Nitrogen, weed control, and moisture conservation benefits of alfalfa mulch applied to organically grown spring wheat.

BY

MATTHEW JAMES WIENS

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

MASTER OF SCIENCE

Department of Plant Science
University of Manitoba
Winnipeg, Manitoba

THE UNIVERSITY OF MANITOBA

FACULTY OF GRADUATE STUDIES

*****

COPYRIGHT PERMISSION

Nitrogen, weed control, and moisture conservation benefits of alfalfa mulch applied to organically grown spring wheat

BY

Matthew James Wiens

A Thesis/Practicum submitted to the Faculty of Graduate Studies of The University of Manitoba in partial fulfillment of the requirement of the degree

Of

MASTER OF SCIENCE

TABLE OF CONTENTS

ACKNOWLEDGEMENTS

The initiation and completion of this thesis was only possible because of the help and support of many people. To the following I extend my thanks:

-To Dr. Martin Entz for the opportunity to take on this challenge, for advice and encouragement throughout, and for his energetic pursuit of better ways to farm.

-To Dr. Don Flaten and Dr. Jane Froese for reviewing this thesis and for instructive comments over the past two years.

-To Keith Bamford for invaluable technical assistance and patient, thoughtful responses to all manner of questions.

-To everyone I've worked with through the cropping systems lab for helping in the plots and good conversations while driving.

-To Dr. Gary Crow and Lyle Friesen for answering many stats questions.

-To organic farmers Robert Guilford and John Finney for allowing me to conduct research on their farms.

-To Debbie Sobering and Helena Cordeiro at the Grain Research Laboratory of the Canadian Grain Commission for generously offering the use of their NIR protein analysis equipment.

-To fellow grad students for making the time at U of M very enjoyable.

-To friends and family for much support, especially my brother-in-law, Chris, my sisters Lori and Debbie, and to my parents, Ernie and Charlotte, for their love and guidance throughout my life.

Above all, I offer thanks to God, who gave me this chance to more fully discover the wonder of creation and "whose power working in us is able to do infinitely more than we can ask or imagine" (Ephesians 3:20).

LIST OF TABLES

Appendix Tables

LIST OF FIGURES

Appendix Figures

ABSTRACT

Wiens, Matthew James. M.Sc., The University of Manitoba, July, 2004. Nitrogen, weed control and moisture conservation benefits of alfalfa mulch applied to organically grown wheat. Major Professor; Martin H. Entz.

Through nitrogen (N) fixation and extensive rooting, alfalfa (*Medicago sativa* L.) contributes N and other benefits to cropping systems, but nutrients are also exported when alfalfa hay is removed from a field. This is of special concern to organic farmers who have limited options for replacing those nutrients. An alternative to growing alfalfa for hay is to use the forage as mulch. Experiments were conducted in 2002 and 2003 at Winnipeg, Manitoba and Carman, Manitoba to measure the N contribution, weed suppression, and moisture conservation potential of alfalfa mulch applied directly to a growing crop of spring wheat (*Triticum aestivum* L). Effects of mulch application timing, mulch incorporation, and mulch particle size were analyzed at low, medium and high mulch rates. The effect of mulch rate on cereal crops was also studied on organic farms at Clearwater, Manitoba and Kenton, Manitoba in 2002. Additional experiments in 2003 measured the mulch-N contribution to the second crop grown after mulch application. Positive relationships were observed between mulch rate and wheat N uptake, grain yield, and grain protein. At Winnipeg, mulch rates between 4 and 5 t dry matter ha^{-1}, containing between 118 and 184 kg N ha^{-1}, applied at emergence or at the three-leaf stage, produced grain yields equivalent to that produced with 20 and 60 kg of ammonium nitrate-N per hectare in 2002 and 2003, respectively. At one site wheat plant stand density and grain yield were reduced, relative to the control, with a high mulch rate of 6.6 t ha^{-1} (dry weight). Where mulch application resulted in yields that were equivalent to yields achieved with ammonium nitrate, grain protein concentration in mulch treatments was often higher, suggesting a slow-release pattern of N availability, rather than a large initial N flush typical of inorganic N fertilizers. N use efficiency of mulch-supplied N by two crops over the two years at Winnipeg was approximately 20%; significantly lower than N use efficiency of ammonium nitrate. However, higher N uptake and grain yield of second-year oats (*Avena sativa* L.) grown on heavily mulched plots ($\geq$ 3.9 t ha^{-1}), relative to oats grown on ammonium nitrate treated plots showed that N from alfalfa residue continued to become available to the second crop while ammonium nitrate-N was largely depleted with the first crop. Mulch rates greater than 3.4 t ha^{-1} reduced weed population density. At several sites, low mulch rates caused an increase in weed population compared to the control. Mulch applied at the three-leaf stage appeared more suppressive on weeds than mulch applied earlier. Soil moisture conservation was observed under the highest mulch rates ($\geq$4.3 t ha^{-1}) at three of four sites. Mulch incorporation increased wheat N uptake compared to surface application at one of two sites, but grain yield was not affected. The incorporation tool (rotary hoe) was also effective at reducing green foxtail (*Setaria viridis* (L.) Beauv.) populations at the lowest mulch rate. However, at the highest mulch rate weed biomass was greater where mulch was incorporated, suggesting that more N was available to weeds where mulch was incorporated. No effect of mulch particle size was observed in the year of application, but a second-year oat (*Avena sativa* L.) crop showed higher yield with the smallest mulch particle size (<5 cm lengths) than the medium particle size (4-6 cm lengths).

1.0 INTRODUCTION

Increasing alfalfa (*Medicago sativa* L.) acreage has been proposed as a strategy to increase the sustainability of agriculture in western Canada (Entz et al. 1995). Growing alfalfa can reduce reliance on chemical inputs because alfalfa fixes N (nitrogen), and because a perennial alfalfa stand has been shown to reduce weed populations (Ominski et al. 1999). Other benefits of including alfalfa in a cropping system include improved soil structure and increased aggregation (Angers 1992; Rasse et al. 2000), increased water infiltration (Cavers 1996; Forster 1999), improved water use by subsequent crops (Forster 1999), access of deep leached nitrates (Kelner et al. 1997), and increased soil organic matter (Angers 1992).

It is estimated that an average annual alfalfa crop (9.0 Mg/ha) will remove approximately 278 kg N, 27 kg P (phosphorus), and 223 kg K (postassium), per hectare per year, as well as significant amounts of S (sulfur), Ca (calcium), Mg (magnesium), Fe (iron) and other micronutrients (Manitoba Agriculture and Food, 2001). With the exception of N, a farmer growing alfalfa will require a method of replacing the extracted nutrients. Spreading manure or applying synthetic fertilizer are both reasonable options for maintaining soil fertility. However, not all farmers have livestock, and organic farmers do not use chemical fertilizers. If the alfalfa hay, which is high in N, could be used as fertilizer it would allow a farmer to grow alfalfa for its soil building benefits and also derive benefit from the hay while keeping the nutrients on the farm. Chopping and spreading the alfalfa as mulch would utilize the hay as an organic fertilizer. Recent work in Finland focused on a strip farming system where strips of annual crops were grown between strips of forage crops, and a modified forage harvester was used to apply the forage to bare soil, or even on top of growing crops (Schäfer et al. 2002). The mulch provides nutrients to a crop as it decomposes, while potentially suppressing weeds and conserving moisture. Using this system, both conventional and organic farmers would gain "free N" from the decomposing alfalfa mulch, while retaining the P, K, S and micronutrients that would otherwise be removed from the soil when alfalfa hay is harvested. An additional benefit of such a strip farming system is some protection from erosion afforded to the annually cropped strips, both from mulch application and from the shelter of the perennial alfalfa strips. The feasibility of this strip farming system depends upon how much benefit can be obtained from the mulch.

The objective of this research project was to investigate the effects of alfalfa mulch applied to wheat (*Triticum aestivum* L.) by:

i) Measuring the N contribution to the wheat crop in terms of N uptake, wheat yield, and wheat protein.

ii) Evaluating the impact of alfalfa mulch on weed populations.

iii) Observing the effect of alfalfa mulch on soil moisture content.

2.0 LITERATURE REVIEW

2.1 Organic wheat production in Manitoba

Organic wheat production in Manitoba has attracted attention in recent years because, in addition to being free from synthetic chemical use, it has potential to be economically profitable. Farmers producing organic wheat in Manitoba have achieved yields similar to, and at times, higher than farmers producing wheat using conventional methods (Entz et al. 2001). Substantial price premiums over conventional wheat are common, and demand for organic wheat has been strong in recent years (A. Scott, pers. comm.; K. Anderson, pers. comm., OPAM (Organic Producers Association of Manitoba)).

Entz et al. (2001) conducted a survey of crop yields and soil nutrient status on 14 organic farms in Manitoba, Saskatchewan, and North Dakota. Eleven of the fourteen farms were located in Manitoba. Average farm size was 200 ha with an average of 15.1% of each farm sown to hard red spring wheat (*Triticum aestivum* L.). The average hard red spring wheat yield on these farms was 1701 kg ha^{-1}, which was 77% of the 10 year average for conventionally grown wheat in Manitoba, but yields ranged from 30 to 121% of conventional wheat yields (Entz et al. 2001). This survey also recorded challenges to crop production faced by these 14 organic farms. Average soil P levels were low on all farms (15 kg ha^{-1}), and soil nitrate-N levels ranged from low (34 kg ha^{-1}) to very high (246 kg ha^{-1}). Problem weed species, in order of importance, included wild mustard (*Brassica kaber* (DC.) L.C. Wheeler), Canada thistle (*Cirsium arvense* (L.) Scop.), redroot pigweed (*Amaranthus retroflexus* L.), green foxtail (*Setaria viridis* (L.)

Beav.), and wild oat (*Avena fatua* L.). Grasshopper was noted as a prevalent insect pest of crops on the surveyed farms (Entz et al. 2001).

In 2003 there were 132 organic wheat producers certified with OPAM (Organic Producers Association of Manitoba) in Manitoba, and they harvested wheat from a total of 2274 hectares, or an average of 17.2 ha per farm (K. Anderson, pers. comm., OPAM). The average price received by these farmers for their 2003 harvest was \$261.24 tonne^{-1} (\$7.11 bu^{-1}) (K. Anderson, pers. comm., OPAM). In comparison, in May 2004, conventional number 1 Canada Western Red Spring wheat with grain protein concentration of 14.5%, after deductions of freight, elevation and dockage had a market value of \$172.55 tonne^{-1} (\$4.70 bu^{-1}) at Winnipeg (anon., pers. comm., Canadian Wheat Board). In a personal interview, Alex Scott, who farms organically at Virden, Manitoba, indicated that on his 1100-acre farm he has a 10-year average wheat yield that is 93% of the average conventionally grown wheat yield in his area. He estimated his average grain protein level to be around 15%, and attributed this high protein level to growing wheat after alfalfa or sweet clover in rotation. He estimated the average price premium that he has received over the past 10 years to be \$110.00/tonne (\$3.00/bu) over conventionally grown wheat. Marketing of organic wheat has become easier in recent years with the entry into the organic wheat market of several large buyers, including N.M Paterson and Sons Ltd. based in Winnipeg, MB and Prairie Flour Mills Ltd. in Elie, MB (A. Scott, pers. comm.).

2.2 Strip intercropping for enhanced sustainability of cropping systems

Strip cropping is the practice of growing two or more crops in the same field in strips perpendicular to the prevailing wind direction or land contours, with the purpose of preventing soil erosion by wind or water. Strip intercropping differs slightly in that crops are planted in strips narrow enough for the crops to interact with enhanced crop yield but wide enough for farm machinery to operate normally. Alfalfa grown in a strip intercropping system has potential to impart benefits to neighbouring crops in addition to improving the soil on which it is grown (Robinson et al. 1972; Fairey and Lefkovitch 1995; Smith and Carter 1998). The present study is based on the premise that including alfalfa in a crop rotation improves the sustainability of the cropping system (Entz et al. 1995).

An important interaction between crops in a strip intercrop system is the edge effect of light interception. Smith and Carter (1998) conducted an experiment at Madison, Wisconsin to test the hypothesis that strip intercropped corn (*Zea mays* L.) and perennial alfalfa would increase productivity compared to sole cropped land due to greater light availability to corn compared to sole cropped corn. Their results showed higher yields with intercropping in two out of three years of the study, with higher productivity from 6 meter wide strips than 3 or 12 meter wide strips (Smith and Carter 1998).

Other benefits observed with strip intercropping include greater abundance of beneficial insects, and complementary utilization of soil N. An increase in numbers of predatory insects was reported in Oklahoma when strips of cotton (*Gossypium hirsutum* L.) were grown between strips of either sorghum (*Sorghum bicolor* (L.) Moench.), peanut (*Arachis hypogea* L.), or alfalfa (*M.sativa*) (Robinson et al. 1972). Total forage yield was greatest when alfalfa and smooth brome grass were strip cropped in 40 cm wide strips, and decreased as strip width increased to 60 and 80 cm (Fairey and Lefkovitch 1995).

The higher yields with the narrowest strips were presumed to be due to the greatest transfer of biologically fixed N from the alfalfa to the brome grass.

A negative effect on border row yield due to reduced soil moisture has been observed during dry years. For example, Ghaffarzadeh et al. (1997) working in Iowa, measured lower corn yield at the border of an oat (*Avena sativa* L.) and alfalfa mixture than at the border with soybeans, due to greater water use by the oat/alfalfa mixture. In a corn/alfalfa intercropping study conducted by Smith and Carter (1998) soil moisture and grain yield in the drought year of 1988 was lowest in corn rows that bordered alfalfa. In 1990, when precipitation was higher, corn yield was highest in rows that bordered alfalfa (Smith and Carter 1998). Therefore, strip intercropping with alfalfa appears suited to more humid rather than arid agro-ecosystems.

The studies referred to above suggest that strips of wheat intercropped with alfalfa have potential advantages over sole cropped wheat. These advantages include greater light interception after alfalfa harvests, some access to biologically-fixed N on the border with alfalfa strips, and a greater abundance of predatory insects. Protection from soil erosion is also an important contribution from perennially cropped strips to more vulnerable annually cropped strips. When these benefits are considered together with the N fixation, weed suppression, and other soil building attributes of alfalfa, a strip farming system with alfalfa appears to warrant further investigation.

A modified approach to strip farming was studied by Schäfer et al. (2002) working in Finland. They investigated the effectiveness of strip intercropping wheat and red clover (*Trifolium pratense* L.), and used the clover top growth as a solution to the problem of N deficiency on land recently converted to organic production. Strips of red clover, six meters wide, were grown between six meter wide strips of wheat. Red clover top growth was harvested and applied directly to the wheat with a modified forage harvester. Application timing was between wheat tillering and stem elongation. After variable results over three years they concluded that the weather conditions of northern Europe made the amount of mulch available and the rate of N mineralization uncertain (Schäfer et al. 2002). As a more viable solution, Schäfer et al. referred to work done by others on strip intercropping wheat and clover, with wheat grown in wide single rows and clover grown in between the wheat and mulched with a special row crop mower to provide N and weed control for the wheat (Schäfer et al. 2002).

2.3 N contribution of alfalfa mulch to the soil/crop system

2.3.1 Introduction

Any type of crop residue mulch applied to soil will eventually release N to the soil/crop system. The amount of residue N that becomes available to a crop depends on factors such as the amount of N contained in the mulch, the rate of mulch decomposition, the magnitude of N losses, and the synchrony between N release and crop demand. Decomposition rate also depends upon mulch characteristics such as C/N ratio, level of lignification, and particle size. Decomposition rate is also dependent on mulch placement (surface applied vs. incorporated), and on prevailing environmental conditions (temperature and moisture). Potentially high N losses may occur from applying high-N containing fertilizers such as alfalfa mulch. N losses due to volatilization, leaching and denitrification will reduce the N benefit to a crop. Finally, the N contribution to the soil/crop system will depend upon timing of application which may influence synchrony between N release from mulch and crop N demand.

2.3.2 Chemical composition of alfalfa

Alfalfa tissue is high in N. On an oven-dry basis, N content of alfalfa top-growth averages 3.5% N, which is higher than most crop residues (Somda et al. 1991; Smith and Sharpley 1993). An average first cut of alfalfa in southern Manitoba may yield approximately 3 tonnes of dry matter ha^{-1} (Seed Manitoba 2001). At 3.5% N, the N contained in this hay would be 105 kg ha^{-1}.

An important factor affecting crop residue decomposition is the C/N ratio, with a low C/N ratio promoting rapid residue decomposition (Parr and Papendick 1978). Alfalfa mulch has one of the lowest C/N ratios of any crop residue (12:1 compared to 97:1 for wheat (Somda et al. 1991)). Perhaps even more significant to the residue decomposition rates than the C/N ratio is the lignin (L) to N ratio (Parr and Papendick 1978; Bross et al. 1995). Alfalfa has low levels of lignification: 6.57% compared to 10.65% for wheat (Somda et al. 1991).

The combination of low C/N ratio and low L/N ratio allows alfalfa mulch to break down rapidly, compared to other crop residues, and release potentially high amounts of N to a growing crop. A laboratory comparison of alfalfa and barley (*Hordeum vulgare* L.) residue decomposition rates revealed that only 35% of alfalfa residue remained after two weeks, while 75% of barley residue remained after two weeks (Somda et al. 1991). The difference was attributed to a lower C/N ratio and lower lignin content in the alfalfa than the barley. Similarly, Bruulsema and Christie (1987) found apparent slower N-release from red clover (*Trifolium pratense* L.) than alfalfa and attributed the slowness to higher lignin concentration and C/N ratio of red clover. Cueto-Wong et al. (2001a) found more loss of N from a soil/crop system with hairy vetch (*Vicia villosa* Roth) than with alfalfa, suggesting that hairy vetch decomposed faster than alfalfa, perhaps due to the lower C/N ratio of hairy vetch.

2.3.3 Decomposition and N mineralization of alfalfa mulch

N mineralization is the conversion of N in organic forms to inorganic NH_4^+ (ammonium) or NH_3 (ammonia) (Jansson and Persson 1982). Soil microbes split proteins and peptides in organic matter into amino compounds, which are further split to release NH_3. Under normal soil conditions, soil bacteria quickly convert ammonium (NH_{4+}) to nitrate (NO_3^-), another inorganic form of N. Plants require inorganic N for growth. Therefore, when applying organic forms of fertilizer such as manure, compost, or mulch, the mineralization process is necessary to create plant-available forms of N. When considering N mineralization it is important to also consider N immobilization, which occurs simultaneously. Immobilization is essentially the reverse of mineralization in that inorganic N is taken up and converted by microorganisms into organic forms of N, making it unavailable to plants. Often referred to as mineralization-immobilization turnover, this process leads to either a net increase or decrease of plant-available N, and is highly correlated with the C/N ratio of a crop residue. Net immobilization is favoured at C/N ratios above 30:1, and net mineralization is favoured when residues have C/N ratios below 20:1 (Havlin et al. 1999).

While mineralization rate is not equivalent to decomposition rate the two are related. Factors that affect the overall decomposition rate generally affect N mineralization in a similar manner but not always to the same extent. For example, a drop in temperature reduced overall decomposition rate more than N mineralization rate (Magid et al. 2001). The actual rate of alfalfa mulch decomposition and mineralization in the field, while more rapid than many other crop residues because of alfalfa's chemical composition, will also depend on such factors as particle size, placement, and climate.

2.3.3.1 Particle size. The effect of particle size on crop residue decomposition and mineralization is inconsistent. Studies show that reducing residue particle size may cause increased (Sims and Frederick 1970), decreased (Stickler and Frederick 1959; Parr and Papendick 1978), or unchanged (Amato et al. 1984; Mohr et al. 1998b) decomposition rates. Amato et al. (1984) found similar decomposition rates of ground (<1 mm) and unground (5 cm) legume (*Medicago littoralis* Lois. and *Medicago truncatula* Gaertner) material incorporated into soil in the field. In a related lab experiment they found that ground legume pods decomposed more rapidly than intact pods, possibly due to increased surface area exposure to microbes. Grinding had no effect on legume stems or leaves (Amato et al. 1984). In contrast, corn (*Zea mays* L.) pith was found to evolve more CO_2 at a particle size of <0.25 mm than at a particle size of 19 mm (Sims and Frederick 1970), indicating more rapid decomposition of smaller particles.

Small particle size has also been found to reduce decomposition and mineralization rates. Fine grinding of alfalfa top-growth (<0.025 cm) produced less nitrate, presumably indicating slower mineralization, than coarsely ground alfalfa top growth (<1.25 cm), possibly due to adsorption of fine particles to soil colloids and subsequent stabilization (Stickler and Frederick 1959). In another study, grinding of alfalfa residue did not significantly affect the rate of N-mineralization compared to 1.5 cm and 5.0 cm particles, although N-mineralization from alfalfa stems was slowed slightly by grinding (Mohr et al. 1998(b)). Parr and Papendick (1978) report faster decomposition of long rice straw compared to short rice straw. Larger particles may provide improved aeration for microbes than small particles (Parr and Papendick, 1978).

2.3.3.2 Surface applied versus soil incorporated. A number of studies have shown crop residues break down faster when incorporated into soil than when left on the soil surface (Aulakh et al. 1991; Smith and Sharpley 1993; Bross et al. 1995; Lafond et al. 1996; Mohr 1997; Mohr et al. 1998a; Mohr et al. 1998b). Residue decomposition has been reported to be 1.5 times faster when residue is incorporated rather than left on the soil surface (Lafond et al. 1996). A lab study by Mohr (1997) found that N was more rapidly released from incorporated alfalfa than from surface applied alfalfa, possibly because of greater contact with microbial populations in the incorporated treatments. In another study by Aulakh et al. (1991), hairy vetch residue under laboratory conditions was 51% mineralized after 35 days when incorporated and only 36% mineralized when surface applied.

Despite increased N availability and decreased volatilization when alfalfa residue is incorporated, Mohr et al. suggest that surface application may result in more efficient use of alfalfa-derived N by subsequent crops. Slower mineralization from surface applications may decrease N loss through leaching and denitrification because plant-available N accumulation occurs at times that are in greater synchrony with crop demands (Mohr et al. 1998b).

2.3.3.3 Prevailing environmental conditions. Researchers suggest that a region's climate may be secondary to residue chemical composition in determining the rate of N mineralization (Amato et al. 1987; Magid et al. 2001). Nevertheless, more moisture generally leads to faster rates of N mineralization (Amato et al. 1984; Havlin

1999). Amato et al. (1984) found that increased frequency of drying and wetting enhanced legume residue decomposition and N mineralization. They also found that increased duration of soil wetness following re-wetting of dry residue increased decomposition and N mineralization. Optimum rates of mineralization occur when soil is between 50 and 70% water-filled pore space, which coincides with optimum conditions for aerobic respiration of soil microbes (Havlin 1999).

Studies also show a positive effect of temperature on N mineralization rate as a result of enhanced microbial activity (Parr and Papendick 1978; Magid et al. 2001), with evidence that temperature is a more important factor than moisture in determining decomposition rates (Ladd et al. 1985). A study of residue (*Medicago littoralis* and *Lolium multiflorum*) decomposition across diverse environments showed a doubling of decomposition rates with each 8-9°C increase in mean annual air temperature (Ladd et al. 1985). Still, mineralization from N rich residues may occur at high rates even in soil as cold as 3°C (Magid et al. 2001).

In a system where alfalfa mulch is applied to cropped land in spring, moisture and temperature will affect whether mineralization occurs in time for nutrients to become available to the crop. In a cool, dry year very little decomposition may take place and very little N would be available to a crop. In contrast, rapid residue breakdown during a warm, wet season may provide excellent N fertility, or may also lead to low amounts of plant-available N due to increased N losses through volatilization, denitrification or leaching.

2.3.4 N losses

Alfalfa mulch, although high in N, may be prone to N losses due to rapid tissue decomposition and release of mobile N-containing compounds. Loss of N from alfalfa mulch is of a concern both because of reduced fertilizer value and because of negative impacts on the environment. The three modes of N loss of most concern are volatilization, leaching and denitrification.

2.3.4.1. Volatilization. N volatilization from crop residue occurs as diffusion of NH_3 (ammonia) from the residue to the atmosphere. Crops and crop residue are minor contributors to atmospheric NH_3 (Kurvits and Marta 1998), but a significant proportion of total N in crop residue may be lost due to volatilization (Janzen and McGinn 1991; O'Deen and Follett 1992; Larsson et al. 1998; Mohr et al. 1998a). Surface-applied alfalfa undergoes a certain amount of volatilization as it breaks down. Under greenhouse conditions, Mohr et al. (1998a) found that after 95 days up to 12% of the N in alfalfa residue was lost through volatilization when the residue was from herbicide-terminated alfalfa and left on the soil surface. Volatile N losses were only 8% when alfalfa was terminated with a simulated tillage treatment instead of herbicide and the residue left on the soil surface. Almost no volatilization losses occurred when the residue was incorporated. These results are in agreement with findings of Janzen and McGinn (1991) who found significant volatilization losses (14% of applied N after 14 days) when lentil green manure residue was left standing or placed on the soil surface, while incorporation virtually eliminated volatilization losses.

Factors affecting volatilization from residues include N concentration and form (labile or recalcitrant) found in crop residue (Janzen and McGinn 1991; O'Deen and

Follet 1992), soil temperature and soil moisture (Terman 1979; Nelson 1982; O'Deen and Follett 1992; He et al. 1999), climate (O'Deen and Follett 1992), and residue application rates (O'Deen and Follett 1992). O'Deen and Follet (1992) found increasing rates of NH_3 volatilization from soybean residue with increased levels of soil moisture, soil temperature, and amount of residue. Larsson et al. (1998) measured volatilization loss of 17% of applied N in alfalfa mulch applied at a rate of 2.32 kg dry matter m^{-2}. Volatilization rates were highest from wet mulch following rain events (Larsson et al. 1998).

2.3.4.2 Leaching. Heavy applications of alfalfa mulch to the surface of bare soil have resulted in leaching of mineralized N from the upper soil layers (Rasse et al. 1999). Working in southwestern Michigan, Rasse et al. (1999) applied alfalfa mulch to the surface of bare fallow in the spring on a loam soil and found significant nitrate leaching from the upper soil horizon by December. In the same study they also observed that no leaching occurred when alfalfa mulch was applied to the soil surface in a growing alfalfa stand (Rasse et al. 1999). These results indicate that mineralized-N from alfalfa mulch is susceptible to loss by leaching if it is not taken up by a growing crop.

The findings of Mohr et al. (1998b) that incorporation of alfalfa mulch leads to more rapid N release than surface application suggests that the risk of nitrate leaching may be less with surface application than with incorporation of mulch.

2.3.4.3 Denitrification. The microbe-mediated conversion of nitrate (NO_3^-) in the soil to gaseous forms of N such as nitrous oxide (N_2O) or dinitrogen (N_2) is called denitrification. Denitrification is a concern because it is a pathway for N loss, and because N_2O is both a powerful greenhouse gas and causes destruction of the ozone layer

(Isermann 1994; Olivier et al. 1998). Avalakki et al. (1995) found that adding wheat straw to a soil increased denitrification rates. This was explained as due to an increased supply of carbon, a supply of hydrogen from the straw to denitrifying soil microorganisms, and an increased anaerobiosity of the soil from oxygen depletion as the straw decomposed. Adding alfalfa mulch to soil could create these same conditions.

Groffman et al. (1987) reported higher levels of denitrification during the growing season when legumes were used as a source of N than when inorganic fertilizer was used because legumes provide carbon substrate for denitrifying microorganisms. However, potential denitrification activity after crop harvest was higher in fertilizer treatments than in legume residue treatments, likely because the crop and weed residues in the fertilizer treatments had higher N content. Overall, denitrification losses appeared to be low in all treatments in this study (Groffman et al. 1987).

As with leaching, the risk of N loss due to denitrification may be greatest where conditions favour more rapid N mineralization, such as soil incorporation rather than surface application of alfalfa mulch (Aulakh et al. 1991; Mohr et al. 1998b). However, Rasse et al. (1999) also found substantial denitrification in surface-applied alfalfa mulch, both on bare fallow and growing alfalfa.

Although total denitrification decreased with temperature, nitrous oxide evolution was higher at 5°C than at 15 and 30°C, possibly because at low temperatures high residual nitrate concentrations may have inhibited reduction of nitrous oxide to dinitrogen (Avalakki et al. 1995). Denitrification is known to be favoured by anoxic conditions, which occur in waterlogged soils. At 60% water-filled pore space denitrification losses from residue-incorporated soils were negligible, compared to losses of 87-127% of the initial soil NO_3 level when water-filled pore space was 90% (Aulakh et al. 1991). Any practice that prolongs a saturated soil condition would be expected to increase denitrification. Adding alfalfa mulch to a soil could presumably increase rates of denitrification through the mechanisms described above, i.e., supplying carbon and donating hydrogen to denitrifying bacteria, potentially decreasing soil temperatures, and increasing soil moisture.

2.3.5 N availability to crops from legume residues

The literature presents a wide range of values for the percentage of N applied in legume residue that becomes available to the first year (11-73%) and second year crop (1-7.5%) after residue application (Fribourg and Bartholomew 1956; Ladd et al. 1981; Mahler and Auld 1989; Janzen et al. 1990; Stute and Posner 1995; Forster 1999; Cueto Wong et al. 2001a; Cueto Wong et al. 2001b). While the recovery rates vary between studies, due to a variety of experimental conditions and procedures, all found that a much greater amount of N is supplied to the first year crop after legume amendment than the second year crop. For example, Fribourg et al. (1956) estimated that 34% of the N in alfalfa tops became available to corn during the first cropping season, and an additional 7.5% became available to oats in the second season. A frequent explanation for the higher N supply in the first season is that legume residues contain both labile and recalcitrant forms of nitrogenous compounds (Janzen et al. 1990; Janzen and McGinn 1991). Studies show that small amounts of legume-derived N is supplied to crops for a number of years after legume residue application (Ladd et al. 1985; Mahler and Auld 1989; Mohr et al. 1999;Cueto Wong et al. 2001b). In a long term field experiment, Ladd et al. (1985) found that 30% of the N applied in legume residue was still remaining in the soil eight years after treatment. Therefore, alfalfa mulch application has potential for both short-term and long-term N benefits.

2.3.5.1 N availability to first crop after application. Using labelled lentil (*Lens culinaris* Medik. 'Indianhead') and Tangier flatpea (*Lathyrus tingitanus* 'Tinga') residue, Janzen et al. (1990) reported 14% recovery of residue-N by a wheat crop grown under semi arid conditions in western Canada. In a field experiment simulating green-manure incorporation, Cueto-Wong et al. (2001a) found 16% recovery of ^{15}N-labelled alfalfa and hairy vetch residue by sorghum (*Sorghum bicolor* [L.] Moench) tops. N recovery in wheat from fall-incorporated alfalfa hay was estimated at 27% using the difference method (Mahler and Hemamda 1993).

Cereal crops grown after termination of perennial legumes such as alfalfa also provide insight into N availability from decomposing legume residues. Higher grain yields and grain N uptake in wheat grown after alfalfa versus wheat grown after wheat, pea, or barley was a result of increased N provided by decomposing alfalfa residue (Forster 1999).

An interesting observation is that studies using the difference, apparent recovery, or fertilizer replacement methods to measure N recovery from legume residue consistently produce higher estimates than studies using the ^{15}N method (Cueto Wong et al. 2001b). This may be explained as a dilution or "pool substitution" effect, where labelled N is immobilized in place of indigenous N (Hart et al. 1986;Bruulsema and Christie 1987). After ^{15}N-labelled residue is applied to a crop, the N that becomes plant-available is a combination of labelled N and indigenous soil N that would otherwise have been immobilized had the added residue not supplied N to the soil inorganic N pool. The effect of this substitution is to dilute the labelled N concentration in the crop and thereby reduce the apparent uptake of legume-derived N. Therefore, the ^{15}N method may underestimate N recovery from labelled crop residues (Hart et al. 1986).

2.3.5.2 N availability to subsequent crops. A significant proportion of the N in legume residues remains in the soil after the initial cropping season. For example, Ladd et al. (1981) measured between 71.9 and 77.7% of the ^{15}N added with labelled *Medicago littoralis* in the organic N pool after a single wheat harvest. The slow release of legume N in subsequent years is either because breakdown of the biochemical compounds that originally contained the N is very slow, or very stable organic compounds were formed as the legume residue became humified (Seligman et al. 1986). Nevertheless, uptake of legume-derived N by crops planted in the second season, or more, after residue application is documented in numerous reports. An Austrian winter pea green manure crop incorporated in early summer provided significant yield benefits to the following winter wheat crop and to the subsequent barley crop planted 22 months after the green manure was incorporated (Mahler and Auld 1989). Oats grown in the second season after incorporation of ^{15}N-labelled alfalfa and hairy vetch residue recovered 3% of residue N, with greater recovery observed from alfalfa residue than from hairy vetch residue (Cueto-Wong et al. 2001b). Janzen et al. (1990) reported less than 2% uptake of residue-N in a second wheat crop after Tangier flatpea and lentil residue incorporation. Using the difference method, Fribourg and Bartholomew (1956) estimated that oats grown in the second season after application recovered 7.5% of the N applied as alfalfa tops. In southern Manitoba, Bullied et al. (2002) found that chickling vetch (*Lathyrus* *sativus* L.) and lentil green manure crops or single-year alfalfa hay contributed significant grain yield and N uptake benefits to a second-year barley crop.

The longevity of organic N contributed to the soil by legume residues was elucidated by Hoyt (1990) in northern Alberta. After perennial alfalfa, yields of twelve subsequent wheat crops were measured and found to be significantly higher than the control up to the 10th crop in the 13th year after breaking the alfalfa (Hoyt 1990). Working in South Australia, Ladd et al. (1985) found that eight years after incorporating labelled legume residue 31-38% of the initial legume N was still present in organic residues. Between 6 and 14% of the labelled residual organic N was present as microbial biomass with a higher proportion of microbial biomass N being derived from the original legume residue than from unlabelled soil N.

2.3.5.3 Synchrony of legume residue N release with crop N demand. Timing of N availability to a crop affects grain yield and grain protein concentration, and has implications for N losses. Optimum crop growth, with little risk of N losses, would be expected if residue N release was perfectly synchronized with crop N demand. However, high amounts of residue N may become available to a crop with an extended time period for residue N mineralization before crop establishment, creating a large inorganic N pool that increases the risk of N loss. Rooting activity will influence timing of plant N uptake, while timing of residue N release will depend on residue chemical composition, residue placement, and environmental conditions.

Timing of N release also affects interactions between protein content and yield. Researchers have repeatedly found higher wheat yield and protein concentration when N application on winter wheat was delayed from fall until spring, possibly because of optimum synchrony between wheat rooting activity and N availability (Sander et al. 1987). N fertilization timing trials in Saskatchewan showed higher wheat yields and lower grain protein concentration with early spring N application than with late spring N application, except under drought conditions where the trends were reversed (Fowler et al. 1990). This latter phenomenon is described as "haying off," where early access to high amounts of N causes wheat to produce large amounts of vegetative growth that depletes soil water reserves and negatively impacts yield under drought conditions.

A large inorganic N pool present at planting has greater potential for N losses through leaching and denitrification than a slow-release supply of inorganic N that becomes available later during rapid root growth and N uptake by a crop. Groffman et al. (1987) showed that ammonium nitrate produced a large, short-lived N pulse, while N release from legume residue was slower. Therefore, if legume residue behaves like a slow release fertilizer and N release is synchronized with crop N demand, application of legume residues may offer an efficient method of delivering N to crops.

Investigations with spring incorporation of hairy vetch and red clover cover crops in Wisconsin revealed that 50% of residue N was released within four weeks, after which time N-release slowed and very little was released after 10 weeks (Stute and Posner 1995). In New Mexico, Cueto-Wong et al. (2001a) found that the greatest inorganic soil N levels occurred 14 days after spring incorporation of alfalfa or hairy vetch. In another study, fall application of 3 t ha^{-1} of baled second-cut alfalfa provided 24 kg N ha^{-1} (26% of applied N) to the following spring wheat crop (Mahler and Hemamda 1993). These studies show that legume residue provides a substantial initial pulse of N to the soil/crop system within a short period of time after residue application, but a large proportion of residue N remains in organic forms with potential for slow release as the growing season progresses.

