EFFICIENCY OF FALL-BANDED UREA FERTILIZER IN MANITOBA: EFFECT OF APPLICATION DATE, LANDSCAPE POSITION AND FERTILIZER ADDITIVES

BY

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A Thesis
Submitted to the Faculty of Graduate Studies of The University of Manitoba
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Efficiency of Fall-Banded Urea Fertilizer in Manitoba: Effect of Application Date, Landscape Position and Fertilizer Additives

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ABSTRACT

Tiessen, Kevin H. D. M.Sc., The University of Manitoba, August, 2003. Efficiency of Fall-Banded Urea Fertilizer in Manitoba: Effect of Application Date, Landscape Position and Fertilizer Additives. Major Professor; Dr. Don Flaten.

A two-year field study was initiated in the fall of 2000 to investigate the effects of application date, landscape position and a urease and nitrification inhibited formulation of urea on the transformation and efficiency of fall-banded nitrogen (N) fertilizer for Canadian Western Red Spring wheat (*Triticum aestivum* L. cv. AC Barrie) production under Manitoba conditions.

Granular urea fertilizer at a rate of 80 kg N ha^{-1} was banded at three application dates in the fall, between mid-September and mid-October, and once in the spring at planting. In addition, there was a treatment where urea formulated with a urease and nitrification inhibitor (NBPT and DCD respectively) was banded in the early fall. During the fall, landscape position did not significantly influence the conversion of banded-urea to nitrate under the moisture conditions present at the intensive sites. However, delaying the date of application of fall-banded urea fertilizer N into the late fall and the presence of NBPT and DCD slowed nitrification and increased the percent recovery of fertilizer N as NH_4^+-N in the soil prior to freeze-up. Date of application, soil temperature on the date of application, the accumulation of soil heat units (SHU) and nitrification heat units (NHU) were all linearly related to the percent of recovered fertilizer N

as NH_4^+-N. Accumulated SHU and NHU best described the relationship with the proportion of fertilizer N recovered as NH_4^+-N at the end of the fall, with and without inhibitors.

In the spring, large over-winter losses of fall-banded N were observed in the first year of the study, with greater losses of apparent fertilizer N in the low landscape positions than in the high landscape positions. Over-winter losses of fall-banded N were significantly reduced by delaying the date of application in the fall, especially in the low landscape positions of the field. In the drier, second year of the study, over-winter losses were not as severe as in 2000/2001, except at Rosser (2001/02), where rains occurred in the fall prior to the soil freezing. Use of NBPT and DCD with early fall-banded N significantly reduced over-winter losses in year one of the study, but not in the second year.

At harvest, the effects of landscape position were apparent at three of the four sites, with significantly greater grain yields, straw yields and total recovery of N in the high landscape positions than in the low landscape positions. In the high landscape positions, there were no significant differences among application dates with respect to total recovered N in the above ground portion of the crop and soil, apparent recovered fertilizer N, or overall crop response. However, in the low landscape positions, total recovered N, apparent recovered fertilizer N, grain yields and grain yield increases for late fall applications were significantly greater than early and mid fall applications, and similar to those for spring-banded N.

In the first year of the study, early fall-banded N with NBPT and DCD produced greater increases in grain yield than early fall-banded N without the inhibitors in the low landscape positions at Kane (2000/01). However, overall, there was little apparent crop benefit to the use of the urease and nitrification inhibitors, as there were few significant differences in overall crop yields, crop N uptake or recovery of N in the crop and soil with the inhibitors than without, in either year or landscape position.

In general, the efficiency of fall-banded urea was not affected by application date, soil temperature on date of application, cumulative soil heat units or cumulative nitrification heat units in the high landscape positions. In the low landscape positions, delaying application until late in the fall, when soil temperatures had cooled to 5 or 6°C, increased grain yields and total N uptake by the crop relative to early fall-banded N. Soil temperature at application gave the best correlation with crop responses to N (relative grain yields, total N uptake, grain yield increases and N use efficiency) in the low landscape positions ($r = -0.79^{**}$, -0.75^{**}, -0.78^{**} and -0.72^{**} respectively); date of application gave slightly lower correlations ($r = 0.66^{*}$, 0.66^{*}, 0.64^{*} and 0.62^{*} respectively). Soil heat units and nitrification heat units accumulated from date of application until freeze-up gave inferior correlations ($r = -0.56^{ns}$, -0.62^{*}, -0.56^{ns} and -0.58^{*}, and $r = -0.49^{ns}$, -0.59^{ns}, -0.49^{ns} and -0.51^{ns} respectively). These results suggest that date of application and soil temperature at application are simple, robust approaches for estimating the effect of weather conditions on the efficiency of fall-banded N in southern Manitoba. The results also suggest that selection of suitable timing for application of fertilizer N to optimize crop yields is much more critical in wet years, for poorly drained fields, and for poorly drained areas within a field, than for better drained land.

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FOREWORD

This thesis has been prepared in the manuscript format in adherence with the guidelines established by the Department of Soil Science at the University of Manitoba. The Canadian Journal of Soil Science was used as the referencing style in this document. Chapters 3, 4, 5 and 6 will be submitted to the Canadian Journal of Soil Science. For all papers, I will be the lead author and co-authorship will be designated accordingly.

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1. INTRODUCTION

> "The producer has attempted to increase crop yields ever since the plant was domesticated, but it was not until the latter part of the 19^{th} century that dramatic yield increases were realized. The higher yields became possible as the knowledge of chemical elements required in plant nutrition increased, prompting producers to supplement the soil with chemical fertilizers" (Yeomans 1991).

The application of nitrogen (N) fertilizer in the fall is a management practice common to the temperate climates of North America where a single spring sown annual crop is often grown. Applying fertilizer N in the fall has numerous benefits to the producer: it reduces the number of tillage operations necessary in the spring, which preserves the quality of the seedbed and soil moisture; it allows the producer to make better use of off-season labour and decrease the workload during the busy spring seeding period; and the producer can capitalize on fertilizer prices that are, on average, 10 to 15% lower in the fall than in the spring (Malhi et al. 1992a; MB Agriculture and Food Soil Fertility Guide 2001). Unfortunately, fall fertilization of N fertilizers comes with certain risks. Under Manitoba's warm, moist soil conditions, applying N fertilizer in the early fall increases the time that the nitrogen is exposed to various transformations in the soil, increasing the potential for losses from the soil system. The quantity of fertilizer nitrogen at risk depends on numerous factors including interactions between fertilizer application date, weather and climatic conditions, landscape position, and the use of fertilizer inhibitors. It is important to develop management techniques that will improve the efficiency of fall-applied N in Manitoba because of the potential for reduced yields, the increasing costs involved in the manufacture, transportation and application of nitrogen fertilizers, and the growing environmental concerns of nitrate (NO_3^-) leaching, eutrophication, and atmospheric contamination from greenhouse gas emissions.

The overall research question we have attempted to answer during this project is: how do the interactive effects of application date, weather, landscape position, and fertilizer additives influence the efficiency of fall-banded N fertilizer under Manitoba conditions? Questions within this topic include: does application date, weather, landscape position and fertilizer additives affect the rate of ammoniacal N transformation into nitrate via the nitrification process (is it possible to develop a soil degree-day or soil degree-moisture-day model to predict nitrification activity from weather observations); and will application date, weather, landscape position and fertilizer additives affect the quantity of over-winter losses of fall-banded fertilizer N after the ammoniacal N has nitrified?

2. LITERATURE REVIEW

The purpose of this chapter is to:

1. Provide a brief review of the importance of nitrogen (N) in crop production.
2. Review the transformations and losses that affect N fertilizers after they have been applied to the soil.
3. Discuss the extensive literature regarding studies of fall-applied N, with specific regard to strategies that improve fertilizer efficiency and ultimately crop yields as affected by climate, soil texture, landscape position, N rate, fertilizer placement, date of application and the use of various fertilizer additives.

2.1 Nitrogen in Crop Production

Nitrogen is the nutrient most frequently deficient in crop production in all regions of the world, and it is generally the fertilizer applied to the soil in the largest quantities (Malhi et al. 2001). Nitrogen is an essential component of plant amino acids, proteins, nucleotides, nucleic acids, chlorophyll, and coenzymes (Raven et al. 1992), and the effective use of inorganic fertilizers has led to dramatic increases in food production worldwide (Harapiak et al. 1993). As a result, when moisture is not limiting, yield response of non-leguminous crops is directly related to N rate (Cowell and Doyle 1993).

Nitrogen also influences grain quality. In Canada, grain protein content is used as a measure of the quality of wheat for baking and milling purposes, and protein content is largely influenced by crop cultivar, available N, moisture and temperature (Gauer et al. 1992). Protein content of the crop will only be increased once sufficient fertilizer N has been applied to the soil so that N is no longer a limiting factor to yield (Gauer et al. 1992), or if proper fertilizer practices are used that decrease fertilizer N losses (Grant and Flaten 1998). Producers of hard red spring wheat have an incentive to add high rates of N fertilizers because at high protein (13.5%) and very high protein (14.5%) contents, they receive a significant price premium. However, producers of soft wheat, used primarily for pastry flour, prefer a low protein content and will apply N fertilizer accordingly (Cowell and Doyle 1993).

2.1.1 Nitrogen Use Efficiency

Fertilizer N is one of the major input costs involved in maintaining continuous cropping systems worldwide, and crop producers must manage fertilizers carefully to reduce N losses and improve nitrogen use efficiency (NUE) (Tisdale et al. 1993). Effective fertilizer management programs must deal with rate, source, placement and timing of application, and they should be "tailor made" for each particular farm (based on soil, crop and environmental conditions) in order to have adequate amounts of N available to the crop when it is required (Malhi et al. 2001). Generally, the overall efficiency of fertilizer N, applied at time of planting, is approximately 50% in the tropics and 70% in temperate climates (Malhi et al. 2001). However, in Western Canada much lower efficiencies have been reported for N fertilizers applied in the fall for spring sown annual crops (Malhi et al. 1992b). Improving the efficiency of fall-applied fertilizer N, specifically in terms of crop yield and N uptake, will improve both economic returns for the producer and minimize environmental risks (Cowell and Doyle 1993).

N uptake by a crop generally increases with higher rates of fertilizer N, because of increases in crop yield and grain protein (to a lesser extent), and it is assumed that NUE will be greatest where the yield response to N is the highest (Gauer et al. 1992). NUE is defined in one of two ways; crop yield per unit of N supplied, or N uptake per unit of N applied (Cowell and Doyle 1993). The definition used usually reflects the goal of the experiment (i.e. increased grain yield/economic return or reduced losses of N fertilizer). Studies of over-winter losses of fall-applied N fertilizers generally define NUE measurements as N uptake in the plant per unit of N applied.

There are two basic techniques used to measure the NUE of a particular crop: indirectly, using the difference method or directly, using N^{15} labelling techniques. Cowell and Doyle (1993) describe these two techniques in detail. The indirect method is based on the difference in N content between fertilized and unfertilized plants and is the method used in this study:

$$\%NUE = \frac{(\text{N uptake by fertilized plants} - \text{N uptake by unfertilized plants})}{\text{N fertilizer added}} \times 100$$

The direct method is determined by comparing the N^{15} content of fertilized plants to the N^{15} content of enriched N fertilizer provided to the crop:

$$\%NUE = \frac{(N^{15}\text{ content of fertilized plants x Total plant N content})}{N^{15}\text{ content of applied fertilizer x Total N fertilizer applied}} \times 100$$

In general, estimates of crop NUE will be slightly higher if measured with the indirect method than with the direct method because indirect measurements do not account for the possible effect of added fertilizer on the release and uptake of soil N (i.e. the priming effect), while direct measurements fail to account for possible immobilization of labelled N and subsequent mineralization of non-labelled N (Cowell and Doyle 1993). Either technique is valuable for use in studies looking at the relative effects of any factor on NUE of the crop and, "...with careful measurement and replication of treatments and a complete understanding of the underlying principles of each technique, the resolution and accuracy of either the indirect or direct method of measuring NUE can be quite satisfactory" (Cowell and Doyle 1993).

2.1.2 Nitrogen Source

Synthetic chemical fertilizers are the most widely used sources of N worldwide. For convenience, chemical N fertilizers are grouped into three categories; ammoniacal, nitrate and slowly available (Havlin et al. 1999). Generally, the efficiency of the various N fertilizers within each group are regarded as similar to one another if they are placed and timed properly (Tisdale et al. 1993). For example, under semi-arid conditions in southern Alberta, the efficiency of urea and anhydrous ammonia were similar when banded at a depth of 15 cm, in either the fall or spring (Kucey 1986). However, the performance among groups may vary, depending on environmental conditions. Under moist conditions, soil microorganisms can immediately denitrify nitrate fertilizers, whereas ammoniacal fertilizers slowly form NO_3^- (Malhi and Nyborg 1983a). In more humid climates, application of nitrate fertilizer has repeatedly been reported to be less effective than ammonium based fertilizer in terms of crop yields, especially if fall-applied (Malhi et al. 1984; Nyborg and Malhi 1986; Harapiak et al. 1993). Therefore, the use of ammonium forming fertilizers, such as urea and anhydrous ammonia, is recommended if N is applied in the fall in regions where fall rains or large snowmelts are anticipated (Malhi et al. 1992b).

Although the use of ammoniacal fertilizers will reduce the potential of biological denitrification, they can increase the potential for small quantities of N gases to be generated by chemical denitrification, due to higher concentrations of nitrite (NO_2^-) accumulating in the edges of the band row (Tisdale et al. 1993). Nonetheless, the type of N fertilizer used by a producer is generally dependent on factors such as cost and availability, ease, safety and expense of handling and storage, compatibility with other fertilizers, and type of seeding/tillage system used by the producer.

2.1.3 Urea-N ($CO(NH_2)_2$)

In 1984, urea (46-0-0) replaced ammonium nitrate as the major N product used worldwide (Yeomans 1991) and it is still the major granular nitrogen fertilizer used today on the Canadian prairies (Grant 1998). Urea is a non-ionic, soluble, mobile organic molecule and was the first organic compound directly synthesized from an inorganic substance (Havlin et al. 1999). The mass production of urea-N fertilizer began in Germany during the 1920s by combining ammonia (NH_3) and carbon dioxide (CO_2) (with catalysts) under extremely high pressure (Jones 1932). Initial concerns about the agronomic suitability of urea as a fertilizer source hindered its adoption by North American producers and it has only been in the past 40 years that urea has received considerable attention as a fertilizer material (Yeomans 1991). The two main agronomic concerns of urea included volatile losses of NH_3 from urea fertilizer exposed on the soil surface, and seed and seedling phytotoxicity due to high concentrations of NH_3 and nitrite NO_2^- produced during the hydrolysis and nitrification of the urea granule (Tisdale et al. 1993). However, numerous research studies, in combination with practical farm experiences, have shown that if used properly (i.e. incorporation and/or band applications, placement of urea away from seed, low rates of urea-N with seed) urea is as efficient as any other granular fertilizer on the market today (Havlin et al. 1999).

After the initial hydrolysis stage, the reaction zone of urea is similar to that of anhydrous ammonia when applied to the soil. Ammoniacal N fertilizers initially have a high pH, but over time will acidify the soil due to the nitrification of NH_4^+ to NO_3^- by soil microorganisms. Ukrainetz et al. (1996) conducted a 10-year study comparing the long-term use of urea and anhydrous ammonia fertilizers on soil acidity, yield and protein content of cereals in Saskatchewan. The authors observed that crop yields were generally the same between the two ammoniacal fertilizers when N was applied at recommended rates. However, at the highest rates of N applications (180 kg N ha^{-1}), only urea was able to positively influence the cereal yields near the end of the study, because of the increased soil acidity from anhydrous ammonia (Ukrainetz et al. 1996). At these higher rates of fertilizer application, both urea and anhydrous ammonia fertilizers gradually acidified the soil, but the acidifying effects were greatest with the anhydrous ammonia.

The increased popularity of urea worldwide can be attributed to its many advantages over other N fertilizers. Urea has a high nitrogen concentration for a dry fertilizer; urea is not sensitive to fire and explosion, making it easy to handle, store and transport; urea is less corrosive than nitrate fertilizers and flexible in its application (i.e. broadcast, banded, placed with seed using an airseeder); urea blends readily with other dry fertilizers (except ammonium nitrate as attraction for moisture causes the mixture to turn to mush); and urea has a relatively low unit cost (Tisdale et al. 1993; Malhi et al. 1996; Grant 1998; Havlin et al. 1999; MB Agriculture and Food Soil Fertility Guide 2001).

2.2 Transformations of Urea-N

When urea fertilizer is added to the soil, numerous biological and/or chemical pathways quickly transform the fertilizer N. These nitrogen transformations include: hydrolysis, mineralization, immobilization and nitrification.

2.2.1 Urea Hydrolysis

As previously mentioned, the two major drawbacks to using urea fertilizer are volatilization losses if not incorporated soon after application and toxicity to young seedlings if seed placed. However, urea-N is not directly subject to volatile losses or responsible for seedling toxicity. These concerns arise from the rapid hydrolysis of the urea-N to ammonia-N and carbon dioxide by the urease enzyme, *urea amidohydrolase*, an enzyme common within the surface horizons of Western Canadian soils (Grant 1998; Grant and Bailey 1999). Many bacteria, fungi and actinomycetes possess the urease enzyme, and it is released from these organisms throughout their lives and as they decompose (Yeomans 1991). The level of soil urease activity is heavily dependent of the microbial population, organic matter, soil texture, temperatures (up to 37°C), moisture content, pH, total N, and cation-exchange capacity (CEC) (Jones 1932; Yeomans 1991;

Tisdale et al. 1993). Urea hydrolysis occurs rapidly in the soil when conditions are favourable for good crop growth, with the hydrolysis rate of urea at 12°C being twice that at 2°C (Kissel et al. 1988). In warm moist soils, the majority of urea-N will be hydrolysed to form ammonium carbamate (NH_4COONH_2), ammonium (NH_4^+) and/or NH_3 within several days (Kissel Undated). In the presence of adequate water, the NH_4^+ form is retained in the soil. However, in dry alkaline soils with a pH greater than 7.5, NH_4^+ can be quickly converted to NH_3 and volatilized to the atmosphere if near the soil surface. This process is described in Havlin et al. (1999) as:

$$CO(NH_2)_2 + H^+ + 2H_2O \rightarrow 2NH_4^+ + HCO_3^-$$

$$NH_4^+ \rightarrow NH_3 + H^+$$

During this hydrolysis stage, there is an initial rise in soil pH and this is of agronomic concern to producers. Increasing soil pH shifts the NH_4^+:NH_3 equilibrium in favour of NH_3 (Kissel et al. 1988), and both seedling damage and volatilization losses are directly related to the concentration of NH_3 in the soil (Grant and Bailey 1999).

2.2.2 Immobilization

After the urea fertilizer has been converted to NH_4^+-N, it can be temporarily "lost" to the mineral N pool through the process of immobilization. Immobilization is the conversion of inorganic N (NH_4^+ or NO_3^-) to organic N and occurs when soil microorganisms decompose crop residues with a high carbon to nitrogen ratio (Havlin et al. 1999). In this situation, the organic residue does not have enough N to satisfy the growth of the microbial population, and the microorganisms incorporate inorganic NH_4^+ or NO_3^- from the soil. Soil microorganisms compete well with plants for NH_4^+ and NO_3^- and it is possible for crops to become N deficient as a result. The potential for fertilizer N to be immobilized is much greater for fall-applied N than spring applications because of the length of time the N is exposed to soil microorganisms (Olson 1982; Malhi and Nyborg 1983a; Aulakh and Rennie 1984; Malhi and Nyborg 1991). In five experiments in Alberta using tracer N^{15}, Malhi and Nyborg (1983a) reported the immobilization of fall-applied fertilizer N to be highly variable within the soil, but noted that in extreme cases up to half of the applied fertilizer N could be immobilized in the year of application (range 7 to 49%). Aulakh and Rennie (1984) suggest that biological immobilization, rather than leaching or denitrification, may be the major reason for reduced efficiencies of fall-applied urea fertilizers under dry soil conditions. However, the immobilization of fertilizer N does not always reduce the overall efficiency of fertilizer N. For example, microbial immobilization of fall-applied fertilizer N can reduce over-winter losses of nitrates in certain situations (Olson 1982). After the crop residue has been decomposed, the immobilized N is slowly mineralized back to NH_4^+. Unfortunately, if the rate of mineralization is not fast enough the next spring, the temporary losses due to immobilization will have a negative effect on the availability of mineral N to the crop early in the season (Cowell and Doyle 1993).

The quantity of N fertilizer at risk to be immobilized can be reduced using various application techniques. The immobilization of fertilizer N, applied in either the fall or spring, is greatly reduced when the fertilizer is placed in bands instead of broadcast and incorporated (Tomar and Soper 1981; Malhi and Nyborg 1983a; Malhi and Nyborg 1985; Malhi et al. 1989; Malhi and Nyborg 1991), because conditions within the band zone are toxic to soil microoganisms. The immobilization of fertilizer N is also affected by type of N fertilizer used. Ammoniacal fertilizers generally have higher rates of immobilization than nitrate fertilizers (Malhi and Nyborg 1983a; Nyborg et al. 1990; Malhi and Nyborg 1991), because heterotrophic microorganisms prefer NH_4^+-N over NO_3^--N (Aulakh and Rennie 1984).

2.2.3 Mineralization

Mineralization is generally considered the reverse of immobilization. Nitrogen mineralization is the conversion of organic N to inorganic NH_4^+ by heterotrophic soil microorganisms (Havlin et al. 1999). The mineralization of organic N is a two-step process described in Havlin et al. (1999) as:

$$\text{Org. N} \rightarrow NH_2 \rightarrow NH_4^+$$

The first step, aminization, is the decomposition of proteins and the release of amines, amino acids and urea by bacteria (in alkaline soils) and fungi (in acidic soils) (Tisdale et al. 1993). The second step of the mineralization process is termed ammonification, and the amines and amino acids produced via aminization are further hydrolyzed to NH_3, which is then converted to NH_4^+.

The rate of mineralization increases with increasing temperature (optimum 25 to 35°C) and is enhanced by adequate but not excessive soil moisture, as aerobic conditions are required by most of the microorganisms involved (optimum 50 to 70% water-filled pore space) (Havlin et al. 1999). There are numerous soil organic matter (SOM) pools contributing to the mineralization potential of a soil including the water-soluble, hemicellulose, cellulose and lignin fractions. The water-soluble fraction is considered the most active component of the SOM, because it the most immediately available fraction for soil microorganisms (Curtin and Wen 1999).

Approximately 1 to 3% of soil organic N mineralizes and becomes available to plants during a single growing season (Curtin and Wen 1999). Although this does not appear to be a large contribution, if a soil contained 4% OM and 2% mineralization occurred: 4% OM x ($2x10^6$ lbs soil/acre to 6") x (5% N) x (2% N mineralized) = 80 lbs N $acre^{-1}$ or 72 kg N ha^{-1}. With this simple example we see that each year there is the potential for 72 kg N ha^{-1} as NH_4^+ to be mineralized from the SOM, which will then enter the soil solution to be utilized by plants or undergo other soil N processes (Tisdale et al. 1993). The mineralized NH_4^+-N is subject to a number of possible fates within the soil environment: immobilized back into organic matter by soil microorganisms, transformed to nitrite (NO_2^-) and NO_3^- via the nitrification process, adsorbed onto clay and soil organic matter (SOM), taken up by plants, or slowly released back to the atmosphere as N_2 (Tisdale et al. 1993).

The balance between the two processes, mineralization and immobilization, is affected by the initial carbon to nitrogen (C/N) ratio of the organic material and the stage of decomposition. Generally, when organic substances having a C/N ratio greater than 30:1 are added to the soil, there is an increase in the net immobilization of soil N. As the residue is decomposed, and soil microoganisms convert carbon to energy and CO_2, the C/N ratio is reduced and mineralization follows immobilization. For organic residue with an initial C/N ratio of less than 20:1, there is enough N to satisfy the soil microorganisms and a release of mineral N to the soil environment occurs (Havlin et al. 1999). The rate of either immobilization or mineralization is dependent upon: availability of the substrate (i.e. readily degradeable, physical mixing of soil via tillage); population of microoganisms, soil pH, aeration, soil moisture, and warm temperatures ($Q_{10} = 2$ from 5° to 35°C) (Tisdale et al. 1993; Havlin et al. 1999).

2.2.4 Nitrification

While the mineralization of proteins, nucleic acids, and other nitrogenous organic substances in the soil releases NH_3, which is then converted to NH_4^+, plant physiologists generally recognize that NO_3^- is the form most readily available to plants in the soil (Schmidt 1982). Therefore, one of the most essential soil nitrogen transformation process in the soil environment is nitrification, the oxidation of NH_4^+ to NO_3^- (Tisdale et al. 1993). Nitrification is a two-step process that occurs naturally in the soil environment wherever NH_4^+ is present and conditions for nitrification are favourable. When ammonium based fertilizers are applied to the soil, aerobic autotrophic bacteria are the primary organisms that oxidize NH_4^+ to NO_2^- and then to NO_3^- (Schmidt 1982). Energy released during nitrification, although small, provides the energy needed by these microorganisms for growth and cell maintenance (Yeomans 1991).

The first step in the nitrification pathway is the oxidation of NH_4^+ to NO_2^- and is described in Havlin et al. (1999) as:

$$2NH_4^+ + 3O_2 \rightarrow 2NO_2^- + 2H_2O + 4H^+$$

This step is performed mainly by certain autotrophic bacteria including: *nitrosomonas, nitrosolobus, nitrospira,* and *nitrosovibrio,* of which the most common species is *nitrosomonas*. Some heterotrophic bacteria can also oxidize NH_4^+ and other reduced N compounds such as amines to NO_2^-, but autotrophic bacteria are the most important in agricultural soils (Havlin et al. 1999). A natural bi-product of this first step in the nitrification process is the acidification of the surrounding soil due to the release of H^+ ions.

The second step of the nitrification process is the oxidation of NO_2^- to NO_3^-. This step is catalyzed by a second group of aerobic, autotrophic bacteria called *nitrobacter*. The oxidation of nitrite is illustrated in Havlin et al. (1999) as:

$$2NO_2^- + 2O_2 \rightarrow 2NO_3^-$$

The presence of high concentrations of NO_2^- in the natural soil environment is rare because the oxidation of NO_2^- is much more rapid than that of NH_4^+ (Schmidt 1982). Nonetheless, high concentrations of NH_3 and high soil pH, as found in a fertilizer band, can lead to incomplete nitrification and the accumulation of NO_2^- in the soil because *nitrobacter* is extremely sensitive these conditions (Pang et al. 1975a). This build-up of NO_2^- is an agronomic concern because NO_2^- is highly toxic to young plants and soil microorganisms (Stevenson 1982). As well, NO_2^- can be reduced directly to nitrous oxide (N_2O) and lost to the atmosphere by chemodenitrification (Yeomans 1991).

The rate at which nitrification proceeds is heavily dependent on soil environmental conditions, in particular, soil temperature, soil moisture, aeration status of the soil, supply of NH_4^+, soil pH and the population of nitrifying organisms (Havlin et al. 1999). Nitrification rates generally increase with increasing temperatures (Chandra 1962; Pang et al. 1977; Malhi and McGill 1982; Schmidt 1982; Yadvinder-Singh and Beauchamp 1987), with fastest rates occurring when soil conditions are moist, well-aerated, have a neutral pH, and a high population of nitrifying soil microorganisms (Pang et al. 1973; Pang et al. 1975b; Gilmour 1984).

The rate of disappearance of ammonium and the formation of nitrate has been reported to obey zero-order kinetics at low temperatures (Gilmour 1984), and first order kinetics at optimal temperatures, especially at low rates of N (Malhi and McGill 1982). The optimum soil temperature for the nitrification of NH_4^+ to NO_3^- is between 25 to 35°C, with a Q_{10} of 2 over the range of 5 to 35°C (Havlin et al. 1999). However, this optimum temperature is not universal. Malhi and McGill (1982) reported that the optimum temperature for nitrification in soils from Alberta was 20°C, and concluded that nitrifying microorganisms are able to adapt to local climates. Nitrification is significantly slower in cool soils and several researchers have reported that nitrification essentially stops when soil temperatures reach 4 to 5°C (Schmidt 1982; Gomes and Loynachan 1984). However, due to local microbial adaptation, nitrification has also been reported to continue in appreciable amounts during the late fall and early winter when soils are at, or near, freezing (Malhi and Nyborg 1979; Malhi and McGill 1982; Malhi and Nyborg 1986). For example, Malhi and Nyborg (1986) sampled fall fertilized trials throughout the winter, and measured an average nitrification rate of 0.19 kg ha^{-1} day^{-1} and a total increase of 48 kg N ha^{-1} in the top 60 cm of a frozen soil in Alberta.

Nitrification rates are generally highest at soil water contents near field capacity (Havlin et al. 1999). Malhi and McGill (1982) determined that the relative nitrification rate increased with increasing soil moisture potential from –1500 to –33 kPa. This indicates that appreciable nitrification can be expected even when the soil is very dry, such as at the permanent wilting point (-1500 kPa). At the other extreme, nitrification ceased at 0 kPa due to the shortage of oxygen in the soil caused by excess water (Malhi and McGill 1982). Malhi and McGill (1982) also reported that at low NH_4^+ concentrations, nitrification rates increased with increasing NH_4^+

concentration from 50 to 200 ug g^{-1} of soil, but was inhibited at higher NH_4^+ concentrations, especially at concentrations common to fertilizer band zones. Extremes in soil pH are another factor limiting nitrification. The optimal pH range for nitrification is between 6.5 and 8 (Pang et al. 1975b). Alkaline soils inhibit the oxidation of nitrite, causing it to build-up in the soil environment, whereas acidic soils often contain significant concentrations of soluble aluminum. Both nitrite and aluminum are toxic to nitrifiers.

2.3 Losses of Fall-Applied Urea

Even under the best field conditions, it is rare for the fertilizer use efficiency of fall-applied N fertilizers in Western Canada to exceed 50% during the first growing season, and recoveries significantly less than 20% are common (Stevenson 1982; Cowell and Doyle 1993). The low efficiencies of fall-applied N compared to spring-applied are frequently attributed to high permanent losses of N rather than temporary losses from immobilization (Malhi and Nyborg 1983a; Bole and Gould 1986; Malhi et al. 1989; Malhi et al. 1990b; Nyborg et al. 1990). The three most likely loss mechanisms that affect fall-applied urea are: volatilization, leaching and denitrification.

2.3.1 Volatilization

The potential for volatile losses of free NH_3 to the atmosphere is greater with urea than with most other N fertilizers (Tisdale et al. 1993). The factors that influence ammonia volatilization of urea fertilizer are similar to those that increase the hydrolysis rate of urea-N to ammonia including: urease activity in the soil, application method, temperature, soil moisture, soil pH and soil cation exchange capacity (Bovis and Touchton 1998; Havlin et al. 1999; Malhi et al. 2001). The rapid hydolysis of urea on or near the soil surface creates the conditions for the loss of ammonia to the atmosphere, especially when the soil dries rapidly (Bovis and Touchton 1998). In Manitoba, the volatilization potential of urea fertilizer was highest under conditions of warm, moist soils with a pH greater than 8.0 (Toews 1971). When ammoniacal fertilizers are added to acidic or neutral soils, little NH_3 volatilization occurs, but as soil pH increases (inherent pH or by reactions that cause a temporary rise) from 8 to 9.3, the concentration of ammonia increases from 10 to 50%. However, soil texture also plays an important role in the magnitude of volatile losses due to its effect on cation exchange capacity (CEC) and pH buffering. Toews (1971) reported that volatilization losses from urea were actually lower on heavy clay soils than sandy soils from Manitoba because of higher CEC in the clay soils, even though the clay soils generally had a higher soil pH.

Since volatilization losses increase with increasing concentrations of ammonia at the soil surface, volatile losses of urea fertilizers will be highest when surface applied without incorporating into the soil (Yeomans 1991). Volatilization losses from urea fertilizer are considerably lower when the urea is placed deep into the soil using such techniques as banding, nesting, or point placement (Hargrove 1988; Yadvinder-Singh et al. 1994; Havlin et al. 1999; Malhi et al. 2001). Therefore, when fertilizer N is banded, differences in grain yield between fall and spring-banded urea are more dependent on the nitrification of the fall-applied N and its subsequent over-winter loss from the rooting zone by leaching and denitrification (biological and/or chemical) (Yadvinder-Singh et al. 1994).

2.3.2 Leaching

In regions of adequate rainfall and good soil infiltration, nitrified N from organic and ammoniacal fertilizers, or NO_3^- directly from nitrate-based fertilizers, has the potential to be leached through the soil profile (Olson 1982). The nitrate form of N is more prone to leaching losses than NH_4^+, because NO_3^- is not readily precipitated or adsorbed by the soil, and consequently moves easily with water through the soil profile (Legg and Meisinger 1982). Nitrate leaching from agricultural soils is an environmental concern because high levels of NO_3^- in surface runoff and water percolating through the soil can pollute drinking water and increase unwanted plant and algal growth in lakes and reservoirs (Havlin et al. 1999). The principal factors affecting leaching losses of fertilizer N are excess moisture, soil texture and structure, organic matter content, and excess nitrate levels which are influenced by crop type and growth, N fertilization rate and frequency of fallow in the crop rotation (Bergstrom and Johansson 1991).

The two main processes involved in the movement of nitrogen in the soil are: convection of dissolved substances due to mass flow of the soil solution, and ionic diffusion due to concentration gradients (Gardner 1965). In Manitoba, various studies have reported that the movement of nitrates in the soil profile is mainly via convective flow and that leaching losses are likely to be a concern only on coarse textured soils following significant precipitation (Racz 1979). Six experiments were conducted in the late 1970s and reported that fertilizer efficiency in Manitoba was not greatly affected by leaching, as leaching of NO_3^--N was not appreciable during the winter or growing season, especially when soils were cropped and N fertilizer was applied at recommended rates (Racz 1979). Even at extremely high N rates (550 kg N/ha), Field-Ridley (1975) did not find significant movement of nitrates below the rooting zone on a Portage loam and Red River clay soils. However, other research in Manitoba found that under fallowed conditions, spring-applied N was easily leached from the rooting zone (120 cm depth) within one year of application on an Almasippi FSL (Chang and Cho 1974).

Numerous other studies from across Canada have reported little to no leaching of nitrate-N below 60 cm from fall-applied urea fertilizers (Malhi and Nyborg 1983a; Aulakh and Rennie 1984; Bole and Gould 1986; Malhi and Nyborg 1986; Malhi et al. 1990b; Malhi et al. 1992b). In the warmer and humid regions of North America (i.e. southern U.S.A.), leaching losses in sandy soils that are not completely frozen throughout the winter may be more significant than denitrification losses (Olson 1982). However, under Western Canadian conditions, where soils are generally frozen for most of the winter months, even well drained soils can become waterlogged for a few days in the spring (Malhi et al. 1992b). The consensus is that the majority of the losses from fall-applied N in the Canadian prairies are a result of denitrification during mild weather events in the winter and during the early spring thaw, especially on poorly drained heavy clay soils such as those in the Red River Valley of Manitoba. Bergstrom and Johansson (1991) reported that leaching losses were much smaller on clay soils than on sandy soils, and according to the Manitoba Agriculture and Food Soil Fertility Guide (2001), "denitrification is the most common way that soil N is lost in southern Manitoba and losses in spring-flooded soils can be as high as 2 to 4 lbs. N ac^{-1} per day." Furthermore, Farrell et al. (1996) observed that on clay soils, in areas of the landscape where water accumulation was at a maximum, denitrification rates were high enough that there was no accumulation of NO_3^- in the upper 3 m of the soil. For these reasons, the section dealing with denitrification losses is much more detailed than for either volatilization or leaching.

2.3.3 Denitrification

Denitrification is the process in which nitrogen oxides are converted to gaseous forms of nitrogen, which are then released to the atmosphere. Denitrification is an important component in the cycling of nitrogen in agricultural ecosystems and is regarded as a major contributor to atmospheric levels of N (Tisdale et al. 1993). In Western Canada, the largest flux of soil N often occurs during the spring thaw (Malhi and Nyborg 1983a; Aulakh and Rennie 1984; Bole and Gould 1986; Malhi and Nyborg 1986; Malhi et al. 1990a; Nyborg et al. 1990; Heaney et al. 1992; Burton and Beauchamp 1994; Nyborg et al. 1997; Muller et al. 2002), with as much as 65% of the total annual denitrification emissions occurring during this period (Wagner-Riddle et al. 1997). In Western Canada, mass balance studies using fall broadcast and incorporated ^{15}N-urea have reported over-winter losses ranging from 5 to 90%, depending on soil and weather conditions (Malhi and Nyborg 1983a; Aulakh and Rennie 1984; Bole and Gould 1986; Nyborg et al. 1990; Heaney et al. 1992).

There are two major pathways that make possible the denitrification of soil and fertilizer N; biological and chemical denitrification. Biological denitrification is the microbially mediated conversion of nitrate (NO_3^-) into nitrous oxide (N_2O) and dinitrogen (N_2) gases (Firestone 1982). Biological denitrification generally occurs under anaerobic conditions and can cause significant losses of soil N when high soil water contents are combined with warm soil temperatures. Chemical denitrification is an abiotic pathway in which nitrogen is oxidized by NO_2^- to yield N_2 gas (Christianson and Cho 1983). The development of sound management policies that conserve fall-applied nitrogen, by minimizing the nitrogen lost from the soil as gaseous N emissions and simultaneously reducing the amount of N necessary to effectively grow crops, requires a better understanding of the sources and controls of the denitrification process.

2.3.3.1 Biological Denitrification. Biological denitrification is a form of anaerobic bacterial respiration during which nitrogen oxides, in particular NO_3^- and NO_2^-, are sequentially reduced through NO and N_2O to N_2 gas (Aulakh et al. 1992). This heterotrophic process couples the reduction pathway of anaerobic respiration with electron transport phosphorylation and enables denitrifying bacteria to conserve energy and maintain growth in the absence of oxygen (Firestone 1982). Almost without exception, denitrifiers are preferential oxygen users and will choose O_2 over NO_3^- as the terminal electron acceptor. The preferred use of oxygen is the reason that biological denitrification is restricted to anoxic sites within the soil matrix. However, with oxygen limited, electron transport branches off from the β-type cytochromes in order to use oxidized forms of N (Paul and Clark 1996). The generally accepted biochemical sequence is:

$$\underset{2NO_3^-}{(+5)} \xrightarrow{NaR} \underset{2NO_2^-}{(+3)} \xrightarrow{NiR} \underset{2NO}{(+2)} \xrightarrow{NOR} \underset{N_2O\uparrow}{(+1)} \xrightarrow{NOS} \underset{N_2\uparrow}{(0)}$$

Specific reductase enzymes catalyze each step in the reduction of NO_3^-: nitrate reductase (NaR), nitrite reductase (NiR), nitric oxide reductase (NOR), and nitrous oxide reductase (NOS) (Paul and Clark 1996). Biological denitrification is usually not limited by enzyme concentrations, but enzyme activity can be slowed by substrate and environmental conditions (i.e. oxygen, higher NO_3 levels, low pH). Denitrifying organisms generate energy in the form of ATP as electrons are transported from an organic or inorganic source to NO_3^- or other N oxides. This process is approximately half as efficient as oxygen reduction, but it does allow the denitrifying microorganisms to maintain growth under anaerobic conditions (Firestone 1982).

The rate and magnitude of biological denitrification is controlled by numerous soil and environmental factors. In Robertson's model (Fig. 2.1), the complex interactions between the "proximal" (microscale) and "distal" (macroscale) regulators of denitrification are shown.

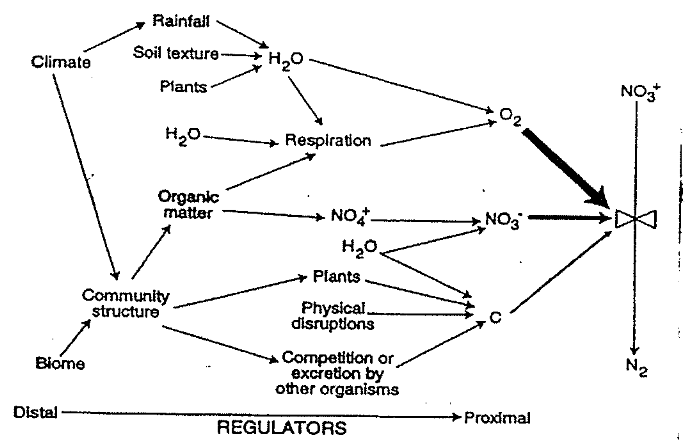

Fig. 2.1. Factors regulating denitrification in the soil (Robertson 1995 *in* Paul and Clark 1996).

The importance of each regulator on the denitrification process is emphasized by the thickness of the arrow. Looking at Robertson's model (Fig. 2.1), the soil and environmental factors that have the greatest influence on biological denitrification are the proximal regulators. These proximal regulators directly affect the activity of denitrification, and the most important of the regulators include the presence of denitrifying microorganisms, organic C supply (electron donor), oxygen status (soil aeration and water content), N oxide concentrations, temperature, and soil pH.

Biological denitrification requires the presence of microorganisms with the ability to reduce NO_3^--N. Heterotrophic bacteria are the most common denitrifiers, but other microorganisms capable of denitrification include chemotrophs, phototrophs, lithotrophs, and diazotrophs (Firestone 1982). The denitrifying microorganisms that predominate in the soil are of the *Pseudomonas*, and *Alcaligenes* genera. Certain genera of microorganisms are capable of performing more than one process within the nitrogen cycle. For example, *Rhizobia* and *Azospirillum* are able to both fix and denitrify nitrogen, while *Thiospara pantotropha* can simultaneously nitrify and denitrify N (Paul and Clark 1996). For many years, denitrification was considered solely a prokaryotic process, and numerous denitrifying bacteria have been studied extensively over the years (Paul and Clark 1996). However, recent studies have shown that eukaryotes, such as yeasts (Tsuruta et al. 1998) and fungi (Shoun et al. 1992; Laughlin and Stevens 2002), are also capable of denitrification. Laughlin and Stevens (2002) suggest that fungi may in fact be the dominant source of N_2O production in temperate soils, especially grassland soils, as they dominate the microbial biomass. Nonetheless, it is suspected that the efficiency of fall-applied fertilizer N is most affected by denitrification losses during the early spring period, when the combined effects of soil saturation and warm soil temperatures create conditions perfect for bacterial, rather than fungal, denitrification of soil NO_3^--N (Dr. M. Tenuta, personal communication, Department of Soil Science, University of Manitoba, Winnipeg, MB).

The intensity of the biological denitrification process is heavily dependent on organic C as an energy source and as a source of cellular material, and the presence of ample supplies of readily decomposable soil organic matter (SOM) will increase the rate of denitrification (Cho et al. 1979). The increased rate of denitrification may reflect increasing denitrifier activity, increased microbial population of the soil, and/or better conditions for denitrification (Paul and Clark

1996). As SOM is decomposed, oxygen is consumed, CO_2 is produced, and the conditions necessary for NO_3 reduction are improved.

In the presence of denitrifying organisms, with an adequate supply of organic matter, the next regulator to consider is the oxygen supply of the soil. The aeration status of the soil is probably the most important of all the regulators of denitrification, as oxygen greatly influences the redox potential of the soil. The redox potential determines if conditions are favourable towards oxidation or reduction reactions. Denitrification is a reduction process and reducing conditions (i.e. low Eh) are necessary. These conditions will occur when oxygen is limited and therefore denitrification activity is inversely proportional to the oxygen concentration in the soil. Anaerobic conditions must arise before the denitrification process will begin. Low oxygen availability causes a shift in the microorganisms, from organisms that rely on aerobic respiration to those that use NO_3^- as an electron acceptor (Tisdale et al. 1993).

Of the various environmental conditions influencing the oxygen status of the soil, soil water content is the most important. Soil water content regulates the diffusion of oxygen through the soil resulting in a direct relationship between denitrification activity and soil moisture content (Aulakh and Rennie 1985). However, the relationship between denitrification and water content is not that simple. Soil texture affects biological denitrification because of physical variations in soil structure, pore size, aggregation, and water infiltration rates affecting aeration. For example, at similar gravimetric water contents, rates of denitrification can be significantly different in soils of varying texture. As a result, a clay soil will have a lower denitrification potential at 50% gravimetric moisture content than a loam or a sandy soil. Clay soils have more pore spaces than sands and at similar soil moisture contents the proportion of pore spaces filled by water will be less in the clay soil (Aulakh et al. 1992). However, the microenvironment most commonly inhabited by denitrifiers is one of reduced oxygen availability, somewhere between fully aerobic and fully anaerobic (Cho 1982; Firestone 1982). Cho (1982) found that denitrification occurred whenever oxygen supply to the soil was limited and microbial electron acceptor demand was in excess of oxygen supply by diffusion. The denitrification process is able to operate under these seemingly aerated soils in anaerobic zones or "hotspots" where the demand for oxygen exceeds the supply (Christianson et al. 1990). These anaerobic pockets are more prevalent at low levels of denitrification activity (i.e. drier conditions), and are probably due to intense respiratory activity, rather than passive anaerobiosis (Tisdale et al. 1993).

Davidson (1992) studied the effects of wetting and drying cycles on denitrification rates and reported that when a soil was wetted, large NO and N_2O fluxes were observed. The potential for denitrification occurs throughout the year because of these wetting and drying cycles. During the growing season, short periods of soil saturation can occur after heavy rainfalls or irrigation (Aulakh and Rennie 1985; Malhi et al. 1989; Davidson 1992; Corre et al. 1995; Malhi et al. 1996). Indirectly, soil water can also affect denitrification by providing suitable conditions for microbial growth, facilitating the release of C and N substrates through wetting/drying cycles, and providing a diffusion medium through which substrate and products are moved to and away from soil microorganisms (Aulakh et al. 1992).

Soil conditions that alternate between aerobic and anaerobic may allow for the highest rates of denitrification. Periodic exposure to oxygen is needed for nitrification to proceed, ensuring an adequate supply of NO_3^- and/or NO_2^- for the subsequent denitrification process.

Biological denitrification is extremely sensitive to temperature. Soil temperature directly affects the rate of microbial activity (Dobbie and Smith 2001), and indirectly influences both the solubility and diffusion of oxygen in water. The minimum temperature for biological activity is considered to be near freezing (Firestone 1982). At temperatures above 15°C, the rate of denitrification increases exponentially with increasing temperature, and this relationship is described by the Arrhenius equation:

$$\ln v = (-\Delta H^*/RT) + C$$

where v is velocity, ΔH^* is the activation energy, R is the gas constant, T is temperature in °K, and C is a constant (Firestone 1982). In 1973, Bailey and Beauchamp determined that the optimum temperature for biological denitrification is in the range of 50 to 70°C. This rapid increase in denitrification at elevated soil temperatures suggests that thermophilic microorganisms play a major role in denitrification (Bailey and Beauchamp 1973). However, at very high temperatures (75°C<), denitrification is inhibited because of the denaturation of microbial proteins (Firestone 1982).

Several researchers have observed that the rate of biological denitrification slows as soil temperatures drop, with lower limits of between 2°C to 5°C typically reported (Bailey and

Beauchamp 1973; Christianson and Cho 1983; Christianson et al. 1990). However, Malhi et al. (1990a) reported slow, yet significant, rates of denitrification in saturated soils at temperatures as low as -4°C. Denitrification rates increased rapidly at soil temperatures greater then -4°C, with the greatest response between 4 and 10°C (Malhi et al. 1990a). Cho et al. (1979) found that in cool soils (<15°C), the temperature dependency of the reaction does not follow the Arrhenius relation, and that a linear rather than an exponential relationship exits between rate of denitrification and temperature. Bailey and Beauchamp (1973) determined that lowering the soil temperature to levels below 5°C decreased the production of N_2, increased the production of NO, and did not significantly affect N_2O production. The increased production of NO at low temperatures was attributed to chemical denitrification, a process that will be explored in further detail later in this paper.

Biological denitrification is also heavily dependant on soil pH. The optimal pH range for biological denitrification varies with species of microorganism and NO_3^- concentration, but most denitrifiers grow optimally at a soil pH of between 6 and 8 (Aulakh et al. 1992). Soil acidity can markedly influence denitrification, as the average rate of denitrification is much lower in acidic soils than in soils with a pH greater than 5 (Muller et al. 1980; Simek and Cooper 2002). Bremner and Shaw (in Tisdale et al. 1993) found dramatic increases in microbial denitrification as a result of increases in soil pH. The mechanism(s) for decreased biological denitrification under acidic conditions is unclear. It could be the direct effect of increased H^+ activity on the NO_3^- ions, or indirectly through nutrient deficiencies and/or toxicities such as the reduction in the availability of molybdenum (synthesis of NaR is facilitated by a molybdo-protein enzyme) (Aulakh et al. 1992). Although rates of biological denitrification are highest in slightly alkaline soils, denitrification can occur in soils with pH ranging from 3.5 to 4.0 and accounts for significant N losses in naturally acidic soils. Denitrification in acid soils is attributed to the selection of species of denitrifier bacteria that tolerate these low pH levels (Firestone 1982).

2.4.3.2 Chemical Denitrification: In addition to microbial denitrification, there are certain conditions in which losses of soil and fertilizer N can occur through chemical reactions involving NO_2^- (Tisdale et al. 1993). Unexplained N losses have been observed in studies looking at sources of NO and N_2O following wetting of dry soil (Davidson 1992) and at the production of gaseous N at temperatures below the lower limits of biological denitrification (2-5°C) (Bailey and Beauchamp 1973; Christianson and Cho 1983). Much of these unexplained N losses have been attributed to chemical denitrification. Chemical denitrification (or chemodenitrification), is defined as an abiotic (nonmicrobial) process by which organic N is oxidized by NO_2^- to gaseous forms of N (Christianson and Cho 1983), and is directly proportional to the concentration of NO_2^- in the soil. The accumulation of NO_2^- is not overly common in the soil, but when it does occur it has a negative impact on plants, microorganisms, and it provides another mechanism for gaseous N loss (Nelson 1982).

Several nonenzymatic pathways have been identified that lead to the production of N_2 and N_2O under fully aerobic conditions. In the Van Slyke reaction, NO_2^- reacts with soil organic matter to yield N_2 gas (amino groups located on the α position combine with $HNO_2 \rightarrow N_2$) (Nelson 1982). An example of a Van Slyke reaction is:

$$RNH_2 + HNO_2 \rightarrow ROH + H_2O + N_2$$

This is one possible reason that losses of N by chemical denitrification increase with increasing OM content. Under aerobic conditions in the soil, this reaction occurs at appreciable rates at pH levels of 5 or lower (Paul and Clark 1996). Other chemical reactions similar to the Van Slyke reaction involve NO_2^- reacting with NH_4, urea, methylamine, purines, or pyrimidines (Brady 1990). Under similar conditions, these reactions typically proceed more slowly than the Van Slyke reaction (Paul and Clark 1996):

$$2HNO_2 + CO(NH_2)_2 \rightarrow CO_2 + 3H_2O + 2N_2$$

There are three main factors that favour the accumulation of NO_2^- in agriculture soils: high pH, the use of ammonium yielding N fertilizers, and low soil temperatures.

Soil pH influences the amount of NO_2^- that accumulates in the soil, because of the reduced activity of *Nitrobacter* relative to *Nitrosomonas* under high soil pH conditions. Therefore, at pH greater than 7.5 the conversion of NH_4^+ to NO_2^- exceeds that of NO_2^- to NO_3^-. However, the form of NO_2^- that most often participates in chemical denitrification pathways is nitrous acid (HNO_2). HNO_2 is much more prevalent under acidic conditions and as a result, the majority of chemical denitrification reactions occur under acidic conditions (Nelson 1982). In a soil solution with a pH of 5, approximately 1.6% of the NO_2^--N is in the HNO_2 form; at pH values of 4 and 3 the proportion of NO_2-N in the HNO_2 form increases to 14 and 63% respectively (Nelson 1982). However, chemical denitrification can occur in all soils because the water films surrounding soil particles can be much more acidic than the bulk soil solution. This will increase the proportion of HNO_2 to NO_2^--N, and concentrations of HNO_2 near the soil surfaces may be much higher than would be expected by pH measurements in bulk soil (Nelson 1982).

Although ammonium based fertilizers can reduce the potential of biological denitrification, they can increase the potential of chemical denitrification, especially when the fertilizer is banded. Ammonium yielding fertilizers cause NH_4^+ and pH levels to temporarily increase, hindering the conversion of NO_2^- to NO_3^- (Tisdale et al. 1993). Low soil temperatures can keep these NO_2^- levels high over several days, encouraging chemical denitrification.

The final major regulator of chemical denitrification is low soil temperature, in particular the cycle of freezing and thawing. When the temperature of a soil drops below freezing, part of the soil water will be frozen to solid ice, but a portion will remain unfrozen. As the water freezes, salts are forced into a narrow unfrozen solution layer between the ice and the soil colloids (the salting out effect) (Christianson and Cho 1983). Temperatures marginally below 0°C increase the NO_2^- concentration in the unfrozen soil solution, which in turn increases the potential for the chemical denitrification of NO_2^-. The subsurface region beneath the ice layer accumulates N gases over the winter and in the spring, thawing of the frozen layer results in the release of these N gases to the atmosphere (Burton and Beauchamp 1994).

Both agricultural production and the environment are affected by biological and chemical denitrification. Agriculturally, the loss of soil and fertilizer N to the atmosphere is an economic loss to producers. On average, the efficiency of fall-applied fertilizer N is less than 50%, with estimates of between 10 to 30% of this loss being linked directly to denitrification (Aulakh et al.

1992). Environmentally, gaseous losses of nitrogen via denitrification pose a risk because N_2O contributes to global warming and the destruction of the ozone layer (Pennock et al. 1992). Increased understanding of the denitrification process will allow improved field management practices better suited to influence the proximal factors that directly contribute to the rate and magnitude of the denitrification of fertilizer N.

2.4 Fall Compared to Spring Applications of N fertilizers

In the northern Great Plains of North America, producers often apply nitrogen fertilizers in the fall rather than in the spring for spring-sown cereal and canola crops because of time and equipment limitations in the spring and lower fertilizer prices in the fall (Malhi et al. 1992b). While variations occur from place to place and year to year, numerous reviews have reported that the efficiency of fall-applied N in Western Canada is generally less effective than spring applications, especially when broadcast and incorporated (Harapiak 1979b; Nyborg and Leitch 1979; Racz 1979; Bole et al. 1984; Malhi et al. 1984; Ukrainetz 1984; Malhi et al. 1992b; Yadvinder-Singh et al. 1994; Malhi et al. 2001). For producers, a decrease in the efficiency of N fertilizers will affect both the agronomic and economic value of a fertilizer because of reduced crop production, increased energy costs and increasing environmental risk (Yadvinder-Singh et al. 1994).

In Manitoba, Ridley (1975; 1976; 1977) reported that the application of urea fertilizer, broadcast and incorporated in the fall was inferior to spring application, especially in the poorly drained region of the Red River Valley. However, Ridley's research provided little information about the influence of date of application, weather conditions, or landscape position on the efficiency of fall-banded N. In central and northern Alberta and Saskatchewan, Nyborg and Malhi (1986) conducted 44 experiments comparing yield and N uptake of spring sown barley and reported similar results to those in Manitoba, with fall broadcast and incorporated N producing significantly lower yields and N uptake than spring broadcast and incorporated applications at 40 of the 44 sites. In this study, overall yield increases and N uptake by the barley crop from fall broadcast and incorporated N were approximately half that for spring-applied trials (grain yield range 23-94%; crop N uptake range 19-93%). Similar results were observed in Saskatchewan, where Ukrainetz (1984) reported that, on average, spring applications of broadcast and incorporated N fertilizers produced larger crop yields than fall broadcast and incorporated applications (range of 69 to 91%). However, other researchers have reported that under certain conditions there is little yield difference between fall and spring-applied N. Results from experiments in south-central Alberta and southern Saskatchewan found that fall broadcast and incorporated N was equal (Harapiak 1979b) and even better (Harapiak and McCulley 1975) than spring broadcast and incorporated N, because the extra tillage operations in the spring negatively affected soil moisture. These contrary results are due to the large number of factors that affect the relative efficiency of fall versus spring-applied N. The performance of fall-applied N is heavily dependent on factors that are both unmanageable (soil and climatic zones, soil texture, and landscape position) and manageable (N rate, fertilizer placement, application date, and inhibitors) by the producer.

2.4.1 Soil and Climate Zones

The efficiency of fall-applied fertilizer N is highly dependent on soil and climatic conditions and is of greater concern in some areas and some years than others. High inputs of fertilizer N are required in those areas in which re-cropping of stubble land is extensive and where low levels of summerfallow are present. As a result, 85% of the potential market for N fertilizers under dryland farming conditions is concentrated within the Black, Dark Gray and Gray soil zones of the Canadian prairies, even though these soil zones account for only 55% of the cultivated acreage in Western Canada (Harapiak et al. 1993). In the Black, Dark Gray and Gray soil zones, weather and climate generally result in poorer efficiencies of fall-applied N than in the drier soil zones of Western Canada (Bole et al. 1984). In Alberta, laboratory and field studies determined that while soils from the various agro-climatic zones had similar potentials for denitrification losses under anaerobic conditions (Cho et al. 1979; Malhi et al. 1990b; Heaney et al. 1992), under field conditions the actual percent of over-winter losses of incorporated N via denitrification was highly variable (range 18 to 93%) and dependent primarily on soil-climatic conditions (Heaney et al. 1992). A good example of this occurred in 1975 when grain yield responses from fall broadcast and incorporated N were 111% that of spring broadcast and incorporated fertilizer N in south-eastern Saskatchewan, but only 60% as effective in central Alberta (Harapiak and McCulley 1975). In general, the Brown and Dark Brown soil zones of Western Canada respond better to fall applications of N fertilizers than the Black and Luvisolic soil zones, because the Brown and Dark Brown soil zones are relatively dry and soils seldom become water saturated, even during the spring thaw (Bole et al. 1984; Malhi et al. 1992b).

