ROTATION BENEFITS OF ALFALFA IN A CROPPING SYSTEM

by

David A. Forster

A Thesis
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Rotation Benefits of Alfalfa in a Cropping System

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ABSTRACT

Including alfalfa (*Medicago sativa* L.) in cropping systems produce nitrogen and non-nitrogen benefits which affect subsequent cereal yield, grain protein concentration and grain nitrogen uptake and is known to improve the soil surface hydrology and increase root activity and soil water extraction by subsequent crops. The objective of this study was to determine the rotation benefit of alfalfa to subsequent wheat (*Triticum aestivum* L.) crops. The effect of including one to six year alfalfa stand lengths in rotation was measured using subsequent wheat yield, grain protein concentration, grain nitrogen uptake as well as rooting depth and soil water extraction by wheat at the Winnipeg Crop Rotation from 1990 to 1997. Short term alfalfa stands of three to four years had similar rotation benefits (both N and non-N) as longer alfalfa stand lengths. In the first wheat crop after alfalfa, wheat yield and grain N uptake benefits from alfalfa were attributed predominantly to N benefits. For the wheat crops two or more years after alfalfa, yield and grain N uptake benefits from alfalfa were attributed mainly to non-N benefits. Increased wheat grain protein concentration (GPC) due to alfalfa was detected in fertilized rotations up to the fifth wheat crop after alfalfa. Economic benefits from alfalfa were attributed to higher yields in unfertilized rotations and higher GPC in N fertilized rotations. Alfalfa used more water than annual crop plants and had a significant effect on the soil surface hydrology. Alfalfa caused deeper rooting depths by subsequent cereal crops for the first two wheat crops in both fertilized and unfertilized rotations and also increased subsequent soil water extraction by wheat plants up to four years after alfalfa termination. Including alfalfa in rotation increased water use efficiency (WUE) of wheat yield (physiological efficiency) in unfertilized rotations while increased water recovery efficiency contributed to higher grain yield in fertilized crop rotations. Results from this study indicate that short term alfalfa stands of two to four years are feasible to increase subsequent cereal yield, grain protein concentration, rooting depth and soil water extraction in the sub-humid regions of Manitoba.

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Introduction

Alfalfa (*Medicago sativa* L.) is produced on a large acreage across western Canada and is primarily used as a feed source for animals. While expansion in alfalfa acreage is limited by the market demand for alfalfa, interest in using alfalfa for rotation crops is increasing. Benefits of including alfalfa in a grain crop rotation include higher yield (Hoyt, 1990) and higher grain protein concentration (Hedlin et al., 1956) in subsequent wheat crops. These agronomic benefits result from a combination of nitrogen and non-nitrogen rotation benefits. A large amount of biologically fixed nitrogen is produced by alfalfa (Kelner et al., 1997), and legume nitrogen availability varies depending on factors such as alfalfa stand length (Holford, 1990), alfalfa termination date and technique (Mohr et al., 1998), forage stand composition (Voss and Shrader, 1984), and climate (Campbell et al., 1990).

Non-nitrogen benefits from alfalfa include factors such as improved soil physical structure (Meek et al., 1990; Cavers, 1996), increased soil organic matter content and aggregation (Angers, 1992; Campbell et al., 1990), reduced weed populations (Entz et al., 1995), and reduced root disease infestation (Cook, 1992). Alfalfa in rotation extracts a significant amount of water from the soil profile and from deeper depths than annual rotations (Carter and Shaeffer, 1983). In semi arid climates, water deficits from alfalfa limit the rotational benefits which contribute to subsequent cereal yield (Krall et al., 1965; Campbell et al., 1990). In more humid climates, previous water use by alfalfa generally does not limit the expression of nitrogen and non-nitrogen benefits resulting in positive yield benefits (Hoyt and Leitch, 1983).

Currently, a high proportion of alfalfa crops are terminated after the economically optimum alfalfa stand length of 4 to 5 years (Entz et al., 1995). Much of the alfalfa is removed from production due to declining forage yield with little emphasis being placed on maximizing the alfalfa rotation benefits (Entz et al., 1995). In cropping systems where alfalfa is used as a rotation crop, reducing the alfalfa stand length would distribute the rotational benefits to more of the land base. As a result, research to identify the minimum alfalfa stand length which maximize rotational benefits is required. As well, the influence of alfalfa stand length on the persistence of nitrogen and non-nitrogen rotational benefits has not been documented for subhumid regions of prairie Canada.

Many previous studies concerning soil water content after alfalfa focused on the water deficits which can occur after alfalfa. In southern Manitoba, precipitation during the recharge period is generally adequate to grow a subsequent wheat crop without having serious yield reduction. Soil conservation practices such as herbicide termination of alfalfa combined with zero or minimum tillage also reduce the risk of drought in subsequent crops (Bullied et al., 1999). In the present study, measurements of wheat rooting depth, soil water extraction and water use efficiency in alfalfa-containing vs annual grain rotations were used to determine if alfalfa has a beneficial effect on the soil water dynamics in a cropping system.

The Winnipeg Crop Rotation study was used to quantify the effect of alfalfa of subsequent wheat grain yield, grain protein concentration and soil water dynamics. The objectives of the present study were: 1) to determine the effect of alfalfa stand length (1 to 6 years) on yield, grain protein concentration, and grain N uptake of wheat, 2) to determine the persistence of the nitrogen and non-nitrogen rotation benefits after alfalfa termination using five subsequent wheat crops, and, 3) to determine the effect alfalfa on rooting depth, soil water extraction, and water use efficiency of following wheat crops.

1.0 Literature Review

1.1 The effect of alfalfa on the yield and protein of subsequent cereal crops

1.1.1 Introduction

Alfalfa (*Medicago sativa* L.) is produced on over 1.1 million ha in western Canada (Biederbeck et al, 1992). While alfalfa is primarily used as a feed source for animals, rotational benefit to subsequent crops, particularly in the Black and Dark Gray soil zones, are also important. Rotation benefits are composed of benefits derived from nitrogen and non-nitrogen sources.

The rotational benefits of alfalfa include higher subsequent cereal yield (Hoyt and Leitch, 1983; Hoyt, 1990; Baldock et al., 1981; Bruuselma and Christie, 1987) and higher cereal grain protein concentration (Hedlin et al., 1956; Badaruddin and Meyer, 1989a). The length of time alfalfa residual benefits persist have also been measured (Hoyt, 1990). In western Canada, the average alfalfa stand length is slightly longer than the economic optimum of 4 or 5 years (Entz et al., 1995). To maximize rotational benefits by distributing alfalfa over a larger land base, the use of shorter alfalfa stand lengths has been suggested (Entz et al., 1995). In humid environments, short term alfalfa stand lengths (2 to 3 years) contribute similar rotation benefits as longer term stands (Hoyt and Leitch, 1983).

1.1.2 Nitrogen benefits of alfalfa in cropping systems

1.1.2.1 Nitrogen fixation in established alfalfa stands

The amount of nitrogen produced by alfalfa through symbiosis with *Rhizobia* bacteria varies depending on climate and soil type. Estimates of nitrogen fixation range from 70 to 400 kg N ha^{-1} yr^{-1} (Peterson and Russelle, 1991). The effect of alfalfa stand length on the amount of nitrogen produced from established alfalfa stands has been measured. In a field study in southern Manitoba, alfalfa fixed 174 kg N ha^{-1} in the establishment year and up to 466 kg N ha^{-1} in the third year of the alfalfa stand (Kelner et al., 1997). Similarly in Minnesota, alfalfa fixed 160-177 kg N ha^{-1} during the seedling year and 224 kg N ha^{-1} in the fourth production year (Heichel et al., 1984). While much of the fixed nitrogen is removed as harvested forage, the root, crown and unharvested aboveground material is added to the soil system. In a Minnesota experiment, harvested alfalfa material contained the equivalent of 270 kg ha^{-1} of symbiotically fixed nitrogen (Lory et al., 1992). In a production system, much of this nitrogen would be removed from the field with the remaining roots and crowns accounting for any increase in soil nitrogen. The net soil N increase in a Manitoba study was 83, 148 and 137 kg N ha^{-1} for the establishment year, second and third year alfalfa stands, respectively (Kelner et al., 1997). Clearly, alfalfa contributes significantly to the soil nitrogen pool.

1.1.2.2 Nitrogen availability to subsequent crops

The amount of alfalfa nitrogen available to subsequent cereal crops depends on plant stand composition (Voss and Shrader, 1984), soil type (Ladd et al, 1983), management (Mohr et al., 1998), and climate (Lyon and Bizzell, 1933; Bowren et al., 1969; Hoyt and Hennig, 1971; Bruuselma and Christie, 1987). The rate of nitrogen availability can also vary.

Quantification of the alfalfa nitrogen benefits to subsequent crops is estimated using several techniques. Measuring changes in soil nitrogen status is a method to quantify the nitrogen contribution of alfalfa to the soil system. Increases in soil nitrogen of 84 ,148 and 137 kg N ha^{-1} were attributed to 1, 2, and 3 year alfalfa stands in southern Manitoba (Kelner et al., 1997). Using this nitrogen budget, no significant difference in the net soil nitrogen status was detected when increasing alfalfa stand length from 2 to 3 years. In field studies in Australia, total soil nitrogen increased by 100 kg N ha^{-1} yr^{-1} in the alfalfa stands up to 2 years and then started to decline due to grazing pressure (Holford, 1990). Holford (1990) found soil NO_3-N concentration to be higher after alfalfa termination than after continuous cereal for the corresponding period.

Potentially mineralizable nitrogen is often used as an indicator of the soil's capacity to supply nitrogen to subsequent crops. Campbell et al. (1993) found a 3year alfalfa and bromegrass (*Bromus inermis* L.) mixture in a 6-year crop rotation increased the nitrogen supplying power of the soil, which in turn increased subsequent wheat yield. Addition of green manure or hay (alfalfa and bromegrass mixture) during a 34 year cropping system at Indian Head, SK produced higher long-term wheat yields than wheat in fallow-wheat-wheat or continuous wheat rotations (Campbell et al., 1993).

Another popular method for quantifying the amount of nitrogen available from plant legume sources is the fertilizer replacement value (Lory et al, 1995). Fertilizer replacement values compare nitrogen responses of non-legume crops after alfalfa to fertilized rotations which do not contain alfalfa (Lory et al, 1995). Nitrogen fertilizer replacement values of 125 to 135 kg N ha^{-1} have been measured for corn after alfalfa (Bruuselma and Christie, 1987; Baldock and Musgrave, 1980).

Nitrogen from legume residue becomes available over time. In 2 years of field studies in South Australia, first wheat crops after addition of legume residue (*Medicago littoralis* L.)

took up 27.8 and 20.2% of the 48.4 kg ha^{-1} of legume N applied (Ladd et al., 1983). The legume residue additions accounted for 6.1 and 10.8% of the nitrogen taken up by wheat (Ladd et al., 1983). Availability to the second wheat crops declined to less than 5% of the applied legume N (Ladd et al.,1983). Similarly, corn recovered 17 and 25% of labeled alfalfa-^{15}N applied to loam and sandy loam soils in Michigan (Harris and Hesterman, 1990). Soil incorporation of legume residue generally increases the total amount of N mineralization. In a green house study, nitrogen accumulation into a barley crop accounted for greater than 60% of the accumulated N uptake when residue was incorporated and only 24% when residue remained on the surface during the first 25 day period after termination (Mohr et al., 1998).

Composition of the alfalfa sward also affects the amount of biologically fixed nitrogen added to the system. Many 'typical' alfalfa fields in Manitoba are either seeded as mixtures with domestic grasses or have grassy perennial weeds encroaching into them. Meadow treatments containing 50-100%, 20-50% and 0-20% alfalfa produced fertilizer nitrogen equivalents of 155, 112 and 22 kg N ha^{-1}, respectively when planted to corn (Voss and Shrader, 1984). Reduction in subsequent crop yield was attributed to lower amounts of biologically fixed nitrogen produced by alfalfa in the mixed sward. Similarly, in northern Alberta, barley after alfalfa-bromegrass mixtures yielded 1990 kg ha^{-1}, compared with 2260 kg ha^{-1} after pure alfalfa and 680 kg ha^{-1} after bromegrass alone (Hoyt and Hennig, 1971).

Harvest management prior to alfalfa termination will also affect the amount of residual nitrogen available to subsequent cereal crops. In a field study in Minnesota, termination after one forage cut released 157 kg ha^{-1} to the soil while termination after three cuts released only 85 kg N ha^{-1} available to subsequent crops (Hesterman et al., 1986). Termination technique and termination date also are known to affect subsequent crop growth (Mohr, 1997; Bullied et al., 1999). Over 60% of the cumulative N uptake was taken up in the initial 25 days after termination by tillage compared to 39% when herbicide termination of alfalfa with residue remaining on the surface (Mohr et al., 1998). In this case, herbicide termination with residues remaining on the surface improve the synchrony of nitrogen release from alfalfa plant material and subsequent cereal crop demand for N, provided adequate conditions for nitrogen mineralization were present. In similar field experiments, termination with herbicide using a no-till system produced equal or higher wheat yields compared to tillage treatments (Mohr, 1997). Increased soil moisture under the no-till system was believed to be partly responsible for the yield increases (Bullied et al., 1999).

Climate and soil moisture also affect decomposition rate and the rate of nitrogen mineralization of alfalfa residue. Schomberg et al. (1994) showed that alfalfa decomposition rate increased linearly with increased water addition to the soil. Slower decomposition of surface applied residue than buried residue in this study was attributed to dry soil conditions (Schomberg et al. 1994). Therefore, nitrogen from organic decomposing alfalfa residue will be less available for plant growth under dry conditions. Under these conditions, a slow rate of nitrogen mineralization may reduce the likelihood of producing maximum rotation benefits to subsequent non-legume crops in the first year. In an experiment in northern Alberta, a lack of yield increases (and in some years decreases) of barley after alfalfa were attributed to a spring soil moisture deficit (Hoyt and Leitch, 1983). Similarly, Westerman and Crothers (1993) found no yield increases in corn after alfalfa as a result of insufficient nitrogen mineralization during the growing season. While organic nitrogen may be present after alfalfa, nitrogen availability is dependent on favorable climate and soil moisture conditions.

1.1.3 Non-nitrogen benefits of alfalfa in crop rotations

While alfalfa nitrogen benefits contribute to yield increases of following crops, non-nitrogen benefits of including perennial legumes in cropping systems also exist. Non-nitrogen benefits of alfalfa include increased soil organic matter levels (Hoyt and Hennig, 1971; Bremer et al., 1994), improved soil physical properties (Angers, 1992; Spratt, 1966), weed suppression (Blackshaw et al., 1994) and plant disease control (Bailey et al., 1992; Cook, 1992). Including alfalfa in crop rotations increased the total soil carbon and increased the amount of aggregation in the soil surface (Drury et al., 1991). Stimulation of the microbial biomass activity and increased microbial biomass nitrogen in green manure and alfalfa containing rotations have also been reported (Campbell et al., 1991).

1.1.3.1 Influence of alfalfa on soil physical properties

Roots of alfalfa extend deep into the soil profile and upon root death leave stable pores (Blackwell et al., 1990). Deep, prolific root systems are important for extraction of deep leached nitrate during the growth of alfalfa. Extraction of NO_3-N has been measured to depths of 2.7 m in Minnesota (Mathers et al., 1975) and 2.4 m in Saskatchewan (Campbell et al., 1994). Evidence of nitrate uptake from the subsoil during alfalfa growth support theories of increased rooting depth with alfalfa. Deep alfalfa roots also extract soil water deep within the soil profile. Further evidence of alfalfa's deep rooting pattern is through higher soil nitrogen levels to a depth of 120 cm in rotations which contain alfalfa (Gault et al., 1995).

Alfalfa grown in rotation improves soil structure (Blackwell et al. 1990; Angers, 1992). Production of stable pores in the subsoil is important for increasing water infiltration in regions with high precipitation and heavy clay soils such as the Red River Valley of Manitoba. This improvement in soil structure from incorporation of forage species is often referred to as "biological tillage" (Blackwell et al., 1990). Increased aeration caused by alfalfa root biopores may alter rooting patterns of subsequent wheat crops. More prolific root growth by subsequent annual crops may also increase access to subsoil water and nutrients (Blackwell et al., 1990).

Improvements in soil water infiltration due to alfalfa in rotation have been documented in several studies. In a Texas study, water infiltration rate increased from 13 mm hour^{-1} in no-till continuous cotton to 89 mm hour^{-1} in a rotation of no-till cotton after alfalfa (Meek et al., 1990). High infiltration rates were attributed to maintenance of macropores under no-till after alfalfa removal (Meek et al., 1990). The effect of alfalfa in rotation on hydraulic conductivity was also measured previously in the Winnipeg crop rotation trial (Cavers, 1996). Hydraulic conductivities in wheat plots which previously contained alfalfa were one to two orders of magnitude higher than the no-till wheat and continuous summerfallow rotations at both the 0 to 25 cm and 25 to 50 cm soil depths. Rapid infiltration in heavy clay soils decrease surface water runoff and soil erosion potential. Deeper root growth and increased infiltration of water into the clay subsoil may indirectly account for subsequent yield increases following alfalfa growth.

1.1.3.2 Influence of alfalfa on disease and weed cycles

Interruption of disease cycles and weed suppression are also important non-nitrogen benefits associated with including alfalfa in cropping systems. Root diseases are prominent in cropping systems with little or no crop rotation (Cook, 1992). In the Pacific Northwest U.S., soil fumigation resulted in 70%, 22% and 7% yield increases in wheat fields planted to wheat every year, every other year and every third year, respectively (Cook, 1992). In this instance, lower yields in the absence of crop rotation were due to take-all (*Gaeumannomyces graminis*), rhizoctonia (*Rhizoctonia solani*) and pythium root rot (*Pythium spp.*). In Saskatchewan, infestation of common rootrot (*Cochiliobolus sativus*) decreased with increased intervals between wheat (Ledingham, 1961). Studies in Kansas indicate alternation of sorghum with wheat reduced the severity of tanspot (*Pyrenophora tritici-repentis*) in wheat compared to monoculture wheat rotations (Bockus, 1992).

The effect of alfalfa in crop rotation has also been analyzed under commercial field conditions. In a survey of Manitoba and Saskatchewan producers, 67% of producers indicated a yield benefit from including forages in crop rotation (Entz et al., 1995). In the same survey, respondents indicated weed control benefits for one (11% of respondents), two (50% of respondents), and greater than two years (33% of respondents) after forages (Entz et al., 1995). Weed control benefits of alfalfa have also been documented in Manitoba by Ominski (1998).

1.1.4 Yield and protein content of cereal crops following alfalfa

1.1.4.1 Crop productivity in the absence of fertilizer N additions

Grain yield is an important measurement of productivity in cropping systems. In the absence of fertilizer N, cereal grain yields are typically increased with the addition of alfalfa into the cropping system (Spratt, 1966; Hoyt and Hennig, 1971; Hoyt, 1990). The magnitude of the yield increase varies depending on soil type, alfalfa stand length and subsequent nitrogen fertilization. In a long-term southern Manitoba study, spring wheat following fallow in a rotation which included alfalfa-bromegrass 3 out of 9 years yielded 400 kg ha^{-1} more than wheat following fallow in a fallow-wheat-wheat rotation (Spratt, 1966). Similarly, in the Peace River region of Alberta, the first unfertilized wheat crop after alfalfa yielded 940 kg ha^{-1} higher than wheat after fallow (Hoyt and Hennig, 1971).

The primary quality indicator of wheat is grain protein concentration (GPC); it strongly affects the economic productivity of wheat in western Canada. Grain protein concentration is controlled by a variety of environmental and genotypic factors (Fowler et al, 1990). Additions of inorganic N (Fowler et al., 1989) and organic N (Johnston et al., 1995) generally increase grain protein concentration. Similarly, including alfalfa in a cropping system typically increases protein concentration of wheat (Hedlin et al., 1956; Ferguson and Gorby, 1971; Asghari and Hanson, 1983). In Missouri, grain protein concentration of field-grown corn following alfalfa was always higher than monoculture corn regardless of the amount of fertilizer N added (Asghari and Hanson, 1983). Similarly, in a study at Brandon MB, increased soil NO_3-N from the termination of four, six, and eight year alfalfa stands resulted in higher subsequent grain protein concentration of wheat (Ferguson and Gorby, 1971).

Grain protein yield (grain yield multiplied by grain protein concentration) is another measure of the amount of nitrogen extracted from the soil in a cropping system (Entz and Fowler., 1989). In experiments measuring grain protein concentration of winter wheat and fall rye, Fowler et al. (1990) found that any environment which increased grain yield increased grain protein yield in wheat and rye. Increased available soil nitrogen status from the addition of decomposing hay roots produced the highest grain N concentration and grain protein yield at Lethbridge, AB (Johnston et al., 1995). In summary, addition of alfalfa into a cropping system increases yield, protein concentration and protein yield of the cropping system.

1.1.4.2 Nitrogen sufficiency in crops following alfalfa in the rotation

Addition of perennial legumes such as alfalfa into a cropping system is an important practice leading to the reduced need for inorganic nitrogen fertilizer (Newbould, 1989). Nitrogen requirements after alfalfa depend on predicted potential yield, seasonal climate, and harvest management practices. Some research indicates that alfalfa can supply most if not all the nitrogen requirement for the first crop of corn in the mid-western United States (Triplett et al, 1979; Asghari and Hanson, 1983; Vanotti and Bundy, 1995), the first wheat crop in the Brown and Dark Brown soil zones of western Canada (Biederbeck et al.,1992; Ferguson and Gorby, 1971) and the first wheat crop in Australia (Holford, 1980). Other studies suggest fertilizer N is required to maximize yield and grain protein yield in the first year after alfalfa. For example, in a study of no-till corn after alfalfa in Idaho, a positive wheat yield response to added fertilizer nitrogen was attributed to insufficient mineralization of alfalfa plant nitrogen (Westerman and Crothers, 1993).

To quantify the requirement of inorganic nitrogen fertilizer after alfalfa, researchers have used the nitrogen fertilizer replacement value approach (Lory et al., 1995). Differences between fertilizer replacement value and plant nitrogen demand can be used to predict the amount of nitrogen required after alfalfa. In the mid-western United States, nitrogen fertilizer replacement values for the growth of corn after highly productive alfalfa stands were 112 to 156 kg ha^{-1} (Voss and Shrader, 1984). In the 1979-1981 period, very little yield increase was found with increases in nitrogen fertilizer additions after alfalfa (Voss and Shrader, 1984).

The yield response to nitrogen fertilizer after alfalfa generally increases with each subsequent crop after alfalfa. Yield response of corn to added nitrogen increased each year up to three years after alfalfa suggesting significant nitrogen benefits from alfalfa were present in the first and second corn crops after a one year stand of alfalfa (Baldock et al, 1981). In the third year after alfalfa, the yield response to added nitrogen was similar to continuous corn (Baldock et al, 1981). Therefore, the N and non-N benefits only lasted two years. In some cases, inorganic N fertilizer may be required in the first crop after alfalfa. For example, Triplett et al. (1979) found that in the first year of corn after alfalfa, a yield response to 56 kg ha^{-1} of added nitrogen was observed in one out of three years. Similar results at Brandon, MB indicated a positive wheat yield response to N fertilizer after alfalfa in one out of three years (Ferguson and Gorby, 1971). No grain protein concentration response to inorganic fertlizer N was observed in the alfalfa-containing rotations (Ferguson and Gorby, 1971).

The nitrogen benefit of alfalfa tends to decrease with increasing number of annual crops planted after alfalfa (Baldock et al., 1981). With decreasing nitrogen benefit, increased fertilizer N is required to produce optimum cereal crop yields. When compared to alfalfa-containing rotations, the greatest yield responses of corn were observed in rotations with no legumes present (Bolton et al., 1976; Voss and Shrader, 1984; Baldock et al, 1981).

1.1.5 Rotational benefits of alfalfa as affected by alfalfa stand length

Rotational benefits of alfalfa may be affected by alfalfa stand length. In northern Alberta, alfalfa stand length of two to six years produced no significant difference in rotational benefits as measured by yield in a following wheat crop (Hoyt and Leitch, 1983). Other studies show that an optimum alfalfa stand length does exist. Working on two different soil types in South Australia, Holford (1980) measured the greatest rotational benefits after 3.5 years compared to alfalfa stand lengths ranging from 1.5 to 3.5 years. In the experiment, fertilizer N use was not warranted for five subsequent years after termination of alfalfa stand lengths of 2.5 years or longer.

Alfalfa stand length may also affect the amount of fertilizer required to maximize grain yield of following crops. For example, in an Iowa field experiment, no significant differences were observed in corn yield responses to nitrogen rates ranging from 0 to 175 kg N ha^{-1} the first year after one, two, and three year alfalfa stand lengths (Shrader et al., 1966). In the second corn crop after alfalfa, Shrader el al. (1966) calculated nitrogen fertilizer equivalents of 65, 73 and 83 kg ha^{-1} for one, two, and three year alfalfa stands. Results of this experiment suggest that the nitrogen contribution increases with increasing alfalfa stand length, however these were not reflected in different fertilizer replacement values until the second crop after alfalfa termination.

1.1.6 Residual benefits of alfalfa in cropping systems

An important question regarding alfalfa rotational nitrogen and non-nitrogen benefits regards the length of time that residual benefits persist. Nitrogen and non-nitrogen benefits are often most evident in the first year after alfalfa (Fox and Piekielek, 1988). In a Pennsylvania study, alfalfa contributed a nitrogen fertilizer equivalence of 167 kg ha^{-1} over 3 years (Fox and Piekielek, 1988). Fox and Piekielek (1988) found alfalfa contributed 70, 20, and 10 percent of the nitrogen in the first, second and third corn crop after alfalfa.

Conversely, other studies indicate rotational benefits persist for several years. In the Peace River region of Alberta, yields of wheat following alfalfa increased by 71, 82, 75 and 65 percent over the unfertilized wheat control in the first, second, fourth and fifth crop after alfalfa (Hoyt and Hennig, 1971). In a similar experiment, Hoyt (1990) measured yield increases of 66 to 114 percent in the first 8 years of non-fertilized wheat after alfalfa. Significant yield increases were also noted in the tenth and thirteenth wheat crop after alfalfa (Hoyt, 1990). Improvement in subsoil nitrogen status from the decomposition of alfalfa roots in the subsoil partly explained the rotational benefits extending past the tenth wheat crop after alfalfa. In this experiment, nitrogen contribution of alfalfa resulted in long-term rotational benefits.

Similarly, increased yields of non-fertilized wheat after alfalfa in southern Australia lasted 7 years in one of two sites. (Holford, 1980). After a 3year alfalfa stand, N uptake in corn was 382 kg ha^{-1} higher than corn after prairie plot over 5 years (Boawn et al., 1962). Results of these studies indicate that alfalfa contributes to yield increases for several years but in some cases the magnitude of the rotational benefits decrease with time.

1.1.7 Rotational benefit summary

Release of nitrogen from alfalfa residue contributes a substantial amount of nitrogen to the soil system. Availability of organic nitrogen from alfalfa residues varies depending on environment and management conditions. Non-nitrogen benefits also contribute to yield increases when alfalfa is included in cereal based cropping systems. The combined benefit of nitrogen and non-nitrogen benefits affect subsequent crop yield and grain protein for many years (in some cases, greater than 10 years) (Hoyt, 1990). The magnitude of the alfalfa rotation benefits depend on factors such as termination date, termination technique, soil type, climate, and subsequent growing conditions.

1.2. The effect of alfalfa on the soil water content

1.2.1. Introduction

Alfalfa as an alternate crop in cereal based rotations has a significant effect on the hydrology of the soil. 'Biological tillage' from the growth of deep tap roots of alfalfa may affect the subsequent rooting patterns of cereal crops (Blackwell et al., 1990). Change in rooting pattern has the potential to increase water use efficiencies of subsequent cereal crops in rotation. Increased dry matter production and yield as a result of nitrogen input from alfalfa increase water use efficiencies (Pierce and Rice, 1998). Another important factor is that because alfalfa uses more water than most annual crops (Badaruddin and Meyer, 1989b; Ash et al., 1992), water availability for subsequent crops depends on the amount of precipitation during the recharge period, and to a lesser extent the soil water conservation during alfalfa termination (Bullied et al., 1999). The amount of water available after alfalfa varies between soil climatic zones. In drier regions of the Canadian prairies, high amounts of water use by alfalfa may cause drought in subsequent cereal crops. As well, the amount of evapotranspiration of the subsequent annual crop affects the water deficit which may occur after perennial forages. For example, high water use crops such as sunflower (*Helianthus annus* L.) may perform poorly after alfalfa compared to lower water use crops such as flax (*Linum ussitatissimum* L.).

1.2.2 Soil water extraction by established alfalfa

1.2.2.1 Depth of water extraction

Production of perennial legume as nitrogen-fixing crops in rotation has decreased in the past 60 years (Power and Doran, 1984). As a result, research to evaluate alfalfa root patterns have also decreased and much of the published data was collected in the early part of this century. Early studies in Nebraska indicate that a 4year stand of alfalfa extracted water to the 'point of exhaustion' to greater than 4.5 m (Kiesselback et al.,1929; Kiesselback et al., 1934). These studies established that alfalfa and other deep-rooted perennials extract water and nutrients from deep in the subsoil. More recent research evaluating the value of alfalfa to control saline seeps in North Dakota indicated alfalfa extracted significant amounts of water to depths of three to four meters (Brun and Worcester, 1975). Clearly, the rooting depth of alfalfa is greater than the rooting depth of annual crops. In a southern Manitoba study, the effective depth of soil water extraction in the establishment year alfalfa was 80-120 cm and 140-180 cm at the time of first and second hay cut, respectively (Bonner, 1997). Similarly, under four different irrigation regimes in Minnesota, soil water depletion by alfalfa was found to be 1.9 m at all levels of irrigation during alfalfa growth (Carter and Shaeffer, 1983). In comparison, the root growth of cereal crops are known to be shallower than alfalfa. Estimates of the effective rooting depth of wheat vary from 70 cm in Saskatchewan (Entz et al., 1992) to 110 cm in North Dakota (Merrill et al., 1996). Entz et al. (1992) determined that 95 percent of the water extracted by wheat crops was from the upper 70 cm of soil and actual rooting depth was highly correlated with soil water extraction.

The amount of precipitation during the growing season in which alfalfa grows affects the amount of soil water extraction. In southern Manitoba, estimated crop water demand for alfalfa is 400 to 450 mm compared to 275 to 325 mm for shorter seasoned annual crops such as wheat and 375 to 400 mm for longer season annual crops such as corn and sunflowers (Ash et al., 1992). Higher water demand by alfalfa also often creates seasonal soil water deficits.

1.2.3 Soil water availability to crops following alfalfa in rotation

1.2.3.1 Water deficit and soil water recharge following alfalfa in humid and sub-humid environments

High water use by alfalfa can lead to water shortages in following crops. However, humid and sub-humid climates typically have adequate precipitation during the recharge period for subsequent crop growth. Although periodic soil moisture deficits may exist in the Black, Dark Gray and Gray soil zones of western Canada, precipitation is generally adequate during the recharge period for recropping (Campbell et al, 1990). At Winnipeg, an average of 305 mm of precipitation occurs between harvest and April (Eilers et al., 1977). It is under these conditions of adequate precipitation following perennial legumes that maximum grain yield benefit from increased nitrogen and non-nitrogen alfalfa rotation benefits are realized (Hoyt and Leitch, 1983).

In humid and sub-humid climates such as the Black and Dark Gray soil zones of western Canada, fallow replacement annual legumes and forage legumes are considered suitable as rotation crops to increase subsequent yields. In a Northern Alberta field experiment, spring soil moisture content in the 0 to 70 cm soil depth after red clover (*Trifolium pratense* L.) and alfalfa termination were not significantly different than the fallow control (Hoyt and Leitch, 1983). Subsoil moisture (60 to 135 cm depth) was slightly lower in the forage treatments, however, barley yields were not compromised in the forage versus the non-fertilized continuous barley rotation (Hoyt and Leitch, 1983), possibly due to adequate growing season precipitation or the fact that cereals do not rely heavily on water below the 70 cm soil depth (Entz et al., 1992). In a related study, only slight decreases in spring soil water content following alfalfa were noted by Hoyt and Hennig (1971), and soil water deficits were not large enough to reduce yield. In a North Dakota study, soil water in spring following field bean (*Phaseolus vulgaris* L.), soybean (*Glycine max* L.), lentil (*Lens culinaris* Medikus) and fababean (*Vicia faba* L.) green manure crops or a 1 year alfalfa crop were not significantly different than following wheat (Badaruddin and Meyer, 1989b).

Another factor influencing available soil water content after alfalfa is the time of alfalfa termination. Earlier termination results in more time available for soil water recharge during the winter. In a northern Alberta study, delaying fescue (*Festuca rubra*) stand termination resulted in decreases in soil water the subsequent spring (Hennig and Rice, 1977). Average available water at spring seeding for the 1969 to 1972 period was 139, 134, 129 and 108 mm in the top 120 cm soil depth for July, August, September and May termination, respectively. However, the authors of this study also noted that differences in spring soil water content between termination date treatments were not enough to cause significant differences in subsequent barley yields, likely as a result of adequate precipitation during the growing season. Similarly, in the US mid-west, 10.7, 9.4 and 5.4 cm were available in the following spring when alfalfa was terminated after the first cut, after the second cut and in the spring just prior to seeding (Voss and Shrader, 1984). Studies in southern Manitoba indicated that variation in termination date did not affect yield of following wheat crops (Bullied et al., 1999) when terminated after first and second hay cuts. Soil water recharge during the fall and winter was as high as 7.2 cm and did not produce significant spring soil moisture differences particularly when using water conservation strategies such as no tillage (Bullied et al, 1999). However, delaying alfalfa termination until spring resulted in yield depression from reduced surface soil water availability (Bullied et al., 1999) or reduced N availability (Mohr et al., 1998).

During growing seasons with higher than normal precipitation, excess water may cause reduced grain production in the humid and sub-humid regions of western Canada. Mean soil water use at Brandon from 1956 to 1958 indicated fertilized alfalfa extracted 300 mm compared to fertilized wheat which extracted 246 mm of water (Eilers et al., 1977). In higher rainfall regions, increased soil water extraction by alfalfa removes excess water from the soil profile in the cropping system. This is important to maximize the amount of water used in a cropping system and to reduce water run-off during periods of excessive precipitation.

1.2.3.2 Water deficit and soil water recharge following alfalfa in semi-arid environments

Soil water availability in the spring is a major factor limiting spring wheat crop production in the arid and semi-arid regions of western Canada and the Northern Great Plains of the United States (Badaruddin and Meyer, 1989b; Fowler et al, 1990). The high water requirement of alfalfa produces water deficits where evapotranspiration exceeds precipitation in arid climates. Studies in Nebraska in the 1920's showed that 2 years of alfalfa depleted soil moisture far beyond the rooting depth of annual cereal crops (Meyers, 1936; Kiesselback et al., 1929).

Reduced subsoil moisture and inadequate precipitation during the recharge period after alfalfa is known to affect the subsequent cereal crop yield. It is for this reason that inclusion of perennial forages in intensive cropping systems is not recommended in the Brown and Dark Brown soil zones of western Canada and the northern Great Plains of the United States (Krall et al., 1965; Campbell et al., 1990). In the Dark Brown soil zone in Saskatchewan, 4 years of alfalfa produced lower subsequent wheat yields compared to wheat yields after bromegrass or no forage crop (Austenson et al., 1970). Austenson et al. (1970) also noted reduced wheat yield due to soil moisture depletion even after one full year of fallow following alfalfa termination. In the more arid regions of the prairie, maximum rotational benefit from perennial legumes are often not realized because of lower available soil water in subsequent years after alfalfa termination. Each of the previous soil water deficits were experienced using conventional tillage systems. The use of no-till system of termination has been suggested to increase soil water conservation after alfalfa and would be particularly valuable in more arid regions of western Canada (Bullied et al., 1999).

