were located at least 6 m from the edge of their main block to minimize the effect of adjacent main blocks on snow entrapment and wind speed.

Winter wheat (Triticum aestivum L. c. Norstar) was sown on September 7 in 1984 and on September 10 in 1985. Spring wheat (Triticum aestivum L. c. Neepawa) was sown on May 7 in 1985 and on May 21 in 1986. The seeding rate was 110 kg ha^{-1} and seed placement depth was approximately 3 cm. The drill used was a Versatile Noble Model 2200 hoe-press drill with 10 hoe-openers 19.6 cm apart. This drill was capable of zero and conventional tillage seeding.

Herbicides for weed control and the fungicide TILT for disease control were used as deemed necessary. In 1985, the winter wheat was sprayed with 0.138 L ha^{-1} of 500 g L^{-1} MCPA amine plus 0.058 L ha^{-1} of 400 g L^{-1} Dicamba on June 4 for broadleaf weed control. The spring wheat was sprayed with 0.243 L ha^{-1} of 500 g L^{-1} MCPA amine on June 12 for broadleaf weed control. The winter wheat was also sprayed with 0.5 L ha^{-1} of 250 g L^{-1} Tilt (registered trademark of Ciba-Giegy Canada Ltd.) on July 22 for disease control. In 1986, the winter wheat was sprayed with 0.138 L ha^{-1} of 500 g L^{-1} MCPA amine + 0.058 L ha^{-1} of 400 g L^{-1} Dicamba on May 19 for broadleaf weed control, and with 0.575 L ha^{-1} of Hoe-Grass II (230 g L^{-1} Diclofop Methyl + 80 g L^{-1} Bromoxynil ester; registered trademark of Hoechst Ag, Germany (West)) on June 4 for broadleaf and grassy weed control. The spring wheat was sprayed with 0.575 L ha^{-1} of Hoe-Grass II on June 4 for broadleaf and grassy weed control. The winter wheat was sprayed on June 16 and July 22, and the spring wheat sprayed on July 22 with 0.5 L ha^{-1} of 250 g L^{-1} Tilt for disease control. All herbicides and the fungicide were applied with 112 L ha^{-1} of water.

3.3 Plant Sampling and Analysis.

When the wheat reached maturity, 2 m of the centre 4 rows in each subplot (2 m in from the end of the subplot) was cut at ground level. The sheaves were bagged, air-dried and threshed using a stationary thresher. Grain and straw samples were weighed and calculated in kg ha^{-1}. Grain samples were tested for moisture and yields adjusted to a 13.5 % moisture content. Grain samples were ground and bagged for laboratory analysis. In 1985, straw samples from the 6 replicates of each treatment were bulked then ground and bagged. In 1986, straw samples from the 6 replicates were not bulked to facilitate statistical analysis.

Grain and straw samples were analyzed for total N using a modified automated micro-Kjeldahl procedure as described by Schuman et al. (1973). A 0.5 g portion of the ground plant material was placed in the digestion tube. An Itecator Special Kjeltab S 3,5 (digestion catalyst containing 3.5 g. K_2SO_4 + 0.0035 g Se) and 10 ml of H_2SO_4 were added. Samples were digested for 1 hour at approximately 400°C and then cooled for 20 minutes. An Itecator Kjeltec Auto 1030 Analyzer was used for N determination. The Auto Analyzer used a 50 % NaOH solution to convert the sample's N to NH_3 gas, collected the NH_3 gas in a 1 % boric acid solution as NH_4^+, and then titrated the

NH_4^+ using 0.1 N H_2SO_4. Percent N was then calculated according to Equation 3.1. The N content of grain was reported in percent protein and thus the percent N was multiplied by 5.7 to arrive at the percent protein.

[3.1]

$$\text{Percent N} = \frac{\text{ml of } H_2SO_4 \ * \ \text{normality of } H_2SO_4 \ * \ \text{atomic wt of N}}{\text{sample weight in mg}} * 100$$

Nitrogen uptake and recovery of applied-N by the above ground portion of the crop, were calculated according to Equation 3.2 and 3.3, respectively. To correct the recovery of applied-N calculation for the amount of N added to the control as P fertilizer (11-51-0), it was assumed that 50 % of this N was used by the crop (Grant et al., 1985).

[3.2]

$$\text{N uptake in kg ha}^{-1} = (\text{Grain yield in kg ha}^{-1} * (\text{\% N of grain} / 100)) + (\text{Straw yield in kg ha}^{-1} * (\text{\% N of straw} / 100))$$

[3.3]

$$\text{Recovery of applied-N in \%} = \frac{\text{N uptake in kg ha}^{-1}\text{ by the treatment} - (\text{N uptake in kg ha}^{-1}\text{ by the control} - (\text{N in kg ha}^{-1}\text{ from 11-51-0 in control} / 2))}{\text{Applied-N in kg ha}^{-1}\text{ for the treatment}} * 100$$

The literature contains many different labels for the measure of the efficiency by which the crop recovers or utilizes added-N, e.g. Paul and Myers (1971) used recovery of tagged nitrogen and Campbell et al. (1977b) used recovery of fertilizer N. Accordingly, the label recovery of applied-N will be used in this discussion.

3.4 Soil Sampling and Analysis.

Selected subplots within each main block were examined for soil moisture content (by gravimetric analysis) prior to spring wheat seeding and at harvest. Soil samples taken prior to seeding of both winter and spring wheat were characterized for pH, conductivity, organic matter, NO_3-N, P, K, and SO_4-S.

3.4.1 Soil moisture sampling, analysis and determination.

Soil samples were taken for selected treatments from 3 replicates only, because of the large number of plots involved. Treatments selected for soil sampling included: all N rates of the conventionally tilled spring wheat and the 12, 60, 90, 180 and 300 kg applied-N ha^{-1} treatments of zero tilled spring wheat and zero tilled winter wheat, in the second, fourth and sixth replicates. Samples were taken by hand at 0-15, 15-30, 30-60, 60-90 and 90-120 cm depths using a 10 cm diameter cup auger or dutch auger. Samples were immediately sealed in plastic bags, kept in the shade, and frozen within 48 hours. A subsample of this soil was used to determine moisture content according to Equation 3.4.

$$\text{Percent moisture} = \frac{\text{wet soil in g} - \text{oven dry soil in g}}{\text{oven dry soil in g}} * 100 \qquad [3.4]$$

Soil moisture was measured to the 60 cm depth in the first crop year and to the 120 cm depth in the second crop year. Pieces of shale mixed throughout the 60 to 120 cm depth inhibited the augering process in the first crop year.

Bulk density of the soil was measured during the first crop year (Table 3.1). All soil was carefully collected by augering from each soil depth (0-15, 15-30, 30-60, 60-90 and 90-120 cm). The hole diameter at 1 and 15 cm was measured using callipers and depths below 15 cm were considered to have a diameter equivalent to that at 15 cm. The volume was calculated for each depth and all the soil from each depth was oven dried and weighed. Bulk density of the soil at each depth was calculated according to Equation 3.5.

$$\text{Bulk density in gcm}^{-3} = \frac{\text{oven dry soil in g}}{\text{volume occupied by soil in cm}^{3}} \qquad [3.5]$$

Three replicates of bulk density measurements were performed and the results for each depth averaged.

The soil moisture content to 60 or 120 cm was calculated by summing the soil moisture content for each sampling depth. These had been calculated according to Equation 3.6.

Table 3.1. Bulk density (g cm^{-3}), and amount of moisture (mm) at field capacity (FC) (- 1/3 atm) and at the permanent wilting point (PWP) (- 15 atm), for the first year soil

Soil depth (cm)	Bulk density	Moisture at FC	Moisture at PWP
0 - 15	1.00	63	30
15 - 30	1.18	73	37
30 - 60	1.25	138	81
60 - 90	1.28	132	74
90 -120	1.38	66	37
0 - 60	----	274	148
0 -120	----	472	259

$$\text{Soil moisture content in mm} = \frac{\text{Bulk density of soil in g cm}^{-3}}{\text{Bulk density of water in g cm}^{-3}} * \frac{\text{Percent moisture of soil}}{100} * \text{Depth of soil in cm} * 10 \qquad [3.6]$$

The field capacity (- 1/3 atm) and permanent wilting point (- 15 atm) moisture levels (mm) were determined for the plot site soil, in the first crop year (Table 3.1).

Precipitation was monitored during the growing season using a Belfort Instrument Company Universal Rainguage. Consumptive water use was calculated according to Equation 3.7.

[3.7]

Consumptive water use in mm =

Soil moisture content in mm to 60 or 120 cm depth at seeding

+ precipitation in mm -

Soil moisture content in mm to 60 or 120 cm depth at harvest

Water use efficiency based on yield of grain only (WUE-G) and water use efficiency based on yield of grain plus straw (WUE-GS) were calculated according to Equation 3.8 and Equation 3.9, respectively.

$$\text{WUE-G in kg ha}^{-1}\text{ mm}^{-1} = \frac{\text{Grain yield in kg ha}^{-1}}{\text{Consumptive water use in mm}} \quad [3.8]$$

$$\text{WUE-GS in kg ha}^{-1}\text{ mm}^{-1} = \frac{\text{Yield of grain + straw in kg ha}^{-1}}{\text{Consumptive water use in mm}} \quad [3.9]$$

3.4.2 Characterization of soil pH, conductivity, organic matter, N, P, K and S.

Soil samples at depths of 0-15; 15-30; 30-60; 60-90; and 90-120 cm were taken from 3 replicates of the zero tilled winter wheat main block just prior to seeding. Three replicates of soil samples were also taken from the plot area assigned to spring wheat, just prior to seeding of that crop. All soil samples were placed immediately in plastic bags, kept in the shade and frozen within 48 hours. At a later date, the samples were thawed, air dried and ground to pass through a 2 mm sieve. Analysis for pH, conductivity, organic matter, extractable P and extractable K was performed on the 0-15 cm samples, only. Extractable NO_3-N and extractable SO_4-S analysis was performed on each sampling depth.

Soil pH was determined on a 1:1 (by weight) soil:water paste using a Fisher Model 825 MP pH meter with a standard glass-calomel combination electrode. Conductivity was measured on the same paste using a Bach-Simpson Ltd. Type CDM 2e Radiometer conductivity meter with a standard conductivity cell.

Organic matter was determined by a process similar to the Walkley and Black method described by Allison (1965). Ten ml of 1.0 N $K_2Cr_2O_2$ and then 20 ml of concentrated H_2SO_4 were added to 0.5 g of soil. This was allowed to react for 30 minutes. Distilled water was then added to produce 250 ml of solution. The unreacted chromic acid was then back-titrated with 0.5 N $FeSO_4$ using an automatic titrator. The percent organic carbon was calculated and converted to percent organic matter (% organic C x 1.7).

Soil NO_3-N was determined using a phenoldisulphonic acid method similar to that described by Bremner (1965). Fifty ml of extracting solution (0.02 M $CuSO_4$ + 0.06% Ag_2SO_4) was added to a flask containing 10 g of soil. This was shaken for 10 to 15 minutes. Contents of the flask were filtered through #1 filter paper and a 10 ml aliquot of the extract evaporated to dryness in an oven. When cool 1.0 ml of phenoldisulphonic acid was added to the residue and allowed to react for 10 minutes. The residue was transferred to a 50 ml volumetric flask by several washings. Concentrated NH_4OH was then added until a yellow colour developed. Nitrate content was then determined colourimetrically using a LKB Biochrom 4050 UV/Visible spectrophotometer set at 415 nm.

$NaHCO_3$-extractable P was determined using a modified Olsen and Dean (1965) method. One-half g of activated charcoal (washed to remove P) and 100 ml of 0.5 M $NaHCO_3$ (pH 8.5) were added to 5 g of soil. Samples were shaken for 30 minutes and filtered through #42 filter paper. A 10 ml aliquot of the extract was acidified using 1 drop of 2,4 dinitrophenol indicator and concentrated H_2SO_4. Two ml of a 4:1 acid molybdate-antimony solution (15.0 g of ammonium paramolybdate + 0.28 g of antimony potassium tartrate + 176.0 ml of H_2SO_4 + 1000 ml of distilled water) : ascorbic acid (2.5 g per 100 ml) solution was then added for colour development. An LKB Biochem 4050 UV/Visible spectrophotometer at 885 nm was used for colourimetric determination of P content.

Extractable K was determined using a modified Pratt (1965) method. Five g of soil was extracted with 100 ml of 1.0 N NH_4OAc (pH 7.0) for 1 hour. After filtering through #1 filter paper, 1.0 ml of 2500 ppm $LiNO_3$ solution and 8.0

ml of deionized water were added to 1.0 ml of extract. K content was determined using a Perkin-Elmer Model 303 atomic absorption spectrophotometer.

Sulphate-S was determined by a method similar to that described by Lazrus et al. (1966) and Hamm et al. (1973). Fifty ml of 0.001 M $CaCl_2$ was added to 25 g of soil. This was shaken for 30 minutes and filtered through #42 filter paper. The extract was passed through a cation exchange resin and reacted with $BaCl_2$ (pH 2.5-3.0). An exact amount of methylthymol blue was added to complex the Ba, and the pH raised to between 12.5 and 13.0 by the addition of 0.18 M NaOH. Since the methylthymol blue and $BaCl_2$ were initially equimolar, the amount of uncomplexed methylthymol blue measured at 460 nm depicted the amount of SO_4-S. A Technician Auto Analyzer II system was used to perform the analysis.

3.5 Statistical Analysis.

All statistical analysis was conducted under release 5.16 of SAS on the University of Manitoba mainframe computer. The PROCEDURE REGRESSION was used to produce lines of best fit (predicted lines) by simple quadratic regression analysis, and upper and lower 95% confidence limits (of the mean treatment value). The confidence limits allowed comparison between rates of applied-N within each tillage regime, however, statistical comparison between wheat-tillage regimes could not be made because replicate blocks were not randomized. The PROCEDURE GPLOT was used to graphically present the predicted lines. Regression parameters are also presented in tabular form following each figure.

As stated previously, the 1985 straw samples were bulked by N treatment for analysis of N content. As a result of this procedure, statistical analysis could not be performed for N content of the straw, N uptake by grain plus straw and recovery of applied-N by grain plus straw. In calculating N uptake, that portion of the calculation representing N uptake by grain was calculated by each N treatment and replicate. However, the portion of the calculation representing N uptake by straw was calculated by averaging straw yield for each N treatment over all replicates and multiplying this by the average N content of straw. Nitrogen uptake by grain was then averaged and added to N uptake by straw to equal the average N uptake by grain plus straw for each N treatment. Recovery of applied-N was calculated as previously noted. However, because N uptake by grain plus straw was an average for each N treatment, so too was recovery of applied-N. Thus the 1985 results for N content of straw, N uptake by grain plus straw and recovery of applied-N grain plus straw are presented in tables as means of observed data.

4. RESULTS AND DISCUSSION.

4.1 1984-85 Crop Year.

Yields of grain and straw, and protein content of grain are presented as lines of best fit based on simple quadratic regression analysis, graphically and in tabular form. Upper and lower 95% confidence limits for each rate of applied-N within each wheat-tillage regime are also presented in the tables. Nitrogen content of straw, and N uptake and recovery of applied-N by the above-ground portion of the crop are presented as means of observed data in tabular form only, due to the bulking of straw samples for N analysis.

Discussion of response curves is limited to those portions of the curve up to the point at which maximum response occurred. Portions of the curve beyond this point were considered of low importance because the maximum response had been achieved. These portions of the curve were also considered to be less accurate because of some lodging of the crop and limitations within the quadratic regression analysis. Furthermore, comparisons of N treatments along any one curve were limited because regression analysis dictated that the curve itself supplant absolute points.

4.1.1 Environmental conditions.

Records from the Morden CDA weather station (approximately 26 km ENE of the plot site) indicate that the non-growing season precipitation (from September 1, 1984 to April 30, 1985) was 251 mm. Although the distribution of precipitation during this non-growing season was somewhat different, the seasonal total was very similar to the long-term average of 244 mm (Table 4.1).

Precipitation during the growing season was considered excellent. Precipitation from May 1 to August 31 was 339 mm at the plot site and 412 mm at the Morden CDA weather station (Table 4.1). This compared favourably with the long-term average level of precipitation at the Morden CDA weather station (286 mm). Distribution of precipitation over the growing season, at the plot site, was generally good and likely did not result in water stress of the crops, although several short periods of limited rainfall did occur (Table 4.2). The favourable growing season provided for yields from 3280 to 4644 kg grain ha^{-1} of Neepawa spring wheat under conventional tillage. This was considerably higher than the long-term average yield (2837 kg grain ha^{-1}) for this variety in Crop Variety Zone No. 2, that zone in

Table 4.1. Monthly precipitation (mm) at the plot site and the Morden CDA weather station and long-term average monthly precipitation (mm) for the Morden CDA weather station

	1984-85 Crop year		Long-term average
	Plot site	Morden CDA	Morden CDA
September	--	32	52
October	--	118	32
November	--	23	26
December	--	24	22
January	--	9	24
February	--	17	19
March	--	13	28
April	--	15	41
May	51	60	66
June	125	116	46
July	22	40	73
August	141	194	71
September to April	--	251	244
May to August	339	410	286
September to August	--	661	530

Table 4.2. Daily precipitation (mm) during the 1985 growing season at the plot site and at the Morden CDA weather station

	Plot site				Morden CDA			
Day	May	June	July	August	May	June	July	August
1	0	0	5	0	0	0	0	0
2	0	0	0	0	0	0	1	5
3	0	0	0	30	1	1	3	13
4	0	0	0	4	0	0	0	4
5	0	0	0	0	0	0	0	2
6	0	0	0	0	2	0	0	0
7	0	0	0	0	0	2	0	0
8	0	0	0	0	0	1	1	5
9	0	0	0	0	0	0	0	0
10		0	0	0	9	0	0	0
11	28[a]	0	0	10	2	0	0	15
12		0	0	20	22	0	0	18
13		0	0	3	0	0	6	2
14	0	8	3	0	0	13	2	0
15	0	10	0	0	0	16	0	0
16	0	8	8	48	0	2	10	108
17	0	0	0	13	0	2	0	9
18	0	0	0	0	0	0	3	0
19	0	0	6	0	0	0	12	0
20	0	0	0	0	0	14	0	0
21	0	8	0	0	0	0	0	0
22	0	0	0	5	0	0	0	9
23	0	0	0	6	0	0	0	0
24	0	40	0	0	2	18	0	0
25	0	21	0	0	0	11	2	0
26	0	0	0	0	0	1	0	0
27	0	22	0	0	0	27	0	0
28	0	8	0	0	13	1	0	1
29	13	0	0	0	2	0	0	0
30	8	0	0	0	5	7	0	3
31	2	--	0	2	2	--	0	0
Total	51	125	22	141	60	116	40	194

[a] 28 mm of precipitation fell between May 10 and 13.

which the plot site was located (Manitoba Agriculture 1988 Field Crop Variety Recommendations for Manitoba).

Characterization of the soil indicated that the K and S content of the soil was adequate for maximum production of wheat (Table 4.3). Soil P levels of 7.1 kg P ha^{-1} in the spring wheat main block and 10.4 kg P ha^{-1} for the winter wheat main block, however, were considered less than adequate. Therefore, 25 kg P ha^{-1}, as 11-51-0, was applied with the seed to all subplot treatments to ensure that P did not limit crop production.

Nitrate-N content of the soil was 20.2 kg ha^{-1} to the 60 cm depth at the time of seeding of winter wheat (Table 4.3). This was considered 'low' by the Manitoba Provincial Soil Testing Laboratory, and thus a response to added-N was expected. Soil samples were not taken to the 120 cm depth because fragments of shale obstructed accurate sampling at lower depths. Nitrate-N content of the soil for spring wheat, sampled on April 23, was 37.5 kg ha^{-1} and 69.5 kg ha^{-1} for the 0 to 60 cm and 0 to 120 cm depths, respectively. This was considered to be a 'medium' level of soil N for the 0 to 60 cm depth by the Manitoba Provincial Soil Testing Laboratory, and thus response to added-N was expected. The higher soil NO_3-N level recorded in the spring for spring wheat compared to that in the fall for winter wheat was

Table 4.3. Soil characteristics at the 1984-85 plot site

pH, water extract, (0-15 cm depth)		7.0
Conductivity (dSm^{-1}), water extract, (0-15 cm depth)		0.4
Organic matter (%), (0-15 cm depth)		5.6
NO_3-N (kg ha^{-1})[a],	Winter wheat (0-60 cm depth)	20.2
	(0-120 cm depth)	--
	Spring wheat (0-60 cm depth)	37.4
	(0-120 cm depth)	69.5
P (kg ha^{-1}), $NaHCO_3$ extractable, (0-15 cm depth)		11.5
K (kg ha^{-1}), NH_4OAc extractable, (0-15 cm depth)		437
SO_4-S (kg ha^{-1}), (0-60 cm depth)		226
(0-120 cm depth)		1429

[a] winter wheat sampled in September prior to seeding and spring wheat sampled in May prior to seeding (mean of 3 samples for each crop).

likely the result of the mineralization of organic-N in late fall and early spring. Soil pH, conductivity and organic content were considered normal for this soil type (Table 4.3).

Winter wheat was seeded into undisturbed barley stubble (approximately 20 cm high) on September 7 and the urea-N fertilizer (46-0-0) was broadcast on September 10. The soil was firm and dry at seeding, however, 20 mm of rain fell within one week of planting. This resulted in good moisture for germination. It would also have assisted in the movement of the fertilizer into the soil. Crop emergence was uniform and the crop was at the 3 to 4 leaf stage at freeze-up. Although plant counts were not taken, spring regrowth of the winter wheat appeared uniform and normal, and thus winter survival was considered good.

Spring wheat under zero and conventional tillage were seeded on May 7 into a firm moist seedbed on undisturbed barley stubble and tilled soil, respectively. Urea-N fertilizer was broadcast May 21 and 23 mm of rain fell from May 29 to 31, thus assisting in the movement of fertilizer-N into the soil. Crop emergence was uniform.

Plant diseases began to appear on the winter wheat in mid-July. These were identified to be leaf rust, septoria and tan spot, thus the winter wheat was sprayed with fungicide for their control. Although these diseases can seriously affect the yield of wheat, particularly winter wheat, survival of the flag leaf and the high yields obtained indicated disease had little affect on the 1985 crop.

The winter wheat was harvested on August 20. The spring wheats were harvested on August 26 and 27.

Soil moisture content for the spring wheat under zero tillage was 229 mm (mean of all subplots sampled within the main block) for the 0 to 60 cm depth, at time of spring wheat seeding (Table 4.4). This compared with 215 mm for the main block of spring wheat under conventional tillage and 232 mm for the main block of winter wheat under zero tillage. Expressed as a percentage of field capacity these levels are 85 %, 84 % and 79 % for winter wheat under zero tillage, spring wheat under zero tillage and spring wheat under conventional tillage, respectively. Although a large difference between main blocks was not apparent, the data did indicate that soil moisture was higher with zero tillage. This was attributed to the standing stubble allowing for greater snow entrapment and reduced loss of soil moisture prior to crop canopy development (by reducing windspeed near the soil surface). Cumulative snow cover was

Table 4.4. Spring soil moisture content (mm) and consumptive water use (mm) to the 60 cm depth[1] during the 1984-85 crop year

	Spring soil moisture content	Consumptive water use
Winter wheat under zero tillage	232	344
Spring wheat under zero tillage	229	350
Spring wheat under conventional tillage	215	353

[1] mean of all samples taken within each main block.

considerably greater on the zero tillage main blocks than on the conventional tillage main block, throughout the 1984-85 winter (Table 4.5). Staple et al. (1960), Smika and Whitfield (1966), Schneider (1979), Aase and Siddoway (1980), Rennie et al. (1983), Campbell et al. (1984), Malhi et al. (1984), Rennie et al. (1984) and Campbell et al. (1985) have also reported increased snow trapping and greater spring soil moisture with standing stubble.

Consumptive water use was similar for each wheat-tillage system (Table 4.4). Consumptive water use (mean of all subplots sampled within each main block) was 344 mm for winter wheat under zero tillage, 350 mm for spring wheat under zero tillage and 353 mm for spring wheat under conventional tillage, measured to the 60 cm depth. However, levels of consumptive water use may have been lower than those reported here. Consumptive water use was calculated by subtracting the soil moisture content at harvest from that at seeding and adding in the precipitation between seeding and harvest. Soil moisture samples were taken to the 60 cm depth only, in the first crop year. Therefore, when high levels of rain fell during a short period of time (i.e., the 91 mm between June 24 and 28) it possible some of this moisture moved below the 60 cm depth, thereby inflating the calculated consumptive water use. Accordingly, water use efficiency levels would have been slightly higher than

Table 4.5. Cumulative snow depth (cm) readings[1] at the plot site during the 1984-85 winter

Date (month /day)	Winter wheat under zero tillage	Spring wheat under zero tillage	Spring wheat under conventional tillage
12/06	19	16	5
12/18	23	22	14
1/4	22	24	13
1/16	24	22	16
1/28	24	24	16
2/5	23	23	14
2/11	29	30	23
2/26	15	13	9
3/11	22	17	13
3/26	0	0	0

[1] mean of 3 measurements; 1 on each of replicates 2, 4 & 6.

those reported.

In a growing season of more normal (less than optimum) precipitation, consumptive water use would be expected to be higher for zero tilled wheat than for conventionally tilled wheat because prairie wheat crops generally consume all the water available to them (Shaykewich, 1974; Baier, 1976) and because zero tillage generally has a greater spring soil moisture content. High precipitation during the 1985 growing season, however, probably provided near optimum moisture for crop growth and, thus, removed the moisture advantage of zero tillage and the greater consumptive water use by the zero-tilled wheats. Similarly, Holt et al. (1964) found above average precipitation during the critical growth of corn minimized the effect of stored soil moisture on grain yield.