2.4.2 Soil Texture

Within each soil climatic zone, soil texture is another factor that will affect the efficiency and losses of nitrogen fertilizers. Fine textured soils, such as clays, have a greater potential for denitrification losses of NO_3^- than coarse textured soils, because the slow infiltration rates in the former soils can create prolonged saturated conditions (Dobbie and Smith 2001). In Alberta, sites were separated by texture, drainage and wetness of soil in the fall to determine the effect that soil conditions had on the relative efficiency of fall-applied N. Sites that were imperfectly drained and had soil moisture above field capacity in the fall had lower relative efficiencies of grain yield and N recovery than sites with good to moderate drainage, and soil moisture below field capacity in the fall (Malhi et al. 1992b). Corre et al. (1996) observed that at the regional scale in Western Canada, sandy soils generally had lower N_2O emissions than did fine-textured soils. In Michigan, annual denitrification rates were found to increase in the order of clay loam>loam>sand and poorly-drained>somewhat poorly drained>well-drained clay loams and loams (Groffman and Tiedje 1989a). In Manitoba, Ridley (1975) reported that in the imperfectly drained soils of the Manitoba lowlands, average yield increases of barley over nine sites resulted in fall broadcast and incorporated urea-N being only 64% as efficient as spring-broadcast and incorporated N. In the better-drained soils of the Manitoba uplands (13 sites), differences in yield increases between fall and spring broadcast and incorporated N were smaller, with fall-applied urea being 87% that of spring-applied over 13 sites. Results similar to Ridley (1975) were reported in southwest Manitoba, where Grant et al. (2001) found that overall, fall-banded N was slightly less effective on a clay loam soil than on a fine sandy loam soil.

2.4.3 Landscape Position

Landscape position is another major factor that will influence the efficiency of fall-applied N. Although yields can vary dramatically within a field, producers normally manage fields as a single unit, applying similar inputs and management practices across all slopes and aspects (Fiez et al. 1994). In regions of semi-arid climate and hummocky terrain, grain yields often increase with convergent character in the landscape (Manning et al. 2001b). This is due in part to thin A horizons on the eroded knolls (yields generally increase with increasing solum thickness) (Moulin et al. 1994) and increased soil moisture, nitrate, phosphate, potassium and sulphate in the lower areas of the field (Manning et al. 2001a). Even in landscapes with very little topographic relief, such as the Red River Valley region of Manitoba (typically <0.5 to 1m km^{-1}), Durand (2002) found that relatively small differences in elevation played a large role in determining yield potential and response to spring broadcast N fertilizer. However, yield responses in this sub-humid region with its nearly level landscape were opposite to those typically found under semi-arid hummocky conditions, with the greatest wheat yields observed at the higher relative elevations (Durand 2002). Part of the reason for the poor yield response in these depressional areas is due to the direct suppression of crop growth by excess water.

Durand (2002) also reported that concentrations of soil NO_3^--N in the spring were consistently lower in the microlow than the more elevated microhigh positions, results similar to other field studies located in the same Red River Valley of Minnesota (Hollands 1996; Franzen et al. 1997). Numerous authors have suggested reasons for the landscape differences in soil NO_3^--N concentrations. After heavy rains or during the early spring, significant ponding of waters can occur in the lower convergent areas of the field (Hanna et al. 1982). In Saskatchewan, Pennock et al. (1992) reported that denitrification activity on a gently sloping landscape displayed a distinct landscape-scale pattern, with denitrification rates higher in the level concave areas of the landscape (max. 20 kg N ha^{-1} day^{-1}) than in the level convex areas (max. 13.2 kg N ha^{-1} day^{-1}). At the landscape scale, the soil variables that were the most highly correlated with denitrification activity were high volumetric water content ($r = 0.45^{**}$) and low soil redox potential ($r = -0.34^{**}$), variables that reflect the aeration status of the soil. Numerous other studies from Saskatchewan have reported similar findings to Pennock et al. (1992), with higher denitrification rates in the wetter convergent footslopes and low level complexes than in the better-drained upper slope positions in both gently sloping (Sutherland et al. 1993; van Kessel et al. 1993; Farrell et al. 1996) and hummocky terrain (Aulakh and Rennie 1984; Elliot and de Jong 1992; Corre et al. 1996), with denitrification losses greater under zero-till (Aulakh and Rennie 1985) and fallow (Elliot and de Jong 1992) than conventionally cropped soils.

Although denitrification activity is influenced by topography, the intensity and distribution of water in the hillslope system is of greatest importance (Pennock et al. 1992). Farrell et al. (1996) reported that denitrification rates were the highest in areas of the landscape where water accumulation was at a maximum. The intensity and distribution of water in the system, is further influenced by temporal variability in soil moisture due to seasonal climatic patterns and daily weather conditions, with greatest denitrification activity reported in the low lying footslope complexes in the spring and fall (Groffman and Tiedje 1989b) and after precipitation events (van Kessel et al. 1993; Corre et al. 1995; Corre et al. 1996). Denitrification rates were also reported to increase sharply in convergent landscape positions after the application of fertilizer N and a combination of warm soil temperatures and adequate rainfall (van Kessel et al. 1993). This suggests that there is potential for ammoniacal fertilizers that have converted to nitrate to be lost via denitrification during the fall prior to the soil freezing. The effects of landscape position on fall-applied N are likely to be the most significant during the early spring period when prolonged ponding of snowmelt waters occurs. However, no experiments have focused on the impact of landscape position on the loss of fall-banded N under Western Canadian conditions.

In conjunction with these unmanageable factors, the performance of fall-applied N is also dependant on factors that can be influenced directly by the producer. In the majority of the previously mentioned studies examining fall versus spring applications of urea fertilizer, the urea fertilizer was broadcast and incorporated into the soil. Unfortunately, this is one of the least effective ways to apply N fertilizer in the fall in Western Canada. During the past 15 to 20 years, researchers have looked at various management techniques available to producers to increase the efficiency of fall-applied N, including N fertilizer rate, fertilizer placement, timing of fertilizer application and the use of additives to slow the conversion of fertilizer N into the nitrate form that is susceptible to denitrification losses from the soil system.

2.4.4 Nitrogen Fertilization Rate

Malhi and Nyborg (1992a) found that as the rate of applied nitrogen fertilizer increased from 25 to 100 kg N ha^{-1}, the efficiency of fall-applied N relative to spring increased from 47 to 73% in terms of yield, and from 42 to 69% for total N uptake in the crop. These results were similar to those from earlier studies in the United States, where differences in corn yields from fall and spring applications of fertilizer N were reduced at higher application rates (Stevenson and Baldwin 1969; Frye 1977). However, it should be noted that higher N rates do not reduce over-winter losses, rather they mask the differences between fall and spring-applied N (Malhi and Nyborg 1992a). The use of higher rates of N fertilizer to compensate for over-winter losses from fall-applied N is an option for the producer, but in the long-term, it is neither an economically nor an environmentally sound practice.

2.4.5 Fertilizer Placement

In comparison to broadcast and incorporation, placing fertilizer N in sub-surface bands or nests has consistently improved the efficiency of fall-applied fertilizers in Western Canada (Ridley 1976; Ridley 1977; Harapiak 1979b; Harapiak 1979a; Racz 1979; Bole et al. 1984; Carter and Rennie 1984; Malhi and Nyborg 1984; Malhi et al. 1984; Ukrainetz 1984; Malhi and Nyborg 1985; Malhi et al. 1989; Malhi and Nyborg 1990b; Malhi and Nyborg 1991; Malhi et al. 1992a; Malhi and Nyborg 1992b; Malhi et al. 1992b; Nyborg and Malhi 1992; Harapiak et al. 1993; Malhi et al. 1996; Malhi et al. 2001). On average, the efficiency of fall-banded urea is 20% higher than that from fall broadcast and incorporated urea, with some yield increases from fall-banded applications being double those from fall broadcast applications (Malhi et al. 1992b). Banding or nesting of fall-applied N reduces the exposure of the fertilizer to the soil (low surface to mass ratio), and the high pH, ammonia concentration and osmotic pressures found within the fertilizer band create a toxic environment for soil microorganisms (Harapiak et al. 1993). Placing fertilizer N in bands also reduces volatilization losses, lowers the risk of immobilization, and slows the rate of nitrification of fertilizer N to NO_3^- in the fall, which reduces the amount of N that is potentially lost in the spring through leaching and/or denitrification (Yadvinder-Singh et al. 1994).

Numerous studies have reported that the percent of fall-applied fertilizer N recovered as NH_4^+-N increased significantly by banding or nesting, compared to broadcasting, especially in soil zones where moisture supply was relatively high (i.e. Black, Dark Gray and Gray) (Malhi and Nyborg 1979; Malhi and Nyborg 1984; Monreal et al. 1986; Malhi and Nyborg 1988a; Yadvinder-Singh et al. 1994; Malhi et al. 2001). The higher percentage of soil NH_4^+-N in the fall translated into reduced over-winter losses of NO_3^- and increased grain yields and total crop N uptake similar to those from spring-broadcast N. However, overall yields and N uptake in these studies were less than those of spring-banded N.

The efficiency of fall-banded N fertilizer compared to spring banding is generally poorest under wet soil conditions and highest under dry conditions during the fall and spring. For example, recent work in south-western Manitoba reported no differences in durum wheat grain yield and total crop N uptake between fall and spring-banded N in two of three years on a clay loam soil, and in all three years on a drier fine sandy loam (Grant et al. 2001). Results similar to Grant et al. (2001) have been reported in the drier soil zones of Western Canada (Bole et al. 1984; Kucey 1986; Kucey and Schaalje 1986; Malhi et al. 1992b; Malhi et al. 2001), and when soil moisture contents in the fall and spring are low (Harapiak 1979b; Ukrainetz 1984).

2.4.6 Date of Fall Application

The timing of fertilizer application is one of the more practical and cost effective tools that producers can use to improve the efficiency of fall-applied N. The proper timing of fertilizer application helps to reduce the over-winter losses of fertilizer N and has enormous implications toward farm profitability and environmental sustainability (Cowell and Doyle 1993). Early in the fall, soil temperatures can remain quite warm and application of ammoniacal fertilizers is expected to form more nitrate prior to the soil freezing than for late fall applications (Malhi and Nyborg 1979; Malhi and McGill 1982). As a result, early fall applications generally have more over-winter/early spring losses than fertilizer applied late in the fall (Nyborg et al. 1990; Nyborg et al. 1997). Current guidelines in Manitoba recommend that producers delay application in the fall until soil temperatures have cooled to 5°C (MB Agriculture and Food Soil Fertility Guide 2001). At 5°C, the rate of nitrification is expected to be half that at 16°C, and a quarter of the rate at 27°C (Chandra 1962).

One of the difficulties faced by producers in the relatively humid region of southern Manitoba is that heavy rains frequently occur in the fall making field operations difficult. For this reason, producers in this region of Manitoba are interested in applying N fertilizer as soon as possible after harvest, while soil conditions are still favourable. However, the severity of over-winter losses of fall-applied fertilizer is further enhanced if heavy rains occur in the fall, especially when N fertilizers are applied early in the season (Malhi and Nyborg 1983a). These producers must weigh the risk of missing the window of opportunity to work on the fields in the fall with the increased probability of N losses and lower fertilizer efficiencies.

Previous research in Alberta has confirmed that late fall applications of broadcast and incorporated urea-N fertilizers produce higher crop yields, increased crop N uptake, and lower losses of N than early fall applications (Malhi et al. 1984; Ukrainetz 1984; Malhi and Nyborg 1990a; Nyborg et al. 1990). For example, the NUE of fall-applied fertilizer N (broadcast and incorporated) relative to spring-applied, increased from 30% with urea applied in late September to 70% when urea was applied in late October (Malhi et al. 1984). In another study from the same region of Alberta, delaying the application date of broadcast and incorporated urea from early October, to mid October and early November gave yield increases that were 46, 60 and 66% of spring-applied urea respectively (Monreal 1981 *in* Nyborg et al. 1990). In subsequent studies, Malhi and Nyborg (1990a) reported that the recovery of fall-applied urea (broadcast and incorporated) as soil mineral N in the spring increased from 30% when N was applied on September 19th to 76% on November 6th, with yield increases from fall relative to spring broadcast urea ranging from 23% on September 10th to 76% on November 6th. In the same study, Malhi and Nyborg (1990a) used four linear regression analyses to predict grain yield increases and NUE from fall broadcast and incorporated N fertilizer, relative to spring application. These regression analyses included date of application, soil temperature on the day of fertilizer application, the number of days from application to the first day of 0°C, and soil degree days accumulated from application to first day of 0°C. Date of fall application and soil temperature on the day of N application resulted in the lowest correlations between grain yield increases from fall and spring-applied N (r values of 0.68 and 0.55 respectively). The authors concluded that the "low" correlations were due to high day-to-day variability in soil temperature during the fall, instead of a smooth decline towards 0°C. The correlations were improved after using the number of days until the first day of 0°C date and total soil degree-days from application to soil freezing (r values of 0.77 and 0.78 respectively). In central Iowa, Gomes and Loynachan (1984) used the accumulation of soil heat units to explain much of the variability of recovered NH_4^+-N from anhydrous ammonia applied at three different times in the fall (Oct. 9, Oct. 27, and Nov. 14). A highly significant linear relationship ($R^2 = 0.84$) was found between the percentage of NH_4^+-N recovered in the bandrow and total accumulation of heat units over the fall and early spring, suggesting that producers who band fertilizer N in the fall, even after the soil temperature has reached a given level (in this case 10°C), must also consider the date of application and the overall length of time that the fertilizer will be in the soil (Gomes and Loynachan 1984).

Malhi and Nyborg (1990a) mention that N fertilizer applied in the fall in either sub-surface bands or nests may be less sensitive to earlier application dates and/or higher soil temperature at time of application. Other work by Malhi et al. (1989) and Nyborg et al. (1990) reported no significant differences in the percent recovery of N^{15} in the crop or soil when the application of banded urea application was delayed from mid to late October. However, in Ontario, grain yields and N uptake of winter wheat were improved by delaying the application of large urea granules in the fall (Yadvinder-Singh and Beauchamp 1988b; Yadvinder-Singh et al. 1994). As a result, Malhi et al. (1992a) reported in their review of published and unpublished fall-banded N studies that grain yield increases from fall-banded urea, relative to spring-banded, were likely to double when N applications were delayed from late September to late October.

2.4.7 Fertilizer Additives

Additives such as urease inhibitors, nitrification inhibitors and physical coatings have been used in research trials to keep ammoniacal fertilizers such as urea from converting into nitrate. If nitrogen losses are proportional to the formation of NO_3^-, it is expected that the use of additives that inhibit the transformations of nitrogen should increase the efficiency of fertilizer N by reducing leaching and denitrification losses. From an agronomic point of view, additives must maintain N in a form, or slowly release N to a form, that is readily available to the plant

(Yeomans 1991). Inhibitors should: be non-toxic to other beneficial soil organisms, enzymes, higher plants, animals or humans; be safe and easy to apply; remain stable in storage (not susceptible to decomposition by air, light, or water prior to application); maintain inhibitory action for periods ranging from several weeks to months after fertilizer application; move with the fertilizer to ensure proper dispersal; and provide sufficient long term benefits to justify the added costs to the producer (Yeomans 1991; Grant 1998; Havlin et al. 1999).

2.4.7.1 Urease inhibitors. The goal of a urease inhibitor is to delay the immediate conversion of the urea molecule to ammonia over a wide range of soil conditions (Yeomans 1991; Malhi et al. 2001). Urease inhibitors slow the hydrolysis of urea-N in one of two ways: by affecting the metabolism of urease producing soil microorganisms (antimetabolites) or through direct interference with the activity of the urease enzyme (Yeomans 1991). In 1977, Mulvaney and Bremner evaluated three antimetabolites patented as inhibitors of urea hydrolysis. These chemicals, designed to inhibit the metabolic activity of soil microorganisms, had no effect on the production of urease in the soil or the hydrolysis of urea or in reducing gaseous losses of urea N as ammonia, even at rates exceeding recommendations (Mulvaney and Bremner 1977). Since then, most research on the inhibition of urea hydrolysis has focussed on developing compounds that directly inhibit the activity of soil urease. One of the more promising urease inhibitors is N-(n-butyl) thiophosphoric triamide (NBPT). NBPT does not directly affect the size and activity of the soil microbial biomass (Banerjee et al. 1999); rather, it inhibits urease activity by competing with urea for active sites on the urease enzyme complex (NBPT and urea are structurally similar) (Rawluk et al. 2001). In Manitoba, spring and summer applications for N fertilizer with NBPT slowed volatilization losses of urea fertilizer for 4 to 7 days after time of application, with the effectiveness of NBPT decreasing with time (Grant 1998). NBPT is more effective over a wider range of soil pH than most other urease inhibitors, allowing for increased diffusion from the placement zone (Watson et al. 1994). The ability to improve diffusion of ammonium-N away from this zone of high pH is a significant factor in the effectiveness of urea inhibitors and could be more important than simply slowing the hydrolysis of urea (Christianson et al. 1993).

In Western Canada, few studies have investigated the use of NBPT to improve the efficiency of fall-banded N fertilizers. Studies over three years on two soils (fine sandy loam and clay loam) near Brandon compared broadcast, banded (fall and pre-plant) and seed-placed urea with and without NBPT under zero and conventional tillage (Grant 1998). Under conventional tillage at both sites, there were generally no crop benefits to using NBPT when the urea was banded in either the fall or spring, because volatile losses were minimal. However, under zero-tillage NBPT increased crop yields from fall-banded urea on the clay loam soil. Where NBPT shows the most promise in crop production is in situations where urea fertilizer is surface applied and/or placed at high rates with the seed (Christianson et al. 1993; Xiaobin et al. 1995; Grant et al. 1996; Malhi et al. 2001; Rawluk et al. 2001). Nonetheless, NBPT has been reported to inhibit the urease enzyme for up to 7 days (Grant and Rawluk 2002), and if used in conjunction with a nitrification inhibitor, the combination should slow the transformation of fall-banded urea compared to either inhibitor alone.

2.4.7.2 Nitrification inhibitors. Numerous nitrification inhibitors have been tested in the past 20 years for their ability to temporarily inhibit the nitrification of fall-applied fertilizer N in the soil in the hopes of improving crop growth, yields and quality. In Western Canada, an effective nitrification inhibitor would be most beneficial to fall-banded N if it could maintain the fertilizer N in the NH_4^+ form until after the soil has thawed and dried in the spring (Malhi and Nyborg 1984), reducing over-winter losses of nitrate and increasing crop yields (Malhi and Nyborg 1985). In Alberta, thiourea, ATC, N-Serve, CS_2, $(NH_4)_2CS_3$, and K_2CS_3 were tested with fall-applied urea and/or aqueous NH_3 in Alberta (Malhi and Nyborg 1983b; Malhi and Nyborg 1984; Malhi and Nyborg 1988b; Malhi and Nyborg 1988a; Malhi et al. 1992b). These inhibitors were effective in slowing nitrification and reducing over-winter N losses of fall-applied fertilizers, especially when the N fertilizer plus inhibitor were banded or nested. However, overall results from these studies were highly variable and crop yields were increased only in situations where conditions for denitrification in the spring were severe. In Virginia, Scharf and Alley (1995) tested five potential nitrification inhibitors (APP, ATS, DCD, MAP, KCl), but none of these five inhibitors increased yield or N uptake of winter wheat despite excellent conditions for N loss. The authors concluded that it was more economical to either delay application or apply a small amount of additional N than to use an inhibitor. (Ashworth and Rodgers 1981). However, in Ontario, fall-applied large urea granules containing low rates of DCD slowed nitrification, reduced over-winter N losses, and improved yield and N uptake of winter wheat (Yadvinder-Singh and Beauchamp 1988b; Yadvinder-Singh et al. 1994). In the U.S., fall-applied urea with DCD improved yields and N uptake of no-till winter wheat in the midwest (Rao 1996; Rao and Popham 1999).

Of the commercially available compounds, the most widely used nitrification inhibitor in agronomic studies has been nitrapyrin (N-Serve) (Yadvinder-Singh et al. 1994). Nitrapyrin was effective in slowing nitrification in the fall and increasing the amount of soil mineral N in the spring in Iowa (Gomes and Loynachan 1984), Alberta (Malhi and Nyborg 1988b; Malhi and Nyborg 1988a; Malhi et al. 1992b), Saskatchewan (Aulakh and Rennie 1984) and South Dakota (Goos and Johnson 1999), but not in Manitoba where limited work at three sites, during two relatively dry years, indicated that the addition of nitrapyrin with urea in bands had little effect on the recovery of applied urea N or on crop yields (Ridley 1977). One of the problems with nitrapyrin is that it has a high vapour pressure. This means that it cannot be used with granular fertilizers, such as urea, because the inhibitor would be lost during processing, storage and handling (Yeomans 1991). To this end, there has been renewed interest in the use of the nitrification inhibitor Dicyandiamide (Didin or DCD). DCD is less volatile than nitrapyrin and can be easily blended with solid N fertilizers (Guiraud and Marol 1992).

DCD is a nonvolatile, non-toxic substance containing about 65% N that specifically affects the *nitrosomonas* bacteria (inhibiting the first stage of nitrification, the oxidation of NH_4^+ to NO_2^-), but does not affect other heterotrophic soil microorganisms (Amberger 1989). Amberger (1989) determined that the inhibiting effects of DCD were dependent on temperature, moisture content, organic matter content and pH, and persisted an average of one to three months. As with other nitrification inhibitors, the effectiveness of DCD decreases rapidly with increasing temperatures above 20°C (Guiraud and Marol 1992). DCD has a half-life of approximately 50 days at 8°C, decreasing to 7 to14 days at 22°C (Bronson et al. 1989). In laboratory experiments, DCD was effective in reducing the nitrification rate of 0.02 g (commercial sized), 2 and 3 g urea granules at relatively low temperatures (5, 10 and 15°C) (Yadvinder-Singh and Beauchamp 1987) and across a range of soil water potentials (-35, -60 and –120 kPa) (Yadvinder-Singh and Beauchamp 1988a). Under field conditions in the north-central United States, the effectiveness of DCD in retarding the nitrification of urea was most effective on coarse-textured soils, under conditions that were conducive to NO_3^- losses, and when N rates were not in excess of crop requirements (Malzer et al. 1989). At Rothamsted in England, DCD was as effective as nitrapyrin in slowing the over-winter nitrification of injected aqueous urea applied late in the fall, when soil temperatures were below 5°C (Ashworth and Rodgers 1981).

A concern in using nitrification inhibitors is that by slowing nitrification, there is an increased risk of volatilization losses and microbial immobilization of the urea fertilizer. However, Clay et al. (1990) found that volatilization of NH_3 from broadcast and incorporated urea did not increase when urea was treated with DCD and that volatilization was further reduced when urea was treated with a mixture of DCD and NBPT. In France, adding DCD to ammonium sulphate increased the incorporation of mineral N in a form that could not be extracted with 2M KCl, as immobilized N was found mainly in amino acids in the NH_4^+ form (Guiraud et al. 1992). In south-central Alabama, Bronson et al. (1991) compared fall-applied ^{15}N-labelled urea (broadcast-incorporated) with and without DCD, and found that in the first year of the study, overall winter wheat yield and N recovery was not affected by DCD treatment; however, immobilization of the ^{15}N increased, leached N at harvest was reduced and denitrification was unaffected when fall-applied urea was applied with instead of without DCD. In the second year of the study, the recovery of ^{15}N in the crop was significantly higher for the fall-applied N with the DCD treatment than fall-applied N without DCD (Bronson et al. 1991). The authors concluded that nitrification inhibitors could affect the N uptake of a second-year crop by enhancing biological immobilization of fertilizer N in the first year following application.

DCD has also been reported to affect NO and N_2O emissions. DCD was reported to significantly decrease the number of denitrifiers in a manure slurry (Yeomans 1991), and DCD amended urea reduced the total N_2O flux over the entire growing period of a wheat crop in China (Xu et al. 2000). Xu et al. (2000) also report that when DCD was combined with hydroquinone, a urease inhibitor, this combination significantly reduced the gaseous N losses, compared to either of the inhibitors alone. However, while DCD eliminated 93% of NO and N_2O emissions produced by nitrification, it did little to reduce N_2O emissions from the soil that occurred under saturated conditions (Skiba et al. 1993).

The effectiveness of a double inhibitor containing both NBPT and DCD has not been investigated in fall-banding trials, using spring wheat, under Western Canadian conditions.

2.4.7.3 Economics of Using Inhibitors. The adoption and use of N inhibitors by Western Canadian farmers has been met with much resistance because N inhibitors are an added expense for both the manufacturer and the producer. The release of N from the inhibited fertilizer is also difficult to synchronize with the uptake by the plant. In the end, economics will most likely determine whether slow-release fertilizers remain restricted to a few specialty crops or whether they will find wide agricultural acceptance (Yadvinder-Singh et al. 1994). As Yeomans (1991) mentions, "it is necessary for an economic evaluation of urease and nitrification inhibitors, against other strategies that improve fertilizer N use, to be completed before the potential of these additives will be realized."

Perhaps in combination with other management techniques, fertilizer additives may become more economical to producers in Western Canada. The combined use of inhibitors and banding or nesting techniques should help in achieving maximum inhibition under a wide range of soil and climatic conditions (Malhi and Nyborg 1984). Such application techniques would also reduce the cost of the inhibitor because less chemical is needed (Yadvinder-Singh et al. 1994). In summary, although inhibitors should not be seen as a substitute for poor fertilizer management, they augment the management alternatives available to producers where the frequency and magnitude of N losses are moderate to high.

2.5 Summary

In the Prairie Provinces of Canada, producers often apply nitrogen (N) fertilizers in the fall for spring-sown crops in order to spread their workload, reduce spring tillage operations and capitalize on lower fertilizer prices (Malhi et al. 1992a). Southern Manitoba historically receives fall rains that make fieldwork difficult and producers are interested in applying N fertilizer as soon as possible after harvest, while soil conditions are still favourable. However, application of ammoniacal fertilizers in the early fall allows formation of more nitrate prior to the soil freezing (Malhi and Nyborg 1979; Malhi and McGill 1982) increasing the potential for over-winter and early spring losses of NO_3^- via leaching and denitrification (Nyborg et al. 1990; Nyborg et al. 1997).

Proper timing of fertilizer application can greatly improve the efficiency of fall-applied N and have enormous implications toward farm profitability and environmental sustainability (Cowell and Doyle 1993). While variations occur from place to place and year to year, numerous reviews have reported that in general the efficiency of fall broadcast and incorporated N in Western Canada is less effective than spring applications (Harapiak 1979b; Nyborg and Leitch 1979; Racz 1979; Bole et al. 1984; Malhi et al. 1984; Ukrainetz 1984; Malhi et al. 1992b; Yadvinder-Singh et al. 1994; Malhi et al. 2001). Further studies in Western Canada comparing various application dates in the fall determined that late fall-applied N (broadcast and incorporated) generally produces higher crop yields, greater crop N uptake and reduces over-winter losses when compared to early fall applications (Malhi and Nyborg 1990a). In Manitoba, fall broadcast and incorporated urea was also reported to be inferior to spring applications, especially in the poorly drained heavy clay soils of the Red River valley (Ridley 1975; Ridley 1976; Ridley 1977). However, Ridley's research provided little information about the influence of date of application, landscape position or weather conditions on the efficiency of fall-banded N.

The performance of fall-applied N is also heavily dependant on application techniques such as broadcasting, banding or nesting of fertilizers. In Western Canada, applying nitrogen in bands or nests has consistently improved the efficiency of fall-applied fertilizers, with average yield increases from fall-banded urea double that of fall broadcast and incorporated urea (Ridley 1977; Racz 1979; Malhi et al. 1984; Malhi and Nyborg 1985; Malhi et al. 1992b). However, in these studies grain yields and N uptake from fall-banded N were still, on average, lower than spring-banded N. Recent work in south-western Manitoba reported no differences in grain yield and total crop N uptake between fall and spring-banded N in 2 of 3 years on a clay loam soil, and in all 3 years on a drier fine sandy loam (Grant et al. 2001). Results similar to Grant et al. (2001) have been reported in the drier soil zones of Western Canada (Bole et al. 1984; Malhi et al.

1992b), and when soil moisture contents in the fall and spring are low (Harapiak 1979b; Malhi et al. 1984; Ukrainetz 1984; Malhi et al. 1992b).

Landscape position is another factor that will influence the loss and recovery of fall-applied N. After heavy rains or during the early spring, significant ponding of waters can occur in the lower convergent areas of the field, conditions ideal for biological denitrification (Hanna et al. 1982). In the Red River Valley of Minnesota and Manitoba, spring soil NO_3-N levels were consistently lower in the depressions than in the more elevated microhigh positions (Hollands 1996; Franzen et al. 1997; Durand 2002). In Saskatchewan, Pennock et al. (1992) reported that denitrification activity under a gently sloping landscape displayed a distinct landscape-scale pattern, with denitrification rates higher in the level concave areas of the landscape than in the level convex areas. Other studies from Saskatchewan have reported similar findings, with consistently higher denitrification rates in the wetter convergent footslopes and low level complexes than in the better-drained upper slope positions under both gently sloping (van Kessel et al. 1993; Farrell et al. 1996) and hummocky terrain (Aulakh and Rennie 1984; Elliot and de Jong 1992; Corre et al. 1996). However, no experiments have focused on the impact of landscape position on the loss of fall-banded N under Western Canadian conditions.

Additives such as urease inhibitors, nitrification inhibitors and coatings have been used in research trials to suppress the rate that ammoniacal fertilizers are converted into nitrate, in the hopes of reducing denitrification losses. The goal of any urease inhibitor is to delay the immediate conversion of the urea molecule to ammonia over a wide range of soil conditions (Yeomans 1991; Malhi et al. 2001). One of the more promising urease inhibitors is N-(n-butyl) thiophosphoric triamide (NBPT). NBPT does not directly affect the size and activity of the soil microbial biomass (Banerjee et al. 1999), rather it inhibits urease activity by competing with urea for active sites on the urease enzyme complex (Rawluk et al. 2001). However, in Western Canada, few studies have investigated the use of NBPT to improve the efficiency of fall-banded N fertilizers. Limited work in southwest Manitoba indicated that there was generally no crop benefit to using NBPT when the urea was banded in either the fall or spring under conventional tillage, because volatile losses were minimal (Grant 1998). However, under zero-tillage NBPT did increase crop yields from fall-banded urea at one of two sites.

Malhi and Nyborg (1988b; 1988a) tested numerous nitrification inhibitors (thiourea, ATC, N-Serve 24E) and found that all were effective in reducing the rate of nitrification and the over-winter losses of fall applied N. Dicyandiamide (Didin or DCD) is a promising nitrification inhibitor that has received renewed interest of late. DCD is less volatile than other nitrification inhibitors (i.e. nitrapyrin) and can be easily blended with solid N fertilizers (Guiraud and Marol 1992). Although DCD has been reported to be phytotoxic to plants (Amberger 1989), DCD applied in the fall is unlikely to damage a crop grown the following year. In England, DCD was as effective as nitrapyrin in slowing the over-winter nitrification of injected aqueous urea applied late in the fall, when soil temperatures were below 5°C (Ashworth and Rodgers 1981). Fall-applied large urea granules containing low rates of DCD slowed nitrification, reduced over-winter N losses, and improved yield and N uptake of winter wheat in Ontario (Yadvinder-Singh and Beauchamp 1988b; Yadvinder-Singh et al. 1994). However, the effectiveness of a double inhibitor containing NBPT and dicyandiamide DCD in slowing the conversion of urea to nitrate has not been investigated in fall banding trials in Western Canada.

3 EFFICIENCY OF FALL-BANDED UREA FOR SPRING WHEAT PRODUCTION IN MANITOBA: INFLUENCE OF APPLICATION DATE, LANDSCAPE POSITION AND FERTILIZER ADDITIVES

Key Words: fall-banded N, spring-banded N, landscape position, inhibitors, N-(n-butyl) thiophosphoric triamide (NBPT), Dicyandiamide (DCD), spring wheat (*Triticum aestivum*), urea fertilizer

3.1 Abstract

A two-year study was conducted to investigate the effects of application date, landscape position and a urease and nitrification inhibited formulation of urea on the efficiency of fall-banded nitrogen (N) fertilizer under Manitoba conditions. At the satellite sites, soil conditions in year one were generally wet during the late fall and early spring, increasing the risk of over-winter losses of fall-banded N and reduced overall efficiency of fall-banded N. In the second year of the project, soil conditions were drier and crop responses to fall and spring application dates were similar. At the intensive sites, the effects of landscape position were apparent at three of the four sites, with significantly greater grain yields, straw yields and total recovery of N in the high landscape positions than in the low landscape positions. Among fertilization treatments, there were no significant differences in crop response within the high landscape positions. However, in the low landscape positions, grain yields and grain yield increases were significantly greater for spring and late fall applications, when compared to early and mid fall applications. In the first year of the study, early fall-banded N with the urease and nitrification inhibitors produced greater increases in grain yield than early fall-banded N without the

inhibitors in the low landscape positions. However, overall there was little apparent crop benefit to the use of the urease and nitrification inhibitors, as there were few significant differences in crop yields or N uptake by the crop with the inhibitors than without, in either year or landscape position.

3.2 Introduction

To spread their workload, reduce spring tillage operations, and capitalize on lower fertilizer prices, many producers in Manitoba prefer to apply nitrogen (N) fertilizer in the fall rather than in spring. Southern Manitoba historically receives fall rains that make fieldwork difficult and producers are interested in applying N fertilizer as soon as possible after harvest, while soil conditions are still favourable. Application of ammoniacal fertilizers in the early fall allows formation of more nitrate prior to the soil freezing (Malhi and Nyborg 1979; Malhi and McGill 1982) and more over-winter/early spring losses than late fall applications (Nyborg et al. 1990; Nyborg et al. 1997). Therefore, Manitoba Agriculture and Food currently recommends that applications of fall-banded N fertilizers be delayed until soil temperatures are below 5°C (MB Agriculture and Food Soil Fertility Guide 2001). However, in delaying application there is the increased risk of the producer being caught by an early freeze-up, making field operations impossible.

Proper timing of application can greatly improve the efficiency of fall-applied N fertilizers and have enormous implications toward farm profitability and environmental sustainability (Cowell and Doyle 1993). While variations occur from place to place and year to year, numerous reviews have reported that the efficiency of fall-applied N in Western Canada is generally less effective than spring applications, especially when the N is broadcast (Harapiak 1979b; Nyborg and Leitch 1979; Racz 1979; Bole et al. 1984; Malhi et al. 1984; Ukrainetz 1984; Malhi et al. 1992b; Malhi et al. 2001). After reviewing 44 experiments comparing fall and spring broadcast and incorporated N fertilizers in Alberta and Saskatchewan, Nyborg and Malhi (1986) reported that overall yield increases and N uptake of barley grain from fall-applied N, broadcast and incorporated, were half as effective as spring-applied N. Further studies in Western Canada have determined that delaying application of broadcast and incorporated fertilizer N in the fall until late October generally produces higher crop yields, greater crop N uptake and reduces over-winter losses when compared to early fall applications (Malhi and Nyborg 1990a). In Manitoba, fall broadcast and incorporated urea was also inferior to spring applications, especially in the poorly drained heavy clay soils of the Red River valley (Ridley 1975; Ridley 1976; Ridley 1977). However, Ridley's research provided little information about the influence of date of application, landscape position, or weather conditions on the efficiency of fall-banded N.

In comparison to broadcast and incorporation, placing fertilizer N in sub-surface bands or nests has consistently improved the efficiency of fall-applied fertilizers in Western Canada (Ridley 1976; Ridley 1977; Harapiak 1979b; Harapiak 1979a; Racz 1979; Bole et al. 1984; Carter and Rennie 1984; Malhi and Nyborg 1984; Malhi et al. 1984; Ukrainetz 1984; Malhi and Nyborg 1985; Malhi et al. 1989; Malhi and Nyborg 1990b; Malhi and Nyborg 1991; Malhi et al. 1992a; Malhi et al. 1992b; Nyborg and Malhi 1992; Harapiak et al. 1993; Malhi et al. 1996; Malhi et al. 2001). On average, the efficiency of fall-banded urea is 20% higher than that of fall broadcast and incorporated urea, with yield increases from fall-banded applications often double those of fall broadcast applications (Malhi et al. 1992b). Banding or nesting of nitrogen reduces the exposure of the fertilizer to the soil; and the high pH, ammonia concentration and osmotic pressures found within the fertilizer band create a toxic environment for soil microorganisms (Harapiak et al. 1993). Placing fertilizer N in bands also reduces volatilization losses, lowers the risk of immobilization, and slows the rate of nitrification of fertilizer N to NO_3^- in the fall, which reduces the risk of the fertilizer N that is potentially lost in the spring through leaching and/or denitrification (Yadvinder-Singh et al. 1994). Numerous studies have reported that the percent of fall-applied fertilizer N recovered as NH_4^+-N increased significantly by banding or nesting, compared to broadcasting, especially in soil zones where moisture supply was relatively high (i.e. Black, Dark Gray and Gray) (Malhi and Nyborg 1979; Malhi and Nyborg 1984; Monreal et al. 1986; Malhi and Nyborg 1988a; Yadvinder-Singh et al. 1994; Malhi et al. 2001). The higher percentage of soil NH_4^+-N in the fall translated into reduced over-winter losses of NO_3^- and increased grain yields and total crop N uptake similar to those from spring-broadcast N. However, overall yields and N uptake in these studies were still less than those of spring-banded N.

The efficiency of fall-banded N fertilizer compared to spring banding is generally poorest under wet soil conditions and highest under dry conditions. For example, recent work in south-western Manitoba reported no differences in durum wheat grain yields and total crop N uptake between fall and spring-banded N in two of three years on a clay loam soil, and in all three years on a drier fine sandy loam (Grant et al. 2001). Results similar to Grant et al. (2001) have been reported in the drier soil zones of Western Canada (Bole et al. 1984; Kucey 1986; Kucey and

Schaalje 1986; Malhi et al. 1992b; Malhi et al. 2001), and when soil moisture contents in the fall and spring are low (Harapiak 1979b; Ukrainetz 1984).

Landscape position is another factor that will influence the efficiency of fall-applied N, through the accumulation of water in lower lying areas of the field (Hanna et al. 1982). The effects of landscape position are most significant during the early spring period, when considerable ponding of snowmelt often occurs. These flooded soil conditions greatly increase the potential for denitrification losses of NO_3^--N (Malhi and Nyborg 1983a). Numerous studies from Saskatchewan have reported that denitrification rates were higher in the wetter footslope and low level complexes than in the well-drained upper slope positions of the field (Elliot and de Jong 1992; Pennock et al. 1992; van Kessel et al. 1993; Corre et al. 1995; Corre et al. 1996; Farrell et al. 1996). In the Red River Valley of Manitoba, Durand (2002) found that relatively small differences in elevation played a large role in determining yield potential and response to spring broadcast N fertilizer. However, no experiments have focused on the impact of landscape position on the loss of fall-banded N under Western Canadian conditions.

Fertilizer additives such as urease inhibitors, nitrification inhibitors and physical coatings have been used in research trials to improve the efficiency of fall-applied N (Malhi et al. 1992b; Yadvinder-Singh et al. 1994). Polymer coatings may be effective tools for preserving fall-applied urea in the ammoniacal form; however, these coated products are often very expensive. In comparison, urease and nitrification inhibitors are a more cost effective means of retarding the conversion of urea to ammonium and then to nitrate. One of the more promising inhibitors of the urease enzyme is N-(n-butyl) thiophosphoric triamide (NBPT). NBPT inhibits urease activity and slows the hydrolysis of urea to NH_4^+ by competing with urea for active sites on the urease enzyme complex (Rawluk et al. 2001). Limited work in southwest Manitoba indicated that there was generally no crop benefit to using NBPT when the urea was banded in either the fall or spring under conventional tillage, because volatile losses were minimal (Grant 1998). However, under zero-tillage NBPT did increase crop yields from fall-banded urea at one of two sites.

A number of nitrification inhibitors (thiourea, ATC, N-Serve, CS_2, $(NH_4)_2$ CS_3, and K_2CS_3) have been tested with fall-applied urea and/or aqueous NH_3 in Western Canada (Malhi and Nyborg 1983b; Malhi and Nyborg 1984; Malhi and Nyborg 1988b; Malhi and Nyborg 1988a; Malhi et al. 1992b). These inhibitors were all effective in slowing nitrification and reducing over-winter N losses of fall-applied fertilizers, especially when the N fertilizer plus inhibitor were banded or nested. However, crop yields were increased only in situations where conditions for denitrification in the spring were severe. Very limited work at three sites in Manitoba indicated that the addition of N-Serve (nitrapyrin) had virtually no effect on the recovery of fall-banded urea fertilizer or on crop yields (Ridley 1977). Dicyandiamide (Didin or DCD) is a promising nitrification inhibitor that has received renewed interest of late. DCD is less volatile than other nitrification inhibitors (i.e. nitrapyrin) and can be easily blended with solid N fertilizers (Guiraud and Marol 1992). Although DCD has been reported to be phytotoxic to plants (Amberger 1989), DCD applied in the fall is unlikely to damage a crop grown the following year. In England, DCD was as effective as nitrapyrin in slowing the over-winter nitrification of injected aqueous urea applied late in the fall, when soil temperatures were below 5°C (Ashworth and Rodgers 1981). In Ontario, fall-applied large urea granules containing low rates of DCD slowed nitrification, reduced over-winter N losses, and improved yield and N uptake of winter wheat

(Yadvinder-Singh and Beauchamp 1987; Yadvinder-Singh and Beauchamp 1988a; Yadvinder-Singh and Beauchamp 1988b; Yadvinder-Singh et al. 1994). However, the effectiveness of a urease and nitrification inhibited formulation of urea in improving the efficiency of fall-banded N has not been investigated in fall banding trials in Western Canada.

The objective of this chapter is to evaluate the interactive effects of application date, landscape position, fertilizer additives, and weather and climate on the agronomic efficiency of fall-banded N fertilizer for spring wheat production under Manitoba conditions.

3.3 Materials and Methods

3.3.1 Site Selection and Description

Field experiments were conducted in Manitoba over two fertilization/growing seasons: fall 2000 to harvest 2001 (year one), and fall 2001 to harvest 2002 (year two). In total, seven small plot sites were established throughout southern Manitoba, consisting of four intensive sites and three satellite sites. In 2000/2001, an intensive experiment was located near the town of Kane on Red River/Osborne (Gleyed Rego Black Chernozem/Rego Humic Gleysol) heavy clay soil. In the second year of the project, two intensive sites were situated on Red River/Osborne heavy clay soil near the towns of Kane and Rosser. A third intensive site was located on Newdale (Orthic Black Chernozem) clay loam soil at the AAFC Brandon Research Centre's Phillips Research Farm. The Red River/Osborne and Newdale soil series represent common soils in eastern and western Manitoba respectively. To complement the intensively monitored experimental sites, three additional satellite sites were established in southern Manitoba (within 50 km of

Winnipeg); one site near Oak Bluff in year one and two sites near Oak Bluff and Sperling in year two. The satellite trials were all located on Red River/Osborne heavy clay soils and employed similar treatments to those of the intensive experiments. However, at the satellite sites, only yield and N uptake of the crop were measured.

3.3.2 Experimental Design and Treatments

Three of the four intensively monitored sites were located in the relatively level lacustrine landscape of the Red River Valley (Kane (2000/01), Kane (2001/02) and Rosser (2001/02)) with typical elevation differences of less than one metre per kilometre within each site. The topography at the intensive site at Brandon (2001/02) was slightly more undulating, and representative of glacial till landscapes in the Black soil zone of south-western Manitoba.

A split-plot design was utilized at the intensive sites, with landscape position main plots and fertilization treatment subplots. At the intensive sites located in the Red River Valley, eight main plots, consisting of four plots in high areas and four plots in low areas, were selected throughout the field using a Total Station and the Surfer grid and contour software (Surfer 1997). Topographical maps and field plans of Kane (2000/01), Kane (2001/02), and Rosser (2001/02) can be found in Appendix A. The landscape positions studied in this experiment were defined as "high" and "low" based on their relative elevations to one another within the field. The individual low landscape positions were localized concave areas in which temporary ponding occurred in the spring after snowmelt or after heavy rainfalls. The high positions were slightly raised divergent areas located between these low positions where more water shedding occurred. Separate main plots were located in an individual high or low landscape position (four of each) throughout the field. Each main plot contained six, two-metre by 10-metre fertilization treatment subplots, with all six treatments assigned at random to the subplots within the main plot. A topographical map of Brandon (2001/02) was not necessary because the slightly more undulating topography made it easy to choose individual high and low landscape positions.

A more simplistic split-plot design was employed at the satellite sites (Appendix A). At each satellite site, four complete replicated blocks of fertilization treatments were placed into one high and one low landscape position respectively, again based on their relative topographic positions in the field.

In each experiment, nitrogen fertilizer was applied at three dates in the fall between mid-September and mid-October, and one time in the spring with the seed. Nitrogen was applied as urea fertilizer (46-0-0) banded at a rate of 80 kg N ha^{-1}, with 40 cm spacing, at a depth of 7.5 cm. The modest rate of nitrogen was meant to keep each N treatment within the crop's responsive range. The six fertilization treatments were based on time of fertilizer application and use of inhibitors. Conventional urea was applied in early fall, mid fall, late fall and spring (mid-row banded at time of planting). In addition, there was a control where no N fertilizer was applied and a treatment where urea formulated with a urease and nitrification inhibitor (IMC-Agrico Super Urea® containing NBPT and DCD) was applied in the early fall. Agrotain International manufactures the IMC-Agrico Super Urea® by combining the NBPT and the DCD in the liquid melt prior to granulation (The Super Nitrogen Story undated). Application of the urea fertilizer in the fall was targeted for September 15 (early fall), September 30 (mid fall) and October 15 (late fall) of each year. However, in year one, excess moisture in the fall caused a delay in application dates to September 29, October 12, and October 26 at Kane and Oak Bluff. In year two, treatments were applied at Kane on September 26, October 9, and October 19, at Rosser, Sperling and Oak Bluff on September 19, October 1, and October 19, and at Brandon on September 15, October 1, and October 15. Therefore, early fall-banded N included all fertilizer applications occurring between September 15 and September 29, mid fall-banded N were those applications occurring between September 30 and October 14, and late fall-banded N included any applications that occurred after October 15. The corresponding soil temperatures at 7.5 cm depth for the three fall application dates at each intensive site were 11.3, 8.8, and 7.8°C at Kane (2000/01); 10.4, 7.8 and 6.6°C at Kane (2001/02); 13.9, 12.5 and 5.6°C at Rosser (2001/02); and 12.2, 11.6 and 5.7°C at Brandon (2001/02).

3.3.3 Crop Measurements

The entire study was conducted using Canadian Western Red Spring wheat (*Triticum aestivum* L. cv. AC Barrie). The wheat was seeded with a 1.8-m-wide plot seeder, at a depth of 2.5 cm (1 inch), on 20 cm (8 inch) spacing and at a rate of 140 kg ha^{-1} (≅ 2 bu $acre^{-1}$). Phosphorus, as monoammonium phosphate (11-52-0), was applied in the seedrow at a rate of 40 kg MAP (P_2O_5) ha^{-1}, adding an additional 4.4 kg N ha^{-1} to all treatments. Registered in-crop pesticides were applied at recommended rates (based on the Manitoba Crop Protection Guide) using a 4 m bicycle sprayer, including a pre-planting burn off with Glyphosate and a fungicide application of Folicur® to minimize fusarium infestations. In year one, continuous wet weather in May delayed planting until June 4th at both Kane (2000/01) and Oakbluff (2000/01). In year two, drier conditions in the spring allowed for all intensive and satellite sites to be seeded between May 21st and May 27th. Wheat was seeded in border areas to reduce border edge effects on the outer plots.

At midseason (50% heading), a one-metre by two-row sample of above ground plant tissue was hand harvested from each subplot. The midseason samples were dried at 35 to 40°C to a constant weight and dry matter biomass (kg ha^{-1}) was calculated. At physiological maturity, a three-metre by two-row sample of above ground plant tissue was harvested from each subplot, dried, threshed and weighed for both grain and straw yields (adjusted to 0% moisture content). Tissue samples collected at midseason and harvest were ground with a Wiley mill to pass a 2 mm sieve and analyzed for total N using a Leco CNS Analyzer (Leco CNS 2000 Elemental Analyzer Instruction Manual 1996). Total above ground N uptake was calculated on a dry matter weight basis for both midseason (% N content x midseason biomass/100) and harvest ([(% grain N x grain yield) + (% straw N x straw yield)]/100) samples.

Prior to threshing in year one, some harvest samples from Kane (2000/01) and Oak Bluff (2000/01) were damaged by mice while in storage. Therefore, grain yields from Kane (2000/01) and Oak Bluff (2000/01) were estimated from actual straw yields using Entz (1988) and the linear regression equation $y = 0.60x + 206.6$ ($r^2 = 0.76$***) (Appendix B). This equation was determined by linear regression analysis of actual grain yields from Kane (2001/02), Rosser (2001/02) and Kane (2000/01) (those samples that were not significantly damaged by mice) as a function of straw yields.

3.3.4 Soil Sampling and Analyses

To characterize the overall N behaviour in each main plot, background soil samples were collected in mid-September prior to fertilization at the satellite sites (Table 3.1) and at the intensive sites (Table 3.2) using a Giddings tractor mounted soil sampler.

Table 3.1. Selected physical and chemical soil properties at the satellite sites prior to fertilization							
		Site					
		Oak Bluff		Oak Bluff		Sperling	
	Depth	(2000/01)		(2001/02)		(2001/02)	
Characteristic	(cm)	High	Low	High	Low	High	Low
Soil Texture	-	clay	clay	clay	clay	clay	clay
pH	0-15	7.1	7.7	7.6	7.5	7.9	7.7
EC (1:2) (mS cm^{-1})	0-15	0.5	0.6	0.6	0.5	0.7	2.6
OM (%)	0-15	5.7	3.7	5.4	4.9	6.6	4.5
Water soluble NO_3^--N (kg ha^{-1})^z	0-60	56	54	50	35	98	58
Water soluble SO_4^--S (kg ha^{-1})^z	0-60	159	134	233	82	939	9926
Extractable P (kg ha^{-1})^z	0-15	52	50	51	34	47	314
Exchangeable K (kg ha^{-1})^z	0-15	1451	1246	1190	949	1562	1004

^{z}Assuming bulk density = 1.24 g cm^{-3} for 0-15 cm depth and 1.33 g cm^{-3} for 15-120 cm.

Table 3.2. Selected physical and chemical soil properties at the intensive sites prior to fertilization									
		Site							
		Kane		Kane		Rosser		Brandon	
	Depth	(2000/01)		(2001/02)		(2001/02)		(2001/02)	
Characteristic	(cm)	High	Low	High	Low	High	Low	High	Low
Soil Texture	-	clay	clay	clay	clay	clay	clay	loam	CL
pH	0-15	7.4	7.7	8.0	8.0	7.1	7.4	7.8	8.0
EC (1:2) (mS cm^{-1})	0-15	0.8	0.7	0.9	0.8	0.8	0.7	0.3	2.4
OM (%)	0-15	3.5	3.1	5.1	4.8	8.4	7.6	7.7	5.7
Exchangeable NH_4^+-N (kg ha^{-1})^z	0-60	90	93	64	96	76	79	134	125
Water soluble NO_3^--N (kg ha^{-1})^z	0-60	36	28	91	31	62	31	48	22
Water soluble SO_4^--S (kg ha^{-1})^z	0-60	1583	3739	11085	2086	802	2692	212	2207
Extractable P (kg ha^{-1})^z	0-15	9	12	17	30	59	51	17	22
Exchangeable K (kg ha^{-1})^z	0-15	1172	1195	1311	1172	1316	1200	787	372

^{z}Assuming bulk density = 1.24 g cm^{-3} for 0-15 cm depth and 1.33 g cm^{-3} for 15-120 cm.

Moist soil samples were refrigerated and stored at a temperature of 2°C, until being air dried at 30-35°C for 48 to 72 hours and ground to pass a 2 mm sieve using a high-speed soil grinding mill. Ground soil samples were analyzed for soil texture, pH and electrical conductivity (EC), organic matter (OM) (modified Walkley-Black), 2M KCl exchangeable ammonium, water-soluble nitrate and sulphate, extractable phosphorus (modified Kelowna) and exchangeable potassium (modified Kelowna).

3.3.5 Weather Data

General weather conditions for Winnipeg (Sept. 2000 to Aug. 2002) and Brandon (Sept. 2001 to Aug. 2002), including mean monthly aerial temperatures and total monthly precipitation, were obtained from Environment Canada's archived weather data, available online at http://climate.weatheroffice.ec.gc.ca (Tables 3.3 and 3.4 respectively). The soils at the intensive sites usually froze and remained snow covered from mid-November until thawing in April. Rainfall data was collected at each site located in the Red River Valley (Table 3.5) using a tipping bucket rainguage and a HOBO® event driven data logger (Onset Computer Corporation - Hobo Event logger User's Manual 1999). Rainfall data during the growing season was also collected at Brandon (2001/02) by Agriculture and Agri-Food Canada (Table 3.5). Additional information, aerial temperatures, relative humidity and regional rainfall near the intensive sites were obtained from the Agrometeorological Centre of Excellence (ACE) weather collection devices located throughout southern Manitoba (data not reported).

Table 3.3. Meterological data for Winnipeg, MB (Sept. 2000 to Aug. 2002)

	Mean monthly temp (°C)		Normal monthly temperature	Total monthly precipitation (mm water equiv.)		Normal monthly precipitation
Month	2000/01	2001/02	(°C)	2000/01	2001/02	(mm water equiv.)
September	11.6	13.6	12.3	63.6	22.2	52.3
October	6.4	4.3	5.3	30.4	13.3	36.0
November	-5.3	1.0	-5.3	75.0	9.1	25.0
December	-22.0	-10.3	-14.4	29.6	25.5	18.5
January	-12.6	-14.6	-17.8	6.9	15.5	19.7
February	-18.3	-9.9	-13.6	7.8	6.0	14.9
March	-6.2	-11.6	-6.1	22.5	16.5	21.5
April	5.1	1.9	4.0	26.8	47.2	31.9
May	12.7	8.0	12.0	99.7	55.8	58.8
June	16.2	17.8	17.0	97.5	73.7	89.5
July	20.4	20.8	19.5	143.6	74.1	70.6
August	19.3	18.2	18.5	65.5	91.3	75.1

Table 3.4. Meterological data for Brandon, MB (Sept. 2001 to Aug. 2002)

Month	Mean Monthly Temp (°C)	Normal Monthly Temp (°C)	Total Monthly Precipitation (mm water equiv.)	Normal Monthly Precipitation (mm water equiv.)
September	12.5	11.9	20.0	48.3
October	3.1	4.9	12.0	28.5
November	0.1	-5.6	8.0	18.6
December	-12.0	-14.7	24.6	20.7
January	-14.8	-17.9	12.0	19.2
February	-10.2	-13.4	2.2	16.0
March	-12.7	-6.1	16.0	23.5
April	1.3	4.0	20.0	29.3
May	7.6	11.8	8.4	52.6
June	17.2	16.6	81.0	75.7
July	19.7	18.9	68.2	72.5
August	17.1	18.0	84.0	69.2

Table 3.5. Total monthy rainfall data at the intensive sites

	Site			
Month	Kane (2000/01)	Kane (2001/02)	Rosser (2001/02)	Brandon (2001/02)
	(mm)			
September	39.2	27.4	27.0	ND[z]
October	16.0	13.4	35.8	ND
November	54.6	2.8	4.5	ND
December	0.0	0.0	0.0	ND
January	0.0	0.0	0.0	ND
February	0.0	0.2	0.0	ND
March	6.8	2.2	0.0	ND
April	30.6	18.8	11.0	ND
May	83.0	20.5	42.8	0.2
June	41.0	105.5	56.4	2.7
July	210.0	50.0	65.5	28.2
August	36.3	53.5	56.6	78.6

[z]ND, data not available.

Overall, growing conditions were fair to good at all sites in both years of the study. However, during both growing seasons, each site situated within the Red River Valley endured one major rainfall event of 6.5 to 13.5 cm (Table 3.5). At Kane (2000/01) and Oak Bluff (2000/01), this storm occurred in July shortly after anthesis. In year two, Kane (2001/02), Rosser (2001/02), Oak Bluff (2001/02) and Sperling (2001/02) received a heavy rainfall event in early June when the crop was at the three to four leaf stage.

In addition, gravimetric soil moisture contents (w%) at depths of 0-7.5, 7.5-15 and 15-30 cm were measured on a weekly basis at the three intensive sites located in the Red River Valley. Monitoring of soil moisture was focused on the periods from mid-September to freeze-up and from early spring to planting. Gravimetric moisture contents at Brandon (2001/02) were not measured due to resource limitations. Field moist soil samples were dried at 105°C for 24 hours and gravimetric moisture contents were determined on a dry basis (wt. of water / wt. of dry soil).

3.3.6 Data Analyses

Statistical analyses were conducted using the General Linear Model procedure of the Statistical Analysis System (SAS) package (SAS 1999). Descriptive statistics were used to test the data for normality and skewness (γ) using the Proc Univariate function of SAS. Most crop and soil variables showed relatively normal distributions, with skewness less than 0.5 (results not presented). Webster (2001) suggests that if data is positively skewed with a value less than 0.5, there is no need to transform the data, but for more skewed data, transformations by square root ($0.5 < \gamma \leq 1.0$) or logarithms ($1 < \gamma$) are likely to give approximate normality. However, statistical analyses of the transformed data did not produce any results different from those of the initial non-transformed data. Therefore, the initial, untransformed data was used in all analyses.

Due to the nature of the split-plot design used at the intensive sites, the ANOVA model used to test the subplot (fertilization) and main plot (landscape position) effects included: fertilization treatment, landscape position, fertilization treatment x landscape position, and block(landscape position) (i.e. block nested within the landscape position). The error term used for testing the main plot effects was "block(landscape position)" (Dr. G. Crow, personal communication, Department of Animal Science, University of Manitoba, Winnipeg, MB). At the satellite sites, a simple RCB ANOVA model (i.e. fertilization treatment, block) was used. Fisher's (protected) least significant difference (LSD) test was used to compare the fertilization (subplot) and landscape position (main plot) treatment means (Steel et al. 1987). LSMEANS was used to compare the fertilization treatments within each landscape position (note: the LSMEANS function in SAS does not provide an LSD value). For the fertilization treatment means, a probability level (α) of 0.05 was used as the significance threshold for the soil and plant variables. However, due to the high variability inherent in field-based landscape experiments a higher probability level is often used to detect treatment differences among landscape positions (van Kessel et al. 1993). Employing the typical probability threshold of 0.05 or lower in landscape studies increases the chances of a Type II error (β), of failing to detect treatment differences when, in fact, these differences did occur (Walley et al. 1996). Therefore, a probability threshold of 0.10 was used for all landscape variables and interactions, which is within the typical range of probability values ($P \leq 0.10$ to 0.20) used in landscape studies (Pennock et al. 1992; van Kessel et al. 1993; Corre et al. 1996; Beckie and Brandt 1997; Jowkin and Schoenau 1998).