The timing of perennial alfalfa stand termination affects spring soil nitrate concentrations and the yield of subsequent crops. Soil nitrate observations following alfalfa termination provide insight into possible N release patterns from alfalfa mulch. In Manitoba, delaying alfalfa termination until after the second cut reduced soil nitrate concentrations the following spring, compared to termination after the first cut, but did not reduce yield at 3 of 4 sites (Mohr et al. 1999). Mineralization of alfalfa residue during the growing season appeared to be sufficient to meet the N demands of the wheat crop regardless of early or late alfalfa termination the previous year. A further delay in alfalfa termination until the spring just prior to wheat planting reduced wheat yields in 3 of 5 site-years possibly due to reduced N release from alfalfa residues causing reduced N uptake by the wheat crop (Mohr et al. 1999).

Method of alfalfa termination was also investigated in the Mohr et al. (1999) study. The use of herbicide rather than tillage to terminate alfalfa stands reduced spring soil nitrate concentrations, but yields of wheat following herbicide-terminated alfalfa were the same or higher than tillage-terminated alfalfa. The authors emphasize that achieving similar wheat yields with a reduced spring inorganic N pool indicates improved synchrony between N release from alfalfa residues and N uptake by the wheat crop. By reducing the size of the inorganic N pool in spring, the herbicide treatments reduced the potential for N losses by denitrification and leaching compared to the tillage treatments (Mohr et al. 1999). Similarly, alfalfa mulch application that is timed to release N when crop uptake is greatest will reduce the risk of N losses.

N uptake into wheat often diminishes at later growth stages because of reduced N and soil water availability as the growing season progresses. As a result, a high proportion of grain N is often translocated from vegetative tissues (Bhatia and Rabson 1987). However, wheat can continue to take up N from the soil during grain filling if sufficient soil water and soil N are present (Simmons 1987), and N taken up later in the season is channeled more directly to the grain than N taken up earlier (Sander et al. 1987). Hence, the benefits of delayed availability of legume-supplied N may include increased wheat grain protein concentration, as well as reduced risk of yield loss from “haying off”, and reduced risk of N loss through denitrification and leaching.

2.4 Effect of mulch application on soil moisture

2.4.1 Introduction

It has long been known that surface soil residues conserve soil moisture (Duley and Russel 1939). This has important implications for regions such as the Canadian prairies where soil moisture is often a limiting factor for crop production. Even for wetter parts of the prairies, climate data provides evidence for the occurrence of moisture stress for spring wheat in most years (Yield Manitoba 2003). Conservation of soil moisture by mulch may reduce yield losses due to inadequate rainfall (Lafond et al. 1992). In Nebraska an increase in corn fodder yield was attributed to moisture conservation under wheat straw mulch (Duley and Russel 1939). On the other hand, mulch has been found to reduce soil temperatures (Parker and Larson 1962; Gauer et al. 1982; Teasdale and Mohler 1993; Wagner et al. 1996) which may negatively impact root growth, water use, and crop productivity in cooler regions (Sharratt 1991).

2.4.2 Infiltration and Evaporation

Maintenance of crop residues on the soil surface increases soil water by improving water infiltration (Duley and Russel 1939; Creamer and Dabney 2002; Findeling et al. 2003) and reducing evaporation (Duley and Russel 1939; Hares and Novak 1992; Lafond et al. 1992; Prihar et al. 1996). Using corn residue mulch, Findeling et al. (2003) found that rates as low as 1.5 tonnes ha^{-1} decreased runoff. Over time the decomposing residue stabilized the soil and increased its ability to absorb and conduct water, thereby increasing water infiltration (Findeling et al. 2003). Duley and Russel (1939) applied straw at a rate of 4.5 tonnes ha^{-1} and found that 54% and 39% of rainfall was conserved in fallow plots where the straw was surface-applied and incorporated respectively. Only 20% of rainfall was conserved in bare-fallow treatments. Rainfall conservation under straw was due to a combination of increased infiltration and reduced evaporation (Duley and Russel 1939).

Evaporation from the soil surface can be divided into two stages: 1) energy limited evaporation (stage I evaporation), and 2) soil limited evaporation (stage II evaporation) (Ritchie 1972). The first stage occurs when the soil surface is wet and therefore evaporation rate is limited only by energy at the soil surface. The second stage starts as the soil surface begins to dry and soil properties which affect water movement to the soil surface become important factors in determining evaporation rate. Surface-applied mulch will affect stage I evaporation, while incorporated mulch may affect both stages of evaporation (Prihar et al. 1996).

Hares and Novak (1992) applied barley straw at rates of 0, 2, 10 and 20 t ha^{-1} and found evidence of crop residues reducing stage I evaporation. Soil temperatures and evaporation rates were reduced in mulched vs. unmulched plots, and volumetric soil water content was increased by as much as 17% (Hares and Novak 1992). Both stage I and stage II evaporation were affected by residue management method in a lab study using soil columns subjected to a single wetting event and controlled evaporation conditions (Prihar et al. 1996). Surface-placed wheat straw reduced stage I evaporation compared to unmulched plots by reducing the energy reaching the soil surface. Stage II evaporation was also reduced with incorporation of wheat residue, perhaps due to disturbance of capillary movement of water to the soil surface. Large amounts (6.0 – 7.5 t ha^{-1}) of surface-placed residue effectively reduced evaporation over short periods of time, while small amounts (2.5 -3.0 t ha^{-1}) of incorporated residues were more effective in reducing evaporation over long periods of time than were large amounts of surface-placed residues. Prihar et al. (1996) acknowledged that the single wetting event in this study differs from the repeated wetting events that occur under field conditions. They also noted that the duration of stage I evaporation under mulch increased with fineness of soil texture, with the exception that very fine textured soil had a short stage I evaporation phase, similar to coarse textured soil (Prihar et al. 1996).

Legume residue also conserves soil moisture. In an experiment at Ithaca, NY, hairy vetch residue surface-applied at a rate of 11.5 tonnes ha^{-1} conserved moisture on uncropped plots from the time of application on June 6-8 until measurements ceased on August 19. Gravimetric soil water content was up to 8% higher in mulched plots than in unmulched plots after prolonged drying periods (Teasdale and Mohler 1993). Hairy vetch residue applied at 4.3 tonnes ha^{-1} conserved moisture only during the early part of the growing season, probably because decomposition reduced amounts of residue as the season progressed (Teasdale and Mohler 1993).

2.4.3 Crop development and water use

Increased soil water under surface-residues compared to residue-free soil often increases crop yields, not only in arid regions but also in humid and sub-humid regions where soils have low water-holding capacity or during periods of low precipitation (Smika and Unger 1986). However, increased soil moisture under crop residues may also have negative impacts.

As a soil nears saturation the rate at which it warms up decreases (Akinremi 2003). This delay in soil warming because of high soil moisture content may reduce the rate of crop development. Barley had reduced root and shoot growth when grown in soil at 5°C compared to 15°C (Sharratt 1991). However, Lafond et al. (1992) did not observe any delay in emergence of spring wheat under the higher moisture conditions of zero-tillage in western Canada. Similarly, the work of Gauer et al. (1981) showed that reduced temperatures under zero-tillage conditions would not be a limiting factor for wheat production in southern Manitoba, but may be a concern for corn production. McCalla and Duley (1946) did not find any negative impact on crop growth due to reduced temperatures under natural rates of mulch.

2.5 Weed control implications of mulch application

2.5.1 Introduction

Mulch applied to a field might be expected to suppress some weeds, but may also promote the growth of other weeds. A thick layer of plant matter applied on top of newly emerged or emerging seedlings would likely have a physical smothering effect. When applied just before crop emergence, the desired effect would be to allow the larger seeded crop to push through the mulch layer while smaller-seeded weeds would deplete their stored seed energy and perish (Teasdale and Mohler 2000). Other weed-suppressing mechanisms of mulch may be light interception, allelopathy, and modification of soil moisture, temperature and nutrient supply. More weeds may be controlled if mulch application is delayed and applied directly on top of a growing crop because a greater proportion of total weed emergence may have occurred compared to an application before crop emergence. However, delaying application may give weeds time to grow large enough to avoid suppression from mulch. Another consideration is that moisture conserved under the mulch layer may allow added germination of weed seeds on the soil surface (Mohler and Teasdale 1993). The added fertility from the decomposing mulch might also create a favourable environment for some weeds (Mohler and Teasdale 1993).

In a review of killing cover crops mechanically, Creamer and Dabney (2002) cite three studies where surface residue from killed cover crops was found to suppress weeds. Conversely, a study in orchard systems found that mulch from alfalfa, while providing the highest fruit yield compared to a number of other mulches, often produced the most weed growth (Granastein et al. 2001). These studies suggest that weed growth will often, but not always, be suppressed under mulch treatments.

2.5.2 Light interception by mulch

Light plays an important role in weed germination. For example, barnyard grass (*Echinochloa crusgali* (L.) Beauv.) requires light exposure for germination (Taylorson and Dinola 1989), while germination of cleavers (*Galium* spp.) is inhibited by light exposure (Malik and Vanden Born 1987). However, light exposure likely has an overall stimulation effect on weed germination since it has been demonstrated that tillage carried out in light stimulates more weed emergence than tillage done in darkness (Ascard 1994; Gallagher and Cardina 1998b). Therefore, since mulch reduces light reaching the surface of a soil (Teasdale and Mohler 1993), it follows that these reduced light conditions under mulch may reduce germination of those species that require light for germination. Teasdale and Mohler (1993) lend support to this hypothesis with their finding that light intensity reduction under rye and hairy vetch mulch appeared to reduce weed emergence. Initially rye (*Secale cereale* L.) and hairy vetch (*Vicia villosa* Roth) mulch intercepted light equally well, but over time hairy vetch allowed more light transmittance because of faster decomposition (Teasdale and Mohler 1993). In another study, Teasdale (1993) found similar weed establishment under shade cloth and under hairy vetch mulch with an equivalent light transmittance, leading him to believe that light interception was a more important factor in weed suppression than other effects such as allelopathy or physical impedance.

2.5.3 Physical impedance of weed growth by mulches

Researchers have suggested that a certain minimum amount of mulch is required before any significant weed suppression will occur (Teasdale et al. 1991). An experiment with rye and hairy vetch produced a model that predicts no weed density reduction until soil coverage by residue reaches 42%. To achieve a 75% reduction in weed density, 97% of the soil must be covered (Teasdale et al. 1991). This experiment found no difference in weed suppression between rye and hairy vetch. The work also highlighted the fact that increased ground cover is more important than increased residue biomass in suppressing weeds (Teasdale et al. 1991).

In a more recent study, Teasdale and Mohler (2000) proposed a model for predicting weed emergence through mulch based on two parameters: mulch area index and solid volume fraction. Mulch area index is defined as mulch surface area per ground surface area. Solid volume fraction is the proportion of mulch volume occupied by mulch material. These researchers investigated the following mulch materials: pine bark, corn (*Zea mays* L.) stalks, rye residue, crimson clover (*Trifolium incarnatum* l.) residue, hairy vetch residue, oak (*Quercus* spp.) leaves, and landscape fabric strips. On the basis of mulch mass or mulch height, the legume residues were equal in weed suppression to corn stalks and rye residue. However, on the basis of mulch area index, corn stalks were more suppressive than the legume residues. Mulch solid volume fraction, which was correlated with light extinction, was highest for pine bark and corn stalks and appeared to explain why these mulch materials were among the most weed suppressive.

Teasdale and Mohler (2000) found that response to mulch application differed between weed species. Weed emergence declined exponentially with increasing mulch rate for every type of mulch, with the notable exception of increased pigweed (*Amaranthus retroflexus* L.) emergence at low rates of legume mulch in one of the two years. Also, for every mulch type the sensitivity of weed species was in the following order: redroot pigweed > common lamb's quarters (*Chenopodium album* L.) > giant foxtail (*Setaria faberi* Herrm.) > velvetleaf (*Abitulon theophrasti* Medik). This ranking is perhaps explained partly by decreased emergence with smaller seed size, and partly by the ability of a species to grow around obstructing mulch particles under reduced light.

Physical impedance and light deprivation were found to be the main weed suppression mechanism (Teasdale and Mohler 2000).

2.5.4 Moisture and temperature

Mulch reduces soil temperature fluctuations and increase soil water content (Teasdale and Mohler 1993; Wagner et al. 1996; Thiessen Martens et al. 2001). At Winnipeg the canopy of a red-clover (*Trifolium pretense* L.) "living mulch" altered the microclimate compared to plots with only winter wheat stubble. The red clover canopy moderated daily air temperature fluctuations at 5 cm above the soil surface with reduced maximum temperatures and increased minimum temperatures (Thiessen Martens et al. 2001). Higher levels of crop residue in zero-till cropping systems compared to conventional tillage systems have also been linked to higher soil moisture and lower soil temperatures in the zero-till systems (Gauer et al. 1982; Lafond et al. 1992; Borstlap and Entz 1994). Therefore, depending on the specific germination requirements of a weed seed, the altered soil moisture and altered soil temperature due to mulch may enhance or suppress weed establishment.

Increased soil moisture under mulch may increase weed emergence (Teasdale and Mohler 1993; Mohler and Teasdale 1993; Boyd and Van Acker 2003). Mohler and Teasdale (1993) found that emergence of dandelion (*Taraxacum officinale* Weber in Wiggers), common chickweed (*Stellaria media* (L.) Cyril), and curly dock (*Rumex crispus* L.) increased at low mulch rates before declining at higher mulch rates. They used rye and hairy vetch mulch, with little difference observed between them in terms of weed emergence response, and postulated that increased soil moisture may have enhanced germination at low mulch levels. Boyd and Van Acker (2003) found that when soil moisture levels fluctuated, emergence of curly dock (*Rumex crispus* L.), foxtail barley (*Hordeum jumbatum* L.), and dandelion was reduced compared to when soil moisture was held at field capacity. Decreased emergence with fluctuating soil moisture was attributed to surface drying which produced unfavourable conditions for germination of these species (Boyd and Van Acker 2003). Therefore, it is expected that reduced surface drying under mulch (i.e., less surface soil moisture fluctuation) will enhance emergence of the weed species listed above.

While increased moisture under mulch may improve conditions for weed emergence, decreased soil temperatures under mulch may reduce emergence of weeds. For example, barnyard grass (*Echinochloa crusgalli* (L.) Beauv.) germination is known to respond positively to increased temperatures (Taylorson and Dinola 1989). Based on soil temperature measurements under zero-tilled and conventional tilled treatments, Gauer et al. (1982) predicted that cooler temperatures under the higher residue conditions of zero-tillage would slow down green foxtail (*Setaria viridis* (L.) Beauv.) emergence more than wheat. In other studies, no significant reduction or delay in emergence of wheat was found under zero-till conditions (Lafond et al. 1992; Borstlap and Entz 1994). Therefore, reduced soil temperature under mulch may give an emergence advantage to crops like wheat over weeds such as barnyard grass and green foxtail.

2.5.5 Effect of mulch-supplied nutrients on weeds

Legume mulches such as alfalfa often contain high amounts of readily mineralizeable nutrients, especially N, which could potentially stimulate weed emergence and growth. However, release of nutrients from mulches, even rapidly decomposable legume mulches, is often slower than from inorganic fertilizers (Groffman et al. 1987), and may therefore influence weed growth differently than nutrients supplied by inorganic fertilizers.

There is some evidence that certain weed species, such as redroot pigweed and lamb's quarters, have increased germination rates as nitrate levels increase (Fawcett and Slife 1978; Blum et al. 1997; Gallagher and Cardina 1998a; Benech Arnold et al. 2000). Increased weed emergence at low application rates of legume mulches has been attributed to nitrate released from mulch (Blum et al. 1997; Teasdale and Mohler 2000). Emergence of redroot pigweed, lamb's quarters, giant foxtail, and velvetleaf was monitored under various rates of the following mulches: bark chips, corn stalks, rye straw, crimson clover, hairy vetch, oak leaves, and landscape fabric strips. Emergence of all weed species declined with increased rates of all types of mulch with the notable exception of redroot pigweed in one of two years, which displayed increased emergence under the low rates of the two legume mulches (*Trifolium incarnatum* and *Vicia villosa*) (Teasdale and Mohler 2000). The authors suggest that nitrate from the legumes may have stimulated redroot pigweed emergence. Despite increased germination when ammonium nitrate was applied to lamb's quarters seeds in the laboratory, no significant increase in germination was seen in field plots when ammonium nitrate was increased from 0 to 280 kg ha^{-1} (Fawcett and Slife 1978). Fawcett and Slife (1978) speculated that perhaps the natural fertility of the soil provided enough nitrate to eliminate any stimulating mechanism from added fertilizer, or perhaps other factors, such as temperature and moisture are more important than nitrate in affecting weed seed germination.

Groffman et al. (1987) found that N from legume inputs became available to plants more slowly than N from ammonium nitrate. They also found that weed growth was higher with legume-N treatments than with ammonium nitrate and suggest one reason may be the difference in N-release pattern between legumes and ammonium nitrate. They failed to elaborate on how slower N-release from legume residue may cause increased weed growth.

2.5.6 Allelopathy

Allelopathy is the effect on surrounding plants from chemicals released by either growing plants or decaying plant residue. Medicarpin, chlorogenic acid, and cinnamic acid and its derivatives (especially *p*-coumaric and *trans*-cinnamic acid) are potentially allelopathic compounds that have been isolated from alfalfa (Miller 1996;Chon and Kim 2002). For example, medicarpin reduced germination and seedling length of alfalfa and velvetleaf (Miller 1996), and *trans*-cinnamic acid reduced root growth of alfalfa and barnyard grass (Chon et al. 2002). Water-soluble extracts from alfalfa residue inhibited root growth of both alfalfa and barnyard grass when seeds were germinated in petri dishes (Chon et al. 2002). Barnyard grass was more affected than alfalfa, suggesting that allelopathic effects of alfalfa on other species are stronger than autotoxic effects (Chon et al. 2002). Hedge and Miller (1990) also concluded that alfalfa allelopathy was stronger than autotoxicity. When alfalfa extracts from different alfalfa plant parts were analyzed separately, alfalfa leaf extracts were more phytotoxic than stem or root extracts (Chon and Kim 2002).

Chung and Miller (1995) reported that when mixed with soil in the greenhouse, alfalfa residue stimulated growth of monocotyledonous weeds while suppressing dicotyledonous weeds. They found that lamb's quarters, pigweed, and velvetleaf were inhibited by alfalfa residue, while giant foxtail, cheatgrass (*Bromus secalinus* L.), and crabgrass (*Digitaria sanguinalis* (L.) Scop.) were stimulated to some extent by alfalfa residue.

2.6 Literature review summary

The high N content and chemical composition of alfalfa enable rapid breakdown and release of N for use by other crops. Factors such as particle size, method of application, environmental conditions, and timing of application will affect the rate of N mineralization of alfalfa residue and will determine the availability of residue N to a crop. Particle size can affect decomposition rates, although effect of particle size on decomposition of legume residue is inconsistent. Decomposition rate is often greater when crop residues are incorporated compared to surface-applied because of greater contact with microbial populations. Surface-application of legume residue often increases volatilization compared to incorporation, while incorporation often leads to increased denitrification and leaching losses. Timing of application of alfalfa mulch will impact the synchrony of N release from mulch with N uptake by a crop.

By improving water infiltration and reducing evaporation crop residues increase soil moisture. Yield benefits due to soil moisture conserved under mulch may be expected even in wetter portions of the Canadian prairies due to frequent moisture shortfalls for maximum spring wheat yield. Cooler soil temperatures due to higher soil water content under crop residues did not negatively affect wheat growth.

Mulch will affect weed germination, emergence and growth through the effects of light interception, physical impedance to weed growth, alteration of soil temperature and moisture, nutrient dynamics, and allelopathy. Light interception by mulch may play a greater role in weed suppression than other suppression mechanisms such as physical impedance or allelopathy. Weed densities will likely decline with increasing mulch rate, but an initial increase in density for some weed species at low levels of legume mulch may be caused by a weed germination response to increased soil nitrate or soil moisture levels. Soil coverage has been found to be more important than total mulch biomass in determining weed suppression. Allelopathy has been observed with alfalfa residues but may be of minor significance in the field.

3.0 MATERIALS AND METHODS

3.1 Background

Experiments were conducted in 2002 and 2003 at the University of Manitoba "Point" research facility, at Winnipeg, MB, and at the U of M Plant Science Research Station at Carman, MB. In 2002 trials were also conducted on organic farms at Kenton, MB and Clearwater, MB. Climate data for the 2002 and 2003 growing seasons were obtained from the weather monitoring stations at the Winnipeg and Carman research locations and are presented in Table 3.1 and Figures 3.1 to 3.4. Climate data for Kenton and Clearwater were obtained from the nearest Environment Canada station and are presented in Table 3.2.

Table 3.1. Total monthly precipitation for Winnipeg and Carman in 2002 and 2003.

Site	Year	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
							mm						
Winnipeg[z]	2002	-	-	-	18.2	45.1	128.9	97.9	101.6	49.3	8.5	-	-
	2003	-	-	-	15.5	72.6	76.4	42.3	82.2	41	-	-	-
	Normal[y]	19.7	14.9	21.5	31.9	58.8	89.5	70.6	75.1	52.3	36	25	18.5
Carman[x]	2002	10.7	4.3	15.5	12.8	41.4	141.0	49.4	129.2	21.0	8.7	9.0	12.6
	2003	8.0	7.4	13.4	32.2	80.2	81.0	56.4	70.8	36.2	24.1	11.8	34.3
	Normal[w]	21.2	19.2	30.1	38.4	61.1	75.5	73.5	66.8	59.9	43.8	21.7	22.8
							% of normal						
Winnipeg													
2002					57.1	76.7	144.0	138.7	135.3	94.3	23.6		
2003					48.6	123.5	85.4	59.9	109.5	78.4			
Carman													
2002		50.5	22.4	51.5	33.3	67.8	186.8	67.2	193.4	35.1	19.9	41.5	55.3
2003		37.7	38.5	44.5	83.9	131.3	107.3	76.7	106.0	60.4	55.0	54.4	150.4

z Source: Point Weather Station, University of Manitoba, Winnipeg, Manitoba.

y Source: Environment Canada 30 year average for 1971-2000 at the Winnipeg International Airport.

x Source: Environment Canada data for University of Manitoba Carman Research Station.

w Source: Environment Canada 30 year average for 1971-2000 at Graysville.

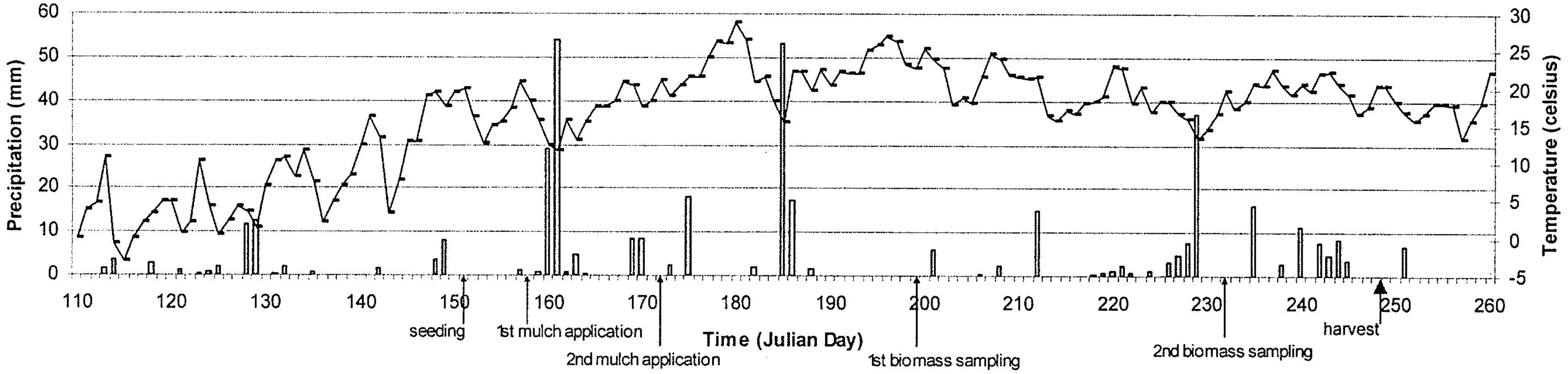

Figure 3.1. Daily growing season (April 20 to September 17) precipitation and mean air temperatures at Winnipeg in 2002, with dates of major operations indicated.

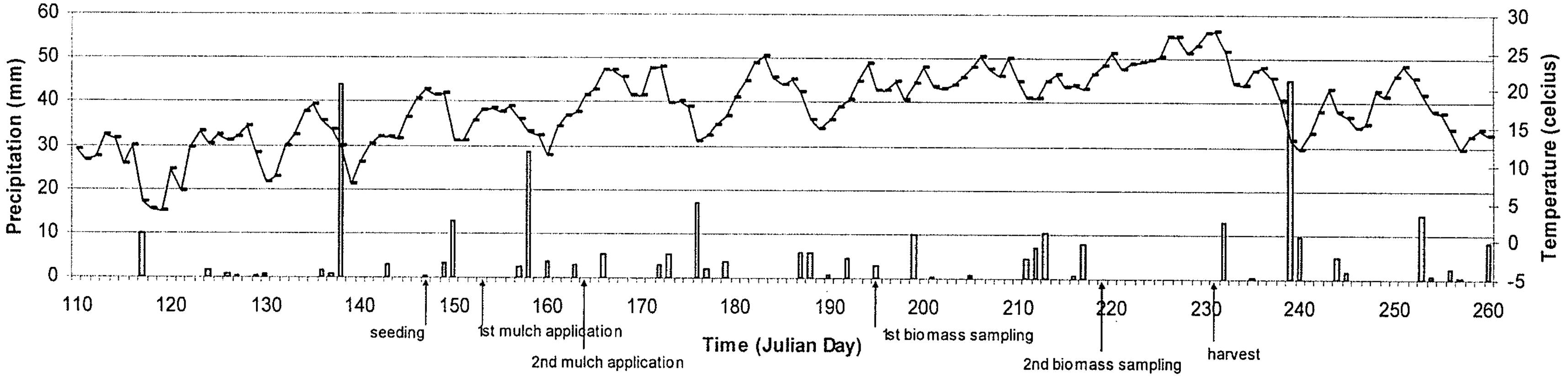

Figure 3.2. Daily growing season (April 20 to September 17) precipitation and mean air temperatures at Winnipeg in 2003, with dates of major operations indicated.

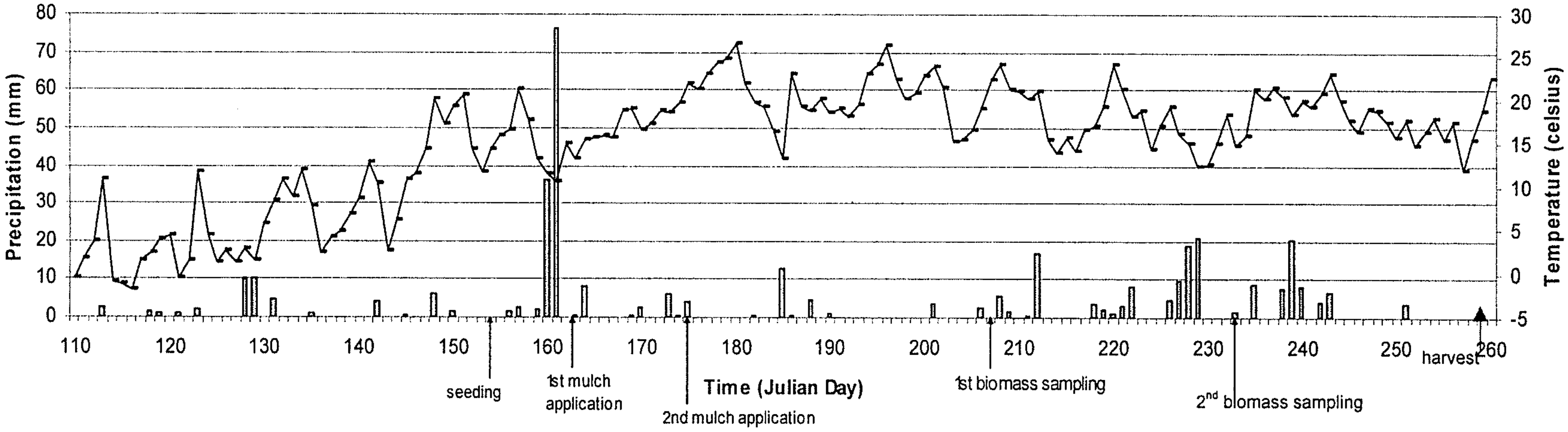

Figure 3.3. Daily growing season (April 20 to September 17) precipitation and mean air temperatures at Carman in 2002, with dates of major operations indicated.

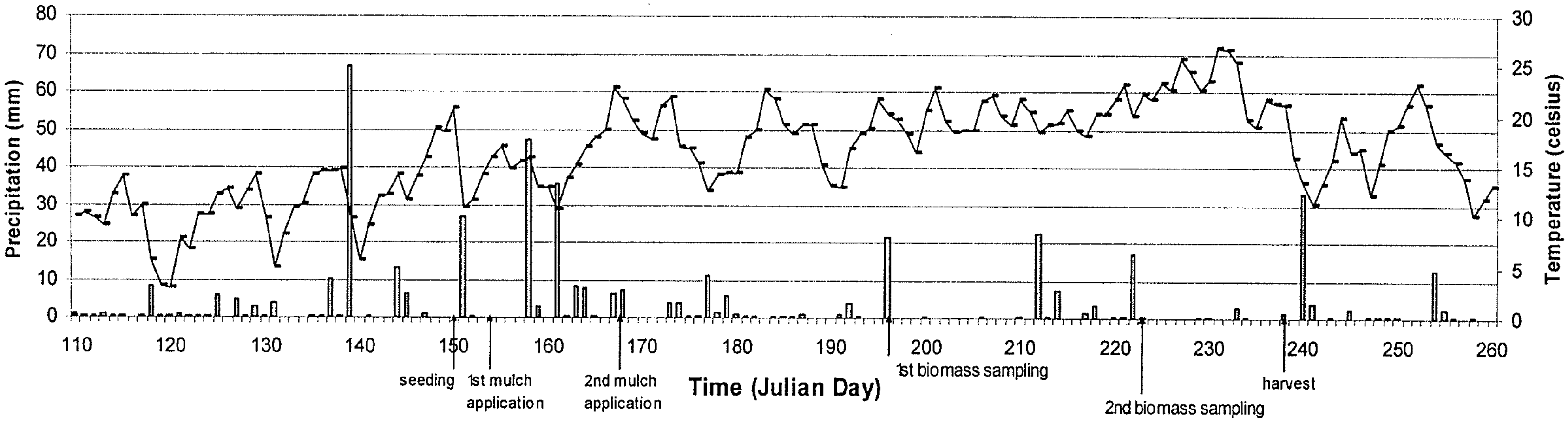

Figure 3.4. Daily growing season (April 20 to September 17) precipitation and mean air temperatures at Carman in 2003, with dates of major operations indicated.

Table 3.2. Total monthly precipitation for Kenton, Manitoba and Clearwater, Manitoba in 2002.

Site	Year	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
		mm											
Kenton^z	2002	7.0	2.0	16.0	18.9	9.2	73.4	71.6	136.2	40.0	8.2	5.0	46.0
	Normal^y	25.9	19.5	24.3	26.1	53.6	88.1	69.6	62.2	52	31.1	18.5	23.5
Clearwater^x	2002	-	-	-	12.8	29.2	141.8	74.8	168.4	14	9	-	-
	Normal^w	21	16.6	22.7	35.9	58.2	82.1	63.6	69.6	56	37.7	20.2	20.3
		% of normal											
Kenton		27.0	10.3	65.8	72.4	17.2	83.3	102.9	219.0	76.9	26.4	27.0	195.7
Clearwater		-	-	-	35.7	50.2	172.7	117.6	242.0	25.0	23.9	-	-

z Source: Environment Canada data for Kenton, Manitoba.

y Source: Environment Canada 30 year average (1971-2000) for Oakner, Manitoba.

x Source: Environment Canada data for Pilot Mound, Manitoba.

w Source: Environment Canada 30 year average (1971-2000) for Pilot Mound, Manitoba.

Before the experiments were established the soil at each experimental site was randomly sampled and sent to Norwest Labs for chemical analysis. Dates of soil sampling, soil nutrient levels, and soil types are summarized in Table 3.3.

Table 3.3. Soil type, sampling dates, and soil nutrient levels for sites at Winnipeg, Carman, Kenton, and Clearwater, Manitoba.

Experiment	Location	Soil type	Sampling Date	Soil Nitrate	P	K	S
				kg ha^{-1}			
Rate x time-of-application	Winnipeg 2002	Riverdale silty clay	May 2, '02	48.2	315.0	3134.0	17.9
	Carman 2002	Hochfeld sandy loam	May 3, '02	53.8	78.5	1041.3	21.3
	Winnipeg 2003	Riverdale silty clay	Oct. 21, '02	66.0	134.5	1267.7	59.4
	Carman 2003	Reinfeld sandy loam	April 22, '03	118.7	54.9	600.8	96.4
	Kenton	Harding clay	--	--	--	--	--
	Clearwater	clay loam	--	--	--	--	--
Rate x incorporation	Winnipeg 2002	Riverdale silty clay	April 26, '02	42.6	143.5	3720.3	90.8
	Carman 2002	Denham sandy clay loam	May 3, '02	77.3	90.8	3141.9	32.5
Rate x particle size	Winnipeg 2002	Riverdale silty clay	April 26, '02	42.6	143.5	3720.3	90.8

The experimental design of all experiments was a randomized complete block with four replicates. Canada Western Red spring wheat (cv. AC Barrie) was seeded at a rate of 135 kg ha^{-1} using a no-till disc drill (Fabro Enterprises Ltd., Swift Current, SK) set at a 15 cm row spacing. Plot size was 2 x 6 m at Winnipeg, and 2 x 8 m at Carman. The 2002 and 2003 seeding dates are summarized in Table 3.4. Previous cropping history is reported in Table 3.5.

Table 3.4. Seeding and harvest information for mulch experiments in 2002 and 2003.

		Seeding information		Harvest information	
Year	Location	Date	Crop and Seeding rate	Date	Harvested area
2002	Winnipeg	May 31	wheat, 135 kg/ha	Sept 5	4x1.2 m
	Carman	June 3	wheat, 135 kg/ha	Sept 12	4x1.2 m
	Clearwater	~May 20	wheat, ~135 kg/ha	Sept 4	8x1.2 m
	Kenton	~May 21	oats, 90 kg/ha	Sept 3	8x1.2 m
2003	Winnipeg	May 6	oats, 119 kg/ha	Aug 13	6x1.2 m
		May 27	wheat, 135 kg/ha	Aug 19	6x1.2 m
	Carman	May 30	wheat, 135 kg/ha	Aug 26	8x1.7 m

Table 3.5. Cropping history of land on which experiments were conducted at Winnipeg, Carman, Kenton, and Clearwater.

Experiment	Location	Previous crop	Crop two years previous
Rate x time-of-application	Winnipeg 2002	oat	wheat
	Carman 2002	wheat	perennial ryegrass followed by a fall rye cover crop
	Winnipeg 2003	wheat	beans/canola/sunflower
	Carman 2003	oat	canola
	Kenton	oat/red clover greenfeed	oat greenfeed
	Clearwater	flax	alfalfa/grass
Rate x incorporation	Winnipeg 2002	oat	wheat
	Carman 2002	wheat	fall rye
Rate x particle size	Winnipeg 2002	oat	wheat

Table 3.6. Mulch amounts and corresponding amounts of N applied to plots.

Experiment	Location	Date cut^z	Initial Soil N kg ha^{-1}	Rate	Dry matter t ha^{-1}	%N in alfalfa	N Applied kg ha^{-1}
Rate x time-of-application	Winnipeg 2002	07 June (Early)	48.2	0.5x	0.97	4.11	39.9
				1.0x	1.97		81.0
				2.0x	3.94		161.9
		21 June (Late)		0.5x	1.31	3.52	46.1
				1.0x	2.61		91.9
				2.0x	5.22		183.7
	Carman 2002	12 June (Early)	53.8	0.5x	0.87	4.19	36.5
				1.0x	1.73		72.5
				2.0x	3.46		145.0
		24 June (Late)		0.5x	1.44	3.62	52.1
				1.0x	2.88		104.3
				2.0x	5.76		208.5
	Kenton/Clearwater 2002	17 June (Late)		0.5x	1.88	3.50	65.8
				1.0x	3.76		131.6
				2.0x	7.52		263.2
	Winnipeg 2003	1 October '02 (Fall)	66.1	0.5x	0.49	3.62	17.7
				1.0x	0.97		35.1
				2.0x	1.93		69.8
		2 June '03 (Early)		0.5x	0.98	3.49	34.2
				1.0x	1.95		68.0
				2.0x	3.9		136.0
		applied 13 June '03 (Frozen)^y		0.5x	0.98	3.49	34.2
				1.0x	1.95		68.0
				2.0x	3.9		136.0
		13 June '03 (Late)		0.5x	1.08	2.74	29.5
				1.0x	2.16		59.1
				2.0x	4.32		118.2

Table 3.6. (continued) Mulch amounts and corresponding amounts of N applied to plots.