At Scott, SK (in the Dark Brown soil zone), including two year alfalfa stands during the 1966 to 1971 period reduced soil water availability to subsequent wheat crops; even with a 12 month fallow period (Campbell et al., 1990). In this study, the two year stand of alfalfa reduced subsequent wheat soil water extraction to 105 mm compared to 124 mm and 111 mm in fallow-*wheat* and fallow-wheat-*wheat* rotations, respectively. Clearly, water deficits after alfalfa limit rotation benefits in more arid climates.

1.2.4 Water use and water use efficiency following alfalfa in cropping systems

Water use efficiency (WUE) is an important indicator of sustainability and measurement of productivity in dryland cropping systems (Entz and Fowler, 1991). Water use efficiencies have been extensively measured in dryland wheat-fallow rotations (Haas and Willis, 1962; Campbell et al., 1987) and with different crop species and tillage systems in Manitoba (e.g. Borstlap and Entz, 1994). Water use efficiencies of cereal crops in rotations previously containing alfalfa are not as well documented.

Crop rotation generally increases WUE (French and Schultz, 1984a). In rain-fed environments, precipitation use efficiency is often calculated. Precipitation use efficiency (PUE) is defined as grain yield per unit of growing season precipitation or annual precipitation received but does not account for soil water use during the growing season. Precipitation use efficiency for corn was greater in a corn-soybean rotation (101.8 kg ha^{-1} cm^{-1}) than with continuous corn (83.6 kg ha^{-1} cm^{-1}) (Varvel, 1994). The increase in PUE in the corn-soybean rotation was attributed to increased nitrogen availability which produced a higher yield per unit of water extraction. As well, in the driest year of the 8 year study, the authors speculated that increased availability of soil water in the soybean rotation resulted in higher PUE compared to monoculture corn (Varvel, 1994).

Provided that overwinter soil water recharge occurs, the amount of evapotranspiration by crops following alfalfa is hypothesized to be higher relative to monoculture cereal rotations. For example, additions of organic nitrogen from alfalfa residues should increase root growth. Additions of inorganic nitrogen are known to increase vegetative growth and soil water extraction prior to heading (Bond et al., 1971; Brown, 1971), and water use efficiency (Entz and Fowler, 1989). Increases in yield at the same level of ET are referred to by Pierce and Rice (1988) as increases in physiological efficiency. In Minnesota, Copeland et al. (1994) observed 16 mm more water use in corn after soybean compared to a continuous corn rotation. The corn after soybean also extracted water 0.5 m deeper than the monoculture rotation (Copeland et al., 1994). Similarly, field studies in Australia indicate a rotation crop such as canola increased subsequent soil water extraction by spring wheat by 40 mm when take-all in wheat was severe (Angus et al., 1991). In another Australian study, a diverse crop rotation reduced take-all disease in spring wheat and was believed to increase rooting depth and rooting activity of the wheat crop (Evans et al., 1991). Evans et al. (1991) hypothesized that reduced disease infestation may facilitate greater extraction of soil mineral nitrogen as well as water. Therefore, higher yields after alfalfa may be due to increased soil water and nutrient extraction. This hypothesis is supported by evidence of 'biological tillage' from alfalfa (Blackwell et al., 1990). Pierce and Rice (1988) referred to this as increasing the water recovery efficiency of cropping systems.

The approach for assessing the influence of crop rotation on WUE proposed by Pierce and Rice (1988) is very logical and allows the rotation effect to be separated into physiological efficiency and recovery efficiency (increases in yield due to increases in ET). There are no published reports on how alfalfa in rotation affects Efficient Water Use (EWU) as defined by these two authors.

1.2.5 Soil Water summary

Alfalfa in crop rotation has a significant effect on soil moisture availability to crops following in the rotation. Depending on climate, termination technique and date, the amount of available soil moisture after alfalfa termination varies. In humid and sub-humid environments, soil water recharge during fall and winter usually results in adequate spring soil moisture for optimum cereal growth in the year after alfalfa stand removal. Increased yield and grain protein as a result of adequate moisture increase water use efficiency. As well, a healthier root system resulting from a diversified crop rotation should increase the ability of following crops to use moisture and nutrients deeper in the soil profile. Conversely, in arid soil climatic zones, yield reductions after alfalfa termination are often observed. Inadequate precipitation during the recharge period results in spring subsoil moisture deficits and reduced water use efficiency. These observations emphasize that high water use forage crops such as alfalfa produce significantly different yield benefits or limitations depending on the environment in which they are grown.

1.3 Influence of experimental design on alfalfa stand length benefits

The nature of the experimental design of longer-term crop rotation studies will affect the results. Previous studies considering alfalfa stand length effects have often used the approach where alfalfa is established in consecutive years and alfalfa rotational benefits are all measured in the same test years (Hoyt and Hennig, 1971; Holford, 1980). Since rotational benefits were measured in only one year, environmental differences between years was not a factor when testing various alfalfa stand lengths. However, the disadvantage of using this approach is that variations in alfalfa establishment and growth in the different years of production may affect the measured stand length benefits.

The experimental design of the Winnipeg crop rotation is a split plot arranged in a RCBD with crop rotation as the main factor and fertilizer nitrogen as the subplot factor. Alfalfa was established in 1990 and a subplot was terminated in each subsequent year. Therefore, yield and grain N rotational benefits from alfalfa were measured in different years and compared to a standard reference rotation. The advantage of this approach is that rotation benefits as affected by alfalfa stand length are compared using one alfalfa stand and are not affected by differences in alfalfa establishment. The disadvantage of this approach is that rotational benefits of wheat crops after various alfalfa stand lengths are measured in different years, and are affected by variations in environment. However in each year rotation benefits are compared to a standard reference rotation.

1.4 Literature Review Summary

Including alfalfa in cropping systems produces positive environmental and agronomic benefits. Reduction in fertilizer nitrogen inputs in the year(s) after alfalfa is an important environmental and economic benefit. Agronomically, alfalfa contributes a significant amount of nitrogen to the subsequent crops in a cropping system. Non-nitrogen benefits include reduced disease infestation, reduced weed population density, increased soil organic matter, and improved soil physical properties. Nitrogen and non-nitrogen benefits of alfalfa combine to increase subsequent grain yield and grain protein yield.

The effect alfalfa stand length on rotational benefits is variable. As well, the length of time residual benefits exist is also quite variable. Both of these questions have received only limited attention by researchers in recent years. The experimental design will, in part, affect the residual benefits measured after different alfalfa stand lengths.

The soil surface hydrology is changed when alfalfa is included in the cropping system. In wetter regions, crops following alfalfa may have higher evapotranspiration resulting from decreased leaf and root disease infestation and improved soil structure. This could increase the water use efficiency of the entire cropping system. However, the ability of alfalfa to produce maximum rotational benefits for subsequent crop depends on climate and recharge precipitation. Prospects in arid regions of western Canada are less optimistic than in wetter areas.

2.0 Materials and Methods

2.1 Background

The Winnipeg crop rotation study (Figure 2.1) was established in 1990 at Winnipeg, MB on a Black Lake clay soil consisting of 13% sand, 45% silt and 42% clay (Mohr, 1996). The experimental design is a split-plot arranged in a Randomized Complete Block Design with crop rotation (either annual: rotations 1, 2 and 3; or rotations previously containing alfalfa: rotations 6 to 15) as the main plot effect and fertilizer nitrogen (either 0 kg ha^{-1} or added to soil test recommendation) as the subplot effect. Between 1990 and 1993, the annual crop rotation included field pea (cv. Victoria) and barley (cv. Argyle) in addition to wheat (cv. Katepwa), and all phases of this rotation appeared in each year (Figure 2.1). However, after 1993 all rotations contained only wheat. The soil test recommended rates of nitrogen fertilizer were between 70 and 80 kg N ha^{-1} and ammonium nitrate (34-0-0) was broadcast evenly in each sub-plot at the two to three wheat leaf stage each year. The amount of actual N added in each year is summarized on Table 2.1. Subplot size was 5.5 by 8 m.

Establishment and management of alfalfa was consistent with recommended practices for Manitoba. In 1990, alfalfa (cv. OAC Minto) was seeded at a rate of 10 kg ha^{-1}. Each successive fall from 1990 to 1995, a treatment of alfalfa was terminated using tillage (Figure 2.1). In the year of termination, two alfalfa cuts were taken; one in mid-June to early July, and a second in late July to mid-August. In years prior to alfalfa termination, alfalfa was managed using a three cut system with the third cut harvested in early October. During the harvests, all above-ground alfalfa plant material was removed from the plot area.

In the present study, the same stand of alfalfa was terminated in consecutive years. It was assumed that the alfalfa stands terminated were of similar condition from 2 to 6 years after establishment and would produce similar rotational benefits (Table A3.3). In this case, variations in alfalfa stand length would be compared using the same alfalfa stand. Dry matter yield of the three cuts of established alfalfa ranged from 15251 kg ha^{-1} in 1991 to 11760 kg ha^{-1} in 1994 (Table A3.3). Similarly, the combined dry matter yield of two harvests of alfalfa decreased from 11976 kg ha^{-1} in 1991 to 8430 kg ha^{-1} in 1995 (Table A3.3). Despite having a somewhat lower alfalfa dry matter yield with increased alfalfa stand length, alfalfa yield benefits were higher with alfalfa stands of 3 years or greater than 2 years alfalfa stands (discussed later in section 3.1).

Although some alfalfa rotations involved no-till alfalfa termination (Figure 2.1), only alfalfa stands terminated with tillage were considered in this study. Alfalfa containing rotations consisted of rotations 6, 7, 8, 9, 12 and 15 (Figure 2.1) which correspond to alfalfa stand lengths of 1 to 6 years. From 1990 to 1992, all plots were in a minimum tillage system. However starting in 1993, all annual crops, other than in the year immediately after alfalfa termination were grown in a zero-tillage system. The annual crops were seeded using a no-till disc drill (Swift Machinery Co., Swift Current, SK).

In annual rotations and following alfalfa, spring wheat (cv. Katepwa) was seeded at 135 kg ha^{-1} and triple super phosphate was added in the seed row to soil test recommended levels (Table 2.1). Seeding dates and rates for 1990 to 1997 are summarized in Table 2.2. A row spacing of 15 cm was used. Weed control was performed using registered herbicides typically used by Manitoba producers. Pesticide application during the growing season is summarized for annual rotations in Table 2.1.

In annual rotations from 1990 to 1993, field pea (cv. Victoria) and barley (cv. Argyle) were used as alternative crops for rotation with wheat. In 1990 and from 1993 to 1997, rotation 1 was used as the control rotation for calculation of rotation benefits. In 1991 and 1992, wheat after barley in rotations 2 and 3, respectively were used as checks. From 1990 to 1993, the crop rotations were diversified enough to provide an adequate reference rotation. After 1993, continuous wheat was used as the reference rotation (rotation 1; Figure 2.1).

Grain samples were harvested using either a small-plot combine or by hand. Wheat yields were measured by threshing 8 by 1.2 m areas using a small plot combine from 1991 to 1995. In 1996 and 1997, wheat grain yield was determined from samples harvested from two adjacent m^2 in the plots. Harvest dates are summarized on Table 2.2. Wheat grain was randomly sub-sampled and coarsely ground in a Cyclone sample mill (Udy Corporation, Fort Collins, CO). Nitrogen concentration was measured using a dry combustion method using a Leco nitrogen analyzer (model FP-428; Leco Corp., Mississauga, ON). Grain N uptake (kg N ha^{-1}) was calculated by multiplying grain yield (kg ha^{-1}) and grain nitrogen concentration.

2.2 Analysis of rotational grain yield, protein concentration and grain N uptake benefits

2.2.1 Individual year analysis of rotation benefits

Grain yield, grain protein concentration and grain N uptake within each year of crop growth were analyzed using analysis of variance (SAS Institute, Inc., 1985). Using data from 1991 to 1997, these parameters were analyzed in a split-plot design with crop rotation (either alfalfa or annual rotations) as the main plot effect and fertilizer nitrogen addition (either 0 kg

ha^{-1} or added to soil test recommendations) as the subplot effect. Summary of the yield and grain N uptake are presented in the appendix as Table A3.1 and Table A3.2. Homogeneity of variance was tested for each parameter using Bartlett's test (Gomez and Gomez, 1984).

2.2.2 Effects of stand length on rotational benefits

To assess the rotational contribution of alfalfa to subsequent cereal crops, yield and grain N uptake in wheat crops preceded by different stand lengths of alfalfa were compared. A separate analysis was conducted for both the N fertilized and unfertilized rotations. A single factor analysis of variance in a Randomized Complete Block Design was used to measure the effect of alfalfa stand length on rotational yield and grain nitrogen benefits. Analysis of variance was performed on the differences in wheat yield (kg ha^{-1}) and differences in grain N uptake (kg N ha^{-1}) between alfalfa-containing and annual rotations (SAS Institute, Inc., 1985). Where significant differences were observed, Fisher's protected Least Significant Difference test (LSD) was used to measure differences among alfalfa stand lengths of 1 to 6 years (Gomez and Gomez, 1984). Differences in yield and grain N uptake in unfertilized rotations were assumed to be largely due to a combination of nitrogen and non-nitrogen rotational benefits. In the N fertilized rotations, rotational benefits were assumed to be due mainly to non-nitrogen benefits.

2.2.3 Persistence of alfalfa rotational benefits

The persistence of rotation benefits after alfalfa was also measured. The differences among the number of years of wheat after alfalfa were used to estimate the length of time residual rotational benefits persisted after alfalfa termination. This was made possible by comparing wheat yield after alfalfa to the check plots in each year. The differences in yield and grain N uptake among 1 to 5 years of wheat after alfalfa were tested using ANOVA and Fisher's protected LSD (Gomez and Gomez, 1984). Similar to alfalfa stand length measurements, a separate analysis were performed for N fertilized and unfertilized rotations.

2.2.4 Separating N and non-N benefits of alfalfa

The relative contribution of nitrogen and non-nitrogen benefits from alfalfa to subsequent wheat yield and grain N uptake was also determined. Grain yield and N uptake increases due to alfalfa in fertilized rotations (assumed to be mainly non-nitrogen benefit) were subtracted from increases due to alfalfa in unfertilized rotations (assumed to be mainly nitrogen + non-nitrogen benefit) to estimate the nitrogen benefit of alfalfa after termination of 1 to 6 year alfalfa stand lengths. The differences in yield and grain N uptake between the fertilized and unfertilized systems were used to determine the contribution of N and non-N benefits to subsequent yield and grain N uptake.

The analysis of rotational N and non-N benefits were tested using combined data of alfalfa stand lengths of 3 and 4 years (i.e. rotations 8 and 9, Figure 2.1). The reasons for this are as follows: 1) 3 and 4 year alfalfa stands are typically used by producers in south central Manitoba (Entz et al., 1995). 2) The two different stand lengths were combined since rotational benefits to yield and grain N uptake were not significantly different among alfalfa stand lengths in each wheat crop (discussed later in section 3.1.1). 3) The wheat reference rotation was a pea-barley-*wheat* rotation for the 3 year stand and a pea-barley-wheat-*wheat* for the 4 year stand. Therefore, in each subsequent year, there was similar number of years of continuous wheat after both the 3 and 4 year alfalfa stands and the annual rotation (Figure 2.1). In this way, non-N rotational benefits would not be overestimated since the reference rotation contained similar crop history as the 3 and 4 year alfalfa stand length prior to termination. Grain yield increase and grain N uptake increase means in each year after alfalfa were summarized for both the nitrogen fertilized and unfertilized rotations. Similar to the alfalfa stand length measurement, rotation benefits in fertilized rotations were assumed to be from non-nitrogen sources, while rotation benefits in unfertilized rotations were from a combination of nitrogen and non-nitrogen sources. These calculations are a general indication of the length of time that nitrogen and non-nitrogen rotational benefits were present after alfalfa termination.

2.2.5 Cumulative benefit of alfalfa in rotation

The cumulative benefit of alfalfa in rotations with and without inorganic N fertilizer were used as a measure of the long-term rotational benefit from alfalfa in a cropping system. The combined yield and grain N uptake increases from rotations in the first five wheat crops after termination of alfalfa in rotations 7, 8, 9, 12 and 15 were used to represent the cumulative differences for alfalfa stand lengths of 2, 3, 4, and 5 years, respectively. Differences in yield and grain N uptake for the various alfalfa stand lengths were tested using a single factor Randomized Complete Block Design for both the unfertilized and N fertilized rotations. Cumulative yield and N uptake increases were also used as an indicator of the long-term benefit of including alfalfa in cereal based crop rotations.

2.2.6 Economic analysis

A simple economic analysis was performed for the combined grain yield and grain protein concentration data for the first five consecutive wheat crops in the 3 and 4 year alfalfa stands. Wheat price was based on The Canadian Wheat Board 1996-1997 payments with estimated freight, elevation and removal of dockage costs deducted for Manitoba transportation costs to export ports (\$48.36 tonne^{-1}). Prices were segregated based on the CWRS No. 2 grade wheat with a base price (12% protein) of \$160.41 tonne^{-1} with protein premiums being distributed for 0.5 % increases in protein to a maximum of 15%. The price premiums for each 0.5% increase in grain protein concentration was approximately 3.75 tonne^{-1} and is summarized in Table 3.10. Fertilizer price was assumed to be \$0.77 kg^{-1} (based on Manitoba Agriculture Guidelines of Estimating 1996 crop production costs). Gross return per hectare and the increased return from including alfalfa in the rotation were calculated for both unfertilized and fertilized rotations (Table 3.10).

2.3 Soil water measurement

Soil water content was measured for annual and alfalfa-containing rotations in each year between 1991 and 1997. Aluminum access tubes were installed in the center of each subplot. Measurements below 10 cm were recorded in 20 cm increments to a depth of 150 and 210 cm in annual and alfalfa containing rotations, respectively using a field calibrated Troxler 4300 neutron probe (Troxler Electronic Laboratories, Triangle Park, N.C.). Soil water in the 0 to 10 cm depth was recorded using the neutron probe with a surface shield as used by Chanasyk and MacKenzie (1986) and Chanasyk and Naeth (1988). The dates and the crop rotations which were used to measure volumetric soil water content are summarized in Table 2.4. Crop rotations which were not included in Table 2.4 are continuous fallow (1991 to 1997), established alfalfa (1991 to 1995), and re-established native prairie grasses (1994 to 1997). The native grass plots consisted of warm and cool season native species in a mixed sward. Precipitation for each growing season was obtained from the Department of Plant Science Winnipeg field weather station in all years except 1994 when data from the Winnipeg Environment Canada monitoring site was used (Table 4.3).

2.3.1 Using soil water data to estimate wheat rooting depth

Effective rooting depth can be estimated from the depth of soil water extraction throughout the growing season (Entz et al., 1992). Estimated maximum rooting depth each year was calculated using two techniques. The first technique measured the deepest 20 cm layer showing a significant difference ($P<0.05$) in soil water content as measured by orthogonal contrasts between each rotation and the continuous fallow (rotation 5, Figure 2.1) treatments. Soil water extraction in the continuous fallow treatment is assumed to be negligible with the exception of surface evaporation. This technique is called the 'difference method'. The second technique compared soil water contents at wheat anthesis and maturity dates to those in the spring sampling date in each year. The deepest 20 cm layer showing statistical significance ($P<0.05$) as measured by a significant orthogonal contrast between the water content in the spring sampling date and the mid-season or harvest sampling date was considered to be the effective rooting depth and is termed the 'water use method'. Within each year, the deepest effective rooting depth represents the maximum rooting depth for each crop rotation.

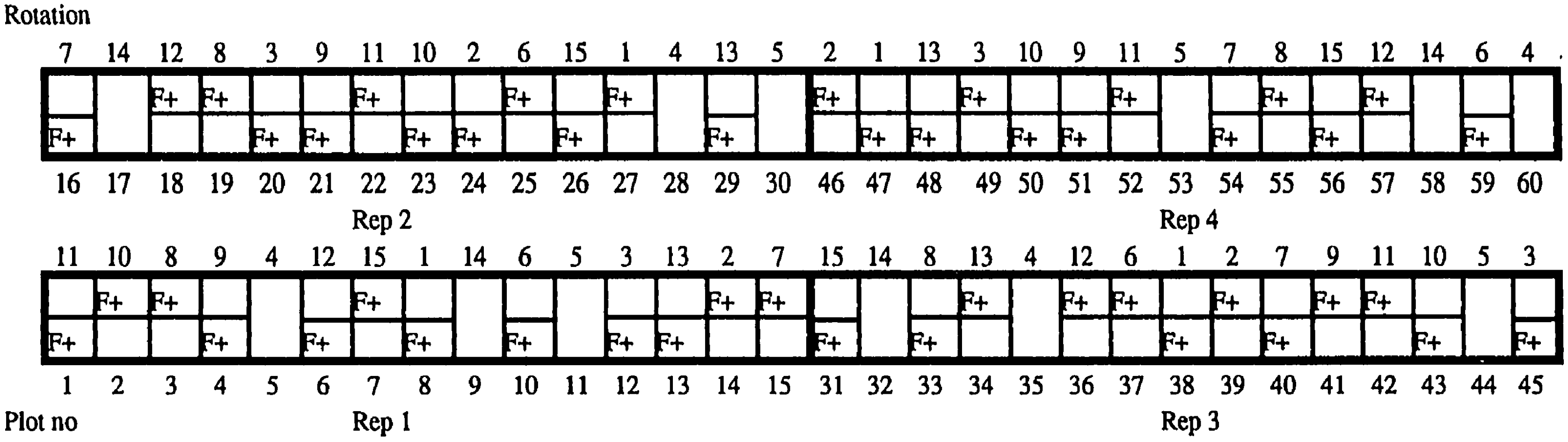
2.3.2 Effect of rotation on soil water extraction by wheat crops

Soil water measurements were also used to determine pre-anthesis and growing season soil water use. Subtraction of soil water content in the mid-season sampling date and the harvest sampling date from the initial spring sampling date is a measurement of soil water extraction. Soil water extraction was calculated for larger soil depth increments (0 to 30 cm; 30 to 90 cm; 90 to 150 cm; 0 to 150 cm) for each rotation measured in each year. Analysis of variance of soil water extraction within each larger soil depth increment was performed using a single factor Randomized Complete Block Design. Differences in soil water extraction among crop rotations were measured using Fisher's protected least significant difference test. Soil water extraction by wheat in annual and rotations previously containing alfalfa were compared in both N fertilized and unfertilized rotations. When calculating soil water extraction, surface runoff, upward soil water movement, and sub-soil deep leaching of water were assumed to be negligible.

2.3.3 Water use efficiency of wheat grain and biomass yield

Water use efficiency (WUE) was calculated by dividing grain or biomass yield (kg ha^{-1}) by evapotranspiration (ET; soil water extraction plus precipitation during the growing season) (Pierce and Rice, 1988). WUE was calculated for grain yield in each year and for biomass production in 1993, 1995, and 1997. Analysis of variance for WUE was calculated using crop rotation (either annual monoculture or alfalfa containing rotations) as the main plot effect and fertilizer nitrogen addition (either 0 kg ha^{-1} or added to soil test recommendation) as the subplot effect.

Figure 2.1. Plot plan for Winnipeg crop rotation study (1990 to 1997).



	Year							
Rotation	90	91	92	93	94	95	96	97
1	W	P	B	W	W	W	W	W
2	B	W	P	W	W	W	W	W
3	P	B	W	P	W	W	W	W
4	W/A	A/W	W/A	A/W	W/A	W	A/W	W
5	Continuous fallow							
6	A/T	W	P	W	W	W	W	W
7	A	A/T	W	W	W	W	W	W
8	A	A	A/T	W	W	W	W	W
9	A	A	A	A/T	W	W	W	W
10	A	A	A	A/H	W	W	W	W
11	A	A	A	A	A/H	W	W	W
12	A	A	A	A	A/T	W	W	W
13	A	A	A	A	A	A/H	W	W
14	A	A	Perennial native grasses					
15	A	A	A	A	A	A/T	W	W

W: Spring wheat
P: Field pea
B: Barley
A: Alfalfa
A/H: Alfalfa terminated with herbicides
A/T: Alfalfa terminated with tillage
F+: N fertilizer added
Adjacent sub-plots have no N added.

Table 2.1. Fertilizer and herbicide use for the Winnipeg crop rotation study, 1990 to 1997.

		Seed placed P2O5	Broadcast nitrogen (F+ subplots only)		Pesticide information	
Year	Crop	(kg ha^{-1})	Date	Rate	Date	Name (rate)
1990	alfalfa				July 6	imazethapyr (0.05)[z]
	wheat			80	July 6	diclofop methyl (0.81), bromoxynil (0.28)
					July 13	dicamba (0.10), MCPAK (0.42)
	barley			80	July 6	diclofop methyl (0.81), bromoxynil (0.28)
					July 13	clopyralid (0.21)
	field pea		-	-	July 6	bentazon (1.09)
					July 23	Malathion (1.0)
1991	wheat	30	May 21	80	June 5	fenoxaprop-p-ethyl (0.05), MCPA ester (0.21),thifensulfuron methyl (0.0008)
	barley	30	May 21	80	June 19	clopyralid (0.21)
	field pea	30	-	-	June 19	sethoxydim (0.51)
1992	wheat	25	May 21	80	June 3	dicamba (0.10), MCPAK (0.42)
	barley	25	May 21	80	June 3	dicamba (0.10), MCPAK (0.42)
	field pea	25	-	-	-	-
1993	wheat	22	May 26	80	May 18	gyphosate (0.87)
					June 28	thifensulphuron methyl (0.01), tribenuron methyl (0.005)
	field pea	22	-	-	Sept 15	diquat (0.4) *used as desiccant
1994	wheat	20	May 27	72	June 1	dicamba (0.14), 2,4-D (0.43)
	field pea	20	-	-	-	-
1995	wheat	20	May 25	80	June 12	dicamba (0.10), MCPAK (0.42)
1996	wheat	18	June 13	70	June 18	tralkoxydim (0.05)
	field pea	18		-	June 18	tralkoxydim (0.05)[y]
1997	wheat	20	June 13	70	June 22	fenoxaprop-p-ethyl (0.05), MCPA ester (0.21),thifensulfuron methyl (0.0008)
					July 16	chlopyrifos (0.43)

[z] kg a.i. ha^{-1} added to each plot. [y] broadleaf weeds hand-weeded where necessary.

Table 2.2. Seeding and harvest information for the Winnipeg crop rotation study from 1990 to 1997.

		Seeding information		Harvest information	
Year	Crop	Date	Rate(kg ha^{-1})	Date	Harvested area
1990	alfalfa	June 15	10	-	-
	wheat	June 18	135	Sept 5	3 by 1.2m
	barley	June 18	120	Aug 30	3 by 1.2m
	field pea	June 18	170	Sept 5	3 by 1.2m
1991	wheat	May 17	135	Aug 19	3 by 1.2m
	barley	May 17	120	Aug 12	3 by 1.2m
	field pea	May 17	170	Aug 23	8 by 5.5m
1992	wheat	May 15	135	Aug 28	8 by 1.2m
	barley	May 15	120	Sept 4	8 by 1.2m
	field pea	May 15	170	Sept 21	8 by 1.2m
1993	wheat	May 19	130	Sept 14	8 by 1.2m
	field pea	May 19	170	Sept 20	8 by 1.2m
1994	wheat	May 9	135	Aug 26	8 by 1.2m
	field pea	May 9	170	Aug 26	8 by 1.2m
1995	wheat	May 18	135	Aug 16	8 by 1.2m
1996	wheat	May 28	135	Sept 2	2 adjacent m^2
1997	wheat	May 28	135	Aug 21	2 adjacent m^2

Table 2.3. Termination treatments of alfalfa and seed bed preparation for the Winnipeg crop rotation study for 1990 to 1996.

Previous			Herbicide use or seedbed preparation	
crop	Year	Method	Date	Technique
alfalfa	1990	tillage	Aug 15	tandem discer (2)^z
	1991	tillage	Sept 9	rototiller (2)
	1992	tillage	Oct 12	rototiller (1)
	1993	tillage	Aug 26	rototiller (2)
	1994	tillage	Sept 12	rototiller (2)
	1995	tillage	Aug 29	rototiller (2)
fallow	1990			cultivate (1)
				tandem discer; deep till
annual	1991		May 15	cultivate (1); harrow
			Aug 27	deep till (1)
			Oct 16	deep till (1)
	1992		May 14	cultivate (1)
			Sept 30	deep till (1)
	1993		May 18	glyphosate (0.87)
			Oct 23	(all annual plots) MCPA (.88)
	1994		-	
			Sept 13	glyphosate(1.76), dicamba (0.30), and 2,4-D (0.5)
	1995		Sept 25	glyphosate (1.23), 2,4-D (0.5)
	1996		May 28	glyphosate (0.66)
	1997		May 27	glyphosate (0.87)

^{z} Number of passes with tillage equipment.
^{y} kg a.i ha^{-1} of actual product.

Table 2.4. Sampling dates for soil volumetric water content measurements taken three times during the growing season in each year between 1991 and 1997.

Year	Between seeding and crop emergence	Mid-season (anthesis)	After harvest	Rotation	Crop sequence
1991	May 20	June 19	August 8	2	annual (B-W)[z]
				6	wheat after alfalfa (1)[y]
1992	May 27	June 31	October 6	3	annual (P-B-W)
				7	wheat after alfalfa (2)
1993	May 27	July 9	Sept 14	1	annual (W-P-B-W)
				8	wheat after alfalfa (3)
1994	May 13	-	August 24	1	annual (W-P-B-W)[x]
				9	wheat after alfalfa (4)
1995	June 14	-	August 11	1	annual (W-P-B-W-W)
				12	1st wheat crop (5)[w]
				9	2nd wheat crop (4)
				8	3rd wheat crop (3)
1996	June 15	July 25	Sept 4	1	annual (W-P-B-W-W-W)
				15	1st wheat crop (6)[w]
				12	2nd wheat crop (5)
				9	3rd wheat crop (4)
1997	June 5	July 21	August 12	1	annual (W-P-B-W-W-W-W)
				15	2nd wheat crop (5)
				12	3rd wheat crop (4)
				9	4th wheat crop (3)

[z] crop sequence; b=barley, p=field pea, w=wheat. [y] Number in brackets represents the alfalfa stand length. [x] only plots fertilized with nitrogen sampled in 1994. [w] In 1995 and 1996, no fertilizer nitrogen added to the first wheat crop after alfalfa.

3.0 Results and Discussion

3.1 Effect of alfalfa stand length on rotation benefits in following wheat crops

3.1.1 Grain yield

The effect of alfalfa stand length on rotational yield benefit was determined by examining the difference in wheat yields in alfalfa-based versus annual crop rotations. A separate analysis was conducted for the fertilized and unfertilized wheat systems.

In the absence of fertilizer N, significant differences for rotational yield benefits were recorded in the first, second and third wheat crops (Table 3.1). Alfalfa stands of 1 and 2 years produced lower ($P<0.05$) wheat yield increases than alfalfa stands of 3 years or greater. Rotational yield benefits after 1 and 2 year alfalfa stands were equal. Low yield benefits from 1 and 2 year stands were partially attributed to high wheat yields in the annual rotation (see section 3.1.2), which served to reduce the measured yield benefits in these years. Variability in rotational yield benefits in the first wheat crop after alfalfa indicate that grain yield was often maximized without fertilizer N and as a result, inorganic nitrogen was not added to the first wheat crop in 1995 and 1996. Previous studies indicate that there was no fertilizer response in the first two wheat crops following alfalfa removal (Holford and Crocker, 1997). In the first wheat crop of the current study, nitrogen addition may have actually reduced or masked non-nitrogen benefits; particularly in 1993 when seasonal precipitation was high (Table 4.15).

Significant effects of alfalfa stand length were also observed in the second wheat crop after alfalfa termination (Table 3.1). In this instance, the 6 year stand resulted in the highest yield benefit; the 4 year stand was comparable to the 6 year stand, but not different from alfalfa stand lengths of 2 and 5 years. Stand length effects in the second wheat crop may be attributed to high yield rotation benefits in 1995 and 1997 (discussed later in 3.1.3.2).

Stand length effects on rotational yield benefits were also observed in the third wheat crop after alfalfa, with the 5 year stand having a significantly higher yield than shorter stand lengths (Table 3.1). The rotational yield benefits of the 5 year alfalfa stand (969 kg ha^{-1}) were not significantly different from the 3 year (628 kg ha^{-1}) and 4 year stand (606 kg ha^{-1}) but significantly higher than the 2 year alfalfa stand (223 kg ha^{-1}). No differences in rotational benefits between alfalfa stand lengths were present in the fourth and fifth wheat crop after termination of 2 and 3 year alfalfa stands (Table 3.1).

In summary, in the absence of inorganic N additions, rotational benefits to grain yield in the first, second and third wheat crop after alfalfa termination tended to be greater after alfalfa stand lengths of 3 or more years than stand lengths of 2 years or less. Results of the present study support previous studies where shorter term alfalfa stands were able to increase subsequent grain yield. However, unlike the northern Alberta study where alfalfa stand lengths of 2 to 6 years produced no significant differences in rotational benefits when yield increases were measured in the first year after alfalfa termination (Hoyt and Leitch, 1983), alfalfa stand lengths greater than 3 years were found to be superior in the present study. In Australia, Holford (1980) found rotational benefits to unfertilized grain yield in the first year of wheat after alfalfa termination to be greatest after a 3.5 year alfalfa stand length compared to shorter stand lengths.

In rotations with fertilizer N added, variation in alfalfa stand length had little effect on rotational yield benefits. In the first wheat crop after alfalfa termination, no significant differences ($P<0.05$) in yield rotation benefits were calculated among alfalfa stand lengths of

1 to 4 years (Table 3.2). In the second wheat crop after alfalfa, rotational benefits of 3 to 6 year stands were higher than the 2 year alfalfa stand where yields were 285 kg ha^{-1} lower in the alfalfa containing vs. the fertilized annual rotations. No significant effects were observed among alfalfa stands greater than 3 years after alfalfa termination (Table 3.2).

In the third wheat crop after alfalfa, the rotational benefits from 3 year (578 kg ha^{-1}) and 5 year (525 kg ha^{-1}) alfalfa stands were significantly higher than the rotational benefits from alfalfa stand lengths of 2 years (97 kg ha^{-1}) and 4 years (120 kg ha^{-1}) (Table 3.2). Non-nitrogen benefits relating to greater soil water extraction (i.e. improved soil physical properties, fewer root diseases) (discussed in section 4.2) were enhanced in these dryer years (1995 and 1997). In the fourth and fifth year after alfalfa removal, no differences in rotational benefits were measured for various alfalfa stand lengths.

Working on a clay soil in southern Ontario, Bolton et al. (1976) observed that under N fertilized conditions, rotational benefits from a 2 year alfalfa stand produced corn yields 520 kg ha^{-1} higher than corn after a 1 year alfalfa stand. They also measured corn yields after a 2 year alfalfa stand to be 1030 kg ha^{-1} higher than fertilized corn after oats and 1480 kg ha^{-1} higher than corn grown in a continuous corn rotation (Bolton et al., 1976). Results of the current study are supported by soil nitrogen changes in a previous study in southern Manitoba where soil nitrogen increases from alfalfa were higher in the 2 and 3 year alfalfa stand than in the 1 year alfalfa stand (Kelner, 1994).

In summary, in the absence of N fertilizer, rotational yield benefits to the first wheat crop tended to be higher when alfalfa stand length was 3 years or greater (Table 3.1). When fertilizer N was added, grain yield rotational benefits were not affected by alfalfa stand length in the first wheat crop; but in the second and third wheat crops were higher in alfalfa stand lengths of 3 years or greater than an alfalfa stand length of 2 years (Table 3.2). In the fourth and fifth wheat crop after alfalfa, rotational grain yield benefits were unaffected by alfalfa stand length in both unfertilized and fertilized rotations (Table 3.1; Table 3.2).

3.1.2 Grain N Uptake

Similar to the results for grain yield, rotational N uptake benefits in the absence of fertilizer N were higher when alfalfa stand length was greater than 2 years (Table 3.3). In the first wheat crop, grain N uptake increases were not significantly different among alfalfa stand lengths of 3 to 6 years (36.5 to 50.2 kg N ha^{-1}) (Table 3.3). The 3 and 5 year alfalfa stands produced significantly higher grain N uptake benefits than the 1 year alfalfa stand while the 2 year alfalfa stand had lower grain N uptake values than each of the other alfalfa stand lengths (Table 3.3). High yield and nitrogen concentration in the unfertilized control may have resulted in an underestimation of the rotational benefits in the first wheat crop after termination of the 2 year stand. No significant differences among grain N uptake in various alfalfa stand lengths were measured in the second, third, fourth, and fifth year after alfalfa stand removal.