3.4 Results and Discussion

3.4.1 Satellite Sites

Weather and soil conditions caused substantial variability in crop growth and N response at the satellite sites. Plots located in the low landscape position at Oak Bluff in 2000/01 and 2001/02 were lost due to excessive flooding during the growing season. Treatments in the high landscape position at Sperling (2001/02) did not show an N response because of extremely high NO_3^--N levels at depth (349 kg NO_3^--N ha^{-1} to 120 cm). Therefore, only results from the three remaining, non-flooded, N responsive locations will be reported: Oak Bluff (High) (2000/01), Oak Bluff (High) (2001/02) and Sperling (Low) (2001/02). The combined analysis of the three satellite sites is not reported because of site year by treatment interactions for all crop variables.

3.4.1.1 Midseason. At midseason, there were no significant differences in total above ground dry matter biomass between spring and fall application dates at any of the satellite sites (Table 3.6). However, spring-banded N produced the highest midseason dry matter biomass at both Oak Bluff (High) (2000/01) and Oak Bluff (High) (2001-02). At Sperling (Low) (2001/02), fall-banded applications produced greater midseason dry matter biomass than the spring-banded N, but again the differences were not significant.

At Oak Bluff (High) (2000/01), midseason N uptake was significantly greater for spring-banded N than for mid and late fall applications, but not for early fall applications, with or without inhibitors; the reasons for this observation are not known. In the second year, there were no significant differences in crop N uptake at midseason among spring and fall application dates at either Oak Bluff (High) (2001/02) and Sperling (Low) (2001/02).

There were no significant differences in crop responses at midseason between the two early fall treatments, with or without NBPT and DCD, at any of the three N responsive satellite sites.

Table 3.6. Midseason biomass and N uptake (dry matter basis) at the N responsive satellite sites

		Site					
		Oak Bluff (High) (2000/01)		Oak Bluff (High) (2001/02)		Sperling (Low) (2001/02)	
Treatment		Biomass	N uptake	Biomass	N uptake	Biomass	N uptake
				(kg ha^{-1})			
Early fall		2549	62.6ab	3802	115.2a	3725a	108.0a
Mid fall		2448	58.5b	3518	108.4a	3550a	106.4a
Late fall		2510	55.7bc	3645	114.5a	3604a	104.0ab
Spring		2992	74.0a	3953	112.6a	3109a	85.4b
Control (no N)		2073	43.8c	3282	81.4b	1787b	39.8c
Early fall w/ inhibitors		2628	62.1ab	3844	112.0a	3689a	105.1ab
LSD ($\alpha = 0.05$)		ns	12.0	ns	17.7	797	20.2
ANOVA	df			$P > F$			
Trt	5	0.15	0.0027*	0.22	0.0079*	0.0008*	0.0001*
Block	3	0.88	0.87	0.20	0.42	0.33	0.33
Residual C.V. (%)		16.9	13.4	10.6	11.0	16.3	14.7

a-c Mean values followed by the same letter (within columns) are not significantly different.

* Significant at $P < 0.05$.

3.4.1.2 Harvest. At maturity, spring-banded N produced grain yields, straw yields and total crop N uptake that were significantly greater than all other fertilization treatments at Oak Bluff-High (2000/01) (Table 3.7). At the same site, grain yield increases (GYI) and fertilizer N use efficiency (NUE) of the crop from fall-banded N were, on average, 58 and 46% that of spring-banded N (Table 3.8). Wet conditions during the fall of 2000 and spring of 2001 prior to planting in southern Manitoba (Table 3.3) likely increased over-winter losses of N from the fall-banded treatments, resulting in the large differences in crop responses between the fall and spring-banded N at Oak Bluff (High) (2000/01).

Table 3.7. Grain yield, straw yield and total crop N uptake (dry matter basis): effect of application date and inhibitors at maturity at the N responsive satellite sites

		Site								
		Oak Bluff (High) (2000/01)[z]			Oak Bluff (High) (2001/02)			Sperling (Low) (2001/02)		
Treatment		Grain yield	Straw yield	Total N uptake	Grain yield	Straw yield	Total N uptake	Grain yield	Straw yield	Total N uptake
		(kg ha^{-1})								
Early fall		2365b	3590b	109.2b	3796a	4614ab	180.3a	2512a	3148a	104.4a
Mid fall		2398b	3646b	110.7b	3650a	4402b	172.0a	2698a	3254a	110.0a
Late fall		2280b	3448b	108.6b	3713a	4428b	168.8a	2742a	3434a	108.2a
Spring		2865a	4422a	148.0a	3835a	4659ab	171.2a	2444a	2822a	95.6a
Control (no N)		1641c	2386c	76.9c	2948b	3412c	119.5b	1104b	1605b	43.0b
Early fall w/ inhibitors		2355b	3574b	108.2b	3984a	4904a	179.6a	2708a	3599a	105.0a
LSD (α = 0.05)		358	596	17.9	369	467	24.9	609	800	19.9
ANOVA	df	$P > F$								
Trt	5	0.0001*	0.0001*	0.0001*	0.0004*	0.0001*	0.0009*	0.0003*	0.0011*	0.0001*
Block	3	0.49	0.49	0.17	0.21	0.24	0.19	0.0037*	0.0021*	0.029*
Residual C.V. (%)		10.3	11.3	10.8	6.7	7.0	10.0	17.1	17.8	14.0

a-c Mean values followed by the same letter (within columns) are not significantly different.

[z] Grain yields for Oak Bluff 2000/2001 were predicted from actual straw yields.

* Significant at $P < 0.05$.

Table 3.8. Grain yield increase and fertilizer N use efficiency (dry matter basis): effect of application date and inhibitors at maturity at the N responsive satellite sites

		Site											
		Oak Bluff (High) (2000/01)				Oak Bluff (High) (2001/02)				Sperling (Low) (2001/02)			
		Grain yield increase		Fertilizer NUE of the crop		Grain yield increase		Fertilizer NUE of the crop		Grain yield increase		Fertilizer NUE of the crop	
Treatment		(kg ha^{-1})	% of spring	% of applied	% of spring	(kg ha^{-1})	% of spring	% of applied	% of spring	(kg ha^{-1})	% of spring	% of applied	% of spring
Early fall		724b	59	40.4b	45	848	96	76	118	1408	105	77	117
Mid fall		757b	62	42.3b	48	702	79	66	102	1594	119	84	127
Late fall		639b	52	39.6b	45	765	86	62	95	1638	122	82	124
Spring		1224a	100	89.0a	100	887	100	65	100	1340	100	66	100
Control (no N)		-	-	-	-	-	-	-	-	-	-	-	-
Early fall w/ inhibitors		714b	58	39.1b	44	1036	117	75	116	1604	120	78	118
LSD (α = 0.05)		370		23.6		ns		ns		ns		ns	
ANOVA	df	$P > F$											
Trt	4	0.032*		0.0022*		0.37		0.77		0.73		0.56	
Block	3	0.014*		0.034*		0.0029*		0.0012*		0.0008*		0.0028*	
Residual C.V. (%)		29.6		30.7		27.8		28.2		24.6		20.6	

a,b Mean values followed by the same letter (within columns) are not significantly different.

* Significant at $P < 0.05$.

The efficiency of fall-banded fertilizer was much better in the second year of the project. Fall-banded N produced similar grain yields, straw yields and total crop N uptake as spring-banded N at both Oak Bluff (High) (2001/02) and Sperling (Low) (2001/02) (Table 3.7). There were also no significant differences between fall and spring application dates in terms of grain yield increases and fertilizer NUE, at either location in 2001/2002 (Table 3.8). The improved efficiency of fall-banded N at Oak Bluff (High) (2001/02) and Sperling (Low) (2001/02), compared to Oak Bluff (High) (2000/01), is attributed to overall drier soil conditions in southern Manitoba during the fall of 2001 and early spring of 2002 (Table 3.3).

There was little apparent crop benefit to the use of the urease and nitrification inhibited formulation of urea at any of the three satellite sites (Tables 3.7 and 3.8), as there were no differences between the two early fall treatments, with and without inhibitors, in terms of grain yield, straw yield, total crop N uptake, increases in grain yield or N use efficiency by the crop.

In Western Canada, applying N fertilizer in concentrated bands has consistently improved the efficiency of fall-applied fertilizers, compared to broadcast applications (Malhi et al. 1992b). However, under certain environmental and soil conditions, fall-banded N is still inferior to spring-banded N. Malhi and Nyborg (1990a) questioned whether N fertilizers applied in the fall in either sub-surface bands or nests require delaying of application date to improve grain yields, as it did for broadcast and incorporated N fertilizers. The results from the satellite sites suggest that banded fertilizer N is not particularly sensitive to application date in the fall. There were differences between fall and spring-banded N in year one, but there was no benefit in delaying application into late October at any of the sites, despite vastly different spring soil conditions during the two years. However, the N responsive satellite sites were all moderately well drained and prolonged saturated soil conditions never occurred, even after the snow melted.

3.4.2 Intensive Sites

Soil conditions at Kane (2000/01), prior to freeze-up in the fall and planting in the spring were wet (Fig. 3.1). During the first week of November in 2000, Kane (2000/01) received approximately 50 mm of rain (Table 3.5). Combined with continuous wet weather during the following May, soil conditions in the low landscape positions were above field capacity for much of the early spring period. Field capacity (-33 kPa) and permanent wilting point (-1500 kPa) for the Red River/Osbourne heavy clay soils were estimated to be at 50% and 20% gravimetric soil moisture content respectively (P. Haluschak, personal communication, Manitoba Agriculture and Food, Winnipeg, MB).

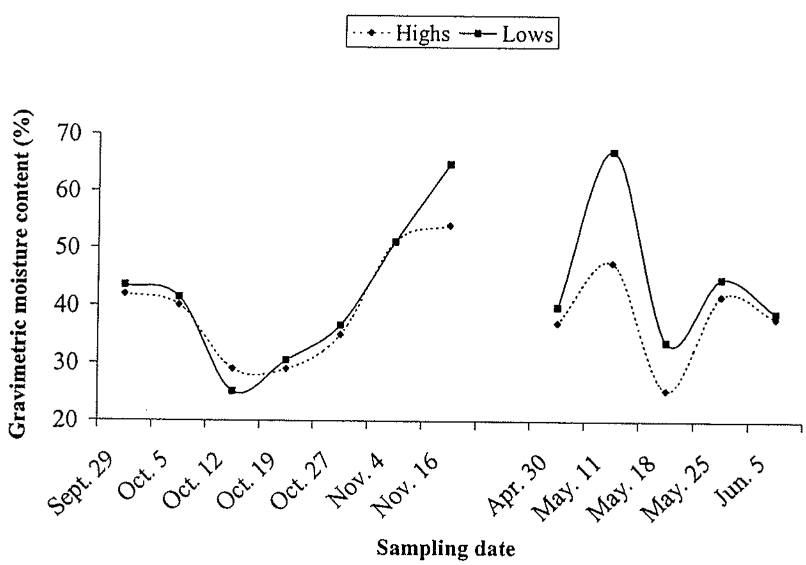

Fig. 3.1. Gravimetric soil moisture content (0-15 cm) from September 29 to freeze-up and from early spring to planting at Kane (2000/01).

In year two, soil conditions were generally drier in the fall and spring than in year one. However, soil conditions at Rosser (2001/02) were wetter than at Kane (2001/02), especially in the early spring (Fig. 3.2 and 3.3 respectively). In October of 2001, the intensive site at Rosser received 22 mm more rain than the site at Kane. Soil conditions in the early spring were presumably dry at Brandon (2001/02) because little precipitation occurred in this region of Manitoba during the fall, winter and early spring period (Tables 3.4 and 3.5).

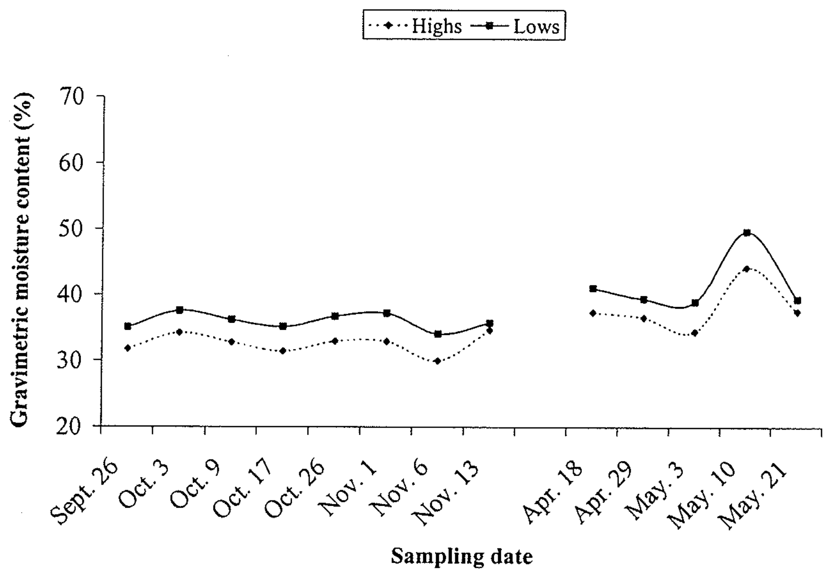

Fig. 3.2. Gravimetric soil moisture content (0-15 cm) from September 26 to freeze-up and from early spring to planting at Kane (2001/02).

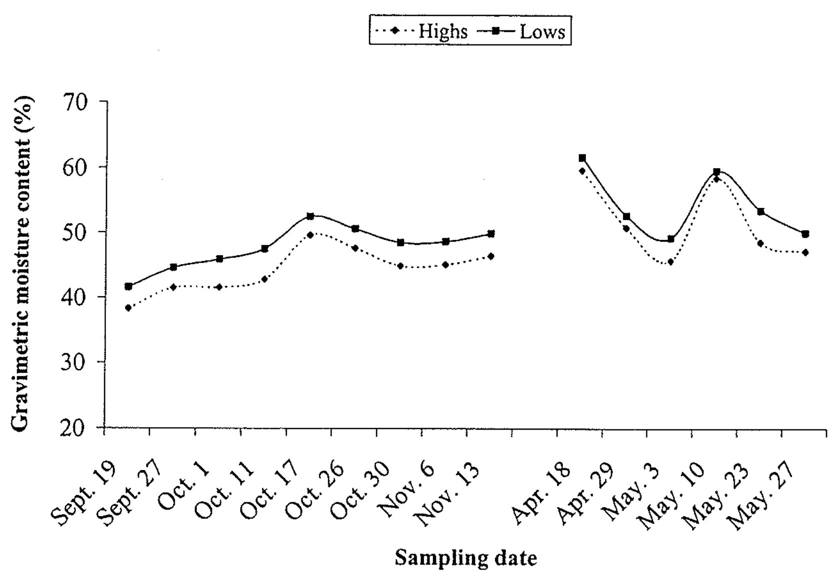

Fig. 3.3. Gravimetric soil moisture content (0-15 cm) from September 19 to freeze-up and from early spring to planting at Rosser (2001/02).

3.4.2.1 Midseason. At midseason, total dry matter biomass and N uptake by the crop was significantly greater in the high landscape positions than in the low landscape positions at two of the four intensive sites, Rosser (2001/02) and Brandon (2001/02) (Tables 3.9 and 3.10 respectively). When the results from all four intensive sites were combined, the high landscape positions produced significantly more midseason biomass than the low positions. The high landscape positions also had significantly greater mean crop N uptake at midseason then the low landscape positions, but due to a site year by landscape position interaction the LSD is not reported.

Application date appeared to influence the midseason crop response at all four intensive sites, with spring-banded N producing the highest midseason biomass and crop N uptake (Tables 3.8 and 3.9). However, significant differences among application dates were only evident at Rosser (2001/02) and Brandon (2001/02). At Rosser (2001/02) late fall and spring-banded N had significantly higher midseason biomass and N uptake than early and mid fall-banded N. At Brandon (2001/02), spring-banded N produced significantly more midseason biomass than mid fall-banded N. Combined statistical analyses of the site-years revealed that spring-banded N produced significantly greater mean dry matter biomass and N uptake by the crop at midseason than any of the fall-banded fertilization treatments, with or without inhibitors.

There were no significant interactions between landscape position and fertilization treatment at any of intensive sites or when combined at midseason. However, for both mean midseason dry matter yield and N uptake, the differences between fall and spring applications in the low landscape positions often appeared to be greater than in the high landscape positions.

Table 3.9. Midseason yield (dry matter basis): effect of landscape position, application date and inhibitors at the intensive sites

Treatment			Site					
Landscape position	Fertilization		Kane (2000/01)	Kane (2001/02)	Rosser (2001/02)	Brandon (2001/02)		Mean all sites
					($kg\ ha^{-1}$)			
High	Early fall		2257	3029	2798	3869		2988
	Mid fall		2148	2786	2838	3848		2905
	Late fall		2091	2763	3594	3881		3083
	Spring		2274	2856	3618	4234		3245
	Control (no N)		1533	2178	2542	2938		2298
	Early fall w/ inhibitors		2143	2914	3484	3378		2980
	LSD (α = 0.05)[z]		-	-	-	-		-
Low	Early fall		2148	2861	1704	2817		2383
	Mid fall		2394	2751	1832	2412		2347
	Late fall		2228	2960	2030	2687		2476
	Spring		2456	3267	2204	3015		2736
	Control (no N)		1533	1564	1221	1686		1501
	Early fall w/ inhibitors		2308	2995	1867	2808		2494
	LSD (α = 0.05)[z]		-	-	-	-		-
Landscape position means								
High			2074	2754	3146a	3692a		2917a
Low			2178	2733	1810b	2571b		2323b
LSD (α = 0.10)			ns	ns	1281	1092		431
	Fertilization means							
	Early fall		2203a	2945a	2251cd	3343ab		2686b
	Mid fall		2271a	2769a	2335bc	3130b		2626b
	Late fall		2159a	2861a	2812a	3284ab		2779b
	Spring		2365a	3061a	2911a	3625a		2991a
	Control (no N)		1533b	1871b	1882d	2312c		1899c
	Early fall w/ inhibitors		2225a	2954a	2676ab	3093b		2737b
	LSD (α = 0.05)		263	406	376	476		188
ANOVA		df			$P > F$		df	$P > F$
Landpos		1	0.77	0.96	0.089†	0.093†		
Trt		5	0.0001*	0.0001*	0.0001*	0.0002**		
Landpos*Trt		5	0.76	0.20	0.49	0.55		
Block(Landpos)		6	0.0001*	0.0001*	0.0001*	0.0001*		
Residual C.V. (%)			12.1	14.5	14.8	14.9		
Site year							3	0.06
Landpos							1	0.027*
Site year*Landpos							3	0.12
Trt							5	0.0001*
Site year*Trt							15	0.20
Landpos*Trt							5	0.64
Site year*Landpos*Trt							15	0.35
Block(Site*Landpos)							24	0.0001*
Residual C.V. (%)								14.5

a-d Mean values followed by the same letter (within columns) are not significantly different.

[z] LSD for individual treatments within a landscape position is not reported because there was no Landpos*Trt interaction.

[y] LSD is not reported because there was a Site year*Landpos interaction.

† Significant at $P < 0.10$ (used only for landscape position variables and interactions).

* Significant at $P < 0.05$.

Table 3.10. Midseason N uptake (dry matter basis): effect of landscape position, application date and inhibitors at the intensive sites

Treatment		Site				
Landscape position	Fertilization	Kane (2000/01)	Kane (2001/02)	Rosser (2001/02)	Brandon (2001/02)	Mean all sites
				(kg ha^{-1})		
High	Early fall	79.8	88.2	86.1	119.9	93.5
	Mid fall	73.6	85.9	94.8	110.4	91.2
	Late fall	74.5	78.9	110.9	122.6	96.7
	Spring	83.2	82.2	117.4	124.8	101.9
	Control (no N)	49.8	55.4	75.1	67.3	61.9
	Early fall w/ inhibitors	74.4	85.4	105.3	97.8	90.7
	LSD (α = 0.05)^z	-	-	-	-	-
Low	Early fall	65.3	87.9	47.3	62.2	65.7
	Mid fall	69.9	83.5	52.0	56.1	65.4
	Late fall	68.2	87.0	59.8	63.1	69.5
	Spring	77.3	97.7	70.2	71.4	79.1
	Control (no N)	41.1	37.8	33.3	34.5	36.7
	Early fall w/ inhibitors	72.3	87.6	58.5	60.6	69.8
	LSD (α = 0.05)^z	-	-	-	-	-
Landscape position means						
High		72.5	79.3	98.3a	107.1a	89.3
Low		65.7	80.3	53.5b	58.0b	64.4
LSD (α = 0.10)		ns	ns	44.1	24.8	-^{y}
	Fertilization means					
	Early fall	72.5a	88.1a	66.7d	91.0ab	79.6b
	Mid fall	71.7a	84.7a	73.4cd	83.2ab	78.3b
	Late fall	71.4a	82.9a	85.4ab	92.9ab	83.1b
	Spring	80.2a	90.0a	93.8a	98.1a	90.5a
	Control (no N)	45.5b	46.6b	54.8e	50.9c	49.3c
	Early fall w/ inhibitors	73.4a	86.5a	81.9bc	79.2b	80.2b
	LSD (α = 0.05)	9.0	12.5	9.4	17.6	6.1

ANOVA	df	P > F				df	P > F
Landpos	5	0.40	0.93	0.096†	0.0084*		
Trt	1	0.0001*	0.0001*	0.0001*	0.0001*		
Landpos*Trt	5	0.78	0.18	0.80	0.52		
Block(Landpos)	6	0.0001*	0.0001*	0.0001*	0.0002*		
Residual C.V. (%)		12.8	15.4	12.1	20.9		
Site year						3	0.59
Landpos						1	0.0019*
Site year*Landpos						3	0.0416*
Trt						5	0.0001*
Site year*Trt						15	0.06
Landpos*Trt						5	0.87
Site year*Landpos*Trt						15	0.33
Block(Site*Landpos)						24	0.0001*
Residual C.V. (%)							16.1

a-d Mean values followed by the same letter (within columns) are not significantly different.

^{z} LSD for individual treatments within a landscape position is not reported because there was no Landpos*Trt interaction.

^{y} LSD is not reported because there was a Site year*Landpos interaction.

^{x} LSD is not reported because there was a Site year*Trt interaction.

† Significant at $P < 0.10$ (used only for landscape position variables and interactions).

* Significant at $P < 0.05$.

At midseason, early fall-banded N with NBPT and DCD had significantly higher midseason biomass and N uptake than early fall-banded without inhibitors at Rosser (2001/02) (Tables 3.9 and 3.10). However, there were no significant effects of inhibitors at the other three intensive sites, or when the data from the intensive sites was combined.

3.4.2.2 Harvest Grain Yields, Straw Yields and Total N Uptake. At physiological maturity, the effects of landscape position on grain yield, straw yield and total above ground crop N uptake were apparent at three of the four intensive sites: Kane (2000/01), Rosser (2001/02) and Brandon (2001/02) (Tables 3.11, 3.12 and 3.13 respectively). At each of these sites, the high landscape positions produced significantly greater grain yields (265, 996, and 1283 kg ha^{-1} respectively), straw yields (441, 1366, and 1071 kg ha^{-1} respectively) and total crop N uptake (19.3, 49.5, and 58.4 kg ha^{-1} respectively) than the low landscape positions. At Kane (2001/02), grain yield, straw yield and total crop N uptake appear to be greater in the low positions than in the high positions, but the differences were not significant. The relatively high grain yield and N uptake in the imperfectly drained lower positions at Kane (2001/02) was likely due to a prolonged dry period at this site during July and August, when the high moisture content in the low landscape positions helped the crop to avoid drought stress.

When all four sites were combined, mean grain yield, straw yield and N removal by the crop were 21, 13 and 25% greater respectively in the high landscape positions than in the low landscape positions (Tables 3.11, 3.12 and 3.13 respectively). However, due to site year by landscape position interactions, statistical analyses of the landscape position effects are reported only for the individual intensive sites.

Table 3.11. Grain yield (dry matter basis): effect of landscape position, application date and inhibitors at the intensive sites

Landscape position	Fertilization	Kane (2000/01)[z]	Kane (2001/02)	Rosser (2001/02)	Brandon (2001/02)	Mean all sites
				(kg ha^{-1})		
High	Early fall	2520	1990	2383	3221	2528a
	Mid fall	2345	1996	2383	3395	2530a
	Late fall	2467	1937	2509	3013	2482a
	Spring	2330	1817	2456	3181	2446a
	Control (no N)	1787	1286	1992	2603	1917b
	Early fall w/ inhibitors	2307	1826	2522	3136	2448a
	LSD (α = 0.05)	-[y]	-[y]	-[y]	-[y]	na[x]
Low	Early fall	1990	2472	1299	1997	1939c
	Mid fall	2066	2566	1329	1676	1910c
	Late fall	2288	2612	1556	2177	2158ab
	Spring	2203	2687	1652	2122	2166a
	Control (no N)	1396	1307	1059	1168	1232d
	Early fall w/ inhibitors	2224	2417	1374	1825	1960bc
	LSD (α = 0.05)	-[y]	-[y]	-[y]	-[y]	na[x]
Landscape position means						
High		2293a	1809	2374a	3091a	2392
Low		2028b	2343	1378b	1828b	1894
LSD (α = 0.10)		184	ns	808	na[x]	-[w]
	Fertilization means					
	Early fall	2255a	2231a	1841a	2609a	2234
	Mid fall	2206a	2281a	1856a	2536a	2220
	Late fall	2377a	2275a	2032a	2595a	2320
	Spring	2267a	2252a	2054a	2651a	2306
	Control (no N)	1592b	1296b	1525b	1885b	1575
	Early fall w/ inhibitors	2266a	2122a	1948a	2481a	2204
	LSD (α = 0.05)	201	354	287	na[x]	-[v]

ANOVA	df	P > F				df	P > F
Landpos	1	0.031*	0.23	0.054†	0.0038*		
Trt	5	0.0001*	0.0001*	0.0092*	0.0004*		
Landpos*Trt	5	0.22	0.27	0.85	0.15		
Block(Landpos)	6	0.03*	0.0001*	0.0001*	0.0001*		
Residual C.V. (%)		9.1	16.7	15.0	13.1		
Site year						3	0.11
Landpos						1	0.0051*
Site year*Landpos						3	0.0028*
Trt						5	0.0001*
Site year*Trt						15	0.49
Landpos*Trt						5	0.033*
Site year*Landpos*Trt						15	0.61
Block(Site year*Landpos)						24	0.0001*
Residual C.V. (%)							13.6

a-d Mean values followed by the same letter (within columns) are not significantly different.
[z] Grain yields for Kane 2000/2001 were predicted from actual straw yields.
[y] LSD for individual treatments within a landscape position is not reported because there was no Landpos*Trt interaction.
[x] Not applicable (na) because Brandon 2001/2002 had unbalanced data: therefore LSMEANS was used, which does not provide an LSD value.
[w] LSD is not reported because of significant Site year*Landpos interaction.
[v] LSD is not reported because of significant Landpos*Trt interaction.
† Significant at $P < 0.10$ (used only for landscape position variables and interactions).
* Significant at $P < 0.05$.

Table 3.12. Straw yield (dry matter basis): effect of landscape position, application date and inhibitors at the intensive sites

Treatment		Site				
Landscape position	Fertilization	Kane (2000/01)	Kane (2001/02)	Rosser (2001/02)	Brandon (2001/02)	Mean all sites
				(kg ha^{-1})		
High	Early fall	3849	2257a	3442	3421	3242
	Mid fall	3558	2397a	3703	3265	3231
	Late fall	3760	2214a	3938	2972	3221
	Spring	3533	2126a	3981	3296	3234
	Control (no N)	2630	1508b	2880	2196	2303
	Early fall w/ inhibitors	3495	2192a	3679	3167	3133
	LSD (α = 0.05)	-[z]	na[y]	-[z]	-[z]	-[z]
Low	Early fall	2967	3673ab	2008	2206	2713
	Mid fall	3094	3574ab	2169	1996	2708
	Late fall	3462	3961a	2402	2450	3069
	Spring	3321	3861ab	2882	2216	3070
	Control (no N)	1978	2147c	1800	1069	1749
	Early fall w/ inhibitors	3356	3347b	2169	1957	2707
	LSD (α = 0.05)	-[z]	na[y]	-[z]	-[z]	-[z]
Landscape position means						
High		3471a	2116	3604a	3053a	3061
Low		3030b	3427	2238b	1982b	2669
LSD (α = 0.10)		305	-[x]	1228	na[w]	-[v]
	Fertilization means					
	Early fall	3408a	2965	2725bc	2813a	2978ab
	Mid fall	3326a	2986	2936ab	2630a	2969ab
	Late fall	3611a	3087	3170ab	2711a	3145a
	Spring	3427a	2993	3431a	2756a	3152a
	Control (no N)	2304b	1828	2340c	1632b	2026c
	Early fall w/ inhibitors	3425a	2770	2924b	2562a	2920b
	LSD (α = 0.05)	335	-[x]	503	na[w]	na[w]

ANOVA	df	$P > F$				df	$P > F$
Landpos	1	0.031*	0.024*	0.074†	0.026*		
Trt	5	0.0001*	0.0001*	0.0031*	0.0001*		
Landpos*Trt	5	0.22	0.058†	0.85	0.31		
Block(Landpos)	6	0.03*	0.0001*	0.0001*	0.0001*		
Residual C.V. (%)		10.1	13.7	16.9	13.9		
Site year						3	0.14
Landpos						1	0.083†
Site year*Landpos						3	0.0009*
Trt						5	0.0001*
Site year*Trt						15	0.26
Landpos*Trt						5	0.13
Site year*Landpos*Trt						15	0.43
Block(Site year*Landpos)						24	0.0001*
Residual C.V. (%)							13.7

a-c Mean values followed by the same letter (within columns) are not significantly different.
[z] LSD for individual treatments within a landscape position is not reported because there was no Landpos*Trt interaction.
[y] Not applicable (na) because LSMEANS was used; which does not provide an LSD value.
[x] LSD is not reported because of significant Landpos*Trt interactions.
[w] Not applicable (na) because Brandon 2001/2002 had unbalanced data: therefore LSMEANS was used, which does not provide an LSD value.
[v] LSD is not reported because of significant Site year*Landpos interaction.
† Significant at $P < 0.10$ (used only for landscape position variables and interactions).
* Significant at $P < 0.05$.

Table 3.13. Total crop N uptake (dry matter basis): effect of landscape position, application date and inhibitors at the intensive sites

Treatment		Site				
Landscape position	Fertilization	Kane (2000/01)	Kane (2001/02)	Rosser (2001/02)	Brandon (2001/02)	Mean all sites
				(kg ha^{-1})		
High	Early fall	135.6	80.4	110.2	139.1	116.3
	Mid fall	124.9	90.8	122.6	129.5	117.0
	Late fall	130.2	86.4	126.6	122.4	116.4
	Spring	125.9	87.6	132.4	126.2	118.0
	Control (no N)	86.7	52.3	88.5	98.4	81.5
	Early fall w/ inhibitors	122.0	84.1	118.0	125.8	112.5
	LSD (α = 0.05)[z]	-	-	-	-	-
Low	Early fall	98.0	104.2	60.1	70.3	83.1
	Mid fall	103.3	106.8	64.1	62.5	84.1
	Late fall	118.4	109.0	75.3	78.0	95.2
	Spring	112.3	115.2	82.6	74.9	96.2
	Control (no N)	66.9	52.1	51.0	38.7	52.2
	Early fall w/ inhibitors	111.1	99.5	68.5	66.6	86.4
	LSD (α = 0.05)[z]	-	-	-	-	-
Landscape position means						
High		120.9a	80.3	116.4a	123.6a	110.3
Low		101.6b	97.8	66.9b	65.2b	82.9
LSD (α = 0.10)		9.6	ns	43.7	na[y]	-[w]
	Fertilization means					
	Early fall	116.8a	92.3a	85.1b	104.7a	99.7ab
	Mid fall	114.1a	98.8a	93.4ab	96.0a	100.5ab
	Late fall	124.3a	97.7a	100.9a	100.2a	105.8ab
	Spring	119.1a	101.4a	107.5a	100.5a	107.1a
	Control (no N)	76.8b	52.2b	69.8c	68.6b	66.8c
	Early fall w/ inhibitors	116.5a	91.8a	93.2ab	96.2a	99.4b
	LSD (α = 0.05)	11.5	19.1	15.2	na[y]	na[y]

ANOVA	df	P > F				df	P > F
Landpos	1	0.0082*	0.32	0.07†	0.0008*		
Trt	5	0.0001*	0.0001*	0.0004*	0.0007*		
Landpos*Trt	5	0.20	0.73	0.83	0.59		
Block(Landpos)	6	0.057†	0.0001*	0.0001*	0.0025*		
Residual C.V. (%)		10.1	23.1	16.2	16.0		
Site year						3	0.17
Landpos						1	0.0012*
Site year*Landpos						3	0.0059*
Trt						5	0.0001*
Site year*Trt						15	0.45
Landpos*Trt						5	0.46
Site year*Landpos*Trt						15	0.84
Block(Site year*Landpos)						24	0.0001*
Residual C.V. (%)							15.8

a-c Mean values followed by the same letter (within columns) are not significantly different.

[z] LSD for individual treatments within a landscape position is not reported because there was no Landpos*Trt interaction.

[y] Not applicable (na) because Brandon 2001/2002 had unbalanced data: therefore LSMEANS was used, which does not provide an LSD value.

[w] LSD is not reported because of significant Site year*Landpos interaction.

† Significant at $P < 0.10$ (used only for landscape position variables and interactions).

* Significant at $P < 0.05$.

Time of N application resulted in few differences in crop response at any of the individual intensive sites (Tables 3.11, 3.12 and 3.13). In general, spring and late fall-banded N applications appeared to produce the highest grain yields, straw yields, and total N uptake by the crop, but in most cases, these differences were not significant. However, at Rosser (2001/02), spring-banded N produced significantly higher straw yields and total crop N uptake than early fall-banded N without inhibitors.

When the combined values from all four intensive sites were analyzed, spring and late fall applications increased mean grain yields over early and mid fall applications in the low landscape positions (Table 3.11). Further statistical analyses of the landscape position by treatment interaction for mean grain yield determined that in the low positions, spring-banded N significantly increased grain yields compared to early fall, mid fall and early fall with inhibitors, whereas in the high landscape positions, there were no significant differences in crop response among fertilization treatments. Grain yields were slightly higher for spring-banded N than for late fall-banded N in the low landscape positions, but statistically they were equal. This suggests that the application date of fall-banded fertilizer N is much more critical for depressional areas than for water shedding areas within a field. It also suggests that delaying application of fertilizer N until late in the fall will increase the efficiency of fall-banded fertilizer and reduce the risk associated with losses in poorly drained areas of the field.

Dry matter straw yield and total crop N uptake did not have a significant landscape position by treatment interaction, but in both cases there are larger differences between late fall and spring-banded N, and early and mid fall application dates in the low landscape positions than in the high landscape positions (Table 3.12 and 3.13 respectively).

As at midseason, there were no significant differences in grain yield, straw yield or total crop N uptake between the two early fall-banded treatments, with and without inhibitors, at any of the four intensive sites. There were also no significant differences between these two treatments in crop response at harvest when the intensive sites were combined, in either landscape position.

3.4.2.3 Harvest Grain Yield Increases and Fertilizer N Use Efficiency. No significant differences in GYI and NUE were evident between landscape positions at any of the individual intensive sites or when the data was combined (Tables 3.14 and 3.15 respectively). However, GYI and NUE frequently appeared to higher in the low landscape positions than in the high landscape positions. The larger apparent N response in the low landscape positions was the result of relatively poor grain yields and N uptake from the control treatment in the low landscape positions, compared to the high landscape positions. The low crop yields and N uptake for the control in the low landscape positions were probably caused, in part, by low concentrations of soil N prior to fertilization in the low areas of the field (Table 3.2).

There were few significant differences in GYI and NUE among application dates at any of the individual sites (Table 3.14). However, there was a significant landscape position by treatment interaction at Kane (2000/01) and Brandon (2001/02), with respect to increases in grain yield. At these two sites, there were no significant differences in yield increases among fertilization treatments in the high landscape positions.

Table 3.14. Increases in grain yield: effect of landscape position, application date and inhibitors at the intensive sites

Treatment		Kane (2000/01)[z] Grain yield increase		Kane (2001/02) Grain yield increase		Rosser (2001/02) Grain yield increase		Brandon (2001/02) Grain yield increase		Mean all sites Grain yield increase	
Landscape position	Fertilization	(kg ha^{-1})	% of spring	(kg ha^{-1})	% of spring	(kg ha^{-1})	% of spring	(kg ha^{-1})	% of spring	(kg ha^{-1})	% of spring
High	Early fall	733	135	704	133	391	84	617	113	611	117
	Mid fall	558	103	710	134	391	84	792	145	613	118
	Late fall	680	125	651	123	517	111	410	75	565	108
	Spring	543	100	531	100	464	100	547[v]	100	521	100
	Early fall w/ inhibitors	520	96	540	102	531	114	533	97	531	102
	LSD (α = 0.05)	ns		-[y]		-[y]		ns		ns	
Low	Early fall	594b	74	1165	84	240	40	829ab	87	707b	76
	Mid fall	670ab	83	1260	91	270	46	508b	53	678b	73
	Late fall	892a	111	1305	95	497	84	1009a	106	926a	99
	Spring	807ab	100	1380	100	593	100	954a	100	934a	100
	Early fall w/ inhibitors	828a	103	1110	80	315	53	657ab	69	728b	78
	LSD (α = 0.05)	na[x]		-[y]		-[y]		na[x]		na[x]	
Landscape position means											
High		607	-	627	-	459	-	580	-	568	-
Low		758	-	1244	-	383	-	791	-	794	-
LSD (α = 0.10)		-[w]		ns		ns		-[w]		-[w]	
	Fertilization means										
	Early fall	664	98	935	98	315	60	723	96	659	96
	Mid fall	614	91	985	103	330	62	650	87	645	95
	Late fall	786	116	978	102	507	96	709	94	745	104
	Spring	675	100	956	100	529	100	751	100	727	100
	Early fall w/ inhibitors	674	100	825	86	423	80	595	79	629	90
	LSD (α = 0.05)	-[w]		ns		ns		-[w]		-[w]	
ANOVA		df	$P > F$	df	$P > F$	df	$P > F$	df	$P > F$	df	$P > F$
Landpos		1	0.54	1	0.11	1	0.81	1	0.50		
Trt		4	0.32	4	0.86	4	0.32	4	0.86		
Landpos*Trt		4	0.071†	4	0.80	4	0.68	4	0.081†		
Block(Landpos)		6	0.0001*	6	0.0001*	6	0.0001*	6	0.0001*		
Residual C.V. (%)			23.4		34.8		59.3		43.1		
Site year										3	0.12
Landpos										1	0.13
Site year*Landpos										3	0.41
Trt										4	0.32
Site year*Trt										12	0.96
Landpos*Trt										4	0.036*
Site year*Landpos*Trt										12	0.65
Block(Site year*Landpos)										24	0.0001*
Residual C.V. (%)											39.9

a,b Mean values followed by the same letter (within columns) are not significantly different.
[z] Grain yields for Kane 2000/2001 were predicted from actual straw yields.
[y] LSD for individual treatments within a landscape position is not reported because there was no Landpos*Trt interaction.
[x] LSD is not applicable (na) because LSMEANS was used, which does not provide an LSD value.
[w] LSD is not reported because of significant Landpos*Trt interaction.
[v] Brandon 2001/2002 had 1 missing spring sample in the high landscape position: therefore values were estimated by SAS.
† Significant at $P < 0.10$ (used only for landscape position variables and interactions).
* Significant at $P < 0.05$.

Table 3.15. Fertilizer N use efficiency at harvest: effect of landscape position, application date and inhibitors at the intensive sites

Treatment		Site: Kane (2000/01)[z] Fertilizer NUE of the crop		Kane (2001/02) Fertilizer NUE of the crop		Rosser (2001/02) Fertilizer NUE of the crop		Brandon (2001/02) Fertilizer NUE of the crop		Mean all sites Fertilizer NUE of the crop	
Landscape position	Fertilization	% of applied	% of spring	% of applied	% of spring	% of applied	% of spring	% of applied	% of spring	% of applied	% of spring
High	Early fall	61.1	124	35.2	80	27.1	49	50.9	151	43.5	96
	Mid fall	47.8	97	48.2	109	42.7	78	38.9	115	44.4	98
	Late fall	54.4	111	42.7	97	47.6	87	30.0	89	43.7	96
	Spring	49.1	100	44.1	100	55.0	100	33.8[y]	100	45.5	100
	Early fall w/ inhibitors	44.2	90	40.0	91	36.8	67	34.3	101	38.8	85
	LSD (α = 0.05)[z]	-		-		-		-		-	
Low	Early fall	38.8	68	65.1	83	11.4	29	39.4	87	38.6	70
	Mid fall	45.4	80	68.4	87	16.3	41	29.6	65	39.9	73
	Late fall	64.3	113	71.1	90	30.4	77	49.1	109	53.8	98
	Spring	56.7	100	78.8	100	39.5	100	45.2	100	55.1	100
	Early fall w/ inhibitors	55.2	97	59.3	75	21.9	55	34.8	77	42.8	78
	LSD (α = 0.05)[z]	-		-		-		-		-	
Landscape position means											
High		51.3	-	42.0	-	459.0	-	37.6	-	43.1	-
Low		52.1	-	68.6	-	383.0	-	39.6	-	46.0	-
LSD (α = 0.10)		ns		ns		ns		ns		ns	
	Fertilization means										
	Early fall	50.0	94	50.2	82	19.3c	41	45.2	114	41.1	83
	Mid fall	46.6	88	58.3	95	29.5bc	63	34.3	87	42.2	85
	Late fall	59.4	112	56.9	93	39.0ab	83	39.6	100	48.7	97
	Spring	52.9	100	61.5	100	47.2a	100	39.5	100	50.3	100
	Early fall w/ inhibitors	49.6	94	49.6	81	29.4bc	63	34.6	88	40.8	81
	LSD (α = 0.05)	ns		ns		17.5		ns		ns	

ANOVA	Kane (2000/01) df	$P > F$	Kane (2001/02) df	$P > F$	Rosser (2001/02) df	$P > F$	Brandon (2001/02) df	$P > F$	Mean all sites df	$P > F$
Landpos	1	0.95	1	0.23	1	0.37	1	0.89		
Trt	4	0.43	4	0.79	4	0.033*	4	0.77		
Landpos*Trt	4	0.12	4	0.95	4	0.96	4	0.46		
Block(Landpos)	6	0.0002*	6	0.0001*	6	0.0001*	6	0.0001*		
Residual C.V. (%)		26.6		41.0		51.7		48.3		
Site year									3	0.20
Landpos									1	0.73
Site year*Landpos									3	0.32
Trt									4	0.12
Site year*Trt									12	0.65
Landpos*Trt									4	0.30
Site year*Landpos*Trt									12	0.95
Block(Site year*Landpos)									24	0.0001*
Residual C.V. (%)										41.0

a-c Mean values followed by the same letter (within columns) are not significantly different.
[z] LSD for individual treatments within a landscape position is not reported because there was no Landpos*Trt interaction.
[y] Brandon 2001/2002 had 1 missing spring sample in the high landscape position: therefore values were estimated by SAS.
† Significant at $P < 0.10$ (used only for landscape position variables and interactions).
* Significant at $P < 0.05$.

In the low landscape positions at Kane (2000/01), late fall-banded N produced grain yield increases that were significantly greater than those for early fall-banded N, but similar to those for mid fall, spring and early fall-banded N with inhibitors. At Brandon (2001/02) late fall and spring-banded N significantly increased grain yields over mid fall-banded N in the low landscape positions, but not over early fall-banded N or early fall-banded N with inhibitors. The reasons for the inconsistent results at Brandon (2001/02) are not known.

When the data from the intensive sites were combined, there was a significant landscape position by treatment interaction for grain yield increase, with late fall and spring-banded N producing significantly greater increases in grain yield than early, mid, and early fall-banded N with inhibitors in the low landscape positions (Table 3.14). Grain yield increases in the low landscape positions were 22 to 27% higher for late fall and spring-banded N than for early fall, mid fall and early fall with inhibitors. These figures correspond quite closely to those in the MB Agriculture and Food Soil Fertility Guide (2001), which state that the efficiency of fall-banded N in Manitoba will be, on average, 20% lower than spring-banded N. There were no differences in fertilizer NUE among treatments when the four intensive sites were combined (Table 3.15). However, late fall and spring-banded N had N use efficiencies that appeared to be 7.9 to 9.5% greater than early and mid fall-banded treatments, with and without inhibitors. Differences in fertilizer NUE among fertilization treatments also appeared to be much larger in the low landscape positions than in the high landscape positions. In the high landscape positions, the average fertilizer NUE of fall-banded N (without inhibitors) was 97% that of spring-banded N, whereas the average fertilizer NUE of fall-banded N in the low landscape positions was only 80% that of spring-banded.

In the low landscape positions at Kane (2000/01), early fall-banded N with inhibitors produced greater increases in grain yield than early fall-banded N without the inhibitors. However, there were few other significant differences between early fall-banded urea with inhibitors and early fall-banded urea with respect to increases in grain yield and fertilizer NUE at the individual sites or when the data was combined, in either landscape position (Table 3.14 and 3.15). Wet conditions in November of 2000 and May of 2001 (prior to planting) at Kane (2000/01) (Table 3.5) likely increased over-winter losses of N from the early fall-banded treatment without inhibitors, compared to early fall-banded N with inhibitors. The results from Kane (2000/01) are similar to those reported in Kentucky, where Super Urea® was evaluated under field conditions for the production of no-till corn (Wells et al. 1999). Wells et al. (1999) reported that under conditions of excessive rainfall, the Super Urea® produced significantly higher corn yields and N uptake then urea alone. However, at the other three intensive sites there were no differences in crop response between the two early fall applications. Our results are also consistent with past N inhibitor research from Western Canada. In Manitoba limited work at three sites, during two relatively dry years, indicated that the addition of nitrapyrin with urea in bands had little effect on the recovery of applied urea N or on crop yields (Ridley 1977). In Alberta, thiourea, ATC, N-Serve, CS_2, $(NH_4)_2 CS_3$, and K_2CS_3 were tested with fall-applied urea and/or aqueous NH_3 (Malhi and Nyborg 1983b; Malhi and Nyborg 1984; Malhi and Nyborg 1988b; Malhi and Nyborg 1988a; Malhi et al. 1992b). These inhibitors were all effective in slowing nitrification and reducing over-winter N losses of fall-applied fertilizers, especially when the N fertilizer plus inhibitor were banded or nested. However, overall results from these studies were highly variable and crop yields were increased only in situations where conditions for denitrification in the spring were severe.

3.5 Summary and Conclusions

Landscape influences on crop productivity were not consistent over all site-years because of variations in local growing season conditions. Grain yield, straw yield and total crop N uptake were greater in the high landscape positions than in the low landscape positions at three of the four intensive sites. In the high landscape positions, prolonged water saturation of the soil was not common, even in the spring, and therefore the potential for over-winter losses of fertilizer N were much lower than in the low landscape positions.

Spring and late fall applications of fertilizer N generally produced the highest grain yields, straw yields and N uptake by the crop, but the differences among application dates were not always significant. The largest differences between spring and early fall-banded N were found in the low landscape positions. In the low landscape positions, grain yield, straw yield, total N uptake, grain yield increases and fertilizer NUE were consistently higher for the late fall and spring applications than for early fall, mid fall and early fall with inhibitors. Higher soil moisture contents in the low areas during the fall and early spring, combined with early fall applications of ammoniacal fertilizers, likely increased the potential for over-winter and early spring losses of NO_3^--N via denitrification. In Saskatchewan, Pennock et al. (1992) reported that denitrification activity under a gently sloping landscape displayed a distinct landscape-scale pattern, with denitrification rates higher in the level convergent areas of the landscape than in the level divergent areas. Further research in Saskatchewan reported that denitrification activity increased in convergent landscape positions following the application of N fertilizer in the spring, in conjunction with warm soil temperatures and adequate rainfall (van Kessel et al. 1993). In the current project, urea fertilizer banded later in the fall, when soil temperatures were cool did not convert to nitrate as quickly (Chapter 4) and was less subject to over-winter losses (Chapter 5) than urea banded early in the fall, especially in the low landscape positions.

Overall, there was little apparent crop benefit to the use of the urease and nitrification inhibitors. Only in the low landscape positions at Kane (2000/01) did the early fall-banded urea with inhibitors improve grain yield increases compared to early fall-banded urea without inhibitors. At the other three intensive sites, there was generally no evidence of greater yield or N uptake by the crop with the inhibitors than without, in either landscape position. One possible explanation for the poor overall performance of the inhibitors is that it may not be feasible to expect the inhibitors to maintain the fertilizer N in the NH_4^+ form from mid September to late May when the sites were planted. Another possible explanation is that the potential for N loss may not have been severe enough to fully utilize the capabilities of the NBPT and DCD inhibitors. Therefore, for most grain producers in Manitoba, it is probably more economical and reliable to delay the application of fall-banded fertilizers than to use an inhibitor.

Ridley (1975) reported that the efficiency of fall broadcast and incorporated N was lower in the lowland regions of Manitoba than in the upland regions. Over nine sites, average yield increases of barley from fall-applied N were two-thirds that of spring applications in the lowland regions. However, in the better-drained soils of the Manitoba uplands (13 sites), fall-applied N was generally 85 to 90% as effective as spring-applied urea. In the present study, we found that the average efficiency of fall-banded N, in terms of grain yield increase as a percent of spring-banded N, was approximately 30% better in the high landscape positions than in the low landscape positions within the same field. These findings suggest that that there is as much variability in efficiency of fall-applied N within a field as there is between regions of southern Manitoba. This also suggests that selection of suitable timing for application of fertilizer N to optimize crop yields is much more critical for poorly drained fields, and for poorly drained areas within a field, than for better drained land. For land that is well-drained, early fall application of N fertilizer is a viable option. However, on poorly drained land where the potential is high for prolonged flooded conditions during the fall or spring, producers should wait as long as possible in the fall, or until the spring, to apply nitrogen fertilizer.

4 TRANSFORMATION OF FALL-BANDED UREA: EFFECT OF APPLICATION DATE, LANDSCAPE POSITION AND FERTILIZER ADDITIVES

Key Words: fall-banded N, spring-banded N, landscape position, inhibitors, N-(n-butyl) thiophosphoric triamide (NBPT), Dicyandiamide (DCD), wheat (*Triticum aestivum*), urea fertilizer, nitrification, soil temperature

4.1 Abstract

A two-year study was initiated in the fall of 2000 to generate fundamental information on the effects of application date, landscape position and a urease and nitrification inhibiter on the rate of transformation of fall-banded urea fertilizer into ammonium and eventually nitrate under Manitoba conditions. Landscape position did not have a significant effect on the conversion of banded-urea to nitrate under the moisture conditions present at the sites. Delaying the date of application of fall-banded urea fertilizer into the late fall and the presence of NBPT and DCD slowed nitrification and increased the percent recovery of fertilizer N as NH_4^+-N in the soil prior to freeze-up. Date of application, soil temperature on the date of application, the accumulation of soil heat units (SHU) and nitrification heat units (NHU) were all linearly related to the percent of recovered fertilizer N as NH_4^+-N. Accumulated SHU and NHU best described the relationship with percent of recovered fertilizer N as NH_4^+-N at the end of the fall, with and without inhibitors.

4.2 Introduction

The application of nitrogen (N) fertilizer in the fall is a management practice common to the temperate climates of North America where a single spring sown annual crop is often grown. Applying fertilizer N in the fall has numerous benefits to the producer: it reduces the number of tillage operations necessary in the spring, preserving the quality of the seedbed and soil moisture; it allows the producer to make better use of off-season labour and decrease the workload during the busy spring planting period; and the producer can capitalize on fertilizer prices that are, on average, 10 to 15% lower in the fall than in the spring (Malhi et al. 1992a; MB Agriculture and Food Soil Fertility Guide 2001). However, there are certain risks involved with fall fertilization of N fertilizers. Soil temperatures in the fall can be warm and application of ammoniacal fertilizers early in the fall is expected to form more nitrate prior to the soil freezing than late fall applications (Malhi and Nyborg 1979; Malhi and McGill 1982), increasing the potential for N losses via leaching and denitrification in the early spring (Malhi and Nyborg 1983a; Malhi and Nyborg 1990a; Nyborg et al. 1990; Nyborg et al. 1997). For example, Malhi and Nyborg (1990a) report that the recovery of fall-applied urea, broadcast and incorporated, as soil mineral N in the spring increased from 30% when N was applied on September 19th to 76% on November 6th.

One of the difficulties faced by producers in the south-eastern region of the Canadian prairies is that heavy rains often occur in the fall making field operations difficult. For this reason, farmers in Manitoba are interested in applying N fertilizer as soon as possible after harvest while soil conditions are still favourable. Current guidelines in Manitoba recommend that producers delay application in the fall until soil temperatures have cooled to 5°C (MB Agriculture and Food Soil Fertility Guide 2001). At 5°C, the rate of nitrification is half that at 16°C, and a quarter the rate at 27°C (Chandra 1962). However, the producer must weigh the risk of missing the window of opportunity to work on the fields in the fall with the increased chance of over-winter N losses and lower fertilizer efficiencies.

Nitrification is a two-step process that occurs naturally in the soil environment wherever ammonium (NH_4^+) is present and conditions for nitrification are favourable. When ammonium based fertilizers are applied to the soil, aerobic, autotrophic bacteria oxidize the NH_4^+ to nitrite (NO_2^-) and then to nitrate (NO_3^-) (Schmidt 1982). Energy released during nitrification, although small, provides the energy needed by these microorganisms for growth and cell maintenance (Yeomans 1991). The first step in the nitrification pathway is the oxidation of NH_4^+ to NO_2^- by certain autotrophic bacteria including *nitrosomonas, nitrosolobus, nitrospira,* and *nitrosovibrio,* of which the most common species is *nitrosomonas*. A natural bi-product of this first step in the nitrification process is the acidification of the surrounding soil due to the release of H^+ ions during the reaction. The second step of the nitrification process is the oxidation of NO_2^- to NO_3^-, which is catalyzed by a second group of aerobic, autotrophic bacteria called *nitrobacter*.

The rate at which nitrification proceeds is heavily dependent on soil environmental conditions, in particular: soil temperature, soil moisture, aeration status of the soil, supply of NH_4^+, soil pH and the population of nitrifying organisms (Havlin et al. 1999). Nitrification rates generally increase with increasing temperatures (Chandra 1962; Pang et al. 1977; Malhi and McGill 1982; Schmidt 1982; Yadvinder-Singh and Beauchamp 1987), with fastest rates occurring when soil conditions are moist, well-aerated, have a neutral pH, and a high population of nitrifying soil microorganisms (Pang et al. 1973; Gilmour 1984). The rate of disappearance of ammonium and the formation of nitrate is reported to obey zero-order kinetics at low temperatures (Gilmour 1984), and first order kinetics at optimal temperatures, especially at low rates of N (Malhi and McGill 1982). The optimum soil temperature for the nitrification of NH_4^+ to NO_3^- is generally between 25 to 35°C, with a Q_{10} of 2 over the range of 5 to 35°C (Havlin et al. 1999). However, this optimum temperature is not universal. Malhi and McGill (1982) reported that the optimum temperature for nitrification in soils from Alberta was 20°C and concluded that soil microorganisms are able to adapt to local climates. Nitrification is significantly slower in cool soils and several researchers have reported that nitrification essentially stops when soil temperatures reach 4 to 5°C (Schmidt 1982; Gomes and Loynachan 1984). However, due to local microbial adaptation, nitrification has also been reported to continue in appreciable amounts during the late fall and early winter when soils are at or near freezing (Malhi and Nyborg 1979; Malhi and McGill 1982; Malhi and Nyborg 1986). For example, Malhi and Nyborg (1986) sampled fall fertilized trials throughout the winter, and measured an average nitrification rate of 0.19 kg ha^{-1} day^{-1} and a total increase of 48 kg N ha^{-1} in the top 60 cm of a frozen soil in Alberta.

Numerous studies have reported that the recovery of applied-N in the fall as NH_4^+-N increased significantly by banding or nesting (compared to broadcast and incorporation), especially in soil zones where moisture supply is relatively high (Malhi and Nyborg 1979; Malhi and Nyborg 1984; Monreal et al. 1986; Malhi and Nyborg 1988a; Malhi and Nyborg 1990b; Yadvinder-Singh et al. 1994; Malhi et al. 2001). Banding or nesting of fall-applied N slows the rate of nitrification of fertilizer N to NO_3^- by reducing the exposure of the fertilizer to the soil (low surface to mass ratio); and the high pH, ammonia concentration and osmotic pressures found within the fertilizer band creates a toxic environment for soil microorganisms (Harapiak et al. 1993). Higher soil NH_4^+-N levels in the fall generally translate into reduced over-winter losses of NO_3^- and increased overall grain yields and total crop N uptake. Malhi et al. (1989) reported no real differences in the percent recovery of N^{15} in the crop or soil when the application of banded urea application was delayed from mid to late October. However, in Ontario, grain yields and N uptake of winter wheat were still improved by delaying the application of large urea granules in the fall (Yadvinder-Singh and Beauchamp 1988b; Yadvinder-Singh et al. 1994). Gomes and Loynachan (1984) used a time-temperature interaction to explain much of the variability of recovered NH_4^+-N in the fall and spring from anhydrous ammonia applied at three different times in the fall (Oct. 9, Oct. 27, and Nov. 14) in central Iowa. These scientists observed a highly significant linear relationship ($R^2 = 0.84$) between the percentage of NH_4^+-N recovered in the bandrow and total accumulation of soil heat units over the fall and early spring.

Landscape position is another factor that could affect the rate of nitrification of fall-banded N fertilizers. After heavy rains in the fall, water often ponds in the lower convergent areas of the field (Hanna et al. 1982). Nitrifying organisms are sensitive to soil moisture and nitrification rates are generally highest at soil water contents near field capacity (Havlin et al. 1999). Malhi and McGill (1982) determined that the relative nitrification rate increased with increasing soil moisture potential from –1500 to –33 kPa. This indicates that appreciable nitrification can be expected even when the soil is very dry, such as the permanent wilting point (-1500 kPa). At the other extreme, nitrification was reported to cease at 0 kPa due to the shortage of oxygen in the soil caused by excess water (Malhi and McGill 1982).