Experiment	Location	Date cut[z]	Initial Soil N kg ha^{-1}	Rate	Dry matter tonnes ha^{-1}	%N in alfalfa	N Applied kg ha^{-1}
Rate x time-of-application	Carman 2003	26 Sept '02(Fall)	118.7	0.5x	0.43	3.30	14.2
				1.0x	0.86		28.3
				2.0x	1.72		56.7
		3 June '03 (Early)		0.5x	0.77	3.78	29.1
				1.0x	1.53		57.8
				2.0x	3.06		115.5
		applied 17 June '03 (Frozen)[y]		0.5x	0.77	3.78	29.1
				1.0x	1.53		57.8
				2.0x	3.06		115.5
		17 June '03 (Late)		0.5x	1.66	2.98	49.4
				1.0x	3.32		98.8
				2.0x	6.64		197.6
Rate x incorporation	Winnipeg 2002	07 June	42.6	0.5x	0.97	4.11	39.9
				1.0x	1.97		81.0
				2.0x	3.94		161.9
	Carman 2002	12 June	77.3	0.5x	0.87	4.19	36.5
				1.0x	1.73		72.5
				2.0x	3.46		145.0
Rate x particle size	Winnipeg 2002	07 June	42.6	0.5x	0.97	4.11	39.9
				1.0x	1.97		81.0
				2.0x	3.94		161.9

[z] Crop stage at date of application is designated as Early for before emergence, Late for three-leaf stage, and Fall for application the previous fall.

[y] Mulch was harvested when wheat was at the emergence stage and stored in a freezer until application at the three-leaf stage.

The base rate of alfalfa mulch used for these experiments was the 'natural rate' of mulch, i.e., the yield (kg ha^{-1}) of alfalfa biomass growing at a location at the time of mulch application. The natural rate of mulch was chosen over the fixed rate (i.e. constant amount at all locations and application timings) in order to mimic what may occur in a strip farming system where strips of perennial forages are grown between equivalent strips of annual crops. In such a system the amount of mulch available for application on the annual crops would be limited to the amount of forage biomass in the field at the time of application. Therefore, the rates of alfalfa mulch applied to wheat in these experiments were always 0.5, 1, and 2 times the yield of alfalfa biomass. Another way to describe these rates is the alfalfa biomass harvested from 0.5x, 1x and 2x the wheat plot area. The amounts of alfalfa dry matter applied and the application dates in each experiment are summarized in Table 3.6.

Alfalfa was harvested with a walk-behind flail mower (Swift Machine and Welding, Swift Current, SK) that cut the alfalfa at approximately 6 cm above the soil surface. The mulch was put into large plastic garbage bags and weighed using a balance scale. Mulch application to wheat plots occurred within several hours of mulch harvest. Mulch was applied to the wheat plots by hand with care taken to ensure uniform application. At the time of each mulch application alfalfa mulch was sub-sampled, weighed, dried at 70°C until dry, weighed again to determine the amount of dry matter applied with each treatment. Random sub-samples were also air-dried and were sent to Norwest Labs in Winnipeg for nutrient analysis.

N content of mulch at each application date is summarized in Table 3.6. The Norwest analysis did not include carbon concentration. Therefore, alfalfa samples were retrieved from Norwest Labs and sent to the Animal Science department at the University of Manitoba to determine %C and %N, and also %S. Values for N concentration differed for the two labs. The discrepancy was assumed to be due to a gain in moisture content during storage and transport between Norwest Labs and Animals Science since samples were not re-dried at the Animal Science Lab. Norwest's values were used to determine mulch N content, while the C and N values determined by Animal Science were used to determine C/N ratio.

Three experiments were conducted to investigate the productivity of organically grown wheat receiving different rates of alfalfa mulch. The rate x time-of-application experiment examined the effect on wheat of alfalfa mulch applied at different rates and at different stages of crop development. The rate x incorporation experiment looked at the effect of mulch rate and mulch incorporation, and the rate x particle size experiment investigated whether mulch particle size caused different effects on wheat with different mulch application rates.

All three of these experiments were initiated in 2002. In 2003 the project was narrowed to focus primarily on the effect of rate and timing of mulch application on wheat productivity. The rate x time-of-application experiment was conducted at four locations in 2002: Winnipeg, Carman, Clearwater, and Kenton, and was repeated in 2003 at Winnipeg and Carman. The rate x incorporation experiment was conducted at only two site years: Winnipeg 2002 and Carman 2002, and the rate x particle size experiment was conducted only at Winnipeg in 2002.

3.2 Rate x time-of-application experiment

To study the effect of mulch application timing on wheat productivity, different rates of alfalfa mulch were applied at two different wheat development stages: before emergence and at the three-leaf stage. Mulch treatments applied before emergence are referred to as "early," while mulch treatments applied at the three-leaf stage are referred to as "late."

At Winnipeg 2002 the experiment was conducted on land that had grown oats in 2001 and wheat in 2000. At Carman 2002 the previous crops were wheat in 2001 and perennial rye grass followed by a fall rye cover crop in 2000 (Table 3.5). The 2002 trials contained ten treatments: three rates of early-applied mulch, three rates of late-applied mulch, three rates of ammonium nitrate (20, 40, and 60 kg N ha^{-1}) and a control (no mulch, no ammonium nitrate). As described above, the mulch rates were determined by using the flail mower to harvest alfalfa in a nearby field from an area 0.5x, 1x and 2x the size of the wheat plots. Ammonium nitrate was broadcast-applied on the same date as the early mulch treatment.

The 2003 experiment at Winnipeg was established on land that was sown to wheat in 2002. At Carman the previous crop was oats. The 2003 trials contained the same 10 treatments as 2002, plus seven additional treatments. The additional treatments in 2003 included three rates of third-cut alfalfa (0.5x, 1x, and 2x) harvested and applied as mulch in the fall of 2002 to provide insight into N availability to wheat from alfalfa mulch applied the previous fall. These treatments are referred to as "fall" treatments. Another additional treatment received a 1x rate of fall-applied mulch plus a 1x rate of mulch applied before wheat emergence in 2003. The fall-applied mulch was incorporated with two passes in opposite directions by a field cultivator traveling the length of the plots.

Because the amount of mulch applied to the wheat depended on the amount of alfalfa top growth available at each location at time of alfalfa harvest, the amount of mulch applied at Winnipeg and Carman at the three-leaf stage was larger than the amount applied at Winnipeg at the emergence stage. Similarly, the mulch amounts applied differed between the two locations. Therefore, adoption of the natural yield of alfalfa as a base rate creates some limitations in analysis of mulch effects. In addition to applying different amounts of mulch, the nutrient composition of the mulch differed with location and time of application. In an attempt to clarify the effect of mulch rate and mulch nutrient composition, another three treatments were added in 2003. These treatments consisted of three rates of alfalfa mulch harvested at the time of the early application but stored until the time of the late application. Storage involved placing harvested alfalfa into air tight plastic bags and immediately placing the bags into a walk-in freezer. These treatments are referred to as the "frozen" treatments. The N content of these treatments was assumed to be the same as the N content of the early treatments which were not frozen.

Due to incorrect settings of the flail mower during the late harvest at Winnipeg in 2003 not all the alfalfa was harvested and so mulch application rates were based on a rate that was estimated at 33% less than the true natural yield. Despite the lower application rates of the late treatments, these data included because they provide valuable information on the effect of mulch applied at increasing rates when wheat is at the three-leaf stage.

Two additional trials were carried out in 2002 on organic farms to assess the effect on grain yield and protein of different rates of alfalfa mulch applied to cereal crops at only the three-leaf stage. The farms were located at Kenton, MB, where alfalfa mulch was applied to an oat crop, and at Clearwater, MB, where alfalfa mulch was applied to spring wheat. Previous crops grown at Kenton were an oat/red clover mixture (predominantly oat) harvested for green feed in 2000 and an oat crop harvested for green feed in 2001. The previous crops at Clearwater were an alfalfa/grass mixture harvested for hay in 2000 and several years prior, and flax in 2001. The mulch applied to these plots was harvested at Glenlea, MB and transported to each location. Treatments consisted of three mulch rates and a control (no mulch). As in the other trials the mulch rates were low, medium and high based on the amount of alfalfa mulch harvested from an area 0.5x, 1x and 2x the size of the wheat plots. The plots were 2 x 8 m in size. The experiments were set up in a randomized complete block design and replicated four times. Grain yield and protein were measured.

3.3 Rate x incorporation experiment

Alfalfa mulch rate and incorporation effects on wheat were tested with a factorial experiment. The design was a randomized complete block replicated four times with a factorial set of fourteen treatments in each block. The treatments consisted of seven treatments without incorporation plus the same seven treatments with incorporation. These seven treatments were three rates of mulch applied before wheat emergence, three rates of ammonium nitrate and a control (no mulch, no ammonium nitrate). A single-pass incorporation operation was done immediately after mulch application using a tractormounted rotary hoe. The tractor was driven over all plots, with the rotary hoe lifted for those plots not receiving the incorporation treatments. Trials were conducted in 2002 at Winnipeg and Carman. For the Winnipeg trial alfalfa mulch was harvested at Glenlea, MB and immediately transported and applied to plots. At Carman alfalfa was harvested from an alfalfa plot located within 100 m of the wheat plots. Wheat was just beginning to emerge at Carman at the time of mulch application. At Winnipeg the land produced an oat crop in 2001 and a wheat crop in 2000. At Carman the previous crops were wheat in 2001 and oats followed by a cover crop of fall rye in 2000.

3.4 Rate x particle size experiment

The effect on spring wheat of different sized alfalfa mulch particles was examined by applying different rates of mulch of three different particle sizes. This experiment was performed only at Winnipeg in 2002 on land that grew oats in 2001 and wheat in 2000. Alfalfa mulch was harvested at Glenlea, MB and immediately transported and applied to the wheat plots in Winnipeg. A total of thirteen treatments were implemented consisting of the seven non-incorporated treatments described in the incorporation experiment with the flail mower mulch treatments designated as the small particle size (<5 cm lengths). The other treatments included three rates (0.5x, 1x and 2x) of long stem alfalfa mulch (~20-25 cm lengths of alfalfa top-growth) produced by cutting alfalfa approximately 7 cm above the ground using a Haldrup forage plot harvester (J. Haldrup a/s, Løgstør, Denmark), and three rates of alfalfa mulch of a medium particle size (4-6 cm lengths), created with a New Holland Model 790 pull-type forage harvester. The Haldrup forage plot harvester was used to cut alfalfa and place it in a swath that was then picked up and chopped with a New Holland forage harvester. The small particles created with the flail mower were crushed to a greater extent than the relatively cleanly cut particles created with the New Holland forage harvester.

3.5 Measurements

Wheat development was estimated by using the Haun stage (Haun 1973). Haun stage was calculated by averaging five randomly selected plants per plot. Plant density counts were conducted one to two weeks after mulch application to determine if mulch application eliminated a significant number of wheat plants. Plant density was determined by counting plants in a 1 m length along two rows of wheat. Plant density values were converted to an area basis (plants m^{-2}).

Weeds were counted in early July after most weeds had emerged, using two counts for each plot using ¼ m^2 quadrats except where weed density was very high, where 1/10 m^2 quadrats were used. Weeds were identified and counted on an individual species basis.

Soil moisture was measured only in the rate x time-of-application experiment. Soil moisture on 0-10 cm core samples was taken with a hand auger between crop rows in one location per plot approximately every ten days, beginning after the late mulch application. Soil moisture content was measured gravimetrically, by weighing soil samples before and after being oven-dried.

Biomass accumulation in the wheat was determined at anthesis and at the soft dough stage. Above ground plant growth was harvested from ¼ m^2 in each plot, dried at 70°C for a minimum of 48 hours and then weighed. Biomass samples were ground to pass through a 2 mm screen using a Wiley Mill (Arthur H. Thomas Co., Philadelphia, PA), then sub-sampled, for analysis of N concentration by a dry combustion method using a Leco N Analyzer (model FP-428; Leco Corp., Mississauga, ON). Total N uptake was calculated by multiplying crop biomass (kg ha^{-1}) by % N. N use efficiency (NUE) was calculated as:

$$\frac{(\text{treatment N uptake} - \text{control N uptake})}{\text{total N applied}} * 100 .$$

The relative effects of ammonium nitrate and alfalfa mulch on grain yield and grain N yield were also compared by calculating yield efficiency and grain N efficiency. Grain yield efficiency was calculated as:

$$\frac{(\text{ grain yield of treatment} - \text{grain yield of control})}{\text{total N applied}}$$

and was expressed as kg of grain per hectare per kg of applied N. Grain N yield efficiency was calculated as:

$$\frac{(\text{grain N yield of treatment} - \text{grain N yield of control})}{\text{total N applied}}$$

and was expressed as kg of grain N per hectare per kg of applied N.

Grain yield for each treatment was determined by harvesting a pre-determined area from each plot (Table 3.4) with a small plot combine and weighing the wheat after it had been cleaned. Harvest dates are also summarized in Table 3.4. Random sub-samples of grain were ground in a Cyclone Sample Mill (Udy Corporation, Fort Collins, CO) and then subjected to an N concentration analysis using the Leco N Analyzer. Wheat protein concentration was calculated by multiplying N concentration by 5.7, the factor used for for wheat intended for human consumption. Oat grain, with hulls still present, was ground to pass through a 2 mm screen using a Wiley Mill before being analyzed for N content with the Leco N Analyzer. A factor of 6.25 was used to convert oat N concentration to grain protein equivalent for feed crops. Straw was removed from all plots following grain harvest.

3.6 Second year mulch effects

In 2003 an oat crop (cv. Assiniboia) was seeded at a rate of 119 kg ha^{-1} on all plots of the three experiments conducted at Winnipeg in 2002. The purpose was to measure second-year N uptake in the plots that contained alfalfa mulch-treated wheat in 2002. The plots received no fertilizer amendments in 2003. Crop biomass was measured when the oats were at the soft-dough stage. Biomass samples were then ground, sub-sampled and analyzed for N content as described for the wheat biomass, and total N uptake was calculated by multiplying biomass yield by N concentration. Oat grain yield and protein concentration were also measured.

3.7 Statistical analysis

The Proc GLM procedure of SAS Institute Inc. (SAS version 8, 1999) was used to analyze variance on all parameters. Effects were considered significant at a P value of <0.05 unless otherwise indicated. Where significant treatment effects were detected, Fischer's protected Least Significant Difference (LSD) test was used to determine if treatments were significantly different from one another.

Heterogeneity of variance across treatments was tested by applying Bartlett's test (Steel et al. 1997) to the residuals of the treatment groups from the randomized complete block analysis. When there was significant heterogeneity of variance, plots of residuals were used to assess the nature of the heterogeneity. Plots of the residuals (vertical axis) versus predicted values (horizontal axis) should show a uniform vertical range of residuals across the range of predicted values. A funnel shaped pattern where vertical range increases with predicted value indicates that the log transformation of the observed variable will make variance across treatments more uniform (Box and Hunter 1978). The log transformation ($Y = \log(y+1)$ or $Y = \log(y)$) was found to produce data which conformed to the ANOVA assumptions. The nature of the response (linear, quadratic, cubic) to the quantitative levels of a factor (mulch rate, ammonium nitrate rate) were evaluated using sets of orthogonal polynomial contrasts (Gill 1978). Other contrasts representing questions of interest were also included.

4.0 RESULTS AND DISCUSSION

4.1 Influence of alfalfa mulch rate and time of application on wheat

The rate by time-of-application experiment was conducted to investigate the effects of applying alfalfa mulch at different rates and at different application timings on wheat growth and productivity. Mulch characteristics, application rates and dates of application are reported in Table 3.6. In general, applying alfalfa mulch to wheat had positive effects, and that those effects increased as alfalfa mulch rate increased. In several situations differences were detected between early (before emergence) and late (three-leaf stage) mulch applications; however, mulch application rate was a more important factor than timing of mulch application.

4.1.1 Wheat plant-stand density

The recommended range of plant densities for wheat in Manitoba is between 250 and 300 plants m^{-2} (Manitoba Agriculture and Food 2001). Final wheat plant densities in 2002 were below those recommendations, with an average density of 220 plants m^{-2} (Table 4.1); however, this was not a result of mulch application as there were no significant differences between treatments. Carman in 2003 was the only site-year where a mulch application caused a significant loss of wheat seedlings compared to the control (Table 4.1) (297 plants m^{-2} vs. 213 plants m^{-2} for the late 2x application only). The loss of plants under this mulch treatment may have been caused by smothering. The double rate of mulch applied at the three-leaf stage at this site-year (6.6 tonnes ha^{-1} (dry basis)) was the highest rate of mulch used at Winnipeg and Carman over the two years of the study. Yunusa et al. (1994) found no difference in the plant population density between control plots and wheat plots mulched with wheat straw at a rate of eight tones per hectare. Nevertheless, the significant loss of plants at Carman 2003 suggests that a rate of 6.6 tonnes ha^{-1} of alfalfa mulch may be excessive for optimum wheat plant establishment. Mulch applied at Carman in 2003 at a rate of 3.32 tonnes ha^{-1} (the 1xLate treatment) did not significantly reduce wheat plant density (Table 4.1). In 2002 mulch applied at the 2x rates of 5.2 and 5.4 tonnes ha^{-1} (late stage application) at Winnipeg and Carman respectively, did not significantly affect plant stand density (Table 4.1).

Table 4.1. The effect of mulch level and application timing on wheat plant density at Winnipeg and Carman in 2002 and 2003.

	---- 2002 ----		---- 2003 ----	
Treatment^z	Winnipeg	Carman	Winnipeg	Carman
	---- plants m^{-2} ----			
control	221	210	325	297a^y
20kgN	218	214	ND^x	ND
40kgN	218	233	ND	ND
60kgN	226	210	ND	ND
0.5xEarly	229	230	ND	ND
1xEarly	219	222	ND	ND
2xEarly	214	228	302	298a
0.5xLate	230	220	ND	ND
1xLate	210	220	ND	ND
2xLate	201	227	272	213b
2xFrozen^w	NA^v	NA	277	278a
LSD(0.05)	NS	NS	NS	32
P>F	0.8474	0.9463	0.209	0.0006
Mean	218	221	294	271
Early vs Late	NS	NS	NA	NA

z 0.5x, 1x and 2x refer to the amount of alfalfa harvested from an area 0.5, 1 and 2 times the wheat plot area. Refer to Table 3.6 for amounts of alfalfa mulch applied. The 20, 40, 60kgN treatments consisted of 20, 40 and 60 kg N/ha applied as ammonium nitrate. Early application timing was before wheat emergence. Late application timing was at the three-leaf stage.

y Means followed by the same letter within a column are not significantly different (*P* > 0.05) according to Fisher's protected LSD.

x ND = not determined.

w Mulch was harvested at the Early application stage and stored in a freezer until the Late stage application.

v NA = not applicable, NS = non-significant.

4.1.2 Wheat development

Delayed wheat development by mulch through delayed emergence or slower plant development was evaluated. Teasdale and Mohler (2000) found delayed emergence of weeds from physical impedance by various mulch materials, including legume mulches. After emergence, mulch may also reduce soil temperatures enough to slow wheat development (Yunusa et al. 1994). In the present study, application of mulch resulted in several significant effects on wheat development. For example, on July 17, 2002 at Winnipeg, the higher rate (40 and 60 kg N ha^{-1}) inorganic N treatments were significantly more advanced than wheat in several of the mulched treatments (Table 4.2). The high-rate inorganic N treatments were at the initial stages of spike emergence (9.1 – 9.3 Haun units), while the least developed mulched treatments were at the initial stages of boot enlargement (8.0 – 8.3 Haun units). This difference in staging may represent a 2 – 4 day difference in development between these treatments. The difference appeared to be due more to stimulation of development rate by the addition of ammonium nitrate than because of delayed development due to mulch application (Table 4.2).

More rapid leaf emergence in wheat that received application of the higher rates of ammonium nitrate relative to the control and mulch treatments was observed on June 26, 2002 in Carman (Table 4.2), suggesting a stimulation effect. Longnecker et. al (1993) also observed more rapid leaf emergence when higher rates of N were supplied to wheat. However, Haun stage measurements taken one month later indicated no significant differences between individual treatments (Table 4.2). While higher fertility may cause more rapid development initially, it may also delay ripening by prolonging vegetative growth (Kataria et al. 1999). A comparison of the early with the late mulch application timings on this date revealed a small but statistically significant delay in wheat with the later mulch application compared to the early application (Table 4.2).

Table 4.2. The effect of mulch level and application timing on rate of wheat development at Winnipeg and Carman in 2002 and 2003.

Treatment[z]	Winnipeg '02 (July 17)	Carman '02 (June 26)	Carman '02 (July 22)	Winnipeg '03 (June 5)	Carman '03 (July 18)
	Haun stage				
Control	8.5bcd[y]	3.7bc	10.0	1.51	9.7bc
20kgN	8.3cd	3.8bc	9.8	ND[x]	9.6bcd
40kgN	9.3a	3.9ab	9.7	ND	9.5cd
60kgN	9.1ab	4.2a	9.7	ND	9.5cd
0.5xEarly	8.2cd	3.7bc	10.2	ND	9.7abc
1xEarly	8.6bcd	3.9b	10.1	ND	9.9ab
2xEarly	8.5bcd	3.6c	10.0	1.46	9.8abc
0.5xLate	8.7abc	3.8bc	9.8	ND	10.0a
1xLate	8.3cd	3.7bc	9.7	ND	9.7bc
2xLate	8.0d	3.8bc	9.6	ND	9.3d
LSD(0.05)	0.7	0.28	NS[w]	NS	0.33
P>F	0.0097	0.0157	0.3708	0.5908	0.0227
Mean	8.6	3.8	9.9	1.48	9.6
Contrasts					
Early vs Late	NS	NS	0.0135	ND	NS

z 0.5x, 1x and 2x refer to the amount of alfalfa harvested from an area 0.5, 1 and 2 times the wheat plot area. Refer to Table 3.6 for amounts of alfalfa mulch applied. The 20, 40, 60 kg N treatments consisted of 20, 40 and 60 kg N ha^{-1} applied as ammonium nitrate. Early application timing was before wheat emergence. Late application timing was at the three-leaf stage.

y Means followed by the same letter within a column are not significantly different ($P > 0.05$) according to Fisher's protected LSD.

x ND = not determined.

w NS = non-significant.

Carman in 2003 showed a significant delay in development with high mulch rate application. Wheat receiving the highest mulch rate, i.e., 6.6 t ha^{-1} in the 2xLate treatment, was the only treatment in which wheat was significantly less developed (9.4 Haun units) than the control (9.7 Haun units) (Table 4.2). This difference may represent a 2-day delay (Haun 1973). Haun stage observations at this site also showed a significant inverse relationship between rate of development and mulch application rate when mulch was applied at the three-leaf stage. Thus, this site provides evidence that alfalfa mulch, when applied at the three-leaf stage, and applied at high rates, may cause a delay in wheat development. Delayed development may have been caused by potentially lower soil temperatures as a result of mulch application (Fortin and Pierce 1991).

Results at time of wheat maturity at Carman 2003 showed that plots receiving the highest rate of mulch and plots receiving the highest rate of ammonium nitrate had significantly more green heads than did the control plots (Table 4.3). This observation appears to be attributed to higher fertility prolonging vegetative growth stages and delaying wheat senescence (Kataria et al. 1999), and is evidence that both nutrient sources delayed maturity.

Table 4.3. Green heads m^{-2} as a measure of wheat maturity on August 21, 2003 at Carman.

Treatment[z]	Green heads m^{-2}	
Control	1.8	bcd[y]
20kgN	2.3	bcd
40kgN	2.8	abcd
60kgN	4.5	a
0.5xEarly	1.5	cd
1xEarly	1.5	cd
2xEarly	2.8	abcd
0.5xLate	1.7	bcd
1xLate	2.0	bcd
2xLate	4.5	a
0.5xFrozen[x]	1.8	bcd
1xFrozen[x]	1.3	d
2xFrozen[x]	3.5	ab
Fall[w] 0.5x	2.8	abcd
Fall 1x	1.0	d
Fall 2x	3.3	abc
Fall 1x+1xEarly	3.3	abc
LSD(0.05)	1.9	
P>F	0.0062	
Mean	2.5	
Contrasts		
Late – linear	0.0079	
Frozen – linear	0.031	
Fertilizer - linear	0.0014	
C.V.(%)	51.5	

[z] 0.5x, 1x and 2x refer to the amount of alfalfa harvested from an area 0.5, 1 and 2 times the wheat plot area. Refer to Table 3.6 for amounts of alfalfa mulch applied. The 20, 40, 60 kg N treatments consisted of 20, 40 and 60 kg N ha-1 applied as ammonium nitrate. Early application timing was before wheat emergence. Late application timing was at the three-leaf stage.

[y] Means followed by the same letter within a column are not significantly different ($P > 0.05$) according to Fisher's protected LSD.

[x] Mulch was harvested at the Early application stage and stored in a freezer until the Late stage application.

[w] Fall indicates fall-applied mulch.

4.1.3 Weed population density

Investigating the effect of mulch application rate and application timing on weed populations and growth was one of the main objectives of this study. At three out of four site years, i.e., Winnipeg and Carman in 2002, and Winnipeg in 2003, significant reductions in weed density compared to the control were observed with the high (2x) mulch rate (Tables 4.4, 4.5, 4.6). The observed reduction in weed density agrees with the findings of Teasedale et al. (1991) and Teasedale and Mohler (2000) where rye (*Secale cereale* L.) and hairy vetch (*Vicia villosa* Roth) mulches at rates greater than 3 tonnes of dry matter ha^{-1} significantly reduced weed density.

At both Winnipeg and Carman in 2002, the late 2x mulch application resulted in significantly lower weed densities than the control or the early 0.5x mulch treatment, pointing to a smothering effect of the highest mulch rates (Tables 4.4, 4.5). At Carman 2002 the late 2x mulch rate also resulted in a significant reduction in weed density compared to the control (Table 4.5). At Winnipeg 2002 weed densities at the time of counting were 35.5 and 6.5 weeds m^{-2} in the control and 2xLate treatments, respectively. Weed pressure was much greater at Carman with weed densities of 1639 and 915 weeds m^{-2} in the control and 2xLate treatments respectively. Although mulch application at Carman caused a significant reduction in weed density, final weed densities with the most suppressive mulch treatment (2xLate) were still far above the provincial average post-weed control densities in spring wheat fields (34.8 m^{-2}) (Leeson et al. 2002).

Winnipeg 2002

At Winnipeg 2002 the early mulch treatments had significantly more weeds than the late mulch treatments (Table 4.4). Whether this was the result of the difference in

Table 4.4. The effect of mulch level and application timing on total and individual weed species population densities at Winnipeg in 2002.

Treatment[z]	red root pigweed	lamb's quarters	dandelion	sow thistle	barnyard grass	foxtail	wild oats	other	Total
	weeds m^{-2}								
control	3.0	0.0	4 bcd[y]	11.5 ab	3.5 abcd	3.0	7.0	3.5	35.5 ab
20kgN	7.5	1.0	2 d	22.0 a	8 abc	1.5	4.5	1.0	47.5 a
40kgN	4.0	1.0	7 ab	19.5 a	2.5 cd	0.0	3.0	1.5	38.5 ab
60kgN	2.0	1.0	4 bcd	22.0 a	19.5 ab	0.0	9.5	3.5	61.5 a
0.5xEarly	4.0	0.0	5.5 abc	20.5 a	12.5 ab	0.0	2.5	5.0	50.0 a
1xEarly	6.5	0.5	5.5 ab	12.0 ab	23 a	5.0	8.0	1.0	61.5 a
2xEarly	3.0	1.5	15.5 a	10.0 ab	6 abc	0.5	4.5	1.0	42.0 ab
0.5xLate	1.0	0.0	5 bcd	14.0 ab	10 bcd	0.0	3.0	3.0	36.0 ab
1xLate	0.0	0.0	2 cd	3.5 b	5 abcd	0.5	4.0	0.0	15.0 bc
2xLate	0.5	0.0	1.5 cd	2.0 b	0 d	0.0	2.0	0.5	6.5 c
LSD(P=0.05)	NS[xw]	NS	[w]	13.2	[w]	NS[w]	NS	NS[w]	28.9
P>F	0.3318	0.5098	0.0119	0.0271	0.0255	0.0609	0.2339	0.4537	0.009
Mean	3.2	0.5	5.2	13.7	9	1.0	4.8	2.0	39.4
Contrasts									
Early vs Late	0.0164	0.1822	0.0007	0.0484	0.0029	0.1088	0.2608	0.5449	0.0005
Fert - linear	0.3689	0.2705	0.9505	0.1648	0.7421	0.0206	0.5316	0.4401	0.1331
Fert - quadratic	0.7363	0.4091	0.6751	0.3862	0.3705	0.4389	0.0443	0.3473	0.5855
Fert - cubic	0.2972	0.7106	0.0117	0.3833	0.0333	0.728	0.4693	0.8817	0.2446
Early - linear	0.9455	0.0812	0.1126	0.1465	0.2404	0.9545	0.7472	0.3767	0.4321
Early - quadratic	0.4369	1	0.7299	0.3852	0.2758	0.0055	0.0803	0.4431	0.2643
Late - linear	0.9398	1	0.3452	0.1041	0.0778	0.8921	0.6677	0.1507	0.0605
C.V.(%)	110.97	238.51	47.09	66.3	66.31	189.6	88.86	124.9	50.57

z 0.5x, 1x and 2x refer to the amount of alfalfa harvested from an area 0.5, 1 and 2 times the wheat plot area. Refer to Table 3.6 for mulch dry matter rates. The 20, 40, 60 kg N treatments consisted of 20, 40 and 60 kg N ha^{-1} applied as ammonium nitrate. Early application timing was before wheat emergence. Late application timing was at the three-leaf stage.

y Means followed by the same letter within a column are not significantly different ($P > 0.05$) according to Fischer's protected LSD.

x NS = non-significant.

w The natural log of the data+1 was used to transform the data to achieve homogeneity of variance and a normal distribution of data. Treatment means are presented as the original untransformed values.

Table 4.5. The effect of mulch level and application timing on total and individual weed species population densities at Carman in 2002.

Treatment[z]	red root pigweed	lamb's quarters	dandelion	foxtail	other	Total
	weeds m^{-2}					
control	756 abc[y]	36	1.0	845	1.0	1639 abc
20kgN	934 ab	19	1.5	956	0.5	1911 abc
40kgN	846 ab	28	1.0	706	1.5	1583 abc
60kgN	955 a	34	0.5	786	2.5	1778 ab
0.5xEarly	598 bcd	32	2.5	934	0.0	1565 abc
1xEarly	391 d	19	5.5	524	0.0	940 d
2xEarly	460 cd	33	3.0	689	0.0	1184 cd
0.5xLate	635 abcd	21	0.0	801	0.5	1458 abcd
1xLate	491 bcd	23	0.0	788	0.5	1302 bcd
2xLate	451 cd	14	0.0	449	0.5	915 d
LSD(0.05)	344	NS[x]	NS	NS	NS[w]	580
P>F	0.0108	0.889	0.2546	0.1266	0.5781	0.0172
Mean	652	26	1.5	748	0.7	1427
Contrasts						
Early vs Late	0.6615	0.3647	0.0058	0.7212	0.2267	0.9766
Fert - linear	0.3464	0.984	0.7678	0.4456	0.653	0.9232
Fert - quadratic	0.7744	0.308	0.7414	0.9	0.7198	0.8497
Fert - cubic	0.3926	0.5763	0.8826	0.2201	0.3498	0.2194
Early - linear	0.5369	0.8091	0.9593	0.3161	1	0.3321
Early - quadratic	0.2882	0.3608	0.1414	0.0417	1	0.0556
Late - linear	0.3227	0.6102	1	0.0372	1	0.0584
C.V.(%)	36.43	86.14	199.92	32.93	185.95	28.01

z 0.5x, 1x and 2x refer to the amount of alfalfa harvested from an area 0.5, 1 and 2 times the wheat plot area. Refer to Table 3.6 for mulch dry matter rates. The 20, 40, 60 kg N treatments consisted of 20, 40 and 60 kg N ha^{-1} applied as ammonium nitrate. Early application timing was before wheat emergence. Late application timing was at the three-leaf stage.

y Means followed by the same letter within a column are not significantly different ($P > 0.05$) according to Fischer's protected LSD.

x NS = non-significant.

w The natural log of the data+1 was used to transform the data to achieve homogeneity of variance and a normal distribution of data. Treatment means are presented as the original untransformed values.

timing of application or whether it was simply because more mulch was applied with the late application at the three-leaf stage is unclear. Teasedale and Mohler (2000) found that more rapid mulch degradation may have accounted for higher redroot pigweed numbers one year compared to another. Early mulch application allowed for earlier mulch degradation and may have allowed greater weed growth through mulch than late mulch treatments.

Weed density was analyzed by species to determine which weed species were responsible for the higher weed populations in the early versus the late mulch treatments. Redroot pigweed, dandelion, barnyard grass (*Echinochloa crus-galli* (L.) Beauv.) and perennial sow thistle (*Sonchus arvensis* L.) were significantly more prevalent in the early than in the late mulch treatments (Table 4.4). Teasdale and Mohler (2000) reported that redroot pigweed was the most sensitive to mulch of four weed species studied (redroot pigweed, lamb's quarters, giant foxtail, velvetleaf). Higher dandelion populations in the early mulch treatments may be explained by dandelion seed addition to the plots with the early application of alfalfa mulch, since the early alfalfa harvest coincided with dandelion seed production. With barnyard grass and sow thistle this would not be the case because these species do not produce seed until later in the season. Higher mulch rates used in the later mulch treatments may explain the lower weed densities in these species compared to the early treatments, or the later timing may have suppressed weeds at a critical growth period. Another explanation in the case of perennial sow thistle is that the weeds identified as sow thistles may have been dandelion seedlings as dandelion and sow thistle seedlings in the cotyledon stage are very difficult to distinguish.

Carman 2002

At Carman 2002 there was no significant difference in total weed numbers between the before-emergence and the three-leaf stage mulch applications. However, when separated by species, dandelion was significantly more prevalent with the early treatments than the late treatments (Table 4.5); possibly indicating that seeds were added to the plots with the early mulch application.

The only other species that showed a significant treatment effect at Carman 2002 was redroot pigweed. Redroot pigweed populations were highest in the 60 kg N treatment; significantly higher than in all of the mulch treatments except the 0.5xLate treatment. Higher redroot pigweed populations in the 60 kg N treatment may be the result of a stimulation effect on redroot pigweed recruitment by immediately available nitrate from the 60 kg N treatment (Blum et al. 1997; Gallagher and Cardina 1998a), contrasted with a physical smothering effect of the mulch on emerging red root pigweed seedlings (Teasdale and Mohler 2000).

Winnipeg 2003

In 2003 at Winnipeg none of the treatments had significantly lower weed density than the control. However, similar to the results of 2002, weed density with the early mulch treatments decreased as mulch application rate increased (see contrasts in Table 4.6), and the highest mulch rate application (2xLate) resulted in a significantly lower weed density than the lowest mulch rate application (0.5xEarly) (Table 4.6). Better weed suppression with high mulch rates than low mulch rates may have been due to a number of factors including greater effects on light interception, physical impedance, and alterations to the microclimate as mulch rate increased. However, there may also have

Table 4.6. The effect of mulch level and application timing on total and individual weed species population densities at Winnipeg in 2003.