Results of the present study differed from those of Shrader et al. (1966) who found no differences in fertilizer replacement values among alfalfa stand lengths of 1 to 3 years in the first corn crop after alfalfa. However, in the second crop after alfalfa, nitrogen fertilizer replacement values were slightly higher when alfalfa stand length increased from 1 to 3 years (Shrader et al., 1996). Other measurements of nitrogen fertilizer replacement indicate alfalfa supplied the same as 112 to 156 kg N ha^{-1} (Voss and Shrader, 1966) and 125 to 135 kg N ha^{-1}

to the first subsequent corn yield (Baldock and Musgrave, 1980; Bruuselma and Christie, 1987). In the current study, nitrogen input from alfalfa was lower than the fertilizer nitrogen replacement values previously measured in the mid-western United States. Lower alfalfa yield, less favourable conditions for nitrogen mineralization, and a lower grain yield potential may have contributed to lower amounts of nitrogen addition in the present study.

When fertilizer N was added to wheat crops following alfalfa, rotational grain N benefits were not affected by alfalfa stand length in each of the first 5 wheat crops after alfalfa termination (Table 3.4). However, grain N concentration and grain N uptake were both consistently increased when alfalfa was included in the rotation (Table A3.5; Table A3.2). This increase in grain N was attributed to a combination of extra nitrogen from alfalfa, reduction in disease, or improved soil physical properties in wheat after alfalfa compared to annual rotations. Therefore, while alfalfa stand length affected rotational yield benefits, grain N uptake benefits were uniform ($P>0.05$) across all alfalfa stand lengths.

In summary, rotational benefits to grain N uptake were higher in the unfertilized rotations than the fertilized rotation (Table 3.3; Table 3.4). In unfertilized rotations, higher grain N uptake in alfalfa containing rotations was attributed to a combination of N and non-N factors, and rotational benefits were superior with alfalfa stand length of 3 or more years. In fertilized rotations, much of the alfalfa rotation benefit was attributed to non-nitrogen sources and benefits due to alfalfa were not significantly different among alfalfa stand lengths of 2 to 6 years. In unfertilized rotations, alfalfa stand lengths of 2 years or less contributed to non-nitrogen benefits but had a smaller nitrogen rotation benefit than the longer alfalfa stand lengths of 3 to 6 years when N uptake benefits were compared.

3.1.3 Influence of growing conditions on expression of rotational benefits

3.1.3.1 Low rotational benefits in 1991 and 1992

Wheat yields in the unfertilized annual rotation were 2489 and 3558 kg ha^{-1} for 1991 and 1992, respectively compared to the overall study mean of 1115 kg ha^{-1} for the unfertilized annual crop rotations (Table A3.1). As a result, inclusion of alfalfa in the crop rotation resulted in yield increases of only 369 and 515 kg ha^{-1} for the first wheat crop after 1 and 2 year alfalfa stands in 1991 and 1992, respectively. Reasons for the high unfertilized wheat yields in the early years include nitrogen mineralization from previous summerfallow, the use of field pea as an alternate crop in the rotation, high subsoil N (estimated 47, 125 and 105 kg ha^{-1} removed in the first, second and third alfalfa crop, respectively) (Kelner, 1994), and favorable conditions for growing wheat. Hence, rotational yield and N uptake benefits due to alfalfa in the first wheat crop after 1 and 2 year stand lengths may have been underestimated in this study. After a nutrient equilibrium was established from 1993 to 1997, unfertilized grain yields averaged 1095 kg ha^{-1} and consistent yield responses from fertilizer nitrogen applications and from including alfalfa in rotations were observed (Table A3.1).

3.1.3.2 High rotational benefits in 1995 and 1997

The years 1995 (i.e. first crop after a 5 year alfalfa stand) and 1997 (i.e. second crop after a 6 year alfalfa stand) produced the highest rotational alfalfa benefits within the first and second wheat crops after alfalfa (Table 3.1). Rotational yield increases were not expressed to the same extent in 1996, despite having similar growing season precipitation (May 1 to July 31; Table A 4.15); likely resulting from a longer growing season and soil water use in August when soil water was available. Larger rotational yield increases due to alfalfa in the dryer years of 1995 and 1997 were attributed to greater expression of the deeper root growth and greater soil water extraction in wheat after alfalfa compared to wheat in the annual rotation (discussed later in sections 4.1 and 4.2). In 1996, and previous years (1991 to 1994), deeper wheat rooting depths after alfalfa were not required to produce maximum grain yield, likely as a result of adequate precipitation during the growing season (see section 4.3 for more detailed discussion). Previous studies indicated that corn yield response to rotation was increased in 'dry' or 'stress' years when growing season precipitation was lower than average. (Barber, 1972; Peterson and Varvel, 1989). Because stand length effects were measured in different years, rotational benefits may be related to environmental conditions in the test year and may not only reflect the rotational benefits of the previous alfalfa.

3.2 Persistence of alfalfa rotation benefits

3.2.1 Grain Yield

Residual benefits from alfalfa in unfertilized rotations were present for up to 6 years (Table 3.1). In a previous study, wheat yield increases in the first, second, third, and fifth year after alfalfa were 71, 82, 75, and 65 percent, respectively (Hoyt and Henning, 1971). In a similar experiment, yield increases were measured for the first 8 years and also in the 10th and 13th crop after alfalfa termination (Hoyt, 1990).

In the unfertilized rotations, the decline in rotational yield benefits over time depended on alfalfa stand length. Alfalfa stand lengths of 4 and 6 years, had yield rotational benefits greater than 1200 kg ha^{-1} extending into the second wheat crop after termination and first and second year rotational yield increases were not significantly different (Table 3.1). The rotational benefits after 3 and 5 year alfalfa stands were significantly lower in the second wheat crop than the first wheat crop (Table 3.1). High yield rotation benefits in this case may in part be explained by environmental conditions (previously discussed in section 3.1.3.2).

When fertilizer N was added to soil test recommended rates in the present study, rotational benefits of alfalfa to wheat yield were present in six consecutive wheat crops after alfalfa stand removal (Table 3.2). Rotation effects from including alfalfa in rotation produced yields which were either slightly higher (i.e. first wheat crop after 1 year stand, third wheat crop after 2 and 4 year stand, and fourth wheat crop after 4 year stand) or lower (i.e. first wheat crop after the 2 year stand; second wheat crop after 2 year stand) than the continuous fertilized wheat rotation (Table 3.2). While alfalfa non-N benefits were measured to be small or negative, the general trend indicates non-N benefits were measured for the five consecutive wheat crops after alfalfa.

Previous studies also indicate that yield of unfertilized corn after alfalfa declined with each subsequent crop after alfalfa, particularly with no fertilizer N added (Vanotti and Bundy, 1995). Barber (1972) reported that corn yields after alfalfa were negatively correlated with the log of the number of years after alfalfa, however corn yields were higher in the alfalfa-containing versus the continuous corn rotation. Clearly, alfalfa contributes to the yield of subsequent crops for many years (>5) under unfertilized conditions.

3.2.2 Grain Nitrogen Uptake

In the absence of fertilizer nitrogen, grain N uptake benefits from alfalfa generally decreased with increasing number of wheat crops after alfalfa stand removal, but remained positive for the first five wheat crops (Table 3.3). Rotational grain N uptake benefits were unaffected by alfalfa stand length after the first wheat crop but generally declined with increasing number of wheat crops after alfalfa termination (Table 3.3). When fertilizer N was added to soil test recommended rates in the present study, increased grain nitrogen uptake was observed for six subsequent wheat crops after alfalfa stand termination (Table 3.4).

Similar results in corn were reported by Boawn et al. (1963) who measured grain N rotation benefits of 31 and 33 percent in unfertilized corn the first and second year after alfalfa termination, respectively, compared with rotations which were previously uncropped. They reported that nitrogen fertilizer additions would not have been practical to produce maximum yields for the first 2 years after alfalfa, and over the 5 year duration of the study, the total increase in N uptake due to previous alfalfa in rotation was 382 kg N ha^{-1} (Boawn et al, 1963).

3.3 Estimation of nitrogen and non-nitrogen alfalfa benefits

3.3.1 Influence of alfalfa stand length on nitrogen benefits

The contribution of nitrogen benefits from alfalfa was estimated using differences between yield increases in unfertilized and fertilized rotations. Yield and grain N increases in unfertilized rotations were assumed to result from a combination of nitrogen and non-nitrogen alfalfa benefits, while yield and grain N increases in fertilized rotations were attributed to non-nitrogen benefits from alfalfa. A separate analysis of variance was performed for yield (Table 3.5) and grain N uptake (Table 3.6) measurements. Since this analysis involved subtraction of yield increases in fertilized rotations from yield increases in unfertilized rotations (i.e., combining several estimates into one value), a high amount of variability was created, and this resulted in few significant differences among the various alfalfa stand length treatments (Tables 3.5 and 3.6).

Generally, alfalfa N benefits to yield decreased with increasing number of wheat crops after alfalfa termination (Table 3.5). Alfalfa stand length did not affect the nitrogen contribution to subsequent yield except for the second wheat crop after alfalfa, where alfalfa N benefits to yield were significantly higher ($P<0.05$) after 2, 4 and 6 year alfalfa stand lengths than after 3 and 5 year alfalfa stands (Table 3.5). Rotational benefits in the 4 and 6 year alfalfa stand lengths were likely higher as a result of lower than average precipitation throughout the growing season in 1995 and 1997 which resulted in accentuated alfalfa N benefits (discussed previously in 3.1.3.1).

Similar to results for grain yield, alfalfa N benefits to grain N uptake were also unaffected by alfalfa stand length (Table 3.6). Alfalfa N benefits to grain N uptake generally decreased with increasing number of wheat crops after alfalfa (Table 3.6). An exception to this trend was for the 2 year alfalfa stand where alfalfa N benefits from the second wheat crop were significantly higher than the N benefits in the first, third, fourth and fifth wheat crop after alfalfa (Table 3.6). In the second wheat crop (1993), non-N benefits to grain yield may have been masked as a result of excessive precipitation during the growing season (Table A 4.15).

After the third wheat crop after alfalfa, rotational yield benefits from nitrogen sources were very low (Table 3.5) and typically negative for grain N uptake benefits (Table 3.6). This indicates that after the third wheat crop, alfalfa rotation benefits were attributed to non-N sources. In the first and second wheat crops, rotation benefits were from a combination of nitrogen and non-nitrogen sources (Tables 3.5 and 3.6) when differences were used to partition how long nitrogen and non-nitrogen rotation benefits persisted.

3.3.2 Nitrogen and non-nitrogen benefits of a typical Manitoba alfalfa stand

Typical alfalfa stand lengths on south-central Manitoba farms are 3 to 5 years (Entz et al., 1995). When the rotation benefits to grain yield and N uptake were measured for different alfalfa stand lengths (discussed previously in section 3.1), rotational benefits were not significantly different for stand lengths of 3 and 4 years. Hence, combined data from the 3 and 4 year stand lengths (3/4 year stand) was used in an effort to determine 1) the length of time nitrogen and non-nitrogen benefits persist, and 2)the relative contribution from nitrogen and non-nitrogen rotational sources under typical Manitoba alfalfa-based cropping systems. Using the 3/4 year alfalfa stands, each wheat crop was compared to a reference rotation which had similar number of years of continuous wheat (i.e. rotation 1; Figure 2.1). This removed the confounding effect of comparing wheat after alfalfa stand lengths of 5 and 6 years (i.e. rotations 12 and 15; Figure 2.1) to continuous wheat, which clearly would accentuate the non-nitrogen benefits of alfalfa. Combined wheat yield and grain N uptake after the 3/4 stand lengths are presented in Figures 3.1 and 3.2.

Rotational N benefits of the 3/4 year alfalfa stands to grain yield were detected in the first wheat crop after alfalfa termination and the magnitude of the N benefit to yield declined each year (Figure 3.1). The non-N benefits, on the other hand, were relatively stable over the 5 wheat crops and averaged 278 kg ha^{-1}. After the second wheat crop, rotational yield benefits of alfalfa to wheat were attributed to both N and non-N sources, in approximately equal proportions. Grain N uptake rotational benefits in the first wheat crop were due to mostly nitrogen benefits (Figure 3.2). After the second wheat crop, grain N rotation benefits were attributed exclusively to non-N rotation benefits. This differed from the individual year analysis (section 3.3) where N benefits were generally observed for the first two wheat crops and non-N benefits were responsible for yield and N uptake increases in wheat crops 3 or more years after alfalfa termination.

Other studies suggest the majority of the yield increase due to alfalfa in rotation is expressed in the first crop after alfalfa. Fox and Piekielek (1988) indicated that 70%, 20% and 10% of the 167 kg N ha^{-1} total nitrogen fertilizer equivalence was expressed in the first, second and third corn crop after alfalfa, respectively. In the present study, 54%, 27%, and 19% of the 76.4 kg ha^{-1} yield increase in unfertilized rotations and 23%, 43%, and 35% of the 38.3 kg ha^{-1} total non-nitrogen contribution to yield were recovered in the first, second, and third wheat crop after the 3/4 alfalfa stand. This indicates that after removal of a typical Manitoba alfalfa stand, nitrogen benefits were expressed in the first year and to a lesser extent in the second and third years, while non-nitrogen benefits were expressed to a higher degree in subsequent years after the first wheat crop.

In summary, nitrogen benefits persisted for 1 year when both rotational grain yield (Figure 3.1) rotational grain N uptake benefits (Figure 3.2) were measured after the 3/4 year alfalfa stand length. Previous studies support the hypothesis that most of the N benefits from alfalfa was expressed in the first year after alfalfa termination and they decline with each subsequent crop. Ladd et al. (1981) observed most of the nitrogen uptake in the first year after legume residue (*Medicago littoralis*) was added to the soil. In the first year after legume residue addition, 27.8 and 20.2 percent of the 48.2 kg ha^{-1} of legume nitrogen was extracted by wheat plants in two experiments. After 2 years, N uptake decreased to less than 5 percent of the total N added (Ladd et al., 1983). In the present study, additions of a larger amount of legume nitrogen may account for nitrogen rotational benefits in the second wheat crop. In a previous study at the Winnipeg crop rotation study, Kelner (1994) measured 2 and 3 year alfalfa stands to increase soil nitrogen content by 148 and 137 kg N ha^{-1}, respectively.

Non-N rotational benefits played an important role in this study resulting in average yield and grain N benefits of approximately 200 and approximately 10 kg ha^{-1} yr^{-1}, respectively. While yield rotation benefits were lower in the first, fourth, and fifth wheat crop after the 3/4 year stand, non-N rotation benefits were positive in each of the first 5 wheat crops. The basis for these non-N benefits likely included improved soil physical factors. Adding legume plant material to the soil improves soil structure (Angers, 1992) and results in stable soil biopores (Blackwell et al., 1990). An increase in soil water infiltration due to alfalfa in rotation occurred in this study (Cavers, 1996). An improvement in soil physical structure was also implicated in allowing deeper root growth and greater soil water extraction in wheat after alfalfa (discussed later in section 4.2). In previous studies, increased soil organic matter has been associated with the addition of legume material (Hoyt and Hennig, 1971; Bremer et al., 1994). Addition of legume organic material into the soil may result in increased microbial activity (Bremer and vanKessel, 1992). Nitrogen from alfalfa roots are distributed deep within the soil profile (Gault et al., 1995) and may indirectly have increased nutrient uptake.

A break in plant disease cycles is also a non-nitrogen benefit of crop rotations (Cook, 1992). Previous studies indicated that the severity of common root rot (*Cochibolus sativus*)

(Lendingham, 1961) and tanspot (*Pyrenophora tritici-repentis*) (Bockus, 1992) decreased with increased diversity of crop rotations compared to continuous wheat. In the current study, non-nitrogen benefits may partially be due to reduced disease, however rotational benefits were present for 3 to 5 years after alfalfa (1995 to 1997) (Table A3.1) and would likely not be attributed to reduced root disease since it is hypothesized that inoculum buildup would be similar in rotations with 3 to 5 consecutive wheat crops after alfalfa and in the annual rotations (Conners et al., 1996). Using the 3/4 stand length analysis allowed a comparison of wheat in alfalfa rotations vs wheat in the annual rotation. Isolating these two alfalfa stand lengths, removed the effect of having a less diverse control rotation (i.e. 5 and 6 year stand comparison), which may have indirectly accentuated the estimated non-N rotational benefits.

3.4 Cumulative benefits of alfalfa in a crop rotation

3.4.1 Grain Yield

Cumulative yield increases from inclusion of alfalfa in rotation were greater in unfertilized than in fertilized rotations (Table 3.7). In unfertilized rotations, the yield increase in the first five wheat crops after the 3 year alfalfa stand was 3799 kg ha^{-1}, which was greater than twice the mean average annual yield for unfertilized annual rotations during the study period (1660 kg ha^{-1}) (Table A3.1). Similar yield benefits were observed in the Peace River region where an average yield increase of 3820 kg ha^{-1} in unfertilized rotation was measured in the first four wheat crops during a 5 year period after removal of 2 to 6 year alfalfa stand lengths (Hoyt and Hennig, 1971). This represents a significant economic yield increase for organic producers or producers choosing to reduce inputs through the reduction of inorganic fertilizer N use.

Producers who add inorganic fertilizer N to wheat crops after alfalfa, also produce higher wheat yields when adding alfalfa into the cropping system (Entz et al., 1995). In the present study, mean yield increase in the first 5 years after a 3 year alfalfa stand for fertilized wheat was 1542 kg ha^{-1} (Table 3.7). The cumulative yield benefit over the 5 year period represents approximately one-half of the mean annual fertilized wheat yield (2756 kg ha^{-1}) in the annual rotation throughout the study period (Table A.3.1). Therefore, a 3 year alfalfa stand in a rotation represents an alternative method for increasing cereal crop production.

In the absence of fertilizer N addition, cumulative yield increase was not affected by alfalfa stand length (Table 3.7). The exception is the first wheat crop where yield rotational benefits were higher after an alfalfa stand length of 3 or more years than after an alfalfa stand length of 2 years (previously discussed in section 3.1.1). Although not significantly different, cumulative yields tended to be higher with alfalfa stand lengths of 3 years or greater than alfalfa stand lengths of 2 years in the second, third and fourth wheat crop after alfalfa termination (Table 3.7). This supports the previous observation that alfalfa stand lengths of 3 years or more resulted in higher rotational benefits than the alfalfa stand length of 2 years.

In rotations with fertilizer N added to soil test recommended levels, no significant effect of alfalfa stand length on cumulative yield benefit was observed in any of the first 5 crops of wheat after alfalfa (Table 3.7). While not significantly different, trends indicate that increasing alfalfa stand length to greater than 2 years slightly increased rotational yield benefits in fertilized crop rotations.

3.4.2 Grain Nitrogen Uptake

In the absence of fertilizer nitrogen addition, including alfalfa in the crop rotation resulted in a substantial increase in N uptake by the following wheat crops, however, cumulative grain N uptake benefits were not affected by alfalfa stand length in any of the first five wheat crops (Table 3.8). A maximum rotational increase of 98.9 kg ha^{-1} nitrogen uptake in the first 5 years after a 3 year alfalfa stand represent a significant input of nitrogen from alfalfa residue over the long term (Table 3.8). In five consecutive corn crops after alfalfa, Boawn et al. (1962) measured a nitrogen uptake increase of 382 kg N ha^{-1} over a previously uncropped region. Lower nitrogen input from the alfalfa and less optimum conditions for complete mineralization of nitrogen may have accounted for the lower nitrogen uptake in the current study.

In this study at the Winnipeg Crop Rotation, soil N increased by 137 kg N ha^{-1} after a 3 year alfalfa stand (Kelner, 1994). Uptake of 98.9 kg ha^{-1} into the wheat grain from this 3 year stand represents a significant extraction of the total nitrogen available from alfalfa residue after 5 years. Therefore, in this experiment 72% of the added alfalfa N was recovered in the wheat grain. Significant losses may have occurred in 1993 where high amounts of precipitation occurred during the growing season (Table 4.15). As well, organic N from alfalfa may remain bound in the soil organic pool. A percent recovery of 72% is higher than previous reports of 14% recovery of green manure N in the following wheat crop (Janzen et al., 1990) and 17.25 to 30% recovery of alfalfa N in the following corn crop (Harris and Hesterman, 1990; Hesterman et al., 1987).

When fertilizer N was added to soil test recommended rates, cumulative grain N uptake rotational benefits were not affected by alfalfa stand length (Table 3.8). Unlike the unfertilized rotations, longer alfalfa stand lengths did not result in higher cumulative grain N benefits. While there were no stand length effects, an average of 64 kg N ha^{-1} was produced as a result of alfalfa.

When comparing means of the total of the first 5 crops after alfalfa, yield increases in unfertilized rotations (3107 kg ha^{-1}) were about 2.3 fold higher than in fertilized rotations (1379 kg ha^{-1}) (Table 3.7). Using grain N uptake data, rotational benefits in unfertilized rotations (77.3 kg N ha^{-1}) were only 1.2 fold higher than in fertilized rotations (64.1 kg N ha^{-1}) (Table 3.8). Rotational grain protein concentration increase in fertilized wheat after alfalfa rotations were higher than in unfertilized rotations (discussed later in section 3.5) (Table 3.8). The nitrogen produced from alfalfa in fertilized rotations resulted in higher GPC (discussed in section 3.5).

In summary, cumulative rotational benefits were measured to be positive in both fertilized and unfertilized rotations. While not statistically significant, cumulative rotational yield and grain N uptake benefits tended to be higher with increasing alfalfa stand length, particularly in rotations with no fertilizer N added.

3.5 Influence of alfalfa in rotation on Grain Protein Concentration (GPC)

Because of the importance of grain protein content in wheat to the prairie industry, the influence of alfalfa on GPC of following wheat crops was considered separately. The grain protein concentration of wheat grown in annual and alfalfa containing rotations for the first six years after alfalfa stand termination are summarized in Table 3.9. The years 1991 to 1994 had well above average seasonal precipitation and resulted in a high grain protein concentration (GPC) in the unfertilized rotations. High initial levels of NO_3 from previous summerfallow as well as low yield in 1993 and 1994 (inverse yield/grain protein relationship) may have resulted in the relatively high GPC in unfertilized plots from 1991 to 1994.

Data from the 1995 field season represents a year of relatively low seasonal precipitation (46% of long term normal precipitation from May 1 to July 31) (Table 4.3). In rotations with no fertilizer N added, grain protein concentration increases of greater than 0.5% were observed for the first wheat crop after alfalfa. Similarly, in rotations fertilized to soil test recommendation protein increases of 1.0 % were observed in the second and third wheat crop after alfalfa and increases of greater than 0.5 % in the fourth wheat crop after a 2 year alfalfa stand.

In 1996 and 1997 more typical amounts of precipitation (89% and 85% of the long term normal from May 1 to July 31 for 1996 and 1997, respectively) (Table 4.3) resulted in consistent GPC trends (Table 3.9). Significant ($P<0.05$) rotation, fertilizer and rotation*fertilizer interactions were observed in 1996. In unfertilized rotations, including alfalfa in rotation increased GPC by 1.6, 0.6, and 0.5% after the first, second, and third wheat crop, respectively (Table 3.9). In rotations fertilized to soil test recommended levels, GPC increases of 1.0, 1.0, 1.2, and 1.3% were observed for the second, third, fourth and fifth wheat crop after alfalfa, respectively (Table 3.9). In 1996, a rotation*fertilizer interaction ($P=0.0493$) indicated that GPC responses to added fertilizer nitrogen were higher in alfalfa containing rotations compared to the annual crop rotation.

In 1997, a highly significant ($P<0.01$) fertilizer effect was observed. In rotations with no fertilizer N added, the second crop after alfalfa resulted in higher grain yield but not a higher GPC. When fertilizer nitrogen was added to soil test recommended level, yield and GPC increases were observed in the second and third crops of wheat after alfalfa compared to the annual crop rotation.

Figures 3.3 and 3.4 show examples of GPC increases after 3 and 4 year alfalfa stands over corresponding annual rotations with fertilizer N added and with no fertilizer N added, respectively. In the presence of N fertilizer, increases in GPC were observed for up to 4 years after alfalfa and increases in GPC were generally not affected by alfalfa stand length. In the absence of fertilizer N, GPC increases were small or negative after the 3/4 year alfalfa stands. In the absence of fertilizer N, N supply from alfalfa was sufficient to increase grain yield but not high enough to affect GPC .

In 1996, the Canadian Wheat Board initiated protein premium payments for 0.5% increases in GPC for the CWRS #1 and #2 grades of wheat up to a maximum of 15%. Fertilized annual rotations in the present study did not reach this maximum protein level with consistency (3 out of 7 years). High protein concentrations were found in annual rotations fertilized with nitrogen as a result of high initial soil NO_3-N (1991) and relatively low grain yield (2018 kg ha^{-1}) in 1993. In years with below average seasonal precipitation (1995, 1996, 1997), relatively stable GPC were measured for fertilized rotations. The protein concentration during these years was lower than the maximum premium level. In alfalfa containing rotations where fertilizer N was added, a GPC greater than 15.0% was achieved consistently for the second and third crop after alfalfa and in 2 out of 3 years for the fourth crop after alfalfa.

3.6 Economic benefit of including 3 and 4 year alfalfa stands in rotation

In the absence of fertilizer N, the total economic advantage of including alfalfa in the rotation was \$702.73 ha^{-1} for the first 5 years after alfalfa stand termination after the 3/4 alfalfa stand (Table 3.10). Rotational economic return declined with increasing number of wheat crops after alfalfa (Table 3.10). This reduced economic benefit was attributed to a decline in the apparent nitrogen contribution from alfalfa source. However, the overall increase in economic return represents a significant economic benefit to organic producers or producers wishing to reduce inputs of fertilizer nitrogen for economic or environmental reasons.

In the presence of N fertilizer, the cumulative economic benefit of including 3/4 alfalfa stand was \$350.09 ha^{-1} for the first 5 fertilized wheat crops after alfalfa. The rotational benefit to economic return was low in the first year after alfalfa (\$33.06 ha^{-1}) (Table 3.10). A low return from alfalfa was attributed to low rotational yield increases (high annual rotation yield) as well as no protein premium payment since both wheat in annual and alfalfa containing rotations were greater than 15%. In the third, fourth and fifth wheat crop, larger increases in wheat gross return due to alfalfa were attributed to a grain protein premiums. Producers who use fertilizer N to maximize protein production may be able to incorporate alfalfa into the rotations to further increase protein production.

Using gross returns in this simulation, additional fertilizer nitrogen added is included in the gross return calculation while other production costs are assumed to be similar for both systems. Gross return values for unfertilized first wheat crop after alfalfa (\$436.09 ha^{-1}) were slightly higher than the fertilized wheat after alfalfa (\$358.56 ha^{-1}) and the fertilized annual rotation (\$325.49 ha^{-1}). In this situation, nitrogen from alfalfa was adequate to produce the highest return in the first wheat crop and fertilizer N did not increase economic returns in the first wheat crop. In subsequent wheat crops, the highest gross return was estimated in the fertilized wheat after alfalfa rotation. In previous studies, fertilizer N was not required to maximize yield of the first corn (Triplet et aL, 1979; Ashgari and Hanson, 1983; Vanotti and Bundy, 1995) or wheat crops (Ferguson and Gorby, 1971; Holford and Crocker, 1997) after alfalfa.

In unfertilized rotations, the total economic benefit of including alfalfa in rotation was about double that of the fertilized rotations. In the absence of fertilizer N addition, increased economic return resulted from increased grain yield (low annual grain yield). In summary, including alfalfa in the crop rotation increased the economic value of the crop through increased yield in unfertilized rotations and increased GPC in fertilized systems.

3.7 Conclusion

In the absence of fertilizer N, wheat yield and grain N uptake rotational benefits from alfalfa were higher for alfalfa stand lengths of 3 years or higher compared with alfalfa stand lengths of 2 years or lower. Alfalfa stand lengths of 3 years or greater produced higher yield increases in the second and third wheat crops after alfalfa termination with fertilizer N added. Low grain N rotational benefits after 1 and 2 year stand lengths were attributed in part to high soil N levels at the beginning of the study, which resulted in high yields and N uptake in the low N check plots.

The residual effect of alfalfa persisted for up to 5 years after alfalfa in unfertilized and fertilized rotations. Whether benefits will last longer than 5 years could not be determined here. Nitrogen benefits were most prominent in the first wheat crop after alfalfa and decreased with time. Non-nitrogen benefits were also positive and remained consistent with each wheat crop after alfalfa. After the second wheat crop, grain yield rotational benefits were entirely from non-nitrogen benefits. In the absence of fertilizer N, the economic benefit of including alfalfa in rotation was primarily from yield increases due to alfalfa, while in the fertilized rotations, the economic benefit was due to a combination of higher yield and grain protein.

Table 3.1. Rotational benefits of alfalfa to unfertilized wheat. Wheat yield increase with the addition of alfalfa in the crop rotation as measured by difference in wheat yield between wheat after alfalfa (A-W F-) and continuous wheat (W-W F-) with no fertilizer nitrogen added. Analysis of variances of differences in wheat yield (kg ha^{-1}) for various alfalfa stand length and number of years after alfalfa are also calculated.

Alfalfa stand length	Years after alfalfa termination 1	2	3	4	5	6	P>F	LSD (0.05)
1	369 B[z]	-	-	-	-	-		
2	515 a[y] B	717 a B	223 a B	599 a A	361 a A	298 a	0.7016 ns	740
3	1450 a A	616 b B	628 b AB	478 b A	626 b A		0.0539 ns	676
4	1358 a A	1201 a AB	606 b AB	390 b A			0.0025 **	454
5	2094 a A	716 b B	969 b A				0.0002 **	350
6	1343 a A	1706 a A					0.3551 ns	1059
Mean	1188	991	607	489	494	298		
LSD (0.05)	818	779	451	626	415			
P>F	0.0041 **	0.0480 *	0.0308 *	0.7271ns	0.1348 ns			

[z] LSD differences among alfalfa stand lengths are represented in upper case letters

[y] LSD differences among the number of years of wheat after alfalfa are represented in lower case letters.

Means followed by the same letter are not significantly different.

*,** Significant at the 0.05 and 0.01 level, respectively.

Table 3.2. Rotational benefits of alfalfa to fertilized wheat. Wheat yield increase with the addition of alfalfa in the crop rotation as measured by difference in wheat yield between wheat after alfalfa (A-W F+) and continuous wheat (W-W F+) in rotations with fertilizer added to soil test recommended rates. Analysis of variances of differences in wheat yield (kg ha^{-1}) also summarized.

Alfalfa stand length	Year after alfalfa termination							LSD (0.05)
	1	2	3	4	5	6	P>F	
1	114 A[z]	-	-	-	-	-		
2	330 ab[y] A	-285 b B	97 ab B	666 a A	407 a A	355 ab	0.1355 ns	688
3	-42 c A	503 ab A	578 a A	287 ab A	216 bc A		0.0102 *	327
4	391 a A	401 a A	120 a B	116 a A			0.8167 ns	920
5	-	384 a A	525 a A				0.4182 ns	480
6	-	539 A						
Mean	198	309	330	356	311	355		
LSD (0.05)	889	433	375	868	604			
P>F	0.6825 ns	0.0079 **	0.0290 *	0.3501 ns	0.3879 ns			

[z] LSD differences among alfalfa stand lengths are represented in upper case letters

[y] LSD differences among the number of years of wheat after alfalfa are represented in lower case letters.

Means followed by the same letter are not significantly different.

*,** Significant at the 0.05 and 0.01 level, respectively.

Table 3.3. Grain nitrogen uptake increase with the addition of alfalfa in the crop rotation as measured by difference in grain N yield between wheat after alfalfa (A-W F-) and continuous wheat (W-W F-) in rotation with no fertilizer nitrogen added. Analysis of variances of differences in grain nitrogen uptake in the seed (kgN ha^{-1}) is also summarized.

Alfalfa stand length	Year after alfalfa termination										P>F		LSD (0.05)
	1		2		3		4		5	6			
1	14.7	BC[z]	-		-		-		-	-			
2	2.2 b	C	30.6 a	AB	4.9 b	B	11.3 b	A	6.8 b	6.1 b	0.0087	**	14.42
3	47.0 a	A	16.4 b	B	14.0 b	AB	9.8 b	A	11.8 b		0.0001	**	9.26
4	38.1 a	AB	25.2 ab	AB	15.0 b	AB	8.6 b	A			0.0714	ns	21.1
5	50.2 a	A	17.8 b	B	20.1 b	A					0.0001	**	4.52
6	36.5 a	AB	35.2 a	A							0.7211	ns	10.67
Mean	31.5		25.0		13.5		9.9		9.3				
LSD (0.05)	27.1		15.2		13.1		8.1		24.8				
P>F	0.0037 *		0.4181ns		0.0874ns		0.3794 ns		0.5693ns				

[z] LSD differences among alfalfa stand lengths are represented in upper case letters

[y] LSD differences among the number of years of wheat after alfalfa are represented in lower case letters.

Means followed by the same letter are not significantly different.

*,** Significant at the 0.05 and 0.01 level, respectively.

Table 3.4. An estimation of non-nitrogen contribution from alfalfa to grain N uptake in subsequent wheat. Grain nitrogen uptake increase is calculated by the difference between grain N uptake in wheat after alfalfa (A-W F+) and continuous wheat (W-W F+) in rotations with fertilizer added to soil test recommended rates. Analysis of variances of differences in grain nitrogen uptake in the seed (kgN ha^{-1}) are also calculated.

Alfalfa stand length	Year after alfalfa 1	2	3	4	5	6	P>F	LSD (0.05)
1	0.1 A[z]	-	-	-	-	-		
2	14.6 a[y] A	9.4 a A	5.6 a A	19.3 ab A	16.4 a A	5.1 a	0.2609 ns	14.8
3	5.4 b A	17.7 ab A	18.8 a A	12.8 ab A	8.2 b A		0.1418 ns	12.3
4	5.4 a A	14.6 a A	7.9 a A	6.3 a A			0.7979 ns	22.7
5	-	14.2 a A	18.9 a A				0.4338 ns	16.8
6	-	19.1 A						
Mean	6.4	15.0	12.8	12.8	12.3			
LSD (0.05)	19.8	17.5	14.4	24.5	19.8			
P>F	0.4577 ns	0.7822 ns	0.1371ns	0.4732 ns	0.2794 ns			

[z] LSD differences among alfalfa stand lengths are represented in upper case letters

[y] LSD differences among the number of years of wheat after alfalfa are represented in lower case letters.

Means followed by the same letter are not significantly different.

*,** Significant at the 0.05 and 0.01 level, respectively.

Table 3.5. Yield increase due to alfalfa in unfertilized rotations subtract the yield increase due to alfalfa in fertilized rotations. An estimation of the nitrogen benefit of alfalfa to subsequent wheat yield. Analysis of variances of differences in yield increase (kg ha^{-1}) are used to estimate nitrogen benefit to wheat yield.

Alfalfa stand length	Year after alfalfa termination							LSD
	1	2	3	4	5	6	P>F	(0.05)
1	255 [z]A	-	-	-	-	-		
2	185 A a[y]	1002 A a	125 A b	-67 A b	-46 A b	-57 b	0.2730 ns	1040
3	1492 A a	113 C b	50 A b	191 A b	411 A b		0.0007 **	572
4	966 A a	800 AB a	485 A a	274 A a			0.2566 ns	786
5	-	331 BC	444 A				0.6587 ns	730
6	-	1167 A						
Mean	724	683	276	133	183			
LSD (0.05)	1524	630	467	718	697			
P>F	0.2385 ns	0.0155*	0.1488 ns	0.5183 ns	0.1285 ns			

[z] LSD differences among alfalfa stand lengths are represented in upper case letters

[y] LSD differences among the number of years of wheat after alfalfa are represented in lower case letters.

Means followed by the same letter are not significantly different.