Other effective tools in retarding the conversion of urea fertilizer into nitrate are urease and nitrification inhibitors. N-(n-butyl) thiophosphoric triamide (NBPT) is a promising urease inhibitor that reduces urease activity and slows the hydrolysis of urea to NH_4^+ by competing with urea for active sites on the urease enzyme complex (Rawluk et al. 2001). Numerous inhibitors of nitrification have been used in research trials to improve the efficiency of fall-applied N (Malhi and Nyborg 1983b; Malhi and Nyborg 1988b; Malhi et al. 1992b; Yadvinder-Singh et al. 1994). Recently, there has been renewed interest in the use of the nitrification inhibitor dicyandiamide (Didin or DCD), because it is less volatile than other nitrification inhibitors (i.e. nitrapyrin) and can be easily blended with solid N fertilizers (Guiraud and Marol 1992). Under field conditions, the effectiveness of DCD in retarding the nitrification of urea was reported to be highest on coarse-textured soils, in poorly drained soils where conditions are conducive to NO_3^- losses, and when N rates were not in excess of crop requirements (Malzer et al. 1989; Yeomans 1991). In England, DCD was as effective as nitrapyrin in slowing the over-winter nitrification of injected aqueous urea, applied late in the fall when soil temperatures were below 5°C (Ashworth and Rodgers 1981). In Ontario, fall-applied large urea granules containing low rates of DCD slowed nitrification (Yadvinder-Singh and Beauchamp 1987; Yadvinder-Singh and Beauchamp 1988a) and reduced over-winter losses in winter wheat (Yadvinder-Singh and Beauchamp 1988b). However, the effectiveness of a double inhibited formulation of urea containing NBPT and DCD in slowing the transformation of urea fertilizer has not been investigated in fall banding trials in Western Canada.

The objective of this chapter is to document the transformation of banded urea fertilizer over the fall and generate fundamental information on the effect of landscape position, application date, soil moisture, soil temperature, and fertilizer additives on the rate of ammoniacal N transformation into nitrate via the nitrification process.

4.3 Materials and Methods

4.3.1 Site Selection and Description

Field experiments were conducted in Manitoba over two fertilization/growing seasons: fall 2000 to harvest 2001 (year one), and fall 2001 to harvest 2002 (year two). In total, four small plot sites were established throughout southern Manitoba. In 2000/2001, one experiment was located near the town of Kane on Red River/Osborne (Gleyed Rego Black Chernozem/Rego Humic Gleysol) heavy clay soil. In the second year of the project, two sites were situated on Red River/Osborne heavy clay soil near the towns of Kane and Rosser, while a third site was located on Newdale (Orthic Black Chernozem) clay loam soil at the AAFC Brandon Research Centre's Phillips Research Farm. The Red River/Osborne and Newdale soil series represent common soils in eastern and western Manitoba respectively.

4.3.2 Experimental Design and Treatments

The experimental design and treatments used in this project have already been described in detail in Chapter 3 (section 3.3.2). Three of the four sites were located in the relatively level lacustrine landscape of the Red River Valley (Kane (2000/01), Kane (2001/02) and Rosser (2001/02)) with typical elevation differences of less than one metre per kilometre within each site. The topography at the Brandon site was slightly more undulating, and representative of glacial till landscapes in the Black soil zone of south-western Manitoba. A split-plot design was utilized at all sites, with landscape position main plots and fertilization treatment subplots. Landscape positions studied in this experiment were defined as "high" and "low" based on their relative elevations to one another within the field. The individual low landscape positions were localized concave areas in which temporary ponding occurred in the spring after snowmelt or after heavy rainfalls, whereas the high positions were slightly raised divergent areas located between these low positions where more water shedding occurred. Separate main plots were located in an individual high or low landscape position (four of each) throughout the field. Each main plot contained six, two-metre by 10-metre fertilization treatment subplots, with all six treatments assigned at random to the subplots within the main plot.

In each experiment, nitrogen fertilizer was applied at three dates in the fall between mid-September and mid-October, and one time in the spring, at planting. All nitrogen fertilizer was applied as urea (46-0-0) banded at a rate of 80 kg N ha^{-1}, with 40 cm spacing, at a depth of 7.5 cm. The modest rate of nitrogen was meant to keep each N treatment within the crop's responsive range. The six fertilization treatments were based on time of fertilizer application and use of inhibitors. Conventional urea was banded in early fall, mid fall, late fall and spring (mid-row banded at time of planting). In addition, there was a control where no N fertilizer was applied and a treatment where a urease and nitrification inhibitor (IMC-Agrico Super Urea® containing NBPT and DCD) was applied in the early fall. Results from only the fall-applied treatments and control are reported in this paper. Application of the urea fertilizer in the fall was targeted for September 15 (early fall), September 30 (mid fall) and October 15 (late fall) of each year. However, in year one, excess moisture in the fall caused a delay in application dates to September 29, October 12, and October 26 at Kane (2000/01). In year two, treatments were applied at Kane (2001/02) on September 26, October 9, and October 19, at Rosser (2001/02) on September 19, October 1, and October 19, and at Brandon (2001/02) on September 15, October 1, and October 15. Therefore, early fall-banded N included all fertilizer applications occurring between September 15 and September 29, mid fall-banded N were those applications occurring between September 30 and October 14, and late fall-banded N included any applications that occurred after October 15. At time of fertilization, the band rows were clearly marked with small wooden stakes and pin flags to ensure precise sampling of the banded areas, especially in the spring.

4.3.3 Soil Sampling and Analyses

To characterize the overall N behaviour in each main plot, the soil was sampled to 120 cm using a Giddings tractor mounted soil sampler in mid-September prior to fertilization (Chapter 3, Table 3.2). Separate soil samples of 0-15 and 15-30 cm were also gathered three times in the fall, at approximately two-week intervals. These soil samples were taken from the band zone and between the band zones to monitor the transformation of banded fertilizer. The band zone was sub-sampled 20 times within each subplot; five cores taken at each of four different band locations, using a JMC "Backsaver" probe with a 2 cm diameter coring tube. The sampling pattern for the band zone was in a "W" shape, with one sub-sample taken from the centre of the band and the other sub-samples taken at 2 and 4 cm on both sides of the band to accurately monitor the transformation of the banded fertilizer over the fall. Zones between bands were also sampled at four locations within each subplot. The between band row samples were also taken as 2 cm diameter cores of 0-15 and 15-30 cm deep, but at distances of 10, 15, 20, 25 and 30 cm from a band (i.e., the sub-samples that are 25 and 30 cm from one band were actually 15 and 10 cm away from the adjacent band). The control treatment was sampled with 20 random cores throughout each subplot. Sub-samples were mixed into one composite for each combination of zone, sample depth and treatment in the field. Weather and soil conditions again dictated when the fall soil samples were collected at the individual sites. In year one at Kane (2000/01), soil samples were collected on October 12th and October 26th but the third fall sampling period was missed because of snow and frozen soil conditions. In the second year of the study, fertilized subplots were sampled three times at Kane (2001/02) (October 9, October 23, November 1) and Brandon (2001/02) (October 1, October 15, and November 1), and twice at Rosser (2001/02) (October 2 and October 30). Wet soil conditions forced the cancellation of the mid October sampling period at Rosser (2001/02).

Moist soil samples were refrigerated and stored at a temperature of 2°C, until being air dried at 30-35°C for 48 to 72 hours and ground to pass a 2 mm sieve. Ground soil samples were extracted for water soluble nitrate and nitrite, exchangeable ammonium, and urea nitrogen by shaking 5 g of soil with a 25 mL solution of 2M KCl and phenyl mercuric acetate (PMA) for 30 minutes and filtered through Whatman no. 40 filter paper. PMA, a urease inhibitor, was added to the solution to stop the significant hydrolysis of urea by soil urease that can occur during the extraction process (Douglas and Bremner 1970). A Technicon Autoanalyzer II Single-Channel Colorimeter was used to determine the concentrations of NO_3^--N + NO_2^--N and NH_4^+-N in the extract using the automated cadmium reduction method and the automated phenate colorimetric method respectively (Maynard and Kalra 1993). In this method, NO_3^--N is reduced to NO_2^--N;

however, NO_2^--N in the extract was measured by analyzing the original extract a second time without the reducing step (Ellis 2001). NO_3^--N was determined by subtracting the NO_2^--N from the NO_3^--N + NO_2^--N value. The Technicon method used in the determination of urea-N is a modification of the carbamido-diacetyl reaction, as described by Douglas and Bremner (1970). Electrical conductivity (EC) and pH were measured using a 2:1 water to soil extract, an Orion conductivity meter and a Fisher Accumet pH meter (Hogg and Henry 1984; Hendershot et al. 1993).

4.3.4 Weather Data

A detailed description of the climatic data collected at the intensive sites has already been described in Chapter 3 (section 3.3.5). General weather conditions, including mean monthly aerial temperature and total monthly precipitation, for the Winnipeg and Brandon areas are reported in Chapter 3 (Tables 3.3 and 3.4 respectively). Rainfall data was collected at each site located in the Red River Valley (Chapter 3, Table 3.5) using a tipping bucket rainguage and a HOBO® event driven data logger (Onset Computer Corporation - Hobo Event logger User's Manual 1999). Rainfall data during the growing season was also collected at Brandon (2001/02) by Agriculture and Agri-Food Canada (Chapter 3, Table 3.5). In addition, gravimetric soil moisture contents (w%) at depths of 0-7.5, 7.5-15 and 15-30 cm were measured on a weekly basis during the fall and early spring at Kane (2000/01), Kane (2001/02) and Rosser (2001/02) (Chapter 3, Fig. 3.1, 3.2 and 3.3 respectively). Gravimetric moisture contents at Brandon (2001/02) were not measured due to resource limitations.

Soil temperatures were monitored electronically every 60 minutes using StowAway® Tidbit® temperature probes (Onset Computer Corporation - Stowaway Tidbit User's Manual 2000). One tidbit was placed directly into one of the fertilizer bands, at a depth of 7.5 cm, within each early fall application subplot. In year one, soil temperatures at Kane (2000/01) reached 0°C on November 18, 2000. In year two, the soil froze at Kane, Rosser, and Brandon on November 26^{th} and 27^{th}. The soils at all sites generally remained frozen and snow covered until thawing in April. Monitoring of both soil moisture and temperature was focused on the periods from mid-September to freeze-up and from early spring to planting. Soil temperature reported for day of application is an average of hourly temperatures during the day.

Gomes and Loynachan (1979) used average weekly soil temperatures as accumulated heat units to predict the rate that anhydrous ammonia was nitrified to NO_3^--N in the soil in the presence and absence of a nitrification inhibitor. A similar method was used by Malhi and Nyborg (1990a), who used soil degree-days, an accumulation of the average daily soil temperature from date of application to the first day that the soil reached 0°C, to predict the relative efficiency of fall broadcast and incorporated urea. In this project, cumulative soil heat units (SHU) were determined as an accumulation of average daily °C (monitored on an hourly basis (T_i)) at 7.5 cm soil depth from date of application to date of soil sampling, using the concepts of Gomes and Loynachan (1979) and Malhi and Nyborg (1990a), in conjunction with the model developed by Sands et al. (1979) for determining the physiological age of potatoes:

$$SHU = \sum \frac{\left(\sum^{i}(T_i)\right)}{24}$$

Nitrification is reported to obey zero-order kinetics at low temperatures (Gilmour 1984) and is significantly slower in cool soils and essentially stops when soil temperatures reach 4 to 5°C (Schmidt 1982; Gomes and Loynachan 1984). Malhi and McGill (1982) found that while significantly slower, nitrification of NH_4^+-N continued at low rates at or near freezing (-4°C) in three different soils (Gray Luvisol, Dark Gray Chernozem, and Black Chernozem), with rates becoming exponentially slower at soil temperatures below 4°C. To account for the exponential changes in nitrification rates at various soil temperatures, we applied the equation from the slope of the line for the Black Chernozemic soil ($y = 0.059e^{0.21x}$, $R^2 = 0.97$***) to the equation for cumulative soil heat units and defined these as cumulative nitrification heat units (NHU) ($A = 0.059$, $B = 0.21$, T_i = hourly soil temperature at 7.5 cm):

$$NHU = \sum \frac{\sum^{i}(Ae^{B(Ti)})}{24}$$

4.3.5 Data Analyses

A detailed description of the statistical analyses used in this experiment can be found in Chapter 3 (section 3.3.6). Statistical analyses were conducted using the General Linear Model procedure of the Statistical Analysis System (SAS) package (SAS 1999). Descriptive statistics were used to test the data for normality and skewness using the Proc Univariate function of SAS. Fisher's (protected) least significant difference (LSD) test was used to compare the subplot (fertilization) and main plot (landscape position) treatment means (Steel et al. 1987). The LSMEANS test was used to compare the fertilization treatments within each landscape position (note: the LSMEANS function in SAS does not provide an LSD value). For the fertilization treatment means, a probability level (α) of 0.05 was used as the significance threshold for the soil and plant variables. However, due to the high variability inherent in field-based landscape experiments a higher probability level of 0.10 was used to detect treatment differences among landscape positions. This higher probability level is within the typical range of probability values ($P \leq 0.10$ to 0.20) used in many landscape studies (Pennock et al. 1992; van Kessel et al. 1993; Corre et al. 1996; Beckie and Brandt 1997; Jowkin and Schoenau 1998).

In addition, simple linear regression analysis (r^2) was used to test the relationship of the percent of recovered fertilizer N as NH_4^+-N as a function of date of fertilizer N application, average soil temperature at 7.5 cm on day of application, cumulative SHU, and cumulative NHU. The percent of recovered fertilizer N as NH_4^+-N was determined as:

$$\frac{NH_4^+\text{-N (kg ha}^{-1}\text{) fertilized plot - }NH_4^+\text{-N (kg ha}^{-1}\text{) in the control plot}}{\text{total inorganic N (kg ha}^{-1}\text{) fertilized plot - total inorganic N (kg ha}^{-1}\text{) control plot}} \times 100$$

with total inorganic N determined by the sum of NH_4^+-N, NO_3^--N, and NO_2^--N. Variability and normality of the residual data was tested using diagnostic plots generated by SAS.

Linear regression analysis was also used to test the relationships of percent of recovered fertilizer N as NH_4^+-N in the absence and presence of NBPT and DCD inhibitors, as a function of cumulative SHU and cumulative NHU. The Proc GLM procedure was used to compare the slopes of the linear relationships between early fall-banded urea, with and without inhibitors.

4.4 Results and Discussion

For each fertilization treatment, the majority of the apparent fertilizer N was found within a zone 5 cm to each side and 7.5 cm above and below the band within two weeks of application date (Appendices O to Z). However, by the final sampling period in the fall it was apparent that the fertilizer N applied in September and early October had already moved downward and laterally from the band zone. Therefore, to account for all banded fertilizer N in the soil, statistical analyses were performed using the bulk band zone and between band zone samples to a depth of 30 cm.

4.4.1 Transformations of Urea Fertilizer over the Fall

In order to monitor the transformation of banded fertilizer over the fall, soil samples were gathered at intervals of approximately two-weeks at each site. The most significant effects in terms of landscape position, application date and fertilizer additives were found at the end of the fall, in both years of the study. Therefore, the early and mid fall sampling periods are not reported. At the final fall soil sampling period in year one, the low landscape positions had significantly more NH_4^+-N than the high landscape positions at Kane (2000/01) (Table 4.1). This suggests that the rate of nitrification of fertilizer N was slower in the low landscape positions than in the high landscape positions at this site. However, there were no significant differences between landscape positions in terms of NO_3^--N and total inorganic N. In year two, there were no significant differences between landscape positions with respect to NH_4^+-N at Kane (2001/02), Rosser (2001/02) and Brandon (2001/02) (Table 4.1).

Table 4.1. Total recovered soil mineral N at the final fall sampling period prior to freeze-up at the intensive sites: 0-30 cm soil depth

Treatment		Site											
		Kane (2000/01) (26/10/2000)			Kane (2001/02) (01/11/2001)			Rosser (2001/02) (30/10/2001)			Brandon (2001/02) (01/11/2001)		
Landscape position	Fertilization	NH_4^+-N	NO_3^--N	Total Inorganic N	NH_4^+-N	NO_3^--N	Total Inorganic N	NH_4^+-N	NO_3^--N	Total Inorganic N	NH_4^+-N	NO_3^--N	Total Inorganic N
		(kg ha^{-1})[z]											
High	Early fall	75.3	32.5	109.5	45.4	60.6	109.4	46.3c	75.3	121.6ab	23.4cd	105.5	131.8b
	Mid fall	79.2	29.7	111.0	55.3	37.8	95.4	70.9b	62.0	133.2a	72.0b	59.7	133.1b
	Late fall	-	-	-	68.0	37.6	107.4	83.7a	39.2	123.0ab	141.9a	40.6	182.6a
	Control (no N)	60.2	17.4	79.1	18.1	37.2	55.3	26.2d	31.5	58.0c	10.6d	24.9	35.6c
	Early fall w/ inhibitors	81.9	30.4	113.9	49.3	60.5	110.5	56.2c	60.2	116.6b	47.5bc	65.9	113.4b
	LSD (α = 0.05)	-[y]	-[y]	-[y]	-[y]	-[y]	-[y]	na[x]	-[y]	na[x]	na[x]	-[y]	na[x]
Low	Early fall	78.5	29.7	111.1	43.5	54.9	102.2	44.2c	63.0	107.3b	11.5b	67.9	80.8a
	Mid fall	96.8	26.0	126.1	70.8	45.7	121.0	65.6b	45.7	111.3b	38.7b	31.8	73.4a
	Late fall	-	-	-	67.0	26.1	95.7	116.9a	31.3	148.3a	73.6a	14.9	89.9a
	Control (no N)	62.5	14.3	79.4	22.2	20.7	43.9	26.9d	21.4	48.3c	7.8b	7.3	15.1b
	Early fall w/ inhibitors	89.4	28.4	120.4	60.6	45.4	108.3	56.8b	48.0	104.9b	36.7b	51.9	88.6a
	LSD (α = 0.05)	-[y]	-[y]	-[y]	-[y]	-[y]	-[y]	na[x]	-[y]	na[x]	na[x]	-[y]	na[x]
Landscape position means													
High		74.1b	27.5	103.4	47.2	46.7	95.6	56.7	53.6a	110.5	59.1	59.3a	119.3
Low		81.8a	24.6	109.2	52.8	39.6	94.2	62.1	41.9b	104.0	33.7	34.7b	69.5
LSD (α = 0.10)		5.7	ns	ns	ns	ns	ns	-[w]	5.5	-[w]	-[w]	12.8	-[w]
	Fertilization means												
	Early fall	76.9b	31.1a	110.3b	44.4c	57.7a	105.8a	45.2	69.2a	114.4	17.5	86.7a	106.3
	Mid fall	88.0a	27.9a	118.5a	63.0ab	41.8b	108.2a	68.2	53.8b	122.3	55.4	45.7c	103.3
	Late fall	-	-	-	67.5a	31.8bc	101.5a	100.3	35.3c	135.7	107.8	27.7d	136.2
	Control (no N)	61.4c	15.8b	79.3c	20.1d	28.9c	49.6b	26.6	26.4d	53.1	9.2	16.1d	25.3
	Early fall w/ inhibitors	85.6a	29.4a	117.1ab	54.9bc	52.9a	109.4a	56.5	54.1b	110.7	42.1	58.9b	101.0
	LSD (α = 0.05)	7.6	4.0	8.2	-[x]	-[x]	-[x]	-[w]	7.3	-[w]	-[w]	11.9	-[w]

ANOVA	df	$P > F$			df	$P > F$			df	$P > F$			df	$P > F$		
Landpos	1	0.04*	0.49	0.27	1	0.15	0.14	0.83	1	0.35	0.006*	0.20	1	0.014*	0.0097*	0.0066*
Trt	3	0.0001*	0.0001*	0.0001*	4	0.0001*	0.0001*	0.0001*	4	0.0001*	0.0001*	0.0001*	4	0.0001*	0.0001*	0.0001*
Landpos*Trt	3	0.17	0.95	0.26	4	0.39	0.19	0.16	4	0.0007*	0.82	0.0018*	4	0.056†	0.30	0.023*
Block(Landpos)	6	0.31	0.0002*	0.029*	6	0.43	0.11	0.24	6	0.0067*	0.19	0.15	6	0.41	0.017*	0.024*
Residual C.V. (%)		9.3	14.6	7.4		20.2	24.6	16.9		14.1	14.9	9.9		49.3	24.4	23.6

a-d Mean values followed by the same letter (within columns) are not significantly different.

[z] Assuming a bulk density of 1.24 g cm^{-3} for 0-15 cm depth and 1.33 g cm^{-3} for 15-120 cm.

[y] LSD for individual treatments within a landscape position is not reported because there was no Landpos*Trt interaction.

[x] Not applicable (na) because LSMEANS was used, which does not provide an LSD value.

[w] LSD is not reported b/c of significant Landpos*Trt interaction.

[v] Total inorganic N = (NH_4^+-N + NO_3^--N + NO_2^--N).

† Significant at P < 0.10 (used only for landscape position variables and interactions).

* Significant at P < 0.05.

One possible explanation for the apparently slower nitrification rate within the low landscape positions at the site situated on heavy clay soil at Kane (2000/01) could be that the high soil moisture contents in the low landscape positions at this site (Chapter 3, Fig. 3.1) reduced the availability of oxygen to soil microorganisms. Nitrifying microorganisms are sensitive to soil moisture, and in areas or soils that are prone to moisture deficiencies nitrification rates are generally highest at higher soil water contents. Nonetheless, the soil moisture during the fall typically remained between permanent wilting point and field capacity at all sites. This range of soil moisture is generally conducive to microbial activity (Malhi and McGill 1982). Under these soil conditions, we did not expect that there would be many significant differences between landscape positions with regards to the nitrification of the fall-banded fertilizer.

The high landscape positions contained significantly more NO_3^--N than the low landscape positions at the earliest fall sampling period at Kane (2001/02) (Appendix H). Similarly, at the final soil sampling period in the fall, concentrations of NO_3^--N were significantly greater in the high landscape positions than the low landscape positions at Rosser (2001/02) and Brandon (2001/02) (Table 4.1). We suspect that these differences in NO_3^--N between landscape positions in the fall are primarily the result of higher residual NO_3^- levels in the high landscape positions than the low landscape positions prior to fertilization (Chapter 3, Table 3.2). However, some of the differences in concentrations of NO_3^--N may have been due to differences in nitrification and losses during the fall sampling period.

In addition to landscape position, it is apparent that the recovery of NH_4^+-N is related to date of fall fertilizer N application and the presence of NBPT and DCD (Table 4.1). At Kane (2000/01) mid fall-banded N had significantly higher concentrations of NH_4^+-N and total inorganic N than the early fall-banded treatment without inhibitors. The greater concentrations of total inorganic N from the mid-banded urea suggests that small losses of N from the early fall-banded urea may have occurred during the fall at this site. The addition of NBPT and DCD also resulted in significantly greater concentrations of NH_4^+-N at Kane (2000/01), compared to early-fall banded urea without inhibitors. However, there were no significant differences in NO_3^--N or total inorganic N between the two early fall-banded treatments. At Kane (2000/01), there was also a 62% increase in total inorganic N in the control plots from mid to late October, suggesting that substantial mineralization of soil N occurred during the fall period (Appendix G).

Fertilizer treatment effects in year two were similar to those from year one. The transformation of banded urea fertilizer into NO_3^--N was significantly slowed by lateness of fall fertilization at Kane (2001/02), Rosser (2001/02) and Brandon (2001/02) (Table 4.1). At each site, late fall-banded N had the highest concentrations of recovered NH_4^+-N and the lowest recovered NO_3^--N at the final sampling period in late October/early November.

At Brandon, there was a significant landscape position by treatment interaction for NH_4^+-N and total inorganic N. Late fall-banded N had significantly more NH_4^+-N and total inorganic N than early and mid fall-banded N in both landscape positions. However, there is no simple solution to explain why the apparent recoveries of fertilizer N were so high in the high landscape positions, especially for the late fall application. At Kane (2001/02), there were no significant differences in total inorganic N among application dates suggesting that there were few losses of fertilizer N during the fall at this sites. However, at Rosser (2001/02), late fall-banded N significantly increased total inorganic N compared to early fall and mid fall-banded N in the low landscape positions. In the high landscape positions, there were no differences in total inorganic N. This suggests that some N losses from the early and mid fall-banded N may have occurred in the low landscape positions during the fall at Rosser (2001/02). During the week following application of the mid fall treatment on October 19th, this site received approximately 35 mm of rain (Chapter 3, Table 3.5), creating saturated soil conditions in the low landscape positions and potentially denitrifying some of the nitrified fertilizer N. However, the apparent fertilizer N recovered from the late fall treatment was greater than the amount of fertilizer N actually applied, so sampling error could also have affected the results.

The NBPT and DCD inhibitors appeared to be less effective in the second year of the study, but the trend still indicates that the inhibitors may have slowed the conversion of the fertilizer N into NO_3^--N (Table 4.1). For example, at Rosser (2001/02) and Brandon (2001/02), the NBPT and DCD treatment significantly reduced the amount of NO_3^--N in the soil. At Rosser (2001/02), early fall-banded N with inhibitors had significantly higher concentrations of NH_4^+-N than early fall-banded N without inhibitors in the low landscape positions. There were no differences between early fall-banded treatments in the high landscape positions at any of the sites.

4.4.2 Predicting Recoveries of NH_4^+-N: Effect of Application Date

Predicting recoveries of NH_4^+-N as a function of application date, soil temperature on date of application and time-temperature interactions, with and without the addition of fertilizer additives, would aid producers in determining when they should apply N fertilizer and what potential of the applied fertilizer is at risk to losses in the spring. Manitoba Agriculture and Food currently recommends that producers who wish to apply ammoniacal N fertilizer in the fall delay application as late as possible until the soil temperature has declined to 5°C or less, to minimize the conversion of fertilizer N to NO_3^--N prior to winter. The regression analyses generated from our data support this recommendation. There is a strong linear relationship between the percent of recovered fertilizer N as NH_4^+-N at the beginning of November and date of application in the fall (adj $r^2 = 0.88$***) (Fig. 4.1). The percent recovery of fertilizer N as NH_4^+-N increased from a minimum of 6% when urea fertilizer was banded on September 17 to a maximum of 96% with application on October 19. This suggests that in a typical fall in Southern Manitoba, producers who band ammoniacal fertilizer N in mid to late September can expect that the majority of the fertilizer will have converted to nitrate prior to freeze-up and therefore be vulnerable to leaching and denitrification losses prior to crop establishment.

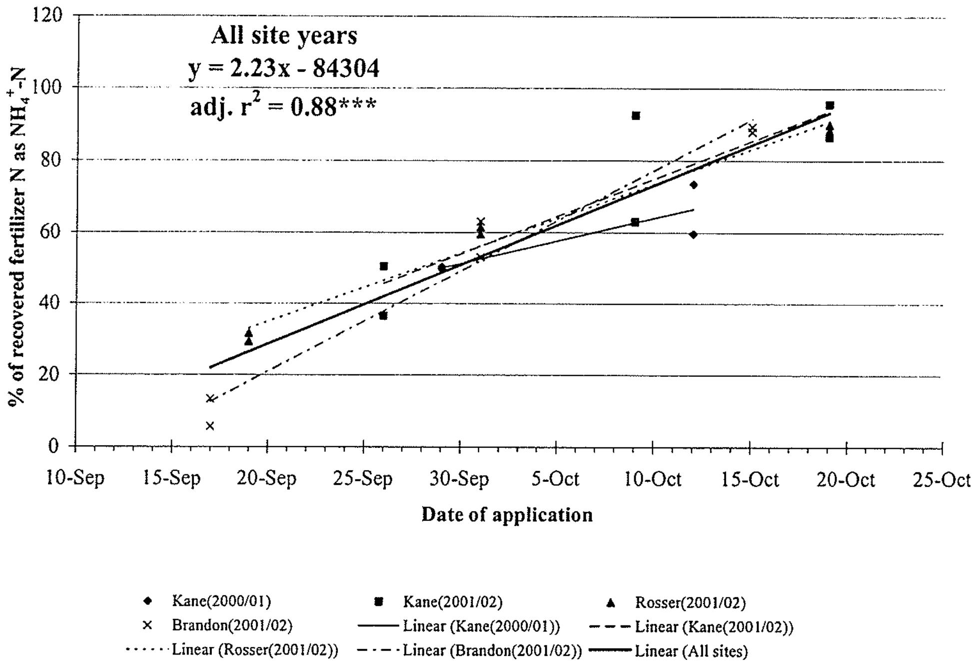

Fig. 4.1. Effect of date of N application in the fall on the percent recovery of fertilizer N as NH_4^+-N in the soil using the final fall sampling period only (*** indicates significance at 0.001 level).

The percent recovery of fertilizer N as NH_4^+-N was inversely related to soil temperature on the date of application in the fall, increasing with decreasing soil temperatures (Fig 4.2). This relationship produced the weakest coefficient of determination of the factors that were tested (adj. $r^2 = 0.69$***), but was still highly significant. Malhi and Nyborg (1990a) reported that soil temperature on the day of fall fertilizer application had a "low" correlation with increases in grain yield (r = -0.55) and attributed the low correlation to day-to-day variability in soil temperatures instead of a steady decline over the fall to the day the soil froze. Nonetheless, delaying application in the fall until soil temperatures had reached 5 to 7°C resulted in 90% (range 87 to 96%) of the fertilizer N remaining as NH_4^+-N at the beginning of November, as opposed to 20% (range 6 to 32%) when fertilizer N was applied when soil temperatures were 12 to 14°C. This should translate into reduced over-winter losses of NO_3^- and increase overall grain yields and total N uptake by the crop. From a practical point of view, both date of fall N application and soil temperature on the date of fall N application adequately describe the transformation of fertilizer N into nitrate. These two variables are the easiest for producers in Manitoba to adopt into their fall fertilization programs.

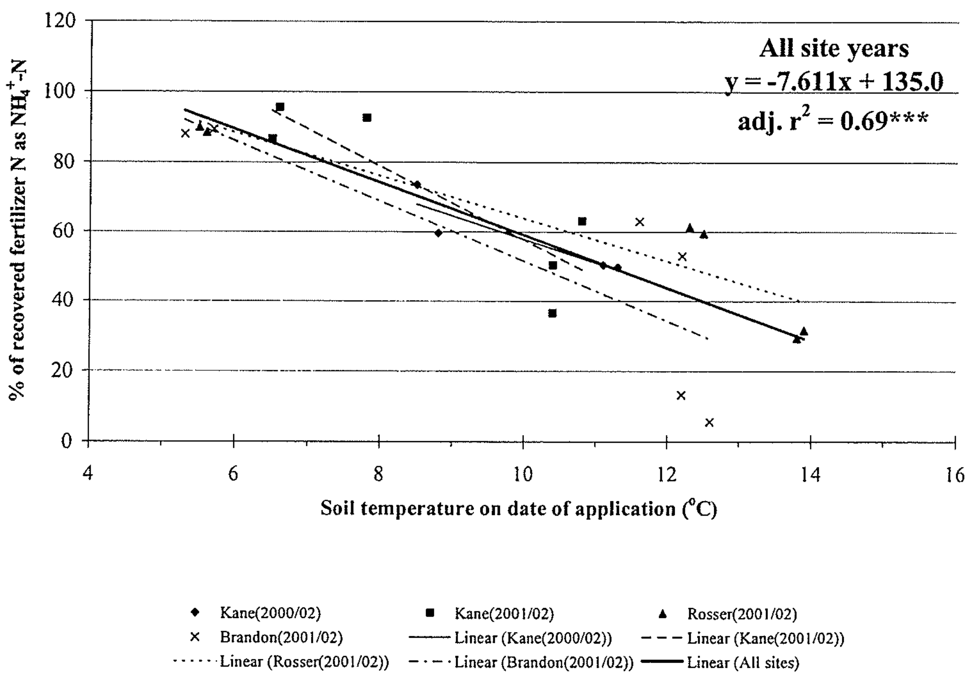

Fig. 4.2. Effect of soil temperature at 7.5 cm on date of N application in the fall on the percent recovery of fertilizer N as NH_4^+-N in the soil using the final fall sampling period only (*** indicates significance at 0.001 level).

However, there is an inherent problem in using date of application or soil temperature on date of application to predict the percent of recovered fertilizer N as NH_4^+-N. Soil temperatures on a particular day or week in the fall of one year may be vastly different from the fall of another year. Therefore, date of application may not adequately reflect environmental conditions for nitrification. Furthermore, day-to-day variability in soil temperature may result in soil temperatures that are much different after fertilizer application than before. In order to account for this year-to-year and day-to-day variability in weather, two time-temperature interactions were examined: cumulative soil heat units (SHU) and cumulative nitrification heat units (NHU).

Regression analysis indicated that there is a very strong negative linear relationship between the percent recovery of NH_4^+-N and both cumulative SHU (adj. $r^2 = 0.90$***) and cumulative NHU (adj. $r^2 = 0.92$***) (Fig. 4.3 and 4.4 respectively). The use of either of these time-temperature parameters to predict nitrification rates were superior to using date of application and soil temperature on the date of application.

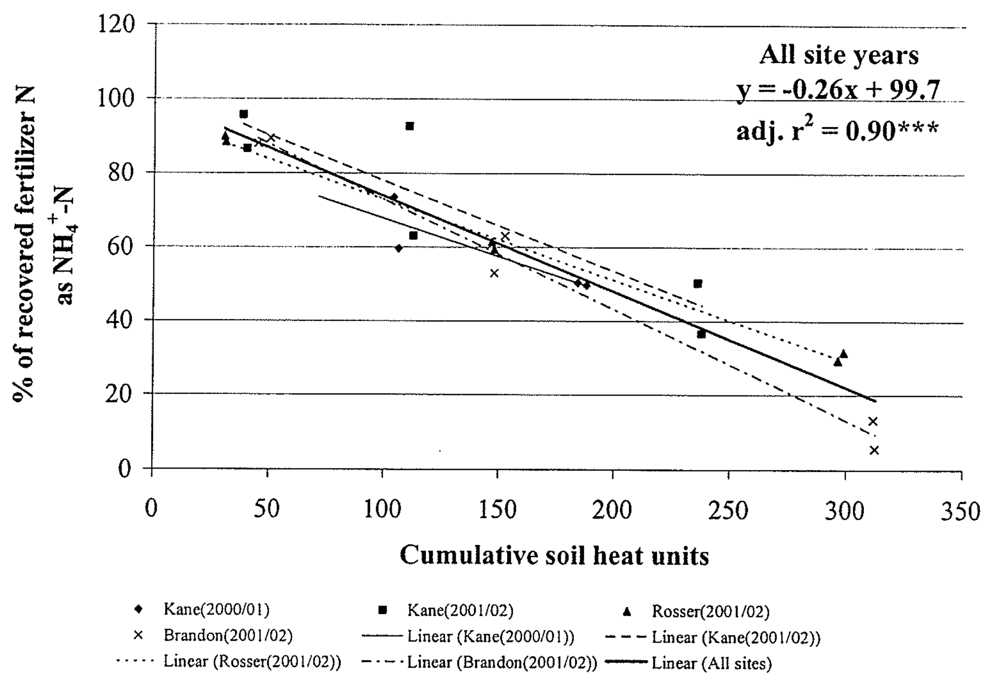

Fig. 4.3. Effect of cumulative soil heat units in the fall on the percent recovery of fertilizer N as NH_4^+-N using the final fall sampling period only (*** indicates significance at 0.001 level).

Overall, the percent recovery of fertilizer N as NH_4^+-N at the end of the fall increased from 22 to 87% when application was delayed from early to late fall and only 50 SHU accumulated as opposed to 300 SHU (Fig. 4.3). This also suggests that producers who band fertilizer N in the fall, even after soil temperatures have declined to a given level, must consider the date of application and the overall length of time that the fertilizer will be exposed to the soil prior to the soil freezing.

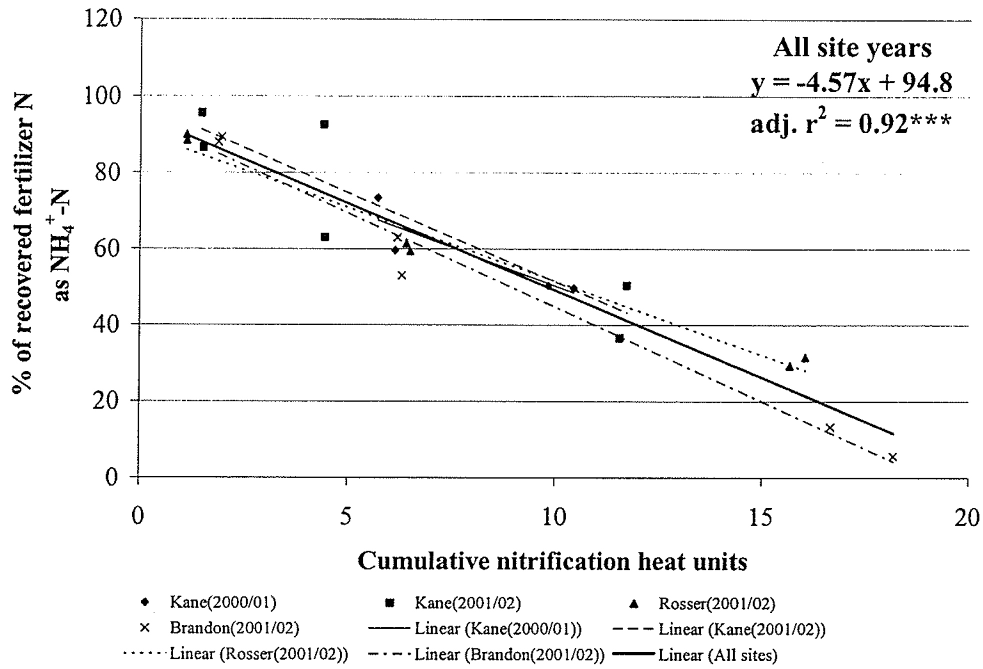

Fig. 4.4. Effect of cumulative nitrification heat units in the fall on the percent recovery of fertilizer N as NH_4^+-N using the final fall fall sampling period only (*** indicates significance 0.001 level).

The best coefficient of determination was generated using NHU, with the percent recovery of fertilizer N as NH_4^+-N decreasing substantially as NHU increased (Fig. 4.4). The regression equation predicted that 88% of the fertilizer N converted to NO_3^--N after 18 NHU accumulated in the soil prior to the soil freezing, as opposed to only 14% when 2 NHU accumulated. We suspect that NHU best described the percent recovery of fertilizer N as NH_4^+-N because nitrification rates slow linearly with decreasing temperatures to approximately 4°C (Chandra 1962), at which point rates begin to slow exponentially (Malhi and McGill 1982). However, the coefficients of determination produced using either SHU or NHU are very similar.

The improved regression coefficient of determination using cumulative SHU and NHU, as compared to date of fall application and soil temperature on the date of fall application, are similar to the results of Malhi and Nyborg (1990a). Using broadcast and incorporated urea fertilizer, the authors reported that correlations between recovered mineral N in the spring, grain yield increases and NUE were increased with soil-degree day values ($r = -0.77$), compared to date of application ($r = 0.54$) and soil temperature on the day of N application ($r = -0.55$). Our findings also agree with those of Gomes and Loynachan (1984), who reported that the accumulation of heat units, calculated on an average weekly basis, was highly correlated with recoverable NH_4^+-N from anhydrous ammonia in central Iowa. Gomes and Loynachan (1984) reported approximately 1000 soil heat units were necessary before 80% of the fertilizer N had been nitrified. However, we estimate that approximately 300 soil heat units, or 16 nitrification heat units, are necessary before 80% of the banded urea-N is converted to NO_3^--N under Manitoba conditions. This supports the claim by Malhi and McGill (1982) that soil microorganisms are able to adapt to local climates, and suggests that the transformation of banded ammoniacal fertilizers is more rapid in Western Canada than the rate that would be predicted on the basis of research in warmer climates.

Similar relationships were observed when linear regression analyses were performed using the data collected from all the fall sampling periods at each site (two or three sampling dates per site depending on weather conditions), for both cumulative SHU and cumulative NHU (Fig. 4.5 and 4.6 respectively). For both SHU and NHU there was a strong negative linear relationship describing the percent recovery of banded fertilizer N as NH_4^+-N (adj. $r^2 = 0.85$*** and 0.83*** respectively), although the coefficients of determination were slightly lower than those generated when only the last fall sampling period was used.

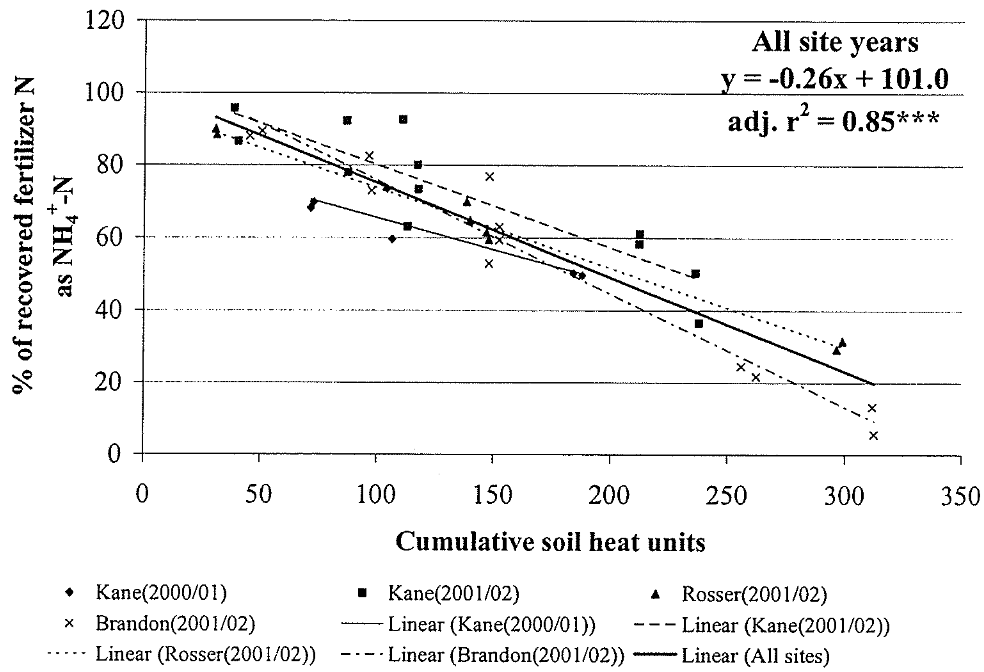

Fig. 4.5. Effect of cumulative soil heat units in the fall on the percent recovery of fertilizer N as NH_4^+-N using all fall sampling periods (*** indicates significance at 0.001 level).

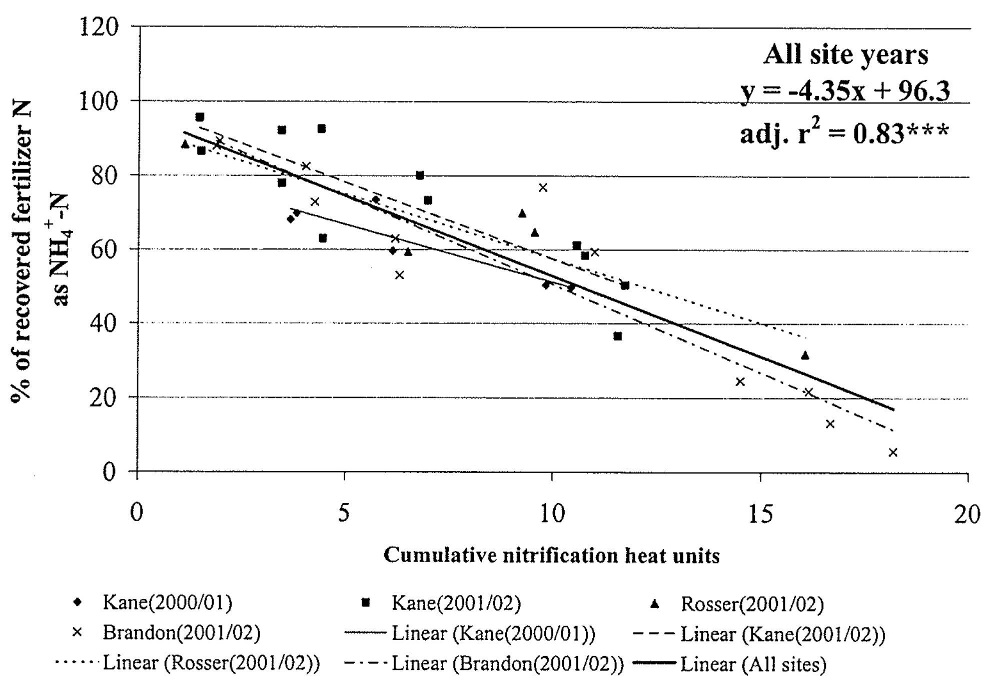

Fig. 4.6. Effect of cumulative nitrification heat units in the fall on the percent recovery of fertilizer N as NH_4^+-N using all fall sampling periods (*** indicates significance at 0.001 level).

This suggests that the time-temperature relationships with nitrification were generally stable over the fall, regardless of when measurements were taken. The slightly lower coefficient of determination generated using all sampling periods may be attributed to the initial hydrolysis of the urea fertilizer and short-term increase in NH_4^+-N during the first week after the urea fertilizer was applied to the soil. This was not a factor when only the final sampling period at the end of the fall was used.

4.4.3 Predicting Recoveries of NH_4^+-N: Effect of Fertilizer Additives

Researchers generally assume that nitrogen losses from fall-applied fertilizers are proportional to the formation of NO_3^- in the fall. Therefore, the use of chemicals that inhibit the transformations of nitrogen prior to winter should increase the overall efficiency of fall-applied fertilizer N. Increased retention of fertilizer N as NH_4^+-N in the fall would allow the producer more latitude to deal with financial and time constraints, as well as soil and weather conditions (Gomes and Loynachan 1984). To be agriculturally useful, additives must maintain inhibitory action for periods ranging from several weeks to months after fertilizer application (Yeomans 1991). The long term benefits from the inhibitor must also be sufficient to justify the added costs to the producer (Grant 1998). Figures 4.7 and 4.8 plot the percentage of recovered fertilizer N as NH_4^+-N, as influenced by the presence or absence of inhibitors and as a function of cumulative SHU and NHU at the final sampling period in the fall.

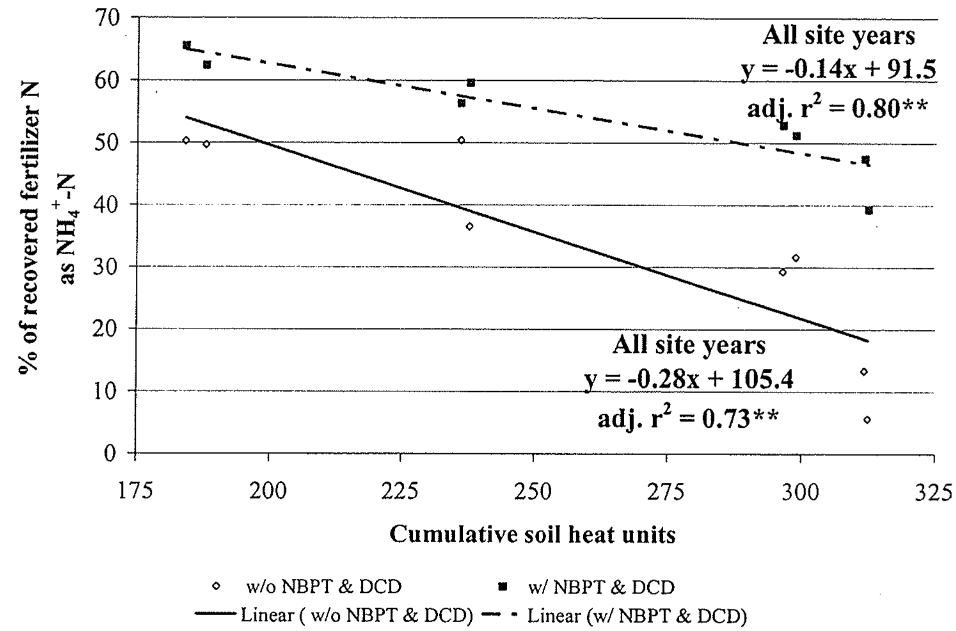

Fig. 4.7. Effect of cumulative soil heat units in the fall on the percent recovery of fertilizer N, with and without NBPT and DCD, as NH_4^+-N using the final fall sampling period only (** indicates significance at 0.01 level) (slope comparison $P = 0.069^{ns}$).

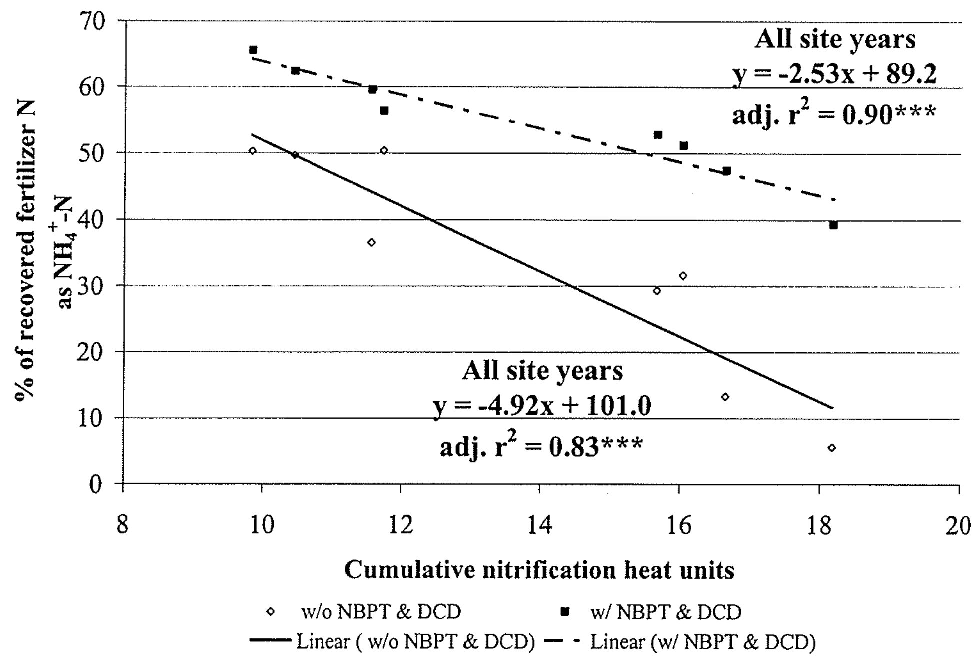

Fig. 4.8. Effect of cumulative nitrification heat units in the fall on the percent recovery of fertilizer N, with and without NBPT and DCD, as NH_4^+-N using the final fall sampling period only (*** indicates significance at 0.001 level) (slope comparison $P = 0.02$*).

In both figures, the percent recovery of fertilizer N as NH_4^+-N prior to the winter is greater for the early fall-banded urea with NBPT and DCD than without. Statistical analyses were performed to determine if the slopes of the linear regression equations for the two early fall-banded treatments, with and without inhibitors, were different. The two slopes were significantly different ($\alpha = 0.05$) for cumulative NHU, but not for cumulative SHU.

When the data from all sampling periods was combined, the linear relationships explaining the percent of recovered N as NH_4^+-N, as a function of both SHU and NHU, were not as strong as when the data from only the final fall sampling period was used (Fig. 4.7 and 4.8), but they were still highly significant (Fig. 4.9 and 4.10).

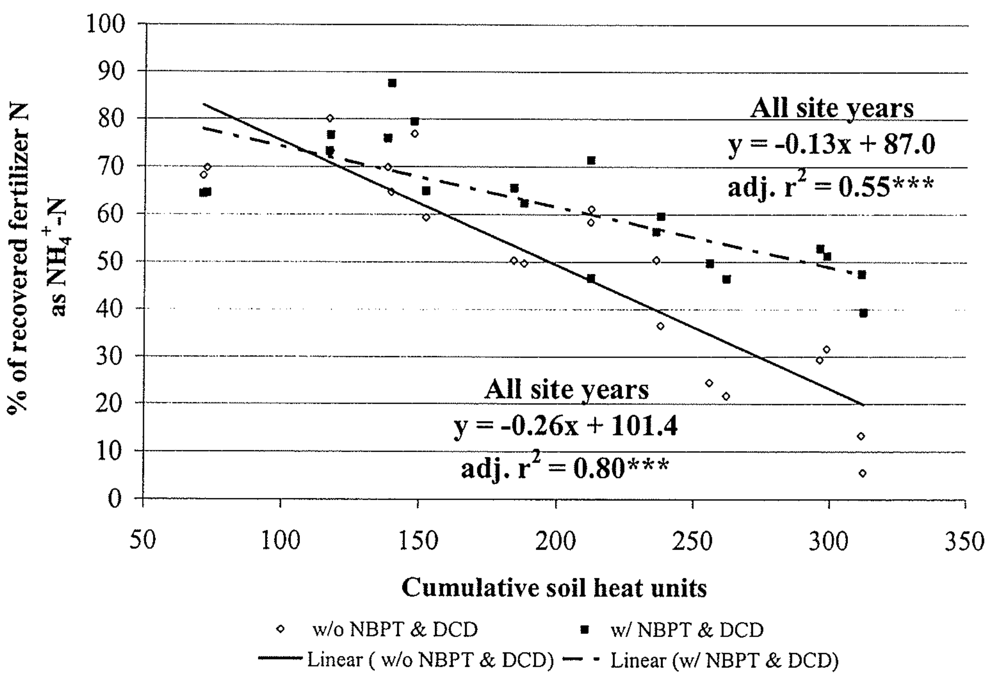

Fig. 4.9. Effect of cumulative soil heat units in the fall on the percent recovery of fertilizer N, with and without NBPT and DCD, as NH_4^+-N using the data from all fall sampling periods (*** indicates significance at 0.001 level) (slope comparison $P = 0.002$**).

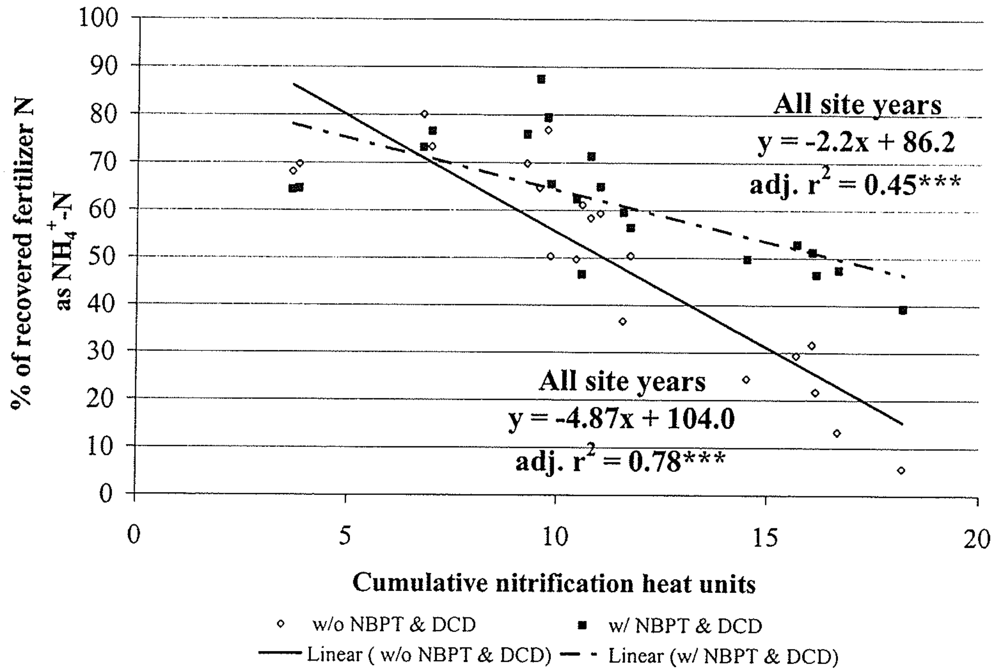

Fig. 4.10. Effect of cumulative nitrification heat units in the fall on the percent recovery of fertilizer N, with and without NBPT and DCD, as NH_4^+-N using the data from all fall sampling periods (*** indicates significance at 0.001 level) (slope comparison $P = 0.002$**).

Increasing the sample size reduced the overall variability within the data set and resulted in significant differences between the slopes of the two early fall-banded treatments, with and without inhibitors, for both cumulative SHU and NHU. However, coefficients of determination were slightly lower than those for the final sampling period due to the same reasons described earlier, the short-term rise in NH_4^+-N following the initial hydrolysis of the urea. This temporary rise in NH_4^+-N was most obvious in the inhibitors treatment, where the NBPT slowed the initial conversion of the urea to NH_4^+-N.

From the regression equations developed in Figure 4.9, an accumulation of 300 soil heat units over the fall corresponds to 49% recovery of fertilizer N as NH_4^+-N for urea fertilizer with NBPT and DCD, but only 23% without the inhibitors. Urea-banded N with NBPT and DCD would need 500 soil heat units to accumulate before reaching the same level of NH_4^+-N. Similarly, only approximately 17 NHU are needed to accumulate before 80% of the urea fertilizer banded in the early fall without inhibitors is converted to NO_3^--N, compared to 30 NHU when NBPT and DCD is added to the fertilizer (Fig. 4.10). Therefore, in an environment where the risk of denitrification and leaching losses of NO_3^--N in the spring is high, using an inhibited formulation of urea containing NBPT and DCD would increase the flexibility of a fall fertilization program and enable a producer to apply fertilizer N earlier in the fall.

The effectiveness of NBPT and DCD in retarding the conversion of urea fertilizer to NO_3^--N during the fall has been shown conclusively in this study and numerous other studies (Yeomans 1991). However, other studies also suggest that under field conditions, slowing the conversion of fertilizer N in the fall with fertilizer additives does not necessarily reduce overall N losses in the spring or translate into increased grain yields and N uptake by the crop. Our data suggests that delaying application of fall-banded N until mid October is as effective, if not more effective in slowing nitrification than using the NBPT and DCD inhibitors. In the end, it is likely easier for most producers to simply delay application date in the fall to improve efficiencies of fall-banded N than to incur the added expenses from using fertilizer additives.