4.1.2 Grain yield.

Grain yield of each wheat-tillage regime was increased by the application of N fertilizer (Figure 4.1 and Table 4.6). Grain yield of winter wheat under zero tillage increased significantly from 3180 kg ha^{-1} with the control (note that the control received 12 kg applied-N ha^{-1}, as 11-51-0) to 5203 kg ha^{-1} at 240 kg applied-N ha^{-1}. However,

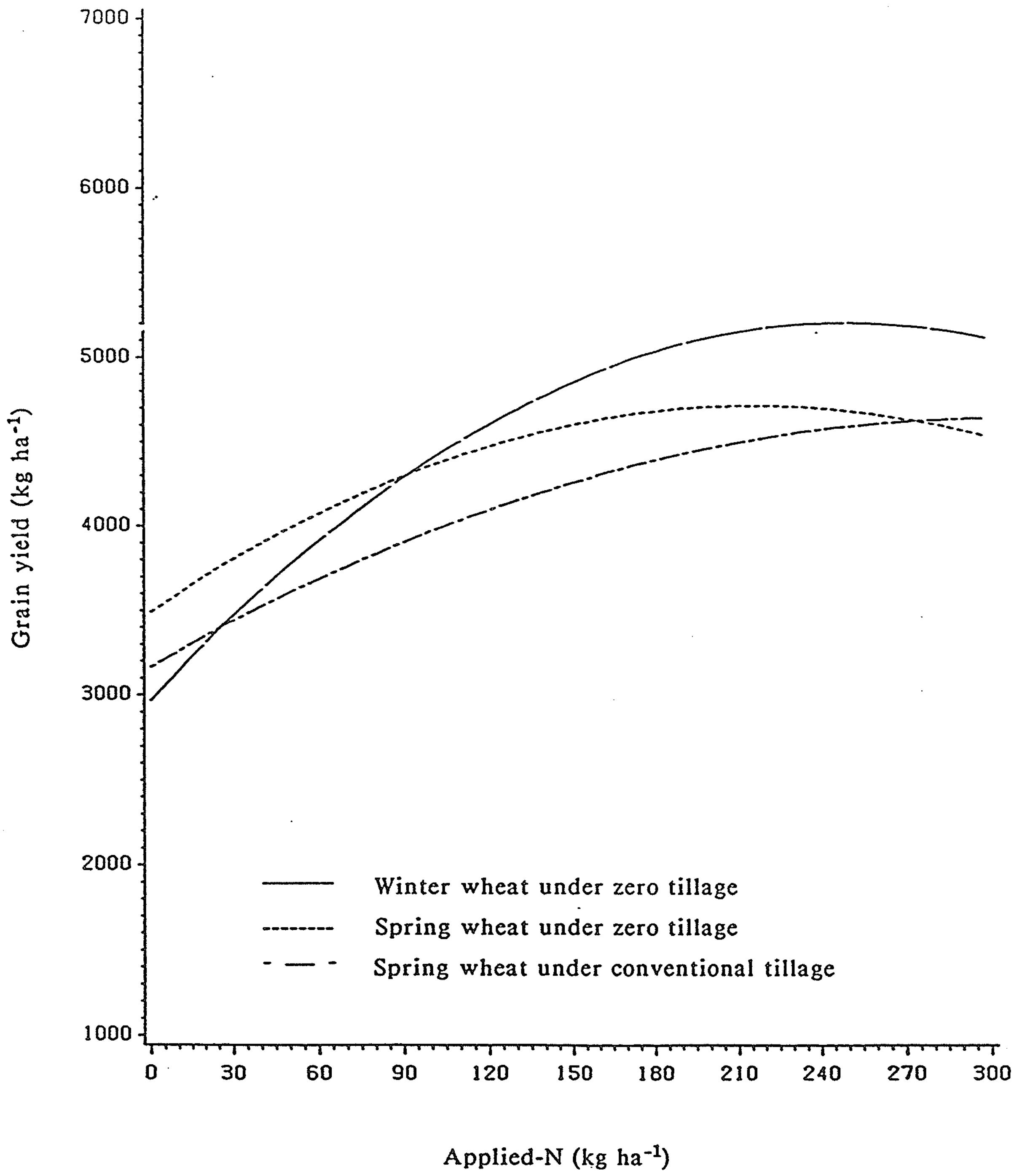


Figure 4.1. Lines of best fit for grain yield as affected by rate of applied-N (1985).

Table 4.6. Grain yield (kg ha^{-1}) as affected by rate of applied-N (1985)

	Wheat-till regime								
	Winter wheat zero till			Spring wheat zero till			Spring wheat conventional till		
Applied-N (kg ha^{-1})	Predicted yield[1]	Upper 95% confidence limit	Lower 95% confidence limit	Predicted yield[2]	Upper 95% confidence limit	Lower 95% confidence limit	Predicted yield[3]	Upper 95% confidence limit	Lower 95% confidence limit
12	3180	3539	2822	3624	3880	3368	3280	3801	2758
30	3470	3750	3190	3805	4005	3605	--	--	--
60	3912	4129	3694	4074	4230	3919	3686	4063	3309
90	4289	4521	4056	4297	4463	4131	--	--	--
120	4601	4868	4334	4472	4663	4282	--	--	--
180	5031	5320	4743	4682	4888	4476	4392	4920	3864
240	5203	5476	4931	4703	4897	4508	--	--	--
300	5117	5566	4668	4535	4855	4214	4644	5226	4063

1 $Y = 2964 + 17.95N - 3.950*10^{-2}N^2$, $R^2 = 0.61^{**}$.

2 $Y = 3488 + 11.35N - 2.620*10^{-2}N^2$, $R^2 = 0.45^{**}$.

3 $Y = 3163 + 9.66N - 1.575*10^{-2}N^2$, $R^2 = 0.42^{**}$.

yield began to level off by 180 kg applied-N ha^{-1}, as indicated by the lack of significant difference between yield at this rate and that at 240 kg applied-N ha^{-1}. An R^2 value of 0.61^{**} indicated that a highly significant relationship existed between grain yield and N application. During both years of study near Minnedosa, Manitoba, Grant (1982) also found that grain yield of winter wheat under zero tillage was increased by the application of N and that yields levelled off at high rates of applied-N. Fowler (1983) reported similar results for the mean of several field trials throughout the Parkland region of Saskatchewan, as did Jan and Bowren (1984) for the mean of 5 years of winter wheat under zero tillage near Melfort, Saskatchewan. Winter wheat yields from this study, however, were considerably higher, at comparable rates of applied-N, than those reported by these authors. Therefore, yields of winter wheat under zero tillage from the first crop year of this study were excellent and a reflection of the excellent growing season precipitation during 1985. The yield response to applied-N was also very good and this was presumably due to the excellent growing season precipitation and the 'low' NO_3-N level of the soil.

Grain yield of spring wheat under zero tillage increased significantly from 3624 kg ha^{-1} with the control to 4703 kg ha^{-1} at 240 kg applied-N ha^{-1}, although the 180 kg applied-N ha^{-1} treatment produced nearly as much as the 240 kg applied-N ha^{-1} treatment. Grain yield at 120 kg N ha^{-1} was also not significantly different from that at 240 kg applied-N ha^{-1}, thereby indicating the early levelling-off of yield. An R^2 value of 0.45^{**} indicated that a highly significant relationship existed between grain yield and N application. At two sites near Carman, Manitoba, Donaghy (1973) also found grain yield of spring wheat under zero tillage was significantly increased by the application of N and that yield levelled off at high rates of applied-N. Jan and Bowren (1984) reported similar results (mean of four years of study) near Melfort, Saskatchewan. At comparable rates of applied-N, however, grain yields of spring wheat under zero tillage from this study were considerably higher than those reported by Donaghy and by Jan and Bowren. The comparatively high yields of this study and the large yield response to applied-N on soil with a 'medium' level of soil-N were attributed to the high growing season precipitation.

Spring wheat under conventional tillage had only four N-rate treatments compared to the eight for winter wheat and spring wheat under zero tillage. This was done because the emphasis of this study was placed on the response to applied-N by winter wheat under zero tillage and by spring wheat under zero tillage. Spring wheat under conventional tillage was included primarily as a reference to the traditional wheat-tillage regime in Manitoba. Grain yield of spring wheat under conventional tillage increased significantly from 3280 kg ha^{-1} with the control to 4644 kg ha^{-1} with 300 kg applied-N ha^{-1} (the maximum rate applied). Although grain yield continued to increase with increased rates of N application, the lack of significant difference between yields at 180 and 300 kg applied-N ha^{-1} was an indication that it was levelling-off by the 180 kg ha^{-1} rate. An R^2 value of 0.42^{**} indicated a highly significant relationship existed between grain yield and N application. Other researchers in southern Manitoba and the Parkland region of Saskatchewan have also reported that grain yield of spring wheat under conventional tillage was increased by N application and that yield levelled off, or began to, at high rates of applied-N (Alkier et al., 1972; Donaghy, 1973; Racz, 1974; Fowler, 1983; Jan and Bowren, 1984; Gehl et al., 1986). The long-term average grain yield of conventionally tilled Neepawa spring wheat for the plot site area is 2837 kg ha^{-1} (Manitoba Agriculture 1988 Field Crop Variety Recommendations for Manitoba). Yields obtained in this study were considerably higher than the long-term average. They were also considerably higher, at comparable rates of applied-N, than those reported by Alkier et al. (1972) as the mean of five non-fallow sites in southern Manitoba, by Donaghy (1973) for two sites near Carman, Manitoba, by Racz (1974) as the mean of twelve site-years in southern

Manitoba, by Jan and Bowren (1984) as the mean of 4 years of study near Melfort, Saskatchewan, and by Gehl et al. (1986) for three sites in southern Manitoba with Katepwa spring wheat. The high yields of spring wheat under conventional tillage obtained in this study were considered the result of the excellent growing season precipitation, and management practices. Response to applied-N was also very good for a soil with a 'medium' NO_3-N level, presumably for the same reason.

Although the wheat-tillage regimes were compared non-statistically rather than statistically (because main blocks were not randomized), the lines of best fit were placed in the same figures rather than separating them and thereby adding to the length of text.

Grain yield of each wheat-tillage regime was significantly increased by the application of N, although yield levelled off (or began to) at high rates of N application. This response to added-N indicated that soil N supply alone, was not adequate to provide for maximum yields of spring wheat or winter wheat in this growing season of high precipitation. Spring wheat under zero tillage outyielded spring wheat under conventional tillage at each rate of applied-N, except when 300 kg N ha^{-1} was applied and then conventionally tilled only slightly outyielded zero-tilled spring wheat. The higher yields of spring wheat under zero tillage were likely the result of the slightly greater spring soil moisture content of the zero-tilled land (Table 4.4). The standing stubble of the zero tillage also likely provided for a slower evaporative loss of soil moisture during the early growing season (Aase and Siddoway, 1980; Brun, 1985), thus extending the soil moisture reserve further into the growing season (Aase and Siddoway, 1980; Gauer, 1982). In western Minnesota and eastern South Dakota, Holt et al. (1964) found above average rainfall during the critical growth period minimized the effect of stored soil moisture on grain yield of corn. Therefore, the yield difference between spring wheat under zero and conventional tillage may have been greater had growing season precipitation been more normal (lower). The yield difference may also have been greater had the fertilizer N been banded. In a review of the literature, Harapiak et al. (1986) concluded that more applied-N is lost from zero-tilled land than from conventionally-tilled land, especially when broadcast-applied and especially when the N source is urea, as in this study. Other researchers have also reported higher yields for spring wheat under zero tillage than for spring wheat under conventional tillage (Bradley and Donaghy, 1977; Spilde and Deibert, 1986). However, as discussed in the Literature Review, still others have reported that spring wheat under zero tillage yielded the same or less than spring wheat under conventional tillage (Donaghy, 1973; Nowatzki, 1980; Jan and Bowren, 1984; Lindwall et al., 1984; Toly, 1984; Deibert et al., 1985; Deibert et al., 1986). Although spring wheat under zero tillage generally outyielded that produced by conventional tillage in this study, the highest yields were obtained by winter wheat under zero tillage at high rates of applied-N, i.e. 90 kg applied-N ha^{-1}, or more. At lower rates winter wheat yielded less than spring wheat under zero tillage and at the control winter wheat yielded less than spring wheat under conventional tillage. The difference in the yield curves between winter and spring wheat suggested an inherent difference in response to applied-N. This has also been reported by Fowler (1983) and may be the result of differences in genetic make-up between varieties. However, the lower yield of winter wheat at low rates of N application may also be indicative of a lower N supply. In this study, fertilizer-N was applied to the winter wheat in fall whereas it was applied to the spring wheat in spring. Fall applied-N has been shown to be less efficiently recovered by barley than spring applied N (Ridley, 1973; Partridge and Ridley, 1974). Therefore, winter wheat may have outyielded the spring wheat at all rates of applied-N had the crops been fertilized at the same time.

4.1.3 Straw yield.

Straw yield of each wheat-tillage regime was increased by the application of N fertilizer (Figure 4.2 and Table 4.7). Straw yield of winter wheat under zero tillage was increased significantly from 4239 kg ha^{-1} with the control to 7023 kg ha^{-1} at 240 kg ha^{-1} of applied-N. However, straw yield at 180 kg applied-N ha^{-1} was not significantly different from that at 240 kg applied-N ha^{-1}. Thus, the treatment rates at which the highest yield occurred and at which the levelling-off of yield became apparent, were the same for grain and straw of winter wheat. An R^2 value of 0.59^{**} indicated a highly significant relationship existed between straw yield and N added. Ramig and Rhoades (1963) and Stanford and Hunter (1973) also reported that straw yield of winter wheat (under conventional tillage) was increased by the application of N.

Straw yield of spring wheat under zero tillage was increased significantly from 5450 kg ha^{-1} with the control to 7277 kg ha^{-1} with the application of 240 kg N ha^{-1}, although the 180 kg applied-N ha^{-1} treatment produced nearly as much straw. The lack of significant difference between straw yields at 120 and 240 kg applied-N ha^{-1}, however, indicated that yield was levelling-off by the 120 kg applied-N ha^{-1} treatment. Thus, the highest yield and the

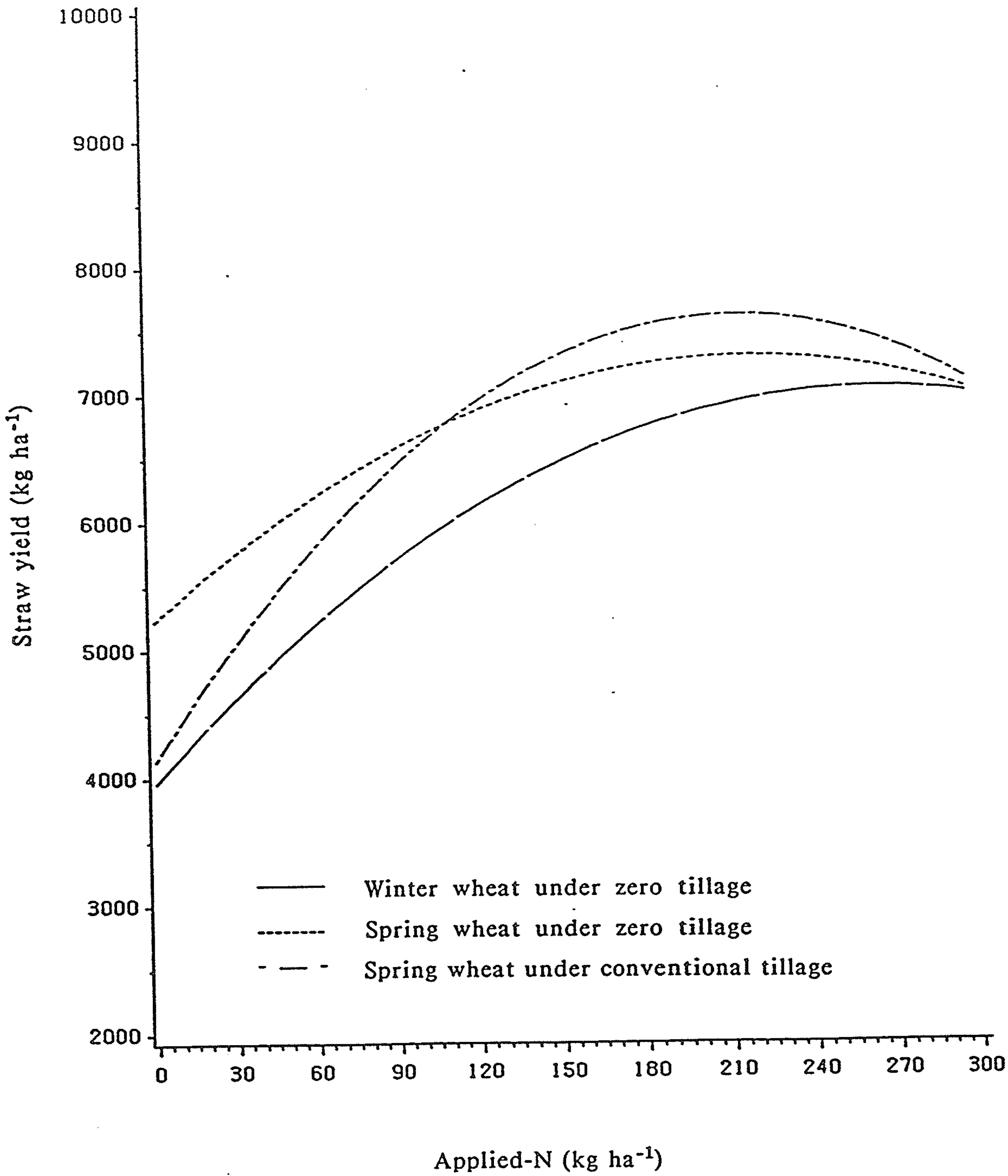


Figure 4.2. Lines of best fit for straw yield as affected by rate of applied-N (1985).

Table 4.7. Straw yield (kg ha^{-1}) as affected by rate of applied-N (1985)

	Wheat-till regime								
	Winter wheat zero till			Spring wheat zero till			Spring wheat conventional till		
Applied-N (kg ha^{-1})	Predicted yield[1]	Upper 95% confidence limit	Lower 95% confidence limit	Predicted yield[2]	Upper 95% confidence limit	Lower 95% confidence limit	Predicted yield[3]	Upper 95% confidence limit	Lower 95% confidence limit
12	4239	4760	3718	5450	5805	5096	4521	5142	3900
30	4619	5026	4213	5752	6029	5476	--	--	--
60	5202	5518	4886	6204	6419	5989	5808	6257	5359
90	5704	6042	5367	6578	6807	6348	--	--	--
120	6127	6515	5740	6873	7137	6609	--	--	--
180	6735	7153	6316	7231	7516	6946	7527	8155	6898
240	7023	7419	6627	7277	7546	7007	--	--	--
300	6992	7644	6340	7011	7454	6567	7065	7758	6373

[1] $Y = 3957 + 23.40N - 4.428*10^{-2}N^2$, $R^2 = 0.59^{**}$.

[2] $Y = 5223 + 18.95N - 4.330*10^{-2}N^2$, $R^2 = 0.55^{**}$.

[3] $Y = 4131 + 32.49N - 7.569*10^{-2}N^2$, $R^2 = 0.70^{**}$.

levelling-off of yield of straw occurred at the same treatment rates as they did with grain. An R^2 value of 0.55^{**} indicated a highly significant relationship between straw yield and applied-N. Although their work was with spring wheat under conventional tillage, McNeal et al. (1971) and Hamid (1973) also found that straw yield of spring wheat was increased by N application.

Straw yield of spring wheat under conventional tillage was also increased by the application of N. Yield increased significantly from 4521 kg ha^{-1} with the control to 7527 kg ha^{-1} when 180 kg ha^{-1} of N was applied, although straw yield like grain yield, began levelling-off at some point between 60 and 180 kg applied-N ha^{-1}. An R^2 value of 0.70^{**} indicated a highly significant relationship between straw yield of spring wheat under zero tillage and N application. McNeal et al. (1971) and Hamid 1973) also reported that the straw yield of spring wheat under conventional tillage was significantly increased by the application of N.

Straw yield of each wheat-tillage regime was significantly increased by the application of fertilizer N, although levelling-off of yield occurred as rates of N application increased. This yield response to applied-N with respect to straw, like that for grain, reflected the low soil N supply and high growing season precipitation.

The straw yield of spring wheat under zero tillage was substantially greater than that under conventional tillage at low rates of applied-N, although, at 180 kg applied-N ha^{-1} the opposite trend occurred and when 300 kg N ha^{-1} was applied the yields were almost equal. This difference in the response curves for spring wheat under zero and conventional tillage may be due to the fewer number of treatments for spring wheat under conventional tillage, i.e. a greater number of treatments increases the accuracy of the regression analysis and the predicted line. The greater yields of straw with spring wheat under zero tillage, at low rates of applied-N, were also observed with respect to grain. This difference in straw yield at low rates of applied-N, like that for grain yield, was likely the result of the slightly greater conservation of soil moisture with zero-tilled land. The straw yield of winter wheat was substantially lower than that of both spring wheats. This was considered unusual considering that Norstar winter wheat produced in Manitoba is normally much taller (by 10 to 15 cm, or more) than spring wheat and in this study it was observed that the winter wheat was approximately 7.5 to 10 cm higher than the spring wheat. Although counts of the numbers of tillers were not made, it is possible that the winter wheat had fewer tillers and thus less straw (by weight) than did the spring wheat. No precipitation fell in the two weeks preceding tillering of winter wheat. However, 23 mm of precipitation fell in the two weeks prior to spring wheat tillering. Dubetz (1960) and Spratt and Gasser (1970) found straw yield decreased as moisture stress at tillering was increased. Therefore, it is likely that the distribution of precipitation prior to crop tillering was responsible for some of the difference between varieties. However, herbicide use and timing may also have contributed to this difference. The spring wheat was sprayed with 0.243 L ha^{-1} of 500 g L^{-1} MCPA amine for broadleaf weed control on June 12, i.e. when the crop was at tillering stage of growth. Alternatively, the winter wheat was sprayed with 0.138 L ha^{-1} of 500 g L^{-1} MCPA amine plus 0.058 L ha^{-1} of 400 g L^{-1} Dicamba for broadleaf weed control on June 4, i.e. when the crop was mid way between tillering and shooting growth stages. The broadleaf weeds in the winter wheat were more advanced than those in the spring wheat and for this reason, the MCPA plus Dicamba treatment was used. The MCPA plus Dicamba treatment has a 'fair' crop tolerance rating for winter wheat whereas the MCPA treatment has an 'excellent' crop tolerance rating for spring wheat (Manitoba Agriculture 1988 Guide to Chemical Weed Control). The 'fair' crop tolerance rating indicates that tolerance is variable depending on growing conditions. Therefore, it was considered possible that the MCPA plus Dicamba treatment shortened the winter wheat plant height or caused the die-back of newly formed tillers, thereby decreasing the straw

yield.

4.1.4 Protein content of the grain.

Protein content (%) of the grain for each wheat tillage-regime was increased by the application of N (Figure 4.3 and Table 4.8). Protein content of the grain of winter wheat under zero tillage was increased significantly from 9.3 % with the control to 12.2 % when 300 kg N ha^{-1} (the maximum rate) was applied. An R^2 value of 0.56^{**} indicated a highly significant relationship existed between protein content of the grain and the application of N. Unlike with grain yield and straw yield, protein content (based on the line of best fit) continued to increase as the application of N increased. Levelling-off of protein content at high rates of applied-N, however, was indicated by the lack of significant difference between levels of protein content for rates of applied-N greater than or equal to 180 kg N ha^{-1}. Review of the means of observed data (Table 4.9) also revealed that protein content was relatively similar for rates of applied-N between and including 180 and 300 kg N ha^{-1}. In the Parkland region of Saskatchewan, Fowler (1973) and Jan and Bowren (1984) also found that protein content of the grain of Norstar winter wheat under zero tillage was increased by application of N and that protein content

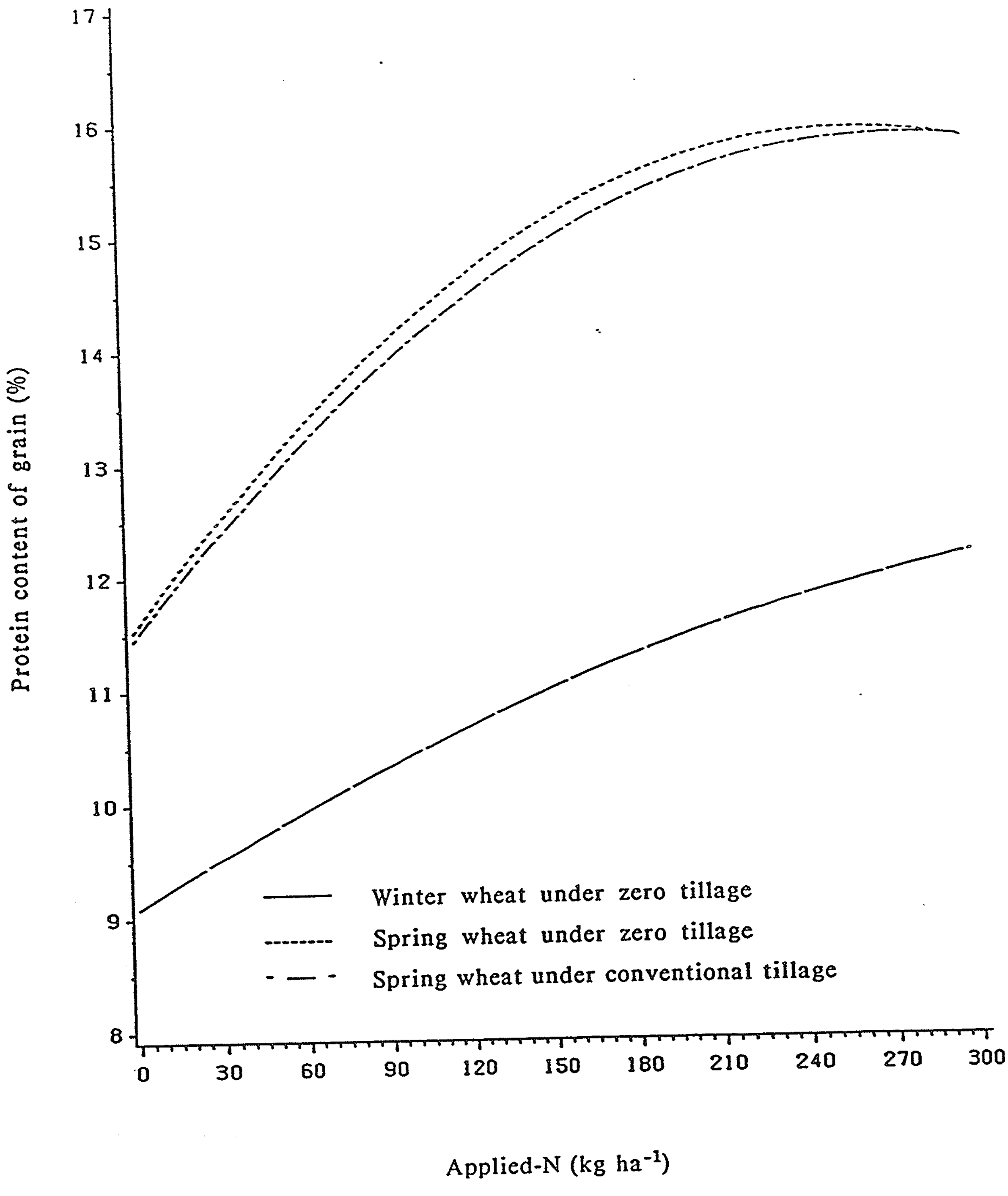


Figure 4.3. Lines of best fit for protein content of grain as affected by rate of applied-N (1985).

Table 4.8. Protein content (%) of grain as affected by rate of applied-N (1985)

	Wheat-till regime								
	Winter wheat zero till			Spring wheat zero till			Spring wheat conventional till		
Applied-N (kg ha^{-1})	Predicted protein content[1]	Upper 95% confidence limit	Lower 95% confidence limit	Predicted protein content[2]	Upper 95% confidence limit	Lower 95% confidence limit	Predicted protein content[3]	Upper 95% confidence limit	Lower 95% confidence limit
12	9.3	9.8	8.7	11.9	12.5	11.4	11.8	12.6	11.1
30	9.5	10.0	9.1	12.5	12.9	12.1	--	--	--
60	9.9	10.3	9.6	13.3	13.7	13.0	13.2	13.7	12.6
90	10.3	10.7	10.0	14.1	14.4	13.7	--	--	--
120	10.7	11.1	10.3	14.7	15.1	14.3	--	--	--
180	11.3	11.7	10.9	15.5	15.9	15.1	15.3	16.1	14.5
240	11.8	12.2	11.4	15.9	16.3	15.5	--	--	--
300	12.2	12.9	11.5	15.8	16.5	15.2	15.8	16.7	15.0

[1] $Y = 9.1 + 1.52{*}10^{-2}N - 1.65{*}10^{-5}N^2$, $R^2 = 0.56^{**}$.