Treatment^z	red root pigweed	lamb's quarters	dandelion	thyme-leaved spurge	purslane	foxtail	canada thistle	other	Total
				weeds m^{-2}					
control	10.5 cd^y	7.0 cde	9.0	12.5	13	77	8.0	3.0 bcd	139 bcde
60kgN	6.5 d	16.5 b	7.0	9.5	31	40	2.0	0.5 d	113 de
0.5xEarly	5 de	3.0 e	20.5	21.0	61	116	6.5	10.5 ab	243 ab
1xEarly	8 d	8.0 bcde	29.5	11.5	50	77	3.0	11.0 abc	197 abcd
2xEarly	2 e	7.5 bcde	20.5	8.5	8	50	3.5	14.5 ab	114 de
0.5xLate	9.5 de	11.5 bcde	7.5	3.0	45	66	4.5	8.5 ab	156 abcde
1xLate	11 bcd	5.5 de	10.0	10.0	33	54	2.0	5.5 abc	131 cde
2xLate	7 de	6.5 cde	6.5	6.5	6	54	2.5	1.0 cd	90 e
0.5xFrozen^x	9 d	9.5 bcde	6.5	11.5	16	124	4.5	4.0 bcd	185 abcde
1xFrozen	8 d	13.0 bcd	6.5	10.0	41	58	6.0	7.0 ab	149 bcde
2xFrozen	6.5 de	9.5 bcde	7.5	5.0	12	36	1.5	5.0 ab	83 e
Fall^w 0.5x	35.5 ab	10.0 bcde	4.5	21.0	79	86	1.0	5.0 abc	234 abc
Fall 1x	39 ab	15.0 bc	7.5	20.0	100	70	3.0	3.5 abc	258 a
Fall 2x	98.5 a	29.0 a	16.5	8.0	17	59	1.0	3.5 bc	233 abc
Fall 1x+1xEarly	32 abc	7.0 cde	21.0	12.0	19	98	6.0	13.5 a	208 abcd
LSD(0.05)	^{v}	9.2	NS^{uv}	NS	NS	NS	NS	^{v}	105
P>F	<0.0001	0.0005	0.354	0.0956	0.5529	0.1023	0.7237	0.025	0.0115
Mean	19.2	10.6	12.0	10.9	35	71	3.7	6.4	169
Contrasts									
Early vs Late	NS	0.5312	0.0473	0.0243	0.6396	0.1663	0.5208	0.0816	0.0544
Fall vs Spring^t	<0.0001	<0.0001	0.7737	0.0956	0.0756	0.9279	0.2162	0.6228	0.0005
Early vs Frozen	0.2216	0.0957	0.0111	0.1226	0.4897	0.608	0.8722	0.51	0.1321
Late vs Frozen	0.7548	0.2893	0.543	0.451	0.8229	0.3776	0.6297	0.2691	0.6597
Early - linear	0.0549	0.4084	0.6296	0.0351	0.1837	0.0315	0.4855	0.582	0.016
Late - linear	0.7814	0.3697	0.735	0.6684	0.3357	0.7036	0.6487	0.0263	0.2082
Frozen - linear	0.2911	0.8681	0.8274	0.2099	0.8222	0.0062	0.3185	0.6246	0.0535
C.V.(%)	36.72	61.2	46.66	69.14	165.22	56.95	137.55	51.82	43.68

z 0.5x, 1x and 2x refer to the amount of alfalfa harvested from an area 0.5, 1 and 2 times the wheat plot area. Refer to Table 3.6 for mulch dry matter rates. The 20, 40, 60 kg N treatments consisted of 20, 40 and 60 kg N ha^{-1} applied as ammonium nitrate. Early application timing was before wheat emergence. Late application timing was at the three-leaf stage.

y Means followed by the same letter within a column are not significantly different (*P* > 0.05) according to Fischer's protected LSD.

x Mulch was harvested at the Early application stage and stored in a freezer until the late stage application.

w "Fall" indicates fall-applied mulch.

v The natural log of the data+1 was used to transform the data to achieve homogeneity of variance and normal distribution. Treatment means are presented as untransformed values.

u NS = Non-significant.

t Fall mulch treatments compared to spring mulch treatments, not including Fall 1x+1xEarly treatment.

Table 4.7. The effect of mulch level and application timing on total and individual weed species population densities at Carman 2003.

Treatment[z]	red root pigweed	lamb's quarters	dandelion	wild buckwheat	sow thistle	foxtail	other	Total	Total minus dandelion
	weeds m^{-2}								
control	10.4	5.2 cd[y]	2 e	1.6	0.4	7.2	0.4	27 de	25.2 b
60kgN	14.5	9.5 abc	3 de	4.5	0.0	5.0	0.5	37 cd	32.5 b
0.5xEarly	13.0	5.5 cd	275 a	4.0	0.0	9.0	0.0	306 a	31.2 b
1xEarly	9.5	5.5 cd	420 a	1.5	0.5	10.0	0.0	447 a	27 b
2xEarly	6.5	4.5 cd	428 a	2.5	0.0	7.0	0.5	449 a	21 b
0.5xLate	10.0	3.3 d	5 cd	1.3	0.0	10.0	0.0	30 de	22 b
1xLate	13.5	4.0 cd	4 de	1.0	0.5	7.5	0.5	31 de	27 b
2xLate	6.0	2.0 d	1 e	2.0	0.0	6.5	0.5	18 e	17 b
0.5xFrozen[x]	16.0	5.0 cd	12 c	4.5	0.5	5.5	0.5	44 bcd	34 b
1xFrozen	10.5	5.5 cd	47 b	1.5	1.0	5.0	0.0	70 bc	23.5 b
2xFrozen	9.5	5.5 cd	45 b	3.0	0.0	7.5	0.5	72 b	26.5 b
Fall[w] 0.5x	18.5	11.5 ab	3 de	3.0	1.0	16.0	2.5	56 bc	52.5 a
Fall 1x	21.3	11.3 ab	3 de	0.7	1.3	21.3	0.7	59 bc	56.7 a
Fall 2x	19.0	15.0 a	4 de	3.5	1.5	17.5	0.5	61 bc	57 a
Fall 1x+1xEarly	12.5	7.0 bcd	254 a	0.5	0.5	10.0	0.0	285 a	30.5 b
LSD(0.05)	NS[v]	5.7	[v]	NS	NS	NS	NS	[v]	17.32
P>F	0.3312	0.0021	<0.0001	0.3808	0.2366	0.268	0.6737	<0.0001	0.0002
Mean	12.6	6.6	102	2.4	0.5	9.4	0.5	134.0	31.89
Contrasts									
Early vs Late	0.9422	0.2253	<0.0001	0.3106	0.8871	0.7643	0.616	<0.0001	0.3272
Fall vs Spring[t]	0.0024	<0.0001	<0.0001	0.8865	0.0024	0.0005	0.559	0.0128	<0.0001
Early vs Frozen	0.4697	0.9176	<0.0001	0.7424	0.3465	0.4126	0.5704	<0.0001	0.7599
Late vs Frozen	0.4388	0.1902	<0.0001	0.185	0.2917	0.6181	0.9601	<0.0001	0.2042
Early - linear	0.2599	0.6962	0.3199	0.5352	0.858	0.6693	0.5917	0.198	0.222
Late - linear	0.4953	0.5762	0.002	0.8361	0.9685	0.6889	0.9417	0.0517	0.5595
Frozen - linear	0.2937	0.8758	0.0183	0.5766	0.2865	0.6835	0.5202	0.1623	0.4894
C.V.(%)	62.28	59.06	21.47	103.99	180.64	83.74	280.7	9.05	37.45

z 0.5x, 1x and 2x refer to the amount of alfalfa harvested from an area 0.5, 1 and 2 times the wheat plot area. Refer to Table 3.6 for mulch dry matter rates. The 20, 40, 60 kg N treatments consisted of 20, 40 and 60 kg N ha^{-1} applied as ammonium nitrate. Early application timing was before wheat emergence. Late application timing was at the three-leaf stage.

y Means followed by the same letter within a column are not significantly different (*P* > 0.05) according to Fischer's protected LSD.

x Mulch was harvested at the Early application stage and stored in a freezer until the late stage application.

w "Fall" indicates fall-applied mulch.

v The natural log of the data+1 was used to transform the data to achieve homogeneity of variance and normal distribution. Treatment means are presented as untransformed values.

u NS = Non-significant.

t Fall mulch treatments compared to spring mulch treatments, not including Fall 1x+1xEarly treatment.

been some stimulation of weed recruitment at low mulch rates that contributed to the significant differences in weed population density between mulch treatments (Table 4.6).

The results of mulch application should be interpreted carefully due to application of different mulch rates at different timings, and mulch having different chemical compositions. The mulch harvested at the earlier timing had a higher N concentration, and a lower C/N ratio (Table 4.19) and likely less lignification (Albrecht et al. 1987) than the later applied mulch. However, the effect of chemical composition may be relatively insignificant in its effect on weed suppression compared to the effects of mulch rate and application timing. Additional treatments in 2003 attempted to distinguish between the effects of mulch rate and mulch timing by applying the same rates of the same mulch at the late stage application as were applied at the early stage application. However, no significant differences were seen between the early, late, or frozen mulch treatments at Winnipeg (Table 4.6). The lack of difference between the early and the frozen treatments, despite the different application times, suggests that mulch rate may be a more important factor in weed suppression than mulch application timing.

While the effect of mulch application timing on total weed density was not significant at Winnipeg 2003, it was significant on an individual species basis for dandelion and thyme-leaved spurge (*Euphorbia glyptosperma* Engelm.). As mentioned earlier, the increased prevalence of dandelion with early compared with late application timing is likely due to addition of dandelion seeds to the plots with earlier application. The increased presence of thyme-leaved spurge in the early mulch treatments compared to the late mulch treatments may be related to the fact that thyme-leaved spurge seedlings were still very small at the time of counting and the greater degree of decomposition of the early compared to the late mulch may have allowed for more successful recruitment through the mulch layer.

A fall-incorporated mulch treatment was added to the 2003 trials. Mulch was applied to selected plots in fall 2002 and the entire 2003 trial area at both Winnipeg and Carman receive tillage. At both locations redroot pigweed and lamb's quarters populations were significantly higher in the fall mulch treatments than in the spring mulch treatments, and in most cases, significantly higher than the control (Tables 4.6, 4.7). Possible explanations for these observations are as follows: 1) over winter mineralization of mulch N resulted in high soil nitrate concentrations, which stimulated germination of pigweed and lamb's quarters; and 2) weed seeds were added with fall applied mulch. Among these possibilities, the soil nitrate mineralization theory is supported by previous studies with pigweed and lamb's quarters (Fawcett and Slife 1978; Blum et al. 1997; Gallagher and Cardina 1998a; Teasdale and Mohler 2000; Benech Arnold et al. 2000). In the present study, observations of significantly higher lamb's quarters populations in both the 60 kg ha^{-1} inorganic N and the 2xFall treatments than in the control (Table 4.6) suggest that nitrate from both sources may have stimulated lamb's quarters' recruitment. However, since only the fall mulch treatments and not the ammonium nitrate application stimulated redroot pigweed recruitment, perhaps weed seed addition occurred with fall applied mulch.

Winnipeg 2003 provided some further evidence that low mulch rates stimulated weed recruitment. The early 0.5x treatment had significantly more weeds than the 60 kg N treatment (Table 4.6). While higher nitrate levels may have caused some increased emergence of lamb's quarters in the 60 kg N treatment, all other weed species were present at higher densities in the 0.5xEarly treatment, suggesting that a weed-stimulating mechanism other than nitrate was at work. The apparent stimulation effect on weed emergence in the 0.5xEarly treatment may be a result of increased soil moisture levels due to mulch application. While higher mulch rates (1x, 2x rates) had even higher soil moisture levels (Tables 4.10, 4.11, 4.12), greater mulch material would have suppressed weeds while the 0.5x mulch rates may have contained only enough material to improve the conditions for germination but not enough to provide weed suppression. It is likely that moisture under mulch affected germination more than nitrate levels. If nitrate had been an important factor causing increased weed establishment in the low-rate mulch treatments at Winnipeg in 2003, then it would follow that the 60 kg N treatment also should have had high weed density. However, weed density in the 60 kg N treatment was equivalent to the control (Table 4.6).

Purslane (*Portulaca oleracea* L.) and foxtail spp. (*Setaria viridis* (L.) Beauv. and *Setaria glauca* (L.) Beauv.) were the weed species most responsible for the higher weed density in the early 0.5x treatment than in the 60 kg N treatment at Winnipeg 2003. Work by Boyd and Van Acker (2003) showed greater green foxtail (*Setaria viridis* (L.) Beauv.) emergence when seeds were slightly buried in the soil than when placed on the soil surface. Mulch application may have provided similar conditions for foxtail seeds on the soil surface as would exist for slightly buried seeds, and thus contributed to the higher density in the early 0.5x plots.

Carman 2003

Weed population density results at Carman in 2003 were dramatically different from all other locations in either 2002 or 2003. Here early mulch application caused a dramatic increase in weed populations compared to all other treatments (Table 4.7). The extra weeds emerging in these treatments were almost exclusively dandelion. The reason for the increased emergence of dandelion in the early mulch treatments is that the alfalfa stand contained dandelions that were going to seed at the time the alfalfa was harvested. High numbers of dandelion seeds were harvested with the alfalfa and applied to the wheat plots. The conditions for recruitment were evidently ideal for dandelion seeds mixed with mulch when the mulch was applied to the wheat plots, as average dandelion density in the early 2x treatment was 449 plants m^{-2}. The mulch harvested two weeks later for the late mulch application contained almost no dandelion seeds because, while still present in the alfalfa stand, the dandelions had finished producing seeds. While dandelion numbers were low in the other three trials, at each site dandelion seedlings were more numerous in plots receiving the early mulch treatment than the late mulch treatment (Tables 4.4, 4.5, 4.6), suggesting that early harvest of alfalfa mulch at these sites also coincided with dandelion seed production leading to dandelion seed addition to plots. In a study of weed seed germination, Chepil (1946) observed that dandelion seed had a maximum length of dormancy of four years and had no marked periodicity of germination throughout the growing season, but emerged in spring, summer, and fall. These germination characteristics of dandelion seed indicate that, if present in the mulch, germination may occur regardless of when application occurs and may continue to occur throughout the growing season and for several years thereafter.

When the numbers of dandelion seedlings at Carman 2003 were subtracted from the overall weed counts and the results were re-analyzed, overall weed density was very low (32 weeds m^{-2}), with the treatments receiving fall-applied mulch having significantly higher weed densities than the other treatments (Table 4.7), possibly because mulch was incorporated in fall, thereby eliminating the weed smothering effects of a surface mulch layer. If weed seeds were added with the fall mulch treatments it would explain why weed density in the fall treatments was significantly higher than the control. Mulch N mineralization during the period from fall application until spring seeding may have caused higher spring soil nitrate levels in the fall mulch treatments, which would explain the significantly higher lamb's quarters populations in the fall treatments compared to the control (Table 4.7).

Weed biomass

In addition to the number of weeds present, weed biomass is another useful indicator of the effect of a treatment on weed growth. At Carman in 2002, weed biomass in the 40kgN and 60kgN treatments was higher than in the all other treatments except the 2xEarly treatment (Table 4.8). Greater weed growth in these plots is likely the result of higher amounts of N added with the treatments. There was a significant positive linear relationship between ammonium nitrate application rate and weed biomass and also between early mulch application rate and weed biomass at this site (Table 4.8). However, high rates of late-applied mulch did not cause increased weed biomass (Table 4.8), yet contributed up to 27.5 kg N ha^{-1} to the wheat crop at Carman 2002 (Table 4.14). Mulch rate did no affect weed biomass when the mulch was applied late. The smothering effect of higher rates of mulch applied at the later stage (Table 4.5), combined with delayed N availability to the weeds may have prevented the positive weed biomass response to mulch application at this stage.

Table 4.8. The effect of mulch application rate and application timing on weed and wheat biomass measured at wheat anthesis on July 26, 2002 at Carman.

Treatment[z]	Weeds		Wheat	
	---------- biomass (kg ha^{-1}) -----------			
Control	1675	cd[y]	1063	c
20kgN	1559	cd	1928	ab
40kgN	2687	ab	1547	bc
60kgN	2860	a	1628	bc
0.5xEarly	1285	d	1751	ab
1xEarly	1433	cd	2052	ab
2xEarly	2068	bc	1651	bc
0.5xLate	1206	d	2321	a
1xLate	1048	d	2066	ab
2xLate	1261	d	2088	ab
LSD(0.05)	759		620	
P>F	0.0002		0.0172	
Mean	1708		1810	
Contrasts				
Early vs Late	0.0577		0.0614	
Fertilizer - linear	0.0004		0.1802	
Early - linear	0.0349		0.5676	
Late – linear	0.8004		0.5165	
C.V.(%)	30.64		23.61	

z 0.5x, 1x and 2x refer to the amount of alfalfa harvested from an area 0.5, 1 and 2 times the wheat plot area. Refer to Table 3.6 for amounts of alfalfa mulch applied. The 20, 40, 60 kg N treatments consisted of 20, 40 and 60 kg N ha^{-1} applied as ammonium nitrate. Early application timing was before wheat emergence. Late application timing was at the three-leaf stage.

y Means followed by the same letter within a column are not significantly different ($P > 0.05$) according to Fisher's protected LSD.

Weed biomass at Carman 2003 showed no significant treatment effect; however, like at Carman in 2002, there was a positive linear relationship between weed biomass and ammonium nitrate application rate. This relationship was also present for mulch application rate for the frozen treatments, but not for the early, late or fall-applied mulch treatments (Table 4.9).

Table 4.9. Weed and wheat biomass measured at wheat soft-dough stage on Aug 11, 2003 at Carman.

Treatment[z]	Weeds	Wheat
	--- biomass (kg ha^{-1}) ---	
Control	253.7	13094
20kgN	328.5	12663
40kgN	762.9	11205
60kgN	523.5	12252
0.5xEarly	333.3	12178
1xEarly	209.5	13201
2xEarly	415.0	12087
0.5xLate	78.7	13753
1xLate	351.9	13313
2xLate	303.4	12686
0.5x Frozen[y]	304.2	12226
1x Frozen	207.1	13367
2x Frozen	663.4	12025
Fall[x] 0.5x	245.1	12702
Fall 1x	261.1	12092
Fall 2x	394.8	13197
Fall 1x +1xEarly	440.9	12510
LSD(0.05)	NS[w]	NS
P>F	0.097	0.6184
Mean	361.5	12619
Contrasts		
Early vs Late	0.4762	0.1661
Early - linear	0.5318	0.7391
Late - linear	0.3232	0.2557
Frozen - linear	0.0299	0.6296
Fall - linear	0.3847	0.5084
Fertilizer - linear	0.0334	0.2043
C.V.(%)	72.14	10.8

z 0.5x, 1x and 2x refer to the amount of alfalfa harvested from an area 0.5, 1 and 2 times the wheat plot area. Refer to Table 3.6 for amounts of alfalfa mulch applied. The 20, 40, 60kgN treatments consisted of 20, 40 and 60 kg N/ha applied as ammonium nitrate. Early application timing was before wheat emergence. Late application timing was at the three-leaf stage.

y "Frozen" refers to mulch harvested at the Early application stage and stored in a freezer until the Late stage application.

x "Fall" indicates fall-applied mulch.

w NS = non-significant.

4.1.4 Soil moisture

Gravimetric soil moisture measurements were conducted to assess effects of mulch application on moisture conservation. Mulch conserved soil moisture in the top 10 cm of the soil profile on several occasions in the rate x time-of-application experiment. For example, at Winnipeg in 2002, soil moisture measured on July 9 was significantly higher (2.2% higher) under the heaviest mulch treatment than in the control (Table 4.10).

Table 4.10. The effect of mulch application rate and mulch application timing on soil water content at Winnipeg in 2002.

Treatment^z	June 27	July 09	July 17
	---------------------	%	-------------------------
Control	41.5ab^y	41.6c	36.6a
20kgN	41.1ab	41.8bc	34.0abcd
40kgN	39.3bc	42.1bc	32.5cd
60kgN	37.1c	42.1bc	31.9d
0.5xEarly	42.3a	42.4bc	36.1a
1xEarly	41.5ab	42.2bc	34.9abc
2xEarly	43.3a	42.5bac	33.0bcd
0.5xLate	40.8ab	41.7c	36.2a
1xLate	41.5ab	43.1ba	36.2a
2xLate	43.0a	43.8a	35.3ab
Mean	41.1	42.3	34.6
LSD(P=0.05)	2.56	1.41	2.60
P>F	0.0016	0.086	0.0052
Contrast			
Early vs Late	NS	NS	NS

z 0.5x, 1x and 2x refer to the amount of alfalfa harvested from an area 0.5, 1 and 2 times the wheat plot area. Refer to Table 3.6 for amounts of alfalfa mulch applied. The 20, 40, 60kgN treatments consisted of 20, 40 and 60 kg N ha^{-1} applied as ammonium nitrate. Early application was before wheat emergence. Late application was at the three-leaf stage.

y Means followed by the same letter within a column are not significantly different (P > 0.05) according to Fischer's protected LSD.

The highest mulch rate treatment also had significantly more soil moisture (2.8% higher) than the control on June 18 at Carman in 2002 (Table 4.11). In 2003, moisture conservation was observed only at Winnipeg on June 30 with the highest rate of mulch resulting in significantly more soil moisture (3.8% higher) than the control (Table 4.12).

Table 4.11. The effect of mulch application rate and application timing on soil water content at Carman on June 28, 2002.

Treatment^z	June 28 ------- % ------
Control	13.0bc^y
20kgN	12.4c
40kgN	12.3c
60kgN	11.7c
0.5xEarly	12.8bc
1xEarly	12.0c
2xEarly	13.9bac
0.5xLate	13.9bac
1xLate	14.9ba
2xLate	15.8a
Mean	13.3
LSD(P=0.05)	2.28
P>F	0.0167
Contrast	
Early vs Late	0.0045

z 0.5x, 1x and 2x refer to the amount of alfalfa harvested from an area 0.5, 1 and 2 times the wheat plot area. Refer to Table 3.6 for amounts of alfalfa mulch applied. The 20, 40, 60kgN treatments consisted of 20, 40 and 60 kg N/ha applied as ammonium nitrate. Early application was before wheat emergence. Late application was at the three-leaf stage.

y Means followed by the same letter within a column are not significantly different (P>0.05) according to Fischer's protected LSD.

Table 4.12. The effect of mulch application rate and application timing on soil water content at Winnipeg on June 30, 2003.

Treatment^z	June 30 ------ % ------
Control	39.0c^y
2xEarly	40.9abc
1xLate	40.5bc
2xLate	42.8a
2xFrozen^x	41.8ab
Mean	41.0
LSD(P=0.05)	2.29
P>F	0.0351

z 0.5x, 1x and 2x refer to the amount of alfalfa harvested from an area 0.5, 1 and 2 times the wheat plot area. Refer to Table 3.6 for amounts of alfalfa mulch applied. The 20, 40, 60 kg N treatments consisted of 20, 40 and 60 kg N^{-1} ha applied as ammonium nitrate. Early application was before wheat emergence. Late application was at the three-leaf stage.

y Means followed by the same letter are not significantly different (P > 0.05) according to Fischer's protected LSD.

x "Frozen" refers to mulch harvested at the Early application stage and stored in a freezer until the Late stage application.

Assuming a soil bulk density of 1.2 g cm^{-3} for the silty clay soil at Winnipeg (W. Akinremi, pers. comm., University of Manitoba), soil water conserved in the top 10 cm under the heavy mulch treatment, compared to the control, was estimated at 2.7 mm on July 9, 2002, and 4.7 mm on June 30, 2003. At Carman, the bulk density of the sandy loam was assumed to be 1.3 g cm^{-3} (W. Akinremi, pers. comm., University of Manitoba), for an estimated 3.4 mm of water conserved under the heavy mulch on June 28, 2002.

Researchers have estimated an 8.5 to 10 kg ha^{-1} yield increase in spring wheat growing under optimum conditions with each mm of plant available water stored in the soil in spring (Akinremi and McGinn 1996). Therefore, the 4.7 mm increase in soil water observed in the 2xLate treatment in Winnipeg on June 30, 2003 may have contributed to an additional grain yield of up to 47 kg ha^{-1} over the control.

Precipitation was above normal at both Winnipeg and Carman in 2002 (Table 3.1) and so it is unlikely that the amount of soil moisture conserved at these sites provided any substantial increase to final yield. In contrast, precipitation at Winnipeg in June of 2003 was only 85% of normal (Table 3.1) and therefore the increased soil water measured under mulch on June 30, 2003 may have contributed to the higher final grain yield recorded in the mulched treatments. Similarly, the significantly higher oat yields measured under the 2x mulch rate compared to the control at Kenton, MB in 2002 (Table 4.13) may have been caused, in part, by better moisture conservation under mulch. Soil moisture was not measured at this location but early season moisture stress was generally severe in this region (Table 3.2). The lack of a grain protein concentration response to mulch application (Table 4.13) suggests that mulch-N may have played a limited role in the yield response, making moisture conservation a more likely explanation.

Table 4.13. Effect of alfalfa mulch rate on grain yield, grain protein concentration (GPC), and grain N yield at Clearwater and Kenton in 2002.

	------------- Clearwater (wheat) ----------						---------------- Kenton (oat) --------------					Mulch rate	
	Yield		GPC		N yield		Yield		GPC	N yield		(dry weight)	N applied
Treatment[z]	kg ha^{-1}		%		kg ha^{-1}		kg ha^{-1}		%	kg ha^{-1}		--------- kg ha^{-1}	-----------
control	971	b[y]	18.7	b	31.8	b	376	c	14.2	8.2	b	0	0
0.5x	1025	ab	18.8	b	33.7	b	576	ab	13.3	12.4	a	1880	66
1x	1122	a	19.1	ab	37.9	a	502	bc	13.8	10.8	ab	3760	132
2x	1109	a	19.4	a	37.7	a	682	a	12.4	13.1	a	7520	264
LSD (0.05)	116		0.5		3.59		165		NS	2.9			
P>F	0.0485		0.0419		0.0108		0.014		NS	0.0173			
Mean	1057		19.0		35.2		534		13.4	11.12			

z 0.5x, 1x and 2x refer to the amount of alfalfa harvested from an area 0.5, 1 and 2 times the wheat plot area.
Refer to table 3.6 for amounts of alfalfa mulch applied.

y Means followed by the same letter within a column are not significantly different (P > 0.05) according to Fisher's protected LSD.

Soil moisture conservation observed under high mulch rates compared to control plots was likely primarily a result of reduced evaporation (Duley and Russel 1939; Prihar et al. 1996). Other possible contributing factors to increased soil moisture under mulch are reduced transpiration, due to possibly lower plant densities or due to lower soil temperatures under mulch causing reduced rooting activity (Yunusa et al. 1994), and enhanced infiltration by the addition of residue to the soil surface (Findeling et al. 2003).

Several other significant soil moisture differences appeared at Winnipeg in 2002. On June 27 and July 17 the 60kgN treatment had significantly less soil moisture than the control (Table 4.10). This may be the result of increased water use due to increased growth at higher fertility rates (Entz and Fowler 1989). Biomass measurements on July 18, when wheat was at the anthesis stage, show significantly more growth in the 60kgN treatment than in all other treatments (Table 4.14).

Table 4.14. The effect of mulch application rate and mulch application timing on wheat biomass accumulation at wheat anthesis at Winnipeg on July 18, 2002.

Treatment[z]	Biomass (kg ha^{-1})	
Control	998	d[y]
20kgN	1924	c
40kgN	3030	b
60kgN	3691	a
0.5xEarly	1402	cd
1xEarly	1190	d
2xEarly	1930	c
0.5xLate	1219	d
1x3Late	1127	d
2x3Late	1329	d
LSD (0.05)	586	
P>F	<0.0001	
Mean	1784	
Contrast		
Early vs Late	NS	

z 0.5x, 1x and 2x refer to the amount of alfalfa harvested from an area 0.5, 1 and 2 times the wheat plot area. Refer to Table 3.6 for amounts of alfalfa mulch applied. The 20, 40, 60kgN treatments consisted of 20, 40 and 60 kg N/ha applied as ammonium nitrate. Early application timing was before wheat emergence. Late Application timing was at the three-leaf stage.

y Means followed by the same letter within a column are not significantly different ($P > 0.05$) according to Fisher's protected LSD.

No moisture conservation effects of mulch were observed after early July. Shading by the wheat canopy may have reduced evaporation, thereby minimizing differences in soil moisture between treatments.

4.1.5 Effect of alfalfa mulch application on wheat N uptake at anthesis and soft-dough stages

N uptake, by analysis of % N in above ground wheat biomass, was measured at the anthesis and soft-dough stages of wheat development. The soft-dough stage was assumed to be the point at which the maximum level of N had accumulated in the wheat (Fowler et al. 1990). The N uptake measurements revealed that alfalfa mulch application at the 2x rates significantly increased N uptake compared to control plots in 3 out of 4 site years (Tables 4.15, 4.17). Carman 2003 was the only site where no increase in N uptake was observed. Lack of a significant effect of mulch on N uptake was attributed to high residual soil N fertility at the beginning of the growing season (Table 3.3).

Winnipeg 2002

Differences in N uptake between early and late mulch application were not significant at Winnipeg in 2002 (Table 4.16). The N uptake measurements taken at wheat anthesis showed that both the early and late 2x mulch rate treatments had equivalent N uptake to wheat fertilized with 20 kg ha^{-1} of inorganic N (26-34 kg ha^{-1}) (Table 4.15). When above-ground biomass N was measured again at the soft-dough stage these high-mulch-rate treatments showed significantly higher N uptake than the control (53-57 vs. 35 kg ha^{-1}), and had equivalent N uptake to the 40 kg ha^{-1} inorganic N treatment (63 kg ha^{-1}). These observations show that when alfalfa mulch was applied to wheat at the higher rates (3.9 to 5.2 t ha^{-1}), either before emergence or at the three-leaf stage, total N uptake was substantially increased over the control treatment. Other measurements support these observations. For example, total grain N yield values in the 2x treatments were significantly higher than the control, and equivalent to grain N yield in the 20 kg N treatment (Table 4.22). Contrast analysis for Winnipeg 2002 showed that N uptake at the soft dough stage increased linearly with rate of applied ammonium nitrate, and also with rate of applied alfalfa mulch for both the early and late treatments (Table 4.16). This positive N uptake response of wheat to mulch application indicates that mulch-supplied N became available to wheat rapidly enough to benefit the wheat whether applied at the early or late stage.

Another factor affecting N mineralization from alfalfa mulch is the chemical composition of alfalfa mulch. The early-applied mulch had a lower C/N ratio than the late-applied mulch (Table 4.19) which favours more rapid breakdown and N release (Parr and Papendick 1978). Lignin, which slows alfalfa decomposition (Bross et al. 1995), was likely higher in the later applied mulch (Albrecht et al. 1987). Lignin is a major component of acid detergent fiber (ADF), and ADF was higher in the later applied mulch (Table 4.19). Therefore, the early-applied mulch would be expected to release N faster than the late-applied mulch, and this may partly explain why similar amounts of N were taken up in both the early and late mulch-treated wheat crops.

Carman 2002

At Carman in 2002 N uptake at the soft dough stage was lowest in the control plots and highest in wheat that received 60 kg ha^{-1} of inorganic N (Table 4.15). All wheat plots receiving mulch treatments, with the exception of the early 0.5x treatment, showed equivalent N uptake to the 60 kg N treatment, and showed significantly higher N uptake than the control. These observations show a significant N contribution to the

Table 4.15. Alfalfa mulch application rate and application timing effects on wheat N uptake measured at anthesis and soft-dough stages at Winnipeg and Carman in 2002.

	Winnipeg		Carman		
	Anthesis	Soft-dough	Anthesis		Soft-dough
			(sprayed)	(unsprayed)	(unsprayed)
Treatment^z	N uptake (kg ha^{-1})				
control	17.9 d^y	34.5 g	36.8 d	22.0 c	50.1 c
20kgN	28.9 bc	50.9 cde	39.7 cd	41.5 ab	72.4 ab
40kgN	49.7 a	62.7 b	58.9 ab	40.8 ab	71.1 ab
60kgN	59.8 a	92.6 a	65.5 a	40.5 ab	81.8 a
0.5xEarly	25.4 bcd	44.8 def	49.5 bcd	39.7 ab	64.1 bc
1.0xEarly	23.3 cd	44.7 def	48.5 bcd	45.1 ab	71.3 ab
2.0xEarly	34.1 b	56.7 bc	54.7 abc	36.3 bc	70.7 ab
0.5xLate	22.2 cd	38.6 fg	48.3 bcd	50.9 a	71.9 ab
1.0xLate	21.4 cd	42.5 efg	49.5 bcd	47.8 ab	66.7 ab
2.0xLate	25.8 bcd	53.2 bcd	50.5 abcd	51.7 a	77.6 ab
LSD(0.05)	10.7	10.02	15.3	14.529	15.78
P>F	<0.0001	<0.0001	0.0316	0.0132	0.0351
Mean	30.84	52.11	50.2	41.65	69.78
C.V.(%)	23.9	13.2	21	23.6	15.58

z 0.5x, 1x and 2x refer to the amount of alfalfa harvested from an area 0.5, 1 and 2 times the wheat plot area. Refer to Table 3.6 for amounts of alfalfa mulch applied. The 20, 40, 60 kg N treatments consisted of 20, 40 and 60 kg N ha^{-1} applied as ammonium nitrate.
Early application timing was before wheat emergence. Late application timing was at the three-leaf stage.

y Means followed by the same letter within a column are not significantly different (*P* > 0.05) according to Fisher's protected LSD.

Table 4.16. Contrast analysis^{z} for N uptake differences between selected treatments, and for relationships between N uptake and increasing ammonium nitrate rate, and between N uptake and increasing mulch rates at Winnipeg and Carman in 2002.

	Winnipeg		Carman		
	Anthesis	Soft-dough	Anthesis		Soft-dough
Contrasts			(sprayed)	(unsprayed)	
Early vs Late	0.1531	0.1732	0.7442	0.0228	0.4601
Control vs Mulch	0.0726	0.0027	0.0265	0.0002	0.0019
Fert - linear	<0.0001	<0.0001	0.0001	0.0203	0.0006
Fert - quadratic	0.9083	0.061	0.7298	0.0646	0.2971
Fert - cubic	0.2209	0.1523	0.2289	0.3903	0.1557
Early - linear	0.0661	0.0132	0.4386	0.4866	0.4679
Early - quadratic	0.2856	0.3526	0.6816	0.2952	0.4688
Late - linear	0.4395	0.0047	0.7758	0.8288	0.3438
Late - quadratic	0.6574	0.8269	0.9452	0.583	0.3055
C.V.(%)	23.9	13.24	21.0	23.61	15.58

z Values are given in units of probability (P), where a small P value indicates a very low probability that the observed relationship occurred due to random effects. For example, if the observed linear relationship between N uptake and increasing ammonium nitrate application rate had a very low P value, then there is a very small probability that this relationship occurred due to random effects, and therefore there is a high probability that the relationship was caused by treatment effects.

wheat from the alfalfa mulch at Carman in 2002. Contrast analysis showed that ammonium nitrate application and N uptake had a positive linear relationship, but no relationship was evident between N uptake and alfalfa mulch application rate (Table 4.16). Nevertheless, when averaged across all mulch treatments, alfalfa mulch-treated wheat took up significantly more N than wheat in the control plots (Table 4.16). The higher total N uptake at Carman than Winnipeg is likely a response to higher initial soil N levels at Carman (Table 3.3), and the effect of historic alfalfa cropping on this field.

The high weed infestation level at Carman 2002 (average density across treatments was 1427 weeds m^{-2}) may have reduced N uptake by the wheat crop. Herbicide was applied to a portion of the plots in an attempt to control the extreme weed infestation, primarily redroot pigweed and green foxtail (Table 4.5). Herbicide application provided poor weed control, especially for green foxtail which was later determined to possess resistance to Group 1 herbicides (L. Friesen, pers. comm., University of Manitoba). Nevertheless, comparison of N uptake at anthesis between the sprayed and unsprayed portions of the plots showed notable differences. When averaged over all treatments, N uptake by the wheat was higher when herbicide was used (Table 4.15), indicating that competition for N by weeds reduced N uptake by wheat in the unsprayed area. No difference in N uptake between early and late treatments was observed where herbicide was applied (Table 4.15). However, in the unsprayed area the level of N uptake in the late treatments was significantly higher than N uptake in the early treatments (Table 4.15), suggesting that heavy weed infestations reduced wheat N uptake more where mulch was applied early than where mulch was applied late, perhaps because of better weed suppression with the late mulch treatments. In the unsprayed area, significantly higher weed biomass was measured in the early 2x treatment compared to the late 2x treatment (Table 4.8). Therefore, it appears that heavy weed infestations will more severely reduce wheat N uptake from early-applied than from late-applied alfalfa mulch.

Winnipeg 2003

At Winnipeg in 2003, N uptake increased significantly with increasing mulch application rate, regardless of whether application timing was early or late (Table 4.17, 4.18). The plots that received the highest application rate of alfalfa mulch (2x rates) at all three application timings, i.e., fall, before emergence, or three-leaf stage applications, all took up significantly more N than the control (Table 4.17). At both the anthesis and soft dough sampling times, the least N uptake was observed in the control and the highest N uptake was observed in the treatment receiving the highest level of ammonium nitrate (60 kg N ha^{-1}) (Table 4.17). A highly significant positive linear relationship existed between N uptake and ammonium nitrate application rate (Table 4.18).