4.5 Summary and Conclusions

Overall, landscape position did not greatly influence the conversion of fall-banded urea fertilizer to nitrate under the moisture conditions present at the four sites. There was also little evidence of substantial losses of fall-banded N during the fall in both years of the study, in either landscape position. Delaying application of banded urea fertilizer into the late fall and adding a double inhibitor slowed nitrification and increased the percent recovery of fertilizer N as NH_4^+-N in the soil prior to freeze-up. Date of application had a positive linear relationship with the percent of recovered fertilizer N as NH_4^+-N at the last fall sampling period (adj. $r^2 = 0.88^{***}$). This relationship suggested that the majority of urea fertilizer, banded in the early fall without inhibitors, will convert to nitrate prior to the soil freezing and is therefore susceptible to losses in the spring. Soil temperature at application showed a negative linear relationship with the percent of recovered fertilizer N as NH_4^+-N at the last fall sampling period (adj. $r^2 = 0.69^{***}$), but had the lowest coefficient of determination of the four approaches used. The lower coefficient was likely due to day-to-day variations in soil temperature during the remainder of the fall after application instead of a smooth decline towards 0°C. The proportion of the percent recovery of fall-banded N fertilizer as NH_4^+-N accounted for by regression analysis were highest when cumulative soil heat units (adj. $r^2 = 0.90^{***}$) and cumulative nitrification heat units (adj. $r^2 = 0.92^{***}$) were used. Accumulated NHU best described the relationship with percent of recovered fertilizer N as NH_4^+-N in the fall, because NHU account for day-to-day variability in the rate of nitrification, especially at temperatures below 4°C. Nonetheless, the regression equations generated for each of the four parameters are similar, and each was highly significant. Had more sites or site years been included in this experiment, we suspect that overall accuracy of date of application and soil temperature on date of application in the fall would have lagged further behind that of SHU and NHU due to annual and daily variability in fall weather. However, practical field use of both SHU and NHU would require accurate forecasting of soil temperature. Therefore, SHU and NHU might only be useful tools in historical monitoring. In contrast, producers in southern Manitoba can easily use date of application or soil temperature on the date of application to predict the proportion of fall-banded fertilizer N remaining as NH_4^+-N at freeze-up.

A strong linear relationship with percent recovery of fall-banded N fertilizer as NH_4^+-N is also evident for both SHU (adj. $r^2 = 0.85^{***}$) and NHU (adj. $r^2 = 0.83^{***}$) when all the fall sampling periods were used, suggesting that the time-temperature relationships used were relatively stable over the fall. The interactions between time, temperature and nitrification suggest that producers must consider the overall length of time that the N fertilizer will be exposed to the soil prior to the soil freezing, even after the soil temperature has reached a given level.

Regression analysis comparing early fall-banded urea with early fall-banded urea that included NBPT and DCD showed that the inhibitors slowed nitrification and increased retention of fertilizer N as NH_4^+-N in the fall. With the NBPT and DCD formulated urea, significantly more SHU and NHU were needed to accumulate before 80% of the urea fertilizer banded in the early fall had been converted to NO_3^--N. This might allow a producer increased flexibility in a fall fertilization program, and hopefully translates into reduced losses of N in the spring.

5 THE INFLUENCE OF APPLICATION DATE, LANDSCAPE POSITION AND FERTILIZER ADDITIVES ON THE RECOVERY OF FALL-BANDED UREA IN THE SPRING AND AT HARVEST

Key Words: fall-banded N, spring-banded N, landscape position, inhibitors, N-(n-butyl) thiophosphoric triamide (NBPT), Dicyandiamide (DCD), over-winter losses, denitrification, spring wheat (*Triticum aestivum*), urea fertilizer

5.1 Abstract

A two-year study was initiated in the fall of 2000 to investigate the effects of application date, landscape position and a urease and nitrification inhibited formulation of urea on the over-winter transformations and losses of fall-banded nitrogen (N) fertilizer under Manitoba conditions. Large losses of fall-banded N were observed in the first year of the study, with greater apparent losses of fertilizer N in the low landscape positions than in the high landscape positions. Over-winter losses of fall-banded N were significantly reduced by delaying the date of application in the fall, especially in the low landscape positions of the field. In the second and drier year of the study, over-winter losses were not as severe as in 2000/2001, except at Rosser (2001/02) where significant rainfall occurred in the fall, shortly before the soil froze. At harvest, there was a significant landscape position by fertilization treatment effect for both total recovered N and apparent recovered fertilizer N in the above ground portion of the crop and soil to 120 cm. In the high landscape positions, there were no differences at harvest between early fall, mid fall, late fall and spring-banded N. In the low landscape positions, delaying fall application until mid October significantly increased the total recovered N in the crop and soil and the apparent

recovered fertilizer N at harvest. Use of NBPT and DCD with early fall-banded N significantly reduced over-winter losses in year one of the study, but not in the second year. At harvest, there was little apparent benefit to the use of the inhibitors in either year. There were no significant differences between the two early fall-banded treatments, with and without inhibitors in terms of total recovery of N or apparent recovered fertilizer N in the crop and soil, in either landscape position.

5.2 Introduction

In the Prairie Provinces of Canada, producers often apply nitrogen (N) fertilizers the previous fall for spring-sown annual crops. However, in Western Canada the efficiency of fall-applied N, especially when broadcast and incorporated, is generally less effective than spring applications (Nyborg and Leitch 1979; Racz 1979; Bole et al. 1984; Malhi et al. 1984; Ukrainetz 1984; Malhi et al. 1992a; Malhi et al. 1992b; Malhi et al. 2001). The lower efficiencies from fall-applied N are mostly due to over-winter losses of nitrate (NO_3^-), especially during the early spring period. Agriculturally, this loss of fertilizer N is an economic loss to producers. In Manitoba alone, producers invest upwards of $200 million per year in nitrogen fertilizer and, on average, the crop uses less than half of this fertilizer in the year of application. Environmental concerns with the loss of fertilizer N include leaching losses of NO_3^--N to the ground water and denitrification losses of N_2O to the atmosphere, which contributes to global warming and the destruction of the ozone layer (Aulakh et al. 1992; Malhi et al. 2001). The quantity of fertilizer N at risk depends on numerous factors including interactions between fertilizer application date, landscape position, the use of fertilizer inhibitors, and weather and climatic conditions.

In regions of adequate rainfall and good soil infiltration, nitrified N from organic and ammoniacal fertilizers, or NO_3^- directly from nitrate-based fertilizers, has the potential to be leached through the soil profile (Olson 1982). However, in Manitoba where soils remain frozen for most of the winter, Racz (1979) reported that the efficiency of fall-applied fertilizer was not greatly affected by leaching, especially when soils were cropped and N fertilizer was applied at recommended rates. Further research in Manitoba reported that even at extremely high N rates (550 kg N/ha), there was no significant movement of nitrates below the rooting zone on a Portage loam or Red River clay soil (Field-Ridley 1975). Numerous other studies from across Canada have reported little to no leaching of nitrate-N below 60 cm from fall-applied urea fertilizers (Malhi and Nyborg 1983a; Aulakh and Rennie 1984; Bole and Gould 1986; Malhi and Nyborg 1986; Malhi et al. 1990b; Nyborg et al. 1990; Malhi et al. 1992b), except under fallow conditions (Chang and Cho 1974). The consensus is that the majority of losses from fall-applied N in Western Canada are a result of denitrification during mild weather events in the winter and during the early spring thaw, especially on poorly drained soils such as those in the Red River Valley of Manitoba. In Western Canada, mass balance studies using broadcast and incorporated ^{15}N-urea have reported over-winter losses ranging from 5 to 90%, depending on soil and weather conditions (Malhi and Nyborg 1983a; Aulakh and Rennie 1984; Bole and Gould 1986; Nyborg et al. 1990; Heaney et al. 1992). On average, the efficiency of fall-applied fertilizer N in Canada is less than 50%, with estimates of between 10 to 30% of these losses in fertilizer N being linked directly to denitrification (Aulakh et al. 1992).

The largest flux of soil N often occurs during the spring thaw when the topsoil is saturated from snow melt (Malhi and Nyborg 1983a; Aulakh and Rennie 1984; Bole and Gould 1986; Malhi and Nyborg 1986; Malhi et al. 1990a; Nyborg et al. 1990; Heaney et al. 1992; Burton and Beauchamp 1994; Nyborg et al. 1997; Muller et al. 2002), with as much as 65% of total annual denitrification emissions occurring during this period (Wagner-Riddle et al. 1997). Malhi et al. (1990a) reported that denitrification rates increased rapidly in saturated soils at soil temperatures above -4°C (greatest response between 4 and 10°C) and with increasing concentrations of NO_3^--N from 50 to 500 mg kg^{-1}. Biological denitrification generally occurs when soils have reached 60% water-filled pore space (Linn and Doran 1984), but denitrification losses can occur in soils that are not completely saturated due to anaerobic microsites (Christianson et al. 1990).

In addition to biological denitrification, there are certain conditions in which losses of soil and fall-applied fertilizer N can occur through chemical reactions involving NO_2^- (Bailey and Beauchamp 1973; Christianson and Cho 1983; Davidson 1992; Tisdale et al. 1993). N_2O and N_2 that has accumulated in the soil over the winter via chemical denitrification will be released to the atmosphere in the spring as the soil thaws (Christianson et al. 1979; Christianson and Cho 1983).

Early fall application of ammoniacal fertilizer is expected to form more NO_3^--N prior to the soil freezing than late fall applications (Malhi and Nyborg 1979; Malhi and McGill 1982; Malhi et al. 1984), increasing the potential for denitrification losses in the spring (Malhi and Nyborg 1983a; Malhi and Nyborg 1990a; Nyborg et al. 1990; Nyborg et al. 1997). Malhi and Nyborg (1990a) reported that the recovery of fall-applied urea (broadcast and incorporated) as soil mineral N in the spring and overall grain yields increased substantially when fall applications were delayed from September 19th to November 6th. The severity of over-winter losses of fall-applied fertilizer is further enhanced if heavy rains occur in the fall, especially when N fertilizers are applied early in the season (Malhi and Nyborg 1983a). In comparison to broadcast and incorporated fertilizers, the efficiency of fall-applied N has been consistently improved by placement in bands (Malhi and Nyborg 1985; Malhi and Nyborg 1990b; Malhi and Nyborg 1991), with fall-banded N often equal to spring-banded N in terms of grain yield and total crop N uptake, especially under dry conditions (Grant et al. 2001). Banding of chemical fertilizers lowers the risk of denitrification because high pH, ammonia concentration and osmotic pressures within the band reduce microbial activity and slow the rate of nitrification of NH_4^+ to NO_3^- in the fall. However, no experiments have looked directly at the impact of fall-banded N applied in early in the fall (mid September to early October) on the over-winter loss and recovery of fall-banded N in Manitoba or Western Canada.

Landscape position can influence over-winter losses and recovery of fall-applied N. During the early spring, significant ponding of snow-melt generally occurs in the lower convergent areas of the field, conditions ideal for bacterial denitrification (Hanna et al. 1982). In Saskatchewan, Pennock et al. (1992) reported that denitrification activity under a gently sloping landscape displayed a distinct landscape-scale pattern, with denitrification rates higher in the level concave areas of the landscape than in the level convex areas. Pennock et al. (1992) concluded that the intensity and distribution of water in the hillslope system was of greatest importance to denitrification losses. The intensity and distribution of water in the system is further influenced by temporal variability due to seasonal climatic patterns (Corre et al. 1996) and rainfall events

(Corre et al. 1995). Other studies from Saskatchewan have reported consistently higher denitrification rates in the wetter convergent footslopes and low level complexes than in the better-drained upper slope positions, in both gently sloping (van Kessel et al. 1993; Farrell et al. 1996) and hummocky terrain (Aulakh and Rennie 1984; Elliot and de Jong 1992; Corre et al. 1996; Ambus 1998). In the relatively level landscape of the Red River Valley of Minnesota and Manitoba, spring soil NO_3^--N levels were consistently lower in the depressional areas than in the slightly more elevated microhigh positions (Hollands 1996; Franzen et al. 1997; Durand 2002). The authors conclude that these differences in nitrate were the result of increased denitrification rather than leaching losses. However, no experiments have focused on the impact of landscape position on the over-winter loss of fall-banded N under Western Canadian conditions.

Fertilizer additives have been used in research trials in order to suppress the conversion of ammoniacal fertilizers into nitrate until after the soil has dried in the spring (Malhi and Nyborg 1983b). Two common fertilizer additives that could be beneficial to producers who apply urea in the fall are urease and nitrification inhibitors. N-(n-butyl) thiophosphoric triamide (NBPT) is a promising urease inhibitor that inhibits urease activity by competing with urea for active sites on the urease enzyme complex (Rawluk et al. 2001). Dicyandiamide (Didin or DCD) is a nitrification inhibitor that has received renewed interest of late, because it is less volatile than other nitrification inhibitors and can be easily blended with solid N fertilizers (Guiraud and Marol 1992). In Ontario, fall-applied large urea granules containing low rates of DCD slowed nitrification and reduced over-winter N losses for winter wheat (Yadvinder-Singh and Beauchamp 1987; Yadvinder-Singh and Beauchamp 1988a; Yadvinder-Singh and Beauchamp 1988b; Yadvinder-Singh et al. 1994). In China, DCD amended urea reduced the total N_2O flux over the entire growing period of a wheat crop (Xu et al. 2000). Xu et al. (2000) also reported that when DCD was combined with hydroquinone, a urease inhibitor, the synergistic combination further reduced gaseous N losses when compared to either of the inhibitors alone. The effectiveness of a urease and nitrification inhibited formulation of urea in reducing over-winter losses from early-fall banded N has not been investigated in fall banding trials in Western Canada.

The objective of this paper is to evaluate the interactive effects of landscape position, application date, fertilizer additives, and weather and climate on the over-winter losses and recovery of fall-banded N fertilizer in Manitoba.

5.3 Materials and Methods

5.3.1 Site Selection and Description

Field experiments were conducted in Manitoba over two fertilization/growing seasons: fall 2000 to harvest 2001 (year one), and fall 2001 to harvest 2002 (year two). In total, four small plot sites were established throughout southern Manitoba. In 2000/2001, one experiment was located near the town of Kane on Red River/Osborne (Gleyed Rego Black Chernozem/Rego Humic Gleysol) heavy clay soil. In the second year of the project, two sites were situated on Red River/Osborne heavy clay soil near the towns of Kane and Rosser, while a third site was located on Newdale (Orthic Black Chernozem) clay loam soil at the AAFC Brandon Research Centre's Phillips Research Farm. The Red River/Osborne and Newdale soil series represent common soils in eastern and western Manitoba respectively, and provide two distinctly different potentials for N fertilizer loss due to differences in soil texture, topography and climate.

5.3.2 Experimental Design and Treatments

The experimental design and treatments used in this project have already been described in detail in Chapter 3 (section 3.3.2). Three of the four sites were located in the relatively level lacustrine landscape of the Red River Valley (Kane (2000/01), Kane (2001/02) and Rosser (2001/02)) with typical elevation differences of less than 1 m per km within each site. The topography at the Brandon site was slightly more undulating, and representative of glacial till landscapes in the Black soil zone of south-western Manitoba. A split-plot design was utilized at all sites, with landscape position main plots and fertilization treatment subplots. Landscape positions studied in this experiment were defined as "high" and "low" based on their relative elevations to one another within the field. The individual low positions were localized concave areas in which temporary ponding occurred in the spring after snowmelt or after heavy rainfalls, whereas the high landscape positions were slightly raised divergent areas located between these low positions where more water shedding occurred. Separate main plots were located in an individual high or low landscape position (four of each) throughout the field. Each main plot contained six, two-metre by 10-metre fertilization treatment subplots, with all six treatments assigned at random to the subplots within the main plot.

In each experiment, nitrogen fertilizer was applied at three dates in the fall between mid-September and mid-October, and one time in the spring, at planting. All nitrogen fertilizer was applied as urea (46-0-0) banded at a rate of 80 kg N ha^{-1}, with 40 cm spacing, at a depth of 7.5

cm. The modest rate of nitrogen was meant to keep each N treatment within the crop's responsive range. The six fertilization treatments were based on time of fertilizer application and use of inhibitors. Conventional urea was banded in early fall, mid fall, late fall and spring (mid-row banded at time of planting). In addition, there was a control where no N fertilizer was applied and a treatment where urea formulated with a urease and nitrification inhibitor (IMC-Agrico Super Urea® containing NBPT and DCD) was applied in the early fall. Application of the urea fertilizer in the fall was targeted for September 15 (early fall), September 30 (mid fall) and October 15 (late fall) of each year. However, in year one, excess moisture in the fall caused a delay in application dates to September 29, October 12, and October 26 at Kane (2000/01). In year two, treatments were applied at Kane (2001/02) on September 26, October 9, and October 19, at Rosser (2001/02) on September 19, October 1, and October 19, and at Brandon (2001/02) on September 15, October 1, and October 15. Therefore, early fall-banded N included all fertilizer applications occurring between September 15 and September 29, mid fall-banded N were those applications occurring between September 30 and October 14, and late fall-banded N included any applications that occurred after October 15. At time of fertilization, the band rows were clearly marked with small wooden stakes and pin flags to ensure precise sampling of the banded areas, especially in the spring.

5.3.3 Crop Measurements

Crop sampling and analysis activities have already been described in detail in Chapter 3 (section 3.3.3). AC Barrie wheat (*Triticum aestivum*) was grown as the test crop at all sites. At physiological maturity, a 3 m x 2 row sample of above ground plant tissue was harvested from each subplot, dried, threshed and weighed for grain and straw yields. Tissue samples collected at harvest were ground with a Wiley mill to pass a 2 mm sieve and analyzed for total N. Registered in-crop pesticides were applied at recommended rates (based on the Manitoba Crop Protection Guide) using a 4 m bicycle sprayer, including a pre-planting burn off with Glyphosate and a fungicide application of Folicur® to minimize fusarium infestations.

5.3.4 Soil Sampling and Analyses

Soil sampling and analysis activities are described in detail in Chapter 4 (section 4.3.3). To characterize the overall N behaviour in each main plot, the soil was sampled to 120 cm in mid-September prior to fertilization (Chapter 3, Table 3.2). The soil from each fertilization subplot was also sampled to 120 cm (0-15, 15-30, 30-60, 60-90, 90-120 cm) in the spring (the day before planting) and at harvest. All soil samples were air dried at 30-35°C for 48 to 72 hours and ground to pass a 2 mm sieve. Ground soil samples were analyzed for water-soluble nitrate and nitrite, exchangeable ammonium, urea, pH and electrical conductivity (EC).

5.3.5 Weather Data

Climatic data and sampling activities are described in detail in Chapter 3 (section 3.3.5) and Chapter 4 (section 4.3.4). General weather conditions, including mean monthly aerial temperature and total monthly precipitation, for the Winnipeg and Brandon areas are reported in Chapter 3 (Tables 3.3 and 3.4 respectively). Rainfall data was collected at each site located in the Red River Valley (Chapter 3, Table 3.5) using a tipping bucket rainguage and a HOBO® event driven data logger (Onset Computer Corporation - Hobo Event logger User's Manual 1999). Rainfall data during the growing season was also collected at Brandon (2001/02) by Agriculture and Agri-Food Canada (Chapter 3, Table 3.5). In addition, gravimetric soil moisture contents (w%) at depths of 0-7.5, 7.5-15 and 15-30 cm were measured on a weekly basis during the fall and early spring at Kane (2000/01), Kane (2001/02) and Rosser (2001/02) (Chapter 3, Fig. 3.1, 3.2 and 3.3 respectively). Gravimetric moisture contents at Brandon (2001/02) were not measured due to resource limitations. The soils at the intensive sites usually froze and remained snow covered from mid-November until thawing in April.

5.3.6 Data Analyses

A detailed description of the statistical analyses used in this experiment can be found in Chapter 3 (section 3.3.6). Statistical analyses were conducted using the General Linear Model procedure of the Statistical Analysis System (SAS) package (SAS 1999). Descriptive statistics were used to test the data for normality and skewness using the Proc Univariate function of SAS. Fisher's (protected) least significant difference (LSD) test was used to compare the subplot (fertilization) and main plot (landscape position) treatment means (Steel et al. 1987). The LSMEANS test was used to compare the fertilization treatments within each landscape position (note: the LSMEANS function in SAS does not provide an LSD value). For the fertilization treatment means, a probability level (α) of 0.05 was used as the significance threshold for the soil and plant variables. However, due to the high variability inherent in field-based landscape experiments a higher probability level of 0.10 was used to detect treatment differences among landscape positions, which is within the typical range of probability values ($p \leq 0.10$ to 0.20) used in many landscape studies (Pennock et al. 1992; van Kessel et al. 1993; Corre et al. 1996; Beckie and Brandt 1997; Jowkin and Schoenau 1998).

5.4 Results and Discussion

5.4.1 Total Recovered N in the Soil Prior to Planting

The soil from each fertilization subplot was sampled to 120 cm in the spring, the day before planting, and in the fall after harvest was complete. In the spring, the majority of the fall-banded N was recovered in the 0-15 and 15-30 cm depths, with lower amounts in the 30-60 cm depth (data not presented). In addition, there was no significant increase in apparent recovered fertilizer N at depths below 60 cm. Therefore, spring soil concentrations of N are based on the 0-60 cm soil depth. However, results reported for total recovered N (section 5.4.2) and the apparent recovered fertilizer N (section 5.4.3) at harvest include all soil depths to 120 cm.

5.4.1.1 Landscape Position. At Kane (2000/01), there were no differences, overall, between high and low landscape positions with regard to recoverable NH_4^+-N, NO_3^--N, and total inorganic N (Table 5.1). However, there was a significant landscape position by fertilization treatment interaction for both total inorganic N and apparent recovered fertilizer N to 60 cm. This interaction will be further explored in section 5.4.1.2.

In the second year of the project, recovery of mineral N in the spring was highly variable. At Kane (2001/02), there were no significant differences between landscape positions in total NH_4^+-N, NO_3^--N, inorganic N and apparent net recovered fertilizer N (Table 5.2). Total monthly precipitation at Kane (2001/02) was low (Chapter 3, Table 3.4) and soil conditions in both the fall and spring were dry (Chapter 3, Fig. 3.2), especially when compared to soil conditions at Kane (2000/01) (Chapter 3, Fig. 3.1). These relatively dry conditions probably account for the lack of significant differences between landscape positions in recoverable mineral N from the fall-banded N at Kane (2001/02). This observation is consistent with other studies from Western Canada which reported few over-winter losses for fall-banded N when soil conditions were dry in the fall and spring (Bole et al. 1984; Ukrainetz 1984).

Table 5.1. Total recovered soil mineral N at seeding and apparent over-winter losses of fall-banded N at Kane (2000/01): 0-60 cm soil depth

Treatment: Landscape position	Treatment: Fertilization	Total NH_4^+-N	Total NO_3^--N	Total inorganic N	Apparent recovered fertilizer N	Apparent over-winter gain/loss of fertilizer N
				(kg ha^{-1})[z]		
High	Early fall	89.3	101.8	191.1a	64.1	-15.9
	Mid fall	88.8	97.3	186.1a	59.1	-20.9
	Late fall	84.4	102.9	187.3a	60.3	-19.7
	Spring	-	-	-	-	-
	Control (no N)	85.2	41.8	127.0b	-	-
	Early fall w/ inhibitors	83.2	104.4	187.6a	60.6	-19.4
	LSD (α = 0.05)	-[y]	-	na[x]	ns	
Low	Early fall	72.2	59.2	131.9b	25.5b	-54.5
	Mid fall	82.9	81.9	165.2a	58.8a	-21.2
	Late fall	87.8	74.7	162.5a	56.1a	-23.9
	Spring	-	-	-	-	-
	Control (no N)	80.5	25.4	106.4c	-	-
	Early fall w/ inhibitors	84.8	91.2	176.1a	69.7a	-10.3
	LSD (α = 0.05)	-[y]	-	na[x]	na[x]	
Landscape position means						
High		86.2	89.6	175.8	61.0	-19.0
Low		81.6	66.5	148.4	52.5	-27.5
LSD (α = 0.10)		ns	ns	-[w]	-[w]	
	Fertilization means					
	Early fall	80.8	80.5b	161.5	44.8	-35.2
	Mid fall	85.9	89.6ab	175.7	59.0	-21.1
	Late fall	86.1	88.8ab	174.9	58.2	-21.8
	Spring		-	-	-	-
	Control (no N)	82.9	33.6c	116.7	-	-
	Early fall w/ inhibitors	84.0	97.8a	181.9	65.2	-14.9
	LSD (α = 0.05)	ns	13.8	-[w]	-[w]	

ANOVA	df	Total NH_4^+-N $P > F$	Total NO_3^--N $P > F$	Total inorganic N $P > F$	df	Apparent recovered fertilizer N $P > F$
Landpos	1	0.74	0.18	0.15	1	0.49
Trt	4	0.84	0.0001*	0.0001*	3	0.13
Landpos*Trt	4	0.36	0.18	0.058†	3	0.047*
Block(Landpos)	6	0.0001*	0.0001*	0.0001*	6	.0096*
Residual C.V. (%)		12.7	17.2	9.9		28.9

a-c Mean values followed by the same letter (within columns) are not significantly different.

[z] Assuming a bulk density of 1.24 g cm^{-3} for 0-15 cm depth and 1.33 g cm^{-3} for 15-120 cm.

[y] LSD for individual treatments within a landscape position is not reported because there was no Landpos*Trt interaction.

[x] LSD is not applicable (na) because LSMEANS was used, which does not provide an LSD value.

[w] LSD is not reported because of significant Landpos*Trt interaction.

† Significant at $P < 0.10$ (used only for landscape position variables and interactions).

* Significant at $P < 0.05$.

Table 5.2. Total recovered soil mineral N at seeding and apparent over-winter loss of fall-banded N at Kane (2001/02): 0-60 cm soil depth

Treatment						
Landscape position	Fertilization	Total NH_4^+-N	Total NO_3^--N	Total inorganic N	Apparent recovered fertilizer N	Apparent over-winter gain/loss of fertilizer N
				(kg ha^{-1})^z		
High	Early fall	42.0	143.0	185.4	70.4	-9.6
	Mid fall	58.8	133.3	193.7	78.7	-1.3
	Late fall	44.9	143.8	189.5	74.5	-5.5
	Spring	-	-	-	-	-
	Control (no N)	37.6	77.4	115.0	-	-
	Early fall w/ inhibitors	48.8	122.8	171.7	56.7	-23.3
	LSD (α = 0.05)^y	-	-	-	-	
Low	Early fall	50.5	117.9	168.4	70.5	-9.5
	Mid fall	65.9	140.7	207.3	109.4	29.4
	Late fall	57.0	112.1	169.9	72.0	-8.0
	Spring	-	-	-	-	-
	Control (no N)	51.9	45.4	97.9	-	-
	Early fall w/ inhibitors	66.0	114.6	181.1	83.3	3.3
	LSD (α = 0.05)^y	-	-	-	-	
Landscape position means						
High		46.4	124.1	171.1	70.1	-9.9
Low		58.3	106.2	164.9	83.8	3.8
LSD (α = 0.10)		ns	ns	ns	ns	
	Fertilization means					
	Early fall	46.3c	130.5a	176.9a	70.5	-9.5
	Mid fall	62.3a	137.0a	200.5a	94.0	14.0
	Late fall	51.0bc	128.0a	179.7a	73.3	-6.7
	Spring	-	-	-	-	-
	Control (no N)	44.8c	61.4b	106.5b	-	-
	Early fall w/ inhibitors	57.4ab	118.7a	176.5a	70.0	-10.0
	LSD (α = 0.05)	9.0	29.4	34.8	ns	

ANOVA	df		$P > F$		df	$P > F$
Landpos	1	0.12	0.30	0.78	1	0.65
Trt	4	0.0021*	0.0001*	0.0001*	3	0.42
Landpos*Trt	4	0.77	0.58	0.76	3	0.64
Block(Landpos)	6	0.001*	0.021*	0.0067*	6	0.0009*
Residual C.V. (%)		16.7	24.7	20.1		42.3

a-c Mean values followed by the same letter (within columns) are not significantly different.

^{z} Assuming a bulk density of 1.24 g cm^{-3} for 0-15 cm depth and 1.33 g cm^{-3} for 15-120 cm.

^{y} LSD for individual treatments within a landscape position is not reported because there was no Landpos*Trt interaction.

† Significant at $P < 0.10$ (used only for landscape position variables and interactions).

* Significant at $P < 0.05$.

At Rosser (2001/02) the effect of landscape position on the apparent over-winter losses of fall-banded N is the strongest of any of the sites in 2001/2002 (Table 5.3). The apparent recovered fertilizer N in the high landscape positions was nearly twice that recovered in the low landscape positions, suggesting that over-winter losses of fall-banded fertilizer N were much greater in the low landscape positions than in the high landscape positions. However, there were no significant differences between landscape positions for total recoverable NH_4^+-N and inorganic N. Although the high landscape positions appeared to contain nearly 32 kg ha^{-1} more NO_3^-- N than in the low landscape positions, the LSD is not reported for NO_3^--N because of the significant landscape position by fertilization treatment interaction.

Table 5.3. Total recovered soil mineral N at seeding and apparent over-winter loss of fall-banded N at Rosser (2001/02): 0-60 cm soil depth

Treatment: Landscape position	Treatment: Fertilization	Total NH_4^+-N	Total NO_3^--N	Total inorganic N	Apparent recovered fertilizer N	Apparent over-winter gain/loss of fertilizer N
				(kg ha^{-1})^z		
High	Early fall	40.6	116.3a	156.9	62.5	-17.5
	Mid fall	46.2	103.9a	150.0	55.7	-24.3
	Late fall	44.6	109.2a	153.8	59.4	-20.6
	Spring	-	-	-	-	-
	Control (no N)	36.9	57.5b	94.4	-	-
	Early fall w/ inhibitors	41.9	119.5a	161.4	67.0	-13.0
	LSD (α = 0.05)	-^{y}	na^x	-^{y}	-^{y}	
Low	Early fall	44.8	90.8a	135.6	49.6	-30.4
	Mid fall	48.9	74.4ab	123.8	37.8	-42.2
	Late fall	50.7	72.8ab	123.5	37.5	-42.5
	Spring	-	-	-	-	-
	Control (no N)	40.4	45.6c	86.0	-	-
	Early fall w/ inhibitors	44.9	65.2b	110.1	24.1	-55.9
	LSD (α = 0.05)	-^{y}	na^x	-^{y}	-^{y}	
Landscape position means						
High		42.0	101.3	143.3	61.2a	-18.8
Low		45.9	69.7	115.8	37.2b	-42.8
LSD (α = 0.10)		ns	-^{w}	ns	20.7	
	Fertilization means					
	Early fall	42.7ab	103.6	146.3a	56.1	-23.9
	Mid fall	47.5ab	89.1	136.9a	46.7	-33.3
	Late fall	47.6a	91.0	138.7a	48.5	-31.5
	Spring	-	-	-	-	-
	Control (no N)	38.6b	51.6	90.2b	-	-
	Early fall w/ inhibitors	43.4ab	92.4	135.7a	45.5	-34.5
	LSD (α = 0.05)	9.0	-^{w}	18.2	ns	

ANOVA	df	$P > F$			df	$P > F$
Landpos	1	0.66	0.15	0.21	1	0.066†
Trt	4	0.23	0.0001*	0.0001*	3	0.68
Landpos*Trt	4	0.99	0.052†	0.21	3	0.42
Block(Landpos)	6	0.0001*	0.0001*	0.0001*	6	0.06
Residual C.V. (%)		19.8	15.6	13.6		38.3

a-c Mean values followed by the same letter (within columns) are not significantly different.

^{z} Assuming a bulk density of 1.24 g cm^{-3} for 0-15 cm depth and 1.33 g cm^{-3} for 15-120 cm.

^{y} LSD for individual treatments within a landscape position is not reported because there was no Landpos*Trt interaction.

^{x} LSD is not applicable (na) because LSMEANS was used, which does not provide an LSD value.

^{w} LSD is not reported because of significant Landpos*Trt interaction.

† Significant at $P < 0.10$ (used only for landscape position variables and interactions).

* Significant at $P < 0.05$.

Rosser (2001/02) received approximately 35 mm of rain during the third week of October (Chapter 3, Table 3.4) creating wet soil conditions heading into the winter, especially in the low landscape positions (Chapter 3, Fig. 3.3). The results at Rosser (2001/02) are similar to those of Malhi and Nyborg (1983a) who reported that the addition of 50 mm of water in the fall, to simulate a wet fall, significantly increased over-winter losses from fall-applied KNO_3 and urea fertilizers. Other reviews have also reported that the efficiency of fall-banded fertilizer N is greatly reduced when conditions in the fall are wet (Bole et al. 1984; Ukrainetz 1984).

Brandon (2001/02) had significantly more NH_4^+-N, NO_3^--N and total inorganic N in the high landscape positions than in the low landscape positions (Table 5.4). However, background levels of mineral N at Brandon (2001/02) were also considerably greater in the high landscape positions than in the low landscape positions at this site (Chapter 3, Table 3.2), and there were no significant differences in apparent recovered fertilizer N. Therefore, we suspect that the differences in NH_4^+-N, NO_3^--N and total inorganic N between landscape positions at this site are likely due to long-term differences in soil N rather than over-winter losses of the fall-banded N. Similar to Kane (2001/02), the Brandon site received lower than average precipitation during the fall and early spring period (Chapter 3, Table 3.4), and this is the probable reason why there were no significant differences in the apparent recovered fertilizer N between the high and low landscape positions.

Table 5.4. Total recovered soil mineral N at seeding and apparent over-winter loss of fall-banded N at Brandon (2001/02): 0-60 cm soil depth

Treatment						
Landscape position	Fertilization	Total NH_4^+-N	Total NO_3^--N	Total inorganic N	Apparent recovered fertilizer N	Apparent over-winter gain/loss of fertilizer N
				(kg ha^{-1})^z		
High	Early fall	37.7	164.7	202.4	90.1	10.1
	Mid fall	36.7	144.0	180.7	68.4	-11.6
	Late fall	34.9	150.9	185.7	73.4	-6.6
	Spring	-	-	-	-	-
	Control (no N)	37.3	75.0	112.3	-	-
	Early fall w/ inhibitors	42.3	138.6	180.8	68.5	-11.5
	LSD ($\alpha = 0.05$)^y	-	-	-	-	
Low	Early fall	28.2	91.0	119.3	68.1	-11.9
	Mid fall	24.0	81.6	105.7	54.5	-25.5
	Late fall	33.7	123.8	157.7	106.5	26.5
	Spring	-	-	-	-	-
	Control (no N)	29.6	21.6	51.2	-	-
	Early fall w/ inhibitors	25.6	72.4	98.0	46.8	-33.2
	LSD ($\alpha = 0.05$)^y	-	-	-	-	
Landscape position means						
High		37.8a	134.6a	172.4a	75.1	-4.9
Low		28.2b	78.1b	106.4b	69.0	-11.0
LSD ($\alpha = 0.10$)		6.3	25.4	28.0	ns	
	Fertilization means					
	Early fall	33.0	127.8ab	160.8ab	79.1	-0.9
	Mid fall	30.4	112.8ab	143.2ab	61.4	-18.6
	Late fall	34.3	137.3a	171.73a	89.9	9.9
	Spring	-	-	-	-	-
	Control (no N)	33.5	48.3c	81.8c	-	-
	Early fall w/ inhibitors	33.9	105.5b	139.4b	57.7	-22.3
	LSD ($\alpha = 0.05$)	ns	27.8	29.0	ns	

ANOVA	df		$P > F$		df	$P > F$
Landpos	1	0.026*	0.005*	0.0038*	1	0.80
Trt	4	0.85	0.0001*	0.0001*	3	0.10
Landpos*Trt	4	0.35	0.48	0.28	3	0.18
Block(Landpos)	6	0.13	0.063†	0.0421*	6	0.0019*
Residual C.V. (%)		23.0	25.4	20.2		38.4

a-c Mean values followed by the same letter (within columns) are not significantly different.

^{z} Assuming a bulk density of 1.24 g cm^{-3} for 0-15 cm depth and 1.33 g cm^{-3} for 15-120 cm.

^{y} LSD for individual treatments within a landscape position is not reported because there was no Landpos*Trt interaction.

† Significant at $P < 0.10$ (used only for landscape position variables and interactions).

* Significant at $P < 0.05$.

When the data sets from all four sites were pooled (Table 5.5), the high landscape positions contained significantly more NO_3^--N and total inorganic N in the top 60 cm than did the low landscape positions. Much of these differences in NO_3^--N and total inorganic N can be attributed to greater background levels of NO_3^--N in the high landscape positions at each site (Chapter 3, Table 3.2), and suggests that over the years, there have been greater losses of soil NO_3^--N in the low landscape positions than in the high landscape positions. However, there were no significant differences between landscape positions in terms of apparent recovered fertilizer N in the spring, suggesting that over-winter losses of fertilizer N were not simply affected by landscape position alone.

Table 5.5. Total mean recovered soil mineral N at seeding and apparent over-winter loss of fall-banded N at all sites: 0-60 cm soil depth

Treatment						
Landscape position	Fertilization	Total NH_4^+-N	Total NO_3^--N	Total inorganic N	Apparent recovered fertilizer N	Apparent over-winter gain/loss of fertilizer N
				(kg ha^{-1})^z		
High	Early fall	52.4	131.5	183.9	71.7	-8.3
	Mid fall	57.6	119.6	177.6	65.4	-14.6
	Late fall	52.2	126.7	179.1	66.9	-13.1
	Spring	-	-	-	-	-
	Control (no N)	49.3	62.9	112.2	-	-
	Early fall w/ inhibitors	54.0	121.3	175.4	63.2	-16.8
	LSD (α = 0.05)^y	-	-	-	-	
Low	Early fall	48.9	89.7	138.8	53.4	-26.6
	Mid fall	55.4	94.7	150.5	65.1	-14.9
	Late fall	57.3	95.8	153.4	68.0	-12.0
	Spring	-	-	-	-	-
	Control (no N)	50.6	34.5	85.4	-	-
	Early fall w/ inhibitors	55.3	85.9	141.3	55.9	-24.1
	LSD (α = 0.05)^y	-	-	-	-	
Landscape position means						
High		53.1	112.4a	165.6a	66.8	-13.2
Low		53.5	80.1b	133.9b	60.6	-19.4
LSD (α = 0.10)		ns	13.7	15.5	ns	
	Fertilization means					
	Early fall	50.7bc	110.6	161.4a	62.6	-17.5
	Mid fall	56.5a	107.2	164.1a	65.3	-14.8
	Late fall	54.8ab	111.3	166.3a	67.5	-12.6
	Spring	-	-	-	-	-
	Control (no N)	49.9c	48.7	98.8b	-	-
	Early fall w/ inhibitors	54.7ab	103.6	158.4a	59.6	-20.5
	LSD (α = 0.05)	4.5	-^{x}	12.4	ns	

ANOVA	df		$P > F$		df	$P > F$
Site year	3	0.0001*	0.011*	0.018*	3	0.21
Landpos	1	0.92	0.0005*	0.0018*	1	0.55
Site year*Landpos	3	0.33	0.36	0.16	3	0.63
Trt	5	0.015*	0.0001*	0.0001*	3	0.61
Site year*Trt	15	0.15	0.044*	0.07	9	0.08
Landpos*Trt	5	0.35	0.58	0.49	3	0.38
Site year*Landpos*Trt	15	0.84	0.30	0.30	9	0.20
Block(Site year*Landpos)	24	0.0001*	0.0001*	0.0001*	24	0.0001*
Residual C.V. (%)		16.8	22.6	16.7		38.8

a-c Mean values followed by the same letter (within columns) are not significantly different.

^{z} Assuming a bulk density of 1.24 g cm^{-3} for 0-15 cm depth and 1.33 g cm^{-3} for 15-120 cm.

^{y} LSD for individual treatments within a landscape position is not reported because there was no Landpos*Trt interaction.

^{x} LSD for is not reported because of significant Site year*Trt interaction.

† Significant at $P < 0.10$ (used only for landscape position variables and interactions).

* Significant at $P < 0.05$.

5.4.1.2 Application Date and Fertilizer Additives. At Kane (2000/01), the conversion of fall-banded urea to NO_3^--N was nearly complete by planting in early June (Table 5.1). There were no significant differences in total recoverable NH_4^+-N and NO_3^--N in the spring between early fall, mid fall and late fall-banded N. Further statistical analyses of the landscape position by treatment interaction for total inorganic N determined that in the low landscape positions, mid and late fall-banded N significantly increased the recovery of total inorganic N compared to early fall applications. These differences in total inorganic N in the low landscape positions were due to total recovered NO_3^--N from the early fall treatment being considerably less than that recovered in the mid fall and late fall treatments. Similarly, there was a landscape position by fertilization treatment interaction for the apparent net recovered fertilizer N in the spring that showed most of this difference in N recovery was due to high apparent losses of early fall-banded fertilizer N in the low landscape positions.

The apparent over-winter losses of early fall-banded N in the low landscape positions at Kane (2000/01) were large (approximately 70% of applied) and more than double those from mid and late fall-banded N. In comparison, there were no differences in the apparent recovered fertilizer N among application date, and over-winter losses of fall-banded N were much less in the high landscape positions (average of 19%). This suggests that date of application of fall-banded fertilizers is much more critical in lower lying areas of the field or in poorly drained fields than in better drained fields, especially when conditions are wet in the fall and spring.

Results at Kane (2000/01) are similar to previous experiments in Alberta, where spring recovery of fall-fertilizer N was increased by delaying application in the fall (Monreal 1981 *in* Nyborg et al. 1990). Our recoveries are also similar to those of Nyborg et al. (1990), who reported recoveries of ^{15}N as mineral N in the soil in spring for fall-banded urea in the range of 25 to 56%.

Aulakh and Rennie (1984) suggest that biological immobilization, rather than leaching or denitrification, may be the major reason for reduced efficiencies of fall-applied urea fertilizers under dry soil conditions. Therefore, immobilization of N by soil microorganisms may have contributed to some of the low recoveries in mineral N at Kane (2000/01), because the potential for fertilizer N to be immobilized is greater for fall-applied N than spring applications due to the length of time the N is exposed to soil microorganisms (Olson 1982; Malhi and Nyborg 1983a; Malhi and Nyborg 1991). However, the immobilization of fertilizer N, applied in either the fall or spring, is greatly reduced when the fertilizer is placed in bands instead of broadcast and incorporated (Tomar and Soper 1981; Malhi and Nyborg 1983a; Malhi and Nyborg 1985; Malhi et al. 1989; Malhi and Nyborg 1991), because conditions within the band zone are toxic to soil microorganisms. Since the urea fertilizer was banded and over-winter losses of fertilizer N were highest for the early fall N in the low landscape positions, presumably, most of these losses were due to denitrification of NO_3^--N during the spring thaw rather than immobilization by soil microorganisms.

In the first year of the project, early fall-banded urea with NBPT and DCD reduced the over-winter losses of fertilizer N at Kane (2000/01) (Table 5.1). Early fall-banded N with inhibitors had significantly more NO_3^--N in the top 60 cm at planting than early fall-banded N without inhibitors in all landscape positions. The recovery of total inorganic N and the apparent fertilizer

N were also significantly greater for the early fall-banded N with inhibitors than the equivalent treatment without inhibitors treatment in the low landscape positions. Overall, the apparent over-winter losses from the early fall-banded N without inhibitors was more than five times greater than that from the early fall with inhibitors treatment in the low landscape positions. In contrast, there were no differences in total inorganic N or apparent recovered fertilizer N between the two early fall treatments in the high landscape positions.

In year two, differences in over-winter losses between application dates in the fall were not as significant as in the first year of the project. The fall of 2001 and spring of 2002 were considerable drier than at Kane (2000/01), especially at Kane (2001/02) and Brandon (2001/02) (Chapter 3, Table 3.4). Under these soil conditions, large losses of fall-banded N were not anticipated. At Kane (2001/02), mid fall-banded N had more recoverable NH_4^+-N in the spring than both early and late fall-banded N (Table 5.2). Reasons for this observation are not easily explained. At Rosser (2001/02) and Brandon (2001/02), practically all the fertilizer N had been converted to NO_3^--N by planting, regardless of application date or use of the inhibitors (Tables 5.3 and 5.4 respectively). The recovery of fall-banded urea fertilizer as total inorganic N in the spring was well short of being complete in the second year of the study, but the differences between early fall, mid fall and late fall applications were not statistically significant at any of the sites. There were also no significant differences among fall application dates in terms of recoverable NO_3^--N and apparent net recovered fertilizer N at any of the sites in year two, in either landscape position. Results in year two were similar to Malhi et al. (1989), who reported no real differences in the percent recovery of N^{15} in the soil at spring when banded urea was delayed from mid to late October.

The effectiveness of the double inhibitor in reducing apparent over-winter losses from early fall-banded urea was not evident in the second year of the project. The addition of inhibitors had no significant effect on total recovered NO_3^--N, inorganic N or apparent fertilizer N at the individual sites in 2001/2002 (Tables 5.2, 5.3 and 5.4). The only site in 2001/2002 where inhibitors affected concentrations of soil N in the spring was at Kane (2001/02), where the addition of inhibitors resulted in significantly more NH_4^+-N than early fall-banded N without NBPT and DCD (Table 5.2). However, there were no differences in NO_3^--N, suggesting that use of the inhibitors did not translate into reduced over-winter losses at this site. One possible explanation for the poor overall performance of the double inhibitor in the second year of the study is that the potential for N loss may not have been severe enough in 2001/2002 to fully utilize the capabilities of the NBPT and DCD inhibitors.

Over all four sites, there were few significant effects of fall application date or the NBPT and DCD inhibitors on total recovered mineral N and apparent recovered fertilizer N in the soil at planting, in either landscape position (Table 5.5).

5.4.2 Total Recovered N in the Crop and Soil at Harvest

At harvest, total recovered N in the crop and soil was consistently greater in the high landscape positions than in the low landscape positions (Table 5.6). However, significant differences between the two landscape positions were found only at Brandon (2001/02) and these differences were likely the result of greater background soil N in the high landscape positions than the low positions. The mean recovered N in the crop and soil over all four sites appeared to be 43 kg ha^{-1}

greater in the high landscape positions than in the low landscape positions, but due to the landscape position by treatment interaction, the LSD is not reported.

At Kane (2000/01) and Kane (2001/02) there were no significant differences between fall and spring applications (Table 5.6). However, at Rosser (2001/02), the total recovered N in the crop and soil was significantly higher for spring and mid fall-banded N than early-fall banded N. N recoveries for late fall-banded N appeared to be greater than for early fall-banded N, but statistically they were the same. At Brandon (2001/02), late fall-banded N resulted in significantly more N recovery than for mid fall-banded N, but not more than for early fall-banded N; the reasons for this observation are not known.

When the four sites were combined, there is evidence that fall-banded treatments behaved differently in the high and low landscape positions (Table 5.6). In the better-drained high landscape positions, there were no differences in total recovered N in the crop and soil at harvest between early fall, mid fall, and late fall-banded applications. However, in the low landscape positions, total recovered N in the crop and soil at harvest was significantly greater for late fall-banded N, than for the early and mid fall applications. Total recovered N in the crop and soil for spring-banded N was not significantly different than that recovered for the early, mid and late fall application dates.

Table 5.6. Total recovered N in the above ground crop (grain and straw) and soil (0-120 cm) at harvest

Treatment		Site				
		Kane	Kane	Rosser	Brandon	Mean
Landscape position	Fertilization	(2000/01)	(2001/02)	(2001/02)	(2001/02)	all sites
				(kg ha^{-1})^{z}		
High	Early fall	395.9	283.5	275.0	277.3	307.9a
	Mid fall	355.5	295.7	310.1	249.9	302.8a
	Late fall	364.5	301.8	282.1	293.9	310.6a
	Spring	359.2	298.2	308.9	247.5^{v}	303.4a
	Control (no N)	317.0	239.7	222.4	233.1	253.1b
	Early fall w/ inhibitors	364.2	300.5	276.1	307.8	312.2a
	LSD (α = 0.05)	-^{x}	-^{x}	-^{x}	-^{x}	na^{y}
Low	Early fall	326.3	269.1	238.5	165.1	249.7bc
	Mid fall	329.2	262.0	294.9	126.4	253.1bc
	Late fall	392.5	283.3	303.2	175.2	288.6a
	Spring	372.5	265.4	285.2	165.7	272.2ab
	Control (no N)	297.0	214.2	247.1	124.6	220.8d
	Early fall w/ inhibitors	332.4	240.9	266.4	140.3	245.0cd
	LSD (α = 0.05)	-^{x}	-^{x}	-^{x}	-^{x}	na^{y}
Landscape position means						
High		359.4	286.6	279.1	268.2a	298.3
Low		341.7	255.8	272.6	149.6b	254.9
LSD (α = 0.10)		ns	ns	ns	na^{y}	-^{w}
	Fertilization means					
	Early fall	361.1a	276.3a	256.7bc	221.2ab	278.8
	Mid fall	342.4ab	278.9a	302.5a	188.2bc	277.9
	Late fall	378.5a	292.6a	292.6ab	234.5a	299.6
	Spring	365.9a	281.8a	297.0a	206.6abc	287.8
	Control (no N)	307.0b	227.0b	234.8c	178.9c	236.9
	Early fall w/ inhibitors	348.3a	270.7a	271.2abc	224.0ab	278.5
	LSD (α = 0.05)	36.8	34.2	38.2	na^{y}	-^{w}

ANOVA	df	$P > F$				df	$P > F$
Landpos	1	0.62	0.55	0.89	0.0085*		
Trt	5	0.0085*	0.0096*	0.0066*	0.031*		
Landpos*Trt	5	0.13	0.80	0.52	0.37		
Block(Landpos)	6	0.0001*	0.0001*	0.0001*	0.0001*		
Residual C.V. (%)		10.3	12.3	13.6	17.4		
Site year						3	0.0007*
Landpos						1	0.044*
Site year*Landpos						3	0.23
Trt						5	0.0001*
Site year*Trt						15	0.38
Landpos*Trt						5	0.095†
Site year*Landpos*Trt						15	0.65
Block(Site year*Landpos)						24	0.0001*
Residual C.V. (%)							13.0

a-d Mean values followed by the same letter (within columns) are not significantly different.

^{z} Assuming a bulk density of 1.24 g cm^{-3} for 0-15 cm depth and 1.33 g cm^{-3} for 15-120 cm.

^{y} LSD is not applicable (na) because LSMEANS was used, which does not provide an LSD value.

^{x} LSD for individual treatments within a landscape position is not reported because there was no Landpos*Trt interaction.

^{w} LSD is not reported because of Landpos*Trt interaction.

^{v} Brandon 2001/2002 had 1 missing spring sample in the high landscape position: therefore values estimated by SAS.

† Significant at $P < 0.10$ (used only for landscape position variables and interactions).

* Significant at $P < 0.05$.

Soil analyses had revealed that the NBPT and DCD formulated urea, banded early in the fall, reduced the rate of nitrification during the fall at two of the four sites (Chapter 4) and reduced over-winter losses of N in the first year of the study (section 5.4.1). However, at harvest there were no significant differences between early fall-banded N, with and without NBPT and DCD inhibitors, in terms of total recovered N in the crop and soil at any of the individual sites, or when the sites were combined (Table 5.6).

5.4.3 Overall Efficiency of Recovered Fertilizer N

The relative efficiency of recovered fertilizer N was highest in the high landscape positions at three of the four sites; Kane (2001/02), Rosser (2001/02) and Brandon (2001/02) (Table 5.7). However, due to variability, there were no significant differences in the apparent recovered and overall efficiency of fertilizer N at harvest between high and low landscape positions at any of the individual sites.

As with landscape position, there were few differences in the apparent recovered fertilizer N between early fall, mid fall, late fall and spring-banded N at the individual sites (Table 5.7). However, when the data sets were combined, the mean apparent recovered fertilizer N had a significant landscape position by treatment interaction (Table 5.7). As reported earlier for total recovered N in the crop and soil at harvest (Table 5.6), differences in the apparent recovered fertilizer N among application dates were large in the low landscape positions and nonexistent in the high landscape positions. The apparent recovered fertilizer N for late fall and spring-banded N was significantly greater than for early fall, mid fall and early fall with inhibitors in the low landscape positions. Late fall-banded N was twice as efficient, in terms of recovered fertilizer N, as early and mid fall application in the low landscape positions.

Table 5.7. The apparent recovered fertilizer N and overall efficiency of recovered fertilizer N in the above ground portion of the crop (grain and straw) and soil (0-120 cm) at harvest

Treatment			Site: Kane (2000/01)		Kane (2001/02)		Rosser (2001/02)		Brandon (2001/02)		Mean all sites		
Landscape position	Fertilization		Apparent recovered fertilizer N (kg ha^{-1})	Efficiency of recovered fertilizer N (%)	Apparent recovered fertilizer N (kg ha^{-1})	Efficiency of recovered fertilizer N (%)	Apparent recovered fertilizer N (kg ha^{-1})	Efficiency of recovered fertilizer N (%)	Apparent recovered fertilizer N (kg ha^{-1})	Efficiency of recovered fertilizer N (%)		Apparent recovered fertilizer N (kg ha^{-1})	Efficiency of recovered fertilizer N (%)
High	Early fall		78.9	99	43.9	55	52.7	66	44.2	55		54.8	69
	Mid fall		38.5	48	56.0	70	87.7	110	16.8	21		49.7	62
	Late fall		47.6	59	62.1	78	59.8	75	60.8	76		57.5	72
	Spring		42.3	53	58.5	73	86.5	108	13.2[w]	17		50.1	63
	Early fall w/ inhibitors		47.2	59	60.8	76	53.7	67	74.7	93		59.1	74
	LSD (α = 0.05)		-[y]		-[y]		-[y]		-[y]			ns	
Low	Early fall		29.3	37	54.8	69	-8.6	-11	40.5	51		28.9bc	36
	Mid fall		32.2	40	47.7	60	47.8	60	1.8	2		32.3bc	40
	Late fall		95.5	119	69.0	86	56.1	70	50.6	63		67.8a	85
	Spring		75.5	94	51.2	64	38.1	48	41.1	51		51.4a	64
	Early fall w/ inhibitors		35.4	44	26.6	33	19.3	24	15.6	20		24.2c	30
	LSD (α = 0.05)		-[y]		-[y]		-[y]		-[y]			na[z]	
Landscape position means													
High			50.9	64	56.3	70	68.1	85	41.9	52		54.3	68
Low			53.6	67	49.9	62	30.5	38	29.9	37		40.9	51
LSD (α = 0.10)			ns		ns		ns		ns			-[x]	
	Fertilization means												
	Early fall		54.1	68	49.3	62	21.9	27	42.3	53		41.9	52
	Mid fall		35.4	44	51.9	65	67.7	85	9.3	12		41.0	51
	Late fall		71.5	89	65.6	82	57.8	72	55.6	70		62.7	78
	Spring		58.9	74	54.9	69	62.2	78	27.2	34		50.8	64
	Early fall w/ inhibitors		41.3	52	43.7	55	36.4	46	45.1	56		41.6	52
	LSD (α = 0.05)		ns		ns		ns		ns			-[x]	
ANOVA		df	*P* > F		*P* > F		*P* > F		*P* > F		df	*P* > F	
Landpos		1	0.88		0.71		0.37		0.67				
Trt		4	0.38		0.80		0.06		0.15				
Landpos*Trt		4	0.13		0.75		0.52		0.29				
Block(Landpos)		6	0.11		0.093†		0.0001*		0.002*				
Residual C.V. (%)			74.1		67.6		67.8		99.9				
Site year											3	0.78	
Landpos											1	0.32	
Site year*Landpos											3	0.73	
Trt											4	0.08	
Site year*Trt											12	0.26	
Landpos*Trt											4	0.084†	
Site year*Landpos*Trt											12	0.54	
Block(Site year*Landpos)											24	0.0001*	
Residual C.V. (%)												75.7	

a-c Mean values followed by the same letter (within columns) are not significantly different.
[z] LSD is not applicable (na) because LSMEANS was used, which does not provide an LSD value.
[y] LSD for individual treatments within a landscape position is not reported because there was no Landpos*Trt interaction.
[x] LSD is not reported because of Landpos*Trt interaction.
[w] Brandon 2001/2002 had 1 missing spring sample in the high landscape position: therefore values estimated by SAS.
† Significant at *P* < 0.10 (used only for landscape position variables and interactions).
* Significant at *P* < 0.05.

The greater apparent efficiency of recovered fertilizer N for the late fall-banded N in the low landscape positions, as compared to its counterpart in the high landscape positions, was the result of relatively poor grain yields and N uptake from the control treatment in the low landscape positions (Chapter 3). We suspect that the low crop yields and N uptake for the control treatment in the low landscape positions were caused, in part, by low concentrations of soil N prior to fertilization in the low areas of the field.

Overall, there were no significant differences in the apparent recovered fertilizer N between the two early fall-banded applications, with and without inhibitors, at any of the four sites or when sites were combined, in either landscape position (Table 5.7).

The lower apparent recovery of fertilizer N in the above ground portion of the crop and the soil (0-120 cm) at harvest than that recovered in the soil at spring indicates that some losses of N fertilizer occurred during the growing season at all sites (Tables 5.5 and 5.7). Average apparent losses of fall-banded fertilizer N (without inhibitors) during the growing season were 14 kg ha^{-1} in the high landscape positions and 19 kg ha^{-1} in the low landscape positions (i.e. the total mean recovered N in the crop and soil at harvest subtracted from the total mean recovered N in the soil at planting). These N losses could have occurred through denitrification events after heavy rainfall events during the summer (Malhi et al. 1989; Nyborg et al. 1990). During both growing seasons, the sites situated within the Red River Valley endured one major rainfall event between 6.5 and 13.5 cm (Chapter 3, Table 3.5). These subsequently saturated soil conditions, combined with little N uptake at the early stage in crop growth, may have resulted in greater growing season losses of fertilizer N in the low landscape positions at Kane (2001/02), Rosser (2001/02) and Kane (2000/01).

5.5 Summary and Conclusions

Landscape influences on over-winter losses were not consistent over all site-years because of variations in local weather conditions. Over-winter losses at Kane (2000/01) and Rosser (2001/02), where conditions from fall to spring were wet, were greater than at Kane (2001/02) and Brandon (2001/02) where conditions were relatively dry. Past research in Manitoba reported that leaching of fall-banded ammoniacal fertilizers is not a concern on heavy clay or clay loam soils (Field-Ridley 1975; Racz 1979). Similarly, based on the spring sampling, there was little increase in N at soil depths below 60 cm at any of the sites in years one or two (data not presented). However, the potential for denitrification losses was high at Kane (2000/01) and Rosser (2001/02), because of heavy rains in the fall prior to freeze-up. These conditions are expected to increase over-winter losses of fall-applied N (Malhi and Nyborg 1983a). Results from Kane (2000/01) and Rosser (2001/02) show that substantial amounts of fertilizer N were lost over the winter, especially in the low landscape positions. Overall, the data suggests that the over-winter losses of fertilizer N were greater for early fall applications than late fall applications and in the low landscape positions than in the high landscape positions. Use of NBPT and DCD with early fall-banded N significantly reduced over-winter losses in year one of the study, but not in the second year.