[2] $Y = 11.5 + 3.39{*}10^{-2}N - 6.53{*}10^{-5}N^2$, $R^2 = 0.73^{**}$.

[3] $Y = 11.5 + 3.20{*}10^{-2}N - 5.79{*}10^{-5}N^2$, $R^2 = 0.73^{**}$.

Table 4.9. Means of observed data for protein content (%) of the grain as affected by rate of applied-N (1985)

Applied-N ($kg\ ha^{-1}$)	Wheat-tillage regime WWZT[1]	SWZT[2]	SWCT[3]
12	9.5	12.3	12.3
30	9.4	12.2	----
60	10.2	12.6	12.5
90	9.8	12.6	----
120	10.3	15.0	----
180	12.0	15.4	15.7
240	11.8	15.7	----
300	12.0	15.9	15.7

[1] winter wheat under zero tillage.
[2] spring wheat under zero tillage.
[3] spring wheat under conventional tillage.

levelled off at high rates of N application. Near Minnedosa, Manitoba, Grant (1982) found that protein content of the grain of Norstar winter wheat under zero tillage was significantly increased by the application of N and that protein content levelled off at high rates of applied-N during a year (1979-80) with high precipitation during the grain filling period. However, protein content continued to increase with high rates of N application (up to 300 kg N ha^{-1}) during a year (1980-81) with low precipitation during the grain filling period. Similarly, Campbell et al. (1977b) found that protein content of the grain of spring wheat was lower with a higher moisture supply than with a 'dry' moisture regime at each of seven rates of applied-N between 0 and 164 kg ha^{-1}. The lower levels of protein content found with the irrigated treatments, however, were accompanied by higher yields of grain and grain plus straw, which therefore indicated a dilution of available N by dry matter production. Thus, the generally low levels of protein content obtained in this study during the 1984-85 crop year reflect the excellent growing season precipitation. Grant (1982) also reported the biological dilution of plant grain protein of winter wheat under zero tillage at low rates of applied-N. She attributed this to large increases in straw and grain production by the plant with the initial applications of N. The line of best fit for protein content of the grain, in this study, did not reveal biological dilution. The means of observed data (Table 4.9), however, showed little (less than 1 %) difference in the level of protein content for rates of applied-N from the control to 120 kg ha^{-1}. Large increases in grain yield and straw yield (Tables 4.6 and 4.7, respectively) accompanied the lack of increase in protein content. Therefore, the biological dilution of grain protein at low rates of N application did occur in the winter wheat of this study. The levels of protein content obtained in this study were considerably lower, at comparable rates of applied-N, than those reported by Jan and Bowren (1984) and those reported by Grant (1982) for the 1979-80 crop year, thereby indicating the excellent growing season precipitation.

Protein content of the grain of spring wheat under zero tillage was increased significantly from 11.9 % with the control to 15.9 % at the 240 kg applied-N ha^{-1} treatment. However, the protein content at 180 kg applied-N ha^{-1} was not significantly different from that at the 240 kg N ha^{-1} rate, thereby indicating the levelling-off of protein content by the 180 kg N ha^{-1} treatment. An R^2 value of 0.73^{**} indicated that a highly significant relationship existed between protein content of the grain and added-N. Donaghy (1973) near Carman, Manitoba, and Jan and Bowren (1984) near Melfort, Saskatchewan, also found that protein content of the grain of spring wheat under zero tillage was increased by application of N, and that protein content levelled off at high rates of applied-N. Levels of protein content obtained in this study, however, were considerably lower than those reported by Jan and Bowren for Neepawa spring wheat, at comparable rates of applied-N. The lower levels of protein obtained in this study, reflect the high growing season precipitation and high yields of grain and straw. In this study, the line of best fit for protein content of the grain of spring wheat under zero tillage did not show the biological dilution of plant protein at low rates of applied-N. Review of the means of observed data (Table 4.9), however, indicated very similar levels of protein content for the control, 30 kg N ha^{-1} and 60 kg N ha^{-1} treatments followed by a large increase in protein content with the application of 90 kg ha^{-1} of N. Review of grain and straw yields (Tables 4.6 and 4.7, respectively) revealed that the similarity in protein content from the control to 60 kg applied-N ha^{-1} was accompanied by large increases in both grain and straw yield. Thus, biological dilution of plant grain protein occurred for spring wheat under zero tillage at low rates of applied-N. Working at numerous sites across southern Manitoba, Alkier et al. (1972) and Racz (1974) both found that the protein content of the grain of Neepawa spring wheat under conventional tillage was subject to the biological dilution of plant protein at low rates of applied-N.

Protein content of the grain of spring wheat under conventional tillage was increased significantly from 11.8 % with the control to 15.8 % with the application of 300 kg ha^{-1} of N (the maximum rate applied). However, protein content at 180 kg applied-N ha^{-1} was nearly as high as (and not significantly different from) that at 300 kg applied-N ha^{-1} according to the line of best fit, and equal according to the means of observed data (Table 4.9). Thus, protein content was levelling-off by the 180 kg N ha^{-1} treatment. An R^2 value of 0.73^{**} indicated a highly significant relationship between protein content of the grain and the application of N. Other research from southern Manitoba and the Parkland region of Saskatchewan also found that protein content of the grain of spring wheat was increased by N application (Alkier et al. 1972; Donaghy, 1973; Racz, 1974; Fowler, 1983; Jan and Bowren, 1984). The levels of protein content obtained in this study were considerably lower, at comparable rates of applied-N, than the levels (mean of four years of study) reported by Jan and Bowren (1984) for Neepawa spring wheat under conventional tillage, near Melfort, Saskatchewan. This difference reflects the high growing season precipitation during the 1984-85 crop year of this study. Alkier et al. (1972) and Racz (1974), however, reported very similar protein levels to those reported in this study (mean of five and twelve non-fallow site years of study, respectively) for the grain of Neepawa spring wheat under conventional tillage. This was not expected because grain yields from this study were considerably greater than those reported by Alkier et al. and Racz, thus eliciting the expectation of lower levels of protein content in this study. Review of the results of Alkier et al. and Racz, however, showed the soil NO_3-N level of their plot sites was usually lower than that for this study. Alkier et al. (1972) and Racz (1974) also reported the biological dilution of plant grain protein at low rates of applied-N. Although this was not indicated in this study by the line of best fit, it was apparent from the means of observed data (Table 4.9), i.e. the protein content of the grain for the control was almost identical to that when 60 kg N ha^{-1} was applied.

Protein content of the grain was significantly increased by the application of N in each wheat-tillage regime, although protein content did level off by 180 kg applied-N ha^{-1} in each case. This response to applied-N indicated soil N supply, alone, was not adequate to provide for maximum protein content. Each wheat tillage-regime also exhibited the biological dilution of plant protein at low rates of applied-N. Protein content of the grain was almost the same for spring wheat under zero and conventional tillage. Near Melfort, Saskatchewan, Jan and Bowren (1984) also found that protein content of the grain of spring wheat under zero tillage was similar to that under conventional tillage (mean of 3 study years). However, at 1 site near Carman, Manitoba, Donaghy (1973) found that protein content of the grain of spring wheat under zero tillage was lower than that under conventional tillage, and significantly lower at 34 and 67 kg applied-N ha^{-1}. In this study, high levels of precipitation prior to and during grain filling negated soil moisture differences between tillage regimes, thereby preventing differences with respect to protein content. Protein content of the grain of winter wheat under zero tillage was much lower than that for the spring wheat under conventional and zero tillage. This difference ranged from approximately 2.5 % protein at the control to approximately 3.5 % protein when 300 kg ha^{-1} was applied and it was attributed to differences in the genetic make-up between winter and spring wheat. Fowler (1983) and Jan and Bowren (1984) have also reported this trend.

4.1.5 Nitrogen content of the straw.

Statistical analysis of N content of the straw, N uptake by grain plus straw and percent recovery of applied-N by grain plus straw, was not possible. In order to discuss the means of observed data like a response curve, adjacent treatments were grouped to represent the portions of that curve.

Nitrogen content (%) of the straw of each wheat-tillage regime was increased by the application of N (Table 4.10). Nitrogen content of the straw of winter wheat under zero tillage generally increased from 0.30 % with the control to 0.48 % when 240 kg N ha^{-1} was applied. Furthermore, N content of the straw was the same for the control and the 30 kg N ha^{-1} rate and very similar for the treatments greater than and including the 120 kg N ha^{-1} rate. Between these two plateau, N content increased. The lower and upper plateau indicated the biological dilution of straw protein at low rates of N application and a levelling-off of N content at high rates of applied-N, respectively. Nitrogen content of the straw was similar to protein content of the grain in these regards. Although their work was based on winter wheat under conventional tillage, Ramig and Rhoades (1963) also found that N content of the straw was increased by the application of N and that biological dilution of plant straw protein occurred at low rates of applied-N.

Nitrogen content of the straw of spring wheat under zero tillage was increased from 0.23 % with the control to 0.59 % with the application of 300 kg N ha^{-1} (the maximum treatment rate). Like protein content of the grain, N

Table 4.10. Means of observed data for nitrogen content (%) of the straw as affected by rate of applied-N (1985)

	Wheat-tillage regime		
Applied-N (kg ha^{-1})	WWZT[1]	SWZT[2]	SWCT[3]
12	0.30	0.23	0.23
30	0.30	0.22	----
60	0.43	0.21	0.27
90	0.30	0.31	----
120	0.44	0.34	----
180	0.46	0.50	0.46
240	0.48	0.54	----
300	0.46	0.59	0.58

[1] winter wheat under zero tillage.
[2] spring wheat under zero tillage.
[3] spring wheat under conventional tillage.

content of the straw continued to increase with increased rates of applied-N although a levelling-off was apparent. Also similar was the biological dilution of plant protein, indicated by the lack of change in N content of the straw between the control and the 60 kg N ha^{-1} treatment. Although their work was on spring wheat under conventional tillage, McNeal et al (1971) also found that N content of the straw of spring wheat was increased by N application, N content continued to increase at high rates of applied-N although levelling-off was apparent, and N content of the straw was subject to biological dilution at low rates of N application.

Nitrogen content of the straw of spring wheat under conventional tillage was increased from 0.23 % with the control to 0.27, 0.46 and 0.58 % with the application of 60, 180 and 300 kg N ha^{-1}, respectively. Other researchers have also found that N content of the straw of spring wheat was increased by the application of N (McNeal et al. 1971; Alessi and Power, 1973). In this study N content of the straw, unlike protein content of the grain, did not exhibit a levelling-off at high rates of applied-N. However, the fewer number of N treatments may have contributed to the masking of this trend. Like protein content of the grain, N content of the straw exhibited biological dilution of plant protein, i.e. N content of the straw was quite similar for the control and the 60 kg N ha^{-1} treatments. The data of McNeal et al. (1971) also showed biological dilution of straw protein.

Nitrogen content of the straw of each wheat-tillage regime was increased by the application of N, although the biological dilution of plant protein at low rates of N application was also apparent. Nitrogen content of the straw of winter wheat and spring wheat under zero tillage levelled off and began levelling-off, respectively, at high rates of N application. This was not readily apparent for the spring wheat under conventional tillage, possibly because of the fewer number of N treatments. This response to applied-N, like that for protein content of the grain, reflected the low soil N supply. Nitrogen content of the straw was very similar for spring wheat under conventional tillage and under zero tillage. This was attributed to high levels of precipitation during grain filling removing the soil moisture advantage of zero tillage and providing for the maximum translocation of plant protein from straw to grain. Nitrogen content of the straw of winter wheat was considerably higher than that for spring wheat under zero and conventional tillage, at rates of applied-N less than 180 kg N ha^{-1}. This trend was opposite to that which occurred with respect to protein content of the grain, and was probably due to differences in genetic make-up between winter and spring wheat or to differences in straw yield caused by pre-tillering precipitation and herbicide application.

4.1.6 Nitrogen uptake by grain plus straw.

Nitrogen uptake (kg N ha^{-1}) by the grain plus straw of each wheat-tillage regime was increased by the application of fertilizer-N (Table 4.11). Nitrogen uptake by the above-ground portion of winter wheat generally increased from 62 kg N ha^{-1} with the control to 143 kg N ha^{-1} when both 240 and 300 kg N ha^{-1} were applied, thereby indicating N uptake also levelled off at high rates of applied-N. Although their work was based on winter wheat under conventional tillage, Ramig and Rhoades (1963) and Stanford and Hunter (1973) also found that N uptake by winter wheat was increased by N application and that N uptake levelled off, or began to level off, at high rates of applied-N.

Nitrogen uptake by the above-ground portion of spring wheat under zero tillage generally increased from 89 kg N ha^{-1} with the control to 172 kg N ha^{-1} when 300 kg ha^{-1} of N was applied. Nitrogen uptake at 180 and 240 kg applied-N ha^{-1}, however, were similar to that at 300 kg applied-N ha^{-1} thus indicating the levelling-off of N uptake at high rates

Table 4.11. Means of observed data for nitrogen uptake (kg N ha^{-1}) by grain plus straw[1] as affected by rate of applied-N (1985)

Applied-N (kg ha^{-1})	Wheat-tillage regime		
	WWZT[1]	SWZT[2]	SWCT[3]
12	62	89	75
30	71	94	----
60	100	107	108
90	93	136	----
120	115	135	----
180	125	165	148
240	143	162	----
300	143	172	171

1 winter wheat under zero tillage.
2 spring wheat under zero tillage.
3 spring wheat under conventional tillage.

of N application. Although their work was done with lysimeters near Swift Current, Saskatchewan, Campbell et al. (1977b) also found N uptake by spring wheat was increased by N fertilization and that N uptake levelled off at high rates of applied-N.

Nitrogen uptake by the grain plus straw of spring wheat under conventional tillage was increased from 75 kg N ha^{-1} with the control to 171 kg N ha^{-1} at 300 kg applied-N ha^{-1} (the maximum rate applied). Although a difference in N uptake of 23 kg N ha^{-1} separated the 180 and 300 kg applied-N ha^{-1} treatments, this was little more than half the increase between the 60 and 180 kg applied-N ha^{-1} treatments. Therefore, although the fewer number of N treatments may have made it more difficult to perceive, N uptake was levelling-off at high rates of N application. Using lysimeters near Swift Current, Saskatchewan, Campbell et al. (1977b) also found that N uptake by spring wheat was increased by N application. They also found that N uptake levelled off at high rates of applied-N.

Nitrogen uptake by grain plus straw of each wheat-tillage regime was increased by the application of N. This reflected the low soil N supply and good precipitation. The levelling-off of N uptake at high rates of N application was also observed for each wheat-tillage regime. Nitrogen uptake by spring wheat under zero tillage was slightly greater than that by spring wheat under conventional tillage. This was considered appropriate because N content of the straw, protein content of the grain and straw yield were similar for spring wheat under zero and conventional tillage, while grain yield was slightly greater for spring wheat under zero tillage. These trends were considered the result of the slightly greater spring soil moisture content and reduced early season evaporative loss of soil moisture with zero tillage. Nitrogen uptake by winter wheat was lower than that by spring wheat under zero and conventional tillage. This was attributed to the considerably lower straw yield and considerably lower protein content of the grain of winter wheat under zero tillage. These phenomena were considered the result of genetic differences or differences due to precipitation distribution and herbicide application.

4.1.7 Recovery of applied-N by grain plus straw.

Recovery of applied-N (%) by the grain plus straw of each wheat-tillage regime, because it is a measure of the efficiency of uptake of applied-N, generally decreased with the increased application of N (Table 4.12). Recovery of applied-N by the grain plus straw of winter wheat under zero

Table 4.12. Means of observed data for recovery of applied-N (%) by grain plus straw as affected by rate of applied-N (1985)

Applied-N (kg ha^{-1})	Wheat-tillage regime		
	WWZT[1]	SWZT[2]	SWCT[3]
12	----	----	----
30	50.5	39.4	----
60	72.7	41.8	64.0
90	41.0	60.0	----
120	48.7	44.0	----
180	38.0	45.8	43.7
240	36.1	33.2	----
300	28.8	29.9	34.0

[1] winter wheat under zero tillage.
[2] spring wheat under zero tillage.
[3] spring wheat under conventional tillage.

tillage was increased from 50.5 % with 30 kg applied-N ha^{-1} to 72.7 % with 60 kg applied-N ha^{-1}, and then generally decreased to 28.8 % when 300 kg N ha^{-1} (the maximum rate) was applied. This trend whereby recovery of applied-N increased initially and then decreased generally with increased rates of applied-N, was also reported by Stanford and Hunter (1973) for winter wheat under conventional tillage and by Grant (1982) for winter wheat under zero tillage near Minnedosa, Manitoba.

Recovery of applied-N by the above-ground portion of spring wheat under zero tillage, like that for winter wheat, was initially increased and then decreased by increasing rates of N application. Recovery increased from 39.4 % with 30 kg applied-N ha^{-1} to 60.0 % at 90 kg applied-N ha^{-1}, and then generally decreased to 29.9 % when 300 kg ha^{-1} of N was applied. Although they worked with lysimeters near Swift Current, Saskatchewan, Campbell and Paul (1978) also found recovery of applied-N by spring wheat initially increased and then decreased as rates of applied-N were increased. Calculations made on the data of McNeal et al. (1971) also indicated this trend.

Recovery of applied-N by the grain plus straw of spring wheat under conventional tillage decreased from 64.0 % with 30 kg applied-N ha^{-1} to 43.7 % when 180 kg N ha^{-1} was applied, and then to 34.0 % when 300 kg N ha^{-1} was applied. Campbell and Paul (1978) also found that recovery generally decreased with increased rates of applied-N, however, they found this was preceded by a small increase in recovery. The small number of N treatments for spring wheat under conventional tillage prevented the observance of whether or not this increase occurred in this study.

Recovery of applied-N by the grain plus straw of each wheat-tillage regime, generally decreased with increasing rates of N application. Winter wheat and spring wheat under zero tillage showed an initial increase followed by a general decrease in recovery. Spring wheat under conventional tillage showed a decrease in recovery, only, although there were fewer number of N-rate treatments for this crop. Recovery of applied-N by spring wheat under zero and conventional tillage appeared relatively similar, although the fewer number of treatments with spring wheat under conventional tillage made this difficult to observe. The similarity of recovery between spring wheat under zero and conventional tillage was due to the lack of appreciable differences in N uptake. Recovery of applied-N by winter wheat under zero tillage, however, was greater than that by spring wheat under zero and conventional tillage at low rates of applied-N, but lower at high rates of applied-N. This reflected the different responses to applied-N by winter and spring wheat.

4.1.8 Water use efficiency based on yield of grain.

Water use efficiency based on yield of grain (WUE-G) and water use efficiency based on yield of grain plus yield of straw (WUE-GS) were determined for selected subplots only, ie. all treatments of spring wheat under conventional tillage, and the 12, 60, 90, 180 and 300 kg applied-N ha^{-1} treatments for winter wheat and spring wheat under zero tillage, on replicates 2, 4 and 6. Soil moisture measurements were obtained for the 0 to 60 cm depth, only, in the first crop year. However, lesser levels of significance for R^2 values, fewer cases of significant difference between treatment rates and 'wide' confidence limits for levels of water use efficiency were indicative of the variability of results involving gravimetric sampling and the fewer number of treatments. The fewer number of treatments was dictated by the size of the field program and the availability of resources.

Water use efficiency based on yield of grain of winter wheat under zero tillage was increased by the application of N (Figure 4.4 and Table 4.13). Water use efficiency increased significantly from 9.0 kg ha^{-1} mm^{-1} with the

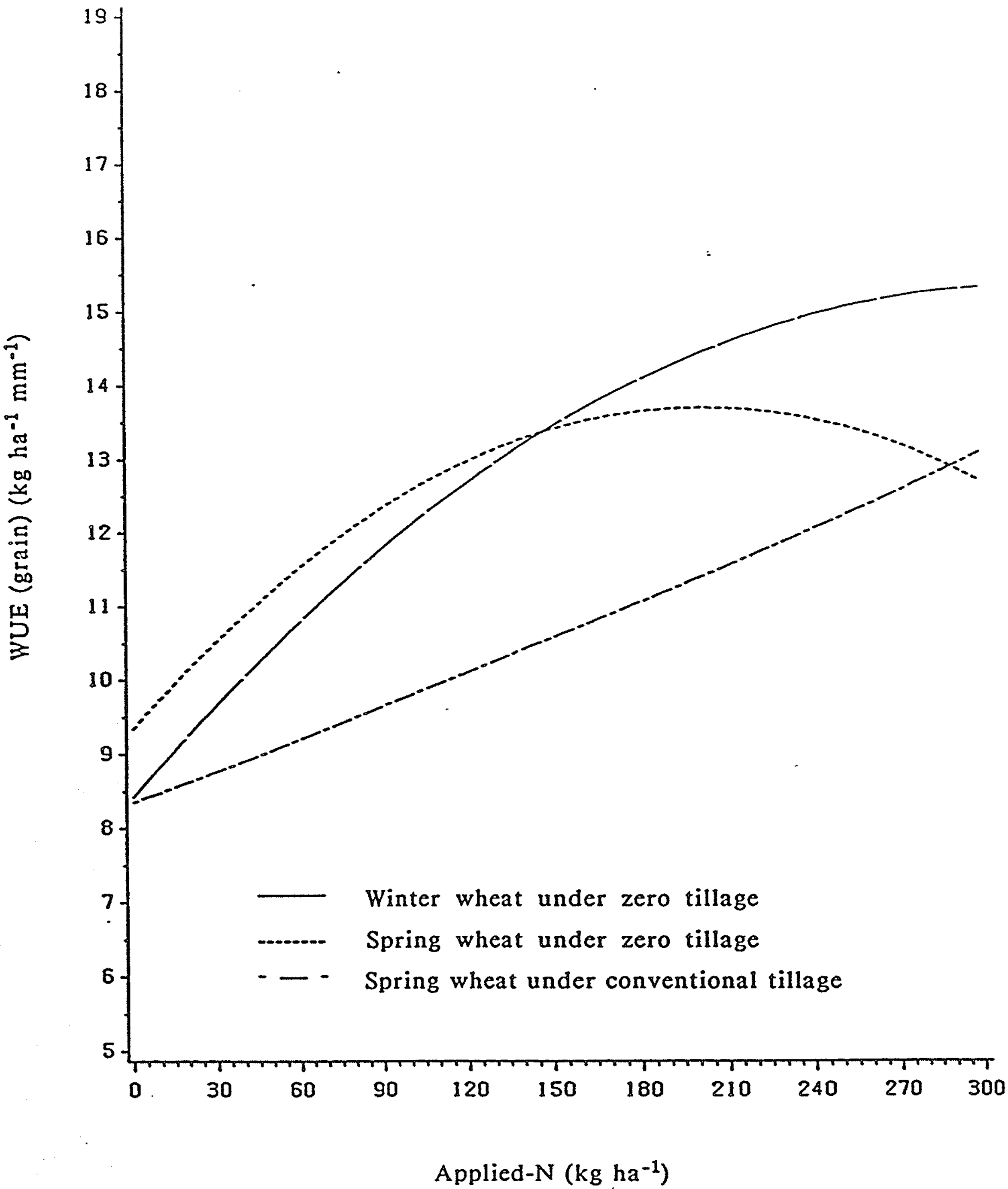


Figure 4.4. Lines of best fit for water use efficiency (WUE) (based on yield of grain) as affected by rate of applied-N (1985).

Table 4.13. Water use efficiency (WUE) based on grain yield (kg ha^{-1} mm^{-1}) as affected by rate of applied-N (1985)

Applied-N (kg ha^{-1})	Wheat-till regime: Winter wheat zero till: Predicted WUE^1	Upper 95% confidence limit	Lower 95% confidence limit	Spring wheat zero till: Predicted WUE^2	Upper 95% confidence limit	Lower 95% confidence limit	Spring wheat conventional till: Predicted WUE^3	Upper 95% confidence limit	Lower 95% confidence limit
12	9.0	11.6	6.3	9.9	11.7	8.1	8.7	11.7	5.8
30	--	--	--	--	--	--	--	--	--
60	10.8	12.5	9.1	11.6	12.7	10.5	9.5	11.6	7.3
90	11.8	13.6	10.0	12.4	13.6	11.2	--	--	--
120	--	--	--	--	--	--	--	--	--
180	14.1	16.4	11.8	13.7	15.3	12.2	11.4	14.3	8.4
240	--	--	--	--	--	--	--	--	--
300	15.3	18.2	12.4	12.8	14.8	10.8	13.5	16.7	10.2

1 $Y = 8.4 + 4.39*10^{-2}N - 6.96*10^{-5}N^2$, $R^2 = 0.56^*$.

2 $Y = 9.4 + 4.33*10^{-2}N - 1.07*10^{-5}N^2$, $R^2 = 0.44^*$.

3 $Y = 8.6 + 1.45*10^{-2}N - 6.26*10^{-6}N^2$, $R^2 = 0.41$.

control to 15.3 kg ha^{-1} mm^{-1} when 300 kg N ha^{-1} (the maximum rate) was applied. Although maximum WUE-G was obtained at 300 kg applied-N ha^{-1}, the WUE-G at 60 kg applied-N ha^{-1} was not significantly different, thereby indicating the early levelling-off of WUE-G. An R^2 value of 0.56^* indicated that a significant relationship existed between WUE-G and rate of N application. Ramig and Rhoades (1963) at North Platte, Nebraska, and Brown (1971) at Bozeman, Montana, also found that WUE-G of winter wheat under conventional tillage was increased by the application of N and that WUE-G levelled off as N application increased.

Water use efficiency based on grain yield of spring wheat under zero tillage was increased significantly from 9.9 kg ha^{-1} mm^{-1} with the control to 13.7 kg ha^{-1} mm^{-1} when 180 kg N ha^{-1} was applied. An R^2 of 0.44^* indicated that a significant relationship existed between WUE-G and rate of N application. Water use efficiency was not significantly different at treatment rates greater than the control. Thus WUE-G began levelling-off at low applied-N. In a lysimeter study near Swift Current, Saskatchewan, Campbell et al. (1977b) also found WUE-G of spring wheat was increased by N application and that WUE-G levelled off as N application increased.

Water use efficiency based on yield of grain of spring wheat under conventional tillage was increased, although not significantly, from 8.7 kg ha^{-1} mm^{-1} with the control to 13.5 kg ha^{-1} mm^{-1} when 300 kg N ha^{-1} (the maximum rate) was applied. An R^2 of 0.41 indicated a significant relationship did not exist between WUE-G and rate of N application. Water use efficiency did not show any indication of levelling-off at high rates of N application. However, this was likely the result of the fewer number of N treatments and the variability of results associated with gravimetric analysis. In a lysimeter study near Swift Current, Saskatchewan, Campbell et al. (1977b) also found WUE-G of spring wheat was increased by application of N, however, unlike this study they also found WUE-G levelled off at high rates of N application.