Regardless of mulch application timing at Winnipeg 2003, the 2x mulch rates resulted in N uptake at the soft-dough stage equivalent to the N uptake observed with 40 kg ha^{-1} inorganic N. The relatively high amount of N taken up by wheat that received the fall 2x treatment is notable considering that the total N applied was about half of that applied with the early 2x and frozen 2x treatments (Table 3.6). This may be a result of increased N mineralization occurring with the longer time for decomposition and mineralization. In addition to the longer time period, incorporation of the fall-applied mulch also likely enhanced the N mineralization rate (Aulakh et al. 1991; Smith and Sharpley 1993; Mohr et al. 1998b; Mohr et al. 1999).

Table 4.17. Alfalfa mulch application rate and application timing effects on wheat N uptake measured at wheat anthesis and soft-dough stages at Winnipeg and Carman in 2003.

Treatment[z]	Winnipeg		Carman	
	Anthesis	Soft-dough	Anthesis	Soft-dough
	N uptake (kg ha^{-1})			
control	27.9 g[y]	38.3 g	113 bcde	164
20kgN	43.0 cdefg	54.1 defg	110 bcde	181
40kgN	70.6 ab	79.1 bc	125 abc	157
60kgN	72.8 a	108.9 a	129 ab	180
0.5xEarly	40.2 defg	51.0 defg	98 e	168
1.0xEarly	40.5 defg	54.7 defg	111 bcde	198
2.0xEarly	66.4 ab	71.5 bcd	115 bcde	198
0.5xLate	36.0 efg	63.7 bcdef	108 cde	184
1.0xLate	52.0 bcdef	60.1 cdefg	104 de	195
2.0xLate	62.2 abc	85.0 b	112 bcde	203
0.5xFrozen[x]	32.4 fg	43.6 fg	103 de	169
1xFrozen	44.4 cdefg	62.2 cdef	107 cde	181
2xFrozen	50.8 bcdef	71.6 bcd	103 de	187
Fall[w] 0.5x	36.6 efg	49.9 defg	102 de	191
Fall 1x	42.4 cdefg	46.6 efg	112 bcde	177
Fall 2x	52.9 abcde	66.5 bcde	138 a	218
Fall 1x+1xEarly	58.2 abcd	67.1 bcde	119 abcd	204
LSD(0.05)	20.28	22.56	20.1	NS[v]
P>F	0.0003	<0.0001	0.0163	0.2307
Mean	48.8	63.04	112	186
C.V.(%)	29.2	24.4	12.4	15.2

z 0.5x, 1x and 2x refer to the amount of alfalfa harvested from an area 0.5, 1 and 2 times the wheat plot area. Refer to Table 3.6 for amounts of alfalfa mulch applied. The 20, 40, 60 kg N treatments consisted of 20, 40 and 60 kg N ha^{-1} applied as ammonium nitrate. Early application timing was before wheat emergence. Late application timing was at the three-leaf stage.

y Means followed by the same letter within a column are not significantly different ($P > 0.05$) according to Fisher's protected LSD.

x "Frozen" refers to mulch harvested at the Early application stage and stored in a freezer until the Late stage application.

w "Fall" indicates fall-applied mulch.

v NS = non-significant.

Table 4.18. Contrast analysis^z for N uptake differences between selected treatments, and for relationships between N uptake and increasing ammonium nitrate rate, and between N uptake and increasing mulch rates at Winnipeg and Carman in 2003.

	------------ Winnipeg ------------		----------- Carman -------------	
Contrasts	Anthesis	Soft-dough	Anthesis	Soft-dough
Early vs Late	0.8602	0.0968	0.9937	0.6141
Early vs Frozen	0.2684	0.8947	0.5228	0.4469
Early vs Fall	0.3908	0.4551	0.1186	0.5212
Late vs Frozen	0.2009	0.1451	0.5295	0.2164
Fall vs Spring	0.5025	0.1028	0.0357	0.3866
Control vs Mulch	0.009	0.0034	0.4785	0.0679
Early - linear	0.0069	0.0535	0.1284	0.2018
Early - quadratic	0.3512	0.7439	0.3817	0.269
Late - linear	0.0165	0.0532	0.6689	0.4319
Late - quadratic	0.4209	0.2611	0.5386	0.839
Frozen - linear	0.0886	0.0269	0.8798	0.4088
Frozen - quadratic	0.5152	0.353	0.6917	0.7478
Fall - linear	0.1083	0.0904	0.0004	0.1123
Fall - quadratic	0.9656	0.3655	0.8754	0.2592
Fertilizer - linear	<.0001	<.0001	0.0407	0.6626
Fert - quadratic	0.3733	0.3678	0.6443	0.8465
Fert - cubic	0.2407	0.8969	0.3589	0.1615
C.V.(%)	29.2	24.4	12.4	15.2

z Values are given in units of probability (P), where a small P value indicates a very low probability that the observed relationship occurred due to random effects. For example, if the observed linear relationship between N uptake and increasing ammonium nitrate application rate had a very low P value, then there is a very small probability that this relationship occurred due to random effects, and therefore there is a high probability that the relationship was caused by treatment effects.

The frozen treatments were included to allow an additional comparison of mulch applied at different timings. Freezing was required to preserve mulch harvested at the early stage for application at the late stage so that mulch of the same chemical composition could be applied at the same rate at both stages. There were no significant differences in N uptake between the wheat in the early treatments and the frozen treatments (Table 4.17, 4.18). Therefore, alfalfa mulch had a similar effect on wheat N uptake whether applied before wheat emergence or whether applied when the wheat was at the three-leaf stage. One might expect greater N uptake from the earlier applied mulch due to earlier N availability and a two-week longer time period for release of mulch N. However, Cueto Wong et al. (2001a) and Stute and Posner (1995) found the majority of initial legume residue N-release occurred within four weeks of application. Therefore, even the late application likely provided sufficient time for mulch N to become available to the wheat before the anthesis sampling time.

It should be mentioned that frozen samples had a different chemical composition than mulch that was not frozen. At Winnipeg, results of tissue analysis (Table 4.19) showed that freezing increased N content and decreased the C/N ratio, suggesting that freezing may have increased N availability of the mulch. The opposite effect was observed for the frozen treatment at Carman. This inconsistency may be a reflection of the difficulty in obtaining a uniform sample of the frozen alfalfa because of the high amount of liquid (presumably rich in solutes) being released as the frozen mulch thawed. Liquid had accumulated in the bottom of each garbage bag by the time the mulch had thawed to the point that it could be broken apart and applied to the plots. However, in spite of difficulties in obtaining reliable tissue analyses of the frozen mulch, the lack of significant differences between the early, late, or frozen mulch treatments in terms of N uptake suggests that mulch rate was more important to wheat N uptake than mulch application timing.

Table 4.19. Results of alfalfa tissue analysis[z] for alfalfa mulch.

Application Site	Harvest Date	N	C:N	ADF[y]
		%		%
Wpg	June 7, '02	4.11	10.54	24.4
	June 21, '02	3.52	13.67	31.0
Carman	June 12, '02	4.19	10.90	24.7
	June 24, '02	3.62	13.27	33.1
Clearwater, Kenton	June 17, '02	3.50	14.57	37.1
Wpg	Oct 1, '02	3.62	12.59	34.2
	June 2, '03	3.49	11.45	34.1
	June 13, '03	2.74	12.87	38.5
	Frozen[x]	3.88	10.94	38.1
Carman	Sept 26, '02	3.30	15.18	34.1
	June 3, '03	3.78	11.33	33.6
	June 17, '03	2.98	14.85	42.2
	Frozen[x]	3.26	14.91	31.8

z %N results differ slightly from those reported in table 3.6 because this analysis was done by Animal Science Department at U of M, whereas N values reported in table 3.6 were determined by Norwest Labs (see Materials and Methods section for a description of differences in analysis techniques between labs).

y ADF=acid detergent fibre.

x "Frozen" refers to mulch harvested at the early application timing and stored in a freezer until application at the late application timing.

As with N uptake, grain N yields at Winnipeg 2003 for all 2x mulch treatments were significantly higher than in the 20 kg N treatment and not significantly different from the 40 kg N treatment (Table 4.23), regardless of whether mulch was applied in fall, before emergence, or at the three-leaf stage. Grain N yield in the early and late 2x mulch treatments were not significantly different than the 60 kg N treatment (Table 4.23). The much greater N uptake response of wheat to alfalfa mulch application in 2003 compared to 2002 is likely a result of more favourable precipitation in 2003, both in terms of timing and amount.

Carman 2003

High background soil N levels at the Carman site in 2003 (Table 3.3) appear to have masked the effects of mulch supplied N (Table 4.17). There was no significant treatment effect of mulch on N uptake at the soft dough stage at this site. However, earlier season N uptake measurements revealed some treatment effects (Table 4.17). The highest N uptake was measured in the wheat that received the double rate of mulch in the fall of 2002. This treatment resulted in significantly greater N uptake at anthesis than all other mulch treatments despite the fact that the total N applied with this treatment was less than half of that applied with the early 2x treatment and less than one third of that applied with the late 2x treatment (Table 3.6). As at Winnipeg in 2003, the high amount of early N uptake with the fall applied mulch at Carman 2003 indicates that N mineralization was likely quite extensive as a result of the extended time period for decomposition of mulch residue, and presumably also as a result of mulch incorporation.

On-farm sites

N uptake at Kenton and Clearwater in 2002, as estimated by grain N yield, was found to be significantly enhanced by alfalfa mulch application (Table 4.13). Both the oat crop at Kenton and the wheat crop at Clearwater yielded significantly higher grain N with the 2x mulch treatments than with no mulch applied, indicating enhanced N uptake with alfalfa mulch application.

4.1.6 N use efficiency measured at wheat soft-dough stage

The total amount of N supplied by the mulch to the wheat crops ranged widely between treatments and between sites. At Winnipeg 2002, the 2xEarly and 2xLate treatments provided the wheat with 22 and 19 kg N ha^{-1}, respectively, representing a N use efficiency (percent of applied N taken up by the crop) of 14 and 10%, respectively (Table 4.20). At Winnipeg 2003, the 2xEarly and 2xLate treatments supplied approximately 33 and 44 kg N ha^{-1} to the wheat, respectively, with corresponding N use efficiency values of 24 and 37%, respectively (Table 4.21).

Table 4.20. Effect of alfalfa mulch application rate and application timing on wheat N uptake, N uptake increase (Increase), and N use efficiency (NUE) measured at wheat soft-dough stage at Winnipeg in 2002.

Treatment[z]	N applied kg ha^{-1}	N uptake kg ha^{-1}	Increase[y] kg ha^{-1}	NUE[x] %
Control	-	34.5 g[w]	-	-
20kgN	20	50.9 cde	16.4 cd	82.2 a
40kgN	40	62.7 b	28.3 b	70.6 a
60kgN	60	92.6 a	58.2 a	97.0 a
0.5xEarly	40	44.8 def	10.4 de	25.9 b
1xEarly	81	44.7 def	10.2 de	12.6 bcd
2xEarly	162	56.7 bc	22.2 bc	13.7 bc
0.5xLate	46	38.6 fg	4.2 e	9.0 d
1xLate	92	42.5 efg	8.1 de	8.8 cd
2xLate	184	53.2 bcd	18.7 bcd	10.2 bcd
LSD(0.05)		10	10.7	[v]
P>F		<0.0001	<0.0001	<0.0001
Mean		52.1	19.6	36.7
C.V. (%)		13.2	37.3	16.87

z 0.5x, 1x and 2x refer to the amount of alfalfa harvested from an area 0.5, 1 and 2 times the wheat plot area. The 20, 40, 60 kg N treatments consisted of 20, 40 and 60 kg N ha^{-1} applied as ammonium nitrate. Early application timing was before wheat emergence. Late application timing was at the three-leaf stage.

y Increase in N uptake = N uptake of a treatment - N uptake of the control.

x N use efficiency (NUE) = ((treatment N uptake - control N uptake)/N applied)*100.

w Means followed by the same letter within a column are not significantly different ($P > 0.05$) according to Fisher's protected LSD.

v The natural log of the data was used to achieve homogeneity of variance and a normal distribution. Treatment means are presented as the original untransformed values.

The improved N use efficiency in 2003 compared to 2002, is likely related to rainfall patterns (Figures 3.1, 3.2). The large rainfall events in 2002 appeared to have a negative effect on wheat growth, and presumably also N uptake. Furthermore, the heavy rains on June 9 and 10 may have caused N loss through volatilization, denitrification, and leaching.

Table 4.21. Effect of alfalfa mulch application rate and application timing on wheat N uptake, N uptake increase (Increase), and N use efficiency (NUE) measured at wheat soft-dough stage at Winnipeg in 2003.

Treatment[z]	N applied kg ha^{-1}	N uptake kg ha^{-1}		Increase[y] kg ha^{-1}		NUE[x] %	
Control	-	38.3	g[w]	-		-	
20kgN	20	54.1	defg	15.8	cd	79	abc
40kgN	40	79.1	bc	40.8	b	102.1	ab
60kgN	60	108.9	a	70.6	a	117.7	a
0.5xEarly	34	51.0	defg	12.7	cd	37.1	cd
1xEarly	68	54.7	defg	16.4	cd	24.1	cd
2xEarly	136	71.5	bcd	33.2	bc	24.4	cd
0.5xLate	30	58.5	bcdefg	13.6	cd	45.9	bcd
1xLate	59	60.1	bcdefg	21.8	bcd	36.9	cd
2xLate	118	81.8	b	43.9	b	37.1	cd
0.5xFrozen[v]	34	43.6	fg	5.4	d	15.6	d
1xFrozen	68	62.2	cdef	24.2	bcd	35.6	cd
2xFrozen	136	71.6	bcd	33.6	bc	24.7	cd
Fall[u] 0.5x	18	49.9	defg	11.6	cd	65.3	abcd
Fall 1x	35	46.6	efg	8.3	d	23.7	cd
Fall 2x	70	66.5	bcdef	28.2	bcd	40.4	cd
Fall 1x+1xEarly	103	67.1	bcde	28.8	bcd	28	cd
LSD(0.05)		22.93		23.7		56.7	
P>F		<0.0001		0.0001		0.0114	
Mean		62.37		25.53		46.80	
C.V.(%)		24.39		61.3		79.9	

z 0.5x, 1x and 2x refer to the amount of alfalfa harvested from an area 0.5, 1 and 2 times the wheat plot area. Refer to Table 3.6 for amounts of alfalfa mulch applied. The 20, 40, 60 kg N treatments consisted of 20, 40 and 60 kg N ha^{-1}applied as ammonium nitrate. Early application timing was before wheat. Emergence. Late application timing was at the three-leaf stage.

y Increase in N uptake = N uptake of a treatment - N uptake of the control.

x N use efficiency (NUE) = ((treatment N uptake - control N uptake)/N applied)*100.

w Means followed by the same letter within a column are not significantly different (*P* > 0.05) according to Fisher's protected LSD.

v "Frozen" refers to mulch harvested at the Early application stage and stored in a freezer until the Late stage application.

u "Fall" indicates fall-applied mulch.

4.1.7 Effect of alfalfa mulch application on wheat grain yield

As expected, wheat grain yield responses to mulch treatments were similar to N uptake responses. In four out of six site years grain yield increased as mulch rate increased (Tables 4.13, 4.22, 4.23).

Table 4.22. Effect of alfalfa mulch application rate and application timing on wheat grain yield, grain protein concentration (GPC), and grain N yield at Winnipeg and Carman in 2002.

	------------ Winnipeg ------------			------------ Carman --------------		
Treatment[z]	Grain yield	GPC	Grain N yield	Grain N yield	GPC	Grain N yield
	(kg ha^{-1})	(%)	(kg ha^{-1})	(kg ha^{-1})	(%)	(kg ha^{-1})
Control	775 e[y]	14.7 bc	20 e	403 b	15.4	10.9 b
20kgN	1072 cd	14.1 cd	26.5 cd	729 a	15.0	19.2 a
40kgN	1534 b	14.1 cd	38 b	825 a	15.6	22.6 a
60kgN	1954 a	13.6 d	46.6 a	842 a	15.7	23.2 a
0.5xEarly	831 de	15.3 ab	22.3 de	655 a	15.4	17.7 a
1xEarly	929 cde	14.9 ab	24.3 de	804 a	16.0	21.7 a
2xEarly	1148 c	15.4 ab	31 c	800 a	15.6	21.9 a
0.5xLate	852 de	14.8 abc	22.1 de	752 a	15.5	20.5 a
1x3Late	852 de	15.3 ab	22.9 de	850 a	15.6	23.3 a
2x3Late	1163 c	15.5 a	31.6 c	795 a	16.5	23.0 a
LSD(0.05)	245	0.7	6.2	208	NS	5.6
P>F	<0.0001	<0.0001	<0.0001	0.0052	0.0621	0.0035
Mean	1111	14.8	28.5	744	15.6	20.3
Contrasts						
Early vs Late	0.8485	0.9405	0.8564	0.4948	0.5468	0.7525
Control vs Mulch	0.0497	0.0605	0.0198	<.0001	0.1883	<.0001
Fert - linear	<.0001	0.0085	<.0001	0.0001	0.149	0.0002
Fert - quadratic	0.4784	0.911	0.6268	0.0375	0.3417	0.0104
Fert - cubic	0.5867	0.3839	0.4289	0.6391	0.1581	0.1935
Early - linear	0.0113	0.6943	0.0057	0.218	0.9031	0.5441
Early - quadratic	0.9413	0.1122	0.73	0.2616	0.0635	0.4849
Late - linear	0.0084	0.0767	0.0022	0.9319	0.0155	0.227
Late - quadratic	0.3356	0.3896	0.3742	0.3298	0.4566	0.0947
C.V.(%)	15.2	3.3	15	18.9	3	18.9

z 0.5x, 1x and 2x refer to the amount of alfalfa harvested from an area 0.5, 1 and 2 times the wheat plot area. Refer to Table 3.6 for amounts of alfalfa mulch applied. The 20, 40, 60 kg N treatments consisted of 20, 40 and 60 kg N ha^{-1} applied as ammonium nitrate. Early application timing was before wheat emergence. Late application timing was at the three-leaf stage.

y Means followed by the same letter within a column are not significantly different (*P* > 0.05) according to Fisher's protected LSD.

Table 4.23. Effect of alfalfa mulch application rate and application timing on wheat yield, grain protein concentration (GPC), and grain N yield at Winnipeg and Carman in 2003.

	------------ Winnipeg ------------			------------ Carman ------------		
Treatment^{z}	Grain Yield (kg ha^{-1})	GPC (%)	Grain N yield (kg ha^{-1})	Grain yield (kg ha^{-1})	GPC (%)	Grain N yield (kg ha^{-1})
Control	1111 f^{y}	15.0 bcd	29.2 g	2308 ab	15.9 e	64.4 abcde
20kgN	1468 def	14.8 bcde	38.1 efg	2089 bc	16.5 cde	60.5 de
40kgN	2225 ab	14.3 de	55.8 abc	2334 ab	16.7 cd	68.4 abcd
60kgN	2412 a	14.7 cde	62.2 a	2091 bc	17.5 ab	64.2 abcde
0.5xEarly	1377 def	15.5 ab	37.5 efg	2146 abc	16.7 cd	62.9 bcde
1xEarly	1575 cde	14.9 bcd	41.2 def	2046 bc	16.6 cde	59.6 e
2xEarly	2191 ab	15.4 abc	59.2 ab	2234 abc	17.5 ab	68.6 abc
0.5xLate	1320 def	14.9 bcd	34.5 fg	2148 abc	16.6 cd	62.5 cde
1xLate	1687 cd	15.8 a	46.8 cde	2318 ab	16.7 cd	67.9 abcde
2xLate	2137 ab	15.3 abc	57.4 ab	1953 c	18.0 a	61.7 cde
2xFrozen^{x}	1232 ef	15.2 abc	32.9 fg	2092 bc	16.2 de	59.5 e
1xFrozen	1395 def	15.5 ab	37.9 efg	2230 abc	16.6 cde	64.9 abcde
2xFrozen$^{\bullet}$	1899 bc	15.3 abc	51.0 bcd	2405 a	17.1 bc	72.2 a
Fall^{w} 0.5x	1279 ef	14.9 bcd	33.4 fg	2435 a	16.7 cd	71.3 ab
Fall 1x	1481 def	14.7 cde	38.2 efg	2250 ab	16.6 cd	65.5 abcde
Fall 2x	1951 bc	14.3 de	48.9 bcd	2273 ab	17.1 bc	68.2 abcd
Fall 1x+1xbe	2097 ab	14.2 e	52.2 abc	2274 ab	17.5 ab	69.8 abc
Mean	1696	15.0	44.5	2215	16.9	65.5
LSD(0.05)	390	0.73	10.4	292	0.7	3.5
P>F	<0.0001	0.0008	<0.0001	0.0384	<0.0001	0.0301
Contrasts						
Early vs Late	0.9978	0.6822	0.9276	0.6797	0.3426	0.807
Fall vs Spring	0.411	0.0002	0.1012	0.0242	0.6458	0.0349
Early vs Frozen	0.0722	0.8206	0.0783	0.2866	0.1176	0.5398
Late vs Frozen	0.0718	0.8548	0.0648	0.1551	0.0157	0.4073
Early vs Fall	0.2036	0.0039	0.0591	0.0377	0.5642	0.0616
Mulch vs Control	0.0002	0.48	0.0001	0.2059	<.0001	0.9011
Early - linear	<.0001	0.9784	<.0001	0.4996	0.0091	0.1413
Late - linear	0.0001	0.5714	<.0001	0.0266	0.0002	0.2466
Late - quadratic	0.5827	0.019	0.3128	0.0927	0.1773	0.1669
Frozen - linear	0.0008	0.8995	0.0007	0.0261	0.0158	0.0028
Fall - linear	0.0009	0.0989	0.0034	0.3062	0.1626	0.5678
Fert - linear	<.0001	0.1927	<.0001	0.3784	<.0001	0.5341
Fert - cubic	0.1195	0.2993	0.2214	0.0336	0.316	0.0647
C.V.(%)	16.2	3.4	16.4	8.7	2.9	8.6

z 0.5x, 1x and 2x refer to the amount of alfalfa harvested from an area 0.5, 1 and 2 times the wheat plot area. Refer to Table 3.6 for amounts of alfalfa mulch applied. The 20, 40, 60 kg N treatments consisted of 20, 40 and 60 kg N ha^{-1} applied as ammonium nitrate. Early application timing was before wheat emergence. Late application timing was at the three-leaf stage.

y Means followed by the same letter within a column are not significantly different (*P* > 0.05) according to Fisher's protected LSD.

x "Frozen" refers to mulch harvested at the Early application stage and stored in a freezer until the Late stage application.

w "Fall" indicates fall-applied mulch.

At Winnipeg wheat yield was significantly increased by mulch rate in both 2002 and 2003, regardless of whether mulch was applied before wheat emergence, at the three-leaf stage, or the previous fall (Tables 4.22, 4.23). Wheat receiving the 2xEarly and 2xlate treatments in 2002 produced the same yield as wheat receiving 20 kg ha^{-1} of inorganic N (Table 4.22). In 2003, the 2x treatments resulted in wheat yields equivalent to those achieved with 60 kg ha^{-1} of inorganic N (Table 4.23).

Grain yield at both Winnipeg and Carman was much higher in 2003 than in 2002. A major reason for the increased yield in 2003 was the more favourable amount and pattern of rainfall in 2003 than in 2002 (Table 3.1; Figures 3.1, 3.2, 3.3, 3.4). In 2002 both Winnipeg and Carman received heavy rains on June 8 and 9. Winnipeg also received heavy rains on July 4 and 5. Overall, excess precipitation at both Winnipeg and Carman in 2002 (~370 mm from May 1 to Aug 30) caused wheat plant stress and provided ideal conditions for leaf disease development. In 2003 there were no excessive rainfall events and total precipitation during the growing season was within the ideal range of 275 to 325 mm (Yield Manitoba 2003) for maximum wheat yields, with good drying conditions between rains which appeared to minimized wheat disease occurrence.

At Winnipeg, the greater grain yield response to alfalfa mulch application in 2003 than in 2002 was likely caused by greater access of mulch N by wheat in 2003. N uptake measurements show higher N uptake in 2003. Wheat N uptake was limited in 2002 likely by apparently high disease and moisture stress. Also, the large amounts of precipitation immediately following the early mulch application at Winnipeg in 2002 (Figure 3.1) may have increased N losses by leaching (Rasse et al. 1999), volatilization (Larsson et al. 1998) and denitrification (Aulakh et al. 1991).

At Carman, mulch rate did not have a consistent effect on grain yield in 2002 or 2003, likely due to the high background soil N levels and the lingering effects of a previous alfalfa crop. Yields at Carman in 2002 were very low as a result of excessive moisture in June (Table 3.1) and the high level of weed competition (Table 4.5). However, the entire group of mulch treatments at this site had significantly higher yield than the control (Table 4.22), indicating the beneficial effect of mulch application. At Carman 2003 the 2xLate treatment yielded significantly less than the control (Table 4.23). Lower yield with the 2xLate treatment may be partly explained by reduced wheat plant density (Table 4.1) due to smothering by the high amount of applied mulch (6.64 t ha^{-1}). The final plant density of 213 plants m^{-2} in this treatment was below the recommended wheat plant density for optimum yield in Manitoba (Manitoba Agriculture and Food 2001). However, at both Clearwater and Kenton the even higher mulch rate of 7.52 t ha^{-1} resulted in significant yield increases compared to control plots (Table 4.13), and so a mulch rate of 6.64 t ha^{-1} may not always be excessive.

The two trials conducted on organic farms (Clearwater and Kenton) both showed significantly higher grain yields at high mulch rates (7.52 t ha^{-1}) than with no alfalfa mulch applied (Table 4.13). At Clearwater the significant yield increase observed in wheat receiving the 2x rate mulch application, relative to the control, was at least partially attributable to increased availability of N, since mulch application increased grain protein concentration and grain N yield. At Kenton the beneficial effect of mulch application, in terms of increased grain yield and grain N yield (Table 4.13), may have been due to mulch-supplied N, but moisture conservation under mulch likely also played an important role in boosting grain yield. Grain protein concentration at Kenton decreased with increasing mulch rate, possibly because mulch-supplied N increased grain yields at the expense of grain protein (Partridge and Shaykewich 1972), or because mulch may have increased soil water content, which has been found to be negatively correlated with grain protein concentration (Fowler et al. 1990). The dry conditions in early summer at Kenton (Table 3.2) may have limited mulch N mineralization and N movement into the root zone, while at the same time magnifying the importance of any moisture conservation due to the mulch.

4.1.8 Effect of alfalfa mulch application on wheat grain protein concentration

The response of grain protein concentration to mulch treatments was variable. A significant increase in grain protein concentration with mulch application rate was observed with the late mulch treatments at Carman 2002, with the early, late and frozen mulch treatments at Carman 2003, and at Clearwater (Tables 4.13, 4.22, 4.23). In most of these cases (the exception was Carman 2002) the 2x mulch rate produced significantly higher grain protein concentrations than the control. The positive relationship between grain protein concentration and mulch application rate indicates that N supplied by the mulch was used by the wheat to increase grain protein concentration. Ammonium nitrate also resulted in increased grain protein concentration at Carman in 2003 (Table 4.23). On two occasions, i.e., Clearwater and the frozen mulch treatments at Carman in 2003, a simultaneous yield and grain protein concentration increase was observed (Tables 4.13, 4.23). Ammonium nitrate did not produce this result. A plausible explanation for the observed increase in grain protein concentration with mulch application rate at several sites is that alfalfa mulch resulted in sustained N mineralization throughout the growing season, thus providing plant-available N during grain filling which was used by the plant in grain protein assimilation (Sander et al. 1987).

In both 2002 and 2003 higher grain protein concentration was observed at Carman than at Winnipeg and this is likely due to the higher initial soil nitrate levels and the history of alfalfa cropping at Carman. The highest grain protein levels, up to 19.4%, were observed in the wheat grown in 2002 on the organic farm at Clearwater, MB (Table 4.22). Unfortunately, a background soil N test was not done at this site. One may hypothesize that the high grain protein concentration at this site was due to a combination of low grain yields and high soil N levels (or substantial N mineralization over the growing season) as a result of the perennial forage/legume stand that was terminated in 2000 (Table 3.5).

Protein levels in mulch-treated wheat were often higher than protein levels in ammonium nitrate treated wheat. For example, at Winnipeg 2002 the late 2x treatment produced wheat with a significantly higher grain protein concentration than wheat treated with 60 kg of inorganic N (15.5% vs. 13.6%) (Table 4.22). However, grain protein concentration in the 60 kg N treatment was likely diluted by high grain yield (Fowler et al. 1990). The late 2x treatment also resulted in significantly higher grain protein concentration than the 20 kg N treatment (15.5% vs. 14.1%). This is perhaps a more meaningful comparison than with the 60 kg N treatment since the 20 kg N and late 2x treatment produced equivalent yields (1072 and 1163 kg ha^{-1} respectively) (Table 4.22) and took up equivalent amounts of N (50.9 and 53.2 kg ha^{-1} respectively) (Table 4.15). A similar comparison was found between the early 2x treatment and the 40 kg N treatment at Winnipeg 2003, where yield and N uptake were equivalent in the two treatments, and yet the mulch treatment resulted in significantly higher protein concentration (15.4% vs.14.3%) (Tables 4.17, 4.23). These examples suggest that, compared to ammonium nitrate N, mulch-supplied N was used more for grain protein synthesis than vegetative growth, possibly because mulch N became available later in the growing season (Sander et al. 1987).

4.1.9 Second-year N uptake, yield, grain protein concentration and grain N yield

Numerous studies have shown that alfalfa residue imparts yield-enhancing qualities to the soil in the second season after application, as well as long-term (Boawn et al. 1963; Hoyt 1990; Forster 1999; Bullied et al. 2002). In light of this knowledge, an oat crop was grown at Winnipeg in 2003 on the site of the 2002 wheat plots to measure second-year N uptake in the 2002 mulch-treated plots. Results showed that timing of mulch application had no significant effect on the second-year oat crop. Neither was any significant difference observed between treatments in terms of oat N uptake, or grain protein concentration (Table 4.24). However, oat grain yield and grain N yield were both significantly affected by mulch rate, with higher amounts measured in plots that had received the highest mulch rates (early and late 2x treatments) in 2002 than in the control or the ammonium nitrate-treated plots. The significantly higher grain N yields in the 2x treatments points to mulch-supplied N as the source of increased yields in these plots (Table 4.24). This conclusion agrees with the findings of Boawn et al. (1963) working at Prosser, Washington where a second corn crop grown after alfalfa in rotation took up more N than a second corn crop grown on previously uncropped grassland. Similarly, Forster (1999) reported positive grain N uptake benefits for five wheat crops grown after perennial alfalfa.

Table 4.24. Effect of alfalfa mulch application rate and application timing on second-year N uptake, grain yield, grain protein concentration (GPC), and grain N yield of oats grown at Winnipeg in 2003 on plots that grew mulch-treated and ammonium nitrate-treated wheat in 2002.

Treatment[z]	N uptake	Grain yield	GPC	Grain N yield
	kg ha^{-1}	kg ha^{-1}	(%)	kg ha^{-1}
Control	52.0	2101 c[y]	9.6	32.3 d
20kgN	56.8	2461 bc	9.8	38.6 cd
40kgN	59.7	2747 b	10.1	44.4 c
60kgN	57.3	2567 bc	9.7	39.8 cd
0.5xEarly	64.3	2967 ab	9.8	46.5 c
1xEarly	50.7	2897 b	9.5	44.0 c
2xEarly	60.4	3531 a	9.9	55.9 ab
0.5xLate	56.2	2570 bc	9.5	39.1 cd
1xLate	60.4	3022 ab	9.8	47.4 bc
2xLate	68.5	3528 a	10.1	57.0 ab
LSD(0.05)	NS[x]	570	NS	9.1
P>F	0.9442	0.001	0.9211	0.0004
Mean	58.6	2814	9.8	44.13
C.V.(%)	30.3	13.2	7.3	13.5
	Contrast			
Early vs. Late	0.6593	0.5813	0.9298	0.7026

z 0.5x, 1x and 2x refer to the amount of alfalfa harvested from an area 0.5, 1 and 2 times the wheat plot area. Refer to Table 3.6 for amounts of alfalfa mulch applied. The 20, 40, 60 kg N treatments consisted of 20, 40 and 60 kg N ha^{-1} applied as ammonium nitrate. Early application timing was before wheat emergence. Late Application timing was at the three-leaf stage.

y Means followed by the same letter within a column are not significantly different (*P* > 0.05) according to Fisher's protected LSD.

x NS = non-significant.

4.1.10 Cumulative N effects of alfalfa mulch application over two years

Total N uptake over two years was calculated for the Winnipeg 2002 site by adding the N uptake measured in the 2002 wheat crop to that measured in the 2003 oat crop (Table 4.25). Crops grown with the both the 2xEarly and 2xLate treatments took up an additional 30.6 and 35.3 kg N ha^{-1}, respectively, compared to crops grown on control plots where no mulch was applied. This represents N use efficiency of 18.9% and 19.2% for the mulch-applied N in the 2xEarly and 2xLate treatments respectively (Table 4.25). The 60 kg N and 40 kg N treatments took up an additional 63.6 and 36.0 kg N ha^{-1}, respectively, compared to the control, corresponding to N use efficiencies of 90.1 and 105.9%, respectively.

These cumulative N uptake results naturally lead to the question of what happened to the remaining 80% of the N that was applied with the alfalfa mulch that was not taken up by the two crops. Frequent rains following mulch application in 2002 may have promoted N losses through volatilization (Janzen and McGinn 1991; Larsson et al. 1998; Mohr et al. 1998a), denitrification (Groffman et al. 1987; Aulakh et al. 1991; Rasse et al. 1999), and leaching (Groffman et al. 1987; Campbell et al. 1994; Rasse et al. 1999). In comparison with ammonium nitrate, alfalfa mulch may be more prone to N loss through volatilization because all N released from alfalfa residue will initially be in the volatilization-prone ammonia form before being converted to nitrate by soil microbes, whereas 50% of the N contained in ammonium nitrate is initially present as nitrate, which does not volatilize. Similarly, N loss through denitrification activity may be greater with alfalfa mulch than ammonium nitrate because mulch provides carbon substrate for denitrifying microorganisms (Groffman et al. 1987). However, the risk of legume residue-N-loss through leaching was reported to be similar to, or less than that from ammonium nitrate application (Stute and Posner 1995). Nevertheless, a large portion of the original N may have remained in the soil in the form of stable organic compounds following the harvest of the second crop (Ladd et al. 1981; Ladd et al. 1985; Janzen et al. 1990).

Table 4.25. Effect of alfalfa mulch application rate and application timing on total N uptake, N uptake increase (Increase), and N use efficiency (NUE) over 2 years at Winnipeg.

	2002 Wheat				2003 Oats			Combined '02+'03		
Treatment[z]	N applied kg ha^{-1}	N uptake kg ha^{-1}	Increase[y] kg ha^{-1}	NUE[x] %	N uptake kg ha^{-1}	Increase kg ha^{-1}	NUE %	2-year N uptake kg ha^{-1}	Increase kg ha^{-1}	2-year NUE %
Control	-	34.5 g[w]	-	-	52.0	-	-	86.4 d	-	-
20kgN	20	50.9 cde	16.4 cd	82.2 a	56.8	4.8	24.1	107.7 bcd	21.3 b	106.4 a
40kgN	40	62.7 b	28.3 b	70.6 a	59.7	7.8	19.4	122.4 b	36.0 ab	90.1 a
60kgN	60	92.6 a	58.2 a	97.0 a	57.3	5.3	8.9	150.0 a	63.6 a	105.9 a
0.5xEarly	40	44.8 def	10.4 de	25.9 b	64.3	12.3	30.8	109.1 bcd	22.7 b	56.7 ab
1xEarly	81	44.7 def	10.2 de	12.6 bcd	50.7	-1.3	-1.6	95.4 bcd	9.0 b	11.1 b
2xEarly	162	56.7 bc	22.2 bc	13.7 bc	60.4	8.4	5.2	117.0 bc	30.6 b	18.9 b
0.5xLate	46	38.6 fg	4.2 e	9.0 d	56.2	4.2	9.1	94.8 cd	8.4 b	18.2 b
1xLate	92	42.5 efg	8.1 de	8.8 cd	60.4	8.5	9.2	102.9 bcd	16.5 b	18.0 b
2xLate	184	53.2 bcd	18.7 bcd	10.2 bcd	68.5	16.5	9.0	121.7 bc	35.3 b	19.2 b
LSD(0.05)		10	10.7	[v]	NS[u]	NS	NS	27.4	27.7	57.9
P>F		<0.0001	<0.0001	<0.0001	0.9442	0.9452	0.9651	0.0038	0.0123	0.0027
Mean		52.1	19.6	36.7	58.6	7.4	12.7	110.7	27	49.4
C.V. (%)		13.2	37.3	16.87	30.3	238.5	299.7	17.1	70.3	80.4

z 0.5x, 1x and 2x refer to the amount of alfalfa harvested from an area 0.5, 1 and 2 times the wheat plot area. The 20, 40, 60 kg N treatments consisted of 20, 40 and 60 kg N ha^{-1} applied as ammonium nitrate. Early application timing was before wheat emergence. Late application timing was at the three-leaf stage.

y Increase in N uptake = N uptake of a treatment - N uptake of the control.

x Nitrogen use efficiency (NUE) = ((treatment N uptake - control N uptake)/N applied)*100.

w Means followed by the same letter within a column are not significantly different ($P > 0.05$) according to Fisher's protected LSD.

v The natural log of the data was used to troansform the data to achieve homogeneity of variance and a normal data distribution. Treatment means are presented as the original untransformed values.