At harvest, both total recovered N in the crop and soil and the apparent recovered fertilizer N had a landscape position by fertilization treatment interaction. There were no significant differences between fertilization treatments in the high landscape positions. However, in the low landscape positions, late fall-banded N had more recovered N in the crop and soil and greater recovered fertilizer N than applications in early fall, mid fall and early fall with inhibitors. The efficiency of recovered fertilizer N in the above ground portion of the crop and soil (0-120 cm) increased from 36 to 85% when application was delayed from early to late fall in the low landscape positions (Table 5.7). In contrast, there were no differences in recovered fertilizer N at harvest between fall application dates in the high landscape positions (average efficiency of recovered fertilizer N from the three application dates in the high landscape positions was 72%). We suspect that the primary reason for the high overall apparent recovery of fertilizer N in this study is because three of the four sites were relatively dry during the fall and summer. In addition, a reasonably low rate of N was used in this experiment in order to ensure that the crop remained within its N responsive zone for all treatments. During wet years and at higher rates of N, the efficiency of recovered fertilizer N is expected to be lower. Nonetheless, our recoveries of apparent fertilizer N in the crop and soil at harvest from fall-banded urea are consistent to those reported from previous fall-banded studies in Western Canada, under conditions where moisture is not excessive (Malhi et al. 1989; Nyborg et al. 1990; Malhi and Nyborg 1991).

There was little apparent benefit to the use of the inhibitors in either year at harvest. There were no significant differences between the two early fall-banded treatments, with and without inhibitors in terms of total recovery of N in the crop and soil or apparent recovered fertilizer N in the crop and soil, in either landscape position.

These results indicate that selection of suitable timing for application of fertilizer N to reduce over-winter losses and improve the efficiency of fall-banded N is much more critical for poorly drained fields, and for poorly drained areas within a field, than for better drained land. In the drier regions of the Canadian prairies and for land that is well-drained, early fall banded applications of N fertilizer is a viable option. However, in the more humid regions of Western Canada, especially on poorly drained land where the potential is high for prolonged flooded conditions during the fall or spring, producers should wait as long as possible in the fall, or until the spring, to apply nitrogen fertilizer.

6 INTERACTIVE EFFECTS OF LANDSCAPE POSITION AND DATE OF APPLICATION ON RESPONSE OF WHEAT TO FALL-BANDED UREA IN MANITOBA

Key Words: fall-banded N, spring-banded N, application date, landscape position, spring wheat (*Triticum aestivum*), urea

6.1 Abstract

The objective of this experiment was to investigate the interactive effects of landscape position and application date on the overall efficiency of fall-banded nitrogen (N) fertilizer, relative to spring-banded N, under Manitoba conditions. Granular urea fertilizer at a rate of 80 kg N ha^{-1} was banded at three application dates in the fall and once in the spring at planting. In the high landscape positions, the performance of fall-banded urea, relative to spring-banded urea, was not affected by application date, soil temperature on date of application, cumulative soil heat units or cumulative nitrification heat units. However, in the low landscape positions, delaying application until late in the fall, when soil temperatures had cooled to 5 or 6°C, greatly increased relative grain yields and total N uptake by the crop. Soil temperature at application gave the best correlation with relative grain yields, total N uptake, grain yield increases and N use efficiency by the crop in the low landscape positions ($r = -0.79^{**}$, -0.75^{**}, -0.78^{**} and -0.72^{**} respectively); date of application gave slightly lower correlations ($r = 0.66^{*}$, 0.66^{*}, 0.64^{*} and 0.62^{*} respectively). Soil heat units (SHU) and nitrification heat units (NHU) accumulated from date of application until freeze-up gave inferior correlations ($r = -0.56^{ns}$, -0.62^{*}, -0.56^{ns} and -0.58^{*}, and $r = -0.49^{ns}$, -0.59^{ns}, -0.49^{ns} and -0.51^{ns} respectively). Overall, the results suggest that selection of suitable timing for application of fertilizer N to optimize crop yields is much more

critical for poorly drained fields, and for poorly drained areas within a field, than for better drained land.

6.2 Introduction

In Manitoba, nitrogen (N) fertilizers are commonly applied during the fall for spring-sown crops. Many producers prefer to apply N in the fall to reduce the spring workload and thereby facilitate more timely planting of their crops (Harapiak 1979b). In addition, producers in Manitoba have historically been able to capitalize on lower fertilizer prices in the fall than in the spring (MB Agriculture and Food Soil Fertility Guide 2001). However, in Western Canada, the efficiency of fall-applied N is generally less effective than spring applications, especially if broadcast and incorporated (Harapiak 1979b; Nyborg and Leitch 1979; Racz 1979; Bole et al. 1984; Malhi et al. 1984; Ukrainetz 1984; Malhi et al. 1992b; Malhi et al. 2001). For example, in Alberta and Saskatchewan, Malhi et al. (1992b) reported that overall yield increases and N uptake of barley grain from fall-applied N (broadcast and incorporated) were half as effective as spring-applied N. In Manitoba, fall broadcast and incorporated urea was also reported to be inferior to spring applications, especially in the poorly drained heavy clay soils of the Red River Valley (Ridley 1975; Ridley 1976; Ridley 1977). Further studies in Western Canada have confirmed that late fall applications of broadcast and incorporated urea-N fertilizers generally increased crop yields and N uptake by the crop, and reduced over-winter losses of N when compared to early fall applications (Malhi et al. 1984; Malhi and Nyborg 1990a; Malhi et al. 1992b).

The performance of fall-applied N is further dependent on application techniques such as broadcasting, banding or nesting of fertilizers. In comparison to broadcast and incorporation, banding or nesting chemical fertilizers slows microbial activity within the soil because of toxic conditions within the band zone. This lowers the risk of N immobilization, slows nitrification and potentially reduces N losses by leaching and denitrification (Harapiak et al. 1993; Yadvinder-Singh et al. 1994). In Western Canada, applying nitrogen in bands or nests has consistently improved the efficiency of fall-applied fertilizers, with average yield increases from fall-banded urea often double that of fall broadcast and incorporated urea (Ridley 1976; Ridley 1977; Harapiak 1979a; Racz 1979; Carter and Rennie 1984; Malhi and Nyborg 1984; Malhi et al. 1984; Malhi and Nyborg 1985; Malhi et al. 1989; Malhi and Nyborg 1990b; Malhi and Nyborg 1991; Nyborg and Malhi 1992; Harapiak et al. 1993; Malhi et al. 1996). However, in these studies grain yields and N uptake from fall-banded N were still, on average, lower than spring-applied N. Recently, Grant et al. (2001) reported similar grain yields and total crop N uptake of durum wheat between fall and spring-banded N in two of three years on a clay loam soil, and in all three years on a drier fine sandy loam in south-western Manitoba. Similar results have been reported in the drier soil zones of Western Canada (Bole et al. 1984; Kucey 1986; Kucey and Schaalje 1986; Malhi et al. 1992b; Malhi et al. 2001), and when soil moisture contents in the fall and spring are low (Harapiak 1979b; Ukrainetz 1984).

Malhi and Nyborg (1990a) questioned whether N fertilizers applied in the fall in either sub-surface bands or nests require delaying of application date to improve grain yields, as recommended for broadcast and incorporated N fertilizers. Other work by Malhi et al. (1989) and Nyborg et al. (1990) reported no significant differences in the percent recovery of N^{15} in the crop or soil when the application of banded urea application was delayed from mid to late October. However, in Ontario, grain yields and N uptake of winter wheat were improved by delaying the application of large urea granules in the fall (Yadvider-Singh and Beauchamp 1988b). As a result, Malhi et al. (1992a) produced a technical report suggesting that grain yield increases from fall-banded N, relative to spring-applied N, were likely to double when N applications were delayed from late September to late October. However, no studies have focussed directly on the effect of early fall applications on the efficiency of banded fertilizer N in Western Canada.

Landscape position is expected to affect the efficiency of fall-banded N especially during the early spring period, when considerable ponding of snowmelt often occurs. These flooded soil conditions greatly increase the potential of denitrification losses of fall-banded N. Numerous studies from Saskatchewan have reported that denitrification rates were higher in the wetter footslope and low level complexes than in the well-drained upper slope positions (Elliot and de Jong 1992; Pennock et al. 1992; van Kessel et al. 1993; Corre et al. 1995; Corre et al. 1996; Farrell et al. 1996). The effects of landscape position on fall-banded N are expected to be greatest if combined with early fall applications of fertilizer N. Early fall applications of ammoniacal fertilizers generally form more nitrate prior to the soil freezing than fertilizer applied later in the season (Nyborg et al. 1990), increasing the potential for over-winter and early spring losses of NO_3^- via denitrification (Yadvinder-Singh et al. 1994). However, no experiments have focused on the impact of landscape position on the efficiency of fall-banded N under Western Canadian conditions. The objective of this project is to investigate the interactive effects of landscape position, application date and weather conditions on the efficiency of fall-banded urea fertilizer in southern Manitoba.

6.3 Materials and Methods

6.3.1 Site Selection and Description

A detailed description of the experimental sites is described in Chapter 3 (section 3.3.1). Four field experiments were conducted in Manitoba over two fertilization/growing seasons: fall 2000 to harvest 2001 (year one), and fall 2001 to harvest 2002 (year two). Three of the four sites were located in the relatively level lacustrine landscape of the Red River Valley (Kane (2000/01), Kane (2001/02) and Rosser (2001/02)), on Red River/Osborne (Gleyed Rego Black Chernozem/Rego Humic Gleysol) heavy clay soil with typical elevation differences of less than 1 m per km within each site. The fourth site was located at the AAFC Brandon Research Centre's Phillips Research Farm on Newdale (Orthic Black Chernozem) clay loam soil. The topography at the Brandon site was slightly more undulating, and representative of glacial till landscapes in the Black soil zone of south-western Manitoba.

6.3.2 Experimental Design and Treatments

The experimental design and treatments used in this project have already been described in detail in Chapter 3 (section 3.3.2). A split-plot design was utilized at all sites, with landscape position main plots and fertilization treatment subplots. Landscape positions studied in this experiment were defined as "high" and "low" based on their relative elevations to one another within the field. The individual low landscape positions were localized concave areas in which temporary ponding occurred in the spring after snowmelt or after heavy rainfalls, whereas the high landscape positions were slightly raised divergent areas located between these low positions where more water shedding occurred. Separate main plots were located in an individual high or low landscape position (four of each) throughout the field.

Nitrogen fertilizer was applied in the fall as urea (46-0-0), banded at a rate of 80 kg N ha^{-1}, with 40 cm spacing, at a depth of 7.5 cm. In the spring, urea fertilizer was mid-row banded at planting. In addition, there was a control where no N fertilizer was applied. At Kane (2000/01), application of fall-banded urea N occurred on September 29, October 12, and October 26. In year two, treatments were applied at Kane (2001/02) on September 26, October 9, and October 19, at Rosser (2001/02) on September 19, October 1, and October 19, and at Brandon on September 15, October 1, and October 15. The corresponding soil temperatures at 7.5 cm depth for the three fall application dates at each site were 11.3, 8.8, and 7.8°C at Kane (2000/01); 10.4, 7.8 and 6.6°C at Kane (2001/02); 13.9, 12.5 and 5.6°C at Rosser (2001/02); and 12.2, 11.6 and 5.7°C at Brandon (2001/02).

6.3.3 Crop and Environmental Measurements

Crop sampling and analysis activities have already been described in detail in Chapter 3 (section 3.3.3). AC Barrie wheat (*Triticum aestivum*) was grown as the test crop at all sites. At physiological maturity, a 3 m x 2 row sample of above ground plant tissue was harvested from each subplot, dried, threshed, weighed for grain and straw yields, and analyzed for total N.

Climatic data and sampling activities are described in detail in Chapter 3 (section 3.3.5) and Chapter 4 (section 4.3.4). Monitoring of both soil moisture and temperature was focused on the periods from mid-September to freeze-up and from early spring to planting. Soil temperature reported for day of application is an average of hourly temperatures during the day.

6.3.4 Data Analyses

A detailed description of the statistical analyses used in this experiment can be found in Chapter 3 (section 3.3.6) and Chapter 4 (section 4.3.5). Statistical analyses were conducted using the General Linear Model (GLM) procedure of the Statistical Analysis System (SAS) package (SAS 1999). Descriptive statistics were used to test the data for normality and skewness using the Proc Univariate function of SAS. Linear correlations (r) (Pearson's correlation coefficients) were determined to test the relationships of percent of recovered fertilizer N as NH_4^+-N as a function of date of fertilizer N application, average soil temperature at 7.5 cm on day of application, cumulative soil heat units (SHU) and cumulative nitrification soil heat units (NHU). A detailed description of cumulative soil heat units and nitrification heat units can be found in Chapter 4 (section 4.3.4). Soil heat units and nitrification heat units were accumulated from date of application to first day of 0°C at 7.5 cm soil depth, and determined using the following equations ($A = 0.059$, $B = 0.21$, T_i = hourly soil temperature at 7.5 cm):

$$SHU = \sum \frac{(\sum^{i}(T_i))}{24}$$

$$NHU = \sum \frac{\sum^{i}(Ae^{B(Ti)})}{24}$$

Variability and normality of the residual data was tested using diagnostic plots generated by SAS. For the fertilization treatment means, a probability level (α) of 0.05 was used as the significance threshold for the slope of the individual linear correlations. Proc GLM was used to compare the slopes of the linear correlations between landscape positions. Due to the high variability inherent in field-based landscape experiments, a higher probability level of 0.10 was used to detect differences between landscape positions. This higher probability level is within the typical range of probability values ($P \leq 0.10$ to 0.20) used in many landscape studies (Pennock et al. 1992; van Kessel et al. 1993; Corre et al. 1996; Beckie and Brandt 1997; Jowkin and Schoenau 1998).

6.4 Results and Discussion

6.4.1 Grain Yield and N Uptake

Correlation coefficients for relative grain yields and total N uptake by the crop from fall-banded N, as a percent of spring-banded N, showed a distinct landscape position effect with regard to date of fall application (Fig. 6.1 and 6.2). In the high landscape positions, regardless of the actual application date in the fall, relative grain yields and crop N uptake of fall-banded N were equivalent to spring-banded N. This suggests that application date for fall-banded N is not a factor in better-drained landscape positions and in well-drained fields. However, in the low landscape positions, delaying application date from mid September to mid October significantly increased both relative grain yield and N uptake by the crop of fall-banded N. Relative grain yields in the low landscape positions ranged from 79% of spring-banded N when applied in mid September, to 104% of spring-banded N when applied in mid to late October. The slope of the correlation coefficients for the high landscape positions was significantly different than the slope of the correlation coefficients for the low landscape positions ($\alpha = 0.10$) for relative grain yields, but not for relative N uptake by the crop.

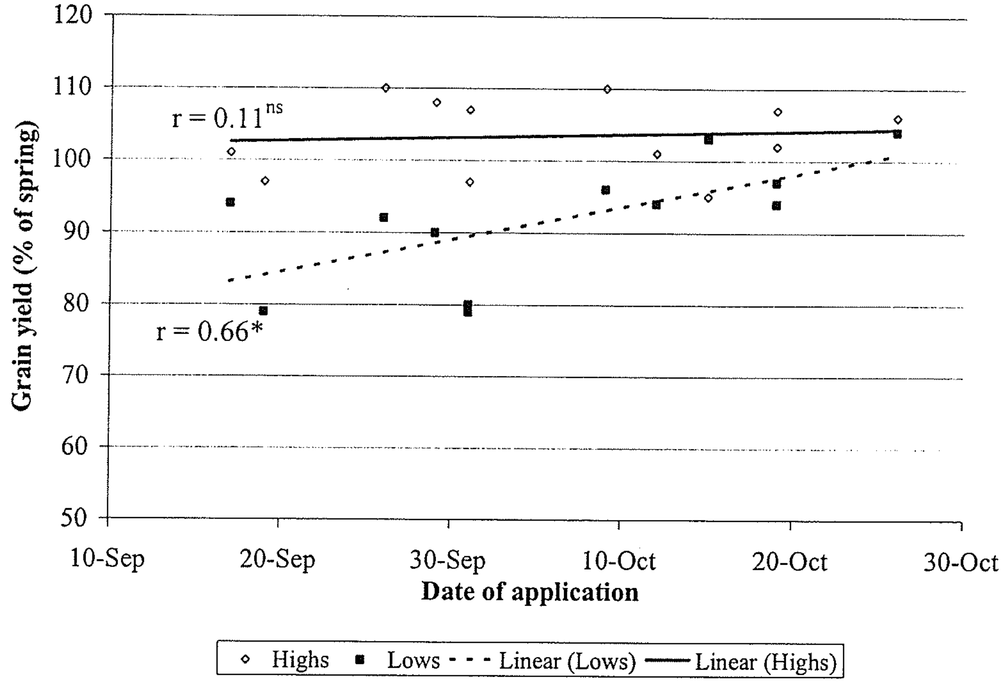

Fig. 6.1. Effect of date of N application in the fall on wheat grain yields from fall-banded urea relative to spring-banded urea (High vs. Low positions $P = 0.067^{\dagger}$) (ns, †, * indicates no significance, and significance at 0.1 and 0.05 levels respectively).

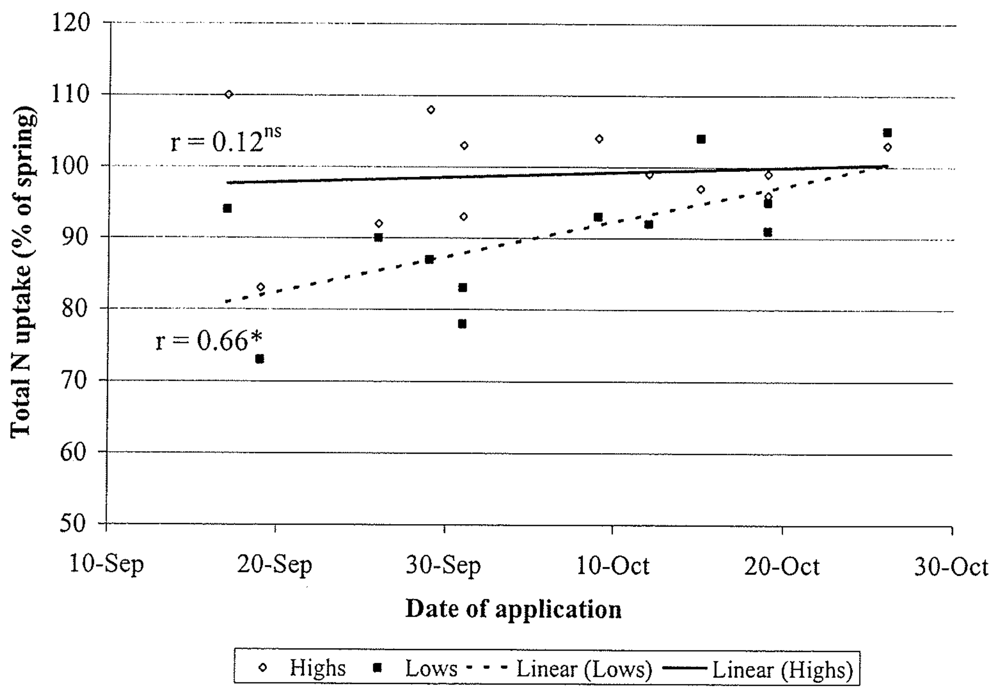

Fig. 6.2. Effect of date of N application in the fall on total N uptake by the crop from fall-banded urea relative to spring-banded urea (High vs. Low positions $P = 0.11^{ns}$) (ns, * indicates no significance and significance at 0.05 level respectively).

Similar results were evident for correlations between soil temperature at application (7.5 cm) and relative grain yield or N uptake by the crop (Fig. 6.3 and 6.4. respectively). In the high landscape positions, the average daily soil temperature on the day of application was not significantly correlated to either relative grain yield or N uptake by the crop. However, in the low landscape positions, the correlations between soil temperature and relative grain yields and between soil temperature and relative N uptake by the crop were strongly negative (r = -0.79** and -0.75** respectively). The slopes of the correlation coefficients were significantly different between landscape positions, for both relative grain yields and crop N uptake ($P = 0.018$* and 0.076† respectively).

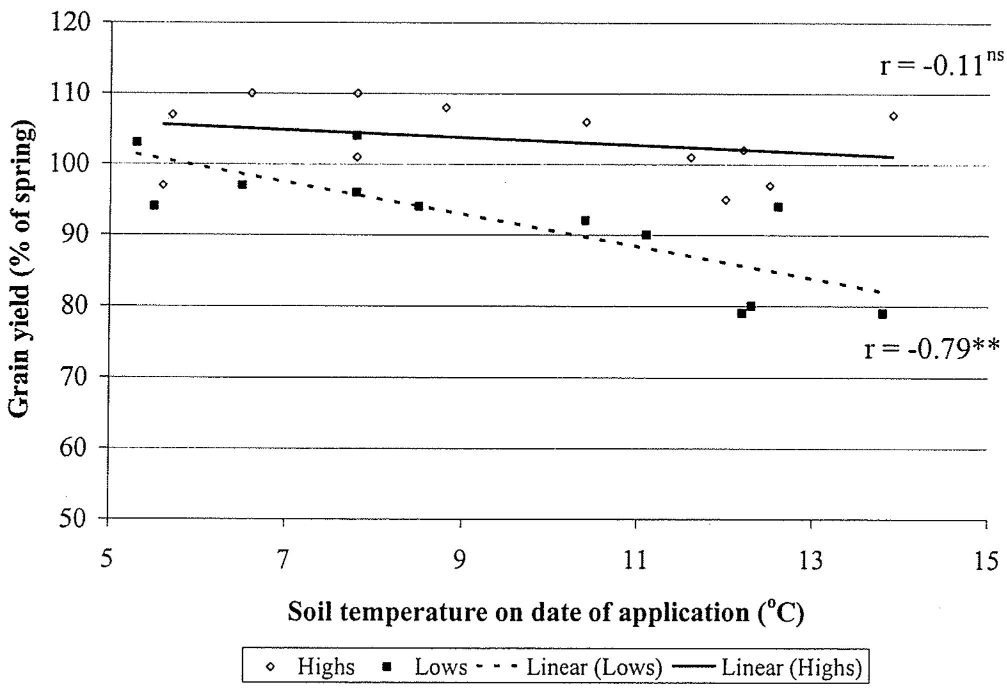

Fig. 6.3. Effect of soil temperature at 7.5 cm on date of N application in the fall on wheat grain yields from fall-banded urea relative to spring-banded urea (High vs. Low positions $P = 0.018$*) (ns, *, ** indicates no significance, and significance at 0.05 and 0.01 levels respectively).

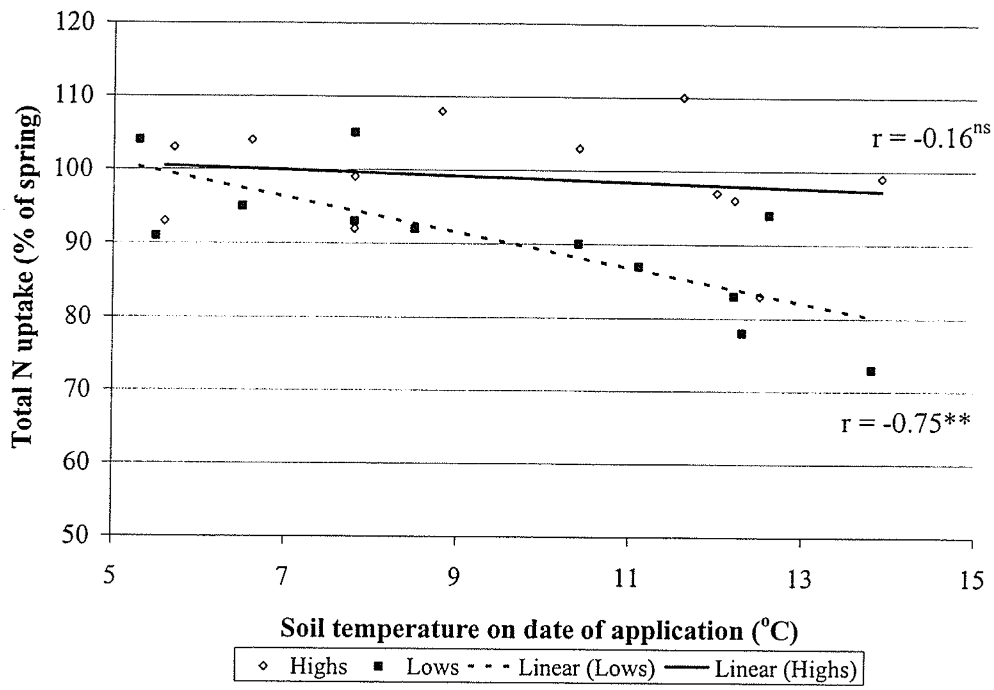

Fig. 6.4. Effect of soil temperature at 7.5 cm on date of N application in the fall on total N uptake by the crop from fall-banded urea relative to spring-banded urea (High vs. Low positions P = 0.076†) (ns, †, ** indicates no significance, and significance at 0.1 and 0.01 levels respectively).

Soil heat units accumulated from the date of fall application until the soil froze produced lower correlations with relative grain yields and total N uptake than did date of application and soil temperature on the date of application. The data suggests that relative grain yield and N uptake by the crop is affected by accumulated SHU in only the low landscape positions. In these poorly drained depressional areas of the field, the relative efficiency of fall-banded N as grain yield and total N uptake decreased with increased SHU prior to winter. The linear correlation coefficient between SHU and total N uptake was significant (r = -0.62*) (Fig. 6.5), but the correlation between SHU and relative grain yield (r = -0.56^{ns}) in the low landscape positions was not quite significant (P = 0.054) (Appendix E). In addition, there was no significant difference between the slopes of the linear correlations in the high and low landscape positions for SHU and total N uptake (Fig. 6.5).

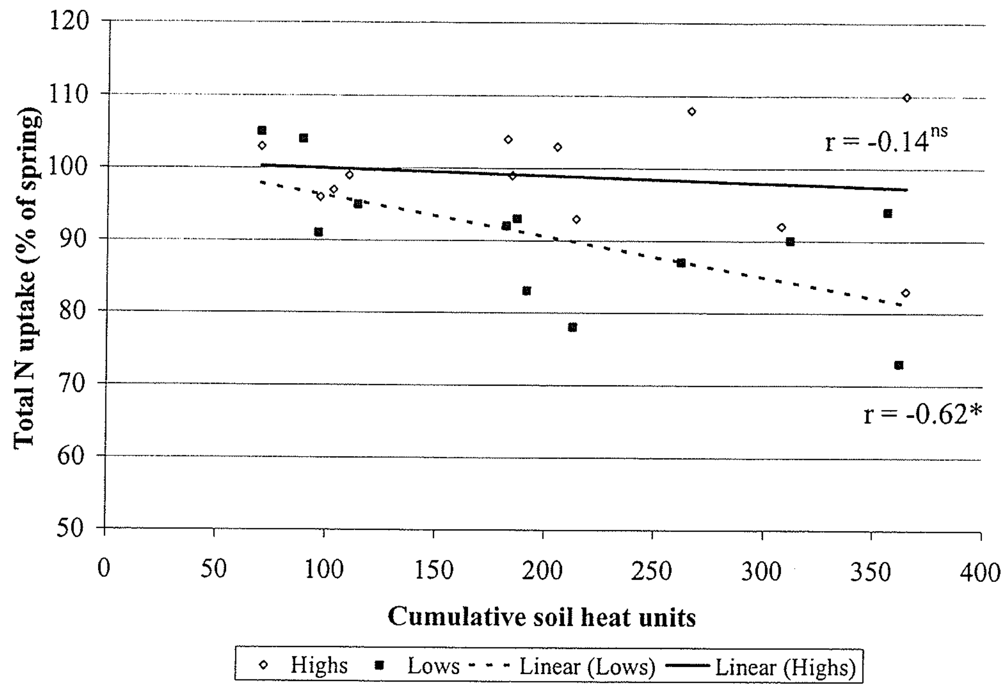

Fig. 6.5. Effect of cumulative SHU in the fall until freeze-up on total N uptake by the crop from fall-banded urea relative to spring-banded urea (High vs. Low positions $P = 0.16^{ns}$) (ns, * indicates no significance and significance at 0.05 level).

The correlation between nitrification heat units accumulated from the date of fall application until the winter produced the poorest correlations of the approaches used (Appendix E). There were no significant correlations between NHU and grain yield or N uptake by the crop in high landscape positions (r = -0.09^{ns} and -0.01^{ns} respectively) or low landscape positions (r = -0.49^{ns} and -0.59^{ns} respectively), and no significant differences between the slopes of the linear correlations in the respective landscape positions.

6.4.2 Grain Yield Increases and Fertilizer N Use Efficiency

Grain yield increases (GYI) and fertilizer nitrogen use efficiency (NUE) from fall-banded urea, relative to spring-banded N, were also tested to determine correlation coefficients as a function of date of fall application, soil temperature on date of application, SHU and NHU. In determining GYI and NUE for each site, variability among samples resulted in some calculated GYI and NUE that were negative after subtracting the grain yield and N uptake of the control plot. This increased variability within the data set resulted in few significant differences being found between the responses for the high and low landscape positions at a probability level (α) of 0.10 or lower. However, the differences between the slopes of the correlation coefficients in the high and low landscape positions produced for both GYI and NUE, as a function of application date, soil temperature on date of application and SHU, would have been regarded as significant if a probability threshold of 0.20 had been used, as is common in many landscape studies.

Results for increases in grain yield and N use efficiency of the crop, as a function of date of fall application, soil temperature on date of application, SHU and NHU were similar to those reported for relative grain yields and N uptake by the crop. There were no significant correlations in the high landscape positions among any of the four approaches used, indicating that the date of application in the fall did not influence fertilizer response in this landscape position. In the low landscape positions, relative increases in grain yield and NUE of the crop improved as date of application was delayed in the fall ($r = 0.64^*$ and 0.62^* respectively) (Fig. 6.6 and 6.7) and with lower soil temperatures on the date of application ($r = -0.78^{**}$ and -0.72^{**} respectively) (Fig 6.8 and 6.9). The slopes of the correlation coefficients for soil temperature on date of application and grain yield increases in the high and low landscape positions were significantly different at a probability level of 0.10 (Fig. 6.8).

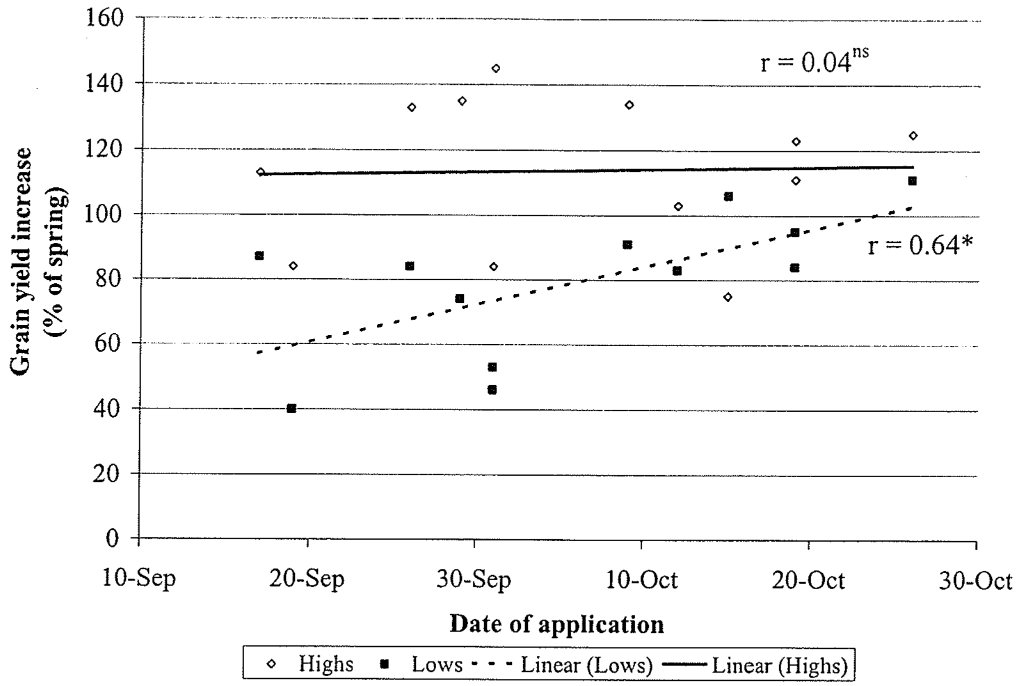

Fig. 6.6. Effect of date of N application in the fall on increases in wheat grain yield from fall-banded urea relative to spring-banded urea (High vs. Low positions $P = 0.15^{ns}$) (ns, * indicates no significance and significance at 0.05 level respectively)

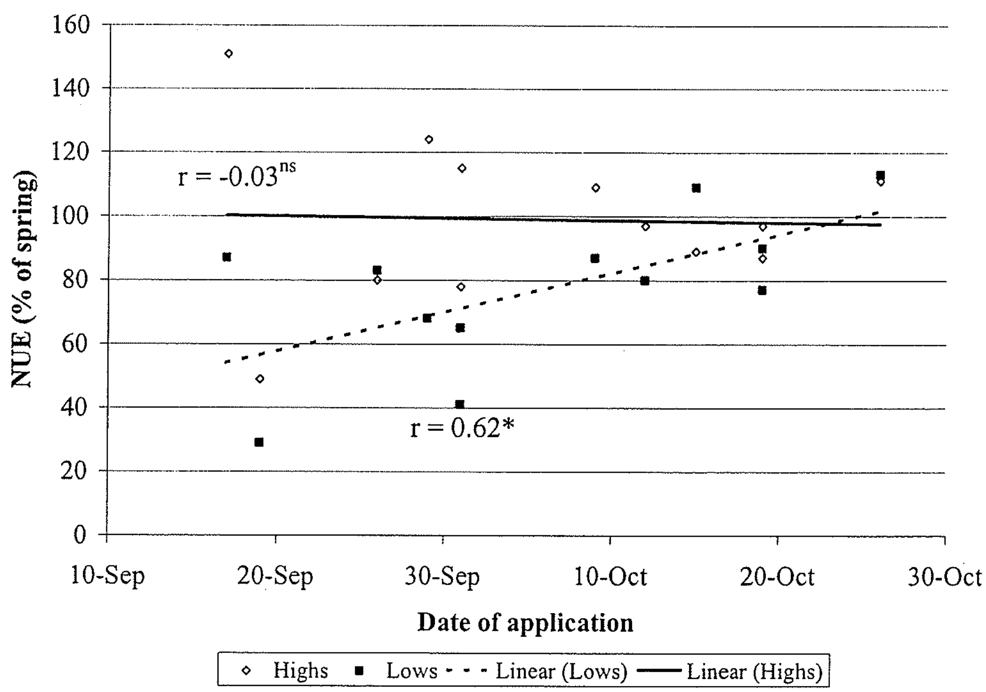

Fig. 6.7. Effect of date of N application in the fall on N use efficiency from fall-banded urea relative to spring-banded urea (High vs. Low positions $P = 0.13^{ns}$) (ns, * indicates no significance and significance at 0.05 level respectively).

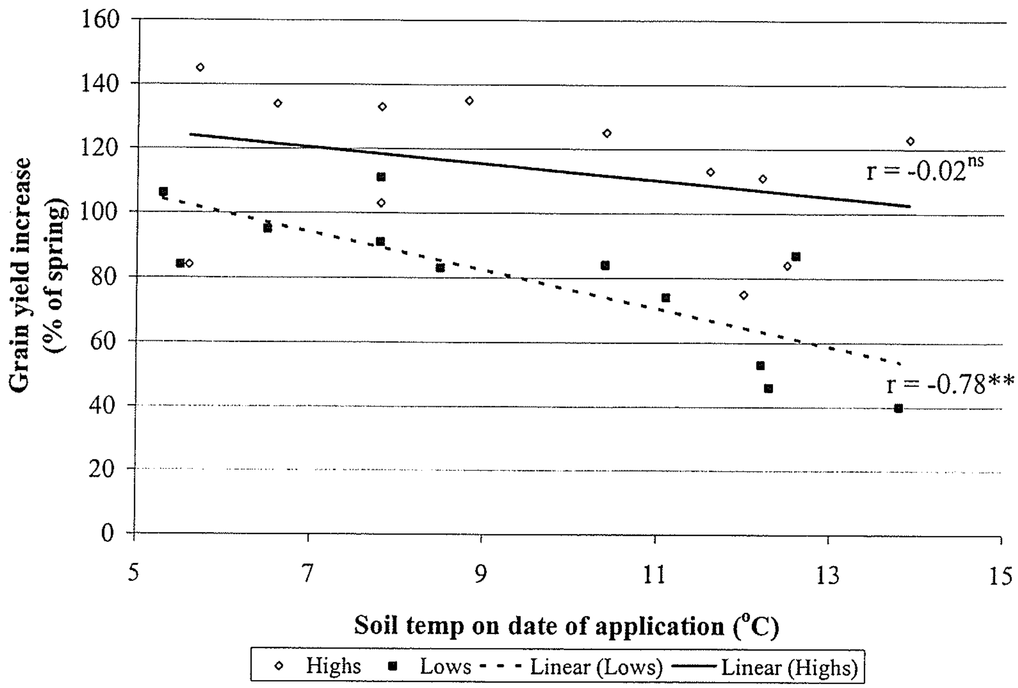

Fig. 6.8. Effect of soil temperature at 7.5 cm on date of N application in the fall on increases in wheat grain yield from fall-banded urea relative to spring-banded urea (High vs. Low positions $P = 0.066^{\dagger}$) (ns, †, ** indicates no significance, and significance at 0.1 and 0.01 levels respectively).

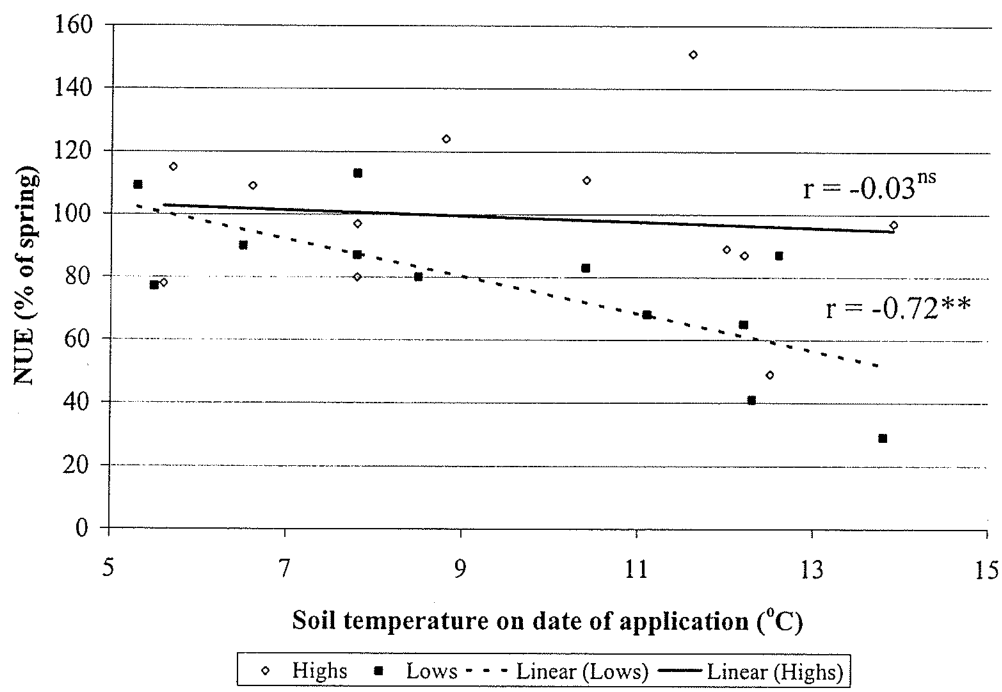

Fig. 6.9. Effect of soil temperature at 7.5 cm on date of N application in the fall on N use efficiency from fall-banded urea relative to spring-banded urea (High vs. Low positions $P = 0.11^{ns}$) (ns, ** indicates no significance and significance at 0.01 level respectively)

Relative grain yield increases from fall-banded N appeared to improve as SHU declined over the fall ($r = -0.56^{ns}$), but again the relationship was not quite significant ($P = 0.056$) (Appendix E). However, N use efficiency of fall-banded N, relative to spring-banded N improved significantly as SHU declined over the fall ($r = -0.58^{*}$) (Fig. 6.10).

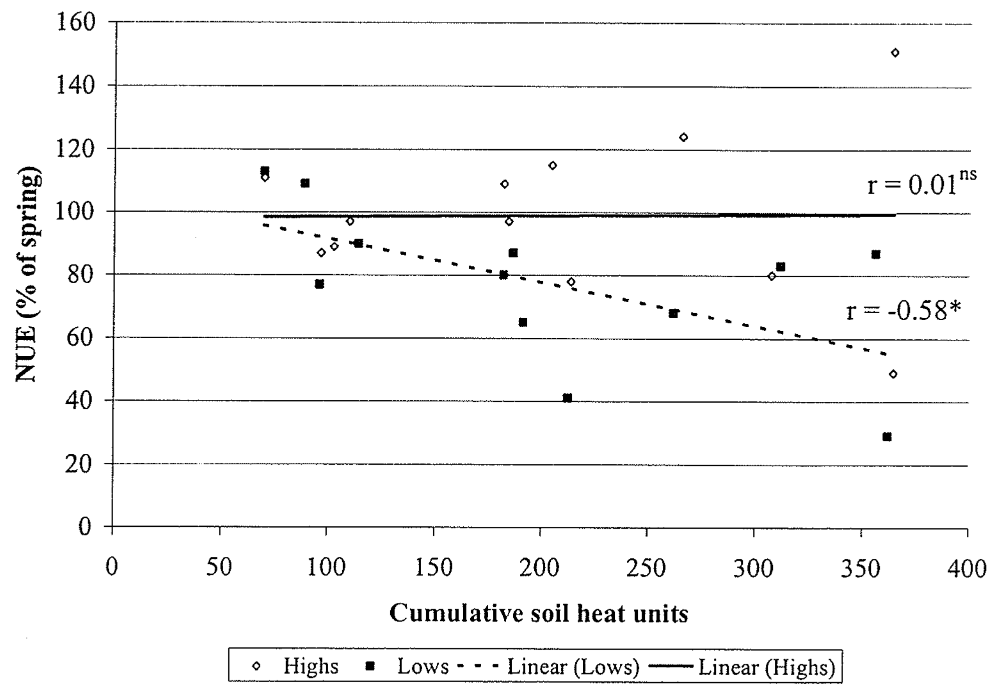

Fig. 6.10. Effect of cumulative SHU until 0°C soil temperature at 7.5 cm in the fall on N use efficiency from fall-banded urea relative to spring-banded urea (High vs. Low positions $P = 0.17^{ns}$) (ns, * indicates no significance and significance at 0.05 level respectively).

As was reported earlier for relative grain yields and N uptake by the crop, nitrification heat units also gave inferior correlations with grain yield increases and N use efficiency. NHU were not significantly correlated with either relative grain yield increases or N use efficiency in the high landscape positions ($r = -0.05^{ns}$ and -0.04^{ns} respectively) or the low landscape positions ($r = -0.49^{ns}$ and -0.51^{ns} respectively) (Appendix E).

Overall, our results are consistent with past research from Western Canada. In Alberta, Malhi and Nyborg (1990a) reported that grain yield increases from fall broadcast and incorporated urea (relative to spring) increased substantially after delaying application in the fall from mid September to early November (23 to 76% respectively). Malhi and Nyborg (1990a) mentioned that N fertilizer applied in the fall in either sub-surface bands or nests may be less sensitive to earlier application dates and/or higher soil temperature at time of application. This appears to be the case in the high landscape positions, as there were no significant relationships between date of application, soil temperature on date of application, SHU or NHU and either relative grain yields or total N uptake by the crop. However, in the low landscape positions, the efficiency of fall-banded N fertilizer appears to decline in response to early application date and higher soil temperatures on the date of application. The high landscape positions were moderately well drained and prolonged saturated soil conditions never occurred, whereas the low landscape positions remained saturated for considerable lengths of time, especially in the spring. Therefore, we suspect that the decline in fertilizer efficiency in the low landscape positions was due to increased over-winter losses, presumably from denitrification.

Malhi and Nyborg (1990a) used four linear regression analyses to predict grain yield increases and NUE from fall broadcast and incorporated N fertilizer, relative to spring application. Their regression analyses included date of application, soil temperature on the day of fertilizer application, the number of days from application to the first day of 0°C, and soil degree days accumulated from application to first day of 0°C. Date of fall application and soil temperature on the day of N application resulted in the lowest correlations between grain yield increases from fall and spring-applied N (r values of 0.68 and 0.55 respectively). Malhi and Nyborg (1990a) concluded that the "low" correlations were due to high day-to-day variability in soil temperature during the fall, instead of a smooth decline towards 0°C. Their correlations were improved after using the number of days until the first day of 0°C date and total soil degree-days from application to soil freezing (r values of 0.77 and 0.78 respectively).

However, the results from the low landscape positions in the present study are opposite to those reported by Malhi and Nyborg (1990a). We found that soil temperature on date of application resulted in the best correlations with relative grain yield and N uptake by the crop, followed by application date, SHU and finally NHU. One possible explanation for this is that banded-N fertilizers may not be as sensitive to daily changes in soil temperature as broadcast and incorporated N, because nitrification rates are already slowed due to toxic microbial conditions present within the band zone. In comparison to Malhi and Nyborg (1990a), we cannot easily explain why the more sophisticated approaches, SHU and NHU accumulated over the fall until the soil froze, were so poorly correlated with harvest yields. We expected that SHU and NHU would produce high correlations with relative grain yield and N uptake by the crop, because these measures best accounted for daily changes in soil temperature in the fall (Chapter 4). Furthermore, nitrification heat units should have accounted for the exponential slowing of nitrification rates at soil temperatures below 4.5°C. One possible explanation for the poor correlations of wheat response with SHU and NHU is that denitrification losses of fall-banded N in the spring are not always directly related to the accumulation of nitrified fertilizer N in the fall. If soil conditions in the spring are dry and not conducive to denitrification, nitrates that built up in the fall will not be lost from the soil system. In year one of the study, soil conditions were wet in the spring, but in the second year, soil conditions were drier at all three sites, especially at

Kane (2001/02) and Brandon (2001/02). Therefore, differences in soil moisture content from one site year to another, factors not considered by SHU and NHU, could have added variability to the measurements of N fertilizer efficiency. Had environmental conditions been conducive to large over-winter losses of fall-applied N in both years of the study, we suspect that SHU and NHU would have performed better. However, practical field use of both SHU and NHU would require accurate forecasting of the first day of soil freezing, and therefore would be most useful as a historical monitoring tool for producers. Conversely, the results suggest that date of application and soil temperature at application are simple, robust approaches for estimating the effect of weather conditions on the efficiency of fall-banded N in southern Manitoba and could be easily implemented into a fall fertilization program.

6.5 Summary and Conclusions

The Manitoba Agriculture and Food Soil Fertility Guide (2001) states that relative efficiencies of fall-banded N fertilizers in southern Manitoba are generally 20% less effective than spring-banded N. In the present study, we found that grain yield increases and N use efficiency from fall-banded N ranged from 40 to 145% and 30 to 150% respectively that of spring banded-N, depending on application date and landscape position. Overall, average grain yield increases and N use efficiency from fall-banded N were both approximately 90% that of spring-banded N (note: average GYI and NUE are a combination of average application date (i.e. early October) and average landscape position). Manitoba Agriculture and Food also recommends that fall applications of ammoniacal fertilizers be delayed until the soil temperature at 10 cm declines to 5°C or lower. We determined that the efficiency of fall-banded urea in the better-drained high landscape positions was not affected by application date, soil temperature on date of application, SHU or NHU. However, in the low landscape positions, relative grain yields, total N uptake, grain yield increases and N use efficiency by the crop were significantly improved after delaying application until the late fall when soil temperatures were 5 or 6°C. Correlations between relative grain yields, N uptake by the crop, grain yield increases and N use efficiency in the low landscape positions were highest with soil temperature at application (r = -0.79**, -0.75**, -0.78** and -0.72** respectively) and date of application (r = 0.66*, 0.66*, 0.64* and 0.62* respectively). Correlations between relative grain yields, N uptake by the crop, increases in grain yield and N use efficiency and SHU were inconsistent (r = -0.56^{ns}, -0.62*, -0.56^{ns} and -0.58* respectively) in the low landscape positions, while NHU accumulated during the fall prior to freeze-up were not significantly correlated with relative grain yields, crop N uptake, grain yield increases or N use efficiency of the wheat crop in either landscape position.

Presumably, the increased efficiency of late fall-banded N was due to reduced nitrification of the fertilizer N prior to winter (Chapter 4), which led to less over-winter losses of NO_3^--N, especially in the low landscape positions (Chapter 5). Malhi and Nyborg (1990a) also suggest that immobilization is reduced when fertilizer N is applied late in the fall after soils have cooled. In the end, selection of suitable timing for application of fertilizer N to optimize crop yields is much more critical for poorly drained fields, and for poorly drained areas within a field, than for better drained land. For land that is well-drained, early fall application of N fertilizer is a viable option. However, in regions or on land where the potential for prolonged flooded conditions during the fall or spring is high, producers should wait as long as possible in the fall, or until the spring, to apply nitrogen fertilizer.

7 GENERAL DISCUSSION

To spread their workload, reduce spring tillage operations, and capitalize on lower fertilizer prices, many producers in Manitoba prefer to apply nitrogen (N) fertilizer in the fall rather than in the spring. While variations occur from place to place and year to year, the efficiency of fall-applied N in Western Canada is generally less effective than spring applications, especially if broadcast and incorporated, and if conditions are wet rather than dry (Ridley 1975; Bole et al. 1984; Malhi et al. 1984). Application of ammoniacal fertilizers in the early fall would allow more nitrate formation prior to the soil freezing (Malhi and Nyborg 1979; Malhi and McGill 1982) and more over-winter/early spring losses than late fall applications (Malhi and Nyborg 1983a; Malhi and Nyborg 1990a; Nyborg et al. 1990; Nyborg et al. 1997). However, the difficulty faced by producers in southern Manitoba is that historically, this region receives fall rains that make fieldwork difficult. Therefore, producers are interested in applying N fertilizer as soon as possible after harvest, while soil conditions are still favourable for fertilizer application.

In comparison to broadcast applications, applying N fertilizer in concentrated bands has consistently improved the efficiency of fall-applied fertilizers in Western Canada (Ridley 1977; Malhi and Nyborg 1985; Malhi and Nyborg 1990b). Therefore, Malhi and Nyborg (1990a) questioned whether N fertilizers applied in the fall in either sub-surface bands or nests require delaying of application date to improve grain yields, as it did for broadcast and incorporated N fertilizers.

Our research indicates that overall, banded N appears to be less sensitive to early application date and soil temperature on date of application than broadcast and incorporated N. The results also suggest that under dry conditions during the fall and early spring, fall-banded N is as efficient as spring-banded N in Manitoba, regardless of application date. However, under wet conditions, fall-banded N was inferior to spring applications. These results are consistent with past research in Western Canada, where the efficiency of fall-banded N fertilizer compared to spring banding was generally poorest under wet conditions and highest under dry conditions.

In addition to application date and local weather conditions, landscape position has the potential to greatly affect the overall efficiency of fall-banded N through the accumulation of water in depressional areas of the field after heavy rains in the fall and in the spring after the snow melts. As previously mentioned, application of ammoniacal fertilizer early in the fall is expected to form more nitrate prior to the soil freezing than late fall applications, subsequently increasing the potential for NO_3^--N losses via leaching and/or denitrification, especially in low lying areas.

During the fall, our results show that delaying application of banded urea fertilizer increased the proportion of fertilizer N recovered as NH_4^+-N in the soil prior to freeze-up at each of the four intensive sites. In addition, date of application, soil temperature on the date of application, the accumulation of soil heat units (SHU) and nitrification heat units (NHU) were all linearly related to the percent of recovered fertilizer N as NH_4^+-N. Accumulated SHU and NHU best described the relationship with percent of recovered fertilizer N as NH_4^+-N at the end of the fall, with and without inhibitors. We suspect that accumulated NHU best described the relationship with percent of recovered fertilizer N as NH_4^+-N in the fall, because NHU accounted for day-to-day variability in the rate of nitrification, especially at temperatures below 4°C. However, practical field use of both SHU and NHU would require accurate forecasting of the soil temperatures during the fall and in the end, SHU and NHU might only be useful tools in historical monitoring, rather than in predicting the percent of recovered fertilizer N as NH_4^+-N remaining in the soil prior to freeze-up. In contrast, producers in southern Manitoba can easily use date of application or soil temperature on the date of application to predict the proportion of fall-banded fertilizer N remaining as NH_4^+-N at freeze-up.

Since the application of ammoniacal fertilizer early in the fall formed more nitrate prior to the soil freezing than late fall applications, we expected that the potential for over-winter N losses would be greatest for the early fall-banded N in the depressional areas of the field. Results from the first year of the study confirmed that substantial amounts of early fall-banded N are lost over the winter, especially in low landscape positions. Overall, the data suggest that the over-winter losses of fertilizer N are greater for early fall applications than late fall applications and in the low landscape positions than in the high landscape positions. Our results are consistent with past research from Saskatchewan, where numerous authors have reported consistently higher denitrification rates in the wetter convergent footslopes and low level complexes than in the better-drained upper slope positions, in both gently sloping (Pennock et al. 1992; van Kessel et al. 1993; Farrell et al. 1996) and hummocky terrain (Aulakh and Rennie 1984; Elliot and de Jong 1992; Corre et al. 1996; Ambus 1998).

Presumably, most of the over-winter losses of fall-banded N were the result of denitrification activity during the early spring period, rather than leaching of nitrates below the root zone.

Based on the spring sampling, there was little increase in N at soil depths below 60 cm at any of the sites in years one or two (the majority of the fall-banded N was recovered in the 0-15 and 15-30 cm depths, with lower amounts in the 30-60 cm depth). Similarly, past research in Manitoba reported that leaching of fall-banded ammoniacal fertilizers is not a concern on heavy clay or clay loam soils (Field-Ridley 1975; Racz 1979). There are also certain conditions in which losses of soil and fertilizer N can occur through chemical reactions of NO_2^-. In our study, the concentrations of NO_2^--N measured at the various sampling periods during the fall and spring were not agronomically significant. Since chemical denitrification is directly proportional to the concentration of NO_2^--N in the soil, we assumed that the efficiency of fall-applied fertilizer N was most affected by biological denitrification losses during the early spring period. However, these small quantities of NO_2^--N may be environmentally significant due to their potential to increase emissions of N_2O. Environmentally, gaseous losses of nitrogen via denitrification pose a risk because N_2O contributes to global warming and the destruction of the ozone layer (Pennock et al. 1992).

At harvest, the results indicate that selection of suitable timing for application of fertilizer N to optimize crop yields is much more critical for poorly drained areas within a field, or for poorly drained fields, than for better drained land. In terms of crop response, the largest differences between spring and fall-banded N were also found in the low landscape positions. In the low landscape positions, grain yields and grain yield increases were significantly greater for spring and late fall applications, as compared to early fall, mid fall and early fall with inhibitors in the low landscape positions. Overall, average grain yield increases and N use efficiency from fall-banded N at the intensive sites were approximately 90% that of spring-banded N (range of 40 to

145% and 30 to 150% respectively, depending on application date, site and landscape position). These overall efficiencies of fall-banded N are similar to those reported in the Manitoba Agriculture and Food Soil Fertility Guide (2001). The Manitoba Agriculture and Food Soil Fertility Guide (2001) suggests that relative efficiencies of fall-banded N fertilizers in southern Manitoba are generally 20% less effective than spring-banded N.

We also found that there was a significant landscape position by fertilization treatment effect with regard to total recovered N and apparent recovered fertilizer N in the crop and soil at harvest, with much greater differences between early and late fall-banded N in the low landscape positions than in the high landscape positions. In the low landscape positions, the efficiency of recovered N increased from 36 to 85% when application was delayed from early to late fall. In contrast, there were no significant differences in recovered fertilizer N at harvest between fall application dates in the high landscape positions (average efficiency of recovered fertilizer N from the three application dates in the high landscape positions was 72%). We suspect that the primary reason for the high overall apparent recovery of fertilizer N in this study is because three of the four sites were relatively dry during the fall and summer. In addition, a reasonably low rate of N was used in this experiment in order to ensure that the crop remained within its N responsive zone for all treatments. During wet years and at higher rates of N, the efficiency of recovered fertilizer N is expected to be lower. Nonetheless, our recoveries of apparent fertilizer N in the crop and soil at harvest from fall-banded urea are consistent to those reported from previous fall-banded studies in Western Canada under conditions where moisture is not excessive (Malhi et al. 1989; Nyborg et al. 1990; Malhi and Nyborg 1991).

In this project, we also focused on the impact of a urease and nitrification inhibited formulation of urea on the overall efficiency of early fall-banded N under Western Canadian conditions. The addition of a urease (NBPT) and nitrification inhibited (DCD) formulation of urea (IMC-Agrico Super Urea®) slowed the nitrification of early fall-banded N and increased the percent recovery of fertilizer N as NH_4^+-N in the soil prior to freeze-up. In the spring, the recovery of total inorganic N and apparent fertilizer N were both significantly greater for the early fall-banded N with inhibitors than the equivalent treatment without inhibitors in the low landscape positions at Kane (2000/01), suggesting that early fall-banded urea with NBPT and DCD reduced the over-winter losses of fertilizer N under these relatively wet conditions. In fact, the over-winter losses in the low landscape positions at this site from the early fall-banded N without inhibitors appeared to be more than five times greater than those from the early fall with inhibitors treatment. However, there were no differences in total inorganic N or apparent recovered fertilizer N in the spring between the two early fall treatments in the high landscape positions at this site, or in either landscape position at any other site.