The WUE-G of each wheat-tillage regime was increased by the application of N. However, this increase was significant for winter wheat and spring wheat under zero tillage only. The shape of the response curves for the zero-tilled crops was curvilinear, thus essentially the same as those for grain yield and straw yield. The response curve for spring wheat under conventional tillage, however, was almost linear. The shape of the response curve, like the lack of significant increase in WUE-G with N application, likely resulted from the fewer number of N treatments and the variability of results associated with gravimetric analysis. The WUE-G of spring wheat under zero tillage was greater than that for spring wheat under conventional tillage at each rate of applied-N except 300 kg N ha^{-1}. This trend was very similar to that which occurred with respect to grain yield. Also similar was that at low rates of applied-N the WUE-G of spring wheat under zero tillage was greater than that of winter wheat under zero tillage whereas at high rates of N application the winter wheat made more efficient use of water. The WUE-G of spring wheat under zero tillage was greater than that for conventional tillage likely because of the slightly greater spring soil moisture content of zero tillage and the decreased evaporative loss of early spring moisture from the zero-tilled land, thereby providing the zero-tilled spring wheat with greater moisture reserves further into the growing season. In a lysimeter study conducted near Swift Current, Saskatchewan, Campbell et al. (1977b) found that the WUE-G of spring wheat was considerably higher for a 'wet' moisture regime than a 'dry' one until 164 kg applied-N ha^{-1}, at which point they were equal. They also found that the WUE-G of spring wheat under the 'wet' moisture regime increased very rapidly with the initial increments of applied-N and then levelled-off as further additions of N were made. Conversely, the WUE-G of spring wheat under the 'dry' moisture regime exhibited a more gradual, almost linear increase with the increased application of N. The results of Campbell et al. were analogous to those in this study between spring wheat under conventional and zero tillage and they substantiate the premise that the standing stubble of the zero tillage allowed for less rapid evaporative loss of early season moisture, thus providing for greater moisture availability to the crop. The effect of this conservation of soil moisture was overcome by the combination of high N application and high growing season precipitation as indicated by the similarity of results at very high levels of N application. Conversely, levels of WUE-G would likely have shown a greater difference, as would have levels of yield, had the fertilizer N been banded (Harapiak et al., 1986). As previously noted, the WUE-G of winter wheat under zero tillage was greater than the WUE-G of spring wheat under zero tillage at high rates of applied-N, only. At low rates the opposite trend occurred. However, as discussed during the comparison of grain yields, N fertilizer was applied to the winter wheat in fall whereas it was applied to spring wheat in spring. Therefore, because spring application of N fertilizer is more efficient than fall application, it is quite likely that the WUE-G for winter wheat would have surpassed that for spring wheat at each rate of applied-N, had the varieties been fertilized at the same time.

4.1.9 Water use efficiency based on yield of grain plus straw.

Water use efficiency based on yield of grain plus straw of each wheat-tillage regime was increased by the application of N (Figure 4.5 and Table 4.14). Water use efficiency based on yield of grain plus straw of winter wheat under zero tillage was significantly increased from 20.9 kg ha^{-1} mm^{-1} with the control to 36.1 kg ha^{-1} mm^{-1} when 300 kg ha^{-1} of N (the maximum rate) was applied. Levelling-off of WUE-GS by the 90 kg applied-N ha^{-1} treatment, however, was indicated by lack of significant difference in levels of WUE-GS for treatments greater than and including the 90 kg applied-N ha^{-1} rate. An R^2 value of 0.58^{**} indicated that a highly significant relationship existed between WUE-GS and N application.

Water use efficiency based on yield of grain plus straw of spring wheat under zero tillage was significantly increased from 24.6 kg ha^{-1} mm^{-1} with the control to 35.1 kg ha^{-1} mm^{-1} with 180 kg applied-N ha^{-1}. However, WUE-GS was not significantly different for treatment rates greater than the control, thereby indicating the very early levelling-off of WUE-GS. An R^2 value of 0.54^{**} indicated that a highly significant relationship existed between WUE-GS and applied-N. Near Swift Current, Saskatchewan, Campbell et al.

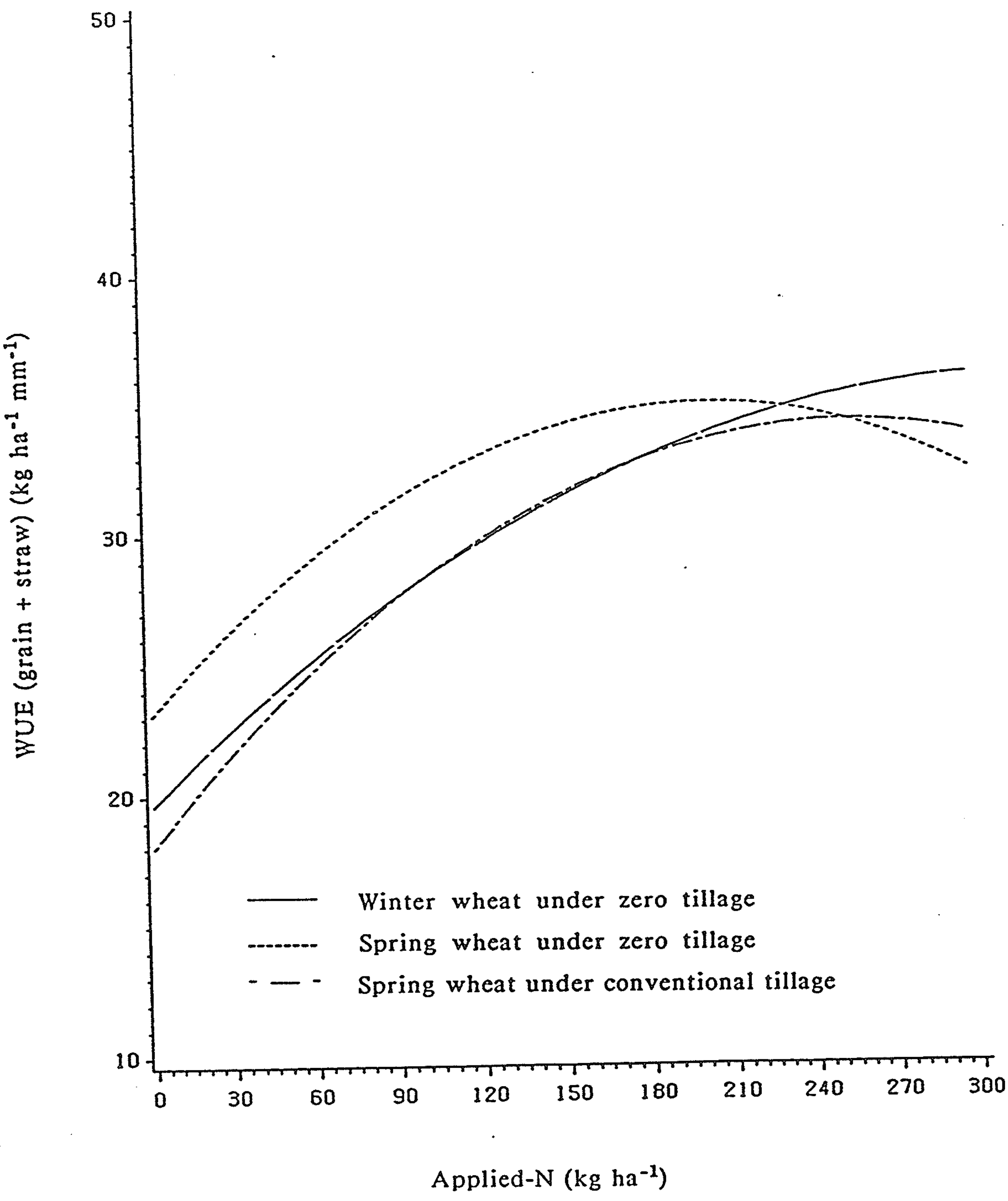


Figure 4.5. Lines of best fit for water use efficiency (WUE) (based on yield of grain plus straw) as affected by rate of applied-N (1985).

Table 4.14. Water use efficiency (WUE) based on grain plus straw yield (kg ha^{-1} mm^{-1}) as affected by rate of applied-N (1985)

	Wheat-till regime								
	Winter wheat zero till			Spring wheat zero till			Spring wheat conventional till		
Applied-N (kg ha^{-1})	Predicted WUE[1]	Upper 95% confidence limit	Lower 95% confidence limit	Predicted WUE[2]	Upper 95% confidence limit	Lower 95% confidence limit	Predicted WUE[3]	Upper 95% confidence limit	Lower 95% confidence limit
12	20.9	27.0	14.8	24.6	28.7	20.6	20.1	24.8	15.4
30	--	--	--	--	--	--	--	--	--
60	25.2	29.1	21.3	29.3	31.8	26.8	25.4	28.8	22.0
90	27.6	31.8	23.4	31.5	34.2	28.8	--	--	--
120	--	--	--	--	--	--	--	--	--
180	33.0	38.3	27.7	35.1	38.7	31.5	33.7	38.5	29.0
240	--	--	--	--	--	--	--	--	--
300	36.1	42.8	29.4	32.5	37.0	28.0	34.7	39.9	29.4

[1] $Y = 19.6 + 0.103N - 1.61{*}10^{-4}N^2$, $R^2 = 0.58^{**}$.

[2] $Y = 23.2 + 0.118N - 2.92{*}10^{-4}N^2$, $R^2 = 0.54^{**}$.

[3] $Y = 18.5 + 0.131N - 2.57{*}10^{-4}N^2$, $R^2 = 0.74^{**}$.

(1977a) using lysimeters also found that WUE-GS of spring wheat was increased by N application and that WUE-GS levelled off with increased rates of N application.

Water use efficiency based on yield of grain plus straw of spring wheat under conventional tillage was also increased by the application of N. Water use efficiency was significantly increased from 20.1 kg ha^{-1} mm^{-1} with the control to 34.7 kg ha^{-1} mm^{-1} with the application of 300 kg N ha^{-1} (the maximum rate applied). The levelling-off of WUE-GS by 180 kg applied-N ha^{-1} was also indicated, however, by the lack of significant difference between levels of WUE-GS for the 180 and 300 kg N ha^{-1} treatments. An R^2 value of 0.74^{**} indicated that a highly significant relationship existed between WUE-GS and rate of N application. In a lysimeter study near Swift Current, Saskatchewan, Campbell et al. (1977a) also found that the WUE-GS of spring wheat was increased by the application of N and that WUE-GS levelled off at high rates of N application.

The WUE-GS of each wheat-tillage regime was significantly increased by the application of N, although the levelling-off of WUE-GS also occurred as rates of N application increased. The WUE-GS of spring wheat under zero tillage surpassed that of spring wheat under conventional tillage at each rate of applied-N except the maximum rate. The greater levels of WUE-GS for spring wheat under zero tillage were attributed to the slightly greater spring soil moisture content of the zero-tilled land and the reduced evaporative loss of early spring moisture from the zero-tilled land, thereby providing for greater soil moisture levels further into the growing season. The WUE-GS of winter wheat, however, was similar to that of spring wheat under conventional tillage. This was attributed to the much lower straw yield of winter wheat. As previously discussed, the lower straw yield of winter wheat was attributed to low precipitation at critical growth stages and the use of a less crop tolerant herbicide program on the winter wheat.

4.2 1985-86 Crop Year.

Straw samples from each wheat tillage-regime were not bulked prior to analysis for N content in the second crop year. This enabled the statistical analysis of N content of the straw, N uptake by grain plus straw and percent recovery of applied-N by grain plus straw, in addition to the yield parameters so analyzed in the first crop year.

4.2.1 Environmental conditions.

Records from the Morden CDA weather station for the period September 1, 1985 to April 30, 1986 indicate that 262 mm of precipitation was received and that this was slightly greater than the long-term average of 244 mm (Table 4.15). The 97 mm of precipitation received during the month of April 1986, however, was over twice the long-term average. As a result seeding in the area was delayed and any moisture advantage due to overwinter snow trapping was minimized.

Cumulative snow cover was similar for the zero tillage main blocks but considerably lower for the conventional till main block (Table 4.16). High precipitation in April, however, negated a soil moisture advantage in the zero till blocks (Table 4.15). Soil moisture content at time of spring wheat seeding (May 21) was 522 mm (111 % of field capacity), 517 mm (110 % of field capacity) and 535 mm (113 % of field capacity) to the 120 cm depth of soil for winter wheat under zero tillage, spring wheat under zero tillage and spring wheat under conventional tillage, respectively (Table 4.17). These abnormally high levels of spring soil moisture were considered the result of a layer of frost (encountered between the 90 and 120 cm depth) inhibiting the downward movement of soil moisture. Once the frost layer melted, soil moisture content would have fallen to the level

Table 4.15. Monthly precipitation (mm) at the plot site and the Morden CDA weather station and long-term average monthly precipitation (mm) for the Morden CDA weather station

	1985-86 Crop year		Long-term average
	Plot site	Morden CDA	Morden CDA
September	--	23	52
October	--	39	32
November	--	54	26
December	--	10	22
January	--	16	24
February	--	11	19
March	--	11	28
April	--	97	41
May	67	76	66
June	59	34	46
July	68	98	73
August	23	18	71
September to April	--	261	244
May to August	217	226	286
September to August	--	487	530

Table 4.16. Cumulative snow depth (cm) readings[1] at the plot site during the 1985-86 winter

Date (month /day)	Winter wheat under zero tillage	Spring wheat under zero tillage	Spring wheat under conventional tillage
11/27	17	22	9
12/10	22	22	13
12/18	21	19	7
1/7	27	23	11
1/21	22	21	9
2/4	23	25	13
3/8	26	29	17
3/5	19	30	22
3/18	1	16	5
4/1	0	0	0

[1] mean of 3 measurements; 1 on each of replicates 2, 4 & 6.

Table 4.17. Spring soil moisture content (mm) and consumptive water use (mm) to the 120 cm depth[1] during the 1985-86 crop year

	Spring soil moisture content	Consumptive water use
Winter wheat under zero tillage	522	346
Spring wheat under zero tillage	517	345
Spring wheat under conventional tillage	535	397

[1] mean of all samples taken within each main block.

of field capacity (Table 3.1).

The high precipitation in April also provided the soil with a moisture reserve that was able to maintain crop yields during a growing-season of below average precipitation. Precipitation during the 1986 growing season was 217 mm at the plot site and 231 mm at the Morden CDA weather station (Table 4.15). This was substantially lower than the 339 mm and the 412 mm received in 1985 at the plot site and Morden, respectively, and somewhat lower than the long term average at the Morden CDA weather station (286 mm). Precipitation distribution was such that only 3 mm of precipitation fell during the 3 weeks prior to tillering of winter wheat (approximately June 2) (Table 4.18). After this precipitation occurred regularly until the winter wheat harvest (August 11). However, only 2 mm of rain fell during the 2 1/2 weeks prior to spring wheat harvest (August 27). Therefore, two extended periods without precipitation occurred: one just prior to winter wheat tillering and during spring wheat emergence, and the second during grain development and filling of spring wheat. Despite the poor level of and the timeliness of growing season precipitation early spring soil moisture levels were excellent. Thus, although yields were considerably lower than those obtained in 1985, yields of spring wheat under conventional tillage (from 2412 to 3548 kg ha^{-1}) were similar to that reported as

Table 4.18. Daily precipitation (mm) during the 1986 growing season at the plot site and at the Morden CDA weather station

	Plot site				Morden CDA			
Day	May	June	July	August	May	June	July	August
1	0	0	0	2	0	0	0	2
2	0	8	0	0	0	0	0	0
3	0	0	10	6	0	0	9	5
4	0	0	0	3	4	0	2	2
5	8	0	2	0	13	0	0	3
6	5	10	0	0	0	3	0	0
7	0	0	0	3	0	0	1	2
8	0	0	0	0	2	0	0	2
9	0	2	0	0	1	1	0	1
10	8	0	12	0	0	0	15	0
11	43	0	12	0	52	0	0	0
12	0	2	5	0	0	0	6	0
13	0	0	4	0	0	0	4	0
14	0	0	0	0	0	3	0	0
15	0	9	0	0	0	8	0	0
16	0	0	0	0	0	0	0	0
17	0	0	0	0	0	0	0	0
18	0	0	0	0	0	0	0	0
19	0	0	10	0	0	7	1	0
20	0	12	0	0	0	9	6	0
21	0	13	0	0	0	0	0	0
22	0	3	0	2	0	2	0	1
23	0	0	0	0	4	0	0	0
24	3	0	0	0	0	0	0	0
25	0	0	0	0	0	1	2	0
26	0	0	4	0	0	0	28	0
27	0	0	0	0	0	0	11	0
28	0	0	4	0	0	0	0	0
29	0	0	5	0	0	0	12	0
30	0	0	0	0	0	0	0	0
31	0	--	0	0	0	--	1	0
Total	67	59	68	23	76	34	98	18

the long-term average (2837 kg ha^{-1}) for this variety in Crop Variety Zone No. 2 (Manitoba Agriculture 1988 Field Crop Variety Recommendations for Manitoba). Therefore, although the 1986 growing season was not as good as that in 1985, it did provide for average yields.

Characterization of the soil indicated that soil K and S levels were adequate for maximum wheat yields (Table 4.19). Soil P levels of 7.9 and 11.6 kg P ha^{-1} for the winter and spring wheat main blocks, respectively, were considered less than adequate. Therefore, 25 kg P ha^{-1}, as 11-51-0, was placed with the seed in all subplot treatments to ensure adequate P levels. Soil NO_3-N was 7.6 and 7.7 kg ha^{-1} to the 60 and 120 cm depths, respectively, for the winter wheat main block, at time of seeding. Soil NO_3-N was 33.6 and 47.4 kg ha^{-1} to the 60 and 120 cm depths, respectively, for the spring wheat main block at time of seeding. Soil NO_3-N levels to 60 cm depths for winter wheat and spring wheat were designated 'very low' and 'medium minus' respectively, by the Manitoba Provincial Soil Testing Laboratory. Thus, a response to applied-N was expected. The higher soil NO_3-N level for the spring wheat main block was attributed to fall and early spring mineralization of organic-N, i.e. the winter wheat main block was sampled in September whereas the spring wheat main blocks were sampled in May. Soil pH, conductivity and organic matter levels

Table 4.19. Soil characteristics at the 1985-86 plot site

pH, water extract, (0-15 cm depth)			6.1
Conductivity (dSm^{-1}), water extract, (0-15 cm depth)			0.3
Organic matter (%), (0-15 cm depth)			5.2
NO_3-N (kg ha^{-1})[a]	Winter wheat	(0-60 cm depth)	7.6
		(0-120 cm depth)	7.7
	Spring wheat	(0-60 cm depth)	33.6
		(0-120 cm depth)	47.4
P (kg ha^{-1}), $NaHCO_3$ extractable, (0-15 cm depth)			9.8
K (kg ha^{-1}), NH_4OAc extractable, (0-15 cm depth)			527
SO_4-S (kg ha^{-1}), (0-60 cm depth)			16.0
(0-120 cm depth)			88.0

[a] winter wheat sampled in September prior to seeding and spring wheat sampled in May prior to seeding (mean of 3 samples for each crop).

were considered normal for this soil type (Table 4.19).

Winter wheat was seeded on September 10 into a firm, moist seedbed on undisturbed barley stubble (approximately 20 cm high) and the urea-N fertilizer was broadcast on September 19. Seven mm of rain fell on September 13 and 13 mm fell on September 20 ensuring adequate moisture for germination and crop emergence. The 13 mm of precipitation that fell on September 20 should also have been adequate to move the urea-N into the soil. Crop emergence was uniform, however, fall growth appeared slow and the crop entered freeze-up at the 2 to 3 leaf stage. Although plant counts were not taken, spring regrowth of the winter wheat appeared uniform and normal. Thus winter survival was good despite the retarded fall growth.

Spring Wheat under zero and conventional tillage were seeded on May 21 into a firm, moist seedbed on undisturbed barley stubble and tilled soil, respectively. Crop emergence was uniform. Urea-N was broadcast May 29, and the 8 and 10 mm of precipitation received on June 2 and June 6, respectively, should have adequately moved the fertilizer into the soil.

Leaf rust began to appear on the winter wheat in mid-June, thus on June 17 the winter wheat was sprayed with the fungicide TILT. Leaf rust, septoria and tan spot began to reappear and appear on the winter wheat and spring wheat, respectively, in mid-July. On July 22 both crops were sprayed with TILT for control of these diseases. Disease control appeared good.

The winter wheat was harvested on August 11. The spring wheats were harvested on August 28 and 29.

Consumptive water use was the same for winter wheat and spring wheat under zero tillage (346 and 345 mm, respectively) (Table 4.17). However, the consumptive water use of spring wheat under conventional tillage was considerably higher (397 mm). This was attributed to a greater evaporative loss of soil moisture prior to crop canopy development of the spring wheat under conventional tillage. Aase and Siddoway (1980) and Brun (1985) have reported similar results.

The levels of consumptive water use reported here were likely higher than those that actually occurred because, as previously stated, spring soil moisture levels were artificially inflated by the frost layer inhibiting the downward movement of soil moisture. Accordingly, water use efficiency levels would have been slightly higher than those reported.

4.2.2 Grain yield.

Grain yield of each wheat-tillage regime was increased by the application of N (Figure 4.6 and Table 4.20). Grain yield of winter wheat under zero tillage increased significantly from 2647 kg ha^{-1} with the control (12 kg applied-N ha^{-1}, as 11-51-0) to 3598 kg ha^{-1} when 180 kg N ha^{-1} was applied. An R^2 value of 0.44^{**} indicated a highly significant relationship between N application and grain yield. Although maximum grain yield was achieved with the 180 kg applied-N ha^{-1} treatment, the grain yield at 90 kg applied-N ha^{-1} was not significantly different, and thus grain yield was levelling-off by 90 kg applied-N ha^{-1}. Grain yield of winter wheat under zero tillage was found to be increased by the application of N although yield levelled-off at high rates of application by Grant (1982) during 2 years of study near Minnedosa, Manitoba. Similar reports have also been made by Fowler (1983) and Jan and Bowren (1984), based on several site-years of study in the Parkland region of Saskatchewan. Grain yields of winter wheat from this study were greater than those obtained by Grant in her first year of study but less than those reported for the second year, at comparable rates of N application. Yields from this study were greater than

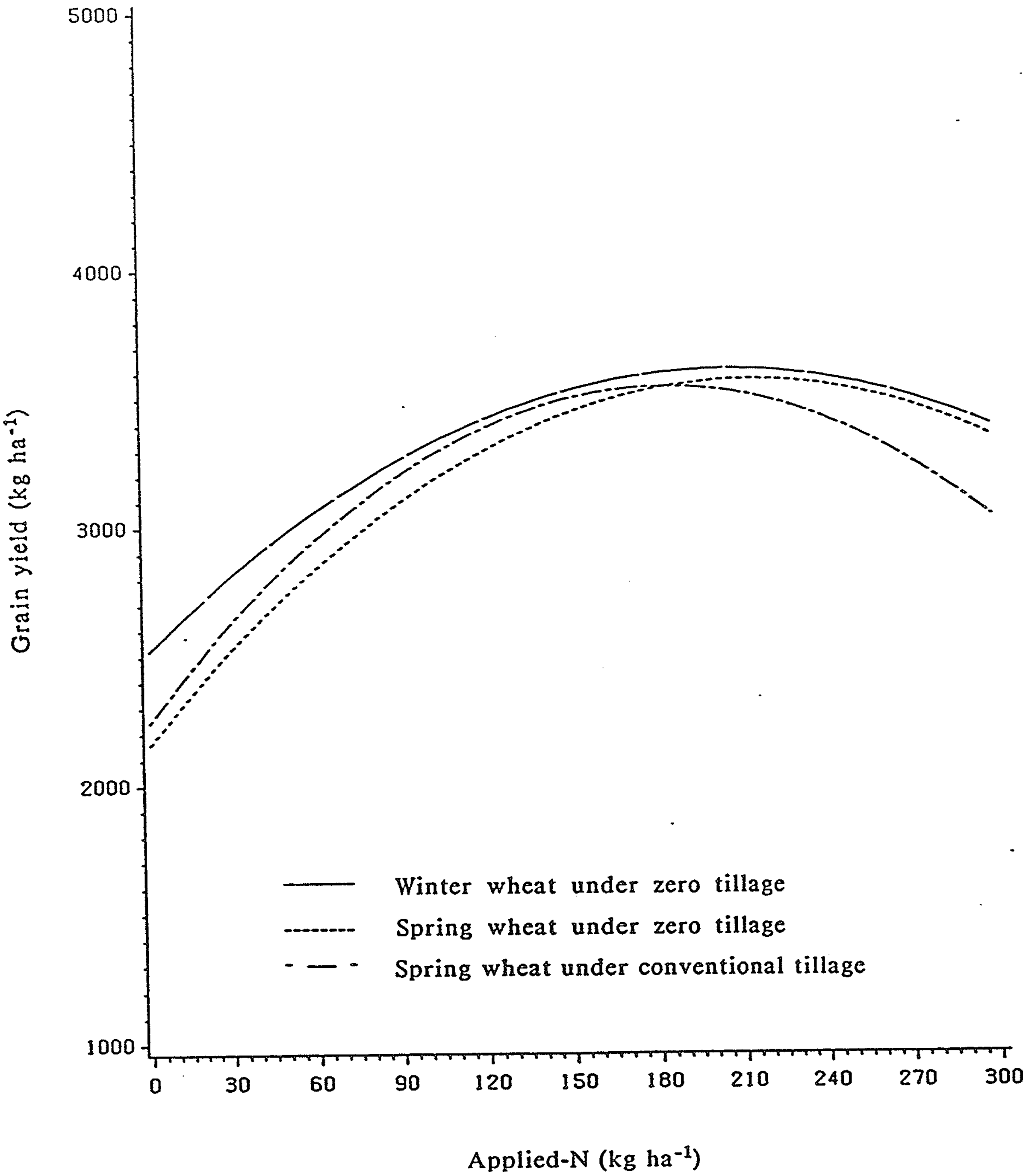


Figure 4.6. Lines of best fit for grain yield as affected by rate of applied-N (1986).

Table 4.20. Grain yield (kg ha^{-1}) as affected by rate of applied-N (1986)

	Wheat-till regime								
	Winter wheat zero till			Spring wheat zero till			Spring wheat conventional till		
Applied-N (kg ha^{-1})	Predicted yield[1]	Upper 95% confidence limit	Lower 95% confidence limit	Predicted yield[2]	Upper 95% confidence limit	Lower 95% confidence limit	Predicted yield[3]	Upper 95% confidence limit	Lower 95% confidence limit
12	2647	2880	2413	2317	2528	2105	2412	2664	2160
30	2815	2998	2632	2527	2692	2362	--	--	--
60	3064	3207	2921	2841	2970	2713	2955	3137	2772
90	3267	3419	3115	3099	3236	2962	--	--	--
120	3424	3598	3250	3302	3459	3144	--	--	--
180	3598	3785	3412	3540	3710	3370	3548	3803	3293
240	3587	3764	3411	3556	3717	3395	--	--	--
300	3391	3682	3101	3349	3614	3084	3033	3315	2752

[1] $Y = 2519 + 10.63N - 2.573*10^{-2}N^2$, $R^2 = 0.44^{**}$.

[2] $Y = 2158 + 13.24N - 3.091*10^{-2}N^2$, $R^2 = 0.61^{**}$.

[3] $Y = 2243 + 14.17N - 3.846*10^{-2}N^2$, $R^2 = 0.62^{**}$.

those reported by Fowler. Therefore, yields obtained in this study were considered approximately average.