The two-year N use efficiency of the ammonium nitrate treatments was significantly higher than that of the mulch treatments, ranging from 90 to 106%. However, the majority of the ammonium nitrate-N was likely already used by the wheat crop during the first cropping season (Boawn et al. 1963), whereas a large portion of mulch-supplied N is presumed to have remained in the soil as decomposing residues with potential to supply N to the following oat crop and subsequent crops (Janzen et al. 1990). Supporting evidence for greater amounts of N supplied to the second crop from mulch than from ammonium nitrate is found in the greater yields and grain N yields in the oats grown on mulched plots than in the oats grown on the ammonium nitrate-treated plots (Table 4.24).

The results of this experiment agree with the numerous studies that report on the long-term N benefits of incorporated alfalfa. Bullied et al. (2002) found significantly greater grain yield, protein content, and grain N yield in second-crop barley grown after single-year alfalfa stands (alfalfa was seeded in spring, hayed twice during the summer and incorporated in the fall) compared to second-crop barley grown after canola or fallow controls. N from the alfalfa may continue to become available to the third crop after mulch application, and perhaps even longer (Ladd et al. 1981; Ladd et al. 1985; Janzen et al. 1990; Hoyt 1990; Janzen and McGinn 1991). Hoyt (1990) reported significantly higher grain yield in the 10th wheat crop grown in the 13th year after breaking a stand of forage alfalfa compared to wheat grown on the fallow-wheat control.

Yield efficiency and grain N yield efficiency were calculated to provide an additional perspective on the relative effects of ammonium nitrate and alfalfa mulch on wheat yield and grain N yield over two years of cropping (Tables 4.26, 4.27).

Ammonium nitrate produced 27 to 35 kg of grain ha^{-1} for every kg ha^{-1} of N applied, while alfalfa mulch produced 10 to 23 kg grain ha^{-1} for every kg ha^{-1} of N applied (Table 4.26). Grain N yield efficiency of ammonium nitrate was calculated as 0.57 to 0.75 kg of grain N ha^{-1} for every kg ha^{-1} of N applied, while alfalfa mulch yielded between 0.19 and 0.41 kg of grain N ha^{-1} for every kg ha^{-1} of N applied (Table 4.27).

After two crops this study revealed higher cumulative efficiencies provided by ammonium nitrate than alfalfa mulch. However, alfalfa residue has been shown to provide more to the long-term N supplying ability of the soil than ammonium nitrate application (Boawn et al. 1963; Janzen et al. 1990; Hoyt 1990; Forster 1999). Furthermore, the majority of alfalfa N was probably fixed by biological N fixation (Kelner et al. 1997), and therefore much less reliant than ammounium nitrate on non-renewable resources.

Table 4.26. Effect of alfalfa mulch application rate and application timing on yield efficiency^{z} over two years at Winnipeg.

Treatment^{y}	N applied kg ha^{-1}	2002 Wheat		2003 Oats		Combined '02+'03	
		kg of grain ha^{-1}/kg of applied N					
20kgN	20	14.86	a^{x}	18.0	ab	32.9	a
40kgN	40	18.99	a	16.2	ab	35.1	a
60kgN	60	19.65	a	7.8	bc	27.4	a
0.5xEarly	40	1.39	b	21.6	a	23.0	ab
1xEarly	81	1.90	b	9.8	bc	12.2	bc
2xEarly	162	2.30	b	5.5	c	11.2	bc
0.5xLate	46	1.67	b	10.2	bc	11.9	bc
1xLate	92	0.84	b	9.4	bc	10.5	c
2xLate	184	2.27	b	7.8	c	10.0	c
Mean		7.10		11.8		20.1	
LSD(0.05)		5.39		10.3		12.5	
P>F		<0.0001		<0.0001		0.0002	
C.V. (%)		52		59.9		40.1	

z Yield efficiency is calculated as (treatment yield - control yield)/N applied, and is expressed in units of kg of grain per ha per kg of applied N.

y 0.5x, 1x and 2x refer to the amount of alfalfa harvested from an area 0.5, 1 and 2 times the wheat plot area. The 20, 40, 60 kg N treatments consisted of 20, 40 and 60 kg N ha^{-1} applied as ammonium nitrate. Early application timing was before wheat emergence. Late application timing was at the three-leaf stage.

x Means followed by the same letter within a column are not significantly different (*P* > 0.05) according to Fisher's protected LSD.

Table 4.27. Effect of alfalfa mulch application rate and application timing on grain N yield efficiency^z over two years at Winnipeg.

Treatment^y	N applied kg ha^{-1}	2002 Wheat		2003 Oats		Combined '02+'03	
		------------ kg of grain N ha^{-1}/kg of applied N ----------------------					
20kgN	20	0.326	a	0.314	ab	0.640	ab
40kgN	40	0.449	a	0.302	ab	0.751	a
60kgN	60	0.443	a	0.126	b	0.569	ab
0.5xEarly	40	0.057	b	0.355	a	0.413	bc
1xEarly	81	0.053	b	0.145	b	0.211	c
2xEarly	162	0.068	b	0.146	b	0.217	c
0.5xLate	46	0.046	b	0.147	b	0.193	c
1xLate	92	0.031	b	0.164	ab	0.188	c
2xLate	184	0.063	b	0.201	ab	0.198	c
Mean		0.171		0.217		0.391	
LSD(0.05)		0.134		0.192		0.2	
P>F		<0.0001		0.0458		<0.0001	
C.V. (%)		53.76		57.18		38.13	

z Grain N yield efficiency is calculated as (treatment grain N yield - control grain N yield)/N applied, and is expressed in the units kg grain N ha^{-1} kg^{-1} applied N.

y 0.5x, 1x and 2x refer to the amount of alfalfa harvested from an area 0.5, 1 and 2 times the wheat plot area. The 20, 40, 60kgN treatments consisted of 20, 40 and 60 kg N ha^{-1} applied as ammonium nitrate. Early application timing was before wheat emergence. Late application timing was at the three-leaf stage.

x Means followed by the same letter within a column are not significantly different.

4.1.11 Conclusions

The positive effects of alfalfa mulch applied to wheat included weed suppression, moisture conservation, and increased N uptake, yield and grain protein concentration. These benefits increased with mulch application rate up to and including the highest rates of mulch used in this study (7.5 t ha^{-1}). The one exception was a loss of wheat plants, a small delay in development rate, and a negative effect on wheat yield observed at one site when a high rate of mulch (6.6 t ha^{-1}) was applied at the 3-leaf stage.

Several significant effects were observed between mulch application timings. Later mulch applications were more suppressive against weeds than early applications, possibly because late applications provided a longer lasting suppressive mulch layer.

Fall-applied and incorporated mulch stimulated weed recruitment, likely through increased soil nitrate levels without the growth inhibiting layer of surface mulch. Low rates of early-applied mulch may stimulate weed recruitment through increased soil moisture levels without sufficient mulch material to suppress weeds. Late applications resulted in significantly less dandelion establishment. Early mulch application provided equivalent N to wheat as late mulch application. Uptake of mulch N by wheat was reduced due to weed competition, but late mulch application appeared to minimize this effect by providing greater weed suppression and delayed N availability to weeds. Application at the three leaf stage provided sufficient time for mulch N to become available to the wheat before the anthesis sampling time.

Mulch application had several advantages over ammonium nitrate application. Significant increases in soil moisture under heavy mulch applications likely contributed to yield increases at several sites. N supplied to wheat by mulch caused greater increases in grain protein concentration than N supplied by ammonium nitrate. A second crop grown after mulch application produced significantly higher grain and grain N yields in plots treated with high rates of mulch than in plots treated with ammonium nitrate. Approximately 19% of mulch N was taken up by two successive crops. The majority of the remaining N is presumed to be present as decomposing organic residues with the ability to supply N to subsequent crops, whereas ammonium nitrate N was largely depleted after one crop. Within a cropping system where alfalfa mulch was applied annually, the soil organic N pool and the N supplying ability of the soil would likely increase over time.

4.2 Influence of alfalfa mulch incorporation on wheat

The effect of mulch incorporation on wheat was determined in a separate experiment by comparing incorporated mulch treatments with unincorporated mulch treatments. Based on the work of Mohr et al. (1998b), and others (Smith et al. 1990; Aulakh et al. 1991; Smith and Sharpley 1993), we hypothesized that incorporation would increase availability of mulch-supplied N to wheat. This experiment consisted of two site-years; Winnipeg 2002 and Carman 2002.

4.2.1 Wheat plant stand density

Rotary hoe incorporation was responsible for eliminating a significant number of wheat seedlings at Winnipeg (Table 4.28); however, final grain yield was not affected (Table 4.35). In contrast to the rotary hoe effect, mulch application caused no significant reduction in wheat seedling numbers in the incorporation experiment (Table 4.28). This may be explained by the relatively low mulch rates used in this experiment. The 2x rates were 3.94 and 3.46 t ha^{-1} alfalfa dry matter at Winnipeg and Carman, respectively. At Carman, no significant effects on plant stand density were caused by either mulch application or by incorporation.

4.2.2 Wheat development

Based on Haun stage measurements, neither mulch application nor rotary hoe incorporation had significant effects on wheat development rate (Table 4.28). However, on July 17 at Winnipeg plots receiving higher amounts of N were significantly more advanced on July 17 than plots receiving lower rates of N (Table 4.28). Stimulation by N

Table 4.28. The effect of mulch level and incorporation on wheat establishment at Winnipeg in 2002.

Treatment^{z}	Plant Density -- plants m^{-2} --	---------- Haun Stage ---------- (June 14)	 (July 17)
Control	262	1.38	8.04e^{y}
0.5x	282	1.41	8.27de
1.0x	236	1.52	8.37cde
2.0x	256	1.46	8.81abcd
20kgN	253	1.45	9.43a
40kgN	ND^{x}	ND	9.30a
60kgN	ND	ND	9.27ab
ControlI^{w}	251	1.36	7.8e
0.5xI	250	1.46	8.53bcde
1.0xI	249	1.4	8.37cde
2.0xI	235	1.42	8.93abcd
20kgNI	243	1.46	8.36cde
40kgNI	ND	ND	9.20ab
60kgNI	ND	ND	9.10abc
Mean	252	1.43	8.7
LSD(0.05)	NS	NS	0.771
P>F	0.0596	0.4683	0.0008
Main Effects – Incorporation			
No	258a	1.44	8.78
Yes	245b	1.42	8.61
LSD(0.05)	11.9	NS	NS
P>F	0.042	0.4303	0.2415
Main Effects – Fertilizer Treatment			
0x	256	1.37	7.92c
0.5x	266	1.43	8.40bc
1x	243	1.46	8.37bc
2x	246	1.44	8.87ab
20kgN	248	1.45	8.90ab
40kgN	ND^{w}	ND	9.25a
60kgN	ND	ND	9.18a
LSD(0.05)	NS^{w}	NS	0.57
P>F	0.1119	0.3166	<0.0001
Interaction Effects - Fertilizer x Incorporation			
P>F	0.198	0.5165	0.2884
C.V.(%)	7.33	6.63	6.2

z The 0.5x, 1x, and 2x mulch rates were 0.87, 1.73, and 3.46 t ha^{-1} (dry weight) respectively.
The 20, 40, 60 kg N treatments consisted of 20, 40 and 60 kg N ha^{-1} applied as ammonium nitrate.
y Means followed by the same letter are not significantly different.
x ND = not determined, NS = non-significant.
w Treatments designated with 'I' received an incorporation operation with a rotary hoe.

fertility of early wheat development was also observed by Longnecker et al. (1993). The plots receiving 40 and 60 kg ha^{-1} inorganic N were significantly more advanced than the control and the 0.5x and 1x mulch treatments. The 2x mulch treatment was also significantly more advanced than the control (Table 4.28), which can be explained as a response to mulch-supplied N (Longnecker et al. 1993). These results suggest that N supply was a more important factor in rate of wheat development than was physical impedance by the alfalfa mulch.

The Carman site showed no difference in rate of development possibly because background soil nitrate levels as measured in spring were relatively high compared to Winnipeg (Table 3.3).

4.2.3 Weed population density and growth

Total weed population density at Winnipeg was not affected by either incorporation or mulch rate (Table 4.29). However, mulch rate did significantly affect lamb's quarters, dandelion and wild oat (*Avena fatua* L.), while incorporation had a significant effect on wild oat population density (Table 4.29). Lamb's quarters numbers were higher in the 0.5x treatments than in all other treatments, indicating that the low rate alfalfa mulch treatments improved recruitment conditions for lamb's quarters. A likely explanation is that moisture conservation under mulch promoted germination of lamb's quarters seedlings, as was observed by Teasedale and Mohler (1993). Greater mulch material in the higher mulch rate treatments (1x, 2x rates) likely suppressed weeds while the 0.5x mulch rates may have contained only enough material to improve the conditions for germination but not enough to provide weed suppression. If nitrate had been an important factor causing increased lamb's quarters establishment, then it would follow that the 20 kg N treatment also should have had high weed density. However, weed

Table 4.29. The effect of mulch level and incorporation on total and individual weed species densities at Winnipeg in 2002.

Treatment	redroot pigweed	b.yard grass	lamb's quarters	dandelion	sow thistle	foxtail	w. buckwheat	wild oats	other	Total
	weeds m^{-2}									
					Incorporation means					
No incorporation	3.1	109.3	18.3	12.4	5.3	21.5	16.7	2.5 b^{z}	13.7	199
Incorporation	2.5	91.2	18.7	16.4	6.0	20.1	12.7	4.0 a	8.9	181
LSD(0.05)	ns^{y}	ns	ns	ns	ns	ns	ns^{x}	^{x}	ns^{x}	ns
					Mulch/fertilizer rate means					
Control^{w}	1.5	106.0	15.5 b	3.3 c	5.0	15.5	6.3	1.8 b	12.8	168
0.5x	4.0	85.8	31.5 a	19.5 a	5.8	17.3	10.0	3.0 ab	10.3	187
1x	2.8	100.8	16.0 b	18.5 a	6.5	30.3	10.5	3.2 ab	9.0	198
2x	2.0	98.5	13.0 b	25.0 a	3.5	15.5	24.3	6.0 a	14.8	190
20kgN	3.8	110.3	16.5 b	5.8 b	7.5	25.5	22.5	2.0 b	9.8	206
LSD(0.05)	ns	ns	^{x}	^{x}	ns	ns	ns^{x}	^{x}	ns^{x}	ns
					ANOVA					
Incorporation	NS	NS	NS	NS	NS	NS	NS	*	NS	NS
Fert type	NS	NS	*	**	NS	NS	NS	*	NS	NS
Incorp x Fert	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Mean	2.8	100.3	18.5	14.4	5.7	20.8	14.7	3.25	11.3	190
C.V.(%)	91.8	50.6	20.24	27.767	65.5	87.6	46.45	66.77	40.28	27.3

z Means followed by the same letter are not significantly different.

y ns = non-significant.

x Log transformation of the data+1 was used for analysis to achieve homogeneity of variance and a normal data distribution.

w The 0.5x, 1x, and 2x mulch rates were 0.87, 1.73, and 3.46 t ha^{-1} (dry weight) respectively. The 20 kg N treatment consisted of 20 kg N ha^{-1} broadcast applied as ammonium nitrate.

**, *, and NS indicate P <0.01, P < 0.05, and P >0.05, respectively.

density in the 20 kg N treatment was equivalent to the control (Table 4.29). These results are similar to the weed density results for the Winnipeg 2003 site of the time-of-application experiment where the early application of mulch at the 0.5x rate caused significantly higher weed population density than the 60 kg N treatment (Table 4.6).

Dandelion population densities were significantly higher in the mulch treatments than in the control or 20 kg N treatments, once again suggesting that dandelion seeds were added with the mulch. Wild oat population densities were low but significantly greater in plots that received incorporation than in those that did not (4 plants m^{-2} vs. 2.5 plants m^{-2}) (Table 4.29). Blum et al. (1997) also observed a stimulation of weed emergence with incorporation of crimson clover (*Trifolium incarnatum* L.), subterranean clover (*T. subterranean* L.), wheat and rye (*Secale cereale* L.) cover crop residues compared to tilled reference plots. They attributed the increased weed emergence with residue incorporation to an increase in "safe" germination sites and elimination (through mixing of residue with soil) of a zone of inhibition produced by certain types surface-placed residues. It seems doubtful that the small amount of incorporation that occurred with the rotary hoe operation at Winnipeg could have sufficiently disrupted the surface mulch layer to eliminate any potential zone of inhibition. Possibly, as suggested by Blum et al. (1997), increased variation in soil microtopography in tilled plots vs. the untilled plots enhanced wild oat germination. Wild oat was also more prevalent in the 2x mulch rate treatments (6 plants m^{-2}) than in the control (1.8 plants m^{-2}) or the 20kgN treatments (2.0 plants m^{-2}) (Table 4.29).

At Carman mulch incorporation with the rotary hoe had the beneficial effect of significantly reducing total weed population density (491 weeds m^{-2} with incorporation vs. 640 without incorporation) (Table 4.30). Green foxtail populations were significantly reduced with the incorporation operation, and this reduction accounted for most of the over-all reduction in weed population density in the incorporated vs. the unincorporated treatments.

Table 4.30. Means for main effects of mulch level and incorporation on total and individual weed species densities at Carman in 2002.

Treatment	redroot pigweed	lamb's quarters	foxtail	dandelion	other	total
	weeds m^{-2}					
			Incorporation means			
No incorporation	93.0	170.7	400.0 a[z]	14.8	1.3	680a
Incorporation	77.0	128.7	259.0 b	23.7	1.9	491b
LSD(0.05)	ns[y]	ns	124.0	ns	ns	119
			Mulch/Fertilizer treatment means			
Control[x]	101.7	134.2	308.0 b	0.3 bc	1.3	546bc
0.5x	86.7	165.8	528.0 a	14.0 ab	0.7	795 a
1x	43.3	132.5	233.0 b	48.7 a	1.7	460 c
2x	89.2	100.0	253.0 b	33.3 a	1.7	477bc
20kgN	105.0	215.8	327.0 b	0.0 c	2.7	651ab
LSD(0.05)	ns	ns	196	[w]	ns	189
			ANOVA			
Incorporation	NS	NS	**	NS	NS	**
Fertilizer treatment	NS	NS	**	**	NS	**
Incorp x Fert	NS	NS	**	NS	NS	*
Mean	85.2	149.67	330	19.26	1.6	586
C.V.(%)	45.26	57.63	37.93	97.2	161.73	26.6

z Means followed by the same letter are not significantly different.
y ns = non-significant.
x The 0.5x, 1x, and 2x mulch rates were 0.87, 1.73, and 3.46 t ha^{-1} (dry weight) respectively. The 20 kg N treatment consisted of 20 kg N ha^{-1} broadcast applied as ammonium nitrate.
w Log transformation of the data+1 was used for analysis to achieve homogeneity of variance and a normal data distribution. The original, untransformed means are presented.
**, *, and NS indicate $P < 0.01$, $P < 0.05$, and $P > 0.05$, respectively.

Weed population density in the incorporation experiment at Carman was significantly higher in the lowest mulch rate (0.5x) plots compared to the control, but decreased as mulch application rate increased (Table 4.30). This is similar to results of the time-of-application experiment, where increased mulch rate resulted in decreased weed numbers (Tables 4.4, 4.6), and where the 0.5x mulch rate at Winnipeg 2003 was observed to stimulated weed recruitment (Table 4.6). Green foxtail populations in the incorporation experiment at Carman were significantly higher in the lowest mulch rate treatments than in all other treatments. It is possible that the low mulch rate created conditions favourable to green foxtail recruitment, such as reduced fluctuations in soil moisture (Boyd and Van Acker 2003), or perhaps higher nitrate levels (Benech Arnold et al. 2000), without the inhibitory effect of the thicker mulch layer that was present in the 1x and 2x treatments.

At Carman, dandelion population density was once again increased with mulch application (Table 4.30), suggesting that dandelion seeds were harvested with the alfalfa and applied to the wheat plots.

A mulch rate by incorporation interaction was observed in Carman, where significantly lower weed population density was observed in the low mulch rate treatments with incorporation than without incorporation. This interaction was observed with green foxtail population density and also with total weed population density (Table 4.31), indicating the weed control benefits of the rotary-hoe at Carman 2002.

Incorporation of mulch caused a significant increase in weed growth in the 2x mulch treatments at Carman (Table 4.32). It is likely, as has been reported by others (Smith et al. 1990; Aulakh et al. 1991; Smith and Sharpley 1993; Mohr et al. 1998b), that the incorporation increased the mineralization of mulch N. The greater weed growth in the incorporated 2x treatment vs. the unincorporated 2x treatment can then be explained as the result of greater N availability to the weeds. In contrast, where ammonium nitrate was applied to wheat at the 60 kg N ha^{-1} rate, incorporation with the rotary hoe resulted in decreased weed biomass compared to the 60 kg N treatment that was unincorporated.

Incorporation had no effect on weed biomass in the 0.5x and 1x mulch rate treatments (Table 4.32). Incorporation appears to provide weed control benefits with low mulch rates by reducing weed population density (Tables 4.30, 4.31), but this advantage was lost with the 2x mulch treatment, presumably due to enhanced N availability causing greater weed growth. Similar results were reported by Groffman et al. (1987) who found higher weed biomass with legume-N treatments compared to ammonium nitrate treatments, especially with conventional tillage over zero-tillage treatments.

Table 4.31. Effect of incorporation and mulch rate on weed density at Carman in 2002.

Treatment[z]	Foxtail	Total
	---------- weeds m^{-2}	-----------
Control	356b[y]	608bc
0.5x	788a	1111a
1.0x	291b	538bc
2.0x	195b	497bc
20kgN	370b	648bc
ControlI[x]	260b	484bc
0.5xI	266b	478bc
1.0xI	175b	381c
2.0xI	310b	457bc
20kgNI	283b	653b
LSD(0.05)	215	267.19
P>F	0.0009	0.0015
Mean	330	585.5
C.V.(%)	37.93	26.6

z The 0.5x, 1x, and 2x mulch rates were 0.87, 1.73, and 3.46 t ha^{-1} (dry weight) respectively.
The 20, 40, 60 kg N treatments consisted of 20, 40 and 60 kg N ha^{-1} applied as ammonium nitrate.
y Means followed by the same letter are not significantly different.
x Treatments designated with 'I' received an incorporation operation with a rotary hoe.

4.2.4 Wheat N uptake

N uptake at Winnipeg was significantly influenced by mulch/fertilizer treatments but not generally by incorporation (Table 4.33). N uptake at Winnipeg increased with mulch rate at both the anthesis and soft-dough sampling times. At the soft dough sampling, total N uptake was 33, 39, and 51 kg ha^{-1} in the 0.5x, 1x and 2x mulch rate treatments

Table 4.32. Effect of mulch application rate and mulch incorporation on weed and wheat biomass measured at wheat anthesis on July 26, 2002 at Carman.

Treatment^{z}	Weeds biomass (kg ha^{-1})		Wheat biomass (kg ha^{-1})
Control	1496	de	5204
0.5x	2555	bcd	3736
1.0x	2611	bcde	3305
2.0x	2911	bcd	3923
20kgN	2953	bcd	3437
40kgN	3347	abc	3930
60kgN	3661	ab	3855
ControlI^{x}	1412	e	5793
0.5xI	2424	bcde	4608
1.0xI	2579	bcde	4409
2.0xI	4653	a	3728
20kgNI	2516	bcde	4499
40kgNI	2023	cde	4976
60kgNI	2165	cde	4895
LSD(0.05)	1465		NS
P>F	0.012		0.5087
Mean	2659		4274
C.V.(%)	33.18		26.3

z 0.5x, 1x and 2x refer to the amount of alfalfa harvested from an area 0.5, 1 and 2 times the wheat plot area. Refer to Table 3.6 for amounts of alfalfa mulch applied. The 20, 40, 60 kg N treatments consisted of 20, 40 and 60 kg N ha^{-1} applied as ammonium nitrate. Early application timing was before wheat emergence. Late application timing was at the three-leaf stage.

y Means followed by the same letter within a column are not significantly different (*P* > 0.05) according to Fisher's protected LSD.

x Treatments designated with 'I' received an incorporation operation with a rotary hoe.

respectively (Table 4.34). N uptake in the 0.5x and 1x treatments was equivalent to the 20 kg N treatment, while N uptake in the 2x mulch treatment was equivalent to the 40 kg N treatment (Table 4.33). A significant interaction between mulch/fertilizer treatments and incorporation at the soft dough stage was attributed to the 60 kg N treatment taking up significantly more N with incorporation than without incorporation (Table 4.34).

Trends for N uptake at Carman were opposite to those at Winnipeg in that incorporation significantly affected overall N uptake but mulch/fertilizer treatment did not (Table 4.33). Incorporated treatments resulted in increased N uptake compared to unincorporated treatments at the soft dough stage and also at the anthesis stage, suggesting that incorporation of mulch and/or ammonium nitrate allowed for better plant availability and uptake of N supplied by the mulch and/or fertilizer. It is also possible that rotary-hoe incorporation increased wheat N uptake through reduced weed competition (Table 4.30). For example, the anthesis-stage measurements taken in

Table 4.33. Effects of incorporation and mulch rate on wheat N uptake at Winnipeg and Carman at anthesis and soft-dough growth stages.

	-------- Winnipeg --------		-------- Carman --------		
	Anthesis	Soft-dough	------------Anthesis------------		Soft-dough
			sprayed	---------unsprayed---------	
Treatment	---------- kg ha^{-1} ----------				
		Incorporation treatment means			
No incorporation	33.2	44.2	95.7	86.4b^z	104.3b
Incorporation	34.4	47.3	89.8	95.5a	120.8a
LSD(0.05)	ns^y	ns	ns	7.1	15.6
		Mulch/Fertilizer Rate treatment means			
Control^x	17.0 e	31.1 d	85.1	87.4	123.8
0.5x	18.8 e	32.6 d	86.8	80.6	110.0
1x	24.8 d	39.3 c	89.7	94.9	102.9
2x	36.1 bc	51.4 b	107.7	97.9	109.4
20kgN	30.0 cd	35.4 cd	86.4	93.5	105.4
40kgN	43.8 b	55.6 b	98.2	90.9	120.8
60kgN	70.3 a	73.5 a	96.6	91.4	114.7
LSD(0.05)	w	6.6	ns	ns	ns
Mean	33.8	45.74	92.8	91	112.35
			ANOVA		
Incorporation	NS	NS	NS	*	*
Fert	**	**	NS	NS	NS
Incorp*Fert	NS	*	NS	NS	NS
C.V.(%)	6.07	14.14	18.611	12.59	18.31

z Means followed by the same letter within a column are not significantly different.
y ns = non-significant.
x The 0.5x, 1x, and 2x mulch rates at Winnipeg were 0.97, 1.97, and 3.94 t ha^{-1} (dry weight) respectively.
The 0.5x, 1x, and 2x mulch rates at Carman were 0.87, 1.73, and 3.46 t ha^{-1} (dry weight) respectively.
The 20, 40, 60 kg N treatments consisted of 20, 40 and 60 kg N ha^{-1} applied as ammonium nitrate.
w Data was log transformed to achieve homogeneity of variance and a normal distribution.
**, *, and NS indicate $P < 0.01$, $P < 0.05$, and $P > 0.05$ respectively.

portions of plots sprayed with herbicide showed no effect of incorporation, indicating that when weed competition for N was reduced, incorporation of mulch and fertilizer made no difference to plant N uptake (Table 4.33). Therefore, the increased N uptake observed in the incorporated vs. unincorporated treatments may be due to a weed control effect of incorporation rather than increased availability of mulch N from incorporation-induced mulch decomposition. This is in contrast to results of other studies that showed increased N availability and uptake where legume residue had been incorporated vs. left on the soil surface (Smith et al. 1990; Aulakh et al. 1991; Smith and Sharpley 1993; Mohr et al. 1998b). High residual soil N levels at Carman in 2002 (77 kg ha^{-1}) may have masked the possible affect of incorporation on mulch N mineralization.

Some evidence that incorporation enhanced mulch N-mineralization is seen in weed biomass results from Carman. At the soft-dough sampling time, plots treated with the incorporated 2x mulch rate resulted in significantly higher weed biomass than plots treated with an unincorporated 2x mulch rate (Table 4.32).

Table 4.34. Soft-dough stage N uptake means at Winnipeg in 2002 for all incorporated and unincorporated mulch and fertilizer treatments.

Treatment	N uptake (Aug 20) ---- kg ha^{-1} ----	
Control	28.3	g
0.5x	32.4	fg
1.0x	40.3	ef
2.0x	48.0	de
20kgN	36.1	fg
40kgN	59.5	bc
60kgN	64.9	b
ControlI^{z}	34.0	fg
0.5xI	32.9	fg
1.0xI	38.4	f
2.0xI	54.8	cd
20kgNI	34.3	fg
40kgNI	51.7	cd
60kgNI	82.1	a
LSD(0.05)	9.4	
P>F	<0.0001	
Mean	45.7	
C.V.(%)	14.14	

z Treatments designated with 'I' received an incorporation operation with a rotary hoe.

4.2.5 Wheat grain yield

Wheat yield was not affected by incorporation at either Winnipeg or Carman (Table 4.35). Several factors may have prevented the rotary-hoe incorporation of alfalfa mulch from increasing wheat N uptake and final yield. First, at Winnipeg the hard soil condition at the time of incorporation limited the effect of the rotary hoe operation, resulting in little mixing of the mulch with the soil. At Carman incorporation resulted in very good mixing of mulch and soil but the high background soil N level (77 kg ha^{-1}), and high level of weed infestation likely masked any increased N availability to the wheat that was caused by incorporation. It is notable that the rotary hoe operation, while not increasing wheat yield, also did not decrease wheat yield at either location (Table 4.35).

Wheat yield at Winnipeg responded positively to increasing mulch application rate. The 0.5x, 1x and 2x mulch rate treatments yielded 604, 765, and 1116 kg ha^{-1} respectively (Table 4.35). The 1x and 2x treatments yielded significantly more than the control and the 2x yield was equivalent to the 20kgN treatment yield (Table 4.35). Wheat yield at Carman was not significantly affected by mulch/fertilizer treatments.

4.2.6 Grain protein and grain N yield effects of mulch incorporation

Wheat grain protein concentration at Winnipeg was not affected by incorporation, but was higher in plots that received alfalfa mulch than in plots that received ammonium nitrate (Table 4.35). Mulch incorporation at Winnipeg did not affect grain N yield.

No significant effects of incorporation or mulch application on grain protein concentration or grain N yield were observed at Carman (Table 4.35).

Table 4.35. Effect of incorporation and mulch level on wheat yield, grain protein concentration (GPC), and grain N yield at Winnipeg and Carman in 2002.

	------------ Winnipeg	------------	------------	------------ Carman	------------	------------
Treatment[z]	Grain yield (kg ha^{-1})	GPC (%)	Grain N yield (kg ha^{-1})	Grain yield (kg ha^{-1})	GPC (%)	Grain N yield (kg ha^{-1})
		Incorporation means				
No Incorporation	1076	12.89	24.12	1335	17.2	39.7
Incorporation	1067	13.05	23.90	1333	17.2	40.2
LSD(0.05)	ns[y]	ns	ns	ns	ns	ns
		Mulch/Fertilizer treatment means				
Control	613 e[x]	13.55 a	14.6 e	1400	16.95	41.7
0.5x	604 e	13.20 b	14.0 e	1382	17.05	39.8
1x	765 d	13.27 ab	17.8 d	1285	17.21	38.8
2x	1116 c	13.34 ab	26.1 c	1258	17.27	38.2
20kgN	1020 c	12.84 c	23.0 c	1464	17.01	43.7
40kgN	1416 b	12.41 d	30.8 b	1307	17.30	39.7
60kgN	1967 a	12.11 d	41.8 a	1243	17.36	37.9
LSD(0.05)	[w]	0.33	[w]	ns	ns	ns
Mean	1072	12.97	24.01	1334	17.17	39.97
		ANOVA				
Incorporation	NS	NS	NS	NS	NS	NS
Fert	**	**	**	NS	NS	NS
Incorp*Fert	NS	NS	NS	NS	NS	NS
C.V.(%)	2.14	2.5	4.75	20.72	1.85	21.3

z The 0.5x, 1x, and 2x mulch rates at Winnipeg were 0.97, 1.97, and 3.94 t ha^{-1} (dry weight) respectively, and 0.87, 1.73, and 3.46 t/ha respectively at Carman.
The 20, 40, 60 kg N treatments consisted of 20, 40 and 60 kg N ha^{-1} applied as ammonium nitrate.
y ns = non-significant.
x Means followed by the same letter within a column are not significantly different.
w Data was log transformed to achieve homogeneity of variance and a normal distribution. Original means are presented.
**, *, and NS indicate $P < 0.01$, $P < 0.05$, and $P > 0.05$ respectively.

4.2.7 Second-year N uptake, yield, grain protein and grain N yield

A second-year oat crop grown at Winnipeg in 2003 on the 2002 wheat plots showed no second-year effects of incorporation on N uptake, grain yield, grain protein, or grain N yield (Table 4.36).

Table 4.36. Effect of mulch incorporation and mulch rate on N uptake, grain yield, grain protein concentration (GPC), and grain N yield of second-year oats grown at Winnipeg in 2003.

Treatment[z]	N uptake kg ha^{-1}	Grain yield kg ha^{-1}	GPC %	Grain N yield kg ha^{-1}
		Incorporation treatment means		
No Incorporation	34.9	1744	9.46	26.4
Incorporation	32.7	1790	9.48	27.1
LSD(0.05)	--	--	--	--
		Mulch/Fertilizer rate treatment means		
Control	29.7b[y]	1649bc	9.65	25.5b
0.5x	29.5b	1676bc	9.37	25.1b
1x	35.4b	1816b	9.36	27.2b
2x	47.2a	2284a	9.44	34.5a
20kgN	31.7b	1703bc	9.34	25.4b
40kgN	28.4b	1576c	9.54	24.0b
60kgN	34.9b	1663bc	9.6	25.5b
LSD(0.05)	7.86	234	ns[x]	3.5
Mean	33.85	1767	9.47	26.8
		ANOVA		
Incorporation	NS	NS	NS	NS
Fert/Mulch	**	**	NS	**
Incorp*Fert	NS	NS	NS	NS
C.V.(%)	22.97	13.1	4.12	13.06

z Oats were seeded on all plots that grew wheat in 2002. No treatments were applied in 2003.
The 0.5x, 1x, and 2x mulch rates in 2002 were 0.97, 1.97, and 3.94 t ha^{-1} (dry weight) respectively.
The 20, 40, 60 kg N treatments consisted of 20, 40 and 60 kg N ha^{-1} applied as ammonium nitrate.
y Means followed by the same letter are not significantly different.
x ns = non-significant
**, *, and NS indicate $P < 0.01$, $P < 0.05$, and $P > 0.05$ respectively.

4.2.8 Cumulative N effects of mulch application over two years

Incorporation did not impact the cumulative N effects of mulch application over two cropping seasons. N use efficiency, yield efficiency, and N yield efficiency were not significantly different between incorporated or unincorporated treatments. N use efficiency over the two years ranged from 31 to 79% for the ammonium nitrate treatments, and 3 to 23% for the mulch treatments (Table 4.37).