At harvest, there was little benefit to the use of the urease and nitrification inhibitors, as there was generally no evidence of greater overall grain yield or N uptake by the crop with the inhibitors than without, in either landscape position. Only in the extremely wet conditions for the low landscape positions at Kane (2000/01) did the early fall-banded urea with inhibitors improve grain yield increases compared to early fall-banded urea without inhibitors. These results are similar to those reported elsewhere (Ridley 1977; Malhi and Nyborg 1983b; Malhi and Nyborg 1984; Malhi and Nyborg 1988b; Malhi and Nyborg 1988a; Malhi et al. 1992a; Malhi et al. 1992b; Goos and Johnson 1999; Wells et al. 1999). In addition, our data suggests that delaying application of fall-banded N until mid October is as effective, if not more effective in slowing nitrification than using the NBPT and DCD inhibitors. Since there were few significant increases in crop response in using the inhibitors, in the end, it is probably more economical and reliable for producers in Manitoba to delay the application of fall-banded fertilizers than to incur the added expenses from using fertilizer additives.

In conclusion, our results confirmed that there is as much variability in the overall efficiency of fall-applied N within an individual field as there is between regions of southern Manitoba. This project determined that the efficiency of fall-banded urea in the better-drained, high landscape positions was generally insensitive to application date, soil temperature on date of application, SHU or NHU. However, in the low landscape positions, crop responses from fall-banded N, relative to spring-banded N, were significantly improved after delaying application until the late fall, when soil temperatures were 5 or 6°C. Therefore, for land that is well-drained, early fall application of N fertilizer is a viable option. However, in wet years or on poorly drained land, where the potential is high for prolonged flooded conditions during the fall or spring, producers should wait as long as possible in the fall, or until the spring, to apply nitrogen fertilizer.

8 SUMMARY AND CONCLUSIONS

The primary objective of this experiment was to investigate the interactive effects of application date, landscape position and fertilizer additives on the efficiency of fall-banded nitrogen (N) fertilizer for the production of spring wheat under Manitoba conditions.

At the satellite sites, the overall efficiency of fall-banded N was less than spring-banded N in the first year of the study because soil conditions were generally wet during the late fall and early spring, increasing the risk of over-winter N losses. In the second year, soil conditions at the satellite sites were drier and there were no significant differences in crop responses between fall and spring-banded N. There was also no benefit in delaying application into late October at any of the satellite sites, despite vastly different spring soil conditions during the two years. However, the N responsive satellite sites were all moderately well drained and prolonged saturated soil conditions never occurred, even after the snow melted.

At the intensive sites, the effects of landscape position on grain yield, straw yield and total above ground crop N uptake were apparent at three of the four intensive sites: Kane (2000/01), Rosser (2001/02) and Brandon (2001/02). At each of these sites, the high landscape positions produced significantly greater grain yields (265, 996, and 1283 kg ha^{-1} respectively), straw yields (441, 1366, and 1071 kg ha^{-1} respectively) and total crop N uptake (19.3, 49.5, and 58.4 kg ha^{-1} respectively) than the low landscape positions. No significant differences in grain yield increases and N use efficiency by the crop were evident between landscape positions at any of the individual intensive sites or when combined. However, when the data sets were combined, there was a significant landscape position by fertilization treatment interaction for both grain yields and increases in grain yield. In the low landscape positions, grain yields and grain yield increases were significantly greater for spring and late fall applications, when compared to early fall, mid fall and early fall with inhibitors. Straw yields, total N uptake, and fertilizer N use efficiency were typically higher for spring and late fall-banded N than for the other fertilization treatments in the low landscape positions. In contrast, there were no significant differences in crop response among fertilization treatments in the high landscape positions. The increased efficiency of late fall-banded N was due to reduced nitrification of the fertilizer N prior to winter, which led to less over-winter losses of NO_3^-- N, especially in the low landscape positions. Malhi and Nyborg (1990a) also suggest that immobilization of fertilizer N is reduced when N is banded and applied late in the fall after soils have cooled.

Overall, in the high landscape positions the performance of fall-banded urea, relative to spring-banded urea, was not affected by application date, soil temperature on date of application, cumulative soil heat units or cumulative nitrification heat units. However, in the low landscape positions, delaying application until late in the fall, after soil temperatures had cooled to 5 or 6°C, greatly increased relative grain yields and total N uptake by the crop. Soil temperature at application gave the best correlation with crop response to N (relative grain yields, total N uptake, grain yield increases and N use efficiency) in the low landscape positions (r = -0.79**, -0.75**, -0.78** and -0.72** respectively); date of application gave slightly lower correlations (r = 0.66*, 0.66*, 0.64*, and 0.62* respectively). Soil heat units and nitrification heat units accumulated from date of application until freeze-up gave inferior correlations ($r = -0.56^{ns}$, -0.62^{*}, -0.56^{ns}, -0.58^{*} and $r = -0.49^{ns}$, -0.59^{ns}, -0.49^{ns} and -0.51^{ns} respectively). These results suggest that date of application and soil temperature at application are simple, robust approaches for estimating the effect of weather conditions on the efficiency of fall-banded N in southern Manitoba.

Early fall-banded N with NBPT and DCD inhibitors produced greater increases in grain yield than early fall-banded N without the inhibitors in the low landscape positions at Kane (2000/01). However, overall, there was little apparent crop benefit to the use of the urease and nitrification inhibitor, as there were few other significant differences in overall crop yields or N uptake by the crop with the inhibitors versus without, in either year or landscape position. One possible explanation for the poor overall performance of the inhibitors is that it may not be feasible to expect the inhibitors to maintain the fertilizer N in the NH_4^+ form from mid September to late May when the sites were planted. Another possible explanation is that the potential for N loss may not have been severe enough to fully utilize the capabilities of the NBPT and DCD inhibitors. In addition, our results suggest that delaying application of fall-banded N until mid October is as effective, if not more effective in improving the efficiency of fall-banded urea than using NBPT and DCD inhibitors applied early in the fall. Therefore, for most grain producers in Manitoba, it is probably more economical and reliable to delay the application of fall-banded fertilizers than to use a fertilizer additive.

Ridley (1975) reported that the efficiency of fall broadcast and incorporated N was lower in the lowland regions of Manitoba than in the upland regions. Over nine sites, average yield increases of barley from fall-applied N were two-thirds that of spring applications in the lowland regions. However, in the better-drained soils of the Manitoba uplands (13 sites), fall-applied N was generally 85 to 90% as effective as spring-applied N. In the present study, we found that the average efficiency of fall-banded N, in terms of grain yield increase as a percent of spring-banded N, was approximately 30% better in the high landscape positions than in the low landscape positions within the same field. Therefore, these findings show that that there is as much variability in efficiency of fall-applied N within a field as there is between regions of southern Manitoba.

The results from this project suggest that selection of suitable timing for application of fertilizer N to optimize crop yields is much more critical for poorly drained fields, and for poorly drained areas within a field, than for better drained land. In the drier regions of the Canadian prairies and for land that is well-drained, early fall banded applications of N fertilizer is a viable option. However, in the more humid regions of Western Canada, especially on poorly drained land where the potential is high for prolonged flooded conditions during the fall or spring, producers should wait as long as possible in the fall, or until the spring, to apply nitrogen fertilizer.

A second objective of this project was to follow the transformation of banded urea fertilizer over the fall and generate fundamental information on the effect of landscape position, application date, soil moisture, soil temperature, and fertilizer additives on the rate of ammoniacal N transformation into nitrate via the nitrification process.

Landscape position did not greatly influence the conversion of fall-banded urea fertilizer to nitrate under the moisture conditions present at the four sites. The soil moisture during the fall typically remained between permanent wilting point and field capacity at all sites. This range of soil moisture is generally conducive to microbial activity (Malhi and McGill 1982).

Delaying the date of application of banded urea fertilizer N into the late fall slowed nitrification and significantly increased the percent recovery of fertilizer N as NH_4^+-N in the soil prior to freeze-up. Date of application and soil temperature at application were both linearly related to the percent of recovered fertilizer N as NH_4^+-N in the fall (adj. $r^2 = 0.88$*** and 0.69*** respectively), with the concentration of NH_4^+-N increasing with delay in application date and decline in soil temperature. The results suggest that the majority of urea fertilizer, banded in the early fall without inhibitors when soil temperatures are still warm, will convert to nitrate prior to the soil freezing and is therefore susceptible to losses in the spring. Linear coefficients of determination explaining the proportion of fall-banded N recovered as NH_4^+-N prior to freeze-up were further improved using SHU (adj. $r^2 = 0.90$**) and NHU (adj. $r^2 = 0.92$**) accumulated from date of application until the final fall sampling period in the last week of October or the first week in November. In the fall, accumulated NHU best described the relationship with percent of recovered fertilizer N as NH_4^+-N because it accounted for day-to-day variability in the rate of nitrification, especially at temperatures below 4°C. The interactions between time, temperature and nitrification suggest that producers who band fertilizer N in the fall, even after soil temperatures have declined to a given level, must consider the overall length of time that the N fertilizer will be exposed to the soil prior to the soil freezing. However, practical field use of both SHU and NHU would require accurate forecasting of soil temperature. Therefore, SHU and

NHU might only be useful tools in historical monitoring. In contrast, producers in southern Manitoba can easily use date of application or soil temperature on the date of application to predict the proportion of fall-banded fertilizer N remaining as NH_4^+-N at freeze-up.

Linear regression analysis comparing early fall-banded urea with early fall-banded urea that included NBPT and DCD showed that the inhibitors slowed nitrification and increased retention of fertilizer N as NH_4^+-N in the fall. With the NBPT and DCD formulated urea, significantly more SHU and NHU were needed to accumulate before 80% of the urea fertilizer banded in the early fall had been converted to NO_3^--N. This may allow producers increased flexibility in a fall fertilization program, and hopefully translates into reduced losses of N in the spring, if environmental conditions are conducive to nitrate loss.

The third objective of this study was to evaluate the interactive effects of landscape position, application date, fertilizer additives, and weather and climate on the over-winter losses and recovery of fall-banded N fertilizer in Manitoba.

The apparent recovery of fall-banded fertilizer N in the spring indicated that there were substantial over-winter losses of N at Kane (2000/01) and Rosser (2001/02), with greater losses in the low landscape positions than in the high landscape positions. Soil conditions at both Kane (2000/01) and Rosser (2001/02) were relatively wet throughout the fall and spring, conditions ideal for denitrification losses of fall-applied N fertilizers during the spring thaw. Results were variable at the two other sites in 2001/2002, Kane (2001/02) and Brandon (2001/02). The data indicated that over-winter losses were not nearly as substantial at these two sites as they were at

Kane (2000/01) and Rosser (2001/02), presumably due to drier weather conditions in the fall and spring. In the low landscape positions, the recovery of N in the crop and soil at harvest generally increased with lateness of fall application, but not in the high landscape positions. Across all four intensive sites, mean total recovered N and mean apparent recovered fertilizer N in the crop and soil were significantly greater for late fall and spring-banded N than early and mid fall applications in the low landscape positions. Past research in Manitoba reported that leaching of fall-banded ammoniacal fertilizers is not a concern on heavy clay or clay loam soils (Field-Ridley 1975; Racz 1979). Similarly, based on the spring sampling, there was little increase in N at soil depths below 60 cm at any of the sites in year one and two (data not presented). Therefore, we suspect denitrification to be the primary loss mechanism for fall-banded N in southern Manitoba. Again, these results indicate that selection of suitable timing for application of fertilizer N to reduce over-winter losses and improve the efficiency of fall-banded N is much more critical for poorly drained fields, and for poorly drained areas within a field, than for better drained land.

Use of NBPT and DCD with early fall-banded N significantly reduced over-winter losses in the low landscape positions at Kane (2000/01), but not in any landscape position at any sites in the second year of the study. At harvest, there was little apparent benefit to the use of the inhibitors in either year as there were no significant differences between the two early fall-banded treatments, with and without inhibitors, in terms of total recovery of N or apparent recovered fertilizer N in the crop and soil, in either landscape position.

Although this project confirmed and generated numerous observations and conclusions, there are a number of issues that require further research in this field of study:

- Placing urea in nests or large urea granules (LUG) has been reported to improve the efficiency of fall-applied N, compared to fall-banded N (Malhi et al. 1984; Malhi et al. 1992b; Yadvinder-Singh et al. 1994). These alternative methods of fertilizer placement may be less sensitive to early application date than banding and have the potential to improve the overall efficiency of fall-applied N, especially in the low landscape positions.
- Generally, the efficiency of the various N fertilizers within each group are regarded to be similar to one another if they are placed and timed properly. However, Grant et al. (2001) reported that yields from fall-banded anhydrous ammonia (applied in mid October) were greater than fall-banded urea under conventional and reduced tillage systems. Therefore, the efficiency of fall-banded N, applied early in the season, might be improved if anhydrous ammonia were used instead of urea.
- The urease and nitrification inhibited formulation of urea may have improved the efficiency of fall-banded N if applied at later application dates in the fall.
- Further detailed study in required to monitor the over-winter transformations and losses of fall-banded N in order to determine why SHU and NHU were best correlated with the transformation of fall-banded urea during the fall, but produced the lowest correlations with crop responses at harvest.
- N_2O emissions from fall-banded N should be monitored to compare the production of greenhouse gases from nitrification and incomplete denitrification in the high and low landscape positions after application of fertilizer N.

- There is also the potential to use the soil temperature and gravimetric moisture data collected during this project and correlate them with air temperatures in the hopes of developing an agrometeorological model to predict the transformation and losses of fall-banded N.

9 CONTRIBUTION TO KNOWLEDGE

Numerous experiments in Canada have compared crop responses from fall and spring applications of N. However, much of this research was conducted using broadcast and incorporated fertilizers. As the knowledge regarding efficient methods of N fertilizer placement has increased, researchers have begun to test the efficiency of fall-applied N using techniques such as banding or nesting. To date, research comparing fall and spring-banded N fertilizers has focussed primarily on later application dates, generally mid to late October. Our study is the first to investigate the efficiency of fall-banded urea as influenced by early, mid and late fall application dates in Western Canada. Our research indicates that banded N appears to be less sensitive to early application date and soil temperature on date of application than broadcast and incorporated N, and that under dry conditions during the fall and early spring, fall-banded N is as efficient as spring-banded N in Manitoba, regardless of application date.

Our research is also the first to investigate the interactive effects of application date and landscape position on fall-banded N in Western Canada. The results suggest that selection of suitable timing for application of fertilizer N to optimize crop yields is much more critical for poorly drained areas within a field, or for poorly drained fields, than for better drained land. For land that is well-drained, early fall application of N fertilizer is a viable option. However, on poorly drained land where the potential is high for prolonged flooded conditions during the fall or spring, producers should wait as long as possible in the fall, or until the spring, to apply nitrogen fertilizer. Our results confirmed that there is as much variability in the overall efficiency of fall-applied N within an individual field as there is between regions of southern Manitoba. We hope that this study will increase the awareness among producers of the variability within their fields, and the impact that this variability has on the efficiency of fall-banded N and overall crop growth. Nonetheless, fall-banded urea, delayed until mid October when soil temperatures have typically declined to 5°C or less, is likely to produce similar yields to spring-banded N, regardless of landscape position.

In addition, no previous experiments have focused on the impact of a double urease and nitrification inhibited formulation of urea on the overall efficiency of early fall-banded N under Western Canadian conditions. Our findings suggest that overall, there was little apparent crop benefit to the use of the urease and nitrification inhibitors, as there was generally no evidence of greater overall grain yield or N uptake by the crop with the inhibitors than without, in either landscape position. For most grain producers in Manitoba, it is likely more economical and reliable to delay the application of banded N fertilizers in the fall than to use an inhibitor.

Finally, this study is the first to provide detailed information about the rate of transformation of fall-banded N as influenced by application date, landscape position and fertilizer additives in Manitoba. Our results suggest that delaying application of banded urea fertilizer into the late fall increased the proportion of fertilizer N recovered as NH_4^+-N in the soil prior to freeze-up at each of the four intensive sites, with date of application, soil temperature on the date of application, the accumulation of soil heat units (SHU) and nitrification heat units (NHU) all significantly related to the percent of recovered fertilizer N as NH_4^+-N prior to winter. While SHU and NHU could be useful tools in historical monitoring, producers in southern Manitoba can easily use date of application or soil temperature on the date of application to predict the proportion of fall-banded fertilizer N remaining as NH_4^+-N at freeze-up.

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11 APPENDICES

Appendix A

Field Plans and Topographical Survey Maps

Trt 1: Early Fall - urea N banded on Sept. 29, 2000
Trt 2: Mid Fall - urea N banded on Oct. 12, 2000
Trt 3: Late Fall - urea N banded on Oct. 26, 2000
Trt 4: Spring - urea N mid-row banded at seeding on June 4, 2001
Trt 5: no N applied
Trt 6: Early Fall w/ inhibitors - Uea N banded on Sept. 29, 2000 with urease and nitrification inhibitors

NORTH

Landscape: High 2

plot	H-201	H-202	H-203	H-204	H-205	H-206
trt	5	1	3	2	4	6

Landscape: Low 2

plot	L-201	L-202	L-203	L-204	L-205	L-206
trt	4	1	5	2	3	6

Landscape: High 3

plot	H-301	H-302	H-303	H-304	H-305	H-306
trt	5	1	3	6	2	4

Landscape: Low 3

plot	L-301	L-302	L-303	L-304	L-305	L-306
trt	3	5	1	6	4	2

Landscape: High 1

plot	H-101	H-102	H-103	H-104	H-105	H-106
trt	1	2	3	4	5	6

Landscape: Low 1

plot	L-101	L-102	L-103	L-104	L-105	L-106
trt	1	2	3	4	5	6

Landscape: High 4

plot	H-401	H-402	H-403	H-404	H-405	H-406
trt	4	6	3	2	5	1

Landscape: Low 4

plot	L-401	L-402	L-403	L-404	L-405	L-406
trt	6	1	3	4	5	2

Road

Note: At this site, each replicate is placed into a separate low or high position interspersed throughout the field.
Plot size: 10m x 2m/plot

Fig. A.1. Field Plan at Kane (2000/01): Producer, Bill Toews.

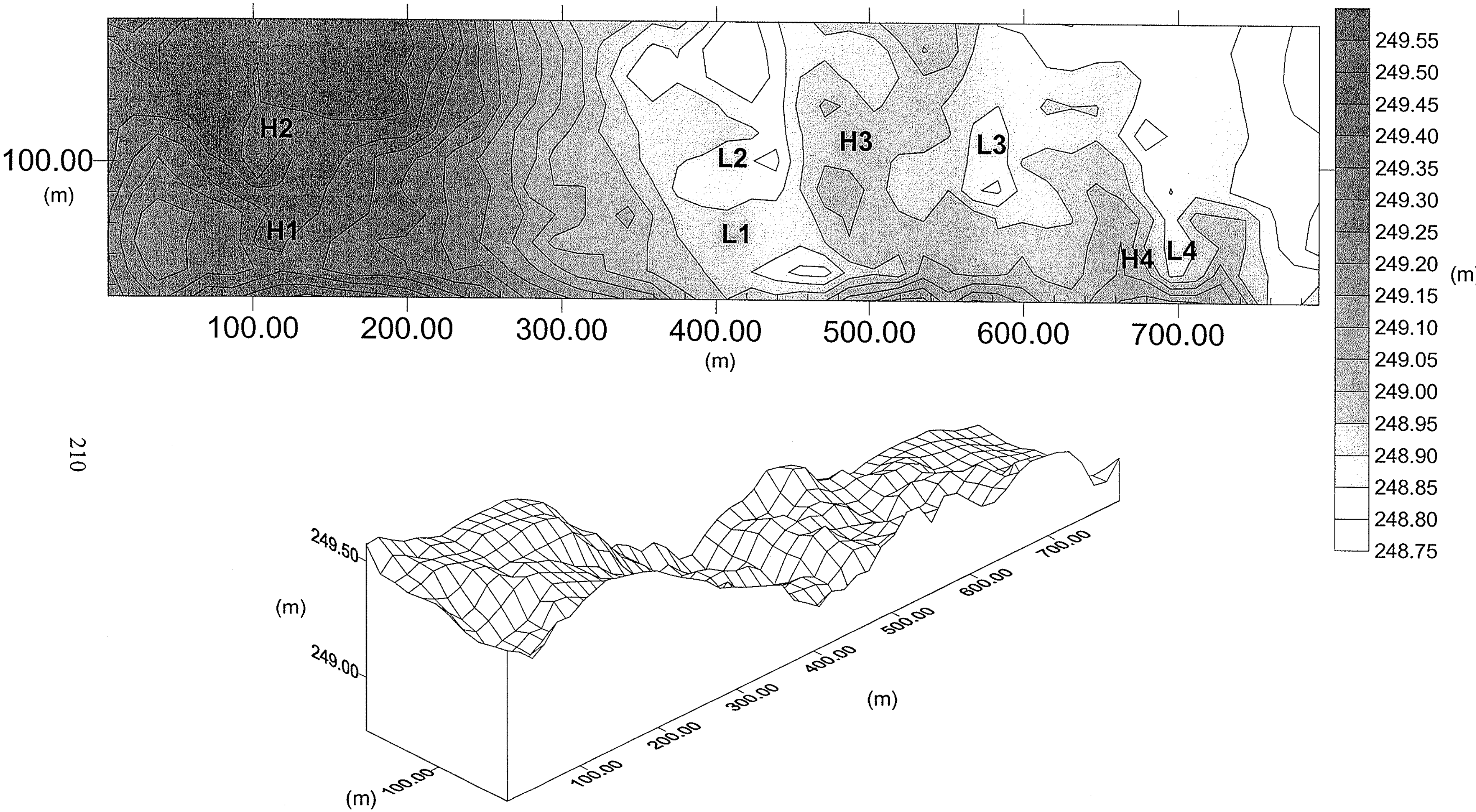


Fig. A.2. Topographic maps of Kane (2000/01).

Trt 1: Early Fall - urea N banded on Sept. 26, 2001
Trt 2: Mid Fall - urea N banded on Oct. 9, 2001
Trt 3: Late Fall - urea N banded on Oct. 19, 2001
Trt 4: Spring - urea N mid-row banded at seeding on May 21, 2002
Trt 5: no N applied
Trt 6: Early Fall w/ inhibitors - Uea N banded on Sept. 26, 2001 with urease and nitrification inhibitors

EAST

Landscape: Low 2

plot	L-201	L-202	L-203	L-204	L-205	L-206
trt	5	2	6	3	4	1

Landscape: High 4

H-401	H-402	H-403	H-404	H-405	H-406
4	3	1	2	6	5

Landscape: Low 4

L-401	L-402	L-403	L-404	L-405	L-406
2	4	3	6	1	5

Landscape: High 2

plot	H-201	H-202	H-203	H-204	H-205	H-206
trt	3	5	4	1	6	2

Landscape: Low 1

plot	L-101	L-102	L-103	L-104	L-105	L-106
trt	1	2	3	4	5	6

DRAINAGE DITCH

Landscape: High 1

plot	H-101	H-102	H-103	H-104	H-105	H-106
trt	1	2	3	4	5	6

Landscape: Low 3

L-301	L-302	L-303	L-304	L-305	L-306
6	1	4	5	2	3

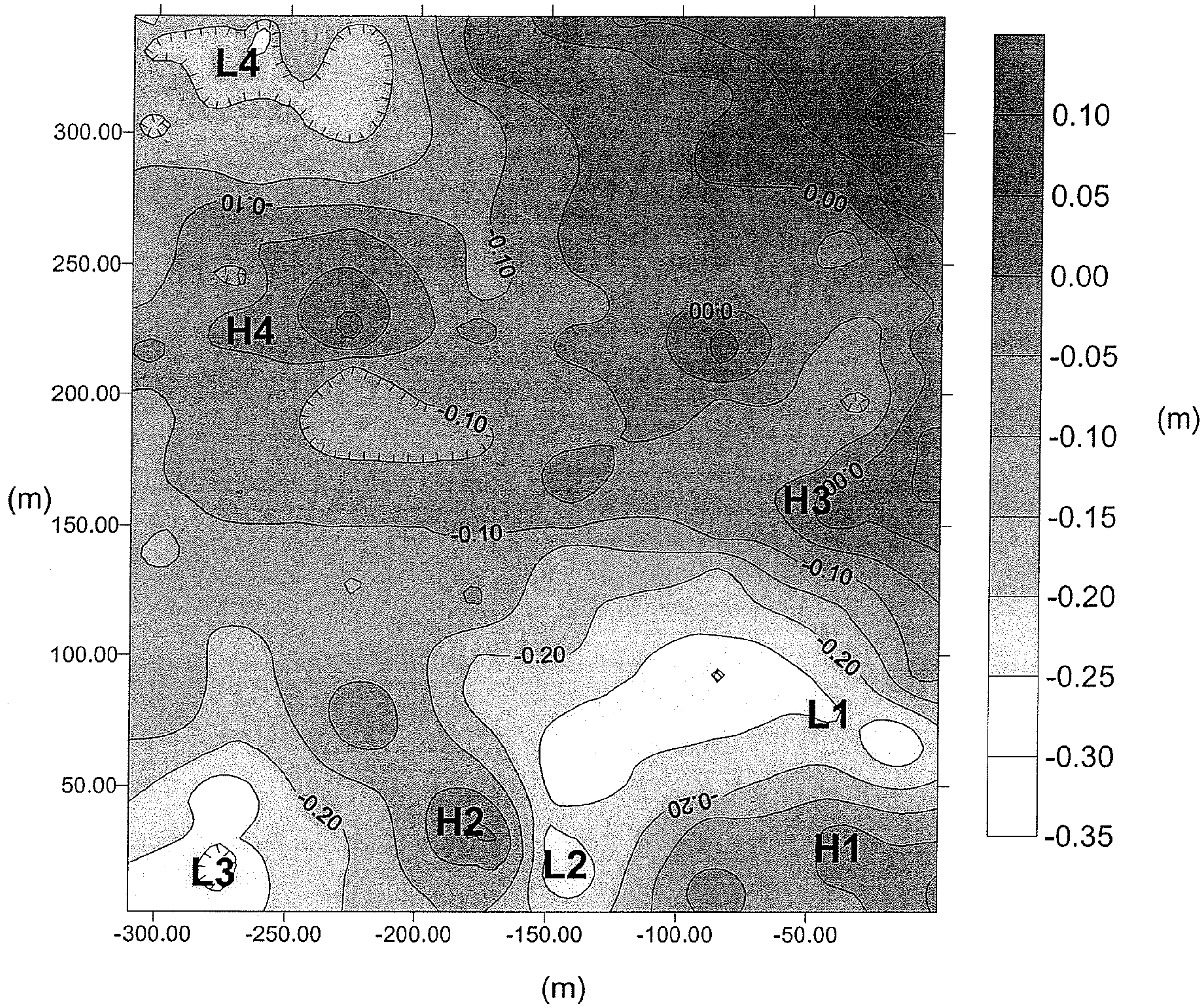
Landscape: High 3

H-301	H-302	H-303	H-304	H-305	H-306
2	6	3	5	4	1

Road to Plum Coulee ==>

Note: At this site, each replicate is placed into a separate low or high position interspersed throughout the field.
Plot size: 10m x 2m/plot

Fig. A.3. Field Plan at Kane (2001/02): Producer, Bill Toews.



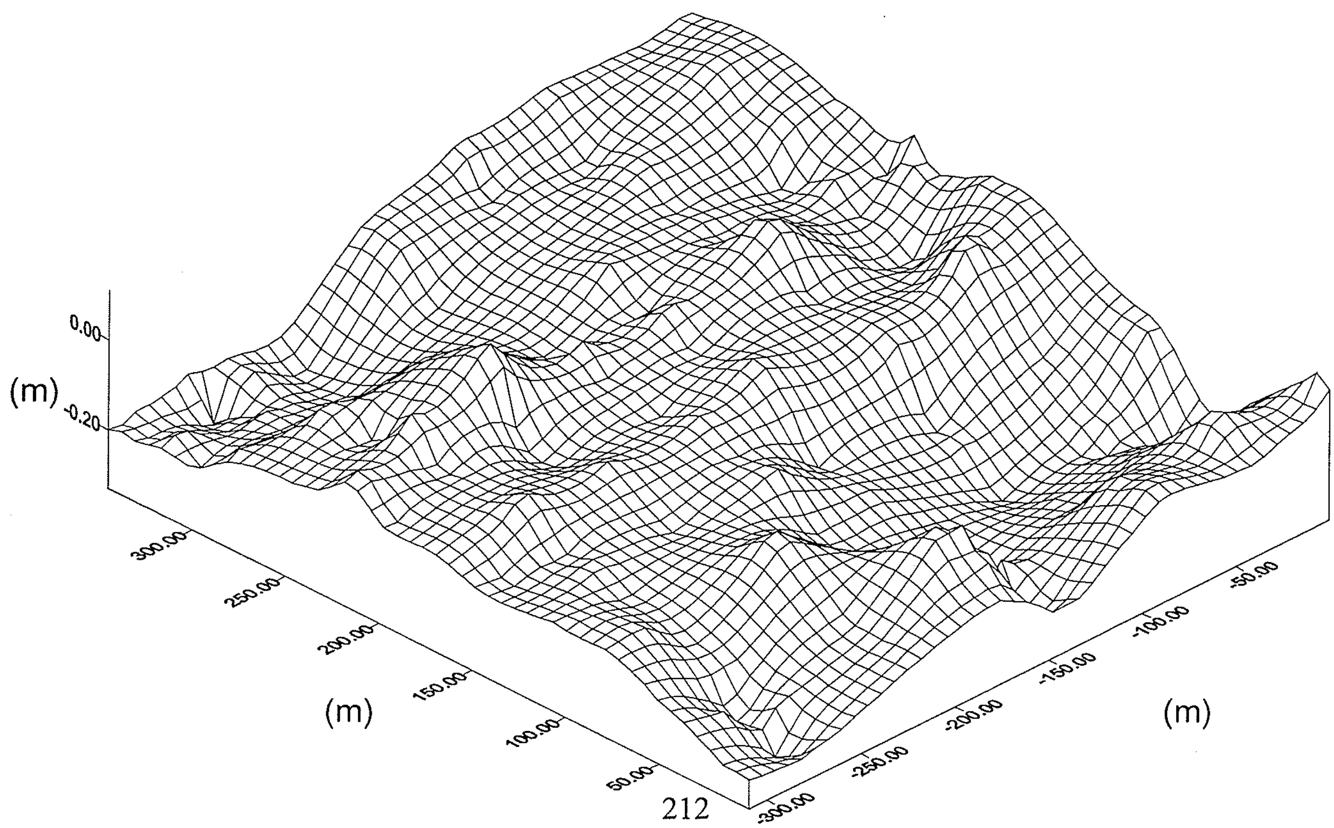


Fig. A.4. Topographic maps of Kane (2001/02).

Trt 1: Early Fall - urea N banded on Sept. 19, 2001
Trt 2: Mid Fall - urea N banded on Oct. 1, 2001
Trt 3: Late Fall - urea N banded on Oct. 19, 2001
Trt 4: Spring - urea N mid-row banded at seeding on May 27, 2002
Trt 5: no N applied
Trt 6: Early Fall w/ inhibitors - Uea N banded on Sept. 19, 2001 with urease and nitrification inhibitors

Note: At this site, each replicate is placed into a separate low or high position interspersed throughout the field.
Plot size: 10m x 2m/plot

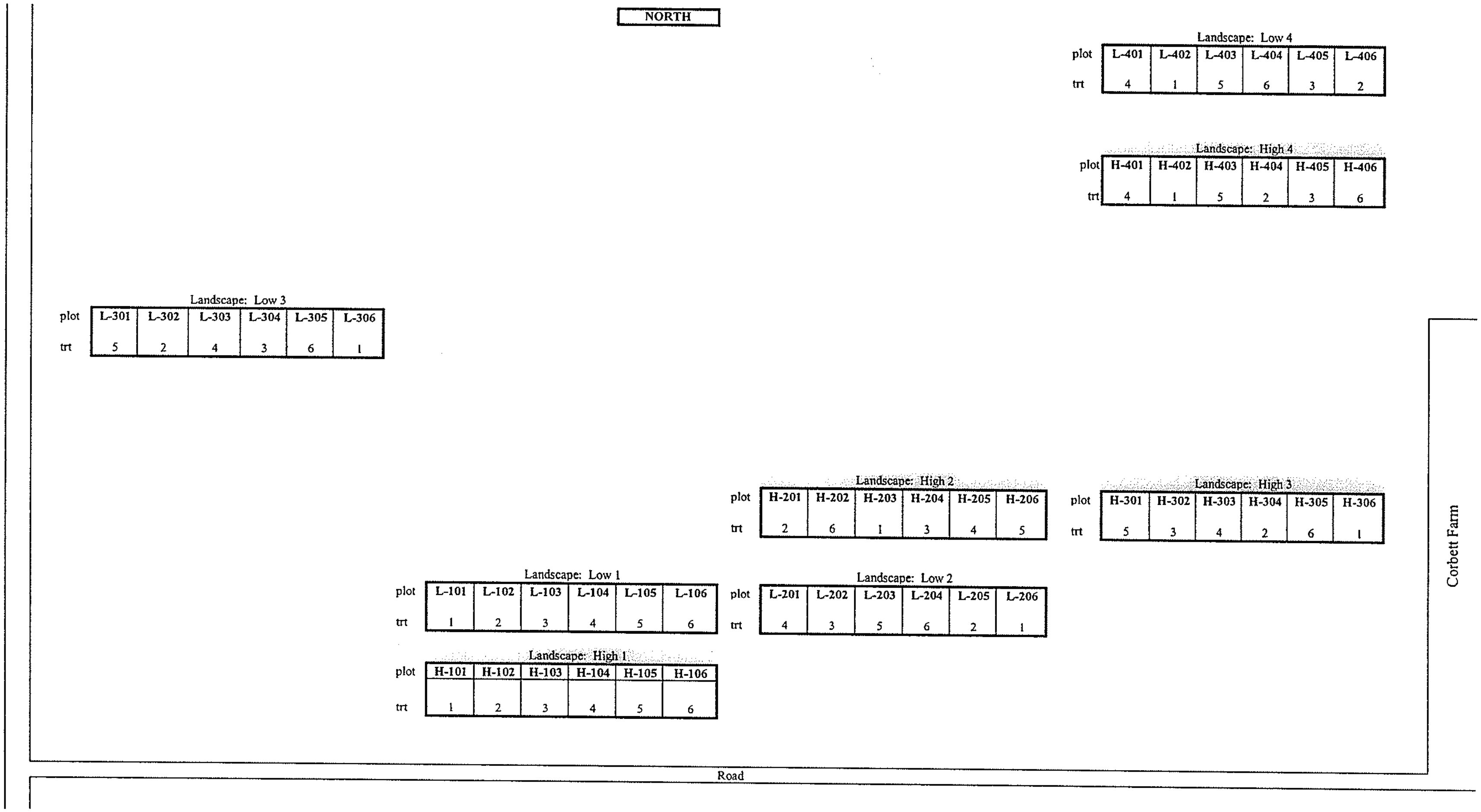


Fig. A.5. Field Plan at Rosser (2001/02): Producer, Scott Corbett.

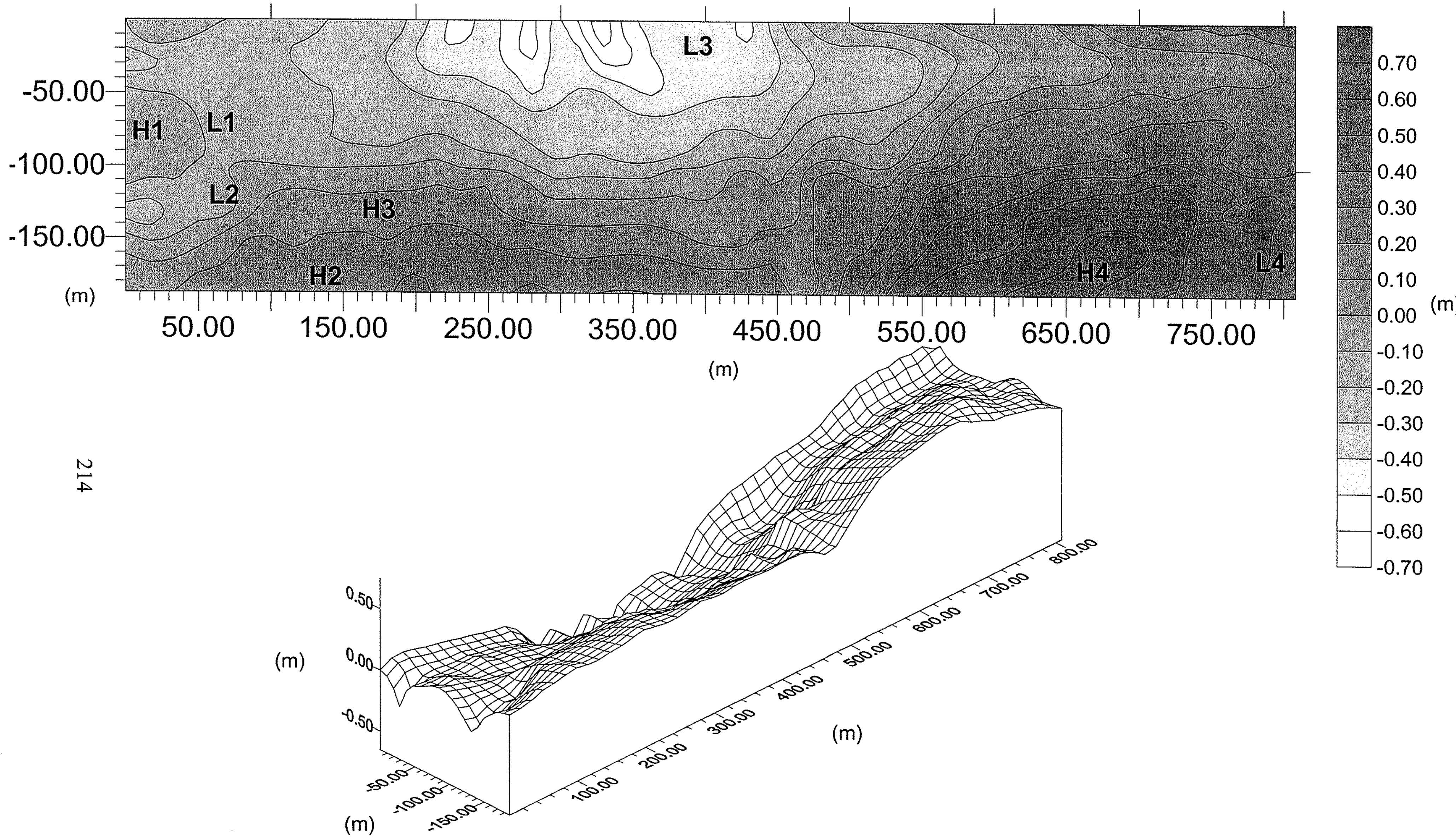
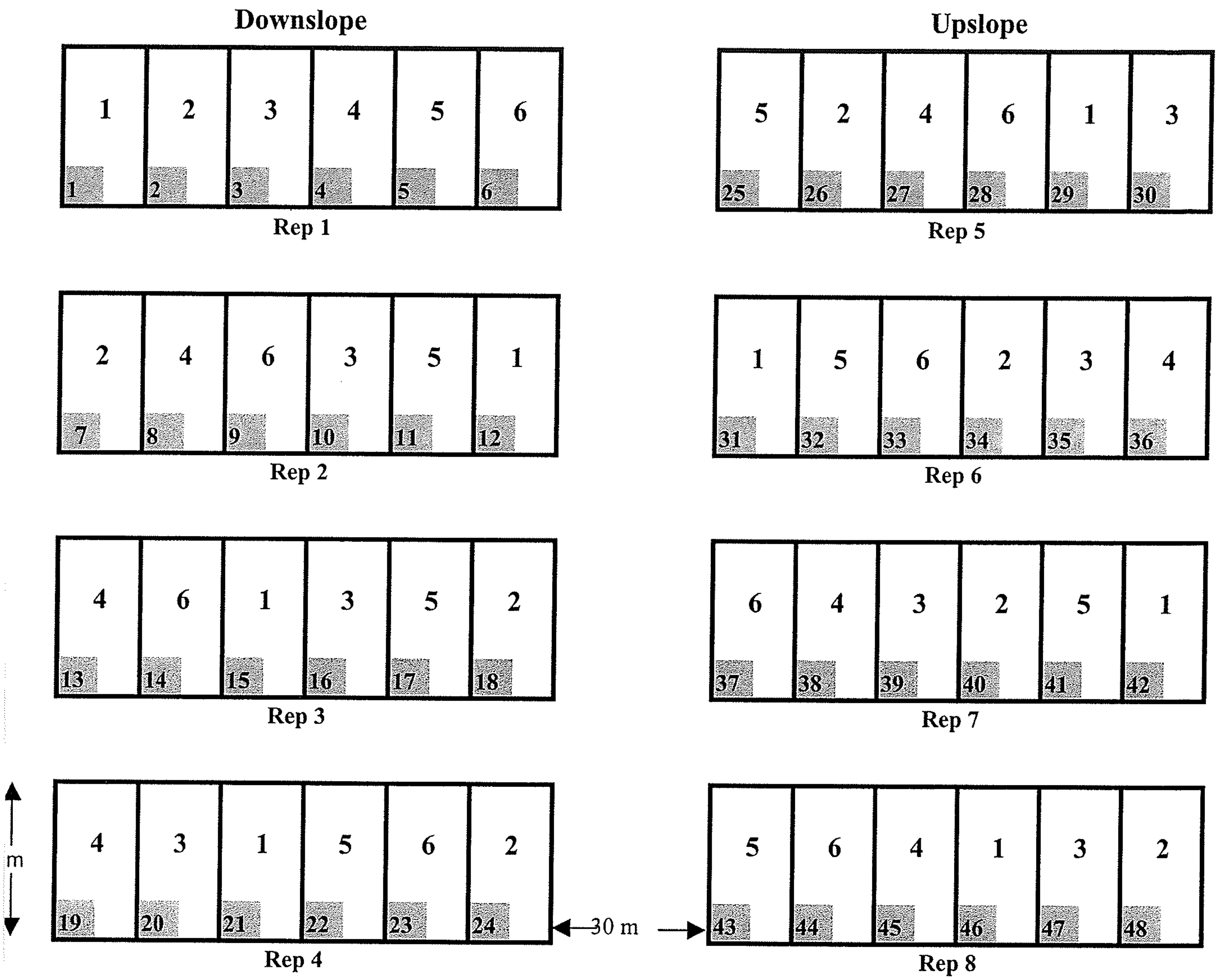


Fig. A.6. Topographic maps of Rosser (2001/02).



reatments:

. Early Fall - urea N banded on September 15, 2001
. Mid Fall - urea N banded on October 1, 2001
. Late Fall - urea N banded on October 15, 2001
. Spring - urea N mid-row banded at seeding (May 21, 2001).
. No N applied
. Early Fall w/ inhibitors - urea N banded on September 15, 2001 with urease and nitrification inhibitor (NBPT and DCD, respectively in Simplot Super Urea).

ote: At this site, each replicate is placed :to a separate low or high position interspersed :roughout the field.
lot size: 10m x 2m/plot

ig. A.7. Field Plan at Brandon (2001/02): AAFC Brandon Research Centre's Philips Research Farm.

Trt 1: Early Fall - urea N banded on Sept. 29, 2000
Trt 2: Mid Fall - urea N banded on Oct. 12, 2000
Trt 3: Late Fall - urea N banded on Oct. 26, 2000
Trt 4: Spring - urea N mid-row banded at seeding on June 5, 2001
Trt 5: no N applied
Trt 6: Early Fall w/ inhibitors - Uea N banded on Sept. 29, 2000 with urease and nitrification inhibitors

Landscape 1: High (East side of field)

plot	H-101	H-102	H-103	H-104	H-105	H-106	H-201	H-202	H-203	H-204	H-205	H-206	H-301	H-302	H-303	H-304	H-305	H-306	H-401	H-402	H-403	H-404	H-405	H-406
trt	1	2	3	4	5	6	2	6	1	4	5	3	5	6	1	2	3	4	4	2	5	3	1	6

Landscape 2: Low (South side of field - across from the lagoon)

plot	L-101	L-102	L-103	L-104	L-105	L-106	L-201	L-202	L-203	L-204	L-205	L-206	L-301	L-302	L-303	L-304	L-305	L-306	L-401	L-402	L-403	L-404	L-405	L-406
trt	1	2	3	4	5	6	5	6	1	4	2	3	4	3	6	2	1	5	6	2	3	1	5	4

Individual plot size: 10m x 2m

Fig. A.8. Field Plan at Oak Bluff (2000/01): Producer, Brad Erb.

Trt 1: Early Fall - urea N banded on Sept. 19, 2001
Trt 2: Mid Fall - urea N banded on Oct. 1, 2001
Trt 3: Late Fall - urea N banded on Oct. 19, 2001
Trt 4: Spring - urea N mid-row banded at seeding on May 22, 2002
Trt 5: no N applied
Trt 6: Early Fall w/ inhibitors - Uea N banded on Sept. 19, 2001 with urease and nitrification inhibitors

Landscape 1: High (South side of field)

plot	H-101	H-102	H-103	H-104	H-105	H-106	H-201	H-202	H-203	H-204	H-205	H-206	H-301	H-302	H-303	H-304	H-305	H-306	H-401	H-402	H-403	H-404	H-405	H-406
trt	1	2	3	4	5	6	3	1	6	4	2	5	6	2	3	5	4	1	1	6	3	5	4	2

Landscape 2: Low (West side of field))

plot	L-101	L-102	L-103	L-104	L-105	L-106	L-201	L-202	L-203	L-204	L-205	L-206	L-301	L-302	L-303	L-304	L-305	L-306	L-401	L-402	L-403	L-404	L-405	L-406
trt	1	2	3	4	5	6	2	6	3	5	1	4	4	1	6	3	2	5	3	1	5	2	4	6

Individual plot size: 10m x 2m

Fig. A.9. Field Plan at Oak Bluff (2001/02): Producer, Brad Erb.

Trt 1: Early Fall - urea N banded on Sept. 19, 2001
Trt 2: Mid Fall - urea N banded on Oct. 1, 2001
Trt 3: Late Fall - urea N banded on Oct. 19, 2001
Trt 4: Spring - urea N mid-row banded at seeding on May 21, 2002
Trt 5: no N applied
Trt 6: Early Fall w/ inhibitors - Uea N banded on Sept. 19, 2001 with urease and nitrification inhibitors

SOUTH

Landscape 2: Low (South plots)

plot	L-101	L-102	L-103	L-104	L-105	L-106
trt	1	2	3	4	5	6

plot	L-201	L-202	L-203	L-204	L-205	L-206
trt	3	6	1	4	2	5

plot	L-301	L-302	L-303	L-304	L-305	L-306
trt	6	3	2	1	4	5

plot	L-401	L-402	L-403	L-404	L-405	L-406
trt	6	1	3	5	2	4

Landscape 1: High (North plots)

	H-101	H-102	H-103	H-104	H-105	H-106
trt	1	2	3	4	5	6

	H-201	H-202	H-203	H-204	H-205	H-206
trt	5	6	2	4	1	3

	H-301	H-302	H-303	H-304	H-305	H-306
trt	5	1	6	2	4	3

	H-401	H-402	H-403	H-404	H-405	H-406
trt	4	3	5	2	1	6

ROAD

Individual plot size: Lows: 10x2m
Highs: 7x2m (couldn't seed to end of plot b/c of length of seeder and the ditch)

note - seeded May 21, 2002

Fig. A.10. Field Plan at Sperling (2001/02): Producer, Bill Rempel.

Appendix B

Methods for Estimating Grain Yields from Actual Straw Yields

Prior to threshing in year one, approximately half of the harvest samples from Kane (2000/01) were severely damaged by mice while in storage. After sorting through the samples, it was apparent that the mice primarily ate the grain, as there was little visible mouse damage on the straw. In 1988, Entz reported that grain yields of winter wheat had a strong linear relationship with both midseason dry matter biomass and harvest dry matter biomass ($r^2 = 0.81$ and 0.85 respectively). Using this background information, linear regression analysis was used to test the relationships between actual grain yields (note: used the undamaged grain from Kane (2000/01) but not the damaged samples) and midseason biomass and harvest straw yields (dry matter basis) at the four intensive sites. Linear regression analysis indicated that midseason biomass was significantly related to actual grain yields at all three of the sites in year two of the study (Kane (2001/02), Rosser (2001/02) and Brandon (2001/02), but not at Kane (2000/01) (Fig. B.1). However, straw yields were significantly related to actual grain yields at all four individual sites (Fig. B.2). Therefore, we decided that the straw yield data from all four intensive sites would be used to develop an equation to predict grain yields at Kane (2000/01). When the data from all four intensive sites were combined, linear regression analysis indicated that there was a significant linear relationship between straw yields and grain yields (adj. $r^2 = 0.59$***) (Fig. B.3). The relationship between undamaged grain yields and straw yields was further improved when the Brandon (2001/02) site was removed, leaving only the sites in the Red River Valley (adj. $r^2 = 0.76$***) (Fig. B.4). Therefore, grain yields from Kane (2000/01) were estimated from actual straw yields using the linear regression equation from the combined analysis of the intensive sites located in the Red River Valley: $y = 0.60x + 206.6$. A plot depicting predicted grain yields versus actual grain yields at all sites in the Red River Valley is found in Fig. B.5; the straight line is a plot of the actual prediction equation. The plot showing predicted grain yields versus actual grain yields at Kane (2000/01) only is shown in Fig. B.6. Diagnostic plots relating residual to independent variables were generated using SAS. The variability of the residuals was determined to be similar across the range of the independent variables and the residual data was normally distributed (data not presented).

In addition to the harvest samples from Kane (2000/01), most of the grain samples from the satellite site at Oak Bluff (2000/01) were also damaged by mice. Since the site at Oak Bluff was located in the Red River Valley, grain yields from Oak Bluff (2000/01) were also estimated from actual straw yields using the same linear regression equation developed for Kane (2000/01). Predicted grain yields at Oak Bluff (2000/01) versus actual grain yields are reported in Fig. B.7. The residual data from Oak Bluff (2000/01) was also determined to be normally distributed (data not presented).

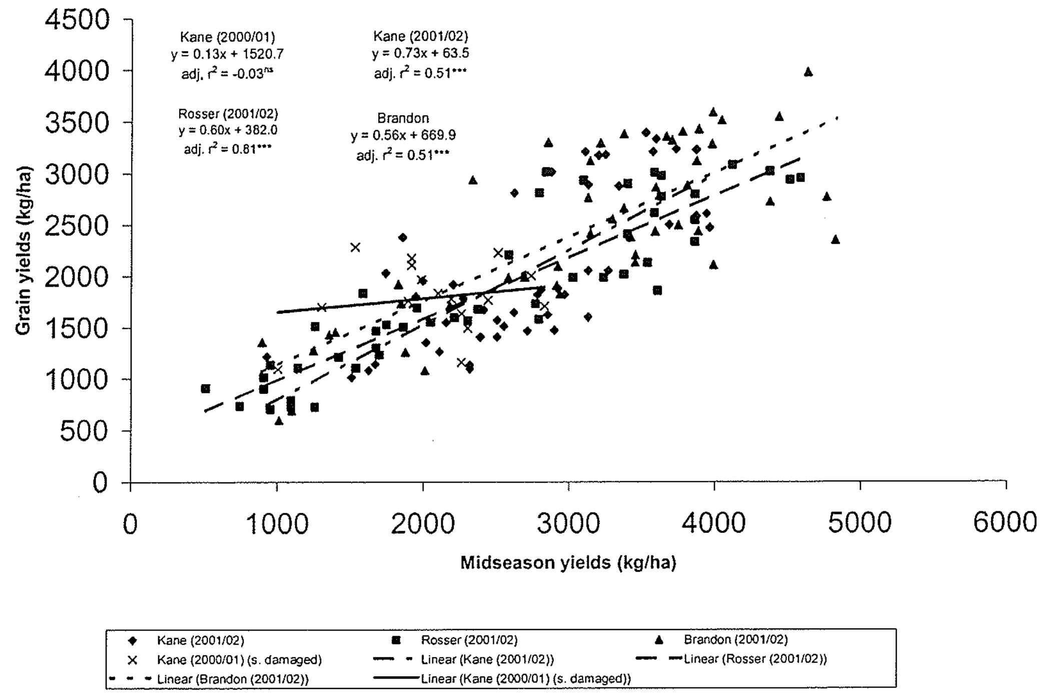


Fig B.1. Relationship between grain yields and midseason biomass (dry matter basis) from all of the individual intensive sites (ns, *** indicates not significant and significance at $P < 0.0001$).

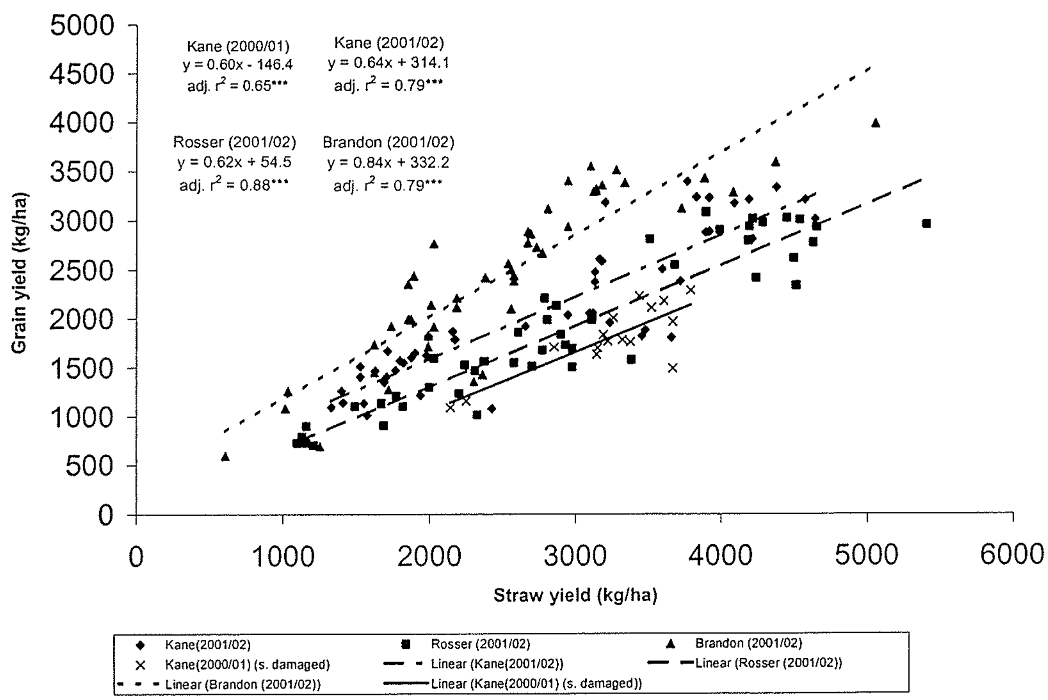


Fig B.2. Relationship between grain yields and straw yields from all of the individual intensive sites (*** indicates significance at $P < 0.0001$).

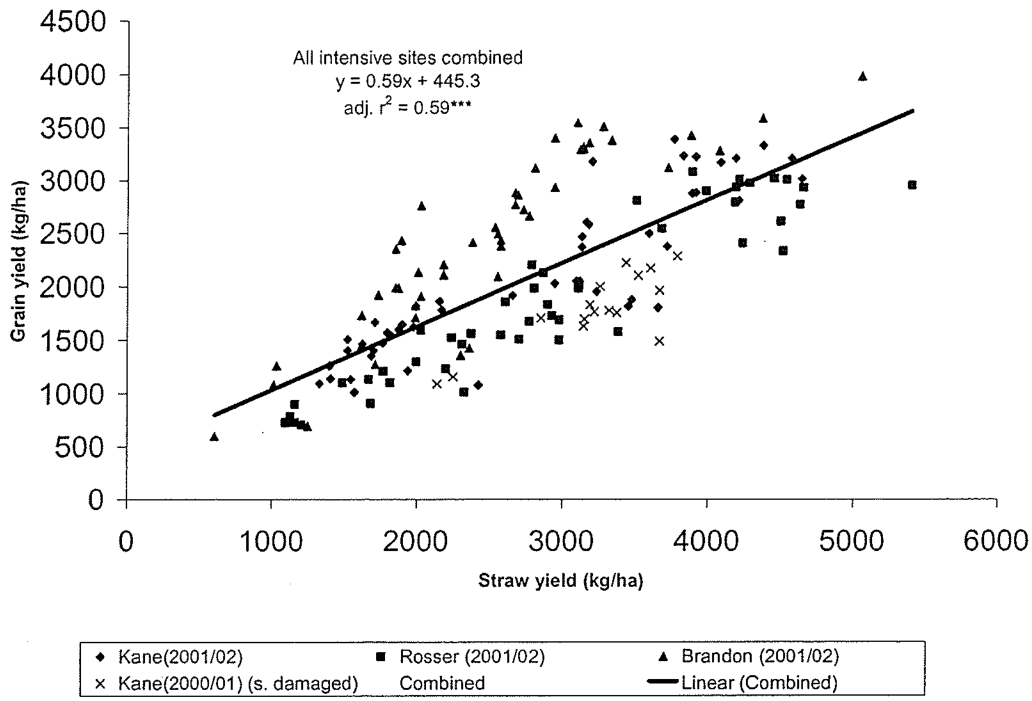


Fig B.3. Relationship between grain yields and straw yields from all of the intensive sites (*** indicates significance at $P < 0.0001$).