Grain yield of spring wheat under zero tillage was increased significantly from 2317 kg ha^{-1} with the control to 3556 kg ha^{-1} when 240 kg N ha^{-1} was applied. An R^2 value of 0.61^{**} indicated a highly significant relationship between N application and grain yield of winter wheat. However, the grain yield at 120 kg applied-N ha^{-1} was not significantly lower than that at 240 kg applied-N ha^{-1}, thereby indicating the levelling-off of grain yield by 120 kg applied-N ha^{-1}. Near Carman, Manitoba, Donaghy (1973) also found that the grain yield of spring wheat under zero tillage was increased by the application of N and that yield levelled-off at high rates of applied-N, at both sites of study. Jan and Bowren (1984) reported similar results from the mean of 4 years of study near Melfort, Saskatchewan. Results from this study were similar to those reported by Donaghy for the A site but less than those for the B site. Results from this study, however, were almost double those reported by Jan and Bowren. Therefore, grain yields of spring wheat under zero tillage obtained in this study were approximately average.

Grain yield of spring wheat under conventional tillage was increased significantly from 2412 kg ha^{-1} with the control to 3548 kg ha^{-1} when 180 kg N ha^{-1} was applied, although grain yield began levelling-off at some point between 60 and 180 kg applied-N ha^{-1}. An R^2 value of 0.62^{**} indicated a highly significant relationship between N application and grain yield. Other researchers in southern Manitoba and the Parkland region of Saskatchewan have also found that grain yield of spring wheat under conventional tillage was increased by application of N and that grain yield levelled-off (or began to) at high rates of applied-N (Alkier et al., 1972; Donaghy, 1973; Racz, 1974; Fowler, 1983; Jan and Bowren, 1984; Gehl et al., 1986). The long-term average grain yield for Neepawa spring wheat under conventional tillage for the plot site Crop Variety Zone is 2837 kg ha^{-1} (Manitoba Agriculture 1988 Field Crop Variety Recommendations for Manitoba). The yields obtained in this study were similar to slightly above this long-term average. Similarly, they were slightly above, at comparable rates of N application, those reported by Alkier et al. (1972) as the mean of 5 non-fallow sites in southern Manitoba, by Donaghy (1973) for 2 sites near Carman, Manitoba, by Racz (1974) as the mean of 12 non-fallow sites in southern Manitoba, by Jan and Bowren (1984) as the mean of 4 years of study near Melfort, Saskatchewan, and by Gehl et al. (1986) for 3 sites in southern Manitoba with Katepwa spring wheat. Grain yields of spring wheat under conventional tillage obtained in this study were therefore average to slightly above average.

The grain yield of each wheat-tillage regime was significantly increased by N fertilization. Grain yield of each wheat-tillage regime also levelled-off as rates of N neared that rate which provided for maximum yield. This response to applied-N indicated that the soil NO_3-N levels did not provide sufficient available N for maximum yield in this year of average precipitation. The grain yields and shape of the N response curve was similar for each wheat-tillage regime. However, grain yield of spring wheat under conventional tillage was slightly greater than that under zero tillage, up to the 180 kg applied-N ha^{-1} treatment. In essence, the N response curve for spring wheat under zero tillage was very much like that for conventional tillage except that it was 'shifted' slightly to the 'right'. This trend is the opposite of that which occurred in the first crop year, however, it was also reported by Donaghy (1973). In this study, this trend also occurs with straw yield, N content of the straw and N uptake by grain plus straw. Spilde and Deibert (1986) found soil NO_3-N level declined after even one year of zero tillage due to reduced mineralization and Deibert et al., (1986) concluded that only after 8 years of zero tillage would the mineralization capacity of a zero-tilled soil equal that of a conventionally tilled soil. Also, in a review on the subject, Harapiak et al. (1986) concluded that considerably more applied-N is lost from zero-tilled fields than from conventionally tilled fields, especially when surface-applied and when urea is the N source (the very same application method and N source used in this study). The trend in this study whereby the N response of spring wheat under zero tillage was similar but 'slower' than that of spring wheat under conventional tillage was therefore attributed to a lower N supply with the zero tillage. A second trend with respect to grain yield was that winter wheat under zero tillage slightly outyielded the spring wheat crops at all rates of N application. This was attributed to a more efficient use of moisture by the winter wheat, due to its advanced growth period. Spring soil moisture content and consumptive water use were the same for winter wheat under zero tillage and spring wheat under zero tillage. However, by avoiding more of the summer heat stress because of its earlier maturity, the winter wheat would have gained a yield advantage (Fowler, 1983; Rourke and Stobbe, 1984).

4.2.3 Straw yield.

The straw yield of each wheat-tillage regime was increased by the application of N (Figure 4.7 and Table

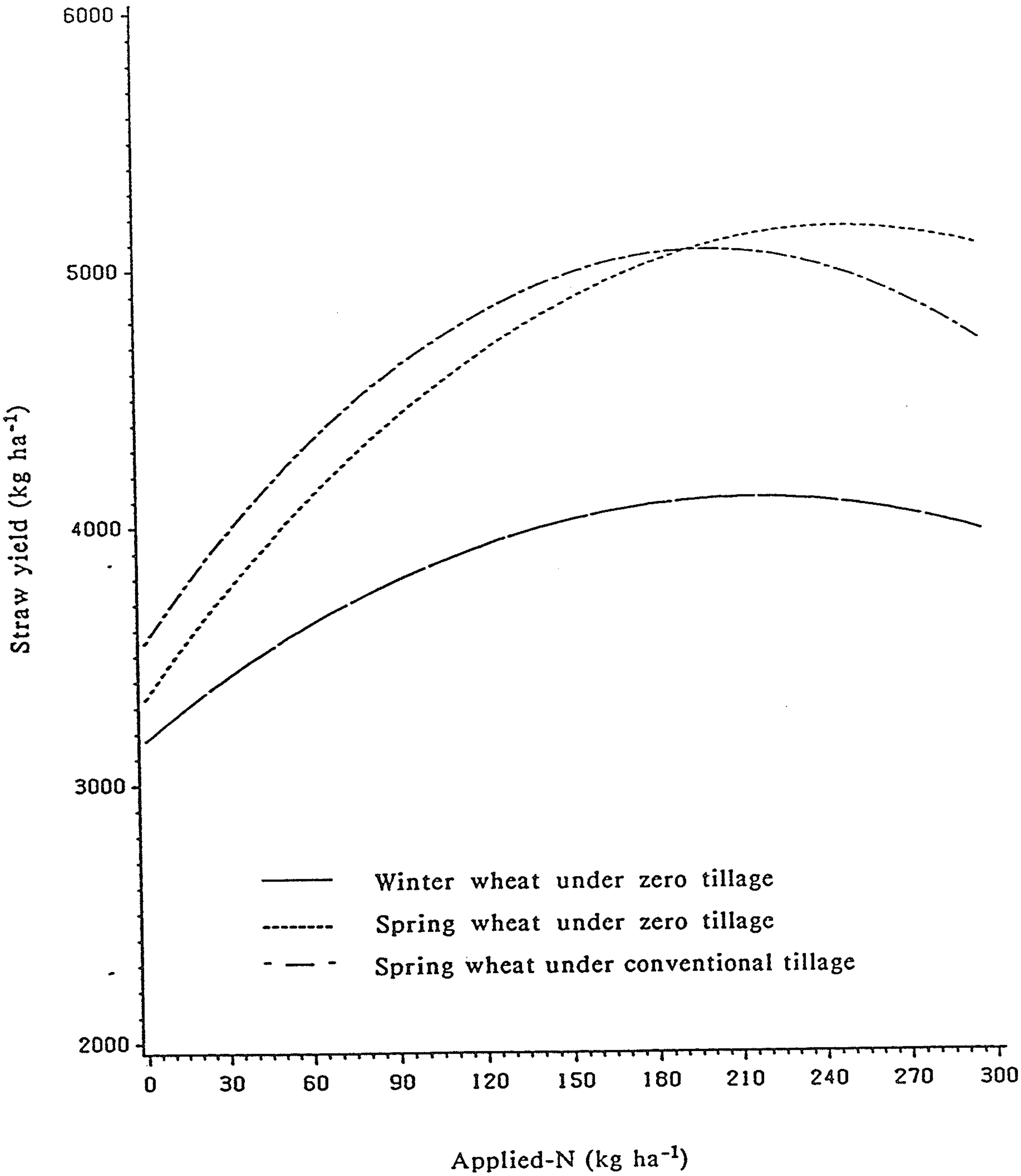


Figure 4.7. Lines of best fit for straw yield as affected by rate of applied-N (1986).

Table 4.21. Straw yield (kg ha^{-1}) as affected by rate of applied-N (1986)

	Wheat-till regime								
	Winter wheat zero till			Spring wheat zero till			Spring wheat conventional till		
Applied-N (kg ha^{-1})	Predicted yield[1]	Upper 95% confidence limit	Lower 95% confidence limit	Predicted yield[2]	Upper 95% confidence limit	Lower 95% confidence limit	Predicted yield[3]	Upper 95% confidence limit	Lower 95% confidence limit
12	3274	3609	2939	3508	3823	3194	3731	4098	3363
30	3413	3676	3150	3747	3992	3501	--	--	--
60	3621	3826	3415	4110	4301	3919	4326	4592	4060
90	3792	4010	3574	4419	4623	4216	--	--	--
120	3926	4176	3677	4675	4909	4441	--	--	--
180	4087	4355	3819	5026	5278	4773	5061	5433	4688
240	4102	4355	3849	5162	5401	4923	--	--	--
300	3971	4387	3554	5084	5478	4691	4699	5109	4289

[1] $Y = 3169 + 8.737N - 2.0215*10^{-2}N^2$, $R^2 = 0.23^{**}$.

[2] $Y = 3330 + 14.78N - 2.978*10^{-2}N^2$, $R^2 = 0.57^{**}$.

[3] $Y = 3548 + 15.25N - 3.806*10^{-2}N^2$, $R^2 = 0.54^{**}$.

4.21). Straw yield of winter wheat under zero tillage was increased significantly from 3274 kg ha^{-1} with the control to 4102 kg ha^{-1} when 240 kg N ha^{-1} was applied. An R^2 value of 0.23^{**} indicated a highly significantly but low relationship between N application and straw yield. Lack of significant difference with respect to straw yield for rates of applied-N between 90 and 240 kg N ha^{-1} indicated that straw yield was levelling-off by the 90 kg applied-N ha^{-1} treatment. Although their work was done using conventional tillage, Ramig and Rhoades (1963) and Stanford and Hunter (1973) also found straw yield of winter wheat was increased by N application and that straw yield levelled off as rates of N application increased.

Straw yield of spring wheat under zero tillage was increased significantly from 3508 kg ha^{-1} with the control to 5162 when 240 kg N ha^{-1} was applied. Thus, straw yield and grain yield were both highest at 240 kg applied N ha^{-1}. An R^2 value of 0.57^{**} indicated that a highly significant relationship existed between straw yield and N application. Lack of significant difference between yields at the 180 and 240 kg applied-N ha^{-1} rates indicated that straw yield was levelling-off by 180 kg applied-N ha^{-1}. Although their work was with conventional tillage, McNeal et al. (1971) and Hamid (1973) also found straw yield was increased by N fertilization. Furthermore, Hamid found straw yield levelled off at high rates of N application. Although McNeal et al. did not show this levelling-off, the highest N rate they used was only 89.7 kg applied-N ha^{-1}. They would likely have found a levelling-off, too, had greater N been applied.

Straw yield of spring wheat under conventional tillage was increased significantly from 3731 kg ha^{-1} with the control to 5061 kg ha^{-1} when 180 kg N ha^{-1} was applied. Although straw yield at 180 kg applied-N ha^{-1} was not significantly different from that at 60 kg applied-N ha^{-1}, the shape of the response curve would indicate that a levelling-off of yield was occurring before the 180 kg applied-N ha^{-1} treatment. An R^2 value of 0.54^{**} indicated a highly significant relationship between straw yield and N applied. M^cNeal et al. (1971) and Hamid (1973) also found that straw yield of spring wheat under conventional tillage was significantly increased by N application.

The straw yield of each wheat-tillage regime was significantly increased by N application. Also, straw yield and grain yield were both highest at the same rate of N application in winter wheat under zero tillage and spring wheat under conventional tillage. Straw yield of spring wheat under zero tillage was highest with 180 kg applied-N ha^{-1}, whereas grain yield was highest at 120 kg applied-N

ha^{-1}, the next treatment lower. Straw yield was similar for spring wheat under zero tillage and spring wheat under conventional tillage. However, as previously discussed the straw yield of spring wheat under conventional tillage was slightly greater at low rates of applied-N while the straw of spring wheat under zero tillage was slightly greater at high rates of applied-N, ie. the N response of spring wheat under zero tillage was slower than that for spring wheat under conventional tillage. As was the case in the first year of this study, the straw yield of winter wheat under zero tillage was considerably lower than that for the spring wheats. Although little rain fell in the 3 weeks prior to winter wheat tillering, soil moisture (from earlier precipitation) was good, as indicated by the rapid germination and emergence of the spring wheat. As in the first crop year, the lower straw yield of winter wheat may have been due to herbicide use and timing. The winter wheat was sprayed with 0.138 L ha^{-1} of 500 g L^{-1} MCPA amine plus 0.058 L ha^{-1} of 400 g L^{-1} Dicamba on May 19 for broadleaf weed control, and with 0.575 L ha^{-1} of Hoe-Grass II (230 g L^{-1} Diclofop Methyl plus 80 g L^{-1} Bromoxynil ester) on June 4 for broadleaf and grassy weed control. Conversely, the spring wheat was sprayed (on June 4) with the Hoe-Grass II only. Thus the winter wheat was sprayed twice for broadleaf weeds whereas the spring wheat was sprayed only once. Furthermore, the initial herbicide treatment to winter wheat had only a 'fair' crop tolerance rating (Manitoba Agriculture 1988 Guide to Chemical Weed Control), and the second herbicide treatment (which had a 'good' crop tolerance rating) was applied at the tillering stage of winter wheat.

4.2.4 Protein content of the grain.

Protein content (%) of the grain of each wheat-tillage regime was increased by the application of N (Figure 4.8 and Table 4.22). Protein content of the grain of winter wheat under zero tillage was increased was significantly increased from 9.7 % with the control to 13.8 % at 240 and 300 kg applied-N ha^{-1}. An R^2 value of 0.82^{**} indicated a highly significant relationship between protein content and N application. The same level of protein content at the 240 and 300 kg applied-N ha^{-1} treatments indicated that protein content levelled off at high rates of N application. However, lack of significant difference in levels of protein content for the 180 and 240 kg N ha^{-1} treatments indicated that protein content was levelling-off by 180 kg applied-N ha^{-1}. Conversely, the means of observed data for protein content (Table 4.23) indicated that although protein content increased more slowly at high rates of N application, it did continue to increase with each higher increment of N. The

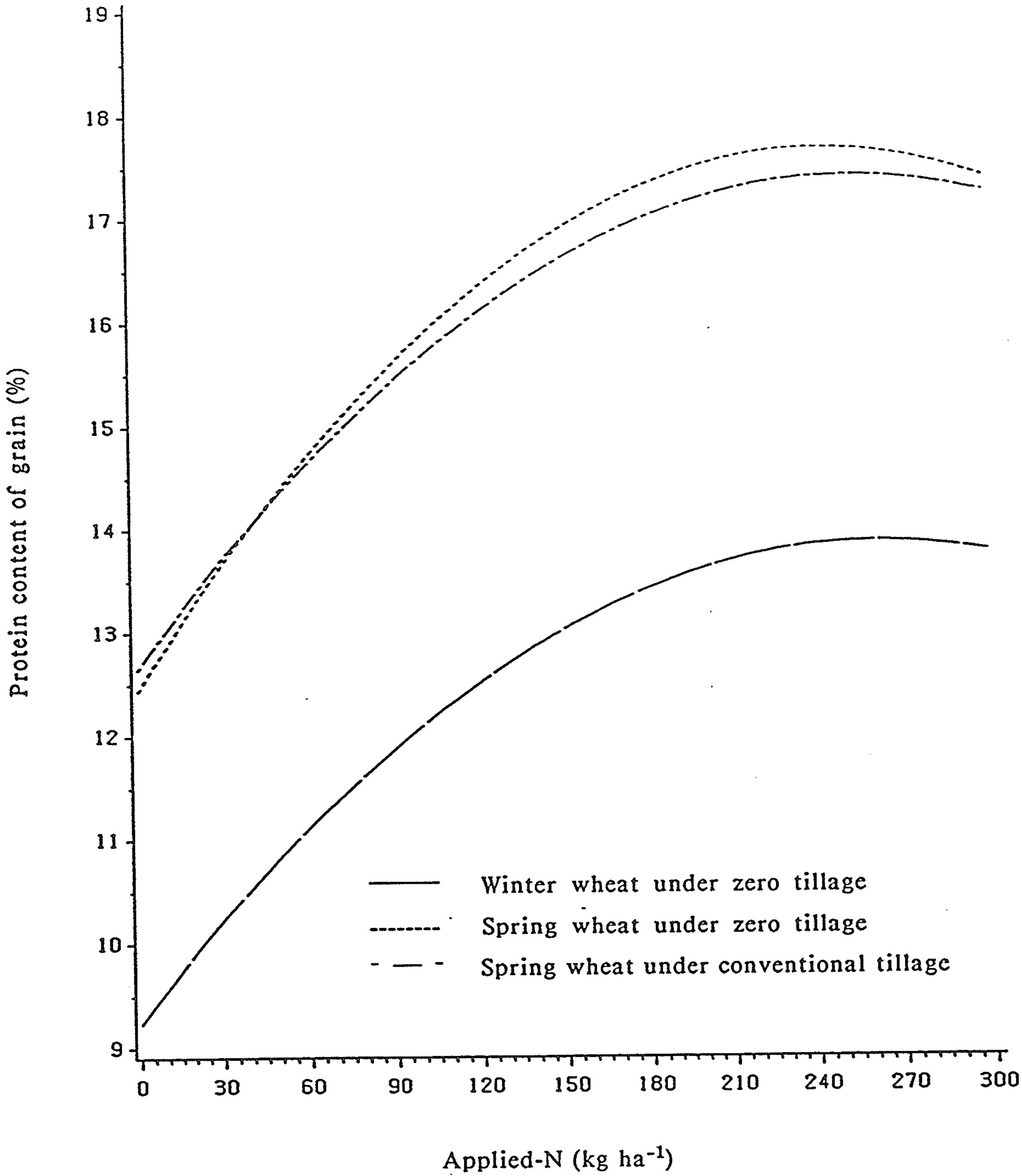


Figure 4.8. Lines of best fit for protein content of grain as affected by rate of applied-N (1986).

Table 4.22. Protein content (%) of grain as affected by rate of applied-N (1986)

	Wheat-till regime								
	Winter wheat zero till			Spring wheat zero till			Spring wheat conventional till		
Applied-N (kg ha^{-1})	Predicted protein content[1]	Upper 95% confidence limit	Lower 95% confidence limit	Predicted protein content[2]	Upper 95% confidence limit	Lower 95% confidence limit	Predicted protein content[3]	Upper 95% confidence limit	Lower 95% confidence limit
12	9.7	10.1	9.2	13.0	13.4	12.5	13.1	13.6	12.6
30	10.4	10.6	9.9	13.7	14.0	13.3	--	--	--
60	11.1	11.4	10.9	14.7	15.0	14.5	14.6	15.0	14.3
90	11.9	12.2	11.6	15.6	15.9	15.3	--	--	--
120	12.5	12.9	12.2	16.3	16.7	16.0	--	--	--
180	13.4	13.8	13.1	17.3	17.7	17.0	17.0	17.5	16.5
240	13.8	14.2	13.5	17.7	18.0	17.4	--	--	--
300	13.8	14.3	13.2	17.4	17.9	16.9	17.3	18.0	16.7

[1] $Y = 9.2 + 3.56*10^{-2}N - 6.80*10^{-5}N^2$, $R^2 = 0.82^{**}$.

[2] $Y = 12.4 + 4.33*10^{-2}N - 8.92*10^{-5}N^2$, $R^2 = 0.86^{**}$.

[3] $Y = 12.6 + 3.78*10^{-2}N - 7.47*10^{-5}N^2$, $R^2 = 0.89^{**}$.

Table 4.23. Means of observed data for protein content (%) of the grain as affected by rate of applied-N (1986)

Applied-N (kg ha^{-1})	Wheat-tillage regime		
	WWZT[1]	SWZT[2]	SWCT[3]
12	9.9	13.6	13.0
30	9.8	13.3	----
60	10.8	14.1	14.9
90	12.3	15.3	----
120	12.8	16.8	----
180	13.3	17.7	16.9
240	13.5	17.5	----
300	14.0	17.4	17.3

[1] winter wheat under zero tillage.
[2] spring wheat under zero tillage.
[3] spring wheat under conventional tillage.

means of observed data also showed little increase in protein content with the initial application of N, a trend not shown by the line of best fit. This trend, which was accompanied by large increases in grain and straw yield, indicated the biological dilution of plant protein. Working near Minnedosa, Manitoba, Grant (1982) also found that the protein content of the grain of winter wheat under zero tillage was increased by N application and that protein content levelled-off at high rates of applied-N, particularly in a dry year. Working in the Parkland region of Saskatchewan, Fowler (1983) obtained similar results. Grant also found the biological dilution of plant protein at low application of N. The levels of protein content obtained during the second crop year of this study were approximately mid way between those reported by Grant for the first and second year of study. The levels reported in this study were also approximately mid way between those reported by Fowler (1983) for a 'normal' and a 'dry' year. These comparisons provided further evidence that precipitation during the second crop year of this study was near normal.

Protein content of the grain of spring wheat under zero tillage was increased significantly from 13.0 % with the control to 17.7 % when 240 kg N ha^{-1} was applied. An R^2 value of 0.86^{**} indicated a highly significant relationship between applied-N and protein content. The lack of significant difference between levels of protein content at the 180 and 240 kg applied-N ha^{-1} treatments indicated the levelling-off of protein content at 180 kg applied-N ha^{-1}. Although the line of best fit did not show the biological dilution of plant protein at low rates of applied-N, the means of observed data did (Table 4.23). Donaghy (1973) working near Carman, Manitoba, and Jan and Bowren (1984) working near Melfort, Saskatchewan, also found that protein content of the grain of spring wheat under zero tillage was increased by the application of N. Although working with spring wheat under conventional tillage, Alkier et al. (1972) and Racz (1974) also found protein content was subject to the biological dilution of plant protein at low rates of N application.

Protein content of the grain of spring wheat under conventional tillage was increased significantly from 13.1 % with the control to 17.3 % at 300 kg applied-N ha^{-1}. An R^2 value of 0.89^{**} indicated a highly significant relationship between N fertilizer application and protein content of the grain. Protein content was very similar at 180 and 300 kg applied-N ha^{-1} according to the line of best fit and the means of observed data (Table 4.23). Therefore protein content levelled off at high rates of N application. Protein content did not exhibit the biological dilution of plant protein in either the line of best fit or the means of observed data. This may have been the result of too few treatment levels masking the phenomenon, or because lower growing season precipitation provided for less than maximum growth from the initial N treatments (Ramig and Rhoades, 1963). Other researchers in southern Manitoba and the Parkland region of Saskatchewan have also found protein content of the grain of spring wheat under conventional tillage was increased by application of N and that protein content levelled off (or began to) at high rates of applied-N (Alkier et al., 1972; Donaghy, 1973; Racz, 1974; Fowler, 1983; and, Jan and Bowren, 1984).

The protein content of the grain of each wheat-tillage regime was significantly increased by the application of N. Furthermore, in each wheat-tillage regime protein content began levelling-off by 180 kg applied-N ha^{-1}. This indicated that 180 kg N ha^{-1} was required in addition to the soil NO_3-N supply to maximize protein content. The means of observed data indicated the biological dilution of plant protein for winter wheat and spring wheat under zero tillage. Although it was not apparent for spring wheat under conventional tillage this was likely because the fewer number of N rate treatments masked the phenomenon. Protein content of the grain was similar for spring wheat under zero and conventional tillage. This was consistent with the results from the first crop year of this study and those of Jan and Bowren (1984). Donaghy (1973), however, found the protein content of the grain of spring wheat under zero tillage was significantly lower than that of spring wheat under conventional tillage. The lack of difference found in this study was attributed to the high amount of early spring precipitation which removed any moisture advantage from snow trap by zero tillage, and the good (55 mm) precipitation during the 2 1/2 weeks just prior to spring wheat flowering. The protein content of the grain of winter wheat under zero tillage was substantially lower (by approximately 3.5 %) than those of the spring wheats. This difference was attributed to differences in genetic make-up between winter and spring wheat. Fowler (1983) and Jan and Bowren (1984) have also reported this trend. Another difference between winter and spring wheats was that whereas the protein content of the spring wheats levelled off at the high rates of N application used in this study, the means of observed data showed that the protein content of the grain of winter wheat continued to increase, albeit not rapidly. Therefore, still higher levels of N application may reduce the degree of difference between spring and winter wheat with respect to protein content.