Table 4.37. Effect of alfalfa mulch incorporation and application rate on cumulative N uptake and N use efficiency (NUE) over 2 years at Winnipeg.

	2002 Wheat				2003 Oats			Combined 2002+2003		
Treatment[z]	N applied	N uptake	Increase[y]	NUE[x]	N uptake	Increase	NUE	2-year N uptake	Increase	2-year NUE
	kg ha^{-1}			%	kg ha^{-1}		%	kg ha^{-1}		%
Control	0	31.1 d[w]	-	-	29.7 b	-		60.9 d	-	-
20kgN	20	35.4 cd	4.3 c	21.4 b	31.7 b	2 b	10.2	67.0 cd	6.1 cd	30.6 bc
40kgN	40	55.6 b	24.5 b	61.3 a	28.4 b	-1.3 b	(-3.3)	84.0 b	23.1 b	57.8 ab
60kgN	60	73.5 a	42.4 a	70.6 a	34.9 b	5.2 b	8.7	108.4 a	47.5 a	79.2 a
0.5x	40	32.6 d	1.5 c	3.9 b	29.5 b	-0.2 b	(-0.4)	62.2 d	1.3 d	3.2 c
1x	81	39.3 c	8.2 c	10.1 b	35.4 b	5.7 b	7.1	74.7 bc	13.8 bc	17.1 c
2x	162	51.4 b	20.3 b	12.5 b	47.2 a	17.5 a	10.8	98.6 a	37.7 a	23.2 c
LSD(0.05)		6.61	8.01	18.3	7.86	7.8	NS[v]	10.6	11.13	30.5
P>F		<0.0001	<0.0001	<0.0001	0.0003	0.0002	0.4872	<0.0001	<0.0001	0.0001
Mean		45.74	17.13	30.14	33.85	4.83	5.52	79.4	21.58	35.2
C.V. (%)		14.14	45.64	59.22	22.97	159.03	319.18	13.16	51.02	85.88

z 0.5x, 1x and 2x refer to the amount of alfalfa harvested from an area 0.5, 1 and 2 times the wheat plot area. Refer to Table 3.6 for amounts of mulch applied. The 20, 40, 60 kg N treatments consisted of 20, 40 and 60 kg N ha^{-1} applied as ammonium nitrate.

y Increase in N uptake = N uptake of a treatment - N uptake of the control.

x N use efficiency (NUE) = ((treatment N uptake - control N uptake)/N applied)*100.

w Means followed by the same letter within a column are not significantly different.

v NS = non-significant.

4.2.9 Conclusions

Mulch incorporation with a rotary hoe at the wheat emergence stage had several significant effects on wheat. At one of two locations wheat plant stand density was reduced with the rotary hoe operation, but the reduction was not great enough to affect final grain yield. Incorporation resulted in a small but significant increase in wild oat population at Winnipeg, possibly due to an increase in "safe" germination sites through increased surface soil roughness. At Carman, total weed density was reduced by the rotary hoe operation, mainly through the elimination of green foxtail seedlings. Incorporation had a greater effect on green foxtail populations at the lowest mulch rate than at the higher mulch rates. At the highest mulch rate, weed biomass was greater where mulch was incorporated, suggesting that more N was available to weeds where mulch was incorporated.

No significant effects of mulch incorporation were observed on wheat yield, grain protein concentration, or grain N yield. This lack of significant effects was attributed to poor conditions for effective incorporation at Winnipeg, and high soil N levels and high weed populations at Carman.

The observed weed control benefits of rotary hoeing, and potential for increased N availability when mulch is incorporated warrants further investigation. A study of the effect of rotary hoe incorporation of alfalfa mulch at later wheat development stages would also shed light on additional applications of this technique.

4.3 Influence of alfalfa mulch particle size on wheat

Three different mulch particle sizes, small (<5 cm in length), medium (4-6 cm), and large (~20 cm) were applied at three rates to test whether mulch particle size had any effect on alfalfa mulch applied to wheat. For most of the measurements taken, the influence of mulch particle size was found to be insignificant.

4.3.1 Wheat plant stand density and development

Particle size did not have any detectable effect on wheat plant density or rate of wheat development (Table 4.38).

4.3.2 Weed population density

Total weed population density was not affected by either mulch particle size or mulch rate (Tables 4.39, 4.40). However, analysis on the basis of individual weed species showed that redroot pigweed and lamb's quarters seedling populations were both significantly affected by mulch particle size, (Table 4.39) but results were inconsistent between species. Redroot pigweed population density was most suppressed with the large mulch particles, while the number of lamb's quarters seedlings was lowest with the medium mulch particle size (Table 4.39).

4.3.3 Wheat N uptake

Particle size did not affect N uptake at either the anthesis or soft dough stages (Table 4.41, 4.42). As was seen in the time-of-application and incorporation experiments, N uptake increased with mulch rate (Table 4.41).

Table 4.38. Effect of mulch particle size and rate on wheat plant stand density and development at Winnipeg in 2002.

Treatment[z]	Plant Density plant m^{-2}	------------ Haun Stage ----------- (June 14)	(July 17)
Control	262ab[y]	1.45	8.52
20kgN	273a	1.52	9.35
40kgN	-	-	9.42
60kgN	-	-	9.22
0.5xSmall	277a	1.41	8.57
1xSmall	280a	1.37	8.62
2xSmall	209c	1.39	8.65
0.5xMedium	267ab	1.40	8.22
1xMedium	280a	1.41	8.54
2xMedium	231bc	1.46	9.07
0.5xLarge	261ab	1.39	8.47
1xLarge	256ab	1.36	8.67
1xLarge	232bc	1.39	9.28
Mean	257	1.41	8.82
LSD(0.05)	36.6	ns[z]	ns
P>F	*	NS	NS
	Main Effects - Particle Size		
Small	255	1.39	8.6
Medium	259	1.42	8.6
Large	249	1.38	8.8
LSD(0.05)	ns	ns	ns
	- Mulch Rate		
0.5x	268a	1.4	8.4
1x	272a	1.38	8.6
2x	224b	1.41	9
LSD(0.05)	21.1	ns	ns
	ANOVA		
Particle size	NS	NS	NS
Mulch rate	**	NS	NS
Size x Rate	NS	NS	NS
Mean	254	1.4	8.7
C.V.(%)	9.86	8.57	7.42

z Small, Medium and Large mulch particle sizes were approximatley 1-5 cm, 4-6 cm, and 20 cm in length, respectively. The 0.5x, 1x, and 2x mulch rates were 0.97, 1.97, and 3.94 t ha^{-1} (dry weight), respectively.

y Means followed by the same letter are not significantly different.

z ns = non-significant.

**, *, and NS indicate $P < 0.01$, $P < 0.05$, and $P > 0.05$ respectively.

Table 4.39. Means for main effects of mulch particle size and rate on weed density at Winnipeg in 2002.

Treatment^{z}	barnyard grass	foxtail	wild oat	dandelion	thyme-leaved spurge	wild buckwheat	redroot pigweed	lamb's quarters	sow thistle	other	total
	weeds m^{-2}										
					Particle Size treatment means						
Small	218	4.0	4.5	23.0	4.3	14.2	6.7 ab	17.7 a	5.7	4.8	303
Medium	136	4.5	2.8	31.3	7.5	9.5	9.5 a	8.0 b	3.2	4.7	217
Large	131	5.5	6.7	28.7	6.0	10	3.8 b	11.2 ab	4.3	3.0	210
LSD(0.05)	ns^{y}	ns	ns	ns	ns	ns	^{x}	7.6	ns	ns	ns
					Mulch Rate treatment means						
0.5x	243 a^{w}	6.2	4.0	14.0 b	5.5	11.0	6.8	11.5	3.0	3.3	308
1x	98 b	3.7	5.0	32.5 a	4.5	10.7	8.2	15.5	5.8	4.3	188
2x	144 ab	4.2	5.0	36.5 a	7.8	12.0	5.0	9.8	4.3	4.8	234
LSD(0.05)	136	ns	ns	12.4	ns	ns	ns	ns	ns	ns	ns
Mean	162	4.7	4.7	27.7	5.9	11.2	6.7	12.3	4.4	4.2	243
					ANOVA						
Particle Size	NS	NS	NS	NS	NS	NS	**	**	NS	NS	NS
Mulch Rate	NS	NS	NS	**	NS	NS	NS	NS	NS	NS	NS
Size x Rate	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
C.V.(%)	100.0	97.7	93.2	53.2	76	64.3	39.1	73.9	75.3	78.7	63.2

z Small, Medium, and Large mulch particle sizes were approximatley <5 cm, 4-6 cm, and 20 cm in length respectively.
The 0.5x, 1x, and 2x mulch rates were 0.97, 1.97, and 3.94 t ha-1 (dry weight) respectively.

y ns = non-significant.

x The natural log of the data+1 was used to achieve normal data distribution and homogeneity of variance.

w Means followed by the same letter are not significantly different (*P*=0.05).

**, *, and NS indicate *P* <0.01, *P* <0.05, and *P* >0.05 respectively.

Table 4.40. Effect of mulch particle size and application rate on weed population density at Winnipeg in 2002.

Treatment^{z}	barnyard grass	foxtail^{y}	wild oat	dandelion	thyme-leaved spurge	wild buckwheat	redroot pigweed	lamb's quarters	sow thistle	other	total
	weeds m^{-2}										
Control	83	4.0	4.0	5.5 de^{x}	5.5	7.0	5.5 abcde	25.0 ab	5.0	2.0	147
20kgN	125	2.5	3.0	5.0 e	7.5	12.0	1.0 e	31.5 a	9.0	6.5	203
40kgN	204	10.5	5.5	14.5 cde	8.0	6.5	5.0 bcde	40.5 ab	5.0	1.0	301
60kgN	65	3.0	1.5	6.5 de	10.5	12.0	10.0 abc	40.0 a	9.0	8.0	166
0.5xSmall	306	3.0	4.5	13.5 cde	5.5	7.5	6.0 abcde	20.5 abcd	5.0	2.0	373
1xSmall	107	2.0	6.5	25.0 abcd	3.5	15.5	11.0 a	24.5 abc	8.0	5.5	209
2xSmall	241	7.0	2.5	30.5 abc	4.0	19.5	3.0 de	8.0 bcd	4.0	7.0	326
0.5xMedium	211	7.0	2.5	16.0 bcde	6.0	10.0	10.0 abc	5.5 d	2.5	3.5	274
1xMedium	74	3.0	3.0	35.0 ab	6.0	10.0	10.5 ab	7.0 cd	3.0	5.5	157
2xMedium	124	3.5	3.0	43.0 a	10.5	8.5	8.0 abcd	11.5 bcd	4.0	5.0	221
0.5xLarge	213	8.5	5.0	12.5 cde	5.0	15.5	4.5 cde	8.5 bcd	1.5	4.5	278
1xLarge	112	6.0	5.5	37.5 a	4.0	6.5	3.0 de	15.0 abcd	6.5	2.0	198
2xLarge	68	2.0	9.5	36.0 a	9.0	8.0	4.0 de	10.0 bcd	5.0	2.5	154
Mean	149	4.8	4.3	21.6	6.5	10.7	6.3	19.0	5.2	4.2	231
LSD(0.05)	ns^{w}	ns	ns^{v}	19.9	ns	ns^{v}	5.6	^{v}	ns	ns^{v}	ns^{v}
P>F	0.3852	0.2637	0.06914	0.001	0.3573	0.0943	0.0068	0.0167	0.2628	0.469	0.3282
C.V.(%)	99	101.1	61.5	64.3	67.9	27.4	62	28.6	80.1	74.8	7.5
Contrasts											
0.5x vs control	0.0676	0.4415	0.7966	0.2957	1.0000	0.2662	0.5559	0.0143	0.4104	0.6913	0.0460
1x vs control	0.8624	0.9057	0.4954	0.0018	0.6988	0.6190	0.2422	0.0806	0.7306	0.5188	0.3196
2x vs control	0.4773	0.9526	0.9170	0.0004	0.3689	0.2964	0.8248	0.0194	0.7829	0.6387	0.1804
0.5x vs 60kgN	0.0431	0.2628	0.3203	0.3554	0.0590	0.7318	0.1665	0.0036	0.0172	0.1442	0.1250
1x vs 60kgN	0.7014	0.8121	0.5802	0.0025	0.0249	0.7792	0.4180	0.0252	0.1955	0.2224	0.6112
2x vs 60kgN	0.3586	0.6776	0.1784	0.0006	0.3053	0.7845	0.0321	0.0051	0.0598	0.1643	0.3903
Fert-linear	0.9386	0.6456	0.4531	0.6894	0.1273	0.8907	0.0515	0.7610	0.3953	0.4190	0.4350
Fert -quad	0.2266	0.2214	0.1641	0.5922	0.9110	0.6826	0.0195	0.7481	1.0000	0.4120	0.0385
Fert-Cubic	0.4407	0.0262	0.3254	0.3813	0.7266	0.0198	0.3936	0.6405	0.0939	0.0200	0.2843

z The 0.5x, 1x, and 2x mulch rates were 0.97, 1.97, and 3.94 t ha^{-1} (dry weight) respectively.

The 20, 40, 60kgN treatments consisted of 20, 40 and 60 kg N ha^{-1} applied as ammonium nitrate.

Small, Medium, and Large refer to mulch particle sizes of approximately <5 cm, 4-6 cm, and 20 cm in length respectively.

y Foxtail data had a non-normal distribution, but was left untransformed because transformation did not improve the distrubition.

x Means followed by the same letter are not significantly different.

w ns = non-significant.

v The natural log of the data+1 was used to achieve normal data distribution and homogeneity of variance.

Table 4.41. Wheat N uptake means for mulch particle size and rate effects at anthesis and soft-dough growth stages at Winnipeg in 2002.

Treatment	Anthesis	Soft-dough
	----------- kg N ha^{-1}	------------
	Particle size means	
Small^{z}	21.4	40.7
Medium	23.4	39.4
Large	24.2	42.6
LSD(0.05)	ns^{y}	ns
	Mulch rate means	
0.5x^{x}	17.9c^{w}	34.7b
1x	21.0b	38.4b
2x	30.1a	49.7a
LSD(0.05)	2.7	5.8
	ANOVA	
Particle Size	NS	NS
Mulch Rate	**	**
Size x Rate	NS	NS
Mean	23.0	40.9
C.V.(%)	13.7	17
	Contrasts	
Rate-linear	<0.0001	<0.0001
Rate-quadratic	0.5393	0.6036

z Small, medium, and large sizes of mulch were approximately <5, 4-6, and 20 cm in length, respectively.
y ns = non-significant.
x The 0.5x, 1x, and 2x mulch rates were 0.97, 1.97, and 3.94 t ha^{-1} (dry weight), respectively.
w Numbers followed by the same letter within a column are not significantly different.
**, *, and NS indicate $P < 0.01$, $P < 0.05$, and $P > 0.05$, respectively.

Table 4.42. Effect of mulch particle size and application rate on wheat N uptake at anthesis and soft-dough growth stages at Winnipeg in 2002.

Treatment[z]	Anthesis	Soft-dough
	----------- kg N ha^{-1}	------------
Control	15.4e[y]	25.9h
20kgN	28.9bc	37.5efg
40kgN	38.7b	65.8ab
60kgN	52.6a	78.56a
0.5xSmall	16.8de	35.5fg
1xSmall	20.2d	39.8def
2xSmall	27.3bc	46.7cde
0.5xMedium	16.9de	30.5gh
1xMedium	21.6cd	34.1fg
2xMedium	31.7b	53.6bc
0.5xLarge	20.1d	38.1efg
1xLarge	21.3cd	41.3def
2xLarge	31.1b	48.6cd
Mean	26.4	44.3
LSD(0.05)	x	x
P>F	<0.0001	<0.0001
Contrasts		
0.5x vs control	0.0582	0.0088
1x vs control	0.0026	0.0006
2x vs control	<0.0001	<0.0001
0.5x vs 20kgN	0.0011	0.4951
1x vs 20kgN	0.0286	0.743
2x vs 20kgN	0.4611	0.0047
Fert-linear	<0.0001	<0.0001
Fert -quad	0.1680	0.3815
Fert-cubic	0.3264	0.1319
C.V.(%)	6.46	4.67

z Small, medium, and large sizes of mulch were approximately <5, 4-6, and 20 cm in length, respectively.
The 0.5x, 1x, and 2x mulch rates were 0.97, 1.97, and 3.94 t/ha (dry weight), respectively.
y Numbers followed by the same letter within a column are not significantly different.
x Natural log transformation was used on the data to achieve homogeneity of variance and a normal data distribution. Treatment means are reported as original, untransformed values.

4.3.4 Wheat grain yield

Particle size did not significantly affect wheat yield (Table 4.43, 4.44), but in this experiment, like the previously described experiments, increasing mulch rate significantly increased yield (Table 4.43). There was a positive linear relationship between mulch rate and yield, as shown by contrast statements (Table 4.44). However, yields from mulch treatments were generally lower than those from ammonium nitrate fertilizer.

Table 4.43. Main effects of mulch particle size and application rate on wheat grain yield, grain protein concentration (GPC), and grain N yield means at Winnipeg in 2002.

Treatment[z]	Grain yield kg ha^{-1}	GPC %	Grain N yield kg ha^{-1}
		Particle size means	
Small	786	13.4	18.5
Medium	806	13.2	18.7
Large	823	13.3	19.2
LSD(0.05)	ns[y]	ns	ns
		Mulch rate means	
0.5x	631c[x]	13.3	14.6c
1x	737b	13.4	17.3b
2x	1048a	13.2	24.5a
LSD(0.05)	68.8	Ns	1.81
		ANOVA	
Particle Size	NS	NS	NS
Mulch rate	**	NS	**
Size x Rate	NS	NS	NS
Mean	805	13.3	18.8
C.V.(%)	10.6	1.9	11.5
		Contrasts	
Rate-linear	<0.0001	0.2752	<0.0001
Rate-quad	0.5532	0.1263	0.6626

Z Small, Medium, and Large mulch particle sizes were approximately <5 cm, 4-6 cm, and 20 cm in length, respectively. The 0.5x, 1x, and 2x mulch rates were 0.97, 1.97, and 3.94 t ha^{-1} (dry weight), respectively.
y ns = non-significant.
x Means followed by the same letter within a column are not significantly different ($P = 0.05$).
**, *, and NS indicate $P < 0.01$, $P < 0.05$, and $P > 0.05$, respectively.

4.3.5 Grain protein concentration and grain N yield

Neither mulch particle size, nor rate significantly affected grain protein concentration (Table 4.43). However, all treatments receiving ammonium nitrate resulted in significantly lower grain protein concentrations than mulched treatments or the control (Table 4.44). The 2x mulch rate treatments, with equivalent or higher grain yields compared to the 20 kg N treatment, all produced significantly higher grain protein concentrations than the 20 kg N treatment. This result suggests, as in the time-of-application and incorporation experiments, that where a certain mulch application level is able to produce a grain yield equivalent to that produced with a certain level of ammonium nitrate, the grain protein concentration will be higher in the wheat receiving the alfalfa mulch.

Grain N yield was not affected by particle size, but increased linearly as mulch application rate increased (Tables 4.43, 4.44).

Table 4.44. Effect of mulch particle size and application rate on wheat grain yield, grain protein Concentration (GPC), and grain N yield at Winnipeg in 2002.

Treatment[z]	Grain yield kg ha^{-1}	GPC %	Grain N yield kg ha^{-1}
Control	542.2f[y]	13.2ab	12.5h
20kgN	956.6d	12.6c	21.1de
40kgN	1372.0b	12.4c	30.0b
60kgN	1771.7a	12.3c	38.1a
0.5xSmall	631.9ef	13.3ab	14.8fgh
1xSmall	724.2e	13.5a	17.1f
2xSmall	1003.1cd	13.4a	23.6cd
0.5xMedium	561.6f	13.2ab	13.0gh
1xMedium	729.1e	13.2ab	16.9f
2xMedium	1128.2c	13.2ab	26.1c
0.5xLarge	699.5e	13.0b	16.0fg
1xLarge	758.1e	13.4a	17.9ef
2xLarge	1012.5cd	13.3ab	23.7cd
LSD(0.05)	137.58	0.369	3.25
Mean	914.7	13.08	20.84
P>F	<0.0001	<0.0001	<0.0001
C.V.(%)	10.50	2.00	10.90
Contrasts			
0.5x vs control	0.1178	0.9025	0.1238
1x vs control	0.0012	0.2356	0.0008
2x vs control	<0.0001	0.3873	<0.0001
0.5x vs 60kgN	<0.0001	<0.0001	<0.0001
1x vs 60kgN	<0.0001	<0.0001	<0.0001
2x vs 60kgN	<0.0001	<0.0001	<0.0001
Fert-linear	<0.0001	<0.0001	<0.0001
Fert-quadratic	0.8800	0.1073	0.8695
Fert-cubic	0.9384	0.4701	0.8348

z Small, Medium, and Large mulch particle sizes were approximately <5 cm, 4-6 cm, and 20 cm in length, respectively. The 0.5x, 1x, and 2x mulch rates were 0.97, 1.97, and 3.94 t ha^{-1} (dry weight), respectively.
y Means followed by the same letter within a column are not significantly different (*P* = 0.05).

4.3.6 Second-year N uptake, yield, grain protein concentration, and grain N yield

Oat grain yield in the second crop after mulch application was significantly higher in the plots that received treatment with the smallest mulch particle size than in plots that received the medium mulch particle size (Table 4.45). One may speculate that these yield differences were caused by differences in N uptake; however, no significant differences in N uptake between the particle size treatments were observed (Tables 4.40, 4.41). Furthermore, the other N-based parameters measured in the oat crop, i.e., grain protein concentration and grain N yield, were not affected by mulch particle size.

Table 4.45. Oat N uptake, yield, grain protein concentration (GPC), and grain N yield for mulch particle size and application rate effects at Winnipeg in 2003.

Treatment[z]	N uptake kg ha^{-1}	Grain yield Kg ha^{-1}	GPC %	Grain N yield kg ha^{-1}
		Particle Size		
Small	38.1	1933a[y]	9.14	28.18
Medium	32.2	1708b	9.44	25.76
Large	34.1	1794ab	9.41	27.03
LSD(0.05)	ns[x]	177.5	ns	ns
		Mulch Rate		
0.5x	31.3b	1657b	9.47	25.07b
1x	32.6b	1654b	9.26	24.56b
2x	40.5a	2124a	9.24	31.34a
LSD(0.05)	6.4	177.5	ns	2.87
		ANOVA		
Particle Size	NS	*	NS	NS
Mulch Rate	**	**	NS	**
Size x Rate	NS	NS	NS	NS
Mean	34.82	1811.8	9.33	26.99
C.V.(%)	21.9	11.62	3.9	12.61
		Contrasts		
Rate-linear	0.0192	0.0005	0.222	0.0009
Rate-quadratic	0.6165	0.1766	0.3469	0.1327

z Small, Medium, and Large mulch particle sizes were approximately <5 cm, 4-6 cm, and 20 cm in length, respectively. The 0.5x, 1x, and 2x mulch rates were 0.97, 1.97, and 3.94 t ha^{-1} (dry weight), respectively.
y Means followed by the same letter within a column are not significantly different ($P = 0.05$).
x ns = non-significant
**, *, and NS indicate $P < 0.01$, $P < 0.05$, and $P > 0.05$ respectively.

4.3.7 Cumulative N effects of alfalfa mulch application over two years

Particle size had no impact on N effects accumulated over the two-year period (Table 4.46).

Table 4.46. N uptake and N use efficiency (NUE) means for mulch particle size and application rate effects over two years at Winnipeg.

	Combined '02+'03		
Treatment	2-year N uptake	Increase	2-year NUE
	kg ha^{-1}	kg ha^{-1}	%
		Particle Size means	
Small^z	78.8	25.7	29.9
Medium	71.6	23.7	20.5
Large	76.8	18.5	26.9
LSD(0.05)	ns^y	ns	ns
		Mulch Rate means	
0.5x	66.0b^x	12.9b	32.3
1x	71.0b	17.9b	22.1
2x	90.1a	37.0a	22.9
LSD(0.05)	10.2	10.2	ns
Mean	75.7	22.6	25.8
		ANOVA	
Particle Size	NS	NS	NS
Mulch Rate	**	**	NS
Size x Rate	NS	NS	NS
C.V.(%)	15.96	53.42	79.44

z Small, Medium, and Large mulch particle sizes were approximately <5 cm, 4-6 cm, and 20 cm in length, respectively. The 0.5x, 1x, and 2x mulch rates were 0.97, 1.97, and 3.94 t ha^{-1} (dry weight), respectively.

y ns = non-significant.

x Means followed by the same letter within a column are not significantly different ($P = 0.05$).

**, *, and NS indicate $P < 0.01$, $P < 0.05$, and $P > 0.05$, respectively.

4.3.8 Conclusions

Particle size had very little influence on the effects of alfalfa mulch application to wheat. N uptake, wheat yield, grain protein concentration, and grain N yield were all unaffected by mulch particle size. This result is not surprising given the findings of others who have reported no effect of particle size in legume residue decomposition rate (Amato et al. 1984; Mohr et al. 1998b). If decomposition rate is unaffected by particle size, it follows that availability of mulch N will not likely change with particle size.

Where effects of particle size were detected the reasons for differences were not well understood. Redroot pigweed and lamb's quarters population densities were affected by mulch particle size but it is unclear why the medium particle size was most suppressive against lamb's quarters, while the large particle size was more suppressive than the medium particle size against redroot pigweed. The smallest particle size resulted in significantly higher second year oat yield compared to the medium particle size, but no clear explanation can be given based on the observations.

The fact that alfalfa mulch particle size had very little influence on wheat implies that farmers will be able to use a variety of forage harvesting machines to apply mulch and achieve good results regardless of how the machine chops the alfalfa.

5.0 GENERAL DISCUSSION AND CONCLUSIONS

The goal of this research was to assess the effect of alfalfa mulch applied to spring wheat in order to determine the feasibility of using this mulch as an organic form of fertilizer. With a high N content and a low C/N ratio, alfalfa was expected to offer substantial potential as an N-supplying mulch. In addition, weed control and moisture conservation benefits from the mulch were anticipated.

The first objective of this study was to measure the N contribution of alfalfa mulch applied to wheat. Wheat N uptake was increased by the addition of alfalfa mulch, and wheat N uptake increased in relation to alfalfa mulch rate. Very few effects of application timing, incorporation, or mulch particle size were observed for wheat N uptake. The relatively high N uptake by wheat grown on plots receiving fall-applied mulch showed that mulch N availability was higher when mulch was incorporated and allowed to decompose prior to establishment, than when mulch was applied after crop emergence. Incorporation of mulch increased wheat N uptake at one of two sites, possibly because weed competition was reduced with the incorporation tool (rotary hoe), but also likely because incorporation of mulch increased N mineralization. However, wheat grain yields were not affected by incorporation at any sites. The lack of consistent effects for incorporation effects may have been due to poor incorporation at Winnipeg and high residual N and weed populations at Carman. Therefore, in-crop rotary hoe incorporation of mulch is worth investigating further for potential combined benefits of weed control and greater N availability to the crop.

Wheat grain yield increased as alfalfa mulch rate increased. The positive linear relationship between yield and mulch rate observed in all three experiments indicates that mulch application rates greater than 5.2 t ha^{-1} could be expected to generate further yield increases. However, a negative effect on yield was observed when mulch was applied at a rate of 6.6 t ha^{-1} to wheat at the three-leaf stage at Carman in 2003, probably as a result of reduced plant stand density. Conversely, a mulch rate of 7.5 t ha^{-1} applied to wheat at the three leaf stage had a positive effect on wheat yield at Clearwater in 2002. Plant stand density was not recorded at Clearwater, but if significant smothering of plants occurred it may be that mulch supplied N compensated for reductions in plant numbers, while high soil N at Carman in 2003 eliminated differences in N uptake between treatments. Further work is necessary to determine optimum maximum mulch rates.

Early and late post-emergent mulch applications provided similar wheat grain yields. Mulch applied and incorporated in fall produced slightly higher yields than spring-applied mulch at one out of two sites, despite lower mulch rates being applied in fall than in spring.

When 4 to 5 t ha^{-1} of mulch, containing between 118 and 184 kg N ha^{-1}, was applied in the time-of-application experiment at Winnipeg, wheat yields were equivalent to that produced with 20 and 60 kg of ammonium nitrate-N per hectare in 2002 and 2003, respectively. Higher yields in 2002 than in 2003 were likely the result of less disease pressure on the wheat in 2003, but may also have been due to greater loss of mulch N in 2002 that may have occurred through leaching, volatilization and denitrification following heavy rainfall events. High background N levels at Carman in both years contributed to the lack of significant yield differences between individual treatments at Carman.

Mulch application had a positive effect on grain protein concentration. Where mulch application resulted in yields that were equivalent to yields achieved with ammonium nitrate, grain protein concentration in mulch treatments was often higher, suggesting a slow-release pattern of N availability, rather than a large initial N flush typical of inorganic N fertilizers.

The second year oat crop grown in the time-of-application experiment showed the highest grain yields and grain N yields in plots that initially received the 2x mulch rates. In the second year for the incorporation and particle size experiments, grain yield, grain N yield and N uptake were all significantly higher in plots treated with the 2x mulch rates compared to control plots or plots that had received ammonium nitrate. The superior performance of second year oats grown on heavily mulched plots (≥ 3.9 t ha^{-1}), relative to the oats grown on ammonium nitrate treated plots highlights that N from alfalfa residue continued to become available to the second crop while ammonium nitrate-N was depleted with the first crop. Annual application of mulch in a cropping system would likely cause a build-up of soil organic N over time and increase the N supplying potential of the soil. Second year effects of mulch application timing and mulch incorporation were non-significant, as were second year effects of mulch particle size, with the exception of medium sized mulch particles resulting in significantly higher yield than the smallest mulch particle size.

Cumulative N uptake from the mulch measured over two years in the 2x mulch rate treatments ranged between 30.6 and 37.7 kg N ha^{-1}, with N-use-efficiencies ranging between 18.9 and 23.2%. While cumulative N uptake of the 2x mulch rate treatments was equivalent or higher than that of the 40kgN treatments in all three experiments, N-use-efficiency was always much lower for the mulch treatments. The fact that only about 20% of the N applied with the mulch was taken up in the two subsequent crops suggests that either a large portion of the mulch-N was lost, or that the majority of the mulch-N remained in the soil in the form of relatively stable organic matter. While some N loss undoubtedly occurred, the superior performance of the second year oat crop grown on the heavily mulched plots indicates that mulch-N was still present and continued to mineralize after the first crop harvest. As well, numerous references in previous studies show the long term N benefits of legume residue to subsequent crops, suggesting that in the present study a significant proportion of the mulch-N remained in the soil even after the second crop was harvested.

The second objective of this study was to evaluate the effect of alfalfa mulch application on weed population density and weed growth. Weed population density was reduced with high mulch rates (>3.4 t ha^{-1}). However, at four out of seven site-years, the 0.5x mulch application rate appeared to stimulate weed recruitment, likely as a result of higher soil moisture levels, or higher soil nitrate levels under mulch that may have stimulated weed recruitment. Higher weed populations with fall-applied mulch provided evidence that mulch N may have stimulated weed recruitment. At several sites the early mulch application was less suppressive on weeds than was the late mulch application. Higher mulch rates applied with the late mulch treatments likely had a greater effect on weed populations than did application timing on its own; however, earlier decomposition of early-applied mulch may have benefited the weeds.

Dandelion populations increased with mulch application rate at six out of seven experimental sites. Increased dandelion populations with higher mulch application rates were probably the result of dandelion seeds being harvested with the alfalfa and subsequently applied to the plots.

Weed biomass measurements at Carman showed a positive response to applied N, whether N was applied in the form of ammonium nitrate or alfalfa mulch. Nevertheless, high amounts of late-applied mulch contributed up to 27.5 kg N ha^{-1} to the wheat crop at Carman 2002 without causing increased weed biomass. Early mulch application resulted in higher weed biomass than late mulch application, indicating that early mulch application may provide an early dose of N to stimulate weed growth.

Use of the rotary hoe to incorporate mulch caused a decrease in weed populations at Carman in 2002. However, incorporation of high amounts of mulch-stimulated weed growth compared to unincorporated mulch, likely through the combined effects of enhanced N availability to weeds, and the elimination of the weed-suppressing mulch layer on the soil surface.

The third objective of this study was to observe the effect of alfalfa mulch application on soil moisture content. Soil moisture was conserved where mulch rates exceeded 4.3 t ha^{-1}. At Winnipeg in 2003 and at Kenton in 2002 soil moisture conservation under mulch likely contributed to the significant yield increases in the highest mulch rate treatments versus the controls.

The use of alfalfa as a mulch on spring wheat was a successful method of extracting value from alfalfa hay without feeding it to cattle. However, relatively high amounts of mulch were required before significant N, weed control, and moisture conservation benefits were observed. On the basis of a cropping system, at least half the land base would need to be sown to alfalfa in order to produce enough mulch to provide significant N benefits to wheat. Weed control and moisture conservation benefits may not occur unless twice as much land was sown to alfalfa as to wheat. Nevertheless, if used in the context of a strip farming system where perennial alfalfa strips were rotated with annually cropped strips, substantial N and weed control benefits would be expected to accumulate from the combined effect of perennial alfalfa cropping and annual mulch application. If practical methods of field scale application are developed, using alfalfa as mulch will be an avenue for farmers to increase alfalfa acreage and thereby reduce reliance on chemical inputs.

5.1 Considerations for implementation of an alfalfa mulch strip cropping system

Simple modifications of current forage harvester models may be sufficient to allow effective application of mulch from alfalfa strips to adjacent crops. A first step in a field scale trial may be to test the mulch application capability of a pull-type forage harvester. Deflector shields attached to the discharge spout would likely be required to direct the mulch in an even pattern across the width of a crop strip. If necessary, the entire spout could be replaced with one that more effectively distributed the mulch. However, a forage harvesting implement that could cut and evenly transfer the alfalfa onto the adjacent crop without chopping it would likely have the advantage over regular forage harvesters of using less energy to operate.

The width of field strips in an alfalfa mulch strip cropping system will depend on the type of machinery available for seeding and harvesting the annually cropped strips as well as for cutting and spreading the mulch. A likely limitation to strip width will be the maximum distance mulch can be deposited in an even pattern by the machine used for mulch application. One approach to maximize the width of strips receiving mulch would be to swath the alfalfa in such a way as to move swaths to the outer edges of the alfalfa strips and then transfer the mulch from either side to the center of the annually cropped strips.

The proportion of a field planted to alfalfa strips depends on the goals of the strip farming system. If the primary goals are weed control, moisture conservation or substantial N delivery through mulch application, then as mulch as two thirds of the land base may be required to produce sufficient mulch. However, if the mulch application benefits are of secondary importance to the N fixation occurring in the perennial alfalfa strips, then a cropping system may have only one third to one half of the land planted to alfalfa, and the alfalfa could be rotated to all parts of the field over a number of years. Mulch could then be concentrated on only a portion of the annually cropped land to maximize mulch supplied N, weed suppression, and moisture conservation, to a crop like wheat while the remainder of the land could be sown to a very competitive crop such as buckwheat. Further research is needed to quantify the long-term N delivery potential of an alfalfa mulch strip cropping system where alfalfa is rotated to the entire land base over a certain number of years. A potentially informative study may be to look at the productivity of a field where 50% of the land was sown to alfalfa strips for three years and then rotated to the remaining land for an additional three years with all of the forage used as mulch on annual crops grown between the alfalfa strips.

The cropping options for the annually cropped strips are not limited to spring wheat. Longer season crops such as corn or sunflowers may be well suited to utilize mulch supplied N because they continue to extract N from the soil later in the growing season than wheat. Later season N uptake would allow a greater amount of time for mulch N mineralization. Fall planted cereals such as fall rye and winter wheat may fit well into a system where mulch was applied just after planting to allow an extended period of time for mulch N mineralization. If large amounts of alfalfa were available in late fall an application of mulch may provide some protection to winter cereals from harsh winter conditions. Mulch application at rates high enough to suppress weeds may be beneficial to an uncompetitive crop such as flax, but the risk of suppressing flax with heavy rates of mulch must be investigated. High value vegetable crops or fruit tree crops (i.e., saskatoons) are also worth considering for adaptation to an alfalfa mulch strip cropping system. High value crops may allow a high proportion of the land base to be dedicated to mulch production and still be profitable economically.