*,** *Significant at the 0.05 and 0.01 level, respectively.*

Table 3.6. Grain nitrogen yield increase due to alfalfa in rotations with no nitrogen added subtract grain nitrogen yield increase due to alfalfa in rotations with nitrogen added to soil test recommendations. An estimation of the nitrogen contribution of alfalfa to subsequent grain nitrogen uptake. Analysis of variances of differences in yield increases (kgN ha^{-1}) are used to estimate N benefits to grain N uptake.

Alfalfa stand length	Year after alfalfa termination 1	2	3	4	5	6	P>F		LSD (0.05)
1	14.6 [z]AB	-	-	-	-	-			
2	-12.4 B [y]b	21.2 A a	-0.7 A b	-8.1 A b	-9.6 A b	1.0 ab	0.0371	**	20.7
3	41.6 A a	-1.3 A b	-4.8 A b	-3.0 A b	3.6 A b		0.8202	ns	20.0
4	32.7 AB a	10.6 A a	7.1 A a	2.3 A a			0.4695	ns	26.3
5	-	3.6 A	1.1 A				0.6108	ns	14.1
6	-	16.1 A							
Mean	19.1	10.0	0.7	-2.9	-3.0				
LSD (0.05)	41.0	27.9	14.0	22.9	19.9				
P>F	0.2027 ns	0.4437 ns	0.3292 ns	0.5699 ns	0.1262 ns				

Note:
[z] LSD differences among alfalfa stand lengths are represented in upper case letters
[y] LSD differences among the number of years of wheat after alfalfa are represented in lower case letters.
Means followed by the same letter are not significantly different.
*,** Significant at the 0.05 and 0.01 level, respectively.

Table 3.7. Cumulative yield increases from including alfalfa stand lengths of 2 to 6 years in rotation. Yield increases are summarized for unfertilized rotations (a) and rotations fertilized to soil test recommendations (b). Analysis of variances of grain yield increase (kg ha^{-1}) performed for each year of wheat after alfalfa.

	(a)						(b)					
Alfalfa stand length	Years after alfalfa termination						Years after alfalfa termination					
	1	2	3	4	5	6	1	2	3	4	5	6
1	369 c	-	-	-	-	-	114 [z]a	-	-	-	-	-
2	515 b	1232 b	1454 b	2053 a	2415 a	2713	330 a	45 a	142 a	808 a	1215 a	1570
3	1450 a	2066 ab	2694 ab	3172 a	3799 a		-42 a	461 a	1039 a	1327 a	1542 a	
4	1357 ab	2559 ab	3164 a	3554			391 a	792 a	913 a	1029 a		
5	2094 a	2810 a	3779 a				-	384 a	910 a			
6	1343 ab	3049 a					-	539 a				
Mean	1188	2343	2773	2926	3107		198	444	751	1055	1379	
LSD (0.05)	818	1333	1649	1802	2590		798	792.7	856.3	1370.8	1744	
P>F	0.0041**	0.0766ns	0.0556 ns	0.1872ns	0.1876ns		0.4153 ns	0.1478 ns	0.0840 ns	0.6681 ns	0.5922 ns	

[z] LSD differences among alfalfa stand lengths are represented in lower case letters.
Means followed by the same letter are not significantly different.
*,** Significant at the 0.05 and 0.01 level, respectively.

Table 3.8. Cumulative grain N yield from including alfalfa stand lengths of 2 to 6 years in rotation. Yield increases are summarized for unfertilized rotations (a) and rotations fertilized to soil test recommendations (b). Analysis of variances of grain N yield increase (kgN/ha) performed for each year of wheat after alfalfa.

(a)

Alfalfa stand length	Years after alfalfa termination					
	1	2	3	4	5	6
1	14.7[z]bc	-	-	-	-	-
2	2.2 c	32.8 a	37.7 a	49.0 a	55.8 a	61.9
3	47.0 ab	63.4 a	77.4 a	87.2 a	98.9 a	
4	38.1 abc	63.3 a	78.3 a	90.1 a		
5	50.3 a	68.1 a	88.2 a			
6	36.5 abc	71.7 a				
Mean	31.5	59.9	70.4	75.4	77.3	
LSD(0.05)	22.7	31.3	42.0	54.7		
P>F	0.0917ns	0.5195 ns	0.1061 ns	0.1595 ns		

(b)

Alfalfa stand length	Years after alfalfa termination					
	1	2	3	4	5	6
1	0.1 [z]a	-	-	-	-	-
2	14.6 a	24.0 a	29.6 a	49.0 a	65.4 a	70.5
3	5.4 a	23.1 a	41.8 a	54.6 a	62.8 a	
4	5.4 a	20.0 a	27.9 a	34.2 a		
5		14.2 a	33.1 a			
6		19.1 a				
Mean	6.4	20.0	33.1	45.9	64.1	
LSD(0.05)	20.5	17.5	23.5	37.5	52.8	
P>F	0.4842 ns	0.7585ns	0.1857 ns	0.4415 ns	0.8863 ns	

[z] LSD differences among alfalfa stand lengths are represented in lower case letters.
Means followed by the same letter are not significantly different.
*,** Significant at the 0.05 and 0.01 level, respectively.

Table 3.9. Grain protein concentration of wheat grain from the Winnipeg crop rotation study as affected by previous crop rotation and fertilizer nitrogen addition. Analysis of variance for grain protein concentration (%) is also summarized within each year, 1991 to 1997.

		Year						
Rotation	Fertilizer	1991	1992	1993	1994	1995	1996	1997
Annual	+	18.6	14.9	17.4	15.9	14.8	14.7	14.0
	-	14.9	15.2	16.2	15.7	13.3	13.7	12.7
		Alfalfa stand length						
		1	2	3	4	5	6	
1st wheat crop	+	18.0	16.0	19.4	16.0	-	-	
after alfalfa	-	16.5	13.5	18.7	12.1	14.3	15.3	
				Alfalfa stand length				
				2	3	4	5	6
2nd wheat crop	+			14.7	16.7	15.9	15.7	15.1
after alfalfa	-			13.1	15.4	13.0	14.3	12.8
					Alfalfa stand length			
					2	3	4	5
3rd wheat crop	+				16.7	15.8	15.7	15.1
after alfalfa	-				15.2	13.4	14.2	12.8
						Alfalfa stand length		
						2	3	4
4th wheat crop	+					15.5	15.9	14.5
after alfalfa	-					12.5	13.5	12.9
							Alfalfa stand length	
							2	3
5th wheat crop	+						16.0	14.6
after alfalfa	-						13.3	12.4
								Alfalfa stand length
								2
6th wheat crop	+							13.5
after alfalfa	-							12.7
Rotation (Main factor)		0.5052	0.6106	0.0006	0.0092	0.1855	0.0172	0.0746
Fertilizer N (subplot)		0.0125	0.0805	0.0004	0.0306	0.0001	0.0001	0.0001
Rotation * Fertilizer N		0.1739	0.0419	0.3237	0.2720	0.0722	0.0493	0.1464

Table 3.10. Economic benefit of including 3 and 4 year alfalfa stands in rotations with and without fertilizer nitrogen addition.

Rotation	Wheat Crop[x]	Yield (kg ha^{-1})	Protein (%)	Price (\$ tonne^{-1})[z]	Fertilizer N price (\$ ha^{-1})[y]	Gross return (\$ ha^{-1})	Increase return from alfalfa (\$ ha^{-1})
Annual (No N added)	1	900	14.5	183.60	0	165.18	-
	2	986	14.5	183.60	0	180.94	-
	3	1211	13.5	172.24	0	208.61	-
	4	1359	13.2	167.75	0	227.99	-
	5	1356	12.7	163.85	0	222.17	-
A-W (No N added)	1	2304	15.4	189.31	0	436.09	270.90
	2	1898	14.2	177.80	0	337.39	156.45
	3	1831	13.8	172.24	0	315.37	106.76
	4	1793	13.2	167.75	0	300.79	72.79
	5	1982	12.4	160.41	0	318.00	95.83
	Total						702.73
Annual (Fertilizer N added)	1	2045	16.7	189.31	61.74	325.49	-
	2	2324	15.4	189.31	61.74	378.12	-
	3	2703	14.7	183.60	61.74	434.52	-
	4	3049	14.3	177.80	61.74	480.30	-
	5	3265	14.0	172.24	61.74	500.68	-
A-W (Fertilizer N added)	1	2220	17.7	189.31	61.74	358.56	33.06
	2	2775	16.3	189.31	61.74	463.68	85.55
	3	3052	15.8	189.31	61.74	516.05	81.54
	4	3250	15.2	189.31	61.74	553.56	73.25
	5	3481	14.6	183.60	61.74	577.36	76.68
	Total						350.09

[z] Wheat price is based on CWRS No. 2 grade wheat using Canadian Wheat Board 1996-1997 Payments (i.e.) base price (\$160.41/tonne) with protein premiums distributed for 0.5 % increase in protein greater 12 % base. An average deduction of \$48.36 tonne^{-1} was removed from the In Store Values at Port (either Vancouver or St. Lawrence).

[y] Fertilizer N price: \$0.77/kg (based on 1996 Manitoba guidelines for estimating crop production costs).

[x] yield and protein concentrations of the first 4 wheat crops are from 3 and 4 year alfalfa stands while the fifth wheat crop is after the 3 year stand only.

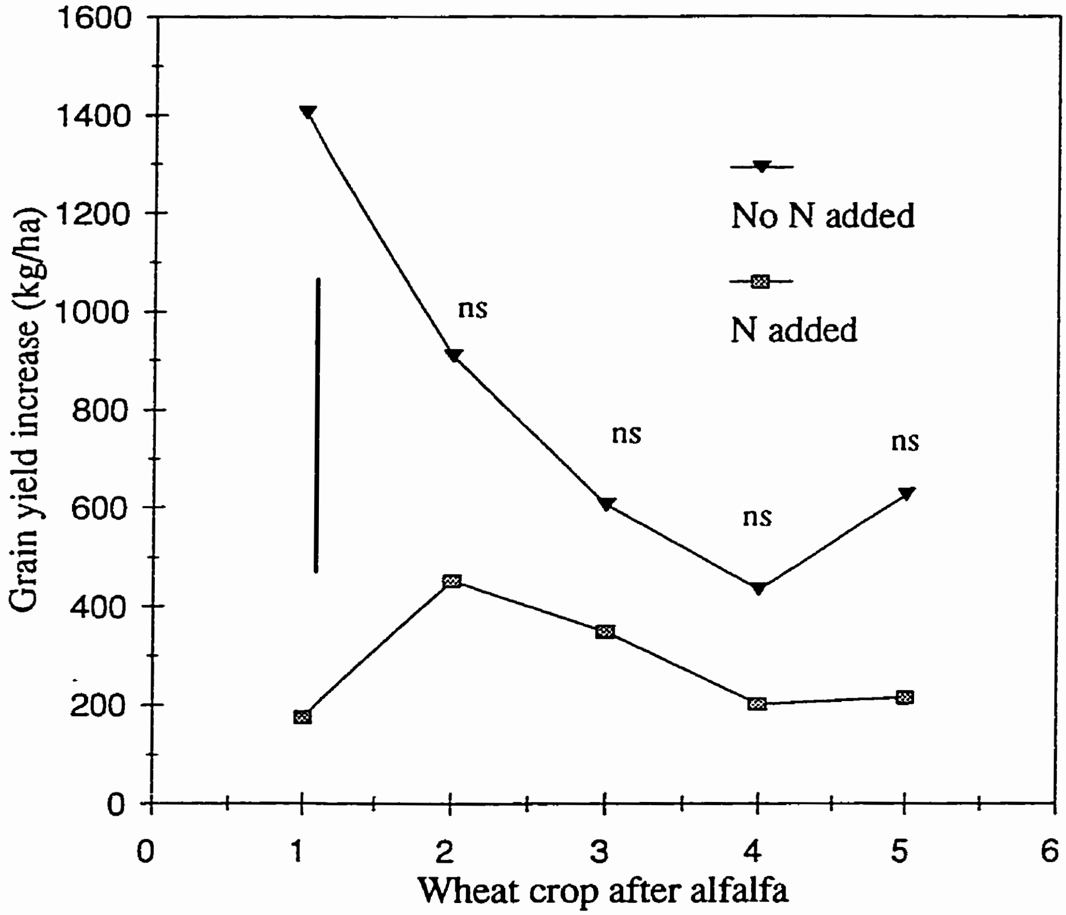


Figure 3.1. Mean grain yield increase after termination of 3 and 4 year alfalfa stands over annual rotations with and without the addition of fertilizer nitrogen in the first five consecutive crops of wheat. The fifth wheat crop after alfalfa contains only data after the 3 year alfalfa stand.

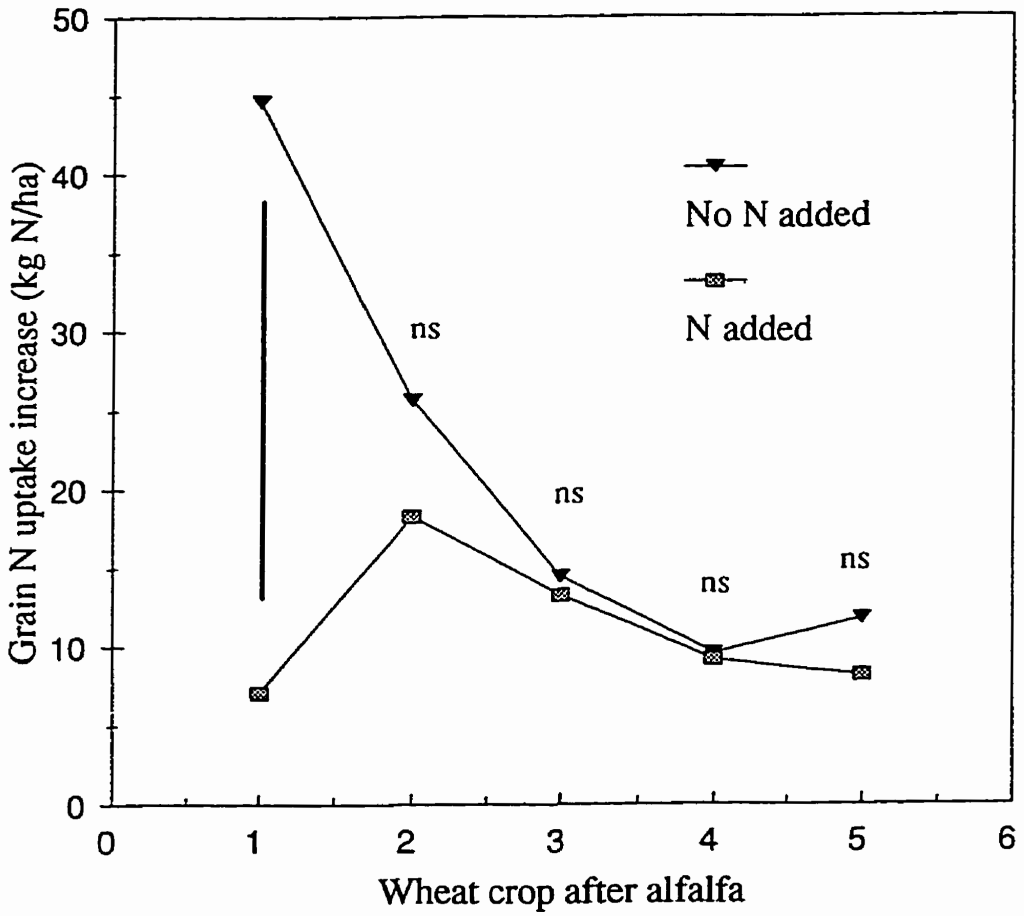


Figure 3.2. Mean grain N uptake increase in alfalfa containing rotations over annual rotations with and without fertilizer nitrogen addition in the first five consecutive wheat crops after termination of 3 and 4 year alfalfa stands. The fifth wheat crop after alfalfa contains only data after the 3 year alfalfa stand.

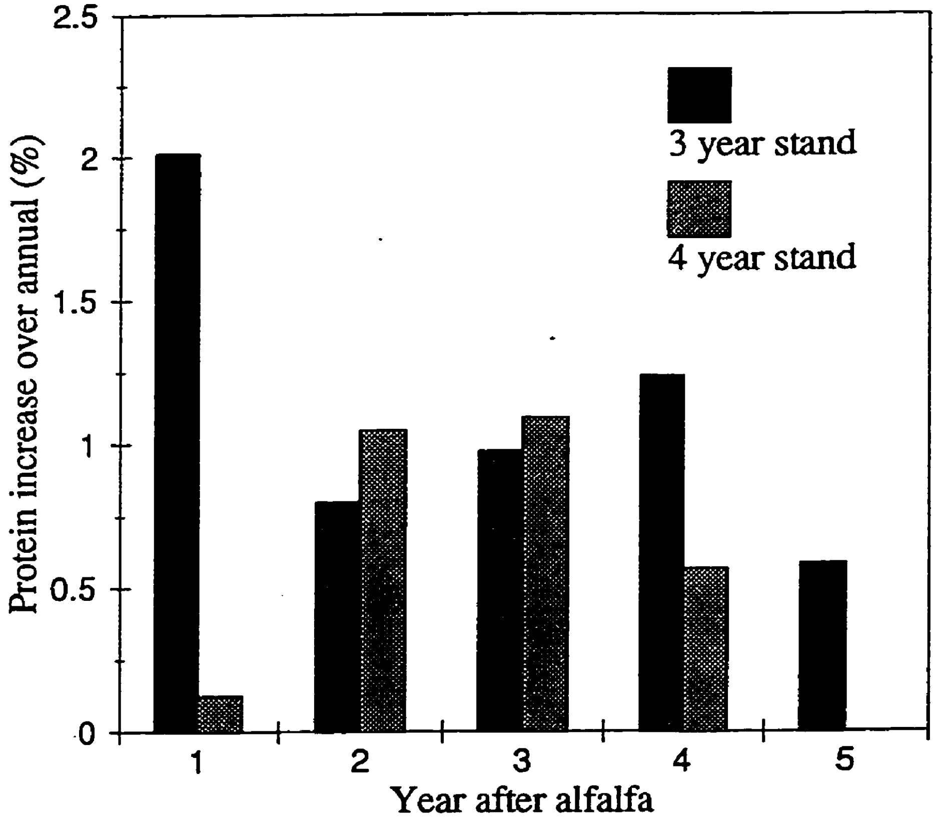


Figure 3.3. Protein concentration increase of wheat after alfalfa compared to annual rotations with N fertilizer added to soil test recommendations.

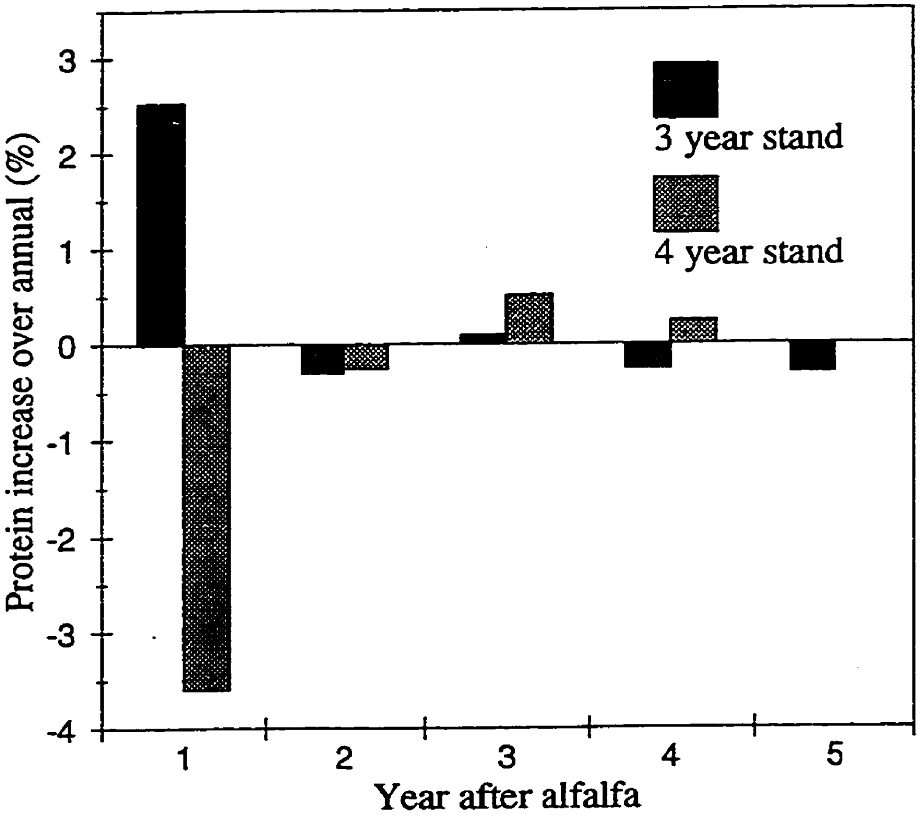


Figure 3.4. Protein concentration increase of wheat after alfalfa compared to annual rotations with no fertilizer nitrogen added.

4.0 Results and discussion

4.1 Rooting depth of alfalfa and soil water extraction in subsequent wheat crops

4.1.1 Techniques and analysis to estimate rooting depth

Two approaches were used to estimate the maximum depth of soil water extraction (referred to as rooting depth) by crops in this study. The first involved orthogonal contrasts between alfalfa crops (or other crops) and a continuous fallow plot. This was referred to as the "difference method". The second approach considered the change in soil water content during the crop growth period, and is referred to as the "water use" method. The water use method is the preferred method and has been used in previous studies (eg. Entz et al., 1992), however under conditions of high growing season precipitation which raises soil water levels from seeding to harvest, this method is of limited value. In the present study, alfalfa rooting depth was determined by both the difference and water use methods (Table 4.1; Table 4.2). However, rooting depth of wheat in various rotations was estimated using the water use method since soil water contents generally declined from the spring to pre-anthesis and the spring to harvest sampling dates at each depth in most years.

4.1.2 Rooting depth of established alfalfa

As has been reported previously in western Canada (Hoyt and Leitch, 1983; Campbell et al. 1990), alfalfa uses water to greater soil depths than annual crops such as wheat. The soil water status of alfalfa and annual crop plots over the seven year study are shown in Figure A4.1. In each year (1991 to 1995), plots containing alfalfa were dryer than wheat plots in the 0 to 150 cm and 30 to 90 cm soil depths (Figure A4.1). In the 90 to 150 cm soil depth, alfalfa soil water contents were lower than the annual rotations in 1991, 1992, 1993 and 1995. In late 1993 and 1994, large amounts of precipitation limited the amount of soil water extraction by alfalfa at the deeper depth (Figure A4.1). Regardless of the amount of precipitation, alfalfa rooted to a deeper depth than annual crops and the prairie treatment.

In 1991, maximum estimated rooting depth of alfalfa was 150 cm using the difference method (Figure 4.1; Table 4.1). Early season water use or inadequate recharge during the winter resulted in significant differences in soil water content to a depth of 130 cm at the spring sampling date (Table 4.1). Due to a combination of lower soil water contents in the spring and high precipitation prior to the harvest sampling date, the water use method resulted in soil water increases throughout the profile and did not accurately predict the rooting depth of alfalfa (Table 4.2).

In 1992, soil water content increased from the spring to mid-season sampling date (Figure 4.2). Maximum rooting depth was estimated to be 170 cm on October 6 using the difference method (Table 4.1) and 110 cm using the water use method in 1992 (Table 4.2).

In 1993, high amounts of precipitation occurred during the growing season (463 mm from May 1 to July 31) (Table 4.3). Differences in soil water content between alfalfa and fallow treatments to a depth of 150 cm were measured at the spring sampling date (Table 4.1). Analysis of variance indicated spring soil water differences to a depth of 190 cm resulting from variation in annual rotation soil water content in the 150 to 190 cm soil zone (Figure 4.3). Early season soil water use or inadequate recharge during the winter may partly explain the dryer soil profile in the spring of 1993. Despite having high seasonal precipitation, alfalfa extracted water to a maximum depth of 170 cm at the July 31 mid-season sampling date when determined using the difference method (Table 4.1). Sampling at the time of harvest indicated that late season precipitation increased the soil water content from the spring to harvest sampling date (Figure 4.3). Therefore, rooting depths of alfalfa were unable to be estimated using the water use method in 1993 (Figure 4.3).

In the spring of 1994, alfalfa plots were dryer than fallow plots to a depth of 90 cm (Table 4.1; Figure 4.4). Established alfalfa extracted water to a maximum depth of 110 cm when the difference method was used to determine rooting depth at the time of harvest (Table 4.1). Since soil water content increased from spring to harvest as a result of high precipitation during the growing season, the water use method could once again not be used to estimate alfalfa rooting depth (Table 4.2).

In 1995, seasonal precipitation during the growing season was lower than the long term average and lower than the years 1991 to 1994 (i.e. 99.6 mm between May 1 and July 31) (Table 4.3). Despite the fact that alfalfa plots had a lower soil water content than fallow plots in spring (Table 4.2; Figure 4.5a), significant soil water extraction occurred at each depth as a result of a soil water deficit throughout the growing season (Figure 4.5a). Maximum rooting depth was 170 cm using the difference method and 150 cm using the water use method.

Rooting depths of established alfalfa in the present study were shallower than those previously reported in more arid regions where forage stands extracted water to depths of 3 to 4 m (Brun and Worcester, 1975) or greater (Kiesselback et al., 1929, Kiesselback et al., 1934). Other studies indicated alfalfa extracted NO_3-N to a depth of 2.7 m in Minnesota (Mathers et al., 1975) and 2.4 m in Saskatchewan (Campbell et al., 1994). Shallower rooting in this study was attributed to a relatively high water table at this site (180 to 200 cm; Entz, unpublished).

In more humid environments and under irrigation, maximum depth of soil water extraction of alfalfa was similar to those measured in the Winnipeg crop rotation study. For example, rooting depth of irrigated alfalfa in Minnesota, was estimated to be 190 cm under four rates of irrigation (Carter and Shaeffer, 1983). In a similar clay type soil as the Winnipeg crop rotation study, the effective rooting depth of alfalfa in the establishment year was 80 to 120 cm after the first cut and 140 to 180 cm after the second hay cut (Bonner, 1997). Measurement of NO_3-N previously at the Winnipeg crop rotation study indicated rooting depth to be 120 cm in the establishment year during drought conditions and 180 cm in the second year of alfalfa compared to 90 to 120 cm depth in cereal rotations (Entz et al., 1993).

Comparison of the difference method (Table 4.1) and the water use method (Table 4.2) indicated the difference method estimated alfalfa rooting depths to be deeper compared to the water use method. In 1991, 1993, 1994, and 1995 soil water contents in the alfalfa rotation were lower than in the fallow rotation at the initial spring sampling date. This indicated early season soil water use or differences resulting from soil water extraction in previous years. In these years, the difference method would predict rooting depth, assuming rooting depths became deeper in succeeding measurements. However, in years such as 1993, excessive precipitation increased soil water content from the spring to mid-season or harvest date and the water use method did not accurately estimate rooting depth (Figure 4.3). In years where plant water use reduced soil water content at increasing depth in successive sampling dates, the water use method is preferred.

4.1.3 Influence of previous alfalfa crops on rooting depth of wheat

It was hypothesized that because the deep rooted alfalfa plants create stable macropores (Blackwell et al., 1990) and increase soil water infiltration (Cavers, 1996), wheat crops grown in rotation after alfalfa should root deeper than crops in annual rotations. To estimate the relative contribution of alfalfa N vs. alfalfa "biological tillage" (i.e. non-N effects), wheat crop rooting depth was assessed in both the unfertilized and N fertilized treatments using the water use method.

4.1.3.1 Low N system

Rooting depths in the first unfertilized wheat crop following alfalfa were higher than the unfertilized annual wheat rotation in 1992, 1995 and 1996 (Table 4.2; Figures 4.2, 4.5a, and 4.6.). In 1995 and 1996, alfalfa in rotation resulted in 80 and 60 cm, respectively, deeper rooting depths than the annual rotation. Deeper rooting in the alfalfa-containing unfertilized rotation was partially attributed to N inputs into the soil system. Deeper rooting depth in low N systems may result from wheat accessing N from decomposing alfalfa residue which is known to be deposited deep into the soil profile (Gault et al., 1995).

Rooting depths in the second wheat crop after alfalfa were either higher (1995, Figure 4.5a; mid-season measurement in 1996, Figure 4.6) or the same (1997; Figure 4.7) as the unfertilized wheat in the continuous cropping system. In the third wheat crop, rooting depths were deeper (1995 and 1996) or similar (1997)compared with the unfertilized annual rotations (Table 4.2).

The first three years of unfertilized wheat after alfalfa were measured in 1995 to 1997.

The mean maximum rooting depth measured was 150, 130, 117 and 90 cm for the first, second, third wheat crop after alfalfa and the annual rotation with no fertilizer nitrogen added, respectively (Table 4.1).

While the mean rooting depth tended to decrease with each successive wheat crop after alfalfa, deeper rooting depths were present in each of the first three wheat crops after alfalfa termination. This decline in maximum rooting depth after alfalfa may have been due to a decline in the available nitrogen from alfalfa residue over time (discussed in section 3.2.2). Non-N benefits may also have contributed to deeper rooting in these low N systems. Increased incidence of root disease with increasing number of wheat crops after alfalfa may also account for the reduction in rooting depth with increasing number of wheat crops after alfalfa (Conners et al., 1996; Cook, 1992). As well, the soil structural benefits resulting from addition of alfalfa in the cropping system (Meek et al., 1990) become more important with increasing number of wheat crops after alfalfa.

4.1.3.2 High N system

Because of N fertilizer application, any increase in rooting depth in these N fertilized rotations were assumed to be largely from alfalfa non-nitrogen benefits such as improved soil structure (Meek et al., 1990; Cavers, 1996) and reduced root diseases in wheat (Cook, 1992).

In 1991, no differences were detected between spring and harvest sampling dates for wheat after alfalfa, however the fertilized annual rotations had soil water extraction to a depth of 90 cm (Table 4.2; Figure 4.1). Higher water infiltration rates into rotations previously containing alfalfa have been measured (Meek et al., 1990; Cavers, 1996) and may have contributed to higher soil water content than the fertilized annual rotations in 1991. In 1992, rooting depth was 80 cm deeper for the first wheat crop after alfalfa than the fertilized annual control (Table 4.2; Figure 4.2). In 1993, maximum rooting depth was similar for wheat after alfalfa and annual rotations with fertilizer N added (Table 4.2; Figure 4.3). In 1994, the rooting depth of the first wheat crop after alfalfa was 50 cm deeper than annual rotations when fertilizer was added to both rotations. In 1995, alfalfa in rotation resulted in only a slightly deeper maximum rooting depth (20 cm) in the first unfertilized wheat crop compared to the fertilized annual control (Table 4.2).

Rooting depths for the second and third fertilized wheat crops after alfalfa were measured from 1995 to 1997 (Table 4.2). In 1995, rooting depth was only slightly deeper (20 cm) in the second and third wheat crops after alfalfa when compared to the fertilized annual wheat rotations. In 1996, maximum rooting depth was 20 and 40 cm deeper in the second and third wheat crop, respectively when compared to the fertilized annual rotation (Table 4.2; Figure 4.6). In 1997, maximum rooting depth was 40 and 20 cm deeper in the second and third wheat crop, respectively than the fertilized annual wheat rotation (Table 4.2; Figure 4.7). Assuming non-nitrogen benefits for 4, 5, and 6 year alfalfa stands were similar, rotational benefits decreased slightly with each successive wheat crop after alfalfa.

Using the water use method to estimate rooting depth, mean maximum rooting depths were 150, 137, 123 and 123 cm for the first unfertilized wheat crop, second fertilized wheat crop, third fertilized wheat crop after alfalfa and the fertilized annual rotation, respectively for the means of 1995, 1996 and 1997 maximum estimated rooting depth within each year (Table 4.2). Therefore, the apparent non-nitrogen benefits after alfalfa termination increased rooting depth for the first two subsequent wheat crops in this study.

Observations that deeper root growth of wheat after alfalfa when N fertilizer was added appears to support the hypothesis that wheat roots grow in decaying alfalfa root channels (Blackwell et al., 1990). Soil structural benefits of alfalfa are known to include more extensive macropores (Blackwell et al., 1990) and increased soil water infiltration (Meek et al., 1990). Supporting evidence for soil structural advantages in the present study was provided by Cavers (1996) who measured infiltration rates to be one to two orders of magnitude higher after alfalfa than compared to zero-till continuous wheat to a depth of 50 cm at the Winnipeg crop rotation trial. In the current study, the benefits of alfalfa 'biological tillage' indicate wheat roots were able to grow deeper in the soil profile as a result of including alfalfa in rotation. Increased access to soil water in clay type soils may have contributed to higher wheat yield and biomass (previously discussed in section 3.1.1). In previous studies, reduction in root diseases such as common root rot (Ledingham, 1961; Conners et al., 1996) and Take-all (Cook, 1992) contributed to higher grain yield with more diversified crop rotations and may have contributed to deeper rooting depths in the N fertilized alfalfa containing rotations in the present study.

4.2 Soil water extraction of wheat as influenced by previous alfalfa in rotation

The amount of soil water extraction in wheat varied between years depending on the growing season precipitation. Growing seasons with periods of low precipitation (i.e. 1995, 1996, and in 1997) produced the highest amount of water extraction from the soil profile. As well, in years such as 1996, precipitation prior to the harvest soil water measurement masked the differences in soil water extraction between rotations which were previously observed at the anthesis sampling date. As a result, rotational benefits as measured by soil water extraction were expressed to a higher degree in years with higher soil water deficit (i.e. 1995) and in periods during the growing season when precipitation was low (i.e. early in 1996).

Season long soil water extraction in the 0 to 150 cm soil zone was not significantly different between rotations in 1991 and 1992 (Figure 4.8b; Figure 4.9b). Lack of significant soil water effects were attributed to a high inherent soil nitrogen status in all treatments as well as above average seasonal precipitation (Table 4.3). In 1993, late season precipitation (Table 4.3) increased soil water contents from the spring sampling date to the harvest sampling date at each depth (Figure 4.10b). In 1994, differences among wheat rotations were not significant as high precipitation recharged the soil profile and resulted in low seasonal soil water extraction (Figure 4.11). Therefore, no significant differences were observed in 1993 or 1994.

The hypothesis that alfalfa increases soil water extraction in following crops was best tested in 1995 (Figure 4.12), early in the 1996 season (Figure 4.13a) and in 1997 (Figures 4.14a and 4.14b). Low amounts of precipitation in these years produced favorable conditions for soil profile water use by crops. In unfertilized systems, any increase in soil water extraction was attributed predominantly to alfalfa N benefits, while changes in soil water extraction in fertilized rotations were attributed mainly to non-N alfalfa benefits.

4.2.1 Low N system

In unfertilized crop rotations, observations of increased soil water extraction due to alfalfa were detected in up to three subsequent wheat crops. In 1993, 4.6 cm more water was extracted from the unfertilized first wheat crop than the unfertilized annual rotation in the 0 to 150 cm soil depth (Figure 4.10a).

In 1995, the second and third wheat crops after alfalfa had soil water extractions which were 4.4 and 4.5 cm higher than the unfertilized control, respectively (Figure 4.12). The fourth wheat crop after alfalfa was not significantly different from the unfertilized annual rotation (Figure 4.12).

In 1996, soil water extraction for the first, second and third wheat crop were 5.3, 3.9, and 2.5 cm higher, respectively, than the unfertilized annual wheat rotation during the pre-anthesis growth period (Fig 4.13a). Soil water extraction in the first and second crops after alfalfa were not significantly different from each other but significantly higher than the third wheat crop, suggesting that alfalfa N benefits increased soil water extraction to a higher degree in the first two wheat crops than in the third wheat crop (Fig 4.13a).

In 1997, soil water extraction in the alfalfa containing rotations was not significantly higher than the unfertilized annual rotation when soil water extraction was measured from June 5 to July 21 (Figure 4.14a). However, significant differences ($P<0.05$) in season long soil water extraction was detected for each soil depth increment measured (Figure 4.14b). Similar to the 1995 data, soil water extraction was higher in the second and third wheat crop (3.6 and 2.1 cm, respectively), after alfalfa than in the unfertilized annual rotation (Figure 4.14b).