4.2.5 Nitrogen content of the straw.

Nitrogen content (%) of the straw of each wheat-tillage regime was increased by the application of N (Figure 4.9 and Table 4.24). Nitrogen content of the straw of winter wheat under zero tillage was significantly increased from 0.33 % with the control to 0.73 % at 240 and 300 kg applied-N ha^{-1}. An R^2 value of 0.79^{**} indicated a highly significant relationship between N application and N content of straw. The same level of N content of the straw at the 240 and 300 kg applied-N ha^{-1} treatments was evidence that N content levelled off at high rates of N application. However, lack of significant difference between levels of N content for the 180 and 240 kg applied-N ha^{-1} rates indicated this levelling-off began by the 180 kg applied-N ha^{-1} treatment. The means of observed data (Table 4.25) also showed this levelling-off. However, the means of observed data did not clearly show the biological dilution of plant protein as in the first crop year, although the only slight increase in N content from the control to 30 kg applied-N ha^{-1} would suggest that this had occurred. Ramig and Rhoades (1963) working with winter wheat under conventional tillage also found that N content of the straw was increased by N application. They also found that biological dilution of straw protein and grain protein became more apparent as preplanting soil moisture increased and that it was

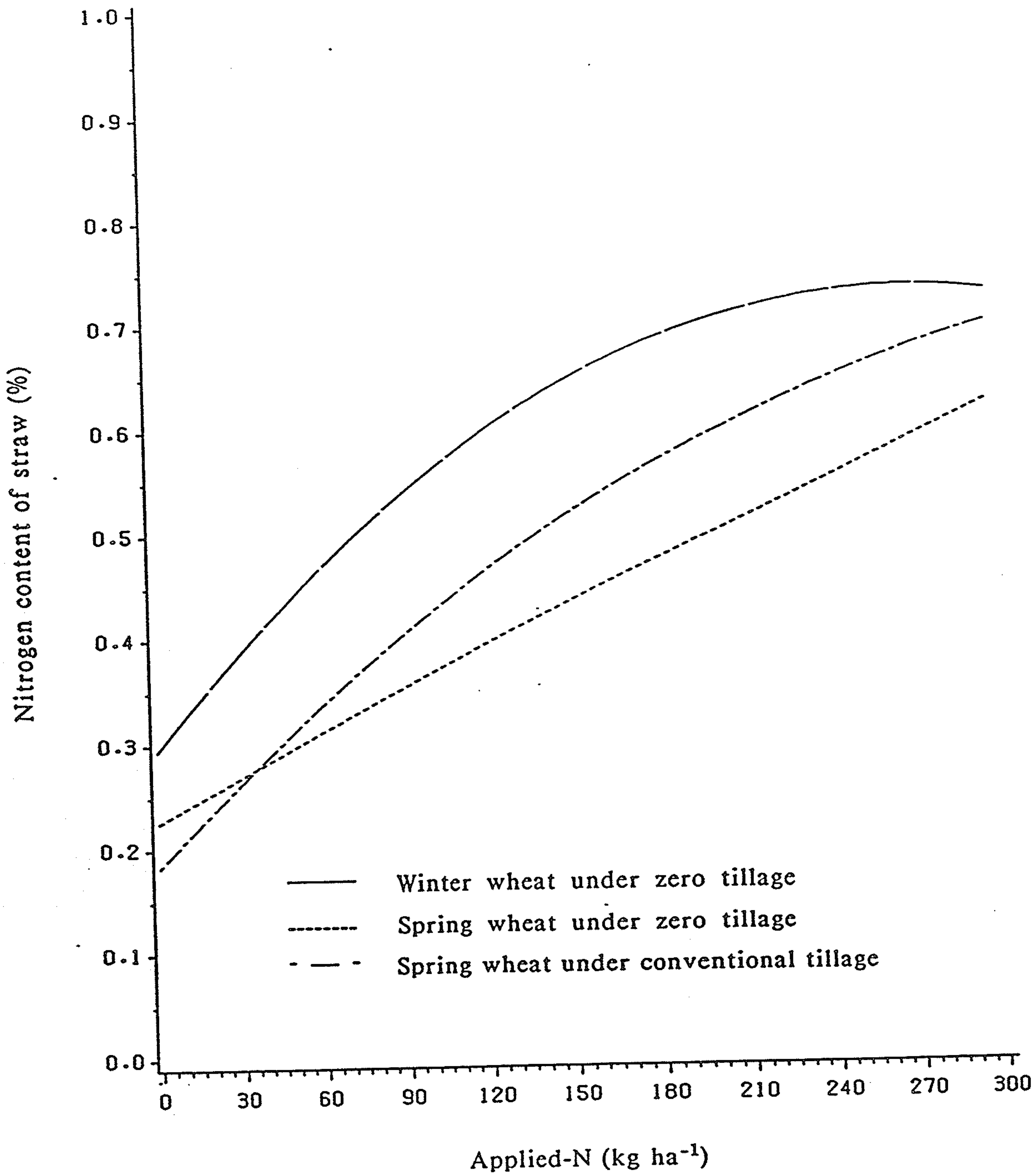


Figure 4.9. Lines of best fit for nitrogen content of straw as affected by rate of applied-N (1986).

Table 4.24. Nitrogen content (%) of straw as affected by rate of applied-N (1986)

	Wheat-till regime								
	Winter wheat zero till			Spring wheat zero till			Spring wheat conventional till		
Applied-N ($kg\ ha^{-1}$)	Predicted N content[1]	Upper 95% confidence limit	Lower 95% confidence limit	Predicted N content[2]	Upper 95% confidence limit	Lower 95% confidence limit	Predicted N content[3]	Upper 95% confidence limit	Lower 95% confidence limit
12	0.33	0.38	0.29	0.24	0.29	0.20	0.22	0.28	0.15
30	0.39	0.42	0.35	0.27	0.30	0.24	--	--	--
60	0.47	0.50	0.44	0.31	0.34	0.29	0.34	0.38	0.29
90	0.54	0.57	0.51	0.35	0.38	0.33	--	--	--
120	0.60	0.63	0.56	0.39	0.43	0.36	--	--	--
180	0.69	0.72	0.65	0.47	0.51	0.44	0.57	0.63	0.50
240	0.73	0.76	0.69	0.55	0.58	0.52	--	--	--
300	0.73	0.78	0.67	0.63	0.68	0.57	0.70	0.77	0.63

1 $Y = 0.29 + 3.27*10^{-3}N - 6.11*10^{-6}N^2$, $R^2 = 0.79^{**}$.

2 $Y = 0.23 + 1.45*10^{-3}N - 3.87*10^{-7}N^2$, $R^2 = 0.78^{**}$.

3 $Y = 0.18 + 2.76*10^{-3}N - 3.48*10^{-6}N^2$, $R^2 = 0.86^{**}$.

Table 4.25. Means of observed data for nitrogen content (%) of the straw[1] as affected by rate of applied-N (1986)

Applied-N ($kg\ ha^{-1}$)	Wheat-tillage regime		
	WWZT[1]	SWZT[2]	SWCT[3]
12	0.34	0.30	0.24
30	0.39	0.26	----
60	0.46	0.27	0.29
90	0.52	0.30	----
120	0.63	0.40	----
180	0.68	0.55	0.59
240	0.72	0.53	----
300	0.73	0.62	0.69

[1] winter wheat under zero tillage.
[2] spring wheat under zero tillage.
[3] spring wheat under conventional tillage.

non-existent at very low preplanting moisture. Although preplanting soil moisture was excellent in this study, little precipitation fell in the 3 weeks prior to winter wheat tillering and the growing season precipitation, in general, was only average. The apparent lack of biological dilution with respect to N content of the straw was thus possibly the result of a lack of precipitation.

Nitrogen content of the straw of spring wheat under zero tillage was significantly increased from 0.24 % with the control to 0.63 % at 300 kg applied-N ha^{-1}. An R^2 of 0.78^{**} indicated a highly significant relationship between N application and N content of the straw. Unlike protein content of the grain, N content of the straw did not level off at the rates of applied-N used in this study. Although the biological dilution of plant protein at low rates of applied-N was not shown by the line of best fit, the means of observed data (Table 4.25) did show this phenomenon. Nitrogen content of straw was lower for the 30 and 60 kg applied-N ha^{-1} treatments than for the control, and N content at the 90 kg applied-N ha^{-1} treatment was equal. McNeal et al. (1971) working with spring wheat under conventional tillage also found N content of the straw was increased by the application of N and that biological dilution of plant protein occurred at low rates of N application. However, McNeal et al. also found that N content of the straw began to level off at high rates of N application.

Nitrogen content of the straw of spring wheat under conventional tillage was increased significantly from 0.22 % with the control to 0.70 % when 300 kg N ha^{-1} was applied. An R^2 value of 0.86^{**} indicated a highly significant relationship between N application and N content of the straw. Although a levelling-off of N content at high rates of applied-N was not distinct, the shape of the response curve and lack of significant difference between levels of N content at 180 and 300 kg applied-N ha^{-1}, indicated that levelling-off had begun. Also not distinct was the biological dilution of plant protein at low rates of N application (Table 4.25). The N content of the straw (based on the means of observed data) at 60 kg applied-N ha^{-1} was only slightly greater than that at the control, however, thus the data did suggest biological dilution. The absence of clarity with respect to these trends may have been the result of the low number of N treatments masking the phenomena. However, the less than optimum growing season precipitation that provided for less than maximum yields would also have lessened the likelihood of biological dilution (Ramig and Rhoades, 1963). McNeal et al. (1971) and Alessi and Power (1973) also found N content of the straw of spring wheat under conventional tillage was increased by the N application. Furthermore, McNeal et al. found that data for N content of the straw indicated the biological dilution of plant protein at low rates of N application and that N content began to level off at high rates of N application.

Nitrogen content of the straw was significantly increased by the application of N with each wheat-tillage regime. This response to applied-N reflected the low soil N supply. The means of observed data indicated the biological dilution of plant protein at low rates of N application for spring wheat under zero tillage, and suggested the same for winter wheat under zero tillage and spring wheat under conventional tillage. The N content of the straw of spring wheat under conventional tillage surpassed that of spring wheat under zero tillage at each rate of N application except the control. This was attributed to a greater N supply for spring wheat under conventional tillage, due to those factors previously discussed. Nitrogen content of the straw of winter wheat under zero tillage, however, was considerably higher than that for spring wheat under both conventional and zero tillage. This trend was opposite to that with respect to yield of straw and protein content of grain. The lower straw yield for winter wheat possibly provided for the greater N content of the straw of winter wheat. However, genetic differences between varieties may also have been responsible for the differences observed.

4.2.6 Nitrogen uptake by grain plus straw.

Nitrogen uptake by the grain plus straw of each wheat-tillage regime was increased by the application of fertilizer-N (Figure 4.10 and Table 4.26). Nitrogen uptake by the grain plus straw of winter wheat under zero tillage increased significantly from 55 kg N ha^{-1} with the control to 116 kg N ha^{-1} when 240 kg ha^{-1} of N was applied. An R^2 value of 0.81^{**} indicated a highly significant relationship between application of fertilizer-N and N uptake by winter wheat. The lack of significant difference between levels of N uptake at 180 and 240 kg applied-N ha^{-1} plus the significant difference between levels of N uptake at 120 and 180 kg applied-N ha^{-1} indicated the levelling-off of N uptake by the 180 kg applied-N ha^{-1} treatment. Working with winter wheat under conventional tillage, Ramig and Rhoades (1963) and Stanford and Hunter (1973) also found N uptake was increased by N application and that this increase levelled-off at high rates of application.

Nitrogen uptake by the grain plus straw of spring wheat under zero tillage was significantly increased from 60 kg N ha^{-1} with the control to 137 kg N ha^{-1} at 240 kg applied-N

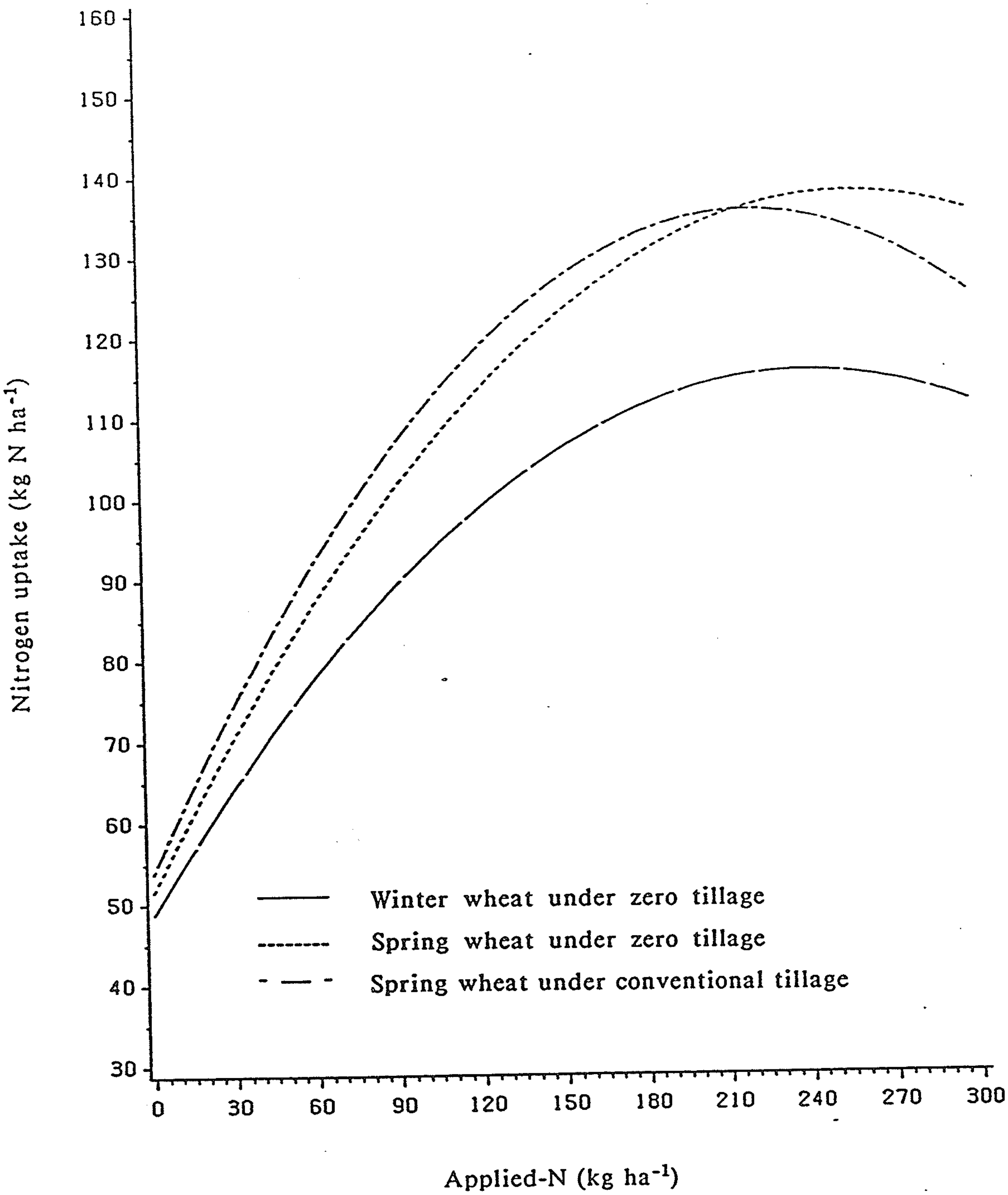


Figure 4.10. Lines of best fit for nitrogen uptake by grain plus straw as affected by rate of applied-N (1986).

Table 4.26. Nitrogen uptake (kg N ha^{-1}) by grain plus straw as affected by rate of applied-N (1986)

	Wheat-till regime								
	Winter wheat zero till			Spring wheat zero till			Spring wheat conventional till		
Applied-N (kg ha^{-1})	Predicted N uptake[1]	Upper 95% confidence limit	Lower 95% confidence limit	Predicted N uptake[2]	Upper 95% confidence limit	Lower 95% confidence limit	Predicted N uptake[3]	Upper 95% confidence limit	Lower 95% confidence limit
12	55	62	49	60	67	53	63	69	56
30	64	69	59	70	76	65	--	--	--
60	78	82	74	87	91	83	92	97	87
90	89	94	85	101	106	97	--	--	--
120	99	104	94	113	118	108	--	--	--
180	111	116	106	130	136	124	133	140	126
240	116	120	111	137	143	132	--	--	--
300	112	120	104	135	144	127	125	133	117

1 $Y = 49 + 0.554^{N} - 1.15*10^{-3}N^{2}$, $R^{2} = 0.81^{**}$.

2 $Y = 52 + 0.672^{N} - 1.31*10^{-3}N^{2}$, $R^{2} = 0.86^{**}$.

3 $Y = 54 + 0.741^{N} - 1.68*10^{-3}N^{2}$, $R^{2} = 0.92^{**}$.

ha^{-1}. An R^2 value of 0.86^{**} indicated a highly significant relationship between application of N and N uptake. The lack of significant difference between levels of N uptake at 180 and 240 kg applied-N ha^{-1} plus the significant difference between N uptake at these rates and lower ones indicated the levelling-off of N uptake by 180 kg applied-N ha^{-1}, the same as with winter wheat under zero tillage. Although their work was with spring wheat grown in lysimeters, Campbell et al. (1977a) also found N uptake was increased by fertilizer-N and a levelling-off of N occurred at high rates of N fertilization.

Nitrogen uptake by the above-ground portion of spring wheat under conventional tillage was increased significantly from 63 kg N ha^{-1} with the control to 133 kg N ha^{-1} when 180 kg ha^{-1} of N was applied. However, the shape of the response curve suggested that N uptake began levelling-off at some point between the 60 and 180 kg applied-N ha^{-1} treatments. An R^2 value of 0.92^{**} indicated a highly significant relationship between N application and N uptake by the crop. Campbell et al. (1977b) also found that N uptake by spring wheat was increased by N fertilization and that N uptake levelled off at high rates of fertilization.

Nitrogen uptake by the above-ground portion of the plant was significantly increased by N fertilization with each wheat-tillage regime. Also, N uptake began levelling-off by 180 kg applied-N ha^{-1} in each wheat-tillage regime. As previously discussed, N uptake by spring wheat under conventional tillage slightly surpassed that under zero tillage (except at 300 kg applied-N ha^{-1}) likely because of the greater N supply to spring wheat under conventional tillage. As in the first crop year, however, N uptake by winter wheat was considerably lower than by spring wheat. Nitrogen uptake is a reflection of grain and straw yields and protein or N content, i.e. plant response to N supply, however, it can also be a measure of N supply available to the crop. The winter wheat had been fertilized in the fall whereas the spring wheat was fertilized in the spring. Thus, the lower N uptake by winter wheat was partially attributed to the lower efficiency of fall applied N compared with spring applied N. However, the N uptake of winter also levelled off at high rates of N application. Therefore, although the lower N supply due to fall application of N fertilizer may have lowered the slope of the response curve of the winter wheat, the levelling-off of N uptake indicated that winter wheat did not use as much N as did spring wheat. The data was not able to indicate whether this difference was due to genetic differences between varieties or some environmental or management factor (i.e. spring soil temperature, timing of precipitation, herbicide application, root disease, etc.).

4.2.7 Recovery of applied-N by grain plus straw.

Recovery of applied-N (%) by the grain plus straw of each wheat-tillage regime generally decreased with increasing rates of N application (Figure 4.11 and Table 4.27). Recovery of applied-N by the grain plus straw of winter wheat under zero tillage decreased significantly from 66.9 % at 30 kg applied-N ha^{-1} to 22.6 % when 300 kg N ha^{-1} was applied. The lack of significant difference between levels of recovery for rates of applied-N greater than 120 kg applied-N ha^{-1}, however, indicated that recovery was levelling-off by the 180 kg applied-N ha^{-1} treatment. An R^2 value of 0.59^{**} indicated a highly significant relationship between N application and recovery of applied-N. The decrease in recovery with increased N application has also been reported by Grant (1982) for winter wheat under zero tillage near Minnedosa, Manitoba, and by Stanford and Hunter (1973) for conventionally-tilled winter wheat.

Recovery of applied-N by the above-ground portion of spring wheat under zero tillage was decreased significantly from 55.2 % with 30 kg applied-N ha^{-1} to 25.9 % when 300 kg N ha^{-1} was applied. An R^2 value of 0.42^{**} indicated a highly significant relationship between recovery and applied-N.

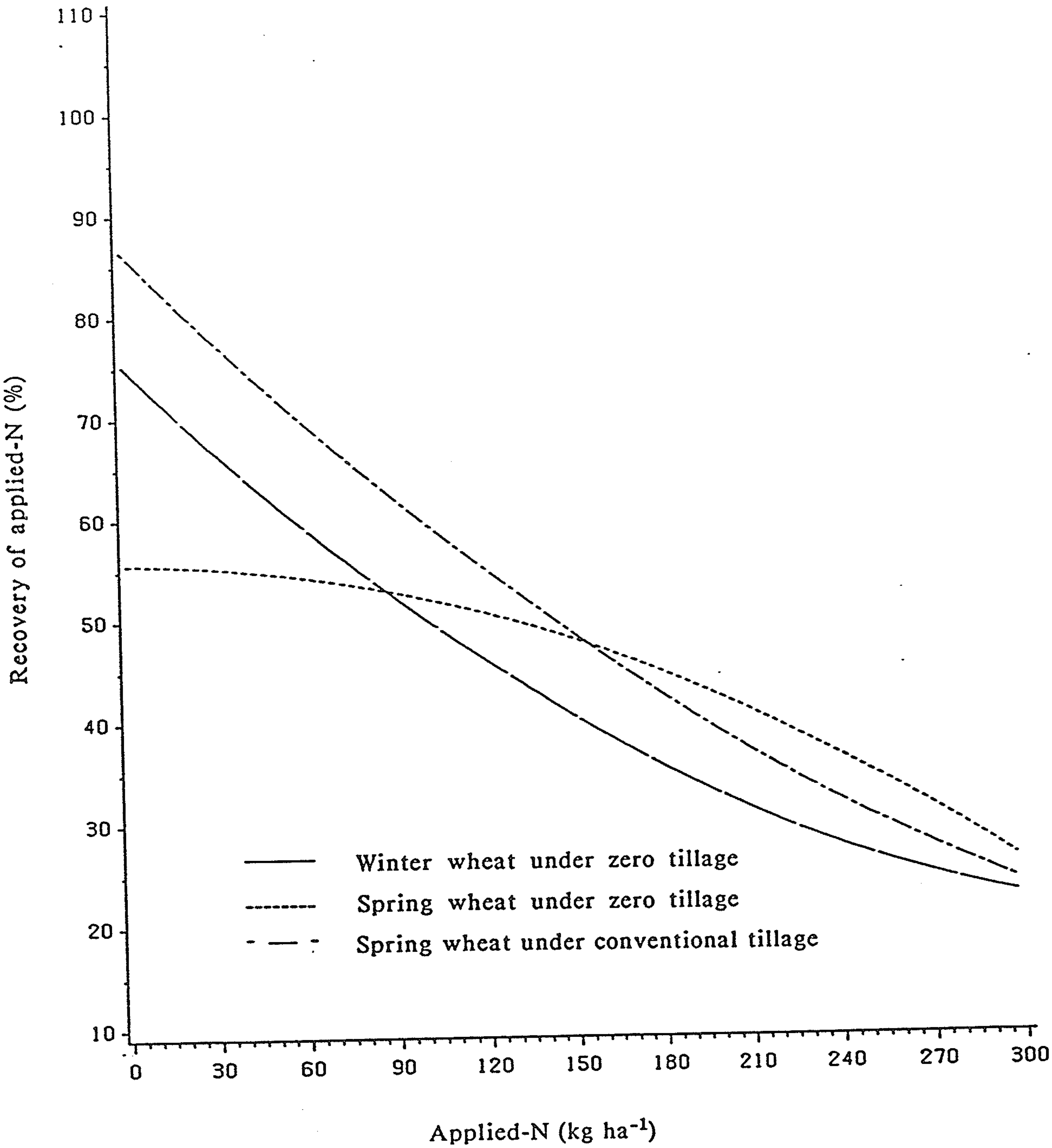


Figure 4.11. Lines of best fit for recovery of applied-N by grain plus straw as affected by rate of applied-N (1986).

Table 4.27. Recovery of applied-N (%) by grain plus straw as affected by rate of applied-N (1986)

	Wheat-till regime								
	Winter wheat zero till			Spring wheat zero till			Spring wheat conventional till		
Applied-N (kg ha^{-1})	Predicted recovery[1]	Upper 95% confidence limit	Lower 95% confidence limit	Predicted recovery[2]	Upper 95% confidence limit	Lower 95% confidence limit	Predicted recovery[3]	Upper 95% confidence limit	Lower 95% confidence limit
12	--	--	--	--	--	--	--	--	--
30	66.9	75.9	60.0	55.2	63.4	47.1	--	--	--
60	59.2	65.2	53.3	54.3	59.7	48.8	69.7	76.1	63.2
90	52.3	57.6	47.0	52.7	57.6	47.9	--	--	--
120	46.0	51.9	40.0	50.6	56.2	45.1	--	--	--
180	35.5	42.2	28.7	44.7	60.0	38.3	42.4	48.9	36.0
240	27.7	33.9	21.5	36.4	42.2	30.6	--	--	--
300	22.6	32.7	12.6	25.9	35.3	16.5	23.8	30.3	17.3

1 $Y = 75.3 - 0.290^{N} + 3.81*10^{-4}N^{2}$, $R^2 = 0.59^{**}$.

2 $Y = 55.6 - 3.58*10^{-3N} - 3.19*10^{-4}N^{2}$, $R^2 = 0.42^{**}$.

3 $Y = 86.5 - 0.299^{N} - 2.99*10^{-4}N^{2}$, $R^2 = 0.89^{**}$.

Recovery decreased slowly with rates of applied-N up to 120 kg ha^{-1} and then decreased more rapidly with higher treatments. This 'shape' of the line of best fit was the result of a slight increase in recovery with the initial applications of N. The means of observed data for recovery were 51.1, 58.5, 53.3, 52.1, 45.1, 31.0 and 28.8 % for the 30, 60, 90, 120, 180, 240 and 300 kg applied-N ha^{-1} treatments, respectively. Therefore, as was the case in the first crop year, recovery initially increased and then decreased as rates of applied-N were increased. Also not apparent with the line of best fit but with the means of observed data was the levelling-off of recovery at high rates of N application. Campbell and Paul (1978) working with spring wheat grown in lysimeters also found recovery of applied-N by grain plus straw was initially increased but overall decreased with increased N application and that recovery levelled-off at high rates of N application. Calculations made on the data of McNeal et al. (1971) showed similar results.

Recovery of applied-N by the grain plus straw portion of spring wheat under conventional tillage was significantly decreased from 69.7 % with 60 kg applied-N ha^{-1} to 42.4 % at 180 kg applied-N ha^{-1} and then to 23.8 % when 300 kg N ha^{-1} was applied. An R^2 value of 0.89^{**} indicated a highly significant relationship between recovery and N application.

Although recovery was significantly different at each rate of applied-N, the shape of the response curve suggested that the levelling-off of recovery did begin at high rates of N application. Campbell and Paul (1978) also reported that recovery of applied-N by the above-ground portion of spring wheat was decreased by N application and that levelling-off occurred at high rates of N application.

Recovery of applied-N by grain plus straw was significantly decreased by N application in each wheat-tillage regime. Recovery of applied-N by spring wheat under conventional tillage was greater than that for spring wheat under zero tillage at low rates of N application. However, at high rates of N application recovery was slightly greater for spring wheat under zero tillage than for spring wheat under conventional tillage. The response curve for spring wheat under zero tillage was different from those of the two other crops in that it decreased at an increasing rate instead of at a decreasing rate. The lower recovery by spring wheat under zero tillage compared to spring wheat under conventional tillage and to some degree the different responses, reflected the greater loss of broadcast urea-N from zero-tilled land (Harapiak et al., 1986) and the reduced soil mineralization of newly zero-tilled soil (Deibert at al., 1986; Spilde and Deibert, 1986). Winter wheat under zero tillage was lower than spring wheat under conventional tillage at all rates of applied-N and lower than spring wheat under zero tillage at all rates of applied-N greater than 60 kg applied-N ha^{-1}. Thus, winter wheat did not use the applied-N as efficiently as did the spring wheats. As previously discussed, this may be because the winter wheat was fertilized in the fall whereas the spring wheats were fertilized in the spring, and that fall fertilization is not as efficient as that done in the spring (Ridley, 1973; Partridge and Ridley, 1974). However, it may also have been due to genetic differences between wheat varieties or some environmental or management factor.

4.2.8 Water use efficiency based on yield of grain.

Water use efficiency based on yield of grain (WUE-G) and water use efficiency based on yield of grain plus straw (WUE-GS) were determined for selected subplots only. All subplots for spring wheat under conventional tillage in replicates 2, 4, and 6, and the control, 60, 90, 180, and 300 kg applied-N ha^{-1} treatments in replicates 2, 4 and 6 for winter wheat and spring wheat under zero tillage, were chosen.

Water use efficiency based on yield of grain of each wheat-tillage regime was increased by N fertilization

(Figure 4.12 and Table 4.28). The WUE-G of winter wheat under zero tillage was increased significantly from 7.6 kg ha^{-1} mm^{-1} with the control to 11.5 kg ha^{-1} mm^{-1} at 180 kg applied-N ha^{-1}. Lack of significant difference between levels of WUE-G at the 90 and 180 kg applied-N ha^{-1} treatments, however, indicated that WUE-G was levelling-off by the 90 kg N ha^{-1} treatment. An R^2 value of 0.67^{**} indicated a highly significant relationship between WUE-G and N application. Although their work was with conventional tillage, Ramig and Rhoades (1963) at North Platte, Nebraska, and Brown (1971) at Bozeman, Montana, also found WUE-G of winter wheat was increased by N fertilization and that WUE-G levelled-off as rates of fertilization increased.