A final consideration brought to light through this study is the almost unavoidable addition of dandelion seeds to the annually cropped land with an early June mulch application. Later mulch application timing may solve the problem because, as was observed over the two years of this study, dandelion seed production was largely finished by the third week in June. Nevertheless, an uncompetitive alfalfa stand is prone to dandelion infestation and will be a source of dandelion seeds to the entire field regardless of whether mulch application delivers them directly to the annually cropped land. To establish and maintain the most competitive alfalfa stands possible is one solution to this problem. Special attention to seed bed preparation and drainage are especially important in successful alfalfa cultivation. Including forage grass species with the alfalfa may increase the competitiveness of the forage stand and reduce dandelion infestation. Tillage will also play an important role in controlling dandelions. In this study dandelions established extremely well when applied with mulch but appeared to have very little impact on the crop. Fall tillage may be sufficient to control dandelions in this system. Spring tillage may also be necessary to control dandelion, but the delayed seeding that is required to allow the alfalfa to grow large enough to provide mulch also allows an extended time frame for pre-seeding tillage. This increase in tillage in an alfalfa mulch strip cropping system may not make the soil excessively prone to soil erosion because of the shelter provided by the alfalfa strips.

6.0 RECOMMENDATIONS

The following is a list of recommendations, based on the findings of this study, to farmers and researchers seeking to implement cropping systems using alfalfa mulch:

- for a significant N contribution from mulch, apply at least 1.5 t ha^{-1} (dry weight) at any time between wheat planting and the 3-leaf stage
- mulch may be applied and incorporated in fall to supply N to the following crop but will not suppress weeds
- for weed control and moisture conservation, apply mulch at rates >3 t ha^{-1} (dry weight)
- mulch application should be delayed until the 3-leaf stage to improve weed control, and to allow greater amounts of alfalfa biomass to accumulate
- incorporation of mulch with a rotary hoe is recommended to control weeds with low mulch rates
- at high mulch rates incorporation may be detrimental for weed control due to the elimination of the weed suppressing surface mulch layer and greater access by weeds to mulch N
- mulch particle size should not be expected to have large effects on weed control or N availability to crops

7.0 REFERENCES

Akinremi, O. O. 40.406 Physical Properties of Soils: class notes. 2003.

Akinremi, O. O. and S. M. McGinn. 1996. Usage of soil moisture models in agronomic research. Can. J. Soil Sci. 76: 285-295.

Albrecht, K. A., W. F. Wedin, and D. R. Buxton. 1987. Cell-wall composition and digestibility of alfalfa stems and leaves. Crop Sci. 27: 735-741.

Amato, M., R. B. Jackson, J. H. A. Butler, and J. N. Ladd. 1984. Decomposition of plant material in Australian soils. II. Residual organic 14C and 15N from legume plant parts decomposing under field and laboratory conditions. Aust. J. Soil Res. 22: 331-341.

Amato, M., J. N. Ladd, A. Ellington, G. Ford, J. E. Mahoney, A. C. Taylor, and D. Walsgott. 1987. Decomposition of plant material in Australian soils. IV. Decomposition in situ of 14C- and 15N-labelled legume and wheat materials in a range of Southern Australian soils. Aust. J. Soil Res. 25: 95-105.

Angers, D. A. 1992. Changes in soil aggregation and organic carbon under corn and alfalfa. Soil Sci. Soc. Am. J. 56: 1244-1249.

Ascard, J. 1994. Soil cultivation in darkness reduced weed emergence. Acta Hortic. 167-177.

Aulakh, M. S., J. W. Doran, D. T. Walters, A. R. Mosier, and D. D. Francis. 1991. Crop residue type and placement effects on denitrification and mineralization. Soil Sci. Soc. Am. J. 55: 1020-1025.

Avalakki, U. K., W. M. Strong, and P. G. Saffigna. 1995. Measurements of gaseous emissions from denitrification of applied nitrogen-15. II. Effects of temperature and added straw. Aust. J. Soil Res. 33: 89-99.

Benech Arnold, R. L., R. A. Sanchez, F. Forcella, B. C. Kruk, and C. M. Ghersa. 2000. Environmental control of dormancy in weed seed banks in soil. Field Crops Res. 67: 105-122.

Bhatia, C. R. and R. Rabson. 1987. Relationship of grain yield and nutritional quality. In R. A. Olson and K. J. Frey, eds. Nutritional quality of cereal grains: genetic and agronomic improvement. Madison: American Society of Agronomy. 11-43.

Blum, U., L. D. King, T. M. Gerig, M. E. Lehman, and A. D. Worsham. 1997. Effects of clover and small grain cover crops and tillage techniques on seedling emergence of some dicotyledonous weed species. Am. J. Altern. Agric. 12: 146-161.

Boawn, L. C., J. L. Nelson, and C. L. Crawford. 1963. Residual nitrogen from ammonium nitrate fertilizer and from alfalfa plowed under. Agron. J. 55: 231-235.

Borstlap, S. and M. H. Entz. 1994. Zero-tillage influence on canola, field pea and wheat in a dry subhumid region: agronomic and physiological responses. Can. J. Plant Sci. 74: 411-420.

Box, G. E. P. and W. G. Hunter. 1978. Statistics for experimenters: an introduction to design, data analysis, and model building. Wiley, New York, NY.

Boyd, N. S. and R. C. Van Acker. 2003. The effects of depth and fluctuating soil moisture on the emergence of eight annual and six perennial plant species. Weed Science. 51: 725-730.

Bross, E. L., M. A. Gold, and P. Nguyen, V. 1995. Quality and decomposition of black locust (Robinia pseudoacacia) and alfalfa (Medicago sativa) mulch for temperate alley cropping systems. Agroforestry Systems. 29: 255-264.

Bruulsema, T. W. and B. R. Christie. 1987. Nitrogen contribution to succeeding corn from alfalfa and red clover. Agron. J. 79: 96-100.

Bullied, W. J., M. H. Entz, S. R. J. Smith, and K. C. Bamford. 2002. Grain yield and N benefits to sequential wheat and barley crops from single-year alfalfa, berseem and red clover, chickling vetch and lentil. Can. J. Plant Sci. 82: 53-65.

Campbell, C. A., G. P. Lafond, R. P. Zentner, and Y. W. Jame. 1994. Nitrate leaching in a udic haploboroll as influenced by fertilization and legumes. J. Environ. Qual. 23: 195-201.

Cavers, C. G. 1996. Characteristics of Red River Clays Pertaining to Vertisolic Criteria and Macropore Flow. M. Sc. Thesis. University of Manitoba.

Chepil, W. S. 1946. Germination of Weed Seeds. Scientific Agriculture. 26: 307-346.

Chon, S. U., S. K. Choi, S. Jung, H. G. Jang, B. S. Pyo, and S. M. Kim. 2002. Effects of alfalfa leaf extracts and phenolic allelochemicals on early seedling growth and root morphology of alfalfa and barnyard grass. Crop Prot. 21: 1077-1082.

Chon, S. U. and J. D. Kim. 2002. Biological activity and quantification of suspected allelochemicals fron alfalfa plant parts. J. Agron. Crop Sci. 188: 281-285.

Chung, I. M. and D. A. Miller. 1995. Natural herbicide potential of alfalfa residue on selected weed species. Agron. J. 87: 920-925.

Creamer, N. G. and S. M. Dabney. 2002. Killing cover crops mechanically: review of recent literature and assessment of new research results. Am. J. Altern. Agric. 17: 32-40.

Cueto Wong, J. A., S. J. Guldan, W. C. Lindemann, and M. D. Remmenga. 2001a. Nitrogen recovery from 15N-labeled green manures. I. Recovery by forage sorghum and soil one season after green manure incorporation. J. Sustain. Agric. 17: 27-42.

Cueto Wong, J. A., S. J. Guldan, W. C. Lindemann, and M. D. Remmenga. 2001b. Nitrogen recovery from 15N-labeled green manures. II. Recovery by oat and soil two seasons after green manure incorporation. J. Sustain. Agric. 17: 43-55.

Duley, F. L. and J. C. Russel. 1939. The use of crop residues for soil and moisture conservation. J. Am. Soc. Agron. 31: 703-709.

Entz, M. H., W. J. Bullied, and F. Katepa Mupondwa. 1995. Rotational benefits of forage crops in Canadian prairie cropping systems. J. Prod. Agric. 8: 521-529.

Entz, M. H. and D. B. Fowler. 1989. Response of winter wheat to N and water: growth, water use, yield and grain protein. Can. J. Plant Sci. 69: 1135-1147.

Entz, M. H., R. Guilford, and R. Gulden. 2001. Crop yield and soil nutrient status on 14 organic farms in the eastern portion of the northern Great Plains. Can. J. Plant Sci. 81: 351-354.

Fairey, N. A. and L. P. Lefkovitch. 1995. Alternating strips of grass and legume, and nitrogen fertilization strategy, for long-term herbage production from a brome-alfalfa stand. Can. J. Plant Sci. 75: 649-654.

Fawcett, R. S. and F. W. Slife. 1978. Effects of field applications of nitrate on weed seed germination and dormancy. Weed Science. 26: 594-596.

Findeling, A., S. Ruy, and E. Scopel. 2003. Modeling the effects of a partial residue mulch on runoff using a physically based approach. Journal of Hydrology. 275: 49-66.

Forster, D. A. 1999. Rotation Benefits of Alfalfa in a Cropping System. M.Sc. Thesis. University of Manitoba.

Fortin, M. C. and F. J. Pierce. 1991. Timing and nature of mulch retardation of corn vegetative development. Agron. J. 83: 258-263.

Fowler, D. B., J. Brydon, B. A. Darroch, M. H. Entz, and A. M. Johnston. 1990. Environment and genotype influence on grain protein concentration of wheat and rye. Agron. J. 82: 655-664.

Fribourg, H. A. and W. V. Bartholomew. 1956. Availability of nitrogen fro crop residues during the first and second seasons after application. Soil Sci. Soc. Proc. 20: 505-508.

Gallagher, R. S. and J. Cardina. 1998a. Phytochrome-mediated Amaranthus germination. II. Development of very low fluence sensitivity. Weed Science. 46: 53-58.

Gallagher, R. S. and J. Cardina. 1998b. The effect of light environment during tillage on the recruitment of various summer annuals. Weed Science. 46: 214-216.

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

Ghaffarzadeh, M., F. Garcia Prechac, and R. M. Cruse. 1997. Tillage effect on soil water content and corn yield in a strip intercropping system. Agron. J. 89: 893-899.

Gill, J. L. 1978. Design and analysis of experiments in the animal and medical sciences: Volume 3 Appendices. Iowa State University Press, Ames, Iowa.

Granastein, D., Mullinix, K., and Hogue, G. Orchard Mulching Trials. Electronic citation. http://organic.tfrec.wsu.edu/OrganicIFP/OrchardFloorManagement/01a.PDF . Date created: 7-8-2001. Date accessed: 9-7-2004.

Groffman, P. M., P. F. Hendrix, and D. A. J. Crossley. 1987. Nitrogen dynamics in conventional and no-tillage agroecosystems with inorganic fertilizer or legume nitrogen inputs. Plant and Soil 97: 315-332.

Hares, M. A. and M. D. Novak. 1992. Simulation of surface energy balance and soil temperature under strip tillage. II. Field test. Soil Sci. Soc. Am. J. 56: 29-36.

Hart, P. B. S., J. H. Rayner, and D. S. Jenkinson. 1986. Influence of pool substitution on the interpretation of fertilizer experiments with 15N. J. Soil Sci. 37: 389-403.

Haun, J. R. 1973. Visual Quantification of Wheat Development. Agronomy J. 65: 116-119.

Havlin, J. L., J. D. Beaton, S. L. Tisdale, and W. L. Nelson. 1999. Soil fertility and fertilizers: an introduction to nutrient management. sixth edition ed. Prentice Hall, Upper Saddle River, New Jersey.

He, Z. L., A. K. Alva, D. V. Calvert, and D. J. Banks. 1999. Ammonia volatilization from different fertilizer sources and effects of temperature and soil pH. Soil Science 164: 750-758.

Hegde, R. S. and D. A. Miller. 1990. Allelopathy and autotoxicity in alfalfa: characterization and effects of preceding crops and residue incorporation. Crop Sci. 30: 1255-1259.

Hoyt, P. B. 1990. Residual effects of alfalfa and bromegrass cropping on yields of wheat grown for 15 subsequent years. Can. J. Soil Sci. 70: 109-113.

Isermann, K. 1994. Agriculture's share in the emission of trace gases affecting the climate and some cause-oriented proposals for sufficiently reducing this share. Environ. Pollut. 83: 95-111.

Jansson, S. L. and J. Persson. 1982. Mineralization and Immobilization of Soil Nitrogen. p. 229-252. In F. J. Stevenson, ed. Nitrogen in Agricultural Soils. ASA-CSSA-SSSA, Madison, WI.

Janzen, H. H., J. B. Bole, V. O. Biederbeck, and A. E. Slinkard. 1990. Fate of N applied as green manure or ammonium fertilizer to soil subsequently cropped with spring wheat at three sites in western Canada. Can. J. Soil Sci. 70: 313-323.

Janzen, H. H. and S. M. McGinn. 1991. Volatile loss of nitrogen during decomposition of legume green manure. Soil Biol. Biochem. 23: 291-297.

Kataria, N., K. Bassi, and R. K. Kataria. 1999. Response of wheat (Triticum aestivum) to nitrogen and mulch application under rainfed conditions. Indian Journal of Agronomy 44: 115-118.

Kelner, D. J., J. K. Vessey, and M. H. Entz. 1997. The nitrogen dynamics of 1-,2- and 3-year stands of alfalfa in a cropping system. Agric. Ecosyst. Environ. 64: 1-10.

Kurvits, T. and T. Marta. 1998. Agricultural NH3 and NOx emissions in Canada. Environ. Pollut. 102: 187-194.

Ladd, J. N., M. Amato, and J. M. Oades. 1985. Decomposition of plant material in Australian soils. III. Residual organic and microbial biomass C and N from isotope-labelled legume material and soil organic matter, decomposing under field conditions. Aust. J. Soil Res. 23: 603-611.

Ladd, J. N., J. M. Oades, and M. Amato. 1981. Distribution and recovery of nitrogen from legume residues decomposing in soils sown to wheat in the field. Soil Biol. Biochem. 13: 251-256.

Lafond, G. P., S. M. Boyetchko, S. A. Brandt, G. W. Clayton, and M. H. Entz. 1996. Influence of changing tillage practices on crop production. Can. J. Plant Sci. 76: 641-649.

Lafond, G. P., H. Loeppky, and D. A. Derksen. 1992. The effects of tillage systems and crop rotations on soil water conservation, seedling establishment and crop yield. Can. J. Plant Sci. 72: 103-115.

Larsson, L., M. Ferm, K. A. Kasimir, and L. Klemedtsson. 1998. Ammonia and nitrous oxide emissions from grass and alfalfa mulches. Nutrient. Cycling. in Agroecosystems. 51: 41-46.

Leeson, J. Y., A. G. Thomas, T. Andrews, K. R. Brown, and R. C. Van Acker. 2002. Manitoba weed survey: cereal and oilseed crops 2002. Weed Survey Series Publication 02-2. Agriculture and Agri-Food Canada, Saskatoon Research Centre, Saskatoon, SK.

Longnecker, N., E. J. M. Kirby, and A. Robson. 1993. Leaf emergence, tiller growth, and apical development of nitrogen-deficient spring wheat. Crop Sci. 33: 154-160.

Magid, J., O. Henriksen, K. K. Thorup, and T. Mueller. 2001. Disproportionately high N-mineralisation rates from green manures at low temperatures: Implications for modeling and management in cool temperate agro-ecosystems. Plant and Soil 228: 73-82.

Mahler, R. L. and D. L. Auld. 1989. Evaluation of the green manure potential of Austrian winter peas in northern Idaho. Agron. J. 81: 258-264.

Mahler, R. L. and H. Hemamda. 1993. Evaluation of the nitrogen fertilizer value of plant materials to spring wheat production. Agron. J. 85: 305-309.

Malik, N. and W. H. Vanden Born. 1987. Germination response of Galium spurium L. to light. Weed Res. 27: 251-258.

Manitoba Agriculture and Food. 2001. Field Crop Production Guide. Revised Edition. Manitoba Agriculture and Food, Winnipeg, MB, Canada.

McCalla, T. M. and F. L. Duley. 1946. Effect of crop residues on soil temperature. J. Am. Soc. Agron. 38: 75-89.

Miller, D. A. 1996. Allelopathy in forage crop systems. Agron. J. 88: 854-859.

Mohler, C. L. and J. R. Teasdale. 1993. Response of weed emergence to rate of Vicia villosa Roth and Secale cereale L. residue. Weed Research 33: 487-499.

Mohr, R. M. 1997. Nitrogen dynamics after alfalfa as infuenced by termination technique. Ph.D. Thesis. University of Manitoba.

Mohr, R. M., M. H. Entz, H. H. Janzen, and W. J. Bullied. 1999. Plant-available nitrogen supply as affected by method and timing of alfalfa termination. Agron. J. 91: 622-630.

Mohr, R. M., H. H. Janzen, and M. H. Entz. 1998a. Nitrogen dynamics under greenhouse conditions as influenced by method of alfalfa termination. 1. Volatile N losses. Can. J. Soil Sci. 78: 253-259.

Mohr, R. M., H. H. Janzen, and M. H. Entz. 1998b. Nitrogen dynamics under growth chamber conditions as influenced by method of alfalfa termination. 2. Plant-available N release. Can. J. Soil Sci. 78: 261-266.

Nelson, D. W. 1982. Gaseous losses of nitrogen other than through denitrification. p. 327-363. In F. J. Stevenson, ed. Nitrogen in Agricultural Soils. ASA-CSSA-SSSA, Madison, WI.

O'Deen, W. A. and R. F. Follett. 1992. Ammonia emission from soybean-amended calcareous soil with various soil temperature and moisture levels. Agron. J. 84: 893-896.

Olivier, J. G. J., A. F. Bouwman, K. W. Hoek, and J. J. M. Berdowski. 1998. Global air emission inventories for anthropogenic sources of NOx, NH3 and N2O in 1990. Environ. Pollut. 102: 135-148.

Ominski, P. D., M. H. Entz, and N. Kenkel. 1999. Weed suppression by Medicago sativa in subsequent cereal crops: a comparative survey. Weed Science 47: 282-290.

Parker, D. T. and W. E. Larson. 1962. Nitrification as affected by temperature and moisture content of mulched soils. Soil Sci. Soc. Am. Proc. 26: 238-242.

Parr, J. F. and R. I. Papendick. 1978. Factors affecting the decomposition of crop residues by microorganisms. p. 101-129. In Crop Residue Management Systems. Madison, WI.

Partridge, J. R. D. and C. F. Shaykewich. 1972. Effects of nitrogen, temperature, and moisture regime on the yield and protein content of Neepawa wheat. Can. J. Soil Sci. 52: 179-185.

Prihar, S. S., S. K. Jalota, and J. L. Steiner. 1996. Residue management for reducing evaporation in relation to soil type and evaporativity. Soil Use. Manage. 12: 150-157.

Rasse, D. P., A. J. M. Smucker, and D. Santos. 2000. Alfalfa root and shoot mulching effects on soil hydraulic properties and aggregation. Soil Sci. Soc. Am. J. 64: 725-731.

Rasse, D. P., A. J. M. Smucker, and O. Schabenberger. 1999. Modifications of soil nitrogen pools in response to alfalfa root systems and shoot mulch. Agron. J. 91: 471-477.

Ritchie, J. T. 1972. Model for predicting evaporation from a row crop with incoplete cover. Water Resources Research. 8: 1204-1213.

Robinson, R. R., J. H. Young, and R. D. Morrison. 1972. Strip-cropping effects on abundance of predatory and harmful cotton insects in Oklahoma. Environ. Entomol. 1: 145-149.

Sander, D. H., W. H. Allaway, and R. A. Olson. 1987. Modification of nutritional quality by environment and production practices. p. 45-82. In R. A. Olson and K. J. Frey, eds. Nutritional Quality of Cereal Grains: Genetic and Agronomic Improvement. ASA-CSSA-SSSA, Madison, WI.

Schäfer, W., Väisänen, J, and Pihala, M. 2002. Technique of Green Mulch Spreading. Agrifood Research Finland, Agriculture Engineering Research (Vakola). Vakolan tutkimusselostus. Report# 79: 1-65.

Seed Manitoba. Seed Manitoba 2002: Variety Guide and Growers Directory. 6-12-2001. Manitoba Cooperator-Manitoba Agriculture and Food-Manitoba Seed Growers' Association, Winnipeg, MB.

Seligman, N. G., S. Feigenbaum, D. Feinerman, and R. W. Benjamin. 1986. Uptake of nitrogen from high carbon-to-nitrogen ratio, 15 nitrogen-labeled organic residues by spring wheat grown under semi-arid conditions. Soil Biol. Biochem. 18: 303-307.

Sharratt, B. S. 1991. Shoot growth, root length density, and water use of barley grown at different soil temperatures. Agron. J. 83: 237-239.

Simmons, S. R. 1987. Growth, Development and Physiology. p. 77-113. In E. G. Heyne, ed. Wheat and Wheat Improvement. ASA, Madison, WI.

Sims, J. L. and L. R. Frederick. 1970. Nitrogen immobilization and decomposition of corn residue in soil and sand as affected by residue particle size. Soil Sci. 109: 355-361.

Smika, D. E. and P. W. Unger. 1986. Effect of surface residues on soil water storage. Adv. Soil Sci. 5: 111-138.

Smith, M. A. and P. R. Carter. 1998. Strip intercropping corn and alfafa. J. Prod. Agric. 11: 345-353.

Smith, S. J. and A. N. Sharpley. 1993. Nitrogen availability from surface-applied and soil-incorporated crop residues. Agron. J. 85: 776-778.

Smith, S. J., A. N. Sharpley, M. S. Aulakh, J. W. Doran, D. T. Walters, A. R. Mosier, and D. D. Francis. 1990. Soil nitrogen mineralization in the presence of surface and incorporated crop residues. Agron. J. 82: 112-116.

Somda, Z. C., Ford, P. B., and Hargrove, W. L. 1991. Decomposition and nitrogen recycling of cover crop residues. p. 103-105. In Hargrove, W. L. ed. Conference Proceedings. Soil and Water Conservation Society, Ankeny, IA.

Stickler, F. C. and L. R. Frederick. 1959. Residue particle size as a factor in nitrate release from legume tops and roots. Agron. J. 51: 271-274.

Stute, J. K. and J. L. Posner. 1995. Synchrony between legume nitrogen release and corn demand in the Upper Midwest. Agron. J. 87: 1063-1069.

Taylorson, R. B. and L. Dinola. 1989. Increased phytochrome responsiveness and a high-temperature transition in barnyardgrass (Echinochloa crus-galli) seed dormancy. Weed Science 37: 335-338.

Teasdale, J. R. 1993. Interaction of light, soil moisture, and temperature with weed suppression by hairy vetch residue. Weed Science 41: 46-51.

Teasdale, J. R., C. E. Beste, and W. E. Potts. 1991. Response of weed to tillage and cover crop residue. Weed Science 39: 195-199.

Teasdale, J. R. and C. L. Mohler. 1993. Light transmittance, soil temperature, and soil moisture under residue of hairy vetch and rye. Agron. J. 85: 673-680.

Teasdale, J. R. and C. L. Mohler. 2000. The quantitative relationship between weed emergence and the physical properties of mulches. Weed Science 48: 385-392.

Terman, G. L. 1979. Volatilization losses of nitrogen as ammonia from surface-applied fertilizers, organic amendments, and crop residues. Adv. Agron. 31: 189-223.

Thiessen Martens, J. R., J. W. Hoeppner, and M. H. Entz. 2001. Legume cover crops with winter cereals in southern Manitoba: Establishment, productivity, and microclimate effects. Agron. J. 93: 1086-1096.

Wagner, R. C., T. J. Gillespie, and C. J. Swanton. 1996. Rye mulch characterization for the purpose of microclimatic modelling. Agricultural and Forest Meteorology. 78:67-81.

Yield Manitoba. Yield Manitoba 2003: A planning tool for Manitoba Farmers. Climate Maps and Statistics. MCIC yield data. 2-20-2003. Manitoba Co-operater-Manitoba Rural Adaptations Council-Manitoba Crop Insurance Corporation-Manitoba Agriculture and Food, Winnipeg, MB.

Yunusa, I. A. M., R. H. Sedgley, and K. M. H. Siddique. 1994. Influence of mulching on the pattern of growth and water use by spring wheat and moisture storage on a fine textured soil. Plant and Soil 160: 119-130.

8.0 APPENDIX

Table A.1. Mean monthly air temperature for Winnipeg and Carman in 2002 and 2003.

Site	Year	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Winnipeg	**2002**	-	-	-	2.3	9	18.8	22	18.6	14.2	1	-4.5	-8.1
	2003	-14.3	-17.4	-7.1	5.9	13.6	17.7	20.6	22	13.2	-	-	-
Carman	**2002**	-	-	-	2.3	8.2	17.8	20.3	17.8	13.7	0.1	-5.0	-7.9
	2003	-13.8	-17.3	-7	5.5	12.3	16.6	19.2	20.7	12.4	-	-	-

Table A.2. Total accumulation of precipitation from April 1 to August 31 at Winnipeg and Carman in 2002 and 2003, and % of normal precipitation for the time period.

Site	Year	mm	% of Normal
Winnipeg^{z}	**2002**	392	120
	2003	289	89
	Normal^{y}	326	
Carman^{x}	**2002**	374	115
	2003	321	98
	Normal^{w}	315	

z Source: Point Weather Station, University of Manitoba, Winnipeg, Manitoba.
y Source: Environment Canada 30 year average for 1971-2000 at the Winnipeg International Airport.
x Source: Environment Canada data for University of Manitoba Carman Research Station.
w Source: Environment Canada 30 year average for 1971-2000 at Graysville.

Table A.3. Total accumulation of precipitation from April 1 to August 31 at Kenton, MB and Clearwater, MB in 2002, and % of normal precipitation for the time period.

Site	Year	mm	% of Normal
Kenton^{Z}	**2002**	309	103
	Normal^{Y}	300	
Clearwater^{X}	**2002**	427	138
	Normal^{W}	309	

z Source: Environment Canada data for Kenton, Manitoba.
y Source: Environment Canada 30 year average (1971-2000) for Oakner, Manitoba.
x Source: Environment Canada data for Pilot Mound, Manitoba.
w Source: Environment Canada 30 year average (1971-2000) for Pilot Mound, Manitoba.

Table A.4. Treatments in the rate x time-of-application experiment.

1. control (no mulch, no ammonium nitrate)
2. 20kgN[z]
3. 40kgN
4. 60kgN
5. 0.5xEarly[y]
6. 1xEarly
7. 2xEarly
8. 0.5xLate[x]
9. 1xLate
10. 2xLate
11.[w] 0.5xFrozen[v]
12. 1xFrozen
13. 2xFrozen
14. Fall[u] 0.5x
15. Fall 1x
16. Fall 2x
17. Fall 1x + 1xEarly

z 20, 40, and 60 kg N ha^{-1} was applied as broadcast ammonium nitrate at the time of the early mulch application.
y "Early" indicates mulch applied after seeding but before emergence of wheat.
x "Late" indicates mulch applied at three-leaf stage of wheat.
w Treatments 11 to 17 were added in 2003.
v "Frozen" indicates mulch harvested at the time of the Early application and stored in a freezer until application at the Late stage.
u "Fall" indicates fall-applied mulch.

Table A.5. Treatments in the rate x incorporation experiment.

1. control (no mulch, no ammonium nitrate)
2. 20kgN[z]
3. 40kgN
4. 60kgN
5. 0.5x[y]
6. 1x
7. 2x
8. control (no mulch, no ammonium nitrate) I[x]
9. 20kgN I
10. 40kgN I
11. 60kgN I
12. 0.5x I
13. 1x I
14. 2x I

z 20, 40, and 60 kg N ha^{-1} was applied as broadcast ammonium nitrate at the time of mulch application.
y Mulch was applied after seeding but before emergence of wheat.
x "I" indicates incorporation with rotary hoe.

Table A.6. Treatments in the rate x particle size experiment.

1. control (no mulch, no ammonium nitrate)
2. 20kgN^{z}
3. 40kgN
4. 60kgN
5. 0.5xS^{yx}
6. 1xS
7. 2xS
8. 0.5xM
9. 1xM
10. 2xM
11. 0.5xL
12. 1xL
13. 2xL

z 20, 40, and 60 kg N ha^{-1} was applied as broadcast ammonium nitrate at the time of mulch application.
y Mulch was applied after seeding but before emergence of wheat.
x S, M, and L indicate small, medium and large particle sizes respectively.

Table A.7. Grain yield efficiency means for mulch particle size and rate effects over two years at Winnipeg.

Treatment	2002 Wheat	2003 Oats	Combined '02+'03
	-------------------- kg of grain ha^{1-} kg^{-1} of applied N --------------------		
		Particle Size means	
Small	2.4	3.9	6.3
Medium	2.1	0.5	2.6
Large	3.2	2.6	5.8
LSD(0.05)	ns^{z}	ns	ns
		Mulch Rate means	
0.5x	2.2	2.4	4.6
1x	2.4	1.1	3.5
2x	3.1	3.5	6.6
LSD(0.05)	--	--	--
Mean	2.6	2.3	4.9
		ANOVA	
Particle Size	NS	NS	NS
Mulch Rate	NS	NS	NS
Size x Rate	NS	NS	NS
C.V.(%)	57.74	176.65	104.6

z ns = non-significant.

Table A.8. Grain N yield efficiency means for mulch particle size and rate effects over two years at Winnipeg.

Treatment	2002 Wheat	2003 Oats	Combined '02+'03
	---------------------- kg of grain N ha^{1-}	kg^{-1} of applied N	----------------------
		Particle Size means	
Small	0.061	0.043	0.104
Medium	0.05	0.004	0.054
Large	0.074	0.033	0.107
LSD(0.05)	ns	ns	ns
		Mulch Rate means	
0.5x	0.051	0.027	0.078
1x	0.059	0.007	0.066
2x	0.074	0.045	0.119
LSD(0.05)	ns	ns	ns
Mean	0.1	0.027	0.088
		ANOVA	
Particle Size	NS	NS	NS
Mulch Rate	NS	NS	NS
Size x Rate	NS	NS	NS
C.V.(%)	60.32	223.14	92.86

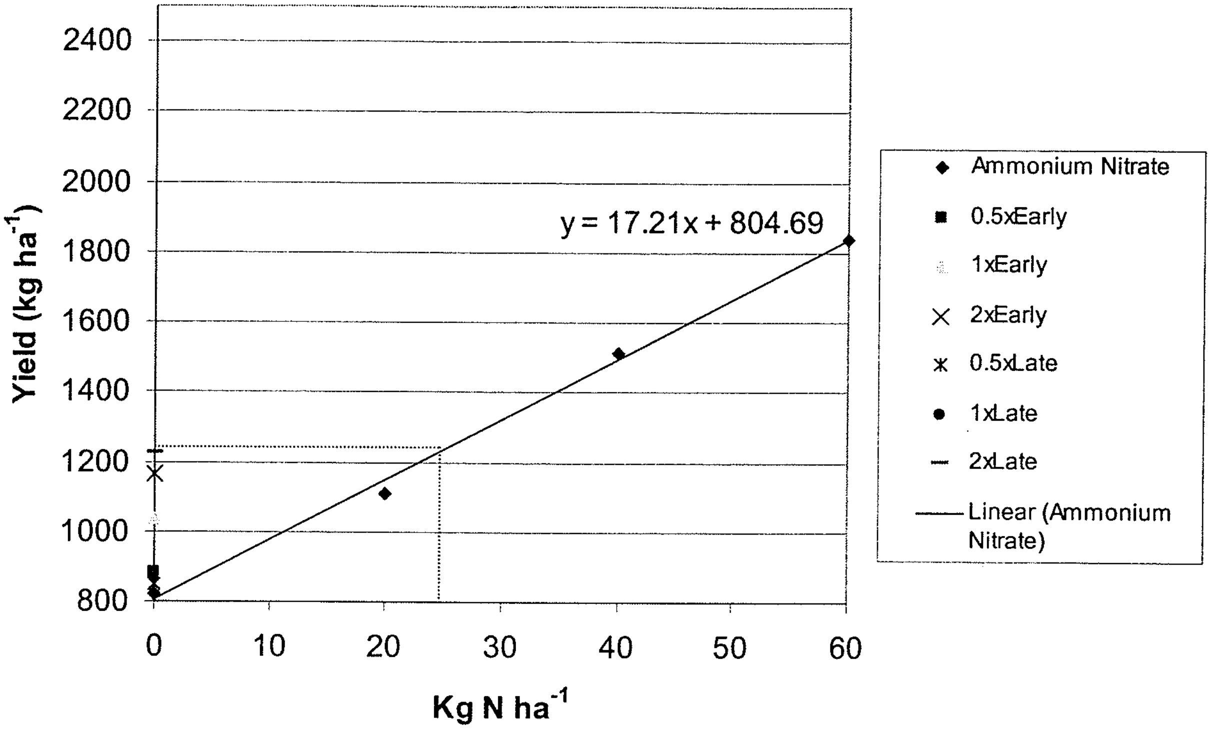

Figure A.1. Effect of ammonium nitrate and alfalfa mulch on wheat yield at Winnipeg in 2002.

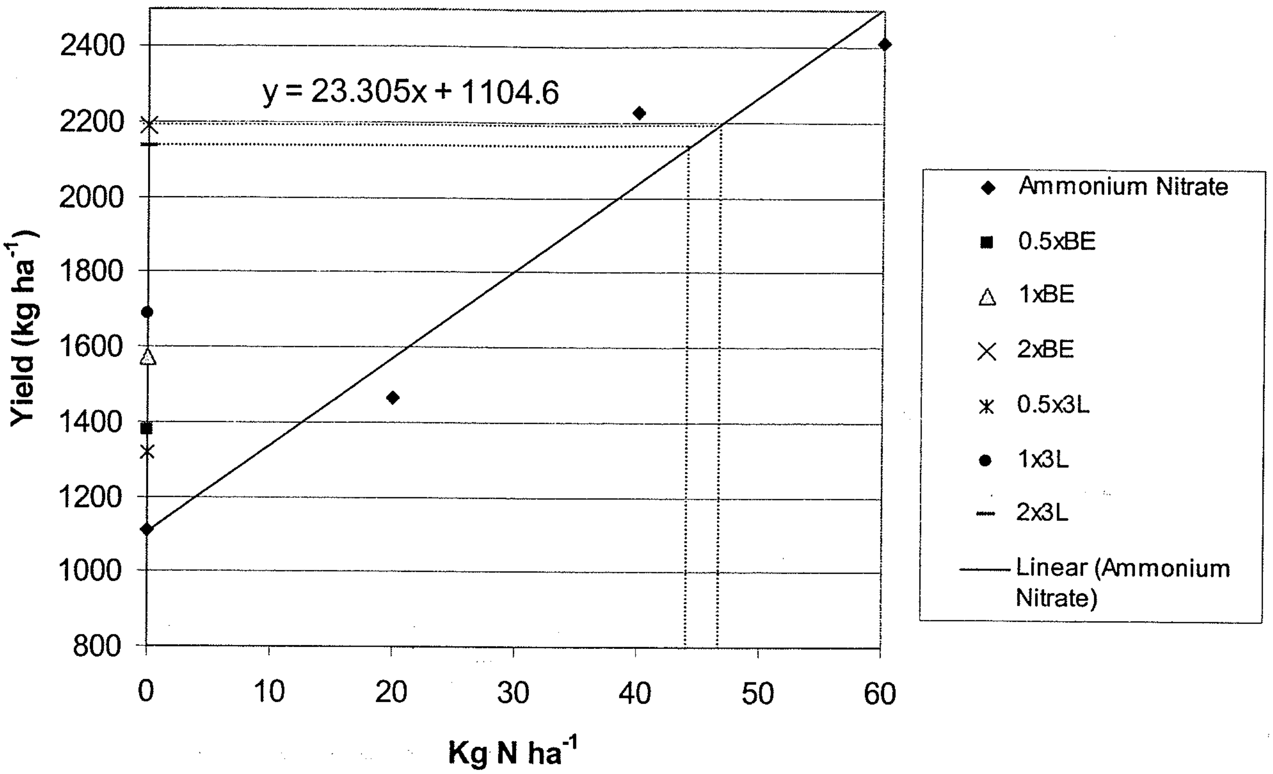

Figure A.2. Effect of ammonium nitrate and alfalfa mulch on wheat yield at Winnipeg in 2003.