In 1995, high soil water extraction in wheat (Figure 4.12) resulted from low amounts of precipitation during the growing season (99.6 mm between May 1 and July 31) and in this year, stored spring soil water accounted for 60% of growing season evapotranspiration (ET). Entz and Fowler (1989) observed that for wheat crops in Saskatchewan, the contribution of soil water present at seeding to the total ET was typically below 20%. Soil water contents in the spring of 1995 were 4.3 cm lower in the wheat after alfalfa rotation than the annual rotation at the spring sampling date for the 0 to 150 cm soil depth. Therefore, soil water extraction was not significantly different between the first unfertilized wheat crop after alfalfa and the corresponding unfertilized annual control for the 150 cm depth in 1995 (Figure 4.12). Lower soil water extraction in the alfalfa containing vs annual rotation was attributed to less water available for plant growth in the wheat following alfalfa. Of the 7 years of this study, 1995 was the only year in which alfalfa breaking had less water than annual-cropped land in the spring.

In summary, alfalfa in rotation resulted in more soil water extraction in up to three wheat crops and benefits of alfalfa to water use declined with each successive wheat crop after alfalfa. This pattern of alfalfa benefit in unfertilized rotations follows closely the pattern of N benefits (section 3.3). Therefore, benefits of alfalfa in rotation in the unfertilized plots appear to be largely due to alfalfa N benefits. In previous studies, increased inorganic nitrogen in the soil system increased soil water extraction prior to heading (Bond et al., 1971; Brown, 1971). In Saskatchewan, dryland continuous wheat extracted 61 mm with nitrogen and phosphate fertilizer added and 50 mm with no N added (Campbell et al., 1987). Nitrogen available at deeper depths (Gault et al., 1995) also may have increased soil water extraction throughout the profile. Reduced water demand by each subsequent wheat crop after alfalfa in the present study may have been due to increased root diseases from the less diverse rotation (Cook, 1992), but primarily from an increased nitrogen deficit with each crop after alfalfa termination (Fox and Piekielek, 1988).

4.2.2 High N system

4.2.2.1 Influence of alfalfa on water extraction by following wheat crops

In rotations with fertilizer N added, benefits from alfalfa were to be mainly due to non-N factors, especially ‘biological tillage’. Any practice which allows for removal of larger amounts of water from the soil profile leads to increases in water recovery efficiency (ratio of water used to available water) of the cropping system (Pierce and Rice, 1988).

In 1991 and 1992, no significant difference in soil water use was measured among rotations within the 0 to 150 cm soil depth increment (Figure 4.8b; Figure 4.9b). While not significantly different, season long soil water extraction was measured to be 1.3 and 4.3 cm higher in the fertilized first wheat crop than in the fertilized annual rotation in 1991 and 1992, respectively (Figure 4.9b). Increased soil water extraction in the growing seasons with relatively high precipitation represents an opportunity to remove excess water which may be otherwise detrimental to annual crops.

Significant differences ($P<0.05$) for soil water extraction among crop rotations in the 0 to 150 cm, 0 to 30 cm, and 30 to 90 cm soil depth increments were detected during the pre-anthesis period in 1993 (Table 4.10a). Soil water extraction was 3.2 cm higher for first wheat crop than the corresponding fertilized annual wheat rotation in the 0 to 150 cm depth (Figure 4.10a) despite having extended periods with high amounts of precipitation (Table 4.3).

In the dry season of 1995, higher soil water use by wheat after alfalfa vs wheat in the annual rotation was measured at least 3 years after alfalfa termination (Figure 4.12). While the second wheat crop after alfalfa did not extract significantly more than annual fertilized rotations, the third and fourth wheat crop after alfalfa increased soil water extraction by 5.8

and 4.5 cm, respectively over the fertilized annual control (Figure 4.12). Total soil water use in the first wheat crop was limited by a spring water deficit which was concentrated in the 30 to 90 cm depth (Figure 4.12). Therefore, non-N benefits in this rotation may have been underestimated or limited by a spring soil water deficit.

In 1996, pre-anthesis soil water extraction in the second and third wheat crops after alfalfa was not significantly higher than the fertilized annual rotation (Figure 4.13a). However, the first unfertilized wheat crop did have significantly higher soil water use than the fertilized annual control (Figure 4.13a).

In 1997, the fertilized second wheat crop extracted 1.6 cm more water than the annual rotation in the 0 to 150 cm soil depth increment from June 5 to July 21 (Figure 4.14a). Water extraction in the fertilized third and fourth wheat crop after alfalfa was not significantly higher than in the fertilized annual rotation (Figure 4.14a). Using season long soil water extraction data, significant differences ($P<0.05$) were measured among the fertilized rotations in the 0 to 150 cm soil depth increment (Figure 4.14b). However, the third and fourth fertilized wheat crops were not significantly different from the fertilized annual control, indicating that the residual benefit of alfalfa on soil water extraction did not extend beyond 2 years in this instance. In summary, results of the present study indicate that non-N benefits increase soil water use in 2 to 4 wheat crops after alfalfa termination.

4.2.2.2 Vertical pattern of soil water extraction

It was hypothesized that in addition to increasing total soil water extraction, alfalfa in rotation may also increase the maximum depth of soil water extraction. Deeper wheat rooting depths in rotation with alfalfa were previously described in section 4.1.3 using soil water measurement in 20 cm intervals. Rooting pattern was also determined soil depth increments of 0 to 30, 30 to 90 and 90 to 150 cm.

In 1993, differences in soil water extraction due to alfalfa in rotation were primarily found in the shallower portions of the soil and the limited effect at greater depths was attributed to higher than average precipitation (Table 4.3). Seasonal soil water extraction was 2.3 and 0.9 cm higher in the 0 to 30 and 30 to 90 cm soil depth increment (Figure 4.10a).

In 1995, despite small differences in estimated maximum rooting depth (previously discussed in Section 4.1.3), including alfalfa in fertilized rotations did not increase soil water in the 0 to 30 or 30 to 90 cm depths, but resulted in differences in water use at the 90 to 150 cm soil depth. In this soil zone, water extraction was 3.0 and 2.2 cm higher in the third and fourth wheat crop, respectively in the fertilized alfalfa vs the fertilized annual control treatment (Figure 4.12). Therefore, during this year of high water extraction (i.e. 1995), alfalfa increased soil water availability to subsequent wheat crops in the 0 to 150 cm zone, with the largest differences occurring deep within the soil profile.

In 1996, previous alfalfa did not affect soil water extraction in the fertilized rotations at any depth. However, soil water extraction in the unfertilized first wheat crop was significantly higher ($P<0.05$) than the fertilized annual control at the 30 to 90 cm soil depth (Figure 4.13a). Assuming previous alfalfa contributed enough N to maximize grain yield, increased soil water extraction resulted from non-nitrogen benefits and increased the recovery efficiency in the first wheat crop.

In 1997, a large proportion of the soil water extraction was concentrated in the surface soil depth (0 to 30 cm). In the surface soil zone, soil water extraction was 2.3, 1.4, and 1.1 cm higher in the second, third and fourth wheat crops, respectively, than the fertilized annual rotation (Figure 4.14b). Previous alfalfa in rotation may create an environment where more water is available (i.e. higher water holding capacity) or existing water is used more efficiently by subsequent wheat (i.e. water used at deeper soil depths).

Results of the N fertilized systems tested in this study indicate that non-nitrogen rotational benefits from alfalfa to soil water extraction in following crops were detected up to the second wheat crop after alfalfa. While differences were present up to the third year after alfalfa in the unfertilized rotation (discussed previously in 4.2.1), no increase in soil water extraction in third and fourth year wheat crops after alfalfa were detected in the N fertilized rotations. Reasons for improved soil water extraction include more prolific root growth within each soil depth increment as a result of reduced disease (Cook, 1992), increased soil organic matter (Angers, 1992) and improved soil physical properties of the heavy clay soil (Blackwell et al., 1990, Cavers, 1996). Each of these factors may increase the availability of water for subsequent crops. Another hypothesis is that access to nitrogen from alfalfa decaying deep within the soil profile (Gault et al., 1995) resulted in a healthier root system, regardless of the amount of nitrogen added.

4.3 Water Use Efficiency (WUE) of wheat in rotations containing alfalfa

An important goal of improving the productivity of cropping systems is to increase the yield per unit of ET. This is known as increasing the physiological efficiency (WUE for grain yield) and reflects the ability of the plant to efficiently convert water into grain yield (Pierce and Rice, 1988). It was hypothesized that increased N from alfalfa results in higher WUE for grain and biomass production.

In unfertilized rotations, including alfalfa in rotation generally increased WUE for grain yield (Table 4.4) and biomass production (Table 4.5). The exception was in 1991 and 1992 where WUE was unaffected by including alfalfa in rotation, largely as a result of high inherent soil nitrogen levels in annual rotation control plots. In 1995, including alfalfa in the unfertilized rotations increased WUE for grain production by 129.9, 40.2, and 17.0 kg $ha^{-1}cm^{-1}$ for the first, second and third wheat crop, respectively (Table 4.4). Similar increases were observed in 1996 and 1997.

In unfertilized rotations, alfalfa in rotation increased WUE (i.e. physiological efficiency) for the first 3 wheat crops. These rotations had higher grain yield despite having higher soil water extraction (previously discussed in section 4.2.1) and ET. In previous studies, WUE for grain yield was found to increase with inorganic nitrogen additions (Bond et al., 1971; Brown, 1971). Similarly, addition of legume N from alfalfa residue increased the physiological efficiency in the present study.

When fertilizer N was added, including alfalfa in rotation generally did not affect WUE for grain production to the same extent as in unfertilized rotations (Table 4.4). In 1995, the unfertilized first wheat crop had significantly higher WUE than the fertilized annual rotation.

This resulted from a rotational yield increase as well as slightly lower soil water extraction in the alfalfa-containing rotation as a result of lower spring soil water contents (Figure 4.5b). In 1996, the WUE was 44 and 22 kg ha^{-1} cm^{-1} higher for the second and third wheat crop, respectively, than the fertilized annual treatment (Table 4.4). Slight increases in biomass production and corresponding slight increases in ET resulted in similar or slightly higher physiological efficiency when fertilizer N was added.

In 1997, including alfalfa in N fertilized rotations did not increase WUE, despite increasing both grain yield (previously discussed in 3.1.1) and ET (previously discussed in 4.2.2). In this situation, yield benefits could have resulted from a higher recovery efficiency as alfalfa increased the water availability to the subsequent wheat crop (Figure 4.12; Figure 4.14b). Increased recovery efficiency of subsequent wheat crops was attributed in-part to reduced evaporative losses in a denser crop canopy (Pierce and Rice, 1988). As well, deeper rooting depths (previously discussed in section 4.1.2), reduced root disease infestation (Cook, 1992) and mineralization of nitrogen throughout the soil profile (Gault et al., 1995) may have increased the availability of soil water for plant growth in fertilized rotations. In summary, these non-N factors contributed to a higher recovery efficiency in fertilized rotations.

4.4 The magnitude of soil water benefits after alfalfa

From 1991 to 1993, wheat was maintained in a pea-barley-*wheat* crop sequence. After 1994, continuous wheat was used as the control treatment for determining the effect of previous alfalfa on rooting depth and soil water extraction. In previous experiments, non-cereal reference crops such as flax (Lafond et al., 1992) or fallow (Hoyt and Leitch, 1983) were used to measure the rotation benefits.

Using rotation crops were also known to increase soil water extraction relative to monoculture cropping (Angus et al., 1991). In an experiment in Australia, canola as a break crop increased soil water extraction by 4.0 cm relative to continuous wheat when infestation of Take-all in wheat was severe (Angus et al., 1991). Similarly in the US mid-west, corn after soybean extracted 1.6 cm more soil water than continuous corn (Copeland et al., 1994). In the present experiment, alfalfa improved soil water extraction by as much as 5.0 cm in the second wheat crop (Figure 4.14b), and 5.8 and 4.5 cm in the third and fourth wheat crops, respectively (Figure 4.12). Since 2 years of wheat production is known to increase the severity of common root rot inoculum in western Canada (Conners et al., 1996), the amount of viable root disease inoculum would not likely be different than the continuous wheat rotation in the third and fourth wheat crop after alfalfa. Therefore, it is clear that alfalfa in rotation has a substantial effect on the rooting pattern and soil water extraction by subsequent crops.

4.5 Comparison of water effects in agriculture systems to re-established native prairie grasses

Maximum rooting depth of a re-established mixed stand of warm and cool season native prairie grasses was measured in 1994, 1995, 1996 and 1997 to be similar to the unfertilized annual wheat rotation but lower than the fertilized annual rotation and all rotations previously containing alfalfa (Table 4.1; Table 4.2). In each year (except 1996), maximum estimated rooting depth was shallower for the prairie rotation than both the fertilized annual rotation and the first unfertilized wheat crop after alfalfa (Table 4.2).

Mean maximum rooting depths from 1995 to 1997 indicated the prairie extracted water to a similar depth as the unfertilized annual rotation but shallower than the fertilized annual rotation and rotations previously containing alfalfa. The fertilized annual rotations and alfalfa containing rotations extracted water >30 cm deeper than the prairie rotation (Table 4.2).

Total soil water use was also lower in the prairie system than the agricultural crop rotations. In growing seasons with a seasonal soil water deficit (i.e. 1995, 1996, and 1997), soil water extraction in the 0 to 150 cm soil depth increment in the prairie rotation was generally similar to the unfertilized annual rotation but lower than first, second, and third wheat crops after alfalfa in both fertilized and unfertilized crop rotations (Figure 4.12; Figure 4.13a; Figure 4.14b).

Previous literature regarding soil water in native prairie systems considered species effects on soil water uptake and water use efficiency (WUE) (Fairbourne, 1982). A classical study in an arid climate (Kansas) measured soil water deficits in native grass sod and soybean plots to 2 meters of soil depth compared to greater than 5 meters in alfalfa plots (Meyers, 1936).

In summary, the native prairie grass rotation had maximum rooting depths similar to the unfertilized rotation but shallower than the fertilized annual and each alfalfa containing rotation. Lower water demand in the prairie rotations may be due to several factors. Native prairie grasses have lower evapotranspiration demand than perennial legumes and tame pasture grasses (Fairbourne, 1982). As well, Fairbourne (1982) measured water use efficiencies (WUE) of native rangeland species to be not significantly different than tame pasture and perennial legume species. Dry matter production in mixed warm and cool season native prairie rotation in this study were 2590 and 2710 kg ha^{-1} in 1995 and 1996, respectively. Dry matter production in the prairie rotations was slightly lower than the unfertilized annual rotation (2253 and 3597 kg ha^{-1}) and considerably lower than the fertilized annual rotation (5236 and 8022 kg ha^{-1} in 1995 and 1996, respectively). Also, an apparent nitrogen deficiency in the prairie rotation contributed to relatively low dry matter yield and low water use. The native grass composition at Winnipeg did not include native legume species or deeper rooting forbs and may have limited soil water use and rooting depth in the mixed sward. In summary, rooting depth and soil water extraction of the prairie system was similar to the unfertilized annual rotation but had shallower rooting depth and lower seasonal soil water extraction than the fertilized wheat and established alfalfa system. These observations suggest the surface hydrology of ‘restored’ native prairie systems are very different than current arable cropping systems, especially those containing alfalfa.

4.6 Summary and conclusion

In this study, established alfalfa extracted water to a greater depth than the annual rotations and even in wet years, extracted water to depths greater than 130 cm. Including alfalfa in rotation resulted in a deeper rooting by subsequent wheat crops. In unfertilized rotations, deeper rooting depth and higher total seasonal soil water use due to alfalfa were attributed to N and non-N benefits. In fertilized rotations, the majority of the alfalfa rotation benefit to water use and rooting depth in following crops was attributed to non-N sources. ‘Biological tillage’ by alfalfa was credited with increasing total water extraction in the 0 to 150 cm soil depth. Alfalfa in rotation generally resulted in increased soil water extraction deeper in the soil profile (90 to 150 cm depth), particularly in growing seasons with a soil water deficit.

Table 4.1. Summary of the maximum estimated rooting depth at each sampling date using orthogonal contrasts for differences ($P<0.05$) in soil water content between various crop rotations and a fallow treatment (difference method) in the years 1991 to 1997. This table summarizes the analysis and data contained in Tables A 4.1 to A4.7.

		Maximum estimated rooting depth (cm soil depth)									
Year	Date	Alfalfa	Crop 1F+	Crop 1 F-	Crop 2F+	Crop 2F-	Crop3F+	Crop 3F-	Annual F+	Annual F-	Prairie
1991	May 20	130[z]	0	0	-	-	-	-	0	0	-
	June 19	150	0	0	-	-	-	-	0	0	-
	August 8	110	90	90	-	-	-	-	90	50	-
1992	May 27	0	0	0	-	-	-	-	0	0	-
	July 9	150	90	90	-	-	-	-	70	50	-
	Oct 6	170	130	130	-	-	-	-	90	30	-
1993	May 27	150	0	0	-	-	-	-	0	0	-
	July 31	170	90	150	-	-	-	-	130	130	-
	Sept 14	90	0	0	-	-	-	-	0	0	-
1994	May 13	90	0	0	-	-	-	-	0	0	0
	August 24	110	0	0	-	-	-	-	70	0	0
1995	June 14	130	-	110	0	0	0	0	0	0	0
	July 26	150	-	-	-	-	-	-	-	110	70
	August 11	170	-	130	130	130	150	130	130	130	130
1996	June 15	-	-	0	0	0	0	0	0	0	0
	July 25	-	-	90	90	70	70	70	30	30	0
	Sept 4	-	-	110	0	0	0	0	0	0	0
1997	June 5	-	-	-	0	0	0	0	0	0	0
	July 21	-	-	-	90	90	50	50	90	90	0
	August 12	-	-	-	110	110	90	90	110	90	50
				Mean maximum rooting depth for 1995 to 1997 (cm)							
				120.0	110.0	103.3	103.3	96.7	90.0	83.3	60.0

[z] Differences in soil water content in the spring represent either water deficit due to a low recharge during the winter or early season water use by alfalfa.

Table 4.2. Summary of the maximum estimated rooting depth using orthogonal contrasts ($P<0.05$) for soil water contents between sampling dates (water use method)for 1991 to 1997. This table summarizes the analysis and data contained in Tables A 4.8 to A4.14.

		Maximum estimated rooting depth (cm soil depth)									
Year	Sampling dates	Alfalfa	Crop 1F+	Crop 1 F-	Crop 2F+	Crop 2F-	Crop3F+	Crop 3F-	Annual F+	Annual F-	Prairie
1991	May 20 vs June 19	0	0	0	-	-	-	-	0	0	-
	May 20 vs Aug 8	inc[z]	0	90	-	-	-	-	90	90	-
1992	May 27 vs July 9	inc	90	50	-	-	-	-	70	50	-
	May 27 vs Oct 6	110	110	70	-	-	-	-	30	30	-
1993	May 27 vs July 31	170	70	70	-	-	-	-	70	50	-
	May 27 vs Sept 14	inc	inc	inc	-	-	-	-	inc	inc	-
1994	May 13 vs Aug 24	inc	50	-	-	-	-	-	0	-	0
1995	June 14 vs July 26	0	-	-	-	-	-	-	-	70	0
	June 14 vs Aug 14	150	-	150	150	130	150	130	130	70	70
1996	June 15 vs July 25	-	-	150	110	150	90	110	130	90	110
	June 15 vs Sept 4[y]	-	-	110	0	0	70	110	70	70	70
1997	June 5 vs July 21	-	-	-	70	70	50	90	70	90	50
	June 5 vs Aug 12	-	-	-	150	110	130	110	110	110	90
				Mean maximum rooting depth for 1995 to 1997 (cm)							
				150.0	136.7	130.0	123.3	116.7	123.3	90.0	90.0

[z] inc denotes rotations where soil water contents increased from spring to either mid-season or harvest sampling dates. In these rotations rooting depth could not be estimated from soil water content at each 20 cm depth. [y] Precipitation between July 25 and September 4 resulted in lower rooting depth estimation during entire growth season in 1996.

Table 4.3. Summary of monthly precipitation during the growing season at the Winnipeg crop rotation study, 1991 to 1997.

	Precipitation (mm)					Total precipitation (mm)		
	Month					May 1 to July 31	May 1 to Aug 31	May 1 to Sept 30
Year	May	Jun	July	Aug	Sept			
1991	54.4	126.5	112.3	13.0	146.3	293.1	306.1	452.4
1992	14.2	117.9	112.8	83.8	88.9	244.9	328.7	417.6
1993	43.9	111.8	307.6	265.9	39.9	463.3	729.3	769.1
1994	69.7	74.8	148.3	123.0	69.6	292.8	415.8	485.4
1995	41.2	25.7	32.8	129.0	38.6	99.6	228.6	267.2
1996	102.1	19.6	71.4	138.9	75.4	193.0	331.9	407.4
1997	36.3	53.1	93.2	73.4	50.5	182.6	256.0	306.6
Mean monthly precipitation, 1991 to 1997[z]								
	51.7	75.6	125.5	118.1	72.8	252.8	370.9	443.7
Long term average monthly precipitation, 1938 to 1990[y]								
	59.8	83.8	72.0	75.3	51.3	215.6	290.9	342.2

[z] Monthly precipitation was calculated from University of Manitoba, Plant Science data in 1991 to 1993, 1995 to 1997; Environment Canada Airport data in 1994. [y] Long term average monthly precipitation was calculated from Environment Canada Airport Data, 1938 to 1990.

Table 4.4. Water use efficiency for grain yield (kg ha^{-1} cm^{-1} ET) at the Winnipeg crop rotation for 1991 to 1997. Analysis of variance was performed for yield WUE within each year with crop rotation as the main effect and fertilizer N addition as the subplot effect.

		Year						
Rotation^z	Fertilizer N	1991	1992	1993	1994	1995	1996	1997
Annual	+	90.2 a	90.4 a	29.2 ab	77.7 a	126.0 bc	139.6 c	150.a 9
	-	80.4 a	90.2 a	12.8 c	-	68.0 g	75.7 e	73.7 d
Crop 1	+	96.0 a	89.6 a	28.4 b	66.9 a	-	-	-
	-	95.0 a	96.8 a	33.9 a	-	^{x} 197.9 a	130.7 cd	-
Crop 2	+	-	-	-	-	132.4 cde	183.5 a	143.0 ab
	-	-	-	-	-	108.2 bcd	121.1 cd	143.9 ab
Crop 3	+	-	-	-	-	121.1 bcd	161.1 b	164.5 a
	-	-	-	-	-	85.0 gfe	110.9 d	114.0 bc
Rotation		0.3787	0.6341	0.0030	0.3424	0.1690	0.0001	0.1285
Fertilizer N		0.1961	0.7680	0.0236	-	0.0001	0.0001	0.0001
Rotation*fertilizer N		0.4496	0.7566	0.0009	-	0.0483	0.5683	0.0215

^{z} Crop rotation represents either annual rotations or alfalfa containing rotations (Crop 1, first wheat crop; Crop 2, second wheat crop; Crop 3, third wheat crop) (^{Y} -, no fertilizer nitrogen added; +, fertilizer N added to soil test recommended rates). ^{x} The unfertilized first wheat crop is not included in the two-way analysis of variance in 1995 and 1996 but is included in the one- way ANOVA and LSD test (Means followed by the same letter are not significantly different).

Table 4.5. Water use efficiency for wheat biomass production (kg ha^{-1} cm^{-1} ET) at the Winnipeg crop rotation for 1991 to 1997. Analysis of variance was performed for biomass WUE within each year with crop rotation as the main effect and fertilizer N addition as the subplot effect.

		Year			
Rotation [z]	Fertilizer N	1993	1995	1996	1997
Annual	+	75.2 b	255.8 bcde	400.0 a	362.6 a
	-	30.9 c	146.5 h	200.1 c	221.4 b
Crop 1	+	87.8 ab	-	-	-
	-	97.8 a	[x] 483.8 a	278.6 bc	-
Crop 2	+	-	298.8 bc	375.2 a	406.9 a
	-	-	226.6 defg	251.1 c	359.9 a
Crop 3	+	-	261.2 bcde	351.3 ab	429.0 a
	-	-	186.4 fgh	266.6 bc	361.0 a
Rotation		0.0218	0.0495	0.9166	0.0140
Fertilizer N		0.0228	0.0001	0.0001	0.0001
Rotation*fertilizer N		0.0017	0.4949	0.2010	0.1341

[z] Crop rotation represents either annual rotations or alfalfa containing rotations (Crop 1, first wheat crop; Crop 2, second wheat crop; Crop 3, third wheat crop) ([Y] -, no fertilizer nitrogen added; +, fertilizer N added to soil test recommended rates). [x] The unfertilized first wheat crop is not included in the two-way analysis of variance in 1995 and 1996 but is included in the one-way ANOVA and LSD test (Means followed by the same letter are not significantly different).

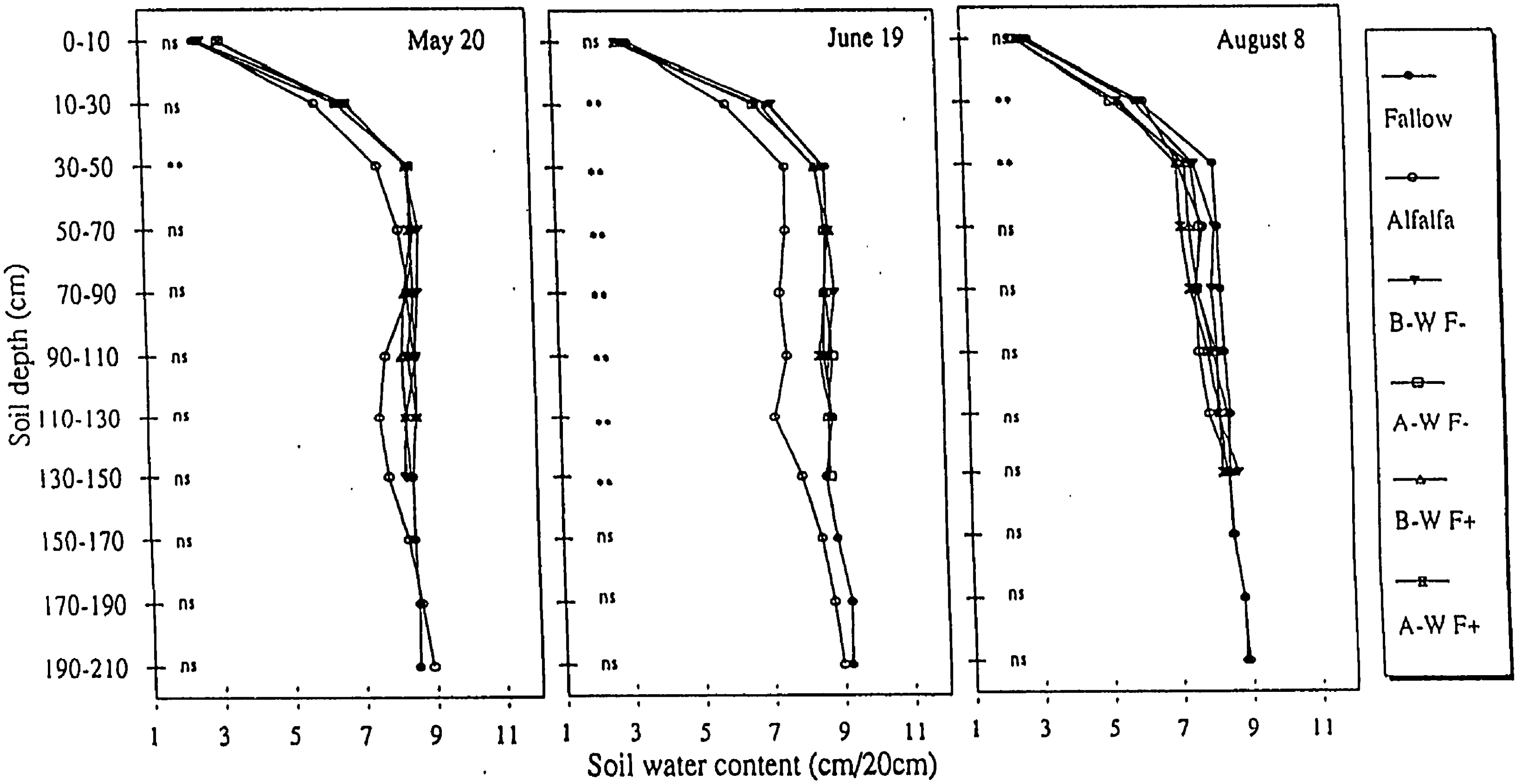


Figure 4.1. Volumetric soil water content at seeding, mid-season and at harvest in 1991. The significance of analysis of variance are summarized for each depth at each date (*, **, significant at 0.05, 0.01 probability levels respectively; ns, non significant). (A-W, wheat after alfalfa; B-W, wheat after barley; F+ fertilizer N added; F-, no fertilizer N added).

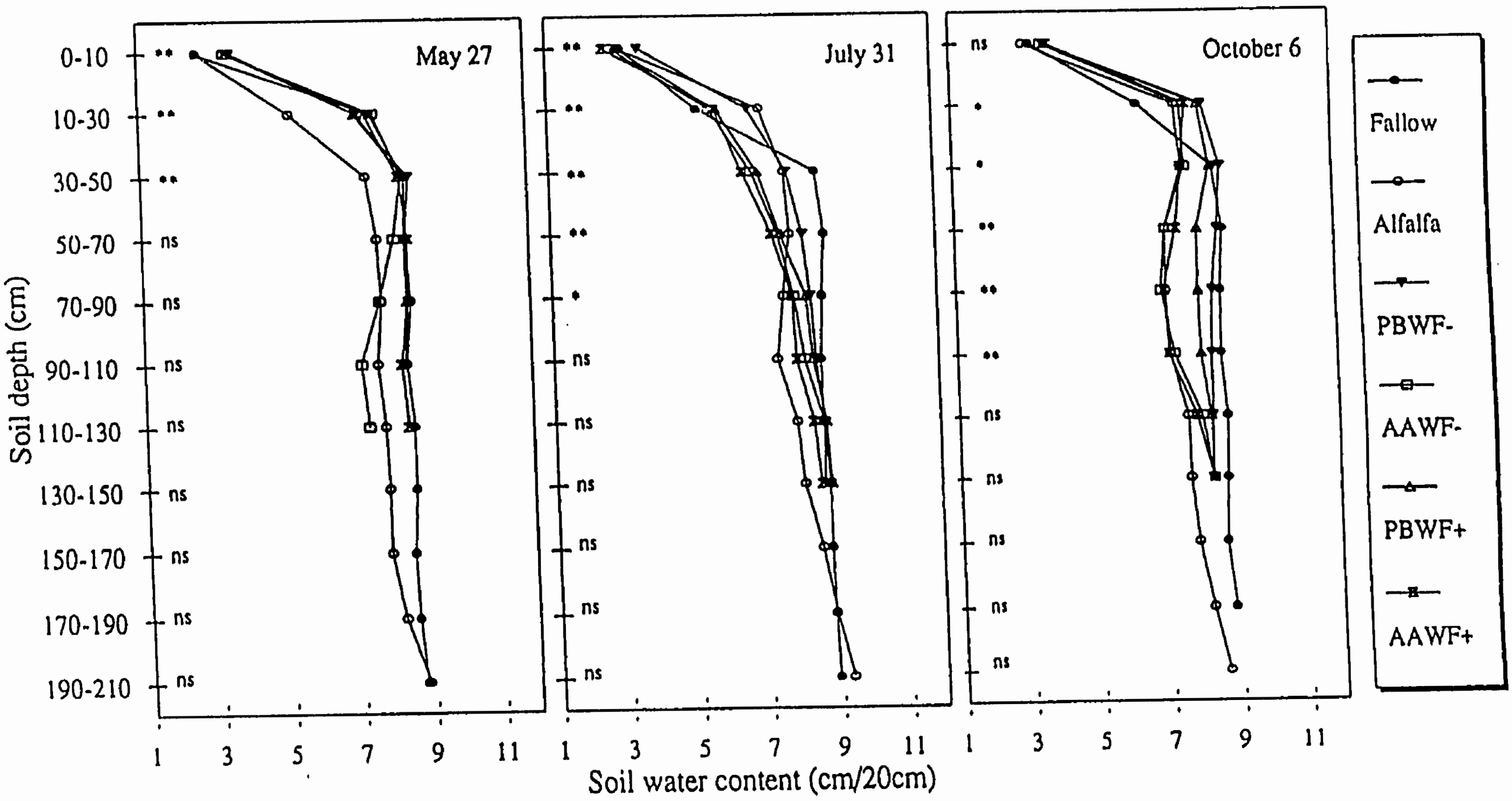


Figure 4.2. Volumetric soil water content at seeding, mid-season and at harvest in 1992. The significance of analysis of variance are summarized for each depth at each date (*, **, significant at 0.05, 0.01 probability levels respectively; ns, non significant). (A, alfalfa; P, field pea; B, barley; F+, fertilizer N added; F-, no fertilizer N added).

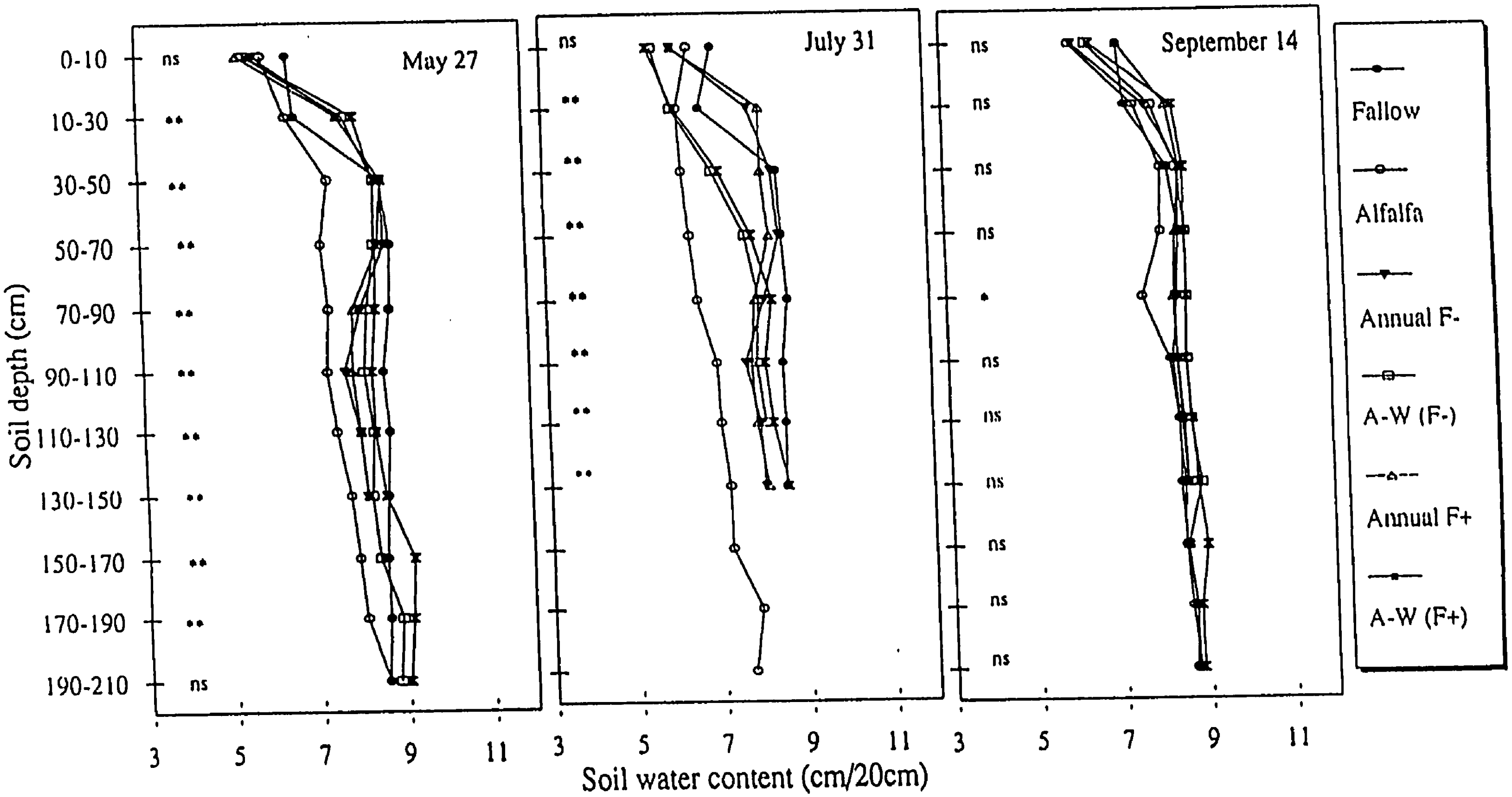


Figure 4.3. Volumetric soil water content at seeding, mid-season and at harvest in 1993. The significance of analysis of variance are summarized for each depth at each date (*, **, significant at 0.05, 0.01 probability levels respectively; ns, non significant). (A-W, wheat after alfalfa; F+, fertilizer N added;, no fertilizer N added).