Water use efficiency based on grain yield of spring wheat under zero tillage was increased, although not significantly, from 7.5 kg ha^{-1} mm^{-1} with the control to 10.3 kg ha^{-1} mm^{-1} at 180 kg applied-N ha⁻1. An R^2 value of 0.37 indicated a significant relationship did not exist between N application and WUE-G for spring wheat under zero tillage. Campbell et al. (1977b) also found WUE-G was increased by N application and that WUE-G levelled-off with increasing rates of N application, in their lysimeter work near Swift Current, Saskatchewan.

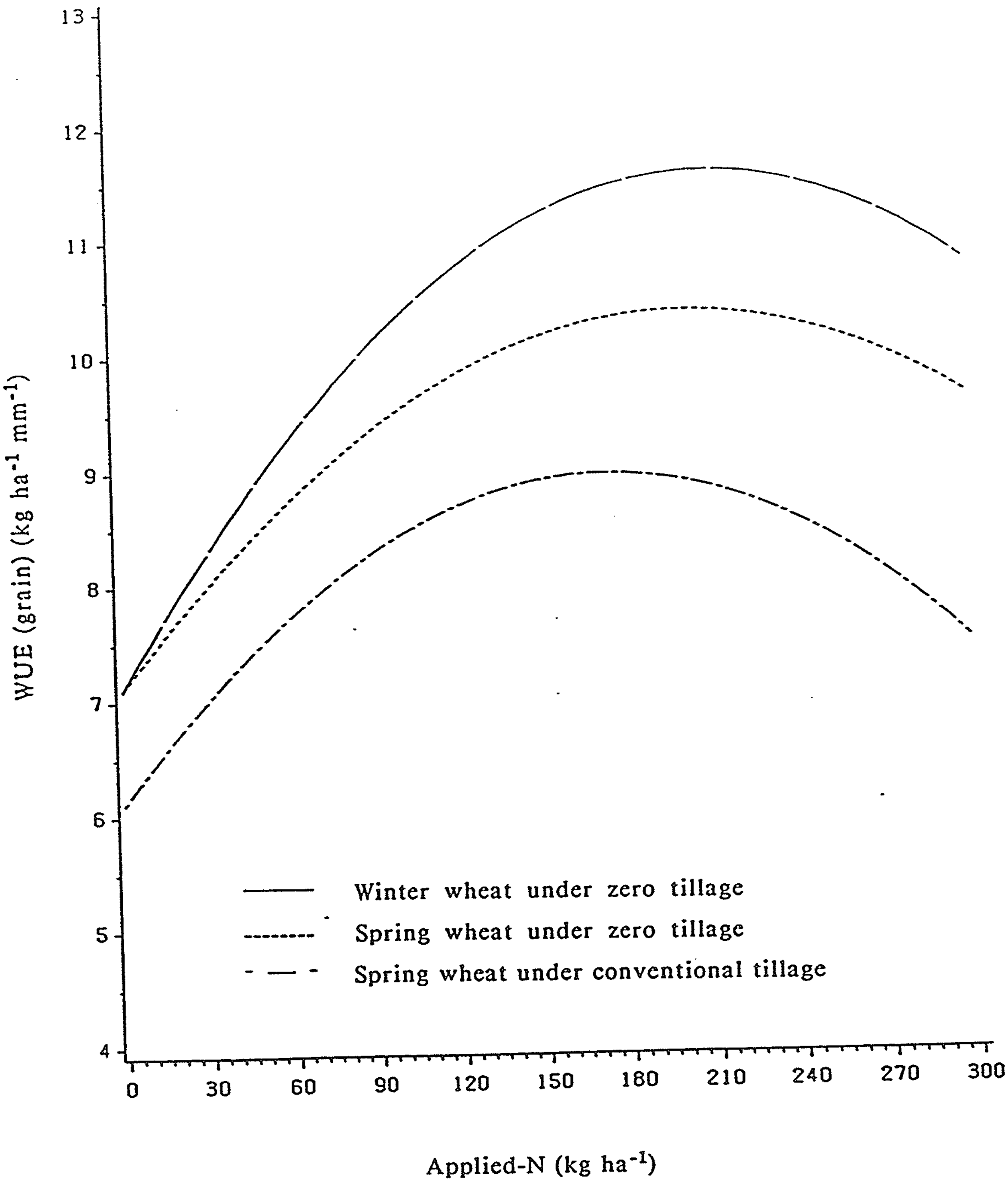


Figure 4.12. Lines of best fit for water use efficiency (WUE) (based on yield of grain) as affected by rate of applied-N (1986).

Table 4.28. Water use efficiency (WUE) based on grain yield (kg ha^{-1} mm^{-1}) as affected by rate of applied-N (1986)

	Wheat-till regime								
	Winter wheat zero till			Spring wheat zero till			Spring wheat conventional till		
Applied-N (kg ha^{-1})	Predicted WUE[1]	Upper 95% confidence limit	Lower 95% confidence limit	Predicted WUE[2]	Upper 95% confidence limit	Lower 95% confidence limit	Predicted WUE[3]	Upper 95% confidence limit	Lower 95% confidence limit
12	7.6	8.9	6.4	7.5	9.0	5.9	6.5	8.1	4.9
30	--	--	--	--	--	--	--	--	--
60	9.3	10.1	8.5	8.8	9.7	7.8	7.7	8.9	6.6
90	10.1	11.0	9.3	9.4	10.4	8.3	--	--	--
120	--	--	--	--	--	--	--	--	--
180	11.5	12.6	10.4	10.3	11.7	9.0	9.0	10.5	7.4
240	--	--	--	--	--	--	--	--	--
300	10.8	12.2	9.4	9.6	11.3	7.9	7.5	9.2	5.7

1 $Y = 7.1 + 4.26*10^{-2}N - 1.01*10^{-4}N^2$, $R^2 = 0.67^{**}$.

2 $Y = 7.1 + 3.23*10^{-2}N - 7.99*10^{-5}N^2$, $R^2 = 0.37$.

3 $Y = 6.1 + 3.28*10^{-2}N - 9.42*10^{-5}N^2$, $R^2 = 0.36$.

Water use efficiency based on yield of grain of spring wheat under conventional tillage was increased, although not significantly, from 6.5 kg ha^{-1} mm^{-1} with the control to 9.0 kg ha^{-1} mm^{-1} at 180 kg applied-N ha^{-1}. An R^2 value of 0.36 indicated that a significant relationship between N application and WUE-G did not exist. Campbell et al. (1977b) working with lysimeters near Swift Current, Saskatchewan, also found WUE-G increased with N application and that WUE-G levelled-off at high N application.

The WUE-G of each wheat-tillage regime was increased by the application of N. However, this increase was significant for winter wheat, only. Although the response for the spring wheats was not statistically significant, the trend was considered real and the lack of significance attributed to the low number of N treatments and replicates thereof examined (i.e. fewer degrees of freedom for statistical calculation). The lack of significance could also be attributed to the average growing season precipitation and the soil NO_3-N level. Had the soil NO_3-N level been lower the WUE-G increase due to applied-N would have been greater, thereby increasing the likelihood of the increase being significant. Had growing season precipitation been higher and more timely the grain yield response to applied-N would have been greater (Ramig and

Rhoades, 1963; Campbell et al., 1977b). Water use efficiency based on grain yield was highest at 180 kg applied-N ha^{-1}, in each wheat-tillage regime. This indicated that approximately the same amount of applied-N was required to maximize water use efficiency for each wheat-tillage regime. The WUE-G for spring wheat under zero tillage was substantially higher than that for spring wheat under conventional tillage. This was attributed to the substantially lower consumptive water use by spring wheat under zero tillage, which was considered primarily the result of less evaporative loss of soil moisture (due to reduced wind speed with standing stubble) prior to crop canopy development (Aase and Siddoway, 1980; Brun, 1985). Moisture conservation due to stubble entrapment of snow did not have an affect here because high precipitation in April and early May removed any moisture advantage of the zero-tilled land. The WUE-G of winter wheat was considerably higher again than that for spring wheat under zero tillage. The grain yield of winter wheat was only slightly higher than that for spring wheat under zero tillage and the spring soil moisture levels were the same. Thus, the earlier growth habit of winter wheat must have allowed for a more efficient use of early spring moisture and the greater avoidance of summer heat stress, thereby providing for the greater WUE-G.

4.2.9 Water use efficiency based on yield of grain plus straw.

Water use efficiency based on yield of grain plus straw of each wheat-tillage regime was also increased by N application (Figure 4.12 and Table 4.29). The WUE-GS of winter wheat under zero tillage increased significantly from 17.2 kg ha^{-1} mm^{-1} with the control to 24.7 kg ha^{-1} mm^{-1} at 180 kg applied-N ha^{-1}. Lack of significant difference between levels of WUE-GS for rates of applied-N between and including 60 and 180 kg N ha^{-1}, however, indicted levelling-off of WUE-GS by the 60 kg applied-N ha^{-1} treatment. An R^2 of 0.57^{**} indicated that a highly significant relationship did exist between N application and WUE-GS.

Water use efficiency based on yield of grain plus straw of spring wheat under zero tillage was also increased, although not significantly, from 19.3 kg ha^{-1} mm^{-1} with the control to 24.2 kg ha^{-1} mm^{-1} at 180 kg applied-N ha^{-1}. An R^2 value of 0.34 indicated no significant relationship between WUE-GS and N application. In their lysimeter work near Swift Current, Saskatchewan, Campbell et al. (1977a) also found the WUE-GS of spring wheat was increased by N application and that WUE-GS levelled-off at high rates of N application.

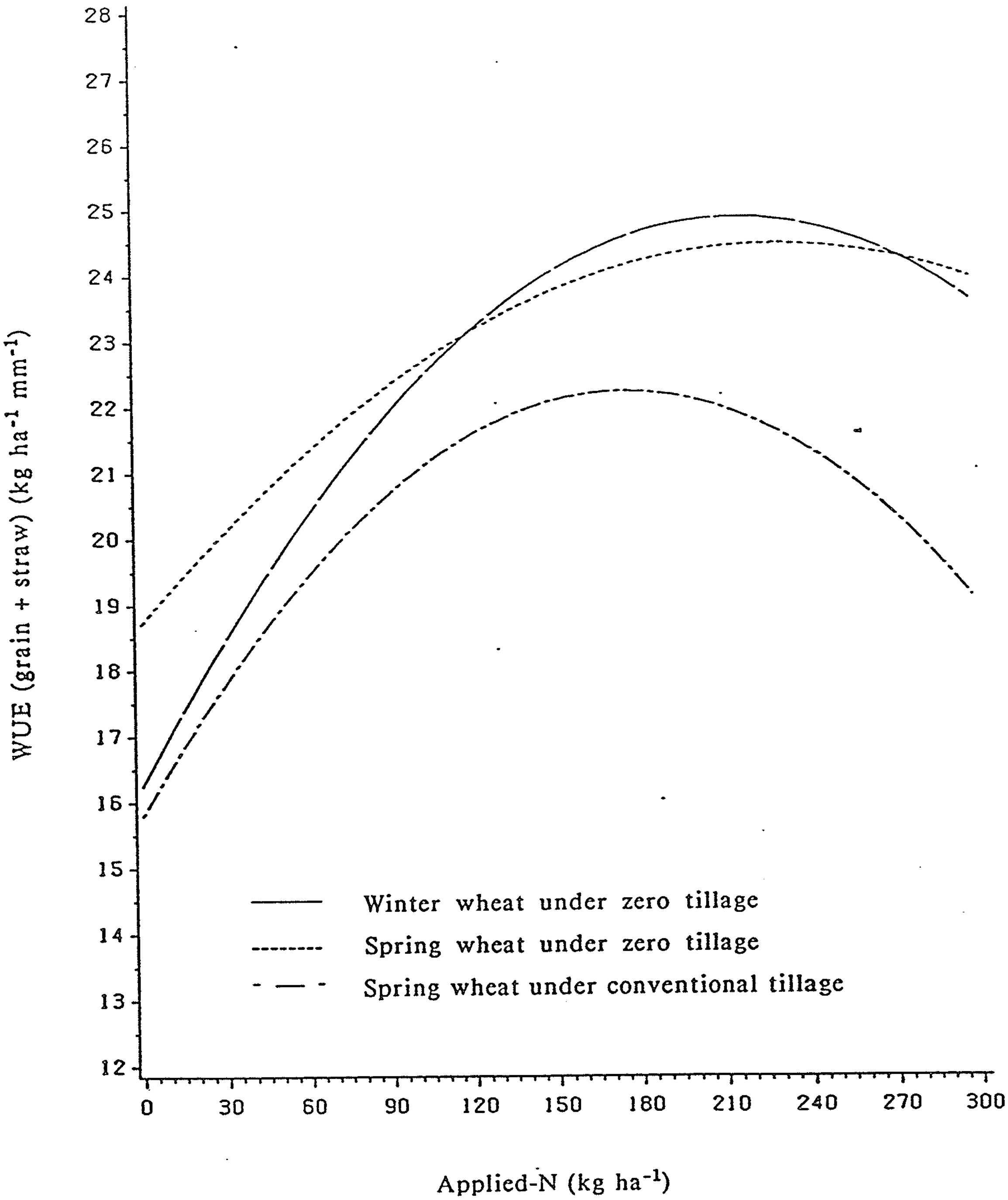


Figure 4.13. Lines of best fit for water use efficiency (WUE) (based on yield of grain plus straw) as affected by rate of applied-N (1986).

Table 4.29. Water use efficiency (WUE) based on grain plus straw yield (kg ha^{-1} mm^{-1}) as affected by rate of applied-N (1986)

	Wheat-till regime								
	Winter wheat zero till			Spring wheat zero till			Spring wheat conventional till		
Applied-N (kg ha^{-1})	Predicted WUE[1]	Upper 95% confidence limit	Lower 95% confidence limit	Predicted WUE[2]	Upper 95% confidence limit	Lower 95% confidence limit	Predicted WUE[3]	Upper 95% confidence limit	Lower 95% confidence limit
12	17.2	20.2	14.2	19.3	22.5	16.2	16.7	20.6	12.7
30	--	--	--	--	--	--	--	--	--
60	20.4	22.3	18.5	21.3	23.3	19.4	19.4	22.3	16.6
90	22.0	24.0	19.9	22.3	24.5	20.2	--	--	--
120	--	--	--	--	--	--	--	--	--
180	24.7	27.3	22.0	24.2	27.0	21.5	22.2	26.2	18.3
240	--	--	--	--	--	--	--	--	--
300	23.6	26.9	20.3	23.9	27.5	20.4	19.0	23.4	14.6

1 $Y = 16.2 + 0.080N - 1.86{*}10^{-4}N^2$, $R^2 = 0.57^{**}$.

2 $Y = 18.7 + 0.050N - 1.09{*}10^{-4}N^2$, $R^2 = 0.34$.

3 $Y = 15.7 + 0.074N - 2.10{*}10^{-4}N^2$, $R^2 = 0.31$.

Water use efficiency based on yield of grain plus straw of spring wheat under conventional tillage was increased, but not significantly, by N application. The WUE-GS increased from 16.7 kg ha^{-1} mm^{-1} with the control to 22.2 kg ha^{-1} mm^{-1} at 180 kg applied-N ha^{-1}. An R^2 value of 0.31 indicated a significant relationship did not exist between N application and WUE-GS of spring wheat under conventional tillage. Near Swift Current, Saskatchewan, Campbell et al. (1977a) also found WUE-GS of spring wheat was increased by N application, and that the WUE-GS levelled-off as rates of N application increased.

The WUE-GS of each wheat-tillage regime was increased by the application of N. However, as with WUE-G, this response was significant for winter wheat under zero tillage, only. Similarly, the lack of significant increase was attributed to working with a low number of treatments and replicates, more than minimal soil NO_3-N, and less than optimum precipitation. Water use efficiency based on yield of grain plus straw was also similar to that based on grain only, in that WUE-GS was highest at 180 kg applied-N ha^{-1} in each wheat tillage regime. This provided further evidence that approximately the same amount of applied-N was required by each wheat-tillage regime to maximize water use efficiency. The WUE-GS of spring wheat under zero tillage was substantially greater than that under conventional tillage. This was attributed to the greater consumptive water use by spring wheat under conventional tillage, which in turn was attributed to greater evaporative loss of soil moisture prior to crop canopy development (Aase and Siddoway, 1980; Brun, 1985). The WUE-GS response curve of winter wheat under zero tillage was similar to that for spring wheat under conventional tillage at low applied-N, but more like that for spring wheat under zero tillage at high applied-N. Although the grain yield of winter wheat was slightly higher than for the spring wheats, the straw yield was considerably lower, thereby providing winter wheat with a WUE-GS intermediate to those of the spring wheats.

4.3 Comparison of Crop Years.

Non-growing season precipitation was near normal in both crop years. However, in the second crop year much of this precipitation fell in April. Thus, in the first crop year the spring soil moisture content was greater for the zero-tilled wheats due to greater snow trapping, whereas in the second crop year it was similar for each wheat-tillage system because high precipitation in April negated any moisture advantage due to snow entrapment. Growing season precipitation was excellent in the first crop year but below normal in the second. However, the high early spring precipitation plus the low growing season precipitation (in 1986) were sufficient to provide for average crop yields. Growing season precipitation in the first crop year was very likely high enough to provide for near maximum crop response, thereby providing for similar consumptive water use and thus removing some of the moisture conservation advantage of zero tillage and some of the yield advantage of winter wheat. Although high early spring precipitation annulled the moisture advantage of zero tillage due to snow trapping in the second crop year, the consumptive water use value for spring wheat under conventional tillage was substantially greater than that for zero-tilled winter wheat and spring wheat. This was attributed to reduced evaporative loss of soil moisture prior to crop canopy development with the standing stubble of zero tillage.

In both crop years the grain yield of each wheat-tillage regime was significantly increased by the application of N. Grain yields were considerably higher in the first crop year and this was due to excellent growing season precipitation in that year. Grain yields were similar for each wheat-tillage regime in both crop years, although, yields were less similar in the first crop year.

Despite this trends were observed. Spring wheat under zero tillage outyielded spring wheat under conventional tillage and winter wheat outyielded both spring wheats at high rates of N application, in both crop years. Thus, Norstar winter wheat exhibited a yield advantage over Neepawa spring wheat and zero tillage exhibited a yield advantage over conventional tillage. It was also apparent that high precipitation increased the yield advantage of winter wheat, but it reduced the yield advantage (due to moisture conservation) of zero tillage. Furthermore, N fertilization should be slightly higher on newly zero-tilled land to compensate for decreased mineralization (Deibert et al., 1986), and if N is surface-applied to compensate for losses of N due to volatilization (Harapiak et al., 1986).

In both crop years straw yield was also significantly increased by N application with each wheat tillage regime. Straw yields, like those of grain, were considerably higher in the first crop year, again due to the excellent precipitation in that year. Straw yields were similar for spring wheat under zero and conventional tillage, in both crop years. However, straw yields of winter wheat were lower, particularly in 1985-86. This was attributed to herbicide use and timing.

Protein content of the grain was significantly increased by N application for each wheat-tillage regime during both years of study. Levels of protein content for each wheat-tillage regime were considerably lower in the first crop year than in the second. This was attributed to higher precipitation during the 1984-85 crop year. However, it was also attributed to the higher soil NO_3-N levels of the 1985-86 plot site soil. In both crop years, the levels of protein content for spring wheat under zero tillage were very close to those for spring wheat under conventional tillage. Conversely, Donaghy (1973) had found protein content of the grain of spring wheat under zero tillage was significantly lower than the protein content of spring wheat under conventional tillage. High precipitation during the growing season of the first crop year and during the early spring of the second crop year, of this study, likely minimized the protein level difference just as it had done with respect to yield. Levels of protein content for winter wheat were found to be very much lower than those for the spring wheats, in both crop years, this was attributed to differences in genetic make-up between varieties.

Although it was not apparent from the lines of best fit, the means of observed data for protein content of the grain did indicate the biological dilution of plant protein at low rates of N application for winter wheat and spring wheat under zero tillage, in both years of study. It was not indicated for spring wheat under conventional tillage in 1984-85 probably because of the few number of N rate treatments used. This may also have been the case for spring wheat under conventional tillage in the 1985-86 crop year, however, the higher soil NO_3-N level or lower precipitation could also have been the cause.

Nitrogen content of the straw was increased by the application of N in the 1984-85 crop year (not statistically evaluated) and significantly increased by the application of N in the 1985-86 crop year, for each wheat-tillage regime. Levels of N content were lower for the first crop year and this was attributed to the high growing season precipitation diluting the concentration of protein. Levels were similar for spring wheat under zero and conventional tillage in 1984-85 but slightly higher for spring wheat under conventional tillage in 1985-86. The similarity in 1984-85 was attributed to the high precipitation removing tillage regime moisture differences, as was the case with grain protein. The lack of similarity in 1985-86 was attributed to less precipitation, and the greater mineralization of N and lower loss of applied-N with conventional tillage providing for a slightly greater N supply to that crop. In 1984-85, N content of the straw of winter wheat was higher than those of the spring wheats at low N application and lesser at high N application. Alternatively, in 1985-86 N content of the straw of winter wheat was higher than those for the spring wheats at all rates of N application. Levels of N content of the straw are undoubtedly tied into straw yield and the genetic partitioning of total N uptake. However, whether the higher straw N content of winter wheat was due to herbicide application or some other environmental or genetic factor, was not answerable by the results of this study.

The biological dilution of plant straw protein was shown by the means of observed data for winter wheat and spring wheat under zero tillage in 1984-85 and for spring wheat under zero tillage in 1985-86. The spring wheat under conventional tillage may also have exhibited biological dilution in 1984-85 had a 30 kg applied-N ha^{-1} treatment been included. This might also have been the case for 1985-86, however, the higher soil NO_3-N that probably inhibited biological dilution of winter wheat straw may similarly have done so for spring wheat under conventional tillage. The higher moisture stress experienced by spring wheat under conventional tillage during 1986 (indicated by the higher consumptive water use) could also have prevented biological dilution (Ramig and Rhoades, 1963).

Nitrogen uptake by grain plus straw was increased by N application in 1984-85 (not statistically evaluated) and significantly increased by N application in 1985-86, for each wheat-tillage regime. Levels of N uptake were considerably higher in the first crop year and this was attributed to the excellent growing season precipitation providing for excellent crop growth. Levels of N uptake were similar for spring wheat under zero and conventional tillage, in both crop years, because the moisture advantage obtained by zero tillage was decreased by high growing season precipitation in 1984-85 and by high early spring precipitation in 1985-86. Nitrogen uptake by winter wheat was considerably lower than that by spring wheat, in both crop years. The lower efficiency of surface-applied urea-N in fall on the winter wheat compared with spring application on the spring wheat likely caused some of this difference. However, genetic differences between varieties may also have been responsible.

Recovery of applied-N by grain plus straw was generally decreased by increasing rates of N application in the first crop year (not statistically evaluated) and significantly decreased by increasing rates of N application in the second crop year, for each wheat-tillage regime. Although comparison between years was difficult because a line of best fit could not be performed on the 1984-85 data, levels of recovery were higher for the first crop year than they were for the second, in each wheat-tillage regime. This was attributed to the higher precipitation in the first crop year (Campbell et al., 1977b; Campbell and Paul, 1978). The type of the N response was similar for winter wheat and spring wheat under conventional tillage (i.e., decreasing at a decreasing rate), in both crop years. Furthermore, the recovery of applied-N for spring wheat under conventional tillage was slightly greater than that for the winter wheat. Conversely, the recovery of applied-N by spring wheat under zero tillage decreased at an increasing rate, and was the lowest of the wheat-tillage regimes at low rates of N application but similar at high rates of N application. The low recovery of applied-N by spring wheat under zero tillage at low rates of application was attributed to the greater loss of surface-applied urea-N from zero tillage than from conventional tillage and the lower mineralization of newly zero-tilled land. The recovery by winter wheat would likely have been greater also, had it been fertilized in the spring when the spring wheat was.

Water use efficiency based on yield of grain of each wheat-tillage regime was increased by N application in both crop years. However, this response was significant only for winter wheat and spring wheat under zero tillage in 1984-85 and winter wheat in 1985-86. Levels of WUE-G obtained could not be compared between crop years because soil moisture was measured to the 60 cm depth in the first crop year and to the 120 cm depth in the second. In both crop years, however, the WUE-G for spring wheat under zero tillage surpassed that for spring wheat under conventional tillage. In the first crop year this was considered the result of the slightly greater spring soil moisture due to snow entrapment and the decreased evaporative loss of soil moisture prior to crop canopy development, with the standing stubble of zero tillage. In the second crop year it was attributed to the decreased evaporative loss of soil moisture, only. In the first crop year the WUE-G for winter wheat surpassed that for spring wheat under conventional tillage at all rates of applied-N, but it surpassed that for spring wheat under zero tillage at high rates of N application, only. The generally better WUE-G of winter wheat was attributed to the more efficient use of early spring moisture and possibly the greater avoidance of summer heat - moisture stresses, due to the growth habit of this crop. The poor performance at low rates of N application, however, was attributed to the high growing season precipitation removing some of the yield - moisture use advantage of winter wheat by removing the occurrence of heat - moisture stresses on spring wheat. It was also attributed to the different timing of fertilizer application. Winter wheat was fertilized in September whereas spring wheat was in May. It was considered likely, therefore, that the winter wheat had a slightly lower N supply than did the spring wheats. This difference would have been most severe at low rates of N application, thus the WUE-G for winter wheat may have surpassed that of spring wheat under zero tillage at all rates of N application had the varieties been fertilized at the same time. In the second crop year this was the case, likely because higher soil N03-N levels and lower precipitation levels decreased the impact of any N supply differences and because lower precipitation levels allowed the yield and moisture use advantages of winter wheat to occur.

Water use efficiency based on yield of grain plus straw of each wheat tillage regime was increased by N application in each year of study. In 1984-85 the response was highly significant for each wheat-tillage regime. However, in 1985-86 this was the case for winter wheat only. In both crop years the WUE-GS of spring wheat under zero tillage surpassed that of spring wheat under conventional tillage. This was attributed to the slightly greater spring soil moisture and the decreased evaporative loss with the zero tillage in the first crop year and the decreased evaporative loss with zero tillage in the second. In the first crop year the WUE-GS response for winter wheat was similar to that for spring wheat under conventional tillage. In the second crop year this was the case at low rates of N application, however, at high rates of N application it was similar to that for spring wheat under zero tillage. It was considered likely, however, that the WUE-GS for winter wheat would have surpassed those for the spring wheats had the straw yield not been lessened by herbicide application.

5. SUMMARY AND CONCLUSIONS

Grain yield, straw yield, protein content of the grain, N content of the straw, N uptake by grain plus straw, water use efficiency based on yield of grain and water use efficiency based on yield of grain plus straw of winter wheat under zero tillage, spring wheat under zero tillage and spring wheat under conventional tillage were increased by the application of N. Alternatively, recovery of applied-N by grain plus straw of each wheat-tillage regime was decreased by the application of N. However, as rates of N application increased a levelling-off of each yield parameter occurred or began to occur.