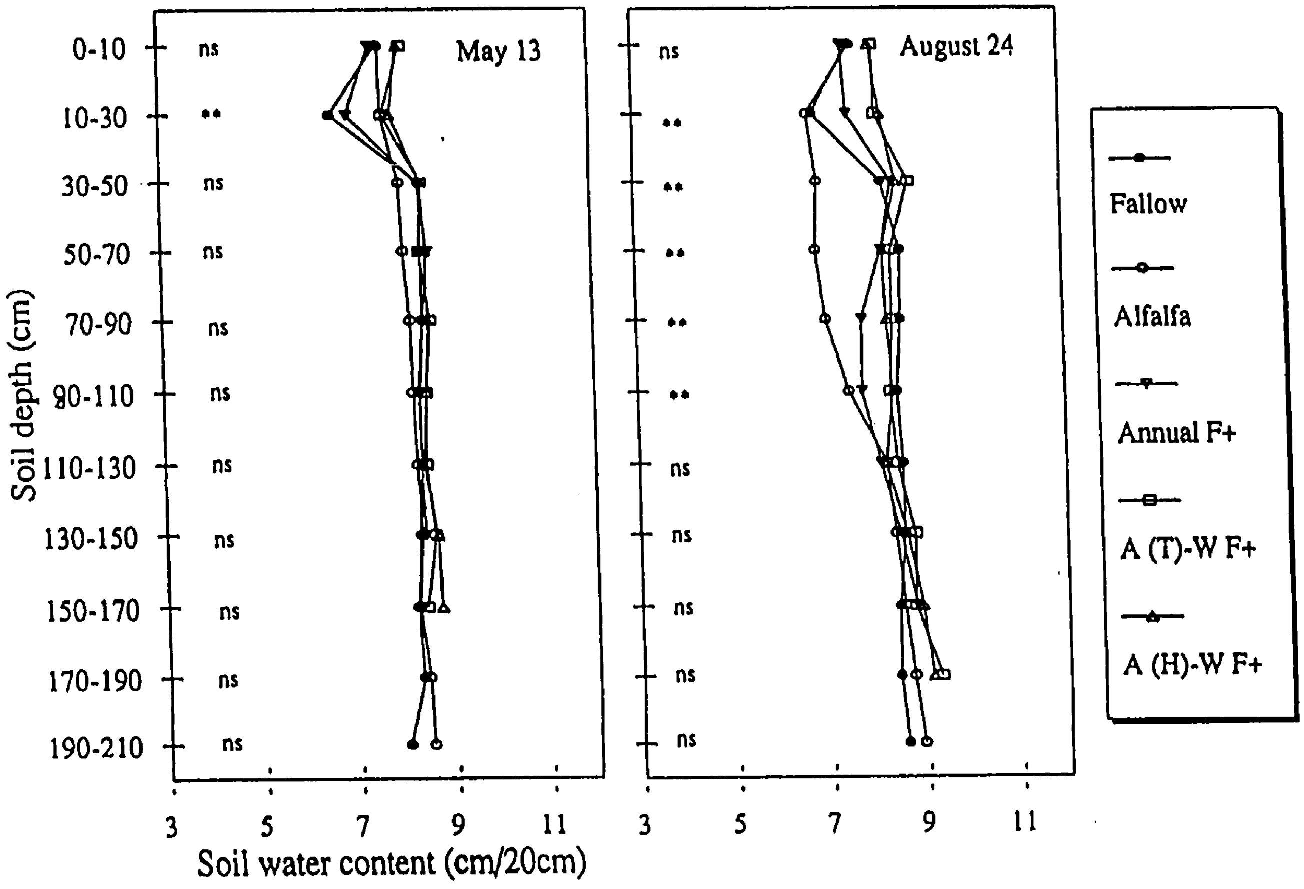


Figure 4.4. Volumetric soil water content at seeding, mid-season and at harvest in 1994. The significance of analysis of variance are summarized for each depth at each date (*, **, significant at 0.05, 0.01 probability levels respectively; ns, non significant). (A (T)-W, alfalfa terminated with tillage; A (H)-W, alfalfa terminated with herbicides).

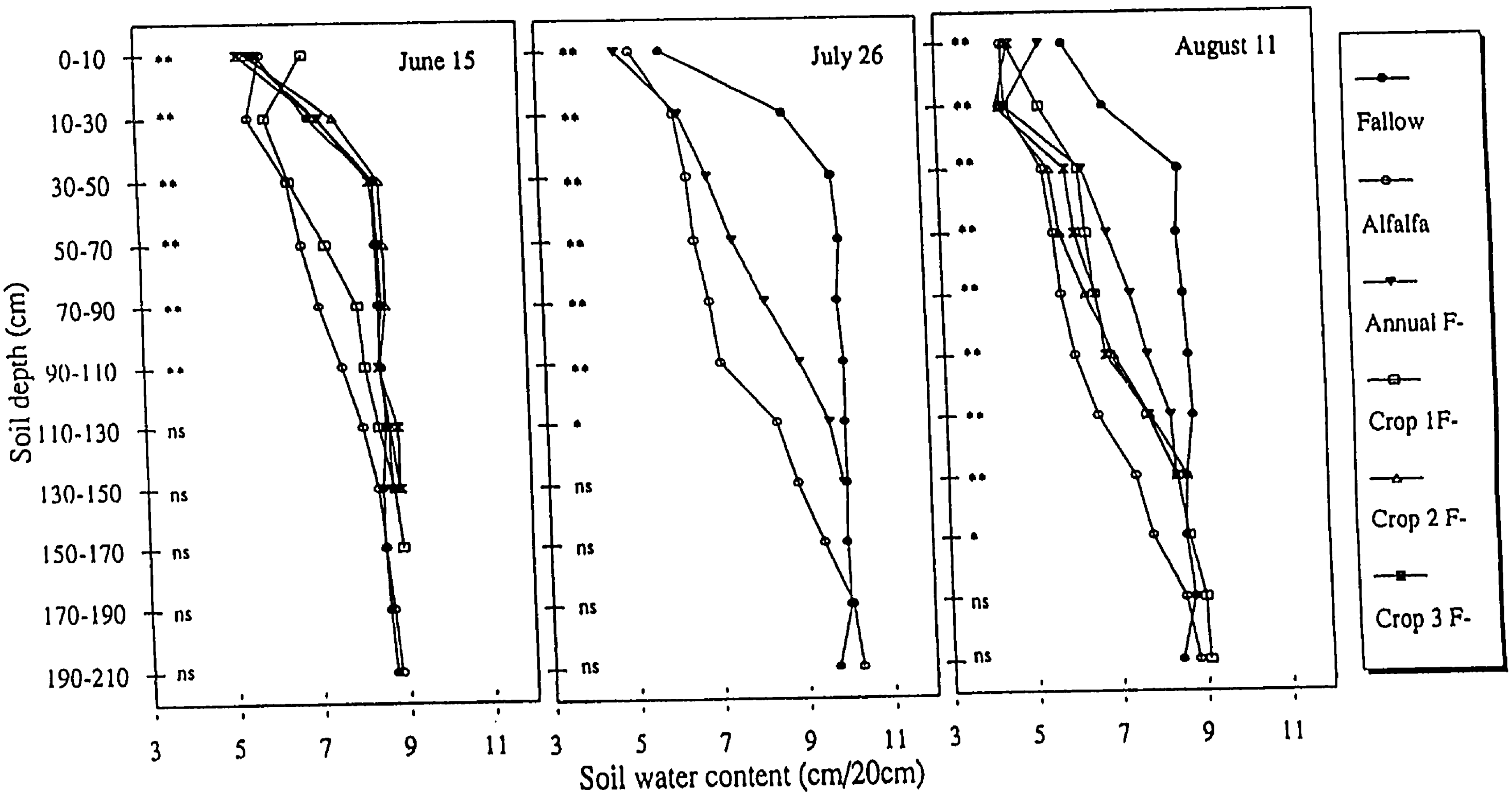


Figure 4.5a. Volumetric soil water content at seeding, mid-season and at harvest in 1995 for plots which were not fertilized with nitrogen. The significance of analysis of variance are summarized for each depth at each date (*, **, significant at 0.05, 0.01 probability levels respectively; ns, non significant). (Annual, continuous wheat; Crop 1, first wheat crop; Crop 2, second wheat crop; Crop 3, third wheat crop; F-, No fertilizer N added).

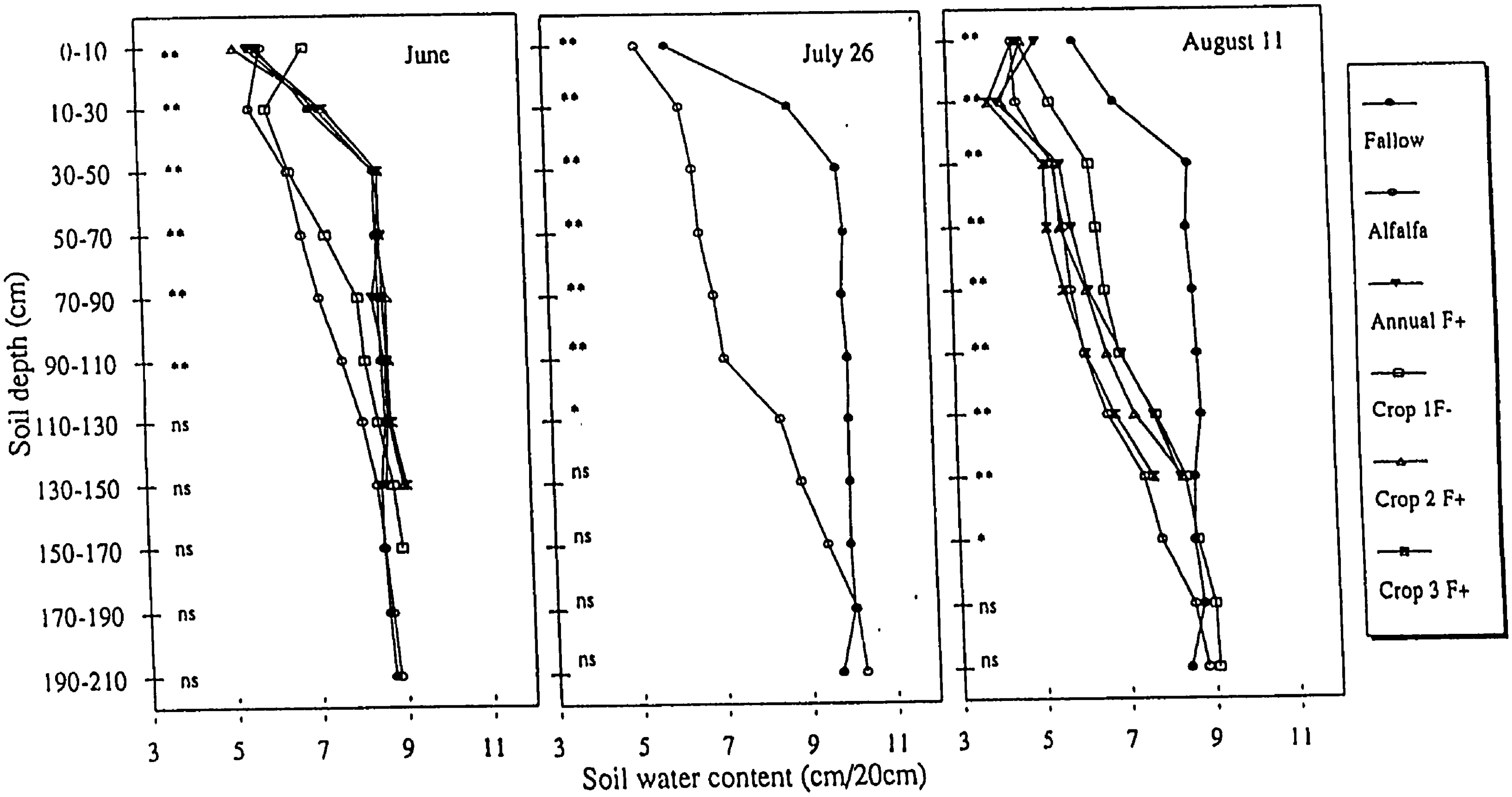


Figure 4.5b. Volumetric soil water content at seeding, mid-season and at harvest in 1995 for plots fertilized with nitrogen. The significance of analysis of variance are summarized for each depth at each date (*, **, significant at 0.05, 0.01 probability levels respectively; ns, non significant). (Annual, continuous wheat; Crop 1, first wheat crop; Crop 2, second wheat crop; Crop 3, third wheat crop; F+, fertilizer N added).

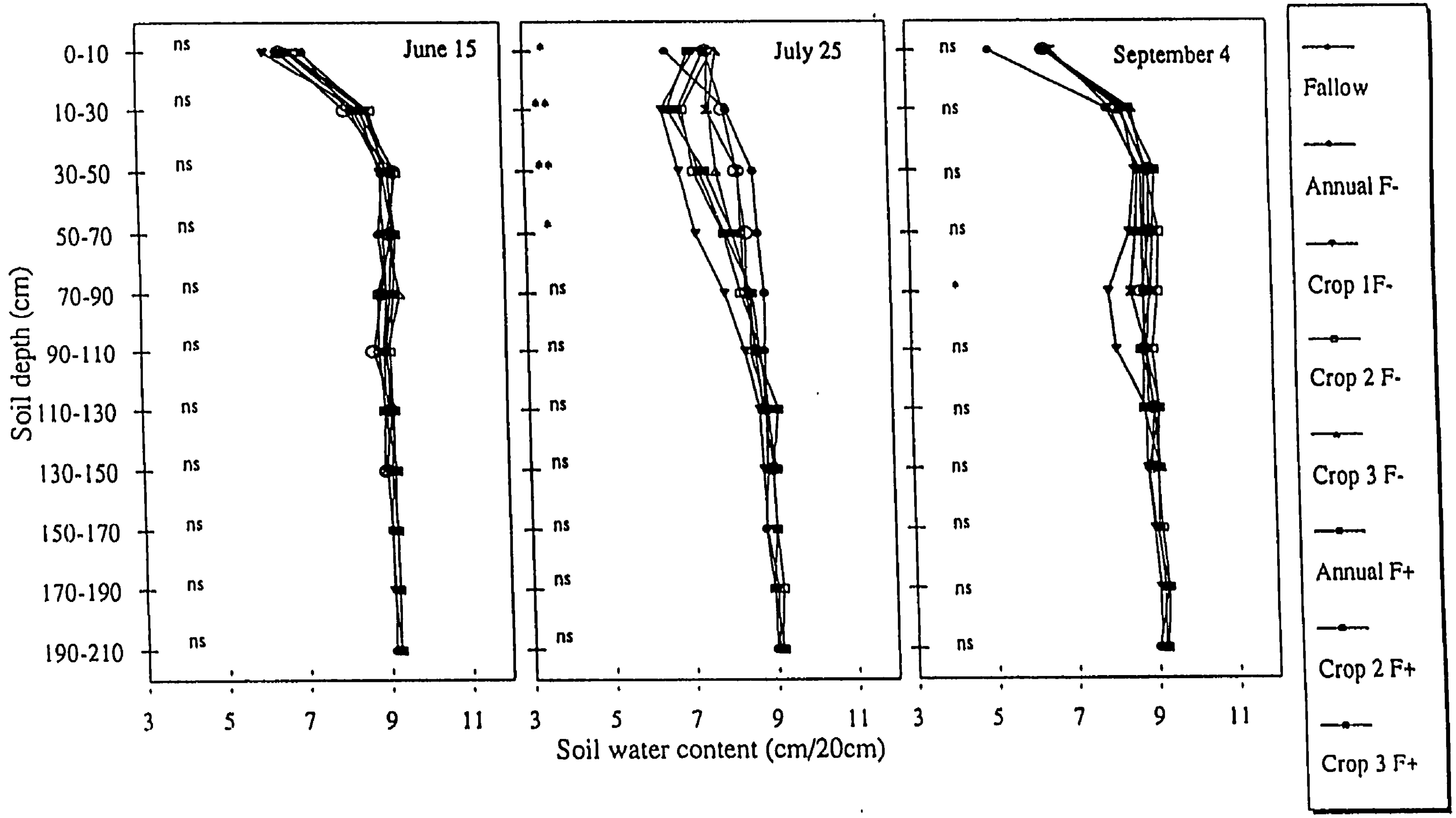


Figure 4.6. Volumetric soil water content at seeding, mid-season and at harvest in 1996. The significance of analysis of variance are summarized for each depth at each date (*, **, significant at 0.05, 0.01 probability levels respectively; ns, non significant). (Annual F-, unfertilized continuous wheat; Crop 1, first crop; Crop 2, second crop; Crop 3, third crop; F-, no fertilizer N added; F+, fertilizer N added).

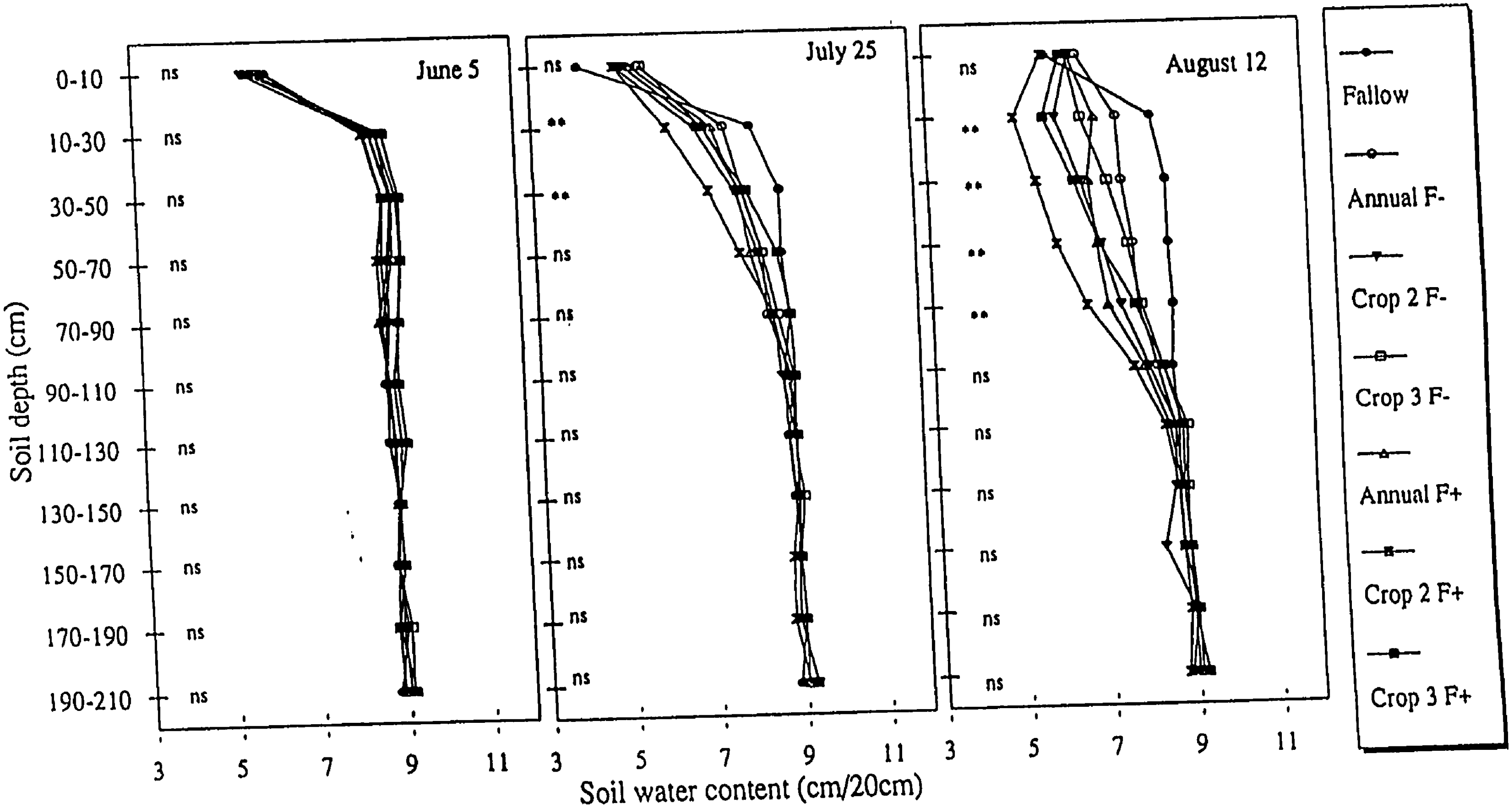


Figure 4.7. Volumetric soil water content at seeding, mid-season and at harvest in 1997. The significance of analysis of variance are summarized for each depth at each date (*, **, significant at 0.05, 0.01 probability levels respectively; ns, non significant). (Annual F-, unfertilized continuous wheat; Crop 1, first crop; Crop 2, second crop; Crop 3, third crop; F-, no fertilizer N added; F+, fertilizer N added).

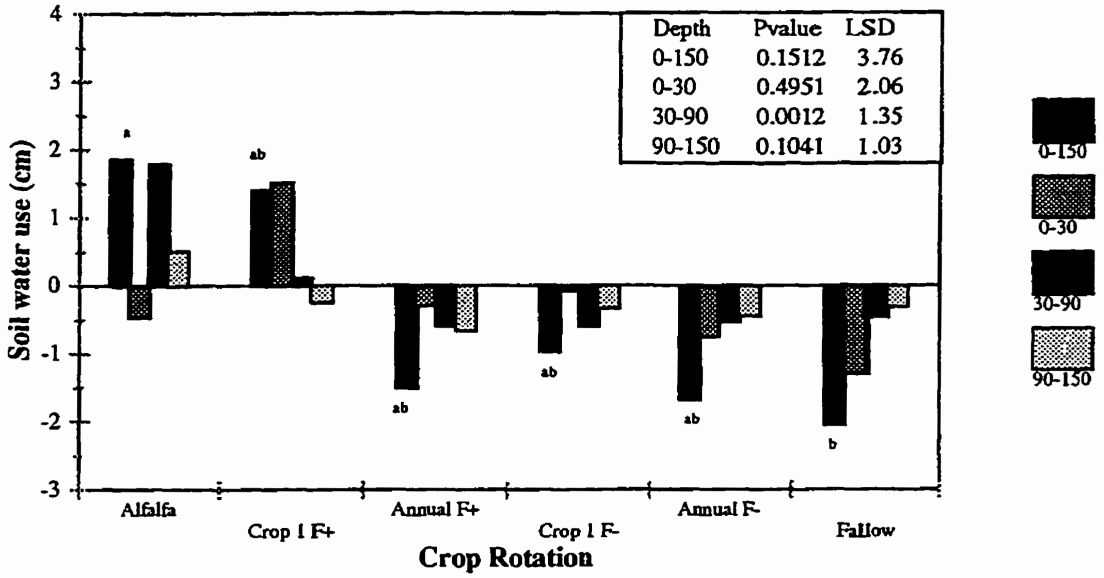


Figure 4.8a. Soil water extraction for period between May 20 and June 19, 1991. Analysis of variance for soil water use is summarized for differences between rotations (including fallow). The LSD test (P<0.05) is summarized for the 0 to 150 soil depth only.

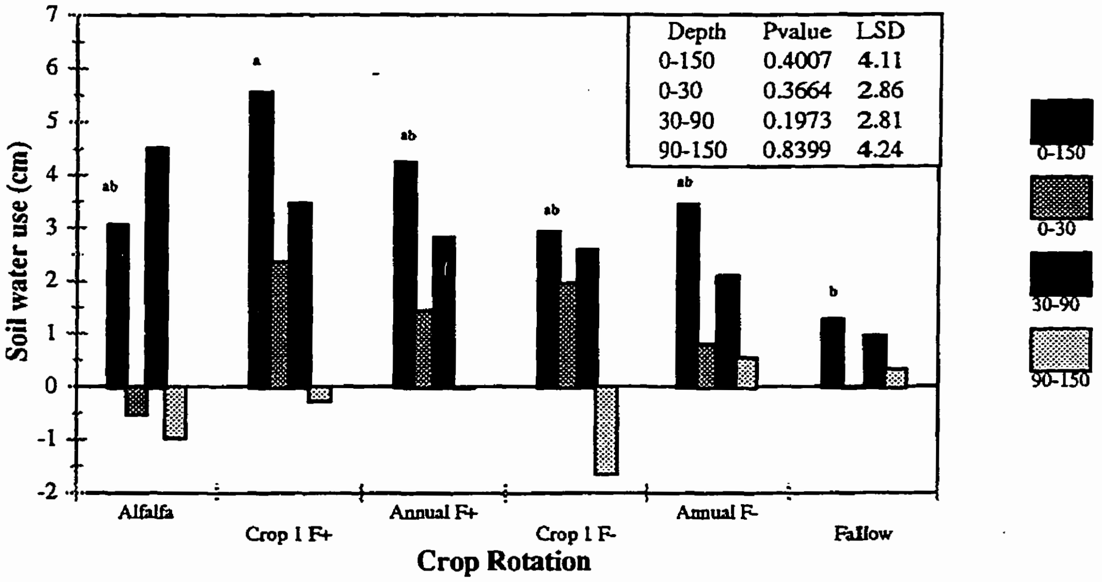
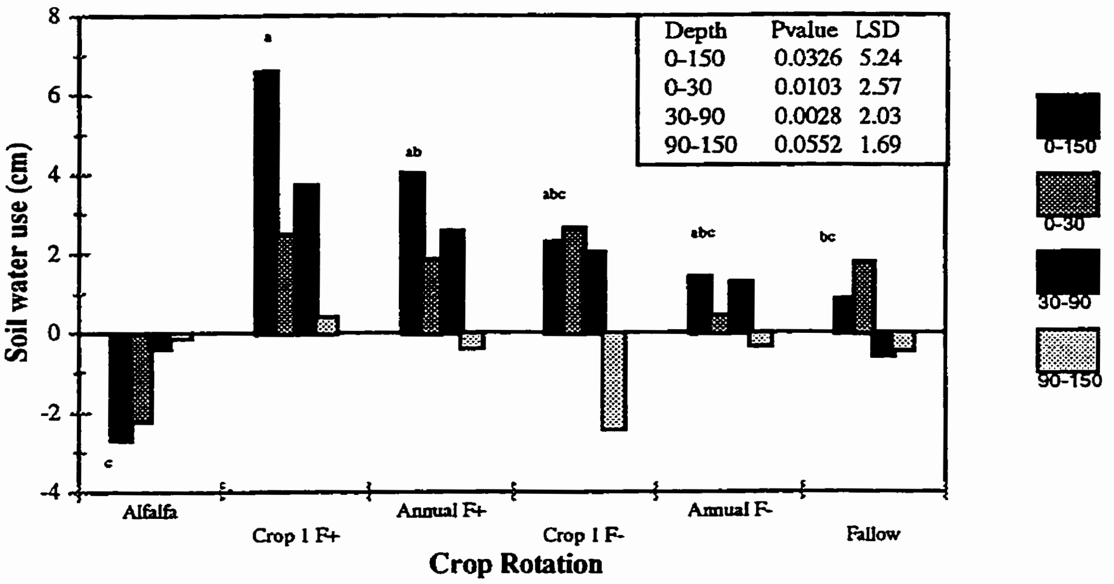
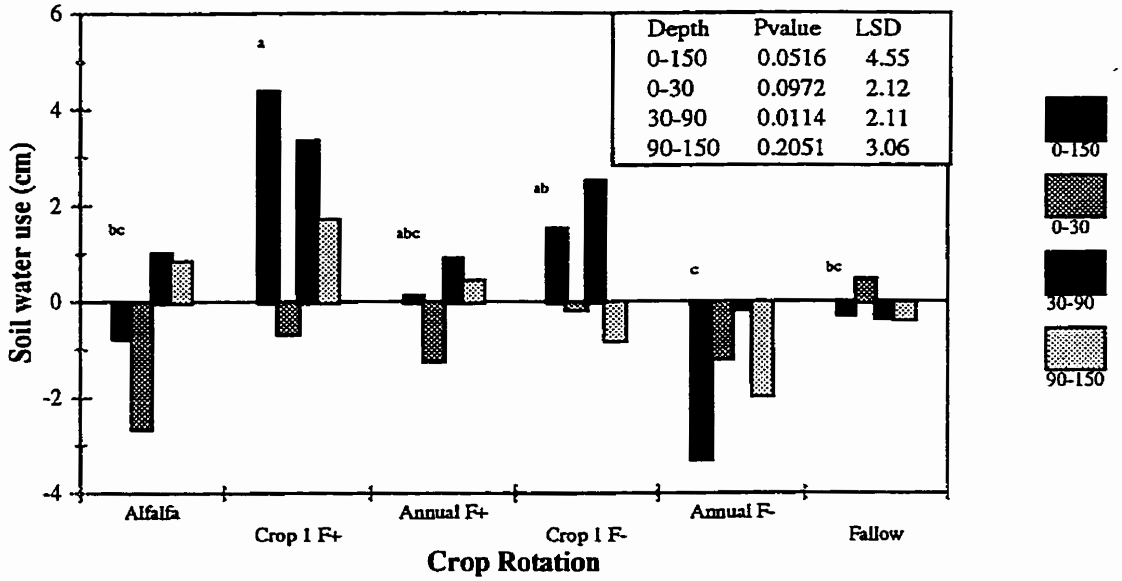


Figure 4.8b. Soil water extraction for period between May 20 and August 8, 1991. Analysis of variance for soil water use is summarized for differences between rotations (including fallow). The LSD test (P<0.05) is summarized for the 0 to 150 soil depth only.



Depth	Pvalue	LSD
0-150	0.0326	5.24
0-30	0.0103	2.57
30-90	0.0028	2.03
90-150	0.0552	1.69

Figure 4.9a. Soil water extraction for period between May 27 and July 31, 1992. Analysis of variance for soil water use is summarized for differences between rotations (including fallow). The LSD test (P<0.05) is summarized for the 0 to 150 soil depth only.



Depth	Pvalue	LSD
0-150	0.0516	4.55
0-30	0.0972	2.12
30-90	0.0114	2.11
90-150	0.2051	3.06

Figure 4.9b. Soil water extraction for period between May 27 and October 6, 1992. Analysis of variance for soil water use is summarized for differences between rotations (including fallow). The LSD test (P<0.05) is summarized for the 0 to 150 soil depth only.

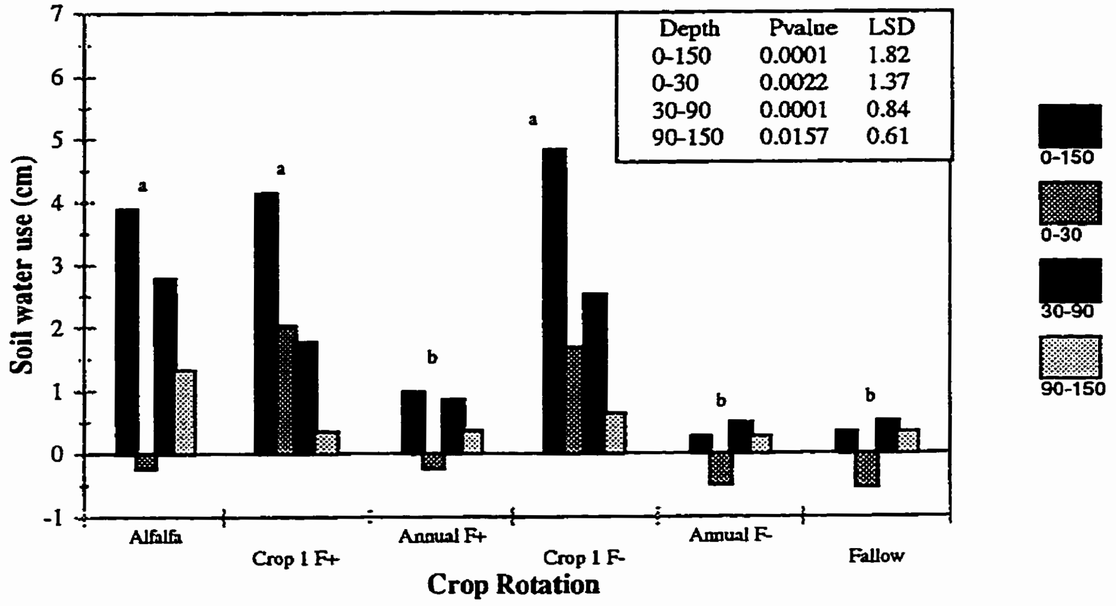


Figure 4.10a. Soil water extraction for period between May 27 and July 9, 1993. Analysis of variance for soil water use is summarized for differences between rotations (including fallow). The LSD test (P<0.05) is summarized for the 0 to 150 soil depth only.

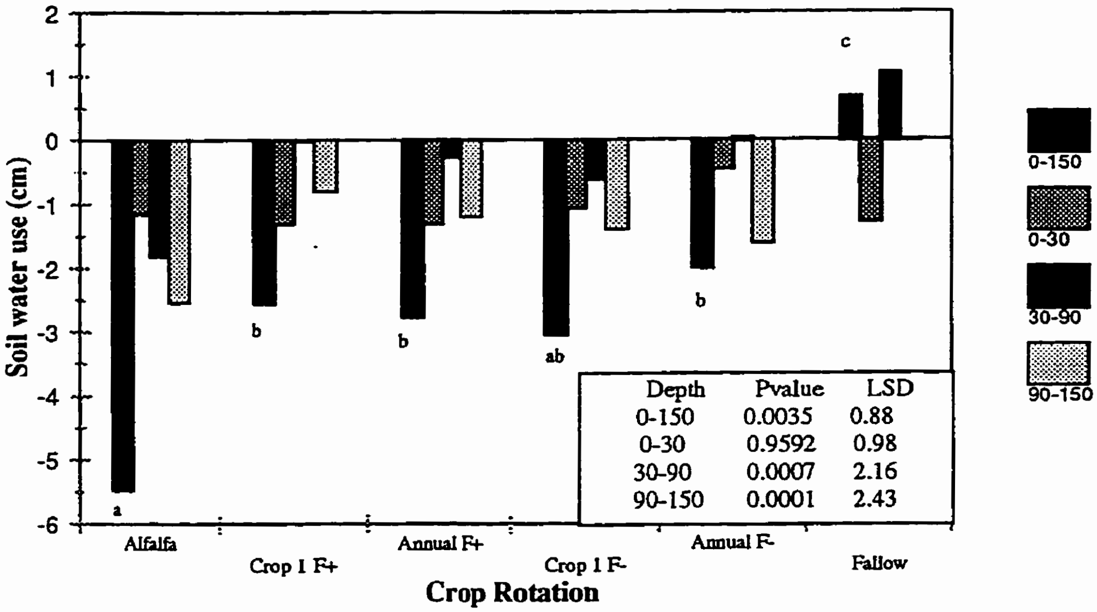


Figure 4.10b. Soil water extraction for period between May 27 and September 14, 1993. Analysis of variance for soil water use is summarized for differences between rotations (including fallow). The LSD test (P<0.05) is summarized for the 0 to 150 soil depth only.