Grain yield of winter wheat was highest in both crop years, but only by a slight margin in the second crop year. Grain yield of spring wheat under zero tillage was higher than that of spring wheat under conventional tillage in the first crop year, but similar in the second. It was therefore concluded that Norstar winter wheat had a yield advantage over Neepawa spring wheat, although high precipitation and high N fertilization were required to realize this. It was also concluded that spring wheat under zero tillage had a yield advantage over spring wheat under conventional tillage, although high levels of precipitation could negate this advantage. Furthermore, N fertilization should be slightly higher on newly zero-tilled land to compensate for losses of N due to volatilization and losses of plant available N due to reduced mineralization. Straw yield was relatively similar for the spring wheats. Straw yield of winter wheat, however, was somewhat lower and this was attributed to the less crop tolerant herbicide program on the winter wheat. Protein content of the grain was very similar for the spring wheats but very much lower for winter wheat. This varietal difference with respect to protein content was attributed to genetic differences between varieties. A clear pattern between wheat-tillage regimes with respect to N content of the straw was not obtained. Nitrogen uptake by grain plus straw was relatively similar for the spring wheats and least for the winter wheat. Recovery of applied-N by grain plus straw was highest for spring wheat under conventional tillage and lowest for winter wheat while that for spring wheat under zero tillage showed a different response curve. Water use efficiency based on yield of grain was greatest for winter wheat under zero tillage and least for spring wheat under conventional tillage. Water use efficiency based on yield of grain plus straw was greater for spring wheat under zero tillage and lesser for spring wheat under conventional tillage while that for winter wheat was mid way.

As previously discussed the grain yield and water use efficiency based on grain yield was highest for winter wheat under zero tillage in both crop years. This was attributed to the earlier and thus more efficient use of spring soil moisture and the earlier maturity of winter wheat which provided for the greater avoidance of summer heat and moisture stresses. However, in the range of N application most commonly used by farmers (30 to 90 kg applied-N ha^{-1}) yield of grain and water use efficiency based on yield of grain were greater for winter wheat in the second crop year but greater for spring wheat under zero tillage in the first crop year. In both crop years protein content of the grain was substantially greater for spring wheat than for winter wheat. Furthermore, the winter wheat required 1 more fungicide application than did the spring wheat in both crop years. Therefore, although Norstar winter wheat can be successfully grown in Manitoba using zero tillage cropping practices, its inconsistent yield advantage, lower value and higher cost of production make it less attractive to the farmer than spring wheat under zero tillage.

The grain yield of spring wheat under zero tillage was equal to or greater than that for spring wheat under conventional tillage, and water use efficiency based on grain yield was greater for spring wheat under zero tillage than for spring wheat under conventional tillage. This was attributed to the greater snow entrapment and decreased evaporative loss of spring soil moisture due to the standing stubble of the zero tillage. Furthermore, protein content of the grain remained the same eventhough grain yield was greater for the spring wheat under zero tillage. Considering these results plus the reduced loss of soil to wind and water erosion with zero tillage, it was concluded that spring wheat production using zero tillage was beneficial to the farmer and the public in general.

6. BIBLIOGRAPHY

Aase, K. and Siddoway, F. H. 1980. Stubble height effects on seasonal microclimate, water balance and plant development of no till winter wheat. Agric. Meteor. 21: 1-20.

Alessi, J. and Power, J. F. (1973). Effect of source and rate of nitrogen on N uptake and fertilizer efficiency by spring wheat and barley. Agron. J. 65: 53-55.

Alkier, A. C., Racz, G. J. and Soper, R. J. 1972. Effect of foliar- and soil-applied nitrogen and soil nitrate-nitrogen level on the protein content of Neepawa wheat. Can. J. Soil Sci. 52: 301-309.

Allison, L. E. 1965. Organic carbon. In, Methods of Soil Analysis, Part II., C. A. Black (Ed.-in-chief)., pp. 1372-1376. Monograph No. 9 in the Series of Agronomy. Amer. Soc. of Agron., Madison, Wisconsin.

Baier, W. 1976. Agroclimate Atlas. Agrometeorology Research and Service Section, Chemestry and Biology Research Institute, Research Branch, Agriculture Canada, Ottawa, Ontario.

Boatwright, G. O., Ferguson, H. and Sims, J. R. 1976. Soil temperature around the crown node influences early growth, nutrient uptake, and nutrient translocation of spring wheat. Agron. J. 68: 227-231.

Bradley, R. A. and Donaghy, D. I. 1977. Zero tillage crop production in western Manitoba. In, Proc. Mb. Agron. Ann. Conf., Winnipeg, Manitoba, pp. 83-86.

Bremner, J. M. 1965. Inorganic forms of nitrogen. In, Methods of Soil Analysis, Part II., C. A. Black (Ed.-in-chief)., pp. 1179-1237. Monograph No. 9 in the Series of Agronomy. Amer. Soc. of Agron., Madison, Wisconsin.

Brown, P. L. 1971. Water use and soil water depletion by dryland winter wheat as affected by nitrogen fertilization. Agron. J. 63: 43-46.

Brown, P. L. and Black, A. L. 1983. Stubble seeding and fertilization of winter wheat. In, New Frontiers in Winter Wheat Production., D. B. Fowler (Ed.-in-chief)., pp. 312-330. Division of Extension and Community Relations, University of Saskatchewan Printing Services, Saskatoon, Saskatchewan.

Brun, L. 1985. Evaporation from bare and stubble-covered soil. Proc. 7th Ann. Manitoba-North Dakota Zero-Tillage Workshop. pp. 52-54.

Campbell, C. A., Cameron, D. R., Nicholaichuk, W. and Davidson, H. R. 1977a. Effects of fertilizer N and soil moisture on growth, N content and moisture use by spring wheat. Can. J. Soil Sci. 57: 289-310.

Campbell, C. A. and Davidson, H. R. 1979. Effect of temperature, nitrogen fertilization and moisture stress on yield, yield components, protein content and moisture use efficiency of Manitou spring wheat. Can. J. Plant Sci. 59: 963-974.

Campbell, C. A., Davidson, H. R. and Warder, F. G. 1977b. Effects of fertilizer N and soil moisture on yield, yield components, protein content and N accumulation in the aboveground parts of spring wheat. Can. J. Soil Sci. 57: 311-327.

Campbell, C. A., Davidson, H. R. and Winkleman, G. E. 1981. Effect of nitrogen, temperature, growth stage and duration of moisture stress on yield components and protein content of Manitou spring wheat. Can. J. Plant Sci. 61: 549-563.

Campbell, C. A., Nicholaichuk, W., Parker, G. E. and Beaton, J. D. 1985. Effect of zero till, snow trapping and fertilization on spring wheat and winter wheat (1983-84). Conservation for the Future - Proc. of the Soils and Crops Workshop. Feb. 18-19, 1985, University of Saskatchewan, Saskatoon, Saskatchewan. Pages 247-253.

Campbell, C. A., Nicholaichuk, W., McAndrew, D. W., Parker, G. E. and Beaton, J. D. 1984. Effect of stubble height and source, rate, time and method of application of N on yield of spring and winter wheat grown under zero till. New Frontiers In Plant Protection - Soils and Crops Workshop, Feb. 13-14, 1984, University of Saskatchewan, Saskatoon, Saskatchewan. Pages 220-233.

Campbell, C. A. and Paul, E. A. 1978. Effects of fertilizer N and soil moisture on mineralization, N recovery and A-values, under spring wheat grown in small lysimeters. Can. J. Soil Sci. 58: 39-52.

Davidson, H. R. and Campbell, C. A. 1984. Growth rates, harvest index and moisture use of Manitou spring wheat as influenced by nitrogen, temperature and moisture. Can. J. Plant Sci. 64: 825-839.

Deibert, E. J., Hoag, B. K. and Goos, R. J. 1985. Nitrogen fertilizer placement in no-tillage and conventional tillage systems with continuous spring wheat. J. Fert. Issues 2:105-110.

Deibert, E. J., French, E., Lizotte, D. A. and Johnson, B. E. 1986. Reduced tillage fertilizer placement on continuous spring wheat in North Dakota. North Dakota Farm Research 43: 30-33.

de Jong, E. and Rennie, D. A. 1969. Effect of soil profile type and fertilizer on moisture use by wheat grown on fallow or stubble land. Can. J. Soil Sci. 49: 189-197.

Donaghy, D. I. 1973. Zero tillage crop production in Manitoba. PhD. Thesis. Dept. of Plant Sci., Univ. of Mb, Winnipeg, Mb.

Dubetz, S. 1961. Effect of soil type, soil moisture, and nitrogen fertilizer on the growth of spring wheat. Can. J. Soil Sci. 41: 44-51.

Eck, H. V. and Tucker, B. B. 1968. Winter wheat yields and response to nitrogen as affected by soil and climatic factors. Agron. J. 60: 663-666.

Ehrlich, W. A., Poyser, E. A. and Pratt, L. E. 1957. Report of Reconnaissance Soil Survey of Carberry Map Sheet Area. Soils Report No. 7. Manitoba Soil Survey.

Ellis, J. H. and Shafer, W. H. 1943. Reprinted March, 1981. Report of Reconnaissance soil survey of South-Central Manitoba. Soils Report No. 4. Manitoba Soil Survey.

Evenson, P. and Olson, T. 1970. Implications of soil temperatures in May. South Dakota Farm and Home Research Quarterly. Vol XXI: 12-16. Winter 1970.

Fowler, D. B. 1983. The effect of management practices on winter survival and yield of winter wheat produced in regions with harsh winter climates. In, New Frontiers in Winter Wheat Production., D. B. Fowler (Ed.-in-chief)., pp. 238-282. Division of Extension and Community Relations, University of Saskatchewan Printing Services, Saskatoon, Saskatchewan.

Gardiner, W. R. 1960. Dynamic aspects of water availability to plants. Soil Sci. 89: 63-73.

Gauer, E., Shaykewich, C. F. and Stobbe, E. H. 1982. Soil temperature and soil water under zero tillage in Manitoba. Can. J. Soil Sci. 62: 311-325.

Gehl, D. T., Sadler, J. M. and Irvine, R. B. 1986. Nitrogen requirements of semi-dwarf vs conventional varieties of wheat under Manitoba conditions. 29th Ann. Rep. MSSM pp. 67-72.

Grant, C. 1982. Nitrogen and phoshorus fertilization in the production of winter wheat under zero tillage management. MSc. Thesis. Dept. of Plant Sci., Univ. of Mb, Winnipeg, Mb.

Grant, C. A., Stobbe, E. H. and Racz, G. J. 1985. The effect of fall-applied N and P fertilizer and timing of N application on yield and protein content of winter wheat grown on zero-tilled land in Manitoba. Can. J. Soil Sci. 65: 621-628.

Gross, K. J., Entz, M. H. and Fowler, D. B. 1987. A comparison of rooting patterns in spring and winter wheat. Soils and Crops Workshop proc., February 19-20, 1987, Univ. of Sask., Saskatoon, Sask., pp. 291-305.

Gupta, S. C., Larson, W. E. and Linden, D. R. 1983. Tillage and surface residue effects on soil upper boundary temperatures. Soil Sci. soc. Am. J. 47: 1212-1218.

Gusta, L. V., Chen, T. H. H. and Fowler, D. B. 1983. Factors affecting the cold hardiness of winter wheat. In, New Frontiers in Winter Wheat Production., D. B. Fowler (Ed.-in-chief)., pp. 1-25. Division of Extension and Community Relations, University of Saskatchewan Printing Services, Saskatoon, Saskatchewan.

Hamid, A. 1973. Effect of time and rate of application on uptake of fertilizer N by wheat. Exp. Agr. 9: 59-62.

Hamm, J. W., Bettany, J. R. and Holstead, E. H. 1973. A soil test for sulpher and interpretative criteria for Saskatchewan. Comm. in Soil Sci. and Plant Analysis 4(3): 219-231.

Harapiak, J. T., Kucey, R. M. and Flaten, D. 1986. Nitrogen Sources and Placement in Wheat Production. In, Wheat Production in Canada - A Review, Proc. of the Can. Wheat Prod. Symp., A. E. Slinkard and D. B. Fowler (Eds.)., pp. 87-135. Division of Extension and Community Relations, University of Saskatchewan Printing Services, Saskatoon, Saskatchewan.

Henry, J. L., Bole, J. B. and McKenzie, R. C. 1986. Effect of Nitrogen Water Interactions on Yield and Quality of wheat in Western Canada. In, Wheat Production in Canada - A Review, Proc. of the Can. Wheat Prod. Symp., A. E. Slinkard and D. B. Fowler (Eds.)., pp. 165-191. Division of Extension and Community Relations, University of Saskatchewan Printing Services, Saskatoon, Saskatchewan.

Hillel, D. 1971. Soil and Water: Physical Principles and Processes. Academic Press, Inc., New York, N. Y.

Hobbs, E. H. and Krogman, K. K. 1967. Observed and Estimated Evapotranspiration in Southern Alberta. Trans. Amer. Soc. Agri. Eng. 11: 502-507.

Holt, R. F., Timmons, D. R., Voozhees, W. B. and Van Doren, C. A. 1964. Importance of stored soil moisture to the growth of corn in the dry to moist subhumid climatic zone. Agron. J. 56: 82-85.

Jan, E. Z. and Bowren, K. E. 1984. Effect of soil temperature of different systems of seeding spring and winter wheat. Presented at, Agrologists Institute of Canada Annual Meeting, August 19-22, 1984, University of Manitoba, Winnipeg, Manitoba. Paper No. 84-103.

Jansson, S. L. and Persson, J. 1982. Mineralization and immobilization of soil nitrogen. In, Nitrogen in Agricultural Soils., F. J. Stevenson (Ed.-in-chief)., pp. 229-252. Monograph No. 22 in the Series of Agronomy. Amer. Soc. of Agron., Madison, Wisconsin.

Kachanoski, R. G., de Jong, E. and Rennie, D. A. 1985. The effect of fall stubble management on over-winter recharge and grain yield. In, Conservation for the Future - Proc. of the Soils and Crops Workshop, Univ. of Sask., Saskatoon, Sask. Feb. 18-19, 1985. pp. 254-261.

Lazrus, A. J., Hill, K. C. and Lodge, J. P. 1966. A new colorimetric determination of sulphate ion. In, Automation in Analytical Chemestry, Technicon Symposium 1965, Mediad, 1966. pp. 291-293.

Lindwall, C. W., Sawatzky, B. and Jenson, T. 1984. Zero tillage in Southern Alberta. 21st Ann. Alberta Soil Sci. Workshop Proc. pp. 128-136.

Malhi, S. S., O'Sullivan, P. A. and Caldwell, C. D. 1984. Preliminary results from a feasibility study of zero tillage in central Alberta. 21st Ann. Alta. Soil Sci. Workshop Proc. pp. 137-148.

Manitoba Agriculture 1988 Field Crop Variety Recommendations for Manitoba. 1988. Manitoba Agriculture Publications Distribution, Winnipeg, Mb.

Manitoba Agriculture 1988 Guide to Chemical Weed Control. 1988. Prepared by Manitoba Agriculture, Winnipeg, Mb.

McNeal, F. H., Berg, M. A., Brown, P. L. and McGuire, C. F. 1971. Productivity and quality response to five spring wheat genotypes, Triticum aestivum L. to nitrogen fertilizer. Agron. J. 63: 908-910.

Nowatzki, R. E. 1980. Crop yields and production costs comparing no-till with several conventional tillage systems. Proc. 2nd Ann. Mb.-N. D. Zero-tillage Workshop. 6pp.

Olsen, S. R. and Dean, L. A. 1965. Phosphorus. In, Methods of Soil Analysis, Part II., C. A. Black (Ed.-in-chief)., pp. 1035-1049. Monograph No. 9 in the Series of Agronomy. Amer. Soc. of Agron., Madison, Wisconsin.

Olson, R. A., Frank, K. D., Deibert, E. J., Dreier, A. F., Sander, D. H. and Johnson, V. A. 1976. Impact of residual mineral N in soil on grain protein yields of winter wheat and corn. Agron. J. 68: 769-772.

Olson, R. A. and Kurtz, L. T. 1982. Crop Nitrogen Requirements, Utilization, and Fertilization. In, F. J. Stevenson et al (Eds.) Nitrogen in Agricultural Soils. Agronomy 22: 567-604. Am. Soc. of Agron., Inc. (Publisher), Madison, Wisconsin.

Partridge, J. R. D. and Ridley, A. O. 1974. Effects of nitrogen fertilizers in spring or fall on yields of barley. 18th Ann. Rep. MSSM pp. 121-126.

Paul, E. A. and Myers, R. J. K. 1971. Effect of soil moisture stress on uptake and recovery of tagged nitrogen by wheat. Can. J. Soil Sci. 51: 37-43.

Pratt, P. E. 1965. Potassium. In, Methods of Soil Analysis, Part II., C. A. Black (Ed.-in-chief)., pp. 1022-1030. Monograph No. 9 in the Series of Agronomy. Amer. Soc. of Agron., Madison, Wisconsin.

Racz, G. J. 1974. Effect of nitrogen supply, water supply and temperature on the yield and protein content of cereal grains. 18th Ann. Rep. MSSM pp. 219-228.

Ramig, R. E. and Rhoades, H. F. 1963. Interrelationships of soil moisture level at planting time and nitrogen fertilization on winter wheat production. Agron. J. 55: 123-127.

Rennie, D. A., Wilkinson, D. B., deJong, E., Kachanoski, G. R. and Voroney, R. P. 1983. Innovative Acres 1982 Report. A Farmlab Project. The Saskatchewan Institute of Pedology, Dept. of Soil Sci., Univ. of Saskatchewan, Saskatoon, Saskatchewan.

Rennie, D. A., Wilkinson, D. B., de Jong, E., Kachanoski, G. R., Voroney, R. P. and Valby, J. 1984. Innovative Acres 1983 Report. A Farmlab Project. The Saskatchewan Institute of Pedology, Dept. of Soil Sci., Univ. of Saskatchewan, Saskatoon, Saskatchewan.

Ridley, A. O. 1973. Effect of nitrogen fertilizers applied in spring or fall on yields of barley. 17th Ann. MSSM pp. 176-181.

Rourke, D. R. S. and Stobbe, E. H. 1984. Intensive management of winter wheat on the prairies. 1984 Proc. Mb. Agron. Ann. Conf. pp. 76-86.

Rourke, D. R. S., Grant, C. A. and Stobbe, E. H. 1983. Fertilizer management practices for winter wheat. 1983 Proc. Mb. Agron. Ann. Conf. pp. 94-107.

Russell, E. W. 1973. Soil Conditions and Plant Growth, 10th edition. Longman, Inc., New York.

Schneider, R. P. 1979. Effects of stubble height on Soil moisture and N utilization. Proc. Mb.-N. D. Zero-tillage Workshop.

Schuman, G. E., Stanley, M. A. and Knudson, D. 1973. Automated total nitrogen analysis of soil and plant samples. Soil Sci. Amer. Proc. 37: 480-481.

Shaykewich, C. F. 1974. Principles of Water Use in Agricultural Production. In, C. G. Morley et al (Eds.) The Allocative Conflicts in Water-Resource Management. Agassiz Center for Water Studies, The Univ. of Manitoba, Winnipeg, Manitoba. pp. 23-42.

Smika, D. E. and Whitfield, C. J. 1966. Effect of standing wheat stubble on storage of winter precipitation. J. Soil Water Conserv. 21: 138-141.

Spilde, L. A. and Deibert, E. J. 1986. Crop yield, water use and soil property changes with conventional, minimum, and no-till systems in the Red River valley. North Dakota Farm Research 43: 22-25.

Spratt, E. D. and Gasser, J. K. R. 1970. Effects of fertilizer-nitrogen and water supply on distrubution of dry matter, and nitrogen between the different parts of wheat. Can. J. Plant Sci. 50: 613-625.

Stanford, G. and Hunter, A. S. 1973. Nitrogen requirements of winter wheat (Triticum aestivum L.) varieties "Blueboy" and "Redcoat". Agron J. 65: 442-447.

Staple, W. J., Lehane, J. J. and Wenhardt, A. 1960. Conservation of soil moisture from fall and winter precipitation Can. J. Soil Sci. 40: 80-88.

Stepphun, H. and Zentner, R. P. 1986. Water Utilization and Water Use Efficiency in Relation to Yield and Quality of Red Spring Wheat. In, Wheat Production in Canada - A Review, Proc. of the Can. Wheat Prod. Symp. pp. 136-164. Dev. of Ext. and Comm. Rel. Univ. of Sask. Saskatoon, Sask. (Publisher). A. E. Slinkard and D. B. Fowler (Eds.).

Stevenson, F. J. 1982. Origin and Distribution of Nitrogen in Soil. In, F. J. Stevenson et al (Eds.) Nitrogen in Agricultural Soils, Agronomy 22: 1-42. Am. Soc. of Agron.,Inc.(Publisher), Madison, Wisconsin.

Tanner, C. B. 1957. Factors affecting evaporation from plants and soils. J. Soil Water Conserv. 12: 221-227.

Toly, A. 1984. Zero tillage versus minimum till trial. 21st Ann. Alta. Soil Sci. Workshop Proc. pp. 149-154.

Viets, Jr., F. G. 1962. Fertilizers and the efficient use of water. Adv. Agron. 14: 223-264.

Young, R. A., Ozbun, J. L., Bauer, A. and Vasey, E. H. 1967. Yield response of spring wheat and barley to nitrogen fertilizer in relation to soil and climatic factors. Soil Sci. Soc. Amer. Proc. 31: 407-410.

APPENDIX A

Means of observed data for grain yield ($kg\ ha^{-1}$) as affected by rate of applied-N (1985)

Applied-N ($kg\ ha^{-1}$)	Wheat-tillage regime		
	WWZT[1]	SWZT[2]	SWCT[3]
12	2969	3498	3012
30	3461	3791	----
60	4205	4216	4134
90	4321	4494	----
120	4762	4292	----
180	4648	4759	4138
240	5260	4495	----
300	5179	4646	4719

1 winter wheat under zero tillage.
2 spring wheat under zero tillage.
3 spring wheat under conventional tillage.

APPENDIX B

Means of observed data for straw yield (kg ha^{-1}) as affected by rate of applied-N (1985)

Applied-N (kg ha^{-1})	Wheat-tillage regime		
	WWZT[1]	SWZT[2]	SWCT[3]
12	3913	5366	4323
30	4505	5572	----
60	5655	6416	6140
90	5946	7038	----
120	6403	6491	----
180	5993	7267	7338
240	7097	7100	----
300	7130	7124	7121

[1] winter wheat under zero tillage.
[2] spring wheat under zero tillage.
[3] spring wheat under conventional tillage.

APPENDIX C

Means of observed data for water use efficiency (kg ha^{-1} mm^{-1}) based on grain yield as affected by rate of applied-N (1985)

Applied-N (kg ha^{-1})	Wheat-tillage regime		
	WWZT[1]	SWZT[2]	SWCT[3]
12	7.9	10.0	7.4
30	----	----	----
60	13.6	11.3	11.7
90	11.7	12.7	----
120	----	----	----
180	13.1	13.7	10.1
240	----	----	----
300	15.6	12.7	13.8

[1] winter wheat under zero tillage.
[2] spring wheat under zero tillage.
[3] spring wheat under conventional tillage.

APPENDIX D

Means of observed data for water use efficiency (kg ha^{-1} mm^{-1}) based on grain plus straw yield as affected by rate of applied-N (1985)

Applied-N (kg ha^{-1})	Wheat-tillage regime		
	WWZT[1]	SWZT[2]	SWCT[3]
12	18.4	24.9	18.1
30	----	----	----
60	30.9	28.3	28.7
90	28.2	32.4	----
120	----	----	----
180	30.3	34.9	31.9
240	----	----	----
300	36.8	32.5	35.2

1 winter wheat under zero tillage.
2 spring wheat under zero tillage.
3 spring wheat under conventional tillage.

APPENDIX E

Means of observed data for grain yield (kg ha^{-1}) as affected by rate of applied-N (1986)

Applied-N (kg ha^{-1})	Wheat-tillage regime		
	WWZT[1]	SWZT[2]	SWCT[3]
12	2407	2096	2279
30	2995	2524	----
60	3159	3093	3177
90	3316	3246	----
120	3477	3292	----
180	3518	3454	3421
240	3445	3312	----
300	3494	3515	3070

[1] winter wheat under zero tillage.
[2] spring wheat under zero tillage.
[3] spring wheat under conventional tillage.

APPENDIX F

Means of observed data for straw yield (kg ha^{-1}) as affected by rate of applied-N (1986)

Applied-N (kg ha^{-1})	Wheat-tillage regime		
	WWZT[1]	SWZT[2]	SWCT[3]
12	2890	3222	3605
30	3638	3743	----
60	4026	4425	4537
90	3713	4623	----
120	3986	4688	----
180	3947	4830	4941
240	3956	4926	----
300	4097	5273	4734

[1] winter wheat under zero tillage.
[2] spring wheat under zero tillage.
[3] spring wheat under conventional tillage.

APPENDIX G

Means of observed data for nitrogen uptake (kg N ha^{-1}) by grain plus straw as affected by rate of applied-N (1986)

Applied-N (kg ha^{-1})	Wheat-tillage regime		
	WWZT[1]	SWZT[2]	SWCT[3]
12	52	59	60
30	66	69	----
60	78	88	96
90	91	101	----
120	103	116	----
180	109	134	131
240	110	127	----
300	115	140	126

[1] winter wheat under zero tillage.
[2] spring wheat under zero tillage.
[3] spring wheat under conventional tillage.

APPENDIX H

Means of observed data for recovery of applied-N (%) by grain plus straw as affected by rate of applied-N (1986)

Applied-N (kg ha^{-1})	Wheat-tillage regime		
	WWZT[1]	SWZT[2]	SWCT[3]
12	----	----	----
30	66.2	51.1	----
60	60.5	58.5	69.7
90	50.7	53.2	----
120	48.1	52.1	----
180	34.9	45.1	42.4
240	26.7	31.0	----
300	23.2	28.8	23.8

[1] winter wheat under zero tillage.
[2] spring wheat under zero tillage.
[3] spring wheat under conventional tillage.

APPENDIX I

Means of observed data for water use efficiency (kg ha^{-1} mm^{-1}) based on yield of grain as affected by rate of applied-N (1986)

Applied-N (kg ha^{-1})	Wheat-tillage regime		
	WWZT[1]	SWZT[2]	SWCT[3]
12	7.3	7.3	6.3
30	----	----	----
60	9.9	8.2	8.1
90	10.3	10.6	----
120	----	----	----
180	11.1	9.6	8.7
240	----	----	----
300	10.9	9.8	7.5

[1] winter wheat under zero tillage.
[2] spring wheat under zero tillage.
[3] spring wheat under conventional tillage.

APPENDIX J

Means of observed data for water use efficiency (kg ha^{-1} mm^{-1}) by grain plus straw as affected by rate of applied-N (1986)

Applied-N (kg ha^{-1})	Wheat-tillage regime		
	WWZT[1]	SWZT[2]	SWCT[3]
12	16.2	18.7	16.4
30	----	----	----
60	23.3	20.2	19.8
90	21.6	25.6	----
120	----	----	----
180	23.8	22.3	22.0
240	----	----	----
300	23.8	24.4	19.1

1 winter wheat under zero tillage.
2 spring wheat under zero tillage.
3 spring wheat under conventional tillage.