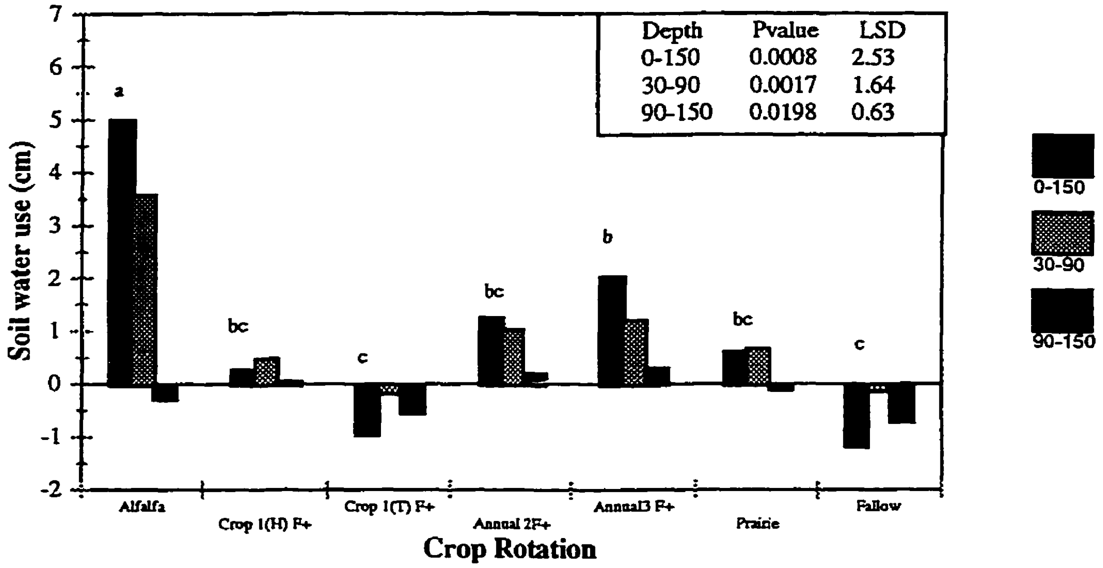


Figure 4.11. Soil water extraction for period between May 13 and August 24, 1994. Analysis of variance for soil water use is summarized for differences between rotations (including fallow). The LSD test ($P<0.05$) is summarized for the 0 to 150 soil depth only.

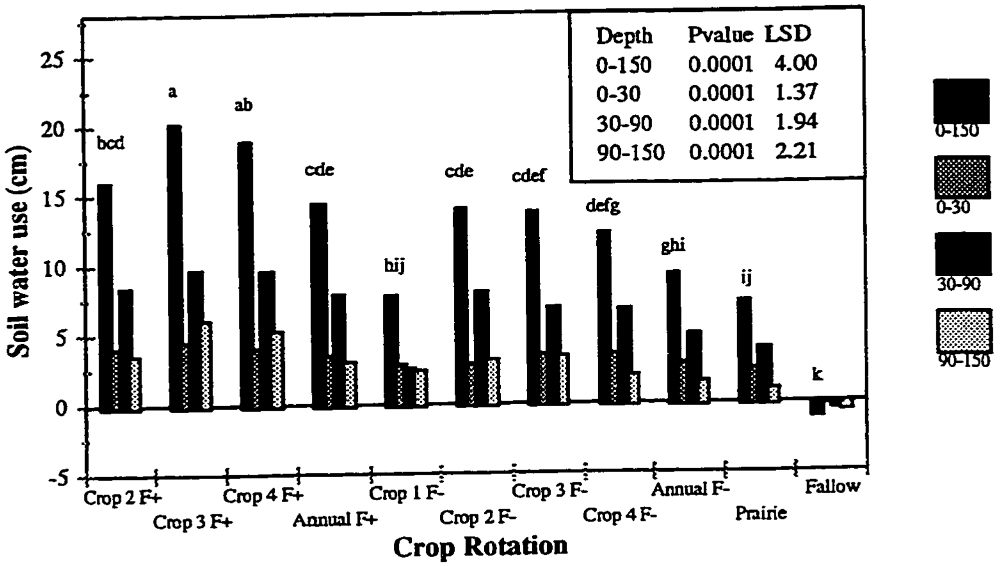


Figure 4.12. Soil water extraction for period between June 15 and August 14, 1995. Analysis of variance for soil water use is summarized for differences between rotations (including fallow). The LSD test ($P<0.05$) is summarized for the 0 to 150 soil depth only.

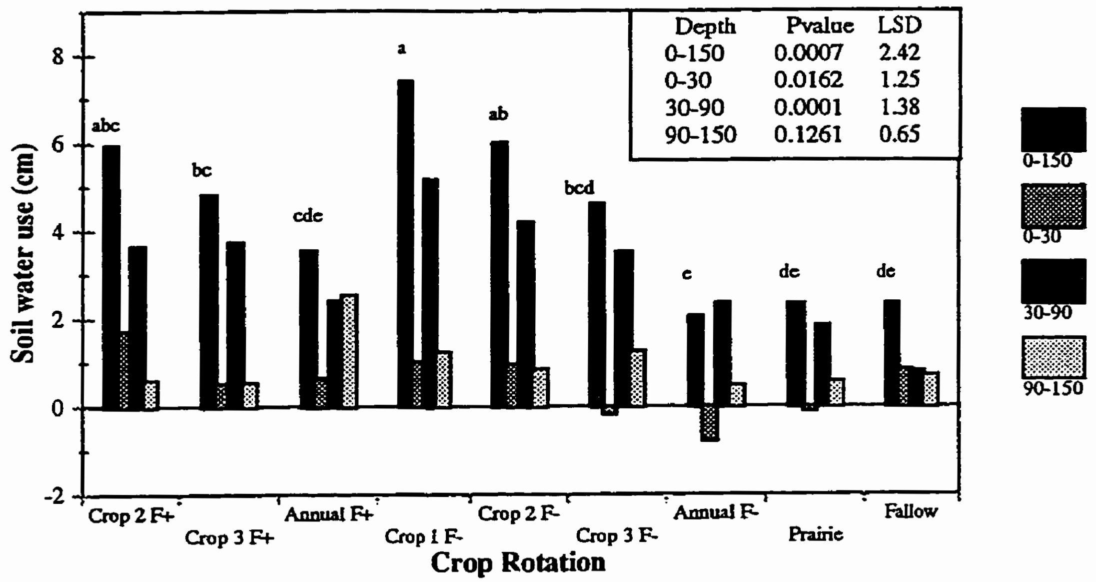


Figure 4.13a. Soil water extraction for period between June 15 and July 25, 1996. Analysis of variance for soil water use is summarized for differences between rotations (including fallow). The LSD test ($P<0.05$) is summarized for the 0 to 150 soil depth only.

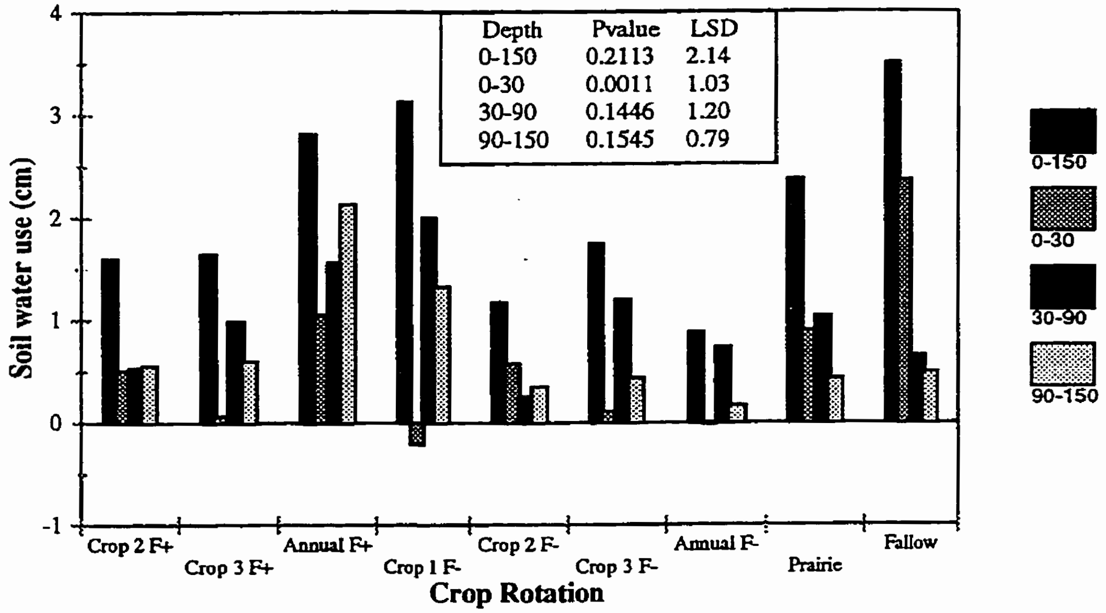
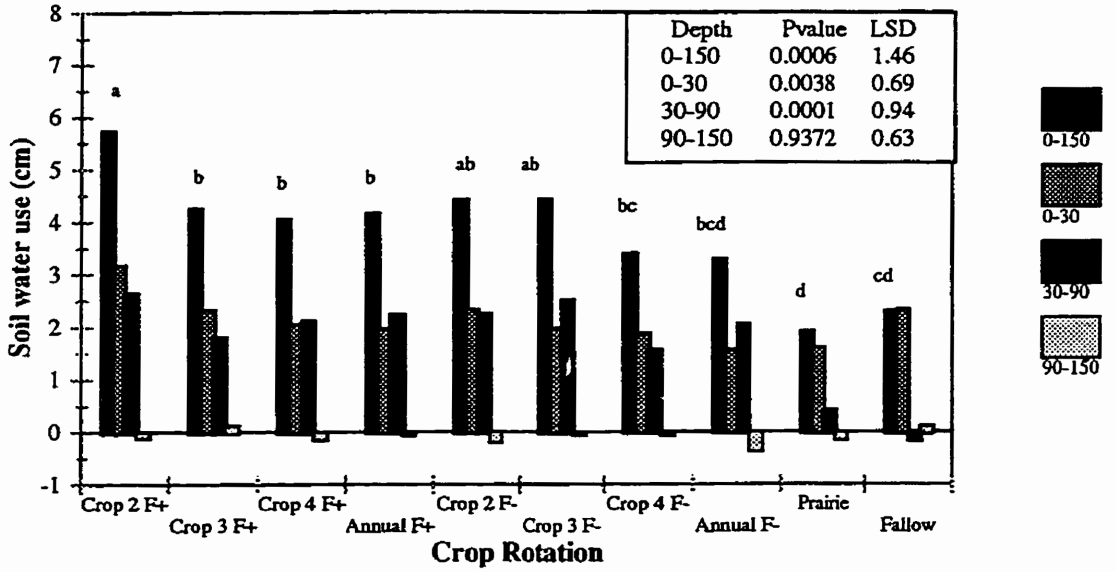
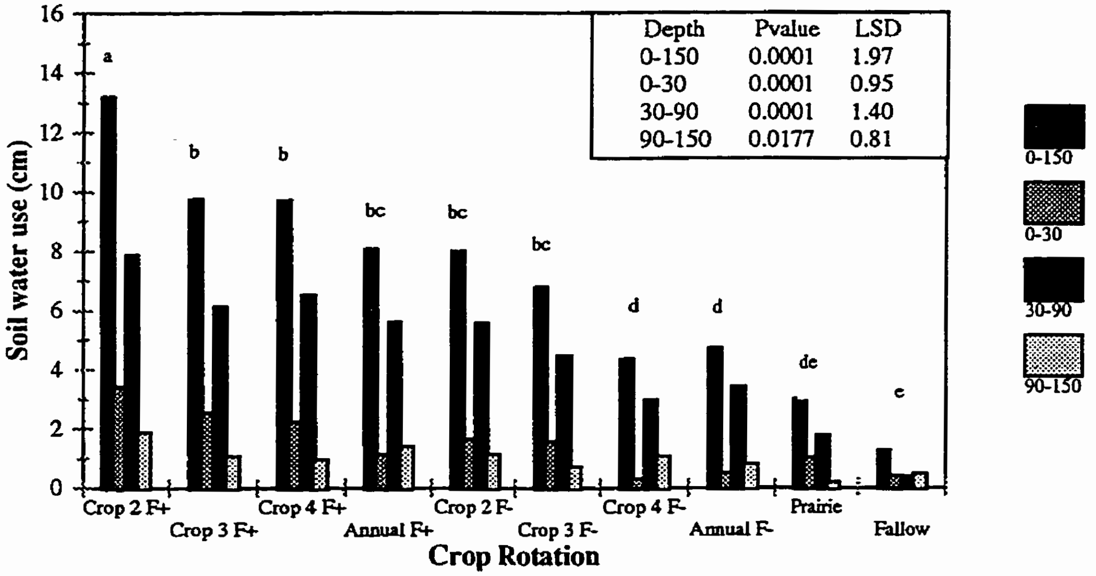


Figure 4.13b. Soil water extraction for period between June 15 and September 4, 1996. Analysis of variance for soil water use is summarized for differences between rotations (including fallow). The LSD test ($P<0.05$) is summarized for the 0 to 150 soil depth only.



Depth	Pvalue	LSD
0-150	0.0006	1.46
0-30	0.0038	0.69
30-90	0.0001	0.94
90-150	0.9372	0.63

Figure 4.14a. Soil water extraction for period between June 5 and July 21, 1997. Analysis of variance for soil water use is summarized for differences between rotations (including fallow). The LSD test (P<0.05) is summarized for the 0 to 150 soil depth only.



Depth	Pvalue	LSD
0-150	0.0001	1.97
0-30	0.0001	0.95
30-90	0.0001	1.40
90-150	0.0177	0.81

Figure 4.14b. Soil water extraction for period between June 5 and August 12, 1997. Analysis of variance for soil water use is summarized for differences between rotations (including fallow). The LSD test (P<0.05) is summarized for the 0 to 150 soil depth only.

5.0 Summary and Conclusions

When no fertilizer N was added to the system, alfalfa stand lengths of 3 years or greater produced significantly higher wheat yield benefits than alfalfa stand lengths of 1 and 2 years. Alfalfa in rotation typically increased wheat yield by more than 1200 kg ha^{-1} and 600 kg ha^{-1} in the first and second wheat crop, respectively. Wheat yield and grain N benefits persisted for up to 5 years after alfalfa termination. Yield benefits in the first wheat crop after alfalfa were attributed mainly to N contributions from alfalfa while, after the first year, yield and grain N increases due to alfalfa were attributed more to non-nitrogen rotational benefits.

When fertilizer N was added, alfalfa stand lengths of 3 years or greater produced significantly higher wheat yield benefits than alfalfa stand lengths of 1 and 2 years. However, grain N uptake rotational benefits were unaffected by alfalfa stand length. Non-nitrogen rotation benefits persisted for up to 5 years after alfalfa termination, regardless of alfalfa stand length.

The combined analysis of rotation benefits after 3 and 4 year alfalfa stands indicated grain yield and N uptake increased in the first wheat crop as a result of nitrogen benefits. After the first wheat crop, changes in yield and N uptake due to alfalfa were attributed more to non-N rotational benefits. These benefits included increased rooting depth and soil water extraction from improved soil structure. Non-N rotational benefits increased grain yield by >200 kg ha^{-1} year^{-1} and grain N uptake by >10 kg ha^{-1} year^{-1} in the first 5 wheat crops after alfalfa the 3/4 alfalfa stand.

Including alfalfa in rotation provide significant cumulative benefits in a cropping system. For example, the cumulative benefit from including a 3 year alfalfa stand in rotation was 3800 kg ha^{-1} grain yield in unfertilized rotations and 1500 kg ha^{-1} grain yield in fertilized rotations in five wheat crops. Similarly, in five wheat crops after the 3 year stand, alfalfa in rotation increased grain N uptake by 99 kg ha^{-1} in unfertilized rotations and 63 kg ha^{-1} in rotations fertilized with nitrogen.

Producing wheat with high grain protein concentration (GPC) is becoming increasingly important in western Canada. In this study, including alfalfa in rotation increased grain protein concentration for the first 5 years after a 3 year alfalfa stand. However, this GPC increase was observed in the N fertilized treatments only. When no fertilizer N was added, nitrogen from alfalfa residue was adequate to increase grain yield but did not affect GPC. Changes in yield and GPC resulted in a 5 year cumulative economic benefit of \$702.71 ha^{-1} for the unfertilized rotation and \$350.09 ha^{-1} for the fertilized wheat crops after alfalfa.

Similar to previous studies in western Canada, this study showed that alfalfa extracted significantly higher amounts of water than spring wheat. Despite having years with high precipitation, alfalfa extracted water to a depth of 130 to 170 cm in this study. Including alfalfa in rotation clearly increases the total water use of the cropping system.

When no fertilizer N was added, alfalfa in rotation typically resulted in >40 cm deeper rooting in the first two wheat crops and >20 cm in the third wheat crop after alfalfa compared with annual crop rotations. Similarly, unfertilized wheat extracted 3.6 to 5.3 cm more water in alfalfa rotations compared to continuous wheat, and soil water extraction benefits were recorded for the first three wheat crops after alfalfa. Soil water extraction in unfertilized rotations was attributed to a combination of N and non-N benefits.

When fertilizer N was added to rotations, alfalfa in rotation caused deeper rooting depth for the first two wheat crops. Soil water benefits due to alfalfa in rotation were most evident in years with low seasonal precipitation (i.e. 1995, 1996 and early in 1997). Similarly, non-nitrogen rotational benefits increased soil water extraction by 1.3 to 5.8 cm in wheat in alfalfa containing rotations compared to wheat in annual rotations. Suggested non-nitrogen benefits which affected rooting depth and soil water extraction in this study include 'biological tillage', which produced deep root channels for wheat root growth, and reduction in root disease.

In unfertilized rotations, WUE was higher when alfalfa was included in the rotation but declined with increasing number of wheat crops after alfalfa termination. Higher WUE with similar or slightly higher ET resulted in a higher physiological efficiency for the first three wheat crops after alfalfa. Improved physiological efficiency of the system resulted higher yields, primarily from alfalfa nitrogen benefits.

When fertilizer N was added, alfalfa in rotation resulted in only a slight increase in WUE, largely as a result of higher yields and higher soil water extraction throughout the growing season. In these fertilized rotations, increased availability of water from previous alfalfa increased the recovery efficiency of the cropping system. Hence, an improved water holding capacity as well as access to water deeper within the profile contributed to an improved recovery efficiency of the cropping system.

When comparing agricultural cropping systems to re-established native prairie, agricultural systems generally resulted in deeper water extraction when the systems were managed for the highest level of productivity. Soil water extraction in the re-established native prairie was approximately equal to the unfertilized annual control but lower than the wheat after alfalfa (both unfertilized and fertilized with N), N fertilized wheat, and the established alfalfa systems.

5.1 Implications for producer management

The use of alfalfa as a rotation crop for cereals and oilseed crops in southern Manitoba is possible based on measured nitrogen and non-nitrogen rotation benefits. Nitrogen benefits from alfalfa reduce the need for inorganic fertilizer nitrogen addition in the first wheat crop after termination. 'Biological tillage' from the deep alfalfa roots provide an opportunity for increased internal drainage and soil water infiltration, which is particularly important for poorly drained heavy clay soils in the Red River Valley. In years with high precipitation, water infiltration and increased soil water extraction by the wheat crop may reduce stress in years where excessive precipitation occurs.

In this study, alfalfa stand lengths of 3 years or greater produced similar yield and grain N benefits as longer stands indicating that shorter term alfalfa stands are agronomically viable in southern Manitoba cropping systems. Large increases in yield due to alfalfa in unfertilized systems should increase the economic return to organic producers. Even producers who typically add N fertilizer could take advantage of the non-nitrogen benefits (and possibly N benefits) of alfalfa such as increased rooting depth, higher soil water holding capacity, increased soil water uptake and deeper root growth, particularly in years with above average precipitation. As well, including shorter term alfalfa stands result in higher grain protein concentrations and increase the likelihood of having wheat eligible for a protein premium payment. Since rotational benefits are generally not affected by alfalfa stand length when fertilizer N is added, shorter stand lengths of 2 to 4 years are feasible as a crop rotation alternative to increase yields, grain protein, and soil water extraction in the sub-humid regions of Manitoba.

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APPENDIX A

Table A3.1. Grain yield of wheat in annual rotations and in alfalfa containing rotations in each year. Analysis of variance for grain yield (kg ha^{-1}) is summarized for each year, 1991 to 1997.

		Year						
Rotation	Fertilizer	1991	1992	1993	1994	1995	1996	1997
Annual	+	2845	3677	2018	2073	2574	2832	3265
	-	2489	3558	888	911	1066	1362	1356
		Alfalfa stand length						
		1	2	3	4	5	6	
1st wheat crop after alfalfa	+	2960	4007	1976	2464	-	-	
	-	2858	4073	2338	2269	3160	2705	
				Alfalfa stand length				
				2	3	4	5	6
2nd wheat crop after alfalfa	+			1733	2576	2975	3216	3805
	-			1605	1528	2267	2078	3062
					Alfalfa stand length			
					2	3	4	5
3rd wheat crop after alfalfa	+				2170	3152	2952	3791
	-				1134	1694	1968	2325
						Alfalfa stand length		
						2	3	4
4th wheat crop after alfalfa	+					3239	3119	3381
	-					1665	1840	1746
							Alfalfa stand length	
							2	3
5th wheat crop after alfalfa	+						3239	3481
	-						1723	1982
								Alfalfa stand length
								2
6th wheat crop after alfalfa	+							3620
	-							1654
Rotation (Main)		0.3787	0.0943	0.0022	0.0001	0.0001	0.0001	0.0001
Fertilizer N (subplot)		0.1961	0.9601	0.0182	0.0001	0.0001	0.0001	0.0001
Rotation * Fert N		0.4496	0.8621	0.0008	0.0001	0.0000	0.0741	0.0204

Table A3.2. Summary of grain N uptake for annual and alfalfa containing rotations at the Winnipeg crop rotation study. Analysis of variance for grain N uptake (kgN ha^{-1}) summarized in each year, 1991 to 1997.

		Year						
Rotation	Fertilizer	1991	1992	1993	1994	1995	1996	1997
Annual	+	84.8	86.1	56.2	54.2	61.0	66.4	73.0
rotation	-	61.0	86.2	23.0	22.1	22.1	29.8	27.5
		Alfalfa stand length						
		1	2	3	4	5	6	
1st wheat crop	+	84.9	100.7	61.6	59.6	-	-	
after alfalfa	-	75.7	88.4	69.9	60.2	72.3	66.3	
				Alfalfa stand length				
				2	3	4	5	6
2nd wheat crop	+			65.6	71.9	75.5	80.6	92.1
after alfalfa	-			53.6	38.5	47.3	47.6	62.7
					Alfalfa stand length			
					2	3	4	5
3rd wheat crop	+				59.8	79.7	74.4	91.9
after alfalfa	-				27.0	36.0	44.8	47.6
						Alfalfa stand length		
						2	3	4
4th wheat crop	+					80.3	79.2	79.2
after alfalfa	-					33.3	39.6	36.1
							Alfalfa stand length	
							2	3
5th wheat crop	+						82.8	81.2
after alfalfa	-						36.6	39.3
								Alfalfa stand length
								2
6th wheat crop	+							78.1
after alfalfa	-							33.6
Rotation (Main factor)		0.4293	0.0615	0.0182	0.0011	0.0001	0.0001	0.0002
Fertilizer N (subplot)		0.0303	0.5738	0.0011	0.0001	0.0001	0.0001	0.0001
Rotation * Fertilizer N		0.2616	0.5677	0.0004	0.0010	0.0001	0.1324	0.5407

Table A3.3. Summary of the dry matter yield of established alfalfa at the Winnipeg crop rotation from 1990 to 1995.

Year	Dry matter yield (kg/ha) 1st cut	2nd cut	3rd cut	Total (3 cuts)[y]	Total (2 cuts)[x]
1990	1897[z]	-	-	-	-
1991	8028	3948	3276	15251	11976
1992	6419	4365	2994	13778	10784
1993	6507	3060	2197	11764	9567
1994	4786	4172	2802	11760	8958
1995	4972	3458	-	-	8430

[z] alfalfa was harvested only once in the establishment year (1990).

[y] Sum of the three harvests within each year.

[x] Sum of the first two dry matter harvests of alfalfa; more typical of the amount of dry matter produced prior to alfalfa termination.

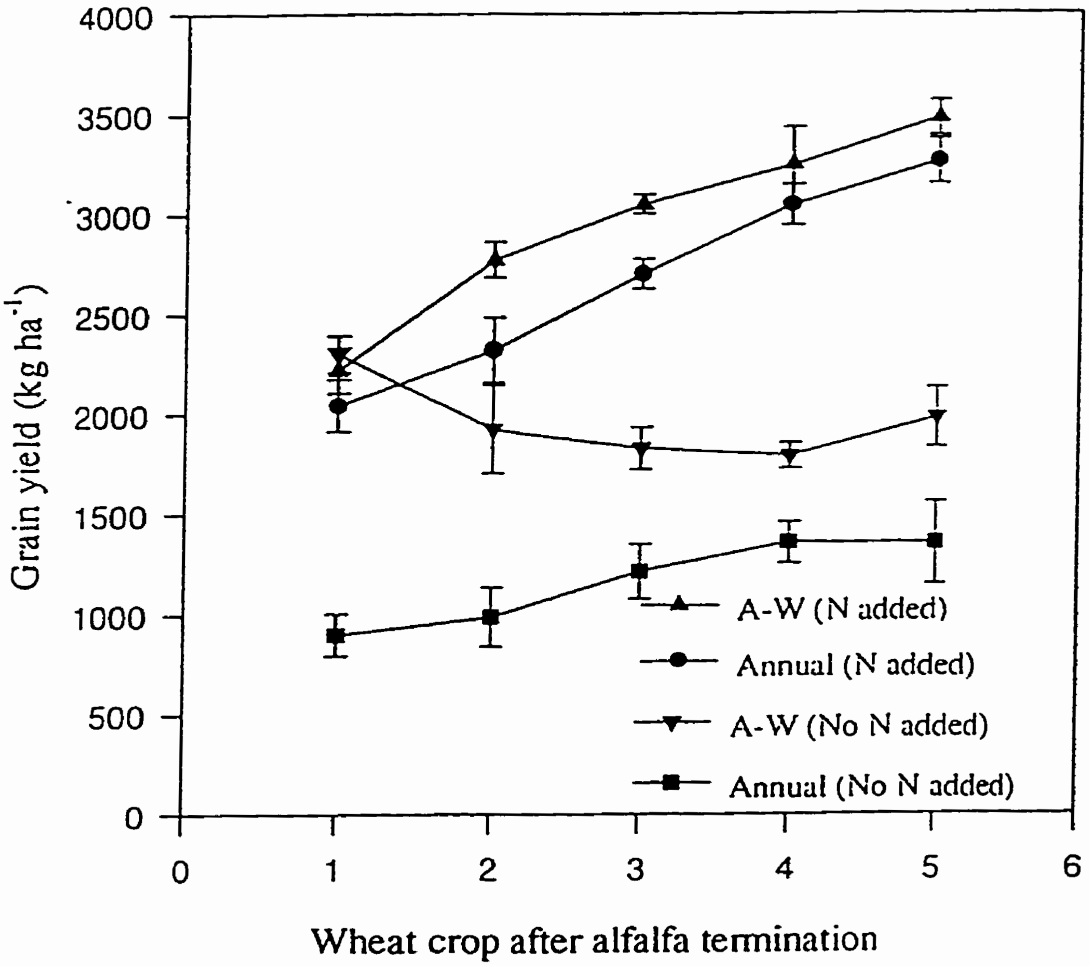

Figure A3.1. Yield of wheat in annual and alfalfa containing rotations with and without fertilizer nitrogen added. Yield data is the mean of grain yield after termination of 3 and 4 year alfalfa stands.

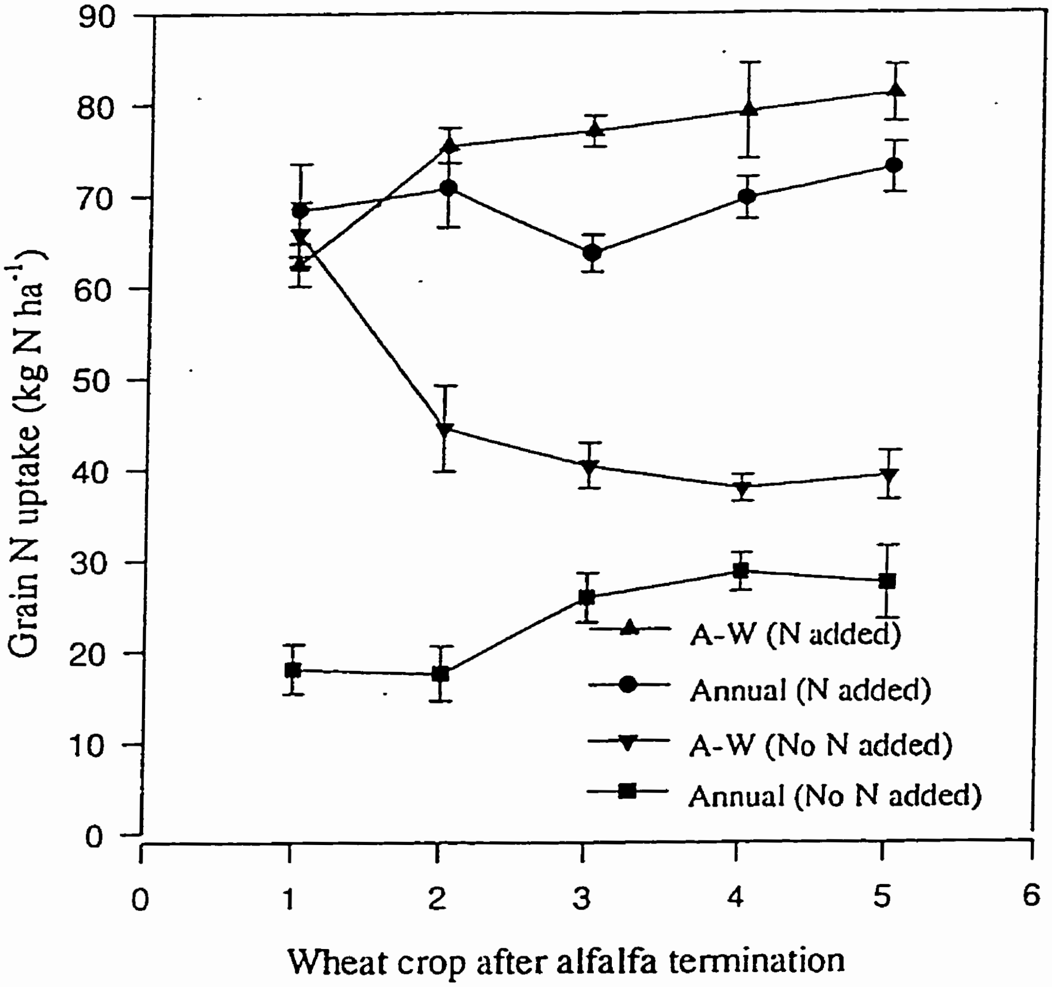

Figure A3.2. Mean grain N uptakes for each rotation with and without fertilizer nitrogen added for the first five consecutive crops of wheat. The fifth wheat crop after alfalfa contains only data after the 3 year alfalfa stand.

Table A4.1. Orthogonal contrasts for differences in soil water content at 20 cm increments to a depth of 210 cm between each rotation and a fallow treatment at each corresponding depth in for 3 dates during the 1991 growing season.

	Contrasts	Soil depth (cm)									
Date	Fallow vs	10-30	30-50	50-70	70-90	90-110	110-130	130-150	150-170	170-190	190-210
							P>F				
May 20	Alfalfa	0.2946	0.0002	0.0315	0.5572	0.0226	0.0180	0.1002	0.5032	0.7320	0.3470
	A-W F+	0.7528	0.7916	0.5154	0.9316	0.6296	0.5497	-	-	-	-
	A-W F-	0.9783	0.6315	0.6902	0.3191	0.9130	0.9042	-	-	-	-
	Annual F+	0.6070	0.4739	0.9022	0.1332	0.2480	0.3857	-	-	-	-
	Annual F-	0.6507	0.5674	0.2241	0.3761	0.9570	0.5410	-	-	-	-
June 19	Alfalfa	0.1407	0.0015	0.0018	0.0001	0.0043	0.0003	0.1492	0.4902	0.3712	0.7563
	A-W F+	0.5952	0.3718	0.9331	0.8110	0.7831	0.5017	-	-	-	-
	A-W F-	0.5642	0.3581	0.8067	0.8232	0.3349	0.8449	-	-	-	-
	Annual F+	0.7750	0.2402	0.7795	0.9505	0.8622	0.6000	-	-	-	-
	Annual F-	0.8849	0.8161	0.8612	0.1536	0.8684	-	-	-	-	-
Aug 8	Alfalfa	0.7628	0.0012	0.0014	0.0064	0.0343	0.6233	0.9884	0.5990	0.5663	0.7759
	A-W F+	0.0155	0.0009	0.0022	0.0019	0.1480	0.0765	0.1609	-	-	-
	A-W F-	0.0038	0.0245	0.0986	0.0107	0.4641	0.8199	0.4325	-	-	-
	Annual F+	0.0321	0.0073	0.0135	0.0107	0.2931	0.7900	0.7445	-	-	-
	Annual F-	0.4509	0.0457	0.7362	0.2925	0.5409	0.9495	0.6409	-	-	-

Rotations measured were alfalfa, 2 year stand; wheat (W) after alfalfa(A); annual rotation; F+, fertilizer N added to soil test recommendations; F-, no fertilizer N added.

Table A4.2. Orthogonal contrasts for differences in soil water content at 20 cm increments to a depth of 210 cm between each rotation and a fallow treatment at each corresponding depth in for 3 dates during the 1992 growing season.

	Contrasts	Soil depth (cm)									
Date	Fallow vs	10-30	30-50	50-70	70-90	90-110	110-130	130-150	150-170	170-190	190-210
							P>F				
May 27	Alfalfa	0.0012	0.0001	0.0001	0.0241	0.0180	0.0411	-	-	-	-
	AA-W F+	0.7984	0.1644	0.6341	0.8585	0.6130	0.5950	-	-	-	-
	AA-W F-	0.8748	0.4308	0.0210	0.0170	0.0008	0.0035	-	-	-	-
	Annual F+	0.4702	0.9471	0.6085	0.6944	0.6408	0.6549	-	-	-	-
	Annual F-	0.5014	0.2351	0.9114	0.7950	0.8739	0.6625	-	-	-	-
July 9	Alfalfa	0.0078	0.0229	0.0147	0.0003	0.0002	0.0589	0.0471	0.3379	0.8856	0.1690
	AA-W F+	0.3823	0.0001	0.0007	0.0030	0.0558	0.4402	0.4879	0.1891	0.5489	0.2586
	AA-W F-	0.5401	0.0001	0.0021	0.0050	0.1841	0.9625	0.6388	0.4521	0.3527	0.5409
	Annual F+	0.3462	0.0003	0.0031	0.0835	0.4740	0.8350	0.8330	-	-	-
	Annual F-	0.0241	0.0314	0.0981	0.1800	0.6421	0.8719	0.9824	-	-	-
Oct 6	Alfalfa	0.0010	0.0038	0.0010	0.0001	0.0004	0.0005	0.0035	0.0343	0.0735	0.3269
	AA-W F+	0.0001	0.0036	0.0054	0.0001	0.0004	0.0044	0.2177	0.4528	0.8121	0.1295
	AA-W F-	0.0003	0.0080	0.0010	0.0001	0.0010	0.0148	0.2204	0.2522	0.1988	0.5418
	Annual F+	0.0001	0.8049	0.1013	0.0342	0.0992	0.1021	0.2150	-	-	-
	Annual F-	0.0001	0.4092	0.7443	0.4138	0.4220	0.1345	0.1843	-	-	-

Rotations measured were alfalfa, 3 year stand; wheat (W) after alfalfa(A); annual rotation; F+, fertilizer N added to soil test recommendations; F-, no fertilizer N added.

Table A4.3. Orthogonal contrasts for differences in soil water content at 20 cm increments to a depth of 210 cm between each rotation and a fallow treatment at each corresponding depth in for 3 dates during the 1993 growing season.

	Contrasts	Soil depth (cm)									
Date	Fallow vs	10-30	30-50	50-70	70-90	90-110	110-130	130-150	150-170	170-190	190-210
							P>F				
May 27	Alfalfa	0.6020	0.8038	0.0001	0.0001	0.0824	0.0001	0.0005	0.0431	0.2112	0.2365
	AAA-W F+	0.0021	0.1123	0.1429	0.1448	0.0988	0.1734	0.7844	0.4792	0.7948	0.4309
	AAA-W F-	0.0085	0.9755	0.0772	0.0254	0.0955	0.1298	0.0806	0.8038	0.3848	0.0831
	Annual F+	0.0177	0.9963	0.1690	0.0013	0.0912	0.0109	0.0368	-	-	-
	Annual F-	0.0177	0.9971	0.4773	0.0073	0.0884	0.0105	0.0254	-	-	-
July 31	Alfalfa	0.9478	0.0001	0.0001	0.0001	0.0001	0.0001	0.2441	0.0003	0.0582	0.7822
	AAA-W F+	0.9408	0.0001	0.0002	0.0801	0.0769	0.1981	0.9625	0.3565	0.9905	0.8575
	AAA-W F-	0.9345	0.0001	0.0001	0.0051	0.0148	0.0388	0.0438	0.0852	0.8140	0.0500
	Annual F+	0.102	0.0583	0.0509	0.0018	0.0042	0.0062	0.6956	-	-	-
	Annual F-	0.8871	0.4909	0.6005	0.0151	0.0011	0.0135	0.6519	-	-	-
Sept 14	Alfalfa	0.6459	0.2628	0.0711	0.0660	0.7690	0.8291	0.6348	0.8713	0.6160	0.5514
	AAA-W F+	0.0265	0.0184	0.4960	0.5799	0.0769	0.1159	0.0609	0.1296	0.8400	0.9383
	AAA-W F-	0.1915	0.1459	0.4890	0.5799	0.0600	0.1638	0.0258	0.9679	0.8929	0.4388
	Annual F+	0.1615	0.0628	0.8015	0.7463	0.5112	0.8068	0.4457	-	-	-
	Annual F-	0.3288	0.0763	0.9818	0.9269	0.4662	0.5669	0.3722	-	-	-

Rotations measured were alfalfa, 4 year stand; wheat (W) after alfalfa(A); annual rotation; F+, fertilizer N added to soil test recommendations; F-, no fertilizer N added.

Table A4.4. Orthogonal contrasts for differences in soil water content at 20 cm increments to a depth of 210 cm between each rotation and a fallow treatment at each corresponding depth in for 2 dates during the 1994 growing season.

	Contrasts	Soil depth (cm)									
Date	Fallow vs	10-30	30-50	50-70	70-90	90-110	110-130	130-150	150-170	170-190	190-210
						P>F					
May 13	Crop 1(H) F+	0.0011	0.7789	0.6896	0.4651	0.3568	0.8519	0.1097	-	-	-
	Crop 1(T) F+	0.0035	0.7317	0.8364	0.3285	0.3640	0.6137	0.1623	-	-	-
	Alfalfa	0.0042	0.0199	0.0700	0.1462	0.5390	0.5953	0.8482	-	-	-
	Annual 2+	0.2844	0.8271	0.4732	0.9281	0.8406	1.0000	0.6136	-	-	-
	Annual 3+	0.0292	0.6079	0.8667	0.3969	0.3154	0.2403	0.5676	-	-	-
	Prairie	0.0013	0.7287	0.9563	0.8672	0.7281	0.8793	0.1413	-	-	-
Aug 24	Crop 1(H) F+	0.0001	0.0960	0.1298	0.4126	0.6361	0.1139	0.8254	0.0064	-	-
	Crop 1(T) F+	0.0001	0.0054	0.4167	0.6258	0.4797	0.6178	0.2622	0.0447	-	-
	Alfalfa	0.6650	0.0001	0.0001	0.0003	0.0002	0.1344	0.3306	0.5067	-	-
	Annual 2+	0.0067	0.2563	0.1022	0.0296	0.0034	0.0472	0.6139	0.0312	-	-
	Annual 3+	0.0028	0.1995	0.0846	0.0153	0.0021	0.1025	0.8153	0.0143	-	-
	Prairie	0.0006	0.5739	0.3474	0.5518	0.5864	0.3406	0.7960	0.0734	-	-

Rotations measured were alfalfa, 5 year stand; wheat (W) after alfalfa(A); annual rotation; F+, fertilizer N added to soil test recommendations; re-established prairie.

Table A4.5a. Orthogonal contrasts for differences in soil water content at 20 cm increments to a depth of 210 cm between each rotation and a fallow treatment at each corresponding depth for the spring sampling date in the 1995 growing season.

	Contrasts	Soil depth (cm)									
Date	Fallow vs	10-30	30-50	50-70	70-90	90-110	110-130	130-150	150-170	170-190	190-210
						P>F					
June 14	Alfalfa	0.0001	0.0001	0.0001	0.0001	0.0001	0.0107	0.5944	0.9473	0.6924	0.6211
	Prairie	0.5247	0.0001	0.9708	0.9725	0.5220	0.9610	0.1636	0.5001	0.2492	0.3674
	A(H)-W F-	0.0045	0.0001	0.0001	0.0018	0.0364	0.4319	0.2066	0.0910	0.0247	0.0369
	A(T)-WW F-	0.0879	0.2660	0.1739	0.2058	0.8700	0.8100	0.5998	-	-	-
	A(T)-WW F+	0.3143	0.3704	0.8693	0.1667	0.3521	0.6349	0.0187	-	-	-
	A(H)-WW F-	0.0493	0.0731	0.0254	0.1171	0.4695	0.5243	0.1138	-	-	-
	A(H)-WW F+	0.1192	0.6606	0.3912	0.8633	0.9444	0.9501	0.0550	-	-	-
	A(T)-WWW F-	0.5342	0.5106	0.5839	0.5588	0.6760	0.1575	0.0580	-	-	-
	A(T)-WWW F+	0.3579	0.3704	0.4882	0.4706	0.4526	0.4541	0.0077	-	-	-
	Annual F+	0.6035	0.8574	0.3531	0.3815	0.6558	0.7546	0.6455	-	-	-
	Annual F-	0.4829	0.7646	0.6744	0.8904	0.7486	0.7357	0.2988	-	-	-

Rotations measured were alfalfa, 6 year stand; wheat (W) after alfalfa(A); A(H), alfalfa terminated with herbicide; A(T), alfalfa terminated with tillage annual rotation; F+, fertilizer N added to soil test recommendations; F-, no fertilizer N added.

Table A4.5b. Orthogonal contrasts for differences in soil water content at 20 cm increments to a depth of 210 cm between each rotation and a fallow treatment at each corresponding depth for the midseason and harvest sampling date during the 1995 growing season.

	Contrasts	Soil depth (cm)									
Date	Fallow vs	10-30	30-50	50-70	70-90	90-110	110-130	130-150	150-170	170-190	190-210
						P>F					
July 26	Alfalfa	0.0001	0.0001	0.0001	0.0001	0.0001	0.0042	0.0132	0.1374	0.8519	0.0838
	Prairie	0.0001	0.0003	0.0001	0.0567	0.0886	0.7488	0.7711	0.6380	0.2670	0.0848
	Annual F-	0.0001	0.0001	0.0001	0.0002	0.0005	0.4447	0.8309	-	-	-
Aug 11	Alfalfa	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0203	0.3312	0.1824
	Prairie	0.0002	0.0001	0.0001	0.0095	0.2693	0.0234	0.8634	0.6430	0.5758	0.1210
	A(H)-W F-	0.0011	0.0001	0.0001	0.0001	0.0001	0.0001	0.3459	0.7989	0.3023	0.0406
	A(T)-WW F-	0.0001	0.0001	0.0001	0.0001	0.0001	0.0002	0.9314	-	-	-
	A(T)-WW F+	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.2193	-	-	-
	A(H)-WW F-	0.0002	0.0001	0.0001	0.0001	0.0001	0.0001	0.4922	-	-	-
	A(H)-WW F+	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.1858	-	-	-
	A(T)-WWW F-	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.2292	-	-	-
	A(T)-WWW F+	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	-	-	-
	Annual F+	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.1361	-	-	-
	Annual F-	0.0001	0.0001	0.0001	0.0009	0.0100	0.0372	0.2799	-	-	-

Rotations measured were alfalfa, 6 year stand; wheat (W) after alfalfa(A); A(H), alfalfa terminated with herbicide; A(T), alfalfa terminated with tillage annual rotation; F+, fertilizer N added to soil test recommendations; F-, no fertilizer N added.

Table A4.6. Orthogonal contrasts for differences in soil water content at 20 cm increments to a depth of 210 cm between each rotation and a fallow treatment at each corresponding depth in for 3 dates during the 1996 growing season.

	Contrasts	Soil depth (cm)									
Date	Fallow vs	10-30	30-50	50-70	70-90	90-110	110-130	130-150	150-170	170-190	190-210
						P>F					
June 15	Crop 1 F-	0.4737	0.0023	0.0322	0.5242	0.9449	0.0352	0.5502	0.6446	0.9079	0.2761
	Crop 2 F-	0.3197	0.0155	0.3000	0.6080	0.4498	0.4117	0.4075	0.7537	0.9341	0.8316
	Crop 2 F+	0.1858	0.0046	0.9253	0.4168	0.6789	0.1509	0.6583	0.3229	0.9473	0.5182
	Crop 3 F-	0.5744	0.0087	0.3000	0.6640	0.1445	0.1929	0.2373	-	-	-
	Crop 3 F+	0.8140	0.0141	0.0328	0.9947	0.4831	0.4197	0.9584	-	-	-
	Annual F+	0.2488	0.0292	0.8848	0.1451	0.0541	0.0374	0.9169	-	-	-
	Prairie	0.1195	0.0243	0.0524	0.1336	0.1795	0.0297	0.4075	0.4238	0.1140	0.5968
July 25	Crop 1 F-	0.0001	0.0001	0.0001	0.0007	0.0106	0.3068	0.9107	0.7821	0.6537	0.7402
	Crop 2 F-	0.0001	0.0001	0.0163	0.1665	0.2484	0.1835	0.9046	0.1066	0.2434	0.5440
	Crop 2 F+	0.0011	0.0001	0.0016	0.0209	0.6185	0.7989	0.9066	0.1066	0.9564	0.3607
	Crop 3 F-	0.1620	0.0018	0.0159	0.2097	0.0679	0.8092	0.9776	-	-	-
	Crop 3 F+	0.0005	0.0001	0.0025	0.2455	0.4966	0.8933	0.8285	-	-	-
	Annual F+	0.1125	0.1560	0.0909	0.0843	0.2056	0.5299	0.0529	-	-	-
	Prairie	0.8066	0.1614	0.8921	0.5867	0.4112	0.9572	0.9451	-	-	-
Sept 4	Crop 1 F-	0.2001	0.3586	0.1755	0.0051	0.0218	0.0744	0.9794	0.6748	0.2882	0.6671
	Crop 2 F-	0.1247	0.0563	0.2322	0.4637	0.6527	0.5255	0.8046	0.2620	0.8847	0.1107
	Crop 2 F+	0.0834	0.3974	0.0750	0.2127	0.6121	0.9049	0.8166	0.5671	0.6035	0.2174
	Crop 3 F-	0.0527	0.6598	0.6701	0.5486	0.9477	0.4439	0.7592	-	-	-
	Crop 3 F+	0.2813	0.5101	0.9017	0.9070	0.8249	0.0409	0.7788	-	-	-
	Annual F+	0.7432	0.6078	0.5024	0.2751	0.9673	0.1639	0.0599	-	-	-
	Prairie	0.8058	0.8485	0.4282	0.9427	0.9281	0.0804	0.8750	0.8247	0.8166	0.0576

Rotations measured were Crop 1, first wheat crop after alfalfa;, Crop 2, second wheat crop after alfalfa; Crop 3, third wheat crop after alfalfa; F+, fertilizer N added to soil test recommendations; F-, no fertilizer N added; re-established native prairie.

Table A4.7a. Orthogonal contrasts for differences in soil water content at 20 cm increments to a depth of 210 cm between each rotation and a fallow treatment at each corresponding depth for the spring sampling date in the 1997 growing season.

	Contrast	Soil depth (cm)									
Date	Fallow vs	10-30	30-50	50-70	70-90	90-110	110-130	130-150	150-170	170-190	190-210
						P>F					
June 5	Crop 2 F+	0.7831	0.8795	0.5646	0.4685	0.5798	0.9814	0.8722			
	Crop 2 F-	0.6207	0.2244	0.3894	0.7810	0.8351	0.5071	0.8564			
	Crop 3 F+	0.0694	0.0095	0.0106	0.2149	0.1218	0.2531	0.9519			
	Crop 3 F-	0.2041	0.0351	0.0108	0.1640	0.2781	0.5602	0.6732			
	Crop 4 F+	0.6130	0.0063	0.7728	0.2658	0.3492	0.2773	0.1850			
	Crop 4 F-	0.2853	0.4180	0.0395	0.2943	0.9668	0.4032	0.8880			
	Annual F+	0.2443	0.1329	0.2922	0.2943	0.5247	0.8335	0.8880			
	Annual F-	0.5531	0.1284	0.1481	0.5972	0.7393	0.4924	0.7326			
	Prairie	0.0160	0.0615	0.1929	0.9894	0.4558	0.5371	0.4124			

Rotations measured were Crop 2, second wheat crop after alfalfa; Crop 3, third wheat crop after alfalfa; Crop 4, fourth wheat crop after alfalfa, F+, fertilizer N added to soil test recommendations; F-, no fertilizer N added; re-established native prairie.

Table A4.7b. Orthogonal contrasts for differences in soil water content at 20 cm increments to a depth of 210 cm between each rotation and a fallow treatment at each corresponding depth for the mid-season and harvest sampling date in the 1997 growing season.

	Contrast	Soil depth (cm)									
Date	Fallow vs	10-30	30-50	50-70	70-90	90-110	110-130	130-150	150-170	170-190	190-210
						P>F					
July 21	Crop 2 F+	0.0001	0.0001	.0008	0.0364	0.6105	0.3146	0.8308			
	Crop 2 F-	0.0001	0.0001	0.0402	0.0273	0.7301	0.5003	0.5778			
	Crop 3 F+	0.0001	0.0001	0.6862	0.9885	0.1412	0.3264	0.6868			
	Crop 3 F-	0.0001	0.0001	0.1024	0.1051	0.1983	0.5570	0.3286			
	Crop 4 F+	0.0001	0.0001	0.1287	0.5454	0.9044	0.6888	0.2798			
	Crop 4 F-	0.0089	0.0029	0.3275	0.1687	0.6966	0.2808	0.7397			
	Annual F+	0.0003	0.0001	0.0095	0.0076	0.3481	0.8805	0.9149			
	Annual F-	0.0085	0.0001	0.1006	0.0043	0.3633	0.5003	0.5618			
	Prairie	0.4735	0.3995	0.6254	0.6445	0.3711	0.9102	0.4427			
Aug 12	Crop 2 F+	0.0001	0.0001	0.0001	0.0001	0.0047	0.1055	0.8502			
	Crop 2 F-	0.0001	0.0001	0.0001	0.0001	0.0770	0.6809	0.6065			
	Crop 3 F+	0.0001	0.0001	0.0001	0.0003	0.4553	0.6718	0.6241			
	Crop 3 F-	0.0001	0.0001	0.0010	0.0098	0.4503	0.3595	0.3747			
	Crop 4 F+	0.0001	0.0001	0.0001	0.0001	0.1002	0.6538	0.3007			
	Crop 4 F-	0.0192	0.0001	0.0537	0.1639	0.0954	0.7552	0.3747			
	Annual F+	0.0004	0.0001	0.0001	0.0001	0.0336	0.2566	0.8601			
	Annual F-	0.0196	0.0001	0.0035	0.0056	0.2373	0.6538	0.6874			
	Prairie	0.0021	0.0036	0.6182	0.7405	0.6616	0.8126	0.3065			

Rotations measured were Crop 2, second wheat crop after alfalfa; Crop 3, third wheat crop after alfalfa; Crop 4, fourth wheat crop after alfalfa, F+, fertilizer N added to soil test recommendations; F-, no fertilizer N added; re-established native prairie.

Table A4.8. Orthogonal contrasts for volumetric soil water content differences in 20 cm increments to a depth of 210 cm for seeding to anthesis and seeding to harvest period for 1991.

Contrasts	Rotation	Soil depth (cm)									
		10-30	30-50	50-70	70-90	90-110	110-130	130-150	150-170	170-190	190-210
						P>F					
May vs June	Alfalfa	0.9820	0.8897	0.0055	0.6959	0.4027	0.2052	0.2947	0.6397	0.8213	0.8768
	A-W F+	0.8017	0.7451	0.5610	0.6588	-	-	-	-	-	-
	A-W F-	0.0123	0.0056	0.0489	0.0133	-	-	-	-	-	-
	B-W F+	0.6862	0.9334	0.0924	0.1090	0.0955	0.0724	0.7662	-	-	-
	B-W F-	0.4714	0.2274	0.8735	0.1866	0.5606	0.1718	-	-	-	-
	Fallow	0.1257	0.1809	0.2491	0.5036	0.6805	0.0511	0.2612	0.0434	0.0003	0.1461
May vs August	Alfalfa	0.6917	0.4171	0.0142	0.9906	0.1632	0.4231	0.0014	0.5691	0.7216	0.8250
	A-W F+	0.0123	0.0056	0.0489	0.0133	-	-	-	-	-	-
	A-W F-	0.0136	0.0027	0.0029	0.0073	0.2038	0.2660	-	-	-	-
	B-W F+	0.0032	0.0001	0.0003	0.0047	0.4108	0.2444	0.9815	-	-	-
	B-W F-	0.1978	0.0029	0.0152	0.0067	0.0508	0.5931		-	-	-
	Fallow	0.2757	0.0210	0.0751	0.0526	0.0275	0.3920	0.8398	0.5936	0.0481	0.4211

Rotations measured were alfalfa, 2 year stand; wheat (W) after alfalfa(A); annual rotation, barley-wheat; F+, fertilizer N added to soil test recommendations; F-, no fertilizer N added.

Table A4.9. Orthogonal contrasts for volumetric soil water content differences in 20 cm increments to a depth of 210 cm for seeding to anthesis and seeding to harvest period for 1992.

		Soil depth (cm)									
Contrasts	Rotation	10-30	30-50	50-70	70-90	90-110	110-130	130-150	150-170	170-190	190-210
							P>F				
May vs	Alfalfa	0.0705	0.1565	0.5092	0.2936	0.2978	0.6351	0.1523	0.0105	0.0035	0.0101
July	AA-W F+	0.0010	0.0031	0.0159	0.0383	0.3313	0.8907	0.0508	0.0647	0.2422	0.5614
	AA-W F-	0.0017	0.0020	0.1597	0.6666	0.0613	0.1606	0.0849	-	-	-
	PB-W F+	0.0004	0.0002	0.0110	0.2516	0.5345	0.0389	-	-	-	-
	PB-W F-	0.1312	0.0010	0.0872	0.1811	0.3936	0.0174	0.0746	-	-	-
	Fallow	0.0213	0.4667	0.0135	0.0573	0.0365	0.8096	0.0841	0.0066	0.1433	0.6644
May vs	Alfalfa	0.0360	0.3120	0.0399	0.0030	0.0517	0.4734	0.2009	0.8317	0.9464	0.1627
October	AA-W F+	0.2431	0.1134	0.0224	0.0011	0.0110	0.1947	-	-	-	-
	AA-W F-	0.9084	0.0084	0.0406	0.1520	0.7862	0.0255	-	-	-	-
	PB-W F+	0.0016	0.9016	0.1383	0.0257	0.0845	0.1508	-	-	-	-
	PB-W F-	0.0050	0.4095	0.4311	0.3481	0.5076	0.3874	-	-	-	-
	Fallow	0.1647	0.8247	0.0293	0.2573	0.0424	0.3703	0.2993	0.0293	0.1531	0.6350

Rotations measured were alfalfa, 3 year stand; wheat (W) after alfalfa(A); annual rotation (pea-barley-wheat); F+, fertilizer N added to soil test recommendations; F-, no fertilizer N added.

Table A4.10. Orthogonal contrasts for volumetric soil water content differences in 20 cm increments to a depth of 210 cm for seeding to anthesis and seeding to harvest period for 1993.

		Soil depth (cm)									
Contrasts	Rotation	10-30	30-50	50-70	70-90	90-110	110-130	130-150	150-170	170-190	190-210
							P>F				
May vs July	Alfalfa	0.1002	0.2100	0.0151	0.1748	0.0175	0.0193	0.0006	0.0121	0.1120	0.1078
	AAA-W F+	0.0001	0.2056	0.0015	0.1495	0.0910	0.2938	0.9633	-	-	-
	AAA-W F-	0.0210	0.0002	0.0016	0.0936	0.2447	0.1744	0.2241	0.1111	0.0915	0.0767
	WPB-W F+	0.2889	0.0001	0.0073	0.7948	0.4210	0.2384	0.5741	-	-	-
	WPB-W F-	0.7665	0.0009	0.0818	0.9692	0.5413	0.4687	0.2832	-	-	-
May vs September	Alfalfa	0.0006	0.0002	0.1025	0.6485	0.0001	0.0008	0.0002	0.0348	0.0588	0.4257
	AAA-W F+	0.0808	0.2772	0.2162	0.1095	0.0741	0.0261	0.3044	-	-	-
	AAA-W F-	0.5159	0.9576	0.1873	0.0193	0.0458	0.1256	0.7110	0.4229	0.1463	0.4281
	WPB-W F+	0.9786	0.1415	0.8071	0.0271	0.0054	0.0441	0.0466	-	-	-
	WPB-W F-	0.8659	0.0761	0.0818	0.0839	0.0007	0.0044	0.0049	-	-	-

Rotations measured were alfalfa, 4 year stand; wheat (W) after alfalfa(A); annual rotation; F+, fertilizer N added to soil test recommendations; F-, no fertilizer N added.

Table A4.11. Orthogonal contrasts for volumetric soil water content differences in 20 cm increments to a depth of 210 cm for the seeding to harvest period for 1994.

		Soil depth (cm)									
Contrast	Rotation	10-30	30-50	50-70	70-90	90-110	110-130	130-150	150-170	170-190	190-210
							P>F				
May vs	Alfalfa	0.0001	0.0004	0.0013	0.0051	0.0472	0.7388	0.0372	0.0045	0.0293	
August	A(H)-W F+	0.0067	0.4192	0.1526	0.1371	0.3353	0.2743	0.8435	0.0052		
	A(T)-W F+	0.0221	0.0010	0.8440	0.0955	0.0851	0.9163	0.2778	0.0640	0.3567	
	Annual 2F+	0.0298	0.6935	0.1617	0.0988	0.0129	0.0432	0.6941			
	Annual 3F+	0.3713	0.7463	0.2266	0.0523	0.0028	0.1223	0.4296			
	Prairie	0.3879	0.2520	0.0459	0.1553	0.1797	0.2065	0.7100	0.5037	0.0249	

Rotations measured were alfalfa, 5 year stand; wheat (W) after alfalfa(A); annual rotation; F+, fertilizer N added to soil test recommendations; re-established prairie.

Table A4.12. Orthogonal contrasts for volumetric soil water content differences in 20 cm increments to a depth of 210 cm for the seeding to harvest period for 1995.

		Soil depth (cm)									
Contrasts	Rotation	10-30	30-50	50-70	70-90	90-110	110-130	130-150	150-170	170-190	190-210
							P>F				
June 14 vs	Alfalfa	0.0035	0.9614	0.4523	0.3755	0.0163	0.4063	0.3698	0.0540	0.0007	0.0001
July 26	Prairie	0.7905	0.8271	0.2725	0.0315	0.0062	0.0003	0.0013	0.0005	0.0001	0.0009
	Annual 1F-	0.0052	0.0002	0.0050	0.2620	0.1742	0.0101	-	-	-	-
June 14 vs	Alfalfa	0.0211	0.0054	0.0160	0.0309	0.0189	0.0032	0.0020	0.1571	0.2281	0.5564
August 14	Crop 1(H) F-	0.0037	0.0032	0.0650	0.0223	0.0003	0.0043	0.0060	0.0256	0.1291	0.1026
	Crop 2(H) F-	0.0602	0.0001	0.0003	0.0056	0.0111	0.0398	0.2556	-	-	-
	Crop 2(T) F-	0.0048	0.0007	0.0004	0.0022	0.0004	0.0175	0.2952	-	-	-
	Crop 3 F-	0.0030	0.0013	0.0023	0.0129	0.0302	0.0371	0.1276	0.0452	0.3973	0.7698
	Crop 4 F-	0.0005	0.0030	0.0080	0.0164	0.0086	0.0341	0.7268	-	-	-
	Crop 5 F-	0.0074	0.0130	0.0930	0.2885	0.4386	0.5203	0.4792	-	-	-
	Annual 1F-	0.0014	0.0036	0.0167	0.0514	0.0993	0.1627	0.1852	-	-	-
	Annual 2F-	0.0008	0.0009	0.0067	0.0168	0.0414	0.1985	0.7669	-	-	-
	Annual 3F-	0.0018	0.0019	0.0187	0.0740	0.1351	0.0624	0.3110	-	-	-
	Prairie	0.0065	0.0147	0.0267	0.1103	0.3052	0.1363	0.3076	0.9225	0.9679	0.8583
	Crop 2(H) F+	0.0030	0.0032	0.0083	0.0188	0.0148	0.0043	0.0056	-	-	-
	Crop 2(T) F+	0.0080	0.0007	0.0001	0.0061	0.0225	0.0214	0.0298	-	-	-
	Crop 3 F+	0.0005	0.0003	0.0016	0.0053	0.0042	0.0045	0.0089	-	-	-
	Crop 4 F+	0.0002	0.0005	0.0002	0.0016	0.0026	0.0021	0.0140	0.7004	0.6821	0.3855
	Crop 5 F+	0.0008	0.0027	0.0051	0.0287	0.0997	0.2288	0.7357	-	-	-
	Annual 1F+	0.0004	0.0007	0.0006	0.0018	0.0226	0.0385	0.0991	-	-	-
	Annual 2F+	0.0033	0.0008	0.0001	0.0006	0.0051	0.0220	0.0544	-	-	-
	Annual 3F+	0.0056	0.0124	0.0124	0.0274	0.0389	0.2285	0.6551	-	-	-
	Fallow	0.6465	0.3816	0.7857	0.3709	0.3283	0.3035	0.5165	0.6944	0.2515	0.1570

Rotations measured were alfalfa, 6 year stand; wheat (W) after alfalfa(A); A(H), alfalfa terminated with herbicide; A(T), alfalfa terminated with tillage annual rotation; F+, fertilizer N added to soil test recommendations; F-, no fertilizer N added..

Table A4.13. Orthogonal contrasts for volumetric soil water content differences in 20 cm increments to a depth of 210 cm for the seeding to anthesis and seeding to harvest period for 1996.

		Soil depth (cm)									
Contrasts	Rotation	10-30	30-50	50-70	70-90	90-110	110-130	130-150	150-170	170-190	190-210
							P>F				
June vs July	Crop 1F-	0.0001	0.0001	0.0003	0.0176	0.1261	0.0204	0.0206	0.0610	0.4459	0.0395
	Crop 2F-	0.0001	0.0001	0.0002	0.0009	0.0025	0.0197	0.0058	0.1858	0.2775	0.2692
	Crop 3F-	0.0309	0.0003	0.0001	0.0004	0.0005	0.0501	0.0022	-	-	-
	Annual F-	0.4119	0.0001	0.0001	0.0048	0.2542	0.0082	0.9179	-	-	-
	Prairie	0.1025	0.0001	0.0020	0.0157	0.0071	0.7370	0.1404	-	-	-
	Crop 2F+	0.0011	0.0024	0.0037	0.0174	0.0039	0.5293	0.2173	0.1884	0.0028	0.3602
	Crop 3F+	0.0004	0.0001	0.0004	0.0206	0.0955	0.3958	0.0947	-	-	-
	Annual F+	0.0029	0.0025	0.0122	0.0542	0.0047	0.0235	0.2604	-	-	-
June vs September	Crop 1F-	0.3170	0.1021	0.0689	0.0209	0.0458	0.0700	0.0522	0.3021	0.6546	0.0517
	Crop 2F-	0.0642	0.5937	0.7118	0.5367	0.0972	0.4443	0.0410	0.4769	0.4710	0.8775
	Crop 3F-	0.7287	0.0664	0.0634	0.0104	0.0427	0.2777	0.3823	-	-	-
	Annual F-	0.6713	0.0365	0.0214	0.1863	0.6041	0.1320	0.6614	-	-	-
	Prairie	0.0914	0.0010	0.0293	0.0293	0.1479	0.5252	0.2130	0.0970	0.7118	0.3581
	Crop 2F+	0.6387	0.9830	0.3397	0.2979	0.0092	0.1885	0.6849	0.2242	0.2392	0.3843
	Crop 3F+	0.8166	0.2283	0.0681	0.1203	0.1385	0.0934	0.1653	-	-	-
	Annual F+	0.0433	0.0322	0.0603	0.0866	0.6885	0.1908	0.2715	-	-	-

Rotations measured were Crop 1, first wheat crop after alfalfa;, Crop 2, second wheat crop after alfalfa; Crop 3, third wheat crop after alfalfa; F+, fertilizer N added to soil test recommendations; F-, no fertilizer N added; re-established native prairie.

Table A4.14. Orthogonal contrasts for volumetric soil water content differences in 20 cm increments to a depth of 210 cm for the seeding to anthesis and seeding to harvest period for 1997.

		Soil depth (cm)									
Contrasts	Rotation	10-30	30-50	50-70	70-90	90-110	110-130	130-150	150-170	170-190	190-210
		P>F									
June vs July	Crop 2F-	0.0001	0.0001	0.0141	0.1527	0.7149	0.0754	0.7276	0.9713	0.6724	0.0454
	Crop 3F-	0.0001	0.0002	0.0281	0.0433	0.8043	0.0731	0.2135	0.3074	0.4600	0.6162
	Crop 4F-	0.0001	0.0012	0.0063	0.0932	0.5725	0.5241	0.8813	-	-	-
	Annual F-	0.0004	0.0001	0.0008	0.0009	0.1840	0.1847	0.5841	-	-	-
	Prairie	0.0001	0.0011	0.7889	0.6394	0.5800	0.5993	0.7181	0.8032	0.8257	0.6188
	Crop 2F+	0.0001	0.0001	0.0005	0.6657	0.9556	0.4952	0.9706	0.5479	0.7404	0.1853
	Crop 3F+	0.0002	0.0031	0.2061	0.7797	0.9635	0.0804	0.6948	0.4291	0.5343	0.1212
	Crop 4F+	0.0001	0.0001	0.0485	0.2777	0.5729	0.1671	0.8207	-	-	-
	Annual F+	0.0007	0.0001	0.0009	0.3439	0.7314	0.7886	0.9365	-	-	-
June vs August	Crop 2F-	0.0001	0.0001	0.0001	0.0005	0.0088	0.1772	0.1156	0.0918	0.8791	0.7635
	Crop 3F-	0.0001	0.0001	0.0021	0.0006	0.0303	0.0778	0.3640	0.7666	0.3850	0.9177
	Crop 4F-	0.0001	0.0001	0.0004	0.0054	0.0121	0.0091	0.7435	-	-	-
	Annual F-	0.0004	0.0001	0.0001	0.0001	0.0007	0.3341	0.0984	-	-	-
	Prairie	0.0001	0.0001	0.0006	0.0390	0.2180	0.9750	0.2381	0.1691	0.8428	0.6800
	Crop 2F+	0.0001	0.0001	0.0001	0.0003	0.0022	0.0046	0.0058	0.2143	0.5907	0.2246
	Crop 3F+	0.0001	0.0001	0.0009	0.0229	0.0087	0.0046	0.3430	0.3612	0.3676	0.1822
	Crop 4F+	0.0001	0.0001	0.0001	0.0001	0.0098	0.8093	0.2813	-	-	-
	Annual F+	0.0003	0.0001	0.0001	0.0002	0.0043	0.0351	0.3220	-	-	-

Rotations measured were Crop 2, second wheat crop after alfalfa; Crop 3, third wheat crop after alfalfa; Crop 4, fourth wheat crop after alfalfa, F+, fertilizer N added to soil test recommendations; F-, no fertilizer N added; re-established native prairie.

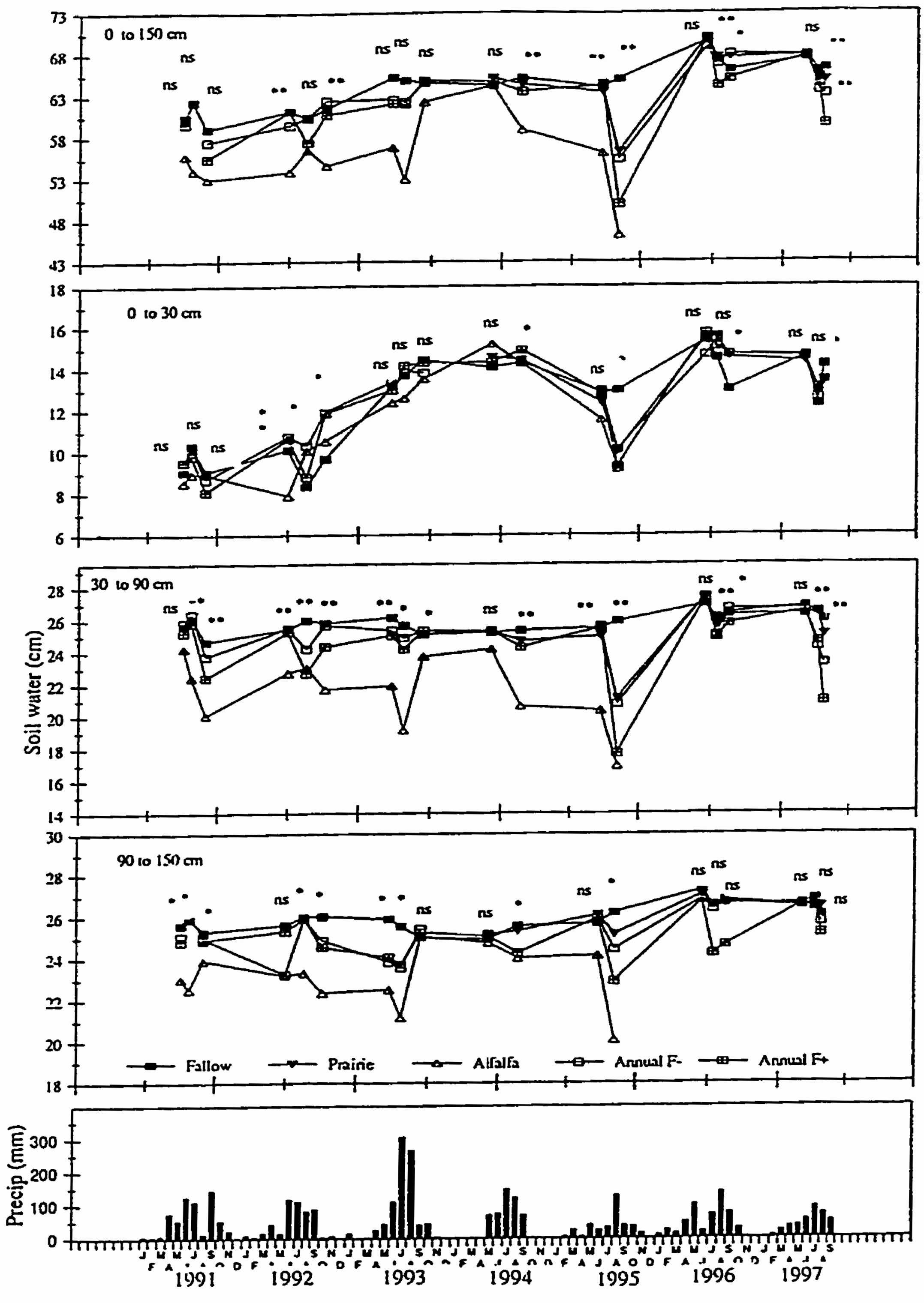

Figure A4.1. Soil water content for fallow, prairie, alfalfa, and annual rotations for 1991 to 1997. Measurements recorded for depths of 0 to 150 cm, 0 to 30 cm, and 90 to 150 cm. Monthly precipitation (mm) is also presented.