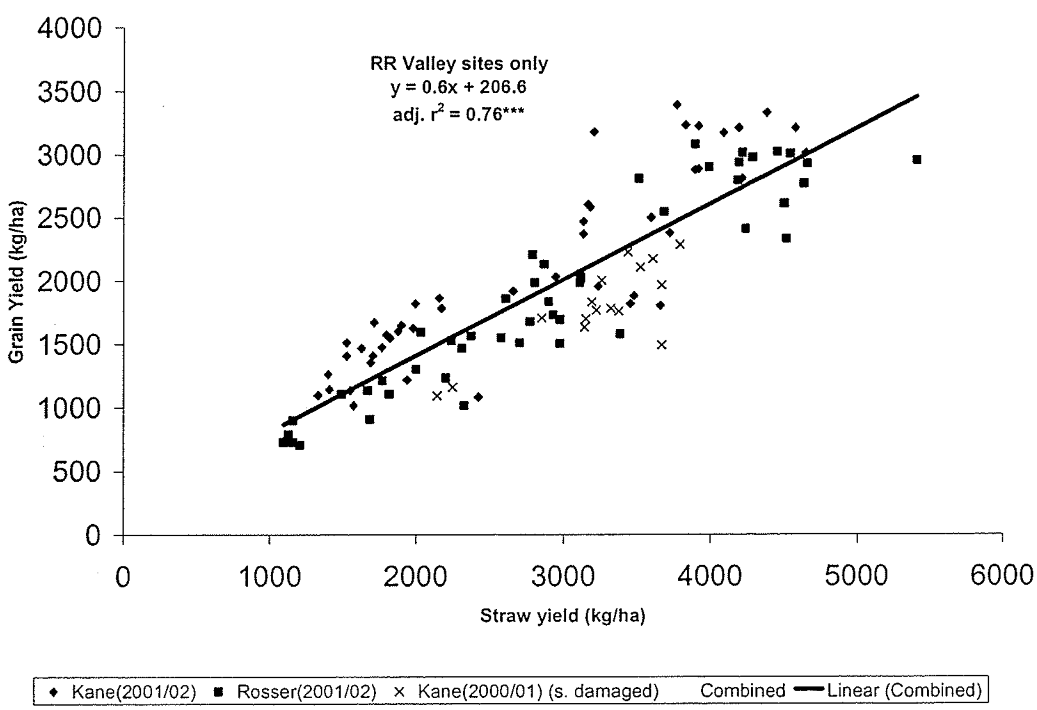


Fig. B.4. Relationship between grain yields and straw yields from all of the intensive sites located in the Red River Valley (*** indicates significance at $P < 0.0001$).

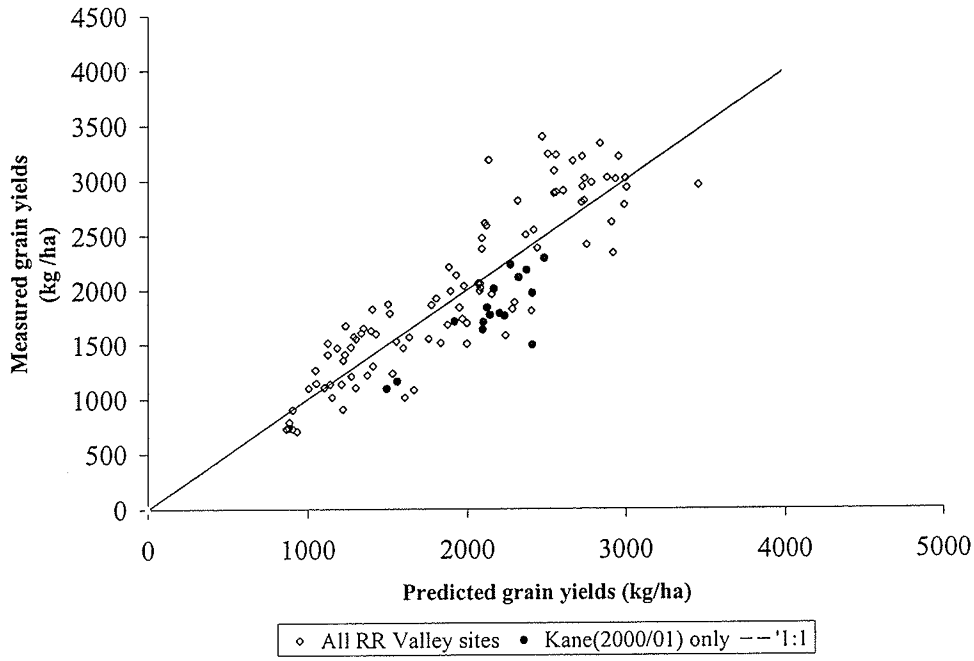


Fig B.5. Measured grain yields versus predicted grain yields at all intensive sites located in the Red River Valley of Manitoba.

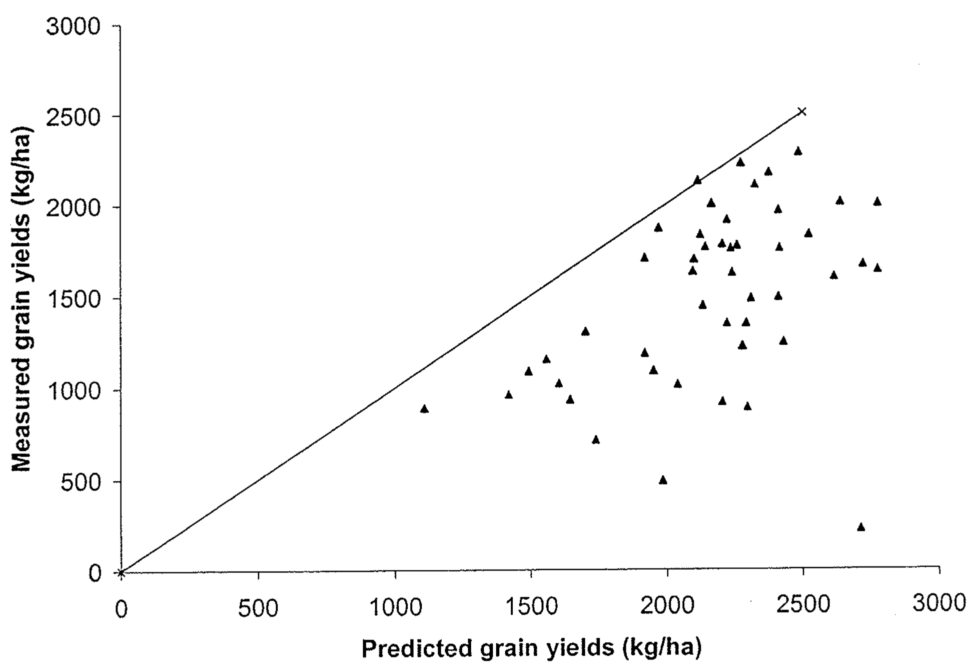


Fig. B.6. Measured grain yields versus predicted grain yields at Kane (2000/01).

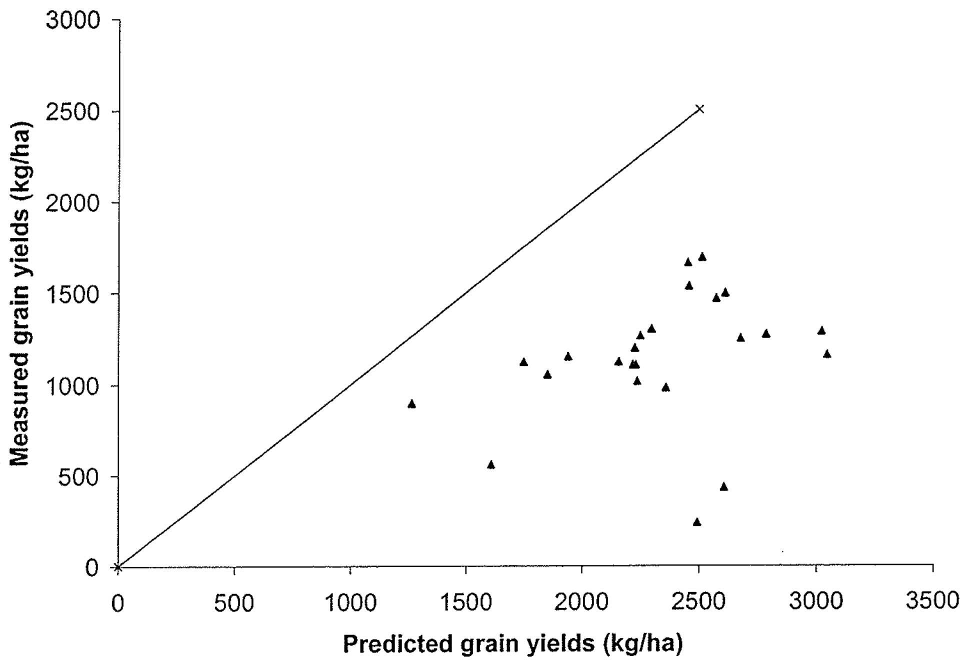


Fig. B.7. Measured grain yields versus predicted grain yields at Oak Bluff (2000/01).

Appendix C

Gravimetric Soil Moisture Contents:

Kane (2000/02), Kane (2001/02) and Rosser (2001/02)

Table C.1. Gravimetric moisture content of the soil during the fall (2000) and spring (2001) at Kane (2000/01)

		Sampling date												
Mainplot	Depth (cm)	Sept. 29	Oct. 5	Oct. 12	Oct. 19	Oct. 27	Nov. 4	Nov. 16	Apr. 24	Apr. 30	May. 11	May. 18	May. 25	Jun. 5
								%						
High 1	0 - 7.5	-[z]	-	8.75	12.67	34.78	60.14	67.78	46.43	30.98	40.25	26.10	39.11	37.68
	7.5 - 15	-	-	33.53	37.64	38.31	44.53	45.08	40.20	41.53	48.48	31.44	44.54	40.59
	15 - 30	-	-	30.68	35.16	35.41	40.55	38.10	40.15	39.36	45.05	31.08	41.19	37.59
High 2	0 - 7.5	-	-	.	13.33	34.65	61.37	63.74	50.86	25.72	47.40	27.98	32.16	38.83
	7.5 - 15	-	-	48.99	37.75	37.40	45.39	45.00	41.04	41.13	47.46	28.73	41.05	39.52
	15 - 30	-	-	31.83	38.71	35.32	41.18	41.15	38.83	39.86	43.81	31.72	39.64	38.53
High 3	0 - 7.5	-	-	9.22	29.09	30.53	51.77	57.64	52.95	37.16	59.45	10.65	42.87	30.67
	7.5 - 15	-	-	37.95	38.64	37.05	47.16	40.48	45.41	39.23	49.01	22.01	46.05	42.75
	15 - 30	-	-	36.10	38.40	34.35	43.56	36.50	42.44	37.76	44.79	34.73	42.16	39.34
High 4	0 - 7.5	-	-	7.72	26.71	28.41	53.57	65.80	45.07	37.47	39.28	23.13	44.15	30.77
	7.5 - 15	-	-	36.66	36.01	38.58	45.80	46.77	45.73	42.64	48.43	32.71	43.74	41.94
	15 - 30	-	-	34.02	33.58	36.78	41.92	39.87	45.03	40.59	46.32	34.03	41.34	38.52
Low 1	0 - 7.5	-	-	8.98	22.09	35.68	53.66	76.87	66.81	34.91	71.75	30.93	37.96	39.39
	7.5 - 15	-	-	39.27	33.42	38.77	44.15	45.16	50.35	43.15	52.07	33.40	48.32	42.65
	15 - 30	-	-	38.25	30.13	34.61	41.06	37.37	43.33	37.44	47.13	34.90	45.34	39.47
Low 2	0 - 7.5	-	-	13.19	21.67	34.21	53.29	66.07	90.04	40.45	86.44	29.72	45.08	40.14
	7.5 - 15	-	-	42.26	43.06	42.01	45.28	45.77	53.14	41.40	66.42	35.53	42.12	43.84
	15 - 30	-	-	40.28	39.07	40.78	45.33	38.92	45.02	39.24	50.45	39.21	47.56	40.25
Low 3	0 - 7.5	-	-	7.83	27.11	31.21	51.86	110.63	75.43	38.20	84.59	44.13	45.71	28.91
	7.5 - 15	-	-	37.24	35.25	38.53	45.34	66.71	51.76	40.88	62.61	34.82	49.70	42.88
	15 - 30	-	-	34.64	34.26	35.45	40.34	42.85	45.51	37.84	49.47	39.89	44.57	38.00
Low 4	0 - 7.5	-	-	14.27	21.67	33.40	68.66	60.33	59.56	36.99	63.69	36.28	41.27	29.73
	7.5 - 15	-	-	37.71	39.32	39.14	46.67	46.94	52.15	42.10	49.30	24.97	47.19	42.54
	15 - 30	-	-	35.29	35.46	35.89	43.54	39.23	42.27	41.16	45.82	34.49	44.69	39.93
						Gravimetric moisture content means (0-15 cm)								
High 1	0 - 15	43.86	39.71	21.14	25.15	36.55	52.34	56.43	43.32	36.26	44.36	28.77	41.82	39.13
High 2	0 - 15	39.25	39.26	48.99	25.54	36.03	53.38	54.37	45.95	33.43	47.43	28.36	36.60	39.18
High 3	0 - 15	42.55	40.27	23.59	33.86	33.79	49.46	49.06	49.18	38.20	54.23	16.33	44.46	36.71
High 4	0 - 15	41.94	40.97	22.19	31.36	33.50	49.68	56.28	45.40	40.06	43.85	27.92	43.94	36.35
Low 1	0 - 15	38.95	38.18	24.12	27.76	37.22	48.90	61.02	58.58	39.03	61.91	32.16	43.14	41.02
Low 2	0 - 15	45.44	44.18	27.72	32.37	38.11	49.28	55.92	71.59	40.92	76.43	32.63	43.60	41.99
Low 3	0 - 15	43.67	38.68	22.54	31.18	34.87	48.60	88.67	63.60	39.54	73.60	39.48	47.70	35.89
Low 4	0 - 15	45.70	44.77	25.99	30.49	36.27	57.67	53.64	55.85	39.55	56.50	30.62	44.23	36.14

[z]note, on Sept. 29 and Oct. 5, only samples of 0-15 and 15-30 cm were taken.

Table C.2. Gravimetric moisture content of the soil during the fall (2001) and spring (2002) at Kane (2001/02)

Mainplot	Depth (cm)	Sept. 26	Oct. 3	Oct. 9	Oct. 17	Oct. 26	Nov. 1	Nov. 6	Nov. 13	Apr. 18	Apr. 29	May. 3	May. 10	May. 21
		Sampling date												
		%												
High 1	0 - 7.5	26.48	29.36	31.35	28.21	30.04	30.10	22.67	35.47	35.18	33.94	37.79	52.01	36.25
	7.5 - 15	30.74	32.80	34.04	34.45	29.93	35.20	28.43	34.33	36.46	34.30	35.85	42.31	37.11
	15 - 30	33.64	31.20	32.24	32.97	25.63	35.73	30.26	35.97	38.47	34.00	34.61	37.02	33.41
High 2	0 - 7.5	21.70	30.04	26.54	27.85	32.41	30.73	28.51	29.53	34.17	39.32	33.83	42.88	32.58
	7.5 - 15	30.53	29.82	30.98	31.85	27.05	31.44	28.41	31.58	31.69	30.08	29.28	36.84	35.25
	15 - 30	33.37	27.40	31.42	30.28	27.37	30.03	32.88	33.41	29.62	22.35	31.10	34.54	36.28
High 3	0 - 7.5	35.06	41.24	32.93	29.14	37.62	35.79	34.02	35.67	38.80	39.95	40.53	47.28	41.97
	7.5 - 15	37.76	37.22	38.02	36.54	37.79	34.45	33.78	36.34	39.70	38.26	38.22	42.60	40.56
	15 - 30	30.23	31.80	23.19	34.05	36.49	33.68	30.31	35.66	37.28	35.04	37.29	39.05	35.41
High 4	0 - 7.5	34.58	35.80	31.97	28.42	31.23	30.50	29.59	36.20	41.17	39.24	24.26	47.76	38.27
	7.5 - 15	37.50	37.48	36.68	35.18	37.65	35.36	34.62	38.07	42.01	37.77	36.01	42.06	38.65
	15 - 30	36.64	36.22	36.49	34.32	34.73	39.84	33.36	36.18	38.02	38.16	35.14	40.34	37.46
Low 1	0 - 7.5	29.28	38.39	31.69	30.23	35.98	32.72	29.49	33.83	35.73	38.28	40.10	48.61	33.63
	7.5 - 15	35.54	37.61	36.21	34.56	36.60	33.47	32.47	33.23	38.79	39.09	36.15	36.19	38.88
	15 - 30	34.71	34.35	33.43	33.47	35.09	36.08	31.68	34.40	34.75	36.08	32.38	32.78	35.45
Low 2	0 - 7.5	28.55	37.79	32.52	33.48	33.28	35.72	32.96	35.38	40.56	38.38	35.12	49.91	36.73
	7.5 - 15	33.47	36.99	37.11	37.68	34.56	37.17	35.54	37.75	37.23	34.72	41.11	41.58	38.43
	15 - 30	31.51	34.36	36.19	34.13	31.63	36.81	33.75	37.78	39.27	34.42	37.60	35.59	33.89
Low 3	0 - 7.5	30.96	34.84	34.69	32.83	35.03	36.09	32.50	33.18	48.29	41.35	39.90	66.17	41.54
	7.5 - 15	34.00	37.03	39.23	37.58	37.77	37.57	34.57	35.88	42.17	41.34	39.28	48.68	37.89
	15 - 30	36.03	35.73	36.37	36.44	37.81	38.11	33.82	34.55	36.45	38.89	36.42	45.49	35.86
Low 4	0 - 7.5	44.78	41.81	38.19	35.40	39.34	44.38	36.20	38.66	43.59	41.94	39.74	62.17	43.44
	7.5 - 15	43.87	36.02	40.22	39.60	41.25	40.76	38.95	38.17	42.26	40.52	40.45	44.40	44.85
	15 - 30	37.73	35.62	38.27	38.46	39.82	36.32	38.55	36.39	35.69	34.63	36.15	42.29	42.46
		Gravimetric moisture content means (0-15 cm)												
High 1	0 - 15	28.61	31.08	32.69	31.33	29.99	32.65	25.55	34.90	35.82	34.12	36.82	47.16	36.68
High 2	0 - 15	26.11	29.93	28.76	29.85	29.73	31.08	28.46	30.56	32.93	34.70	31.56	39.86	33.91
High 3	0 - 15	36.41	39.23	35.47	32.84	37.70	35.12	33.90	36.01	39.25	39.10	39.37	44.94	41.27
High 4	0 - 15	36.04	36.64	34.32	31.80	34.44	32.93	32.10	37.14	41.59	38.50	30.13	44.91	38.46
Low 1	0 - 15	32.41	38.00	33.95	32.40	36.29	33.09	30.98	33.53	37.26	38.69	38.13	42.40	36.26
Low 2	0 - 15	31.01	37.39	34.82	35.58	33.92	36.44	34.25	36.56	38.90	36.55	38.12	45.75	37.58
Low 3	0 - 15	32.48	35.94	36.96	35.21	36.40	36.83	33.54	34.53	45.23	41.34	39.59	57.42	39.71
Low 4	0 - 15	44.33	38.92	39.21	37.50	40.29	42.57	37.57	38.42	42.93	41.23	40.09	53.29	44.14

Table C.3. **Gravimetric moisture content of the soil during the fall (2001) and spring (2002) at Rosser (2001/02)**

Mainplot	Depth (cm)	Sept. 19	Sept. 27	Oct. 1	Oct. 11	Oct. 17	Oct. 26	Oct. 30	Nov. 6	Nov. 13	Apr. 18	Apr. 29	May. 3	May. 10	May. 23	May. 27
		Sampling date (%)														
High 1	0 - 7.5	34.39	45.98	42.81	46.56	47.43	46.02	51.72	48.55	48.79	60.93	50.61	45.05	61.70	50.47	46.97
	7.5 - 15	42.66	44.48	43.55	45.96	46.15	46.91	47.55	45.17	46.07	50.23	46.23	28.36	48.58	49.13	46.11
	15 - 30	42.06	43.56	43.03	44.17	41.80	46.57	44.69	44.32	44.49	49.93	46.45	46.00	53.10	47.46	42.60
High 2	0 - 7.5	35.50	35.55	43.54	39.93	54.99	51.80	43.54	46.30	49.49	65.70	59.59	48.18	72.57	46.67	48.29
	7.5 - 15	44.49	47.54	46.60	46.94	48.64	49.56	44.79	47.15	45.61	55.32	50.37	49.36	60.48	48.69	47.27
	15 - 30	42.57	46.57	42.66	42.48	47.15	44.46	44.99	46.28	41.53	53.03	47.59	47.80	53.15	45.95	44.58
High 3	0 - 7.5	31.80	37.01	32.62	35.65	49.93	44.88	36.16	42.09	45.21	68.93	52.81	47.39	68.27	48.51	45.58
	7.5 - 15	40.38	41.73	39.61	41.33	48.17	44.16	41.63	40.63	41.73	53.79	48.75	48.11	53.57	49.59	48.62
	15 - 30	37.81	39.96	37.88	37.78	43.28	41.68	40.46	40.33	41.37	50.27	47.51	44.88	53.07	46.01	45.06
High 4	0 - 7.5	36.19	35.36	38.34	41.78	55.08	49.24	47.87	45.49	49.67	69.61	51.19	51.38	54.19	48.37	49.11
	7.5 - 15	41.02	44.42	45.57	44.23	46.54	48.57	46.12	45.69	45.34	52.53	46.67	48.21	48.30	47.39	45.58
	15 - 30	39.30	40.62	43.00	42.53	42.39	44.13	42.33	42.27	43.40	51.98	46.20	45.66	47.81	46.09	44.17
Low 1	0 - 7.5	41.75	41.17	48.04	43.87	59.34	55.02	49.19	48.70	50.90	62.31	55.05	51.98	69.85	57.49	51.78
	7.5 - 15	47.29	47.03	48.76	47.18	50.41	52.59	47.20	47.92	47.75	55.14	50.75	49.26	51.74	52.69	49.21
	15 - 30	44.59	46.66	46.22	45.96	48.53	50.23	44.55	43.85	46.20	51.11	49.75	47.90	57.64	49.10	46.54
Low 2	0 - 7.5	35.96	44.96	43.20	52.27	47.61	44.46	45.51	48.75	51.59	74.97	59.73	49.89	66.53	54.41	50.22
	7.5 - 15	45.58	49.47	45.60	50.16	46.60	50.80	48.41	47.07	46.76	56.32	49.69	49.82	53.12	51.64	48.54
	15 - 30	44.10	47.00	44.58	45.00	41.82	45.90	43.85	43.87	40.08	54.45	49.21	47.87	51.20	46.89	46.43
Low 3	0 - 7.5	34.90	40.57	38.46	46.43	56.89	49.79	51.23	47.35	50.50	69.81	54.36	49.57	64.85	57.37	53.84
	7.5 - 15	42.32	46.87	45.52	45.35	46.87	48.65	46.10	48.21	47.54	53.70	47.51	46.63	52.01	48.97	46.80
	15 - 30	41.35	41.28	40.98	41.73	41.94	44.52	45.26	41.09	41.36	51.38	44.15	43.43	50.15	45.12	41.35
Low 4	0 - 7.5	36.05	36.64	47.88	47.16	60.42	50.72	51.32	50.53	52.48	68.33	53.80	47.81	64.22	55.46	48.98
	7.5 - 15	48.96	50.00	49.85	47.76	51.78	52.75	49.17	50.84	51.83	52.40	50.36	48.74	54.08	49.94	51.06
	15 - 30	43.88	44.14	44.05	44.42	49.94	47.45	45.99	49.25	45.02	53.60	47.68	46.99	51.07	48.19	44.83
		Gravimetric moisture content means (0-15 cm)														
High 1	0 - 15	38.52	45.23	43.18	46.26	46.79	46.46	49.63	46.86	47.43	55.58	48.42	36.70	55.14	49.80	46.54
High 2	0 - 15	40.00	41.55	45.07	43.43	51.82	50.68	44.16	46.72	47.55	60.51	54.98	48.77	66.53	47.68	47.78
High 3	0 - 15	36.09	39.37	36.12	38.49	49.05	44.52	38.90	41.36	43.47	61.36	50.78	47.75	60.92	49.05	47.10
High 4	0 - 15	38.60	39.89	41.95	43.01	50.81	48.91	47.00	45.59	47.50	61.07	48.93	49.79	51.25	47.88	47.34
Low 1	0 - 15	44.52	44.10	48.40	45.52	54.87	53.80	48.20	48.31	49.32	58.73	52.90	50.62	60.80	55.09	50.50
Low 2	0 - 15	40.77	47.21	44.40	51.21	47.10	47.63	46.96	47.91	49.17	65.64	54.71	49.86	59.82	53.02	49.38
Low 3	0 - 15	38.61	43.72	41.99	45.89	51.88	49.22	48.66	47.78	49.02	61.75	50.93	48.10	58.43	53.17	50.32
Low 4	0 - 15	42.50	43.32	48.86	47.46	56.10	51.74	50.25	50.69	52.15	60.36	52.08	48.28	59.15	52.70	50.02

Appendix D

Analysis of Variance and LSDs for the Effects of Application Date and Inhibitors on Midseason and Harvest Yields at the Satellite Sites

Table D.1. Effect of application date and inhibitors on midseason yield (dry matter basis) at the satellite sites

Treatment	df	Oak Bluff 2000/01 High	Oak Bluff 2000/01 Low	Oak Bluff 2001/02 High	Sperling 2001/02 High	Sperling 2001/02 Low	Mean all sites
				(kg ha^{-1})			
Early fall		2549	2543ab	3802	4111ab	3725a	3346
Mid fall		2448	2543ab	3518	4105ab	3550a	3233
Late fall		2510	2857a	3645	3985ab	3604a	3320
Spring		2992	2880a	3953	3556bc	3109a	3298
Control (no N)		2073	2135b	3282	3290c	1787b	2513
Early fall w/ inhibitors		2628	2656a	3844	4389a	3689a	3435
LSD ($\alpha = 0.05$)		ns	458	ns	597	797	-[z]
ANOVA	df			$P > F$			
Trt	5	0.1493	0.0364*	0.2212	0.0137*	0.0008*	
Block	3	0.8808	0.0562	0.2006	0.1741	0.3291	
Residual C.V. (%)		16.85	11.69	10.59	10.13	16.32	
Site year	4						0.0001*
Trt	5						0.0001*
Site year*Trt	20						0.01*
Block(Site)	15						0.1523
Residual C.V. (%)							13.02

a-c Mean values followed by the same letter (within columns) are not significantly different.

[z] LSD is not reported b/c of the Site year*Trt interaction.

* significant at $P < 0.05$.

Table D.2. Effect of application date and inhibitors on midseason N uptake (dry matter basis) at the satellite sites

Treatment	df	Oak Bluff 2000/01 High	Oak Bluff 2000/01 Low	Oak Bluff 2001/02 High	Sperling 2001/02 High	Sperling 2001/02 Low	Mean all sites
		(kg ha^{-1})					
Early fall		62.6ab	57.8c	115.2a	132.9ab	108.0a	95.3
Mid fall		58.5b	61.4c	108.4a	132.3ab	106.4a	93.4
Late fall		55.7bc	75.3ab	114.5a	126.1ab	104.0ab	95.1
Spring		74.0a	84.1a	112.6a	119.6bc	85.4b	95.1
Control (no N)		43.8c	45.6d	81.4b	108.1c	39.8c	63.7
Early fall w/ inhibitors		62.1ab	65.0bc	112.0a	138.1a	105.1ab	96.5
LSD ($\alpha = 0.05$)		12.0	11.5	17.7	17.6	20.2	-[z]
ANOVA	df	$P > F$					
Trt	5	0.0027*	0.0001*	0.0079*	0.0275*	0.0001*	
Block	3	0.8719	0.0486*	0.4214	0.1272	0.3290	
Residual C.V. (%)		13.43	11.71	10.96	9.27	14.69	
Site year	4						0.0001*
Trt	5						0.0001*
Site year*Trt	20						0.0001*
Block(Site)	15						0.1220
Residual C.V. (%)							11.96

a-c Mean values followed by the same letter (within columns) are not significantly different.

[z] LSD is not reported b/c of the Site year*Trt interaction.

* significant at $P < 0.05$.

Table D.3. Effect of application date and inhibitors on grain yield (dry matter basis) at the satellite sites

		Site				
		Oak Bluff[z] 2000/01	Oak Bluff 2001/02	Sperling 2001/02		Mean
Treatment		High	High	High	Low	all sites
		(kg ha^{-1})				
Early fall		2365b	3796a	2849	2512a	2880
Mid fall		2398b	3650a	3051	2698a	2950
Late fall		2280b	3713a	3117	2742a	2963
Spring		2865a	3835a	3045	2444a	3047
Control (no N)		1641c	2948b	3176	1104b	2217
Early fall w/ inhibitors		2355b	3984a	3064	2708a	3027
LSD (α = 0.05)		358	369	ns	609	-[y]
ANOVA	df			$P > F$		
Trt	5	0.0001*	0.0004*	0.6357	0.0003*	
Block	3	0.4919	0.2082	0.0374*	0.0037	
Residual C.V. (%)		10.26	6.69	8.68	17.07	
Site year	3					0.0001*
Trt	5					0.0001*
Site year*Trt	15					0.0001*
Block(Site)	12					0.0001*
Residual C.V. (%)						10.39

a-c Mean values followed by the same letter (within columns) are not significantly different.

[z] Grain yields for Oak Bluff 2000/2001 were predicted from actual straw yields.

[y] LSD is not reported b/c of the Site year*Trt interaction.

* significant at $P < 0.05$.

Table D.4. Effect of application date and inhibitors on straw yield (dry matter basis) at the satellite sites

		Site				
		Oak Bluff 2000/01	Oak Bluff 2001/02	Sperling 2001/02		Mean
Treatment		High	High	High	Low	all sites
				(kg ha^{-1})		
Early fall		3590b	4614ab	3939	3148a	3823
Mid fall		3646b	4402b	4185	3254a	3872
Late fall		3448b	4428b	4112	3434a	3855
Spring		4422a	4659ab	4064	2822a	3992
Control (no N)		2386c	3412c	4035	1605b	2860
Early fall w/ inhibitors		3574b	4904a	4181	3599a	4065
LSD ($\alpha = 0.05$)		596	467	ns	800	-[z]
ANOVA	df			$P > F$		
Trt	5	0.0001*	0.0001*	0.9472	0.0011*	
Block	3	0.4919	0.2368	0.0054*	0.0021*	
Residual C.V. (%)		11.26	7.03	9.77	17.83	
Site year	3					0.001*
Trt	5					0.0001*
Site year*Trt	15					0.0004*
Block(Site)	12					0.0001*
Residual C.V. (%)						11.12

a-c Mean values followed by the same letter (within columns) are not significantly different.

[z] LSD is not reported b/c of the Site year*Trt interaction.

* significant at $P < 0.05$.

Table D.5. Effect of application date and inhibitors on total N uptake (dry matter basis) at the satellite sites

Treatment	df	Oak Bluff 2000/01 High	Oak Bluff 2001/02 High	Sperling 2001/02 High	Sperling 2001/02 Low	Mean all sites
		(kg ha^{-1})				
Early fall		109.2b	180.3a	133.7	104.4a	131.9
Mid fall		110.7b	172.0a	146.0	110.0a	134.7
Late fall		108.6b	168.8a	146.2	108.2a	133.9
Spring		148.0a	171.2a	139.6	95.6a	138.6
Control (no N)		76.9c	119.5b	139.6	43.0b	94.7
Early fall w/ inhibitors		108.2b	179.6a	141.7	105.0a	133.6
LSD ($\alpha = 0.05$)		17.9	24.9	ns	19.9	-^{z}
ANOVA	df	$P > F$				
Trt	5	0.0001*	0.0009*	0.5219	0.0001*	
Block	3	0.1740	0.1933	0.0034*	0.0292*	
Residual C.V. (%)		10.76	10.00	7.10	13.96	
Site year	3					0.0001*
Trt	5					0.0001*
Site year*Trt	15					0.0001*
Block(Site)	12					0.0017*
Residual C.V. (%)						10.26

a-c Mean values followed by the same letter (within columns) are not significantly different.

^{z} LSD is not reported b/c of the Site year*Trt interaction.

* significant at $P < 0.05$.

Table D.6. Effect of application date and inhibitors on grain N uptake (dry matter basis) at the satellite sites

		Site				
		Oak Bluff 2000/01	Oak Bluff 2001/02	Sperling 2001/02		Mean all sites
Treatment		High	High	High	Low	
				($kg\ ha^{-1}$)		
Early fall		79.0b	129.0a	97.1	79.0a	96.0
Mid fall		81.5b	121.7a	106.1	84.4a	98.4
Late fall		78.6b	121.4a	108.4	83.0a	97.8
Spring		108.9a	121.8a	103.2	75.9a	102.5
Control (no N)		56.3c	90.7b	106.4	32.0b	71.4
Early fall w/ inhibitors		81.8b	130.6a	105.8	82.0a	100.0
LSD ($\alpha = 0.05$)		12.6	17.0	ns	16.9	-[z]
ANOVA	df			$P > F$		
Trt	5	0.0001*	0.0019*	0.5619	0.0001*	
Block	3	0.1570	0.1107	0.0371*	0.0396*	
Residual C.V. (%)		10.33	9.46	8.53	15.42	
Site year	3					0.0001*
Trt	5					0.0001*
Site year*Trt	15					0.0001*
Block(Site)	12					0.0029*
Residual C.V. (%)						10.63

a-c Mean values followed by the same letter (within columns) are not significantly different.

[z] LSD is not reported b/c of the Site year*Trt interaction.

* significant at $P < 0.05$.

Table D.7. Effect of application date and inhibitors on straw N uptake (dry matter basis) at the satellite sites

		Site				
		Oak Bluff 2000/01	Oak Bluff 2001/02	Sperling 2001/02		Mean
Treatment		High	High	High	Low	all sites
				($kg\ ha^{-1}$)		
Early fall		30.2b	51.3a	36.6	25.4a	35.9
Mid fall		29.1b	50.3a	39.9	25.6a	36.2
Late fall		30.1b	47.4a	37.7	25.2a	35.1
Spring		39.0a	49.4a	36.4	19.7ab	36.1
Control (no N)		20.6c	28.7b	33.1	11.0c	23.4
Early fall w/ inhibitors		26.4bc	48.9a	36.0	23.2ab	33.6
LSD ($\alpha = 0.05$)		6.7	8.9	ns	4.4	-[z]
ANOVA	df			$P > F$		
Trt	5	0.0012*	0.0006*	0.6978	0.0001*	
Block	3	0.2511	0.2835	0.0364*	0.0317*	
Residual C.V. (%)		15.20	12.82	15.64	13.39	
Site year	3					0.0001*
Trt	5					0.0001*
Site year*Trt	15					0.0047*
Block(Site)	12					0.0125*
Residual C.V. (%)						14.66

a-c Mean values followed by the same letter (within columns) are not significantly different.

[z] LSD is not reported b/c of the Site year*Trt interaction.

* significant at $P < 0.05$.

Appendix E

Grain Yield, Total N Uptake, Grain Yield Increase and N Use Efficiency as a Function of Soil Heat Units and Nitrification Heat Units (Chapter 6)

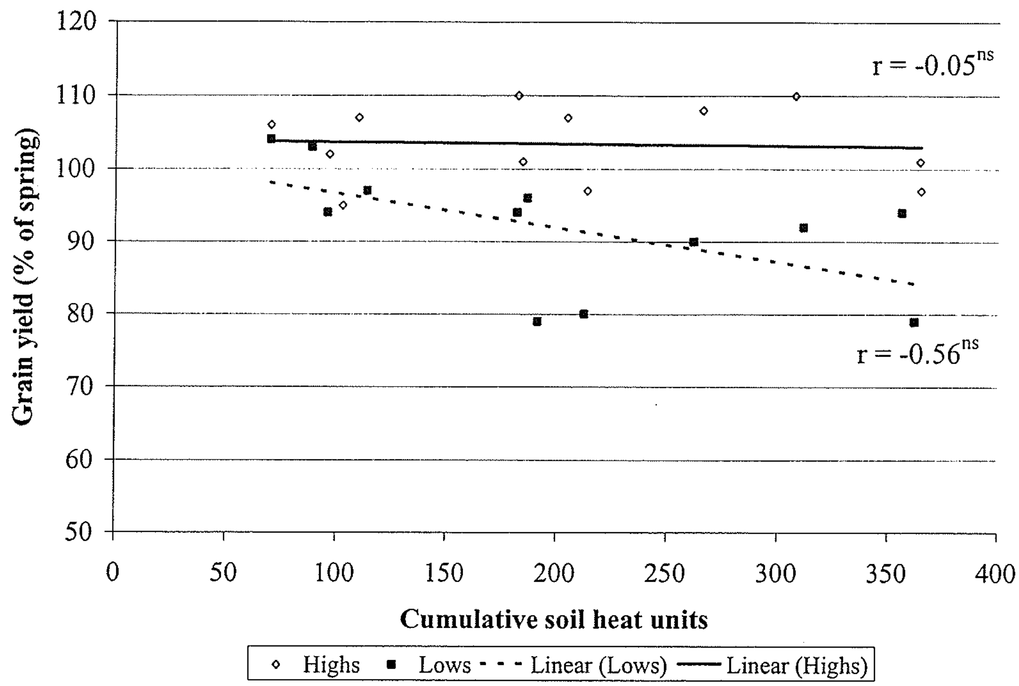


Fig. E.1. Effect of cumulative SHU in the fall until freeze-up on wheat grain yields from fall-banded urea relative to spring-banded urea (ns, indicates no significance) (High vs. Low positions $P = 0.11^{ns}$).

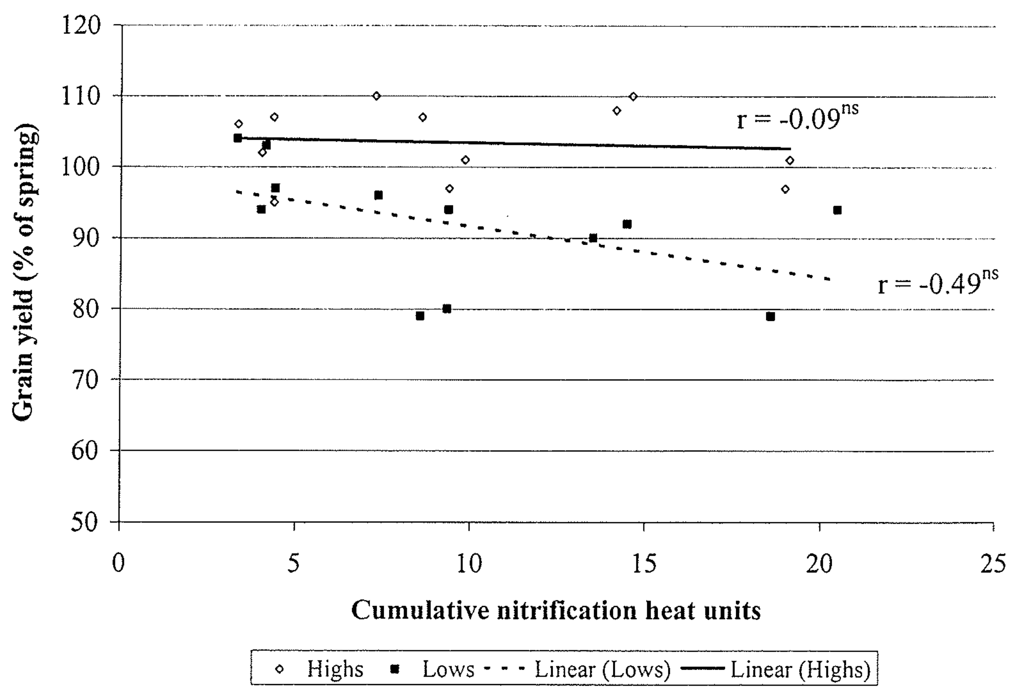


Fig. E.2. Effect of cumulative NHU in the fall until freeze-up on wheat grain yields from fall-banded urea relative to spring-banded urea (ns, indicates no significance) (High vs. Low positions $P = 0.22^{ns}$).

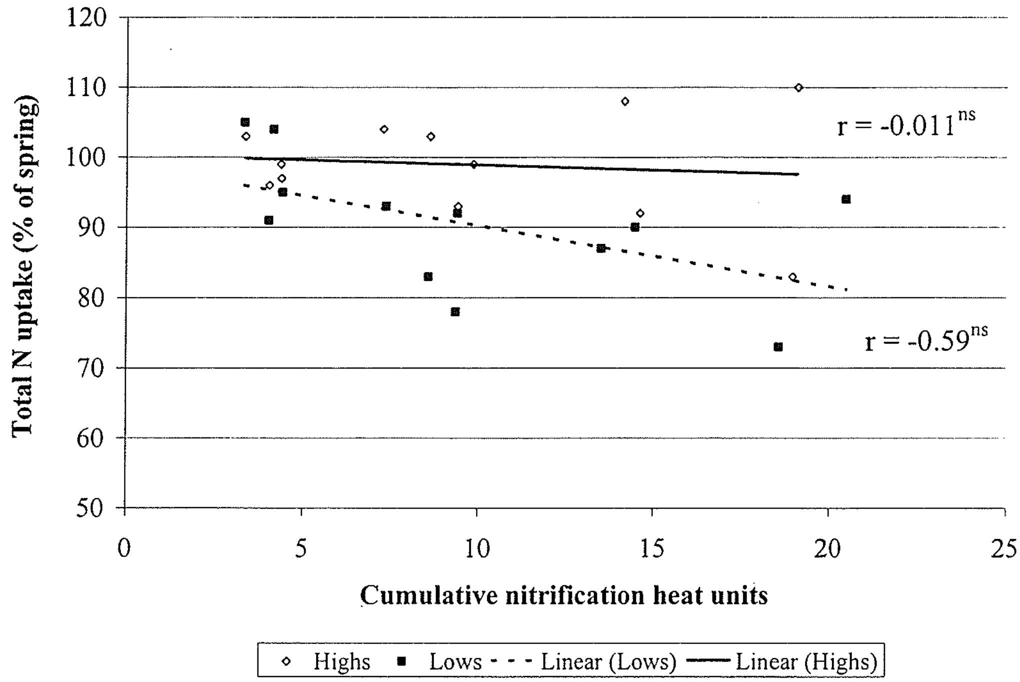


Fig. E.3. Effect of cumulative NHU in the fall until freeze-up on total N uptake by the crop from fall-banded urea relative to spring-banded urea (ns, indicates no significance) (High vs. Low positions $P = 0.24^{ns}$).

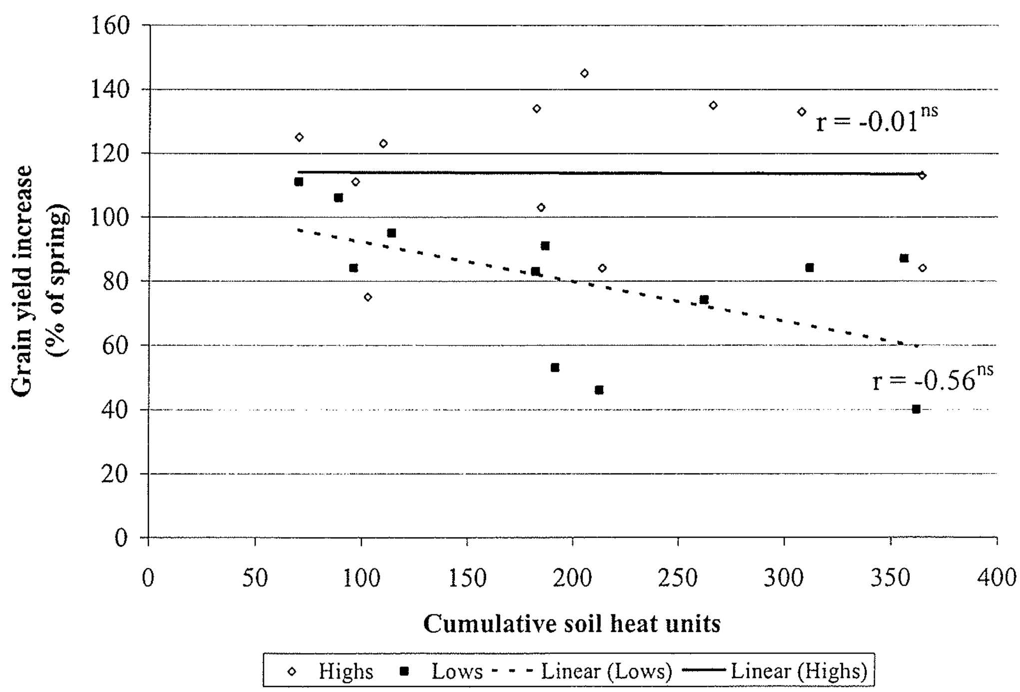


Fig. E.4. Effect of cumulative SHU until 0°C soil temperature at 7.5 cm in the fall on increases in wheat grain yield from fall-banded urea relative to spring-banded urea (ns, indicates no significance) (High vs. Low positions $P = 0.20^{ns}$).

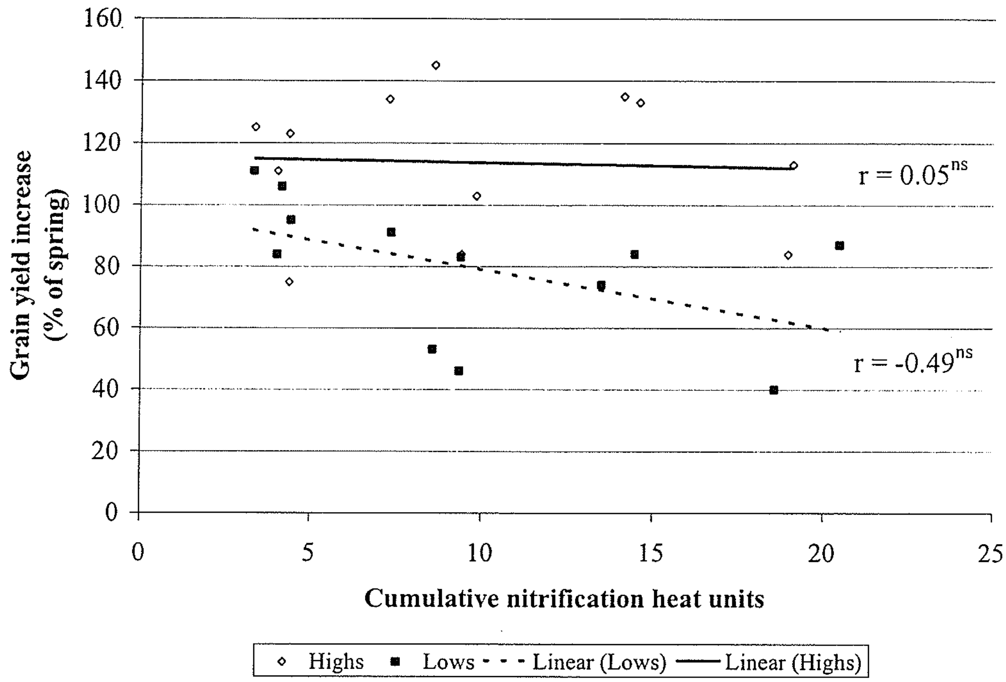


Fig. E.5. Effect of cumulative NHU until 0°C soil temperature at 7.5 cm in the fall on increases in wheat grain yield from fall-banded urea relative to spring-banded urea (ns, indicates no significance) (High vs. Low positions $P = 0.31^{ns}$).

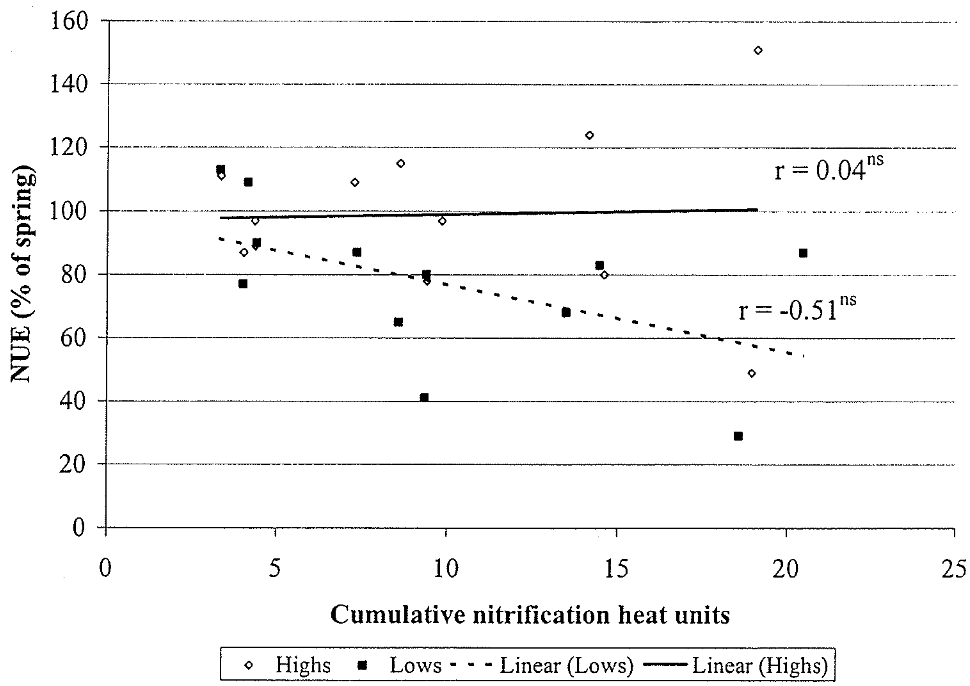


Fig. E.6. Effect of cumulative NHU until 0°C soil temperature at 7.5 cm in the fall on N use efficiency from fall-banded urea relative to spring-banded urea (ns, indicates no significance) (High vs. Low positions $P = 0.22^{ns}$).

Appendix F

Analysis of Variance and LSDs for the Effects of Landscape Position, Application Date and Inhibitors on Crop Response at Midseason and Harvest at the Intensive Sites

Table F.1. Effect of landscape position, application date, and inhibitors on mean midseason yield and N uptake (dry matter basis) at all the intensive sites, Red River Valley sites only, and 2001/02 sites only

Treatment		All intensive site years		Red River Valley sites only		2001/02 sites only	
Landscape position	Fertilization	Biomass	N uptake	Biomass	N uptake	Biomass	N uptake
		(kg ha^{-1})					
High	Early fall	2988	93.5	2695	84.7	3232	98.0
	Mid fall	2905	91.2	2591	84.8	3158	91.0
	Late fall	3083	96.7	2816	88.1	3413	104.1
	Spring	3245	101.9	2916	94.3	3569	108.2
	Control (no N)	2298	61.9	2084	60.1	2553	65.9
	Early fall w/ inhibitor:	2980	90.7	2847	88.4	3259	96.2
	LSD (α = 0.05)^z	-	-	-	-	-	-
Low	Early fall	2383	65.7	2238	66.8	2461	65.8
	Mid fall	2347	65.4	2326	68.5	2332	63.8
	Late fall	2476	69.5	2406	71.7	2559	70.0
	Spring	2736	79.1	2642	81.7	2829	79.7
	Control (no N)	1501	36.7	1439	37.4	1490	95.2
	Early fall w/ inhibitor:	2494	69.8	2390	72.8	2556	68.9
	LSD (α = 0.05)^z	-	-	-	-	-	-
Landscape position means							
High		2917a	89.3	2658	83.4	3197a	94.9
Low		2323b	64.4	2240	66.5	2371b	63.9
LSD (α = 0.10)		431	-^{y}	-^{y}	-^{y}	548	-^{y}
	Fertilization means						
	Early fall	2686b	79.6b	2466b	75.8	2847bc	81.9
	Mid fall	2626b	78.3b	2458b	76.6	2745c	80.4
	Late fall	2779b	83.1b	2611ab	79.9	2986ab	87.1
	Spring	2991a	90.5a	2779a	88.0	3199a	93.9
	Control (no N)	1899c	49.3c	1762c	48.7	2022d	50.6
	Early fall w/ inhibitor:	2737b	80.2b	2618ab	80.6	2908bc	82.5
	LSD (α = 0.05)	188	6.12	199	-^{x}	237	-^{x}

ANOVA	df	$P > F$		df	$P > F$		df	$P > F$	
Site year	3	0.0588	0.5852	2	0.2196	0.5978	2	0.2627	0.8408
Landpos	1	0.0268*	0.0019*	1	0.1507	0.0643†	1	0.0176*	0.0035
Site year*Landpos	3	0.1189	0.0416*	2	0.0918†	0.0937†	2	0.2182	0.0747†
Trt	5	0.0001*	0.0001*	5	0.0001*	0.0001*	5	0.0001*	0.0001*
Site year*Trt	15	0.1966	0.0572	10	0.0777	0.0087*	10	0.2681	0.0467*
Landpos*Trt	5	0.6375	0.8727	5	0.4292	0.6678	5	0.7156	0.9388
Site year*Landpos*Trt	15	0.3538	0.3260	10	0.3076	0.2789	10	0.2371	0.1945
Block(Site*Landpos)	24	0.0001*	0.0001*	18	0.0001*	0.0001	18	0.0001*	0.0001*
Residual C.V. (%)		14.50	16.09		14.13	13.64		14.82	16.79

a-d Mean values followed by the same letter (within columns) are not significantly different.

^{z} LSD for individual treatments within a landscape position is not reported b/c there was no Landpos*Trt interaction.

^{y} LSD is not reported b/c there was a Site year*Landpos interaction.

^{x} LSD is not reported b/c there was a Site year*Trt interaction.

† Significant at $P < 0.10$ (used only for landscape position variables and interactions).

* Significant at $P < 0.05$.

Table F.2. Effect of landscape position, application date and inhibitors on grain yield (dry matter basis)

Landscape position	Fertilization	Kane 2000/01^{x}	Kane 2001/02	Rosser 2001/02	Brandon 2001/02
		(kg ha^{-1})			
High	Early fall	2520	1990	2383	3221
	Mid fall	2345	1996	2383	3395
	Late fall	2467	1937	2509	3013
	Spring	2330	1817	2456	3181
	Control (no N)	1787	1286	1992	2603
	Early fall w/ inhibitors	2307	1826	2522	3136
	LSD (α = 0.05)^{y}	-	-	-	-
Low	Early fall	1990	2472	1299	1997
	Mid fall	2066	2566	1329	1676
	Late fall	2288	2612	1556	2177
	Spring	2203	2687	1652	2122
	Control (no N)	1396	1307	1059	1168
	Early fall w/ inhibitors	2224	2417	1374	1825
	LSD (α = 0.05)^{y}	-	-	-	-
Landscape position means					
High		2293a	1809	2374a	3091a
Low		2028b	2343	1378b	1828b
LSD (α = 0.10)		184	ns	808	na^{z}
	Fertilization means				
	Early fall	2255a	2231a	1841a	2609a
	Mid fall	2206a	2281a	1856a	2536a
	Late fall	2377a	2275a	2032a	2595a
	Spring	2267a	2252a	2054a	2651a
	Control (no N)	1592b	1296b	1525b	1885b
	Early fall w/ inhibitors	2266a	2122a	1948a	2481a
	LSD (α = 0.05)	201	354	287	na^{z}
ANOVA	df				
Landpos	1	0.0309*	0.2271	0.0536†	0.0038*
Trt	5	0.0001*	0.0001*	0.0092*	0.0004*
Landpos*Trt	5	0.2189	0.2734	0.8531	0.1452
Block(Landpos)	6	0.0296*	0.0001*	0.0001*	0.0001*
Residual C.V. (%)		9.12	16.70	14.98	13.06

a,b Mean values followed by the same letter (within columns) are not significantly different.

^{z} Brandon 2001/2002 had unbalanced data: therefore used LSMEANS which does not provide an LSD value.

^{y} LSD for individual treatments within a landscape position is not reported b/c there was no Landpos*Trt interaction.

^{x} Grain yields for Kane 2000/2001 were predicted from actual straw yields.

† Significant at $P < 0.10$ (used only for landscape position variables and interactions).

* Significant at $P < 0.05$.

Table F.3. Effect of landscape position, application date, and inhibitors on straw yield (dry matter basis)

Treatment		Site			
Landscape position	Fertilization	Kane 2000/01	Kane 2001/02	Rosser 2001/02	Brandon 2001/02
		(kg ha^{-1})			
High	Early fall	3849	2257a	3442	3421
	Mid fall	3558	2397a	3703	3265
	Late fall	3760	2214a	3938	2972
	Spring	3533	2126a	3981	3296
	Control (no N)	2630	1508b	2880	2196
	Early fall w/ inhibitors	3495	2192a	3679	3167
	LSD (α = 0.05)	-^{y}	na^{x}	-^{y}	-^{y}
Low	Early fall	2967	3673ab	2008	2206
	Mid fall	3094	3574ab	2169	1996
	Late fall	3462	3961a	2402	2450
	Spring	3321	3861ab	2882	2216
	Control (no N)	1978	2147c	1800	1069
	Early fall w/ inhibitors	3356	3347b	2169	1957
	LSD (α = 0.05)	-^{y}	na^{x}	-^{y}	-^{y}
Landscape position means					
High		3471a	2116	3604a	3053a
Low		3030b	3427	2238b	1982b
LSD (α = 0.10)		305	-^{w}	1228	na^{z}
	Fertilization means				
	Early fall	3408a	2965	2725bc	2813a
	Mid fall	3326a	2986	2936ab	2630a
	Late fall	3611a	3087	3170ab	2711a
	Spring	3427a	2993	3431a	2756a
	Control (no N)	2304b	1828	2340c	1632b
	Early fall w/ inhibitors	3425a	2770	2924b	2562a
	LSD (α = 0.05)	335	-^{w}	503	na^{z}
ANOVA	df	$P > F$			
Landpos	1	0.0309*	0.0243*	0.074†	0.0255*
Trt	5	0.0001*	0.0001*	0.0031*	0.0001*
Landpos*Trt	5	0.2189	0.0583†	0.8529	0.3101
Block(Landpos)	6	0.0296*	0.0001*	0.0001*	0.0001*
Residual C.V. (%)		10.09	13.71	16.88	13.93

a-c Mean values followed by the same letter (within columns) are not significantly different.

^{z} Brandon 2001/2002 had unbalanced data: therefore used LSMEANS which does not provide an LSD value.

^{y} LSD for individual treatments within a landscape position is not reported b/c there was no Landpos*Trt interaction.

^{x} Not applicable b/c used LSMEANS which does not provide an LSD value.

^{w} LSD is not reported b/c of Landpos*Trt interactions.

† Significant at $P < 0.10$ (used only for landscape position variables and interactions).

* Significant at $P < 0.05$.

Table F.4. Effect of landscape position, application date, and inhibitors on total crop N uptake (dry matter basis)

Treatment		Site			
Landscape position	Fertilization	Kane 2000/01	Kane 2001/02	Rosser 2001/02	Brandon 2001/02
		(kg ha^{-1})			
High	Early fall	135.6	80.4	110.2	139.1
	Mid fall	124.9	90.8	122.6	129.5
	Late fall	130.2	86.4	126.6	122.4
	Spring	125.9	87.6	132.4	126.2
	Control (no N)	86.7	52.3	88.5	98.4
	Early fall w/ inhibitors	122.0	84.1	118.0	125.8
	LSD (α = 0.05)[y]	-	-	-	-
Low	Early fall	98.0	104.2	60.1	70.3
	Mid fall	103.3	106.8	64.1	62.5
	Late fall	118.4	109.0	75.3	78.0
	Spring	112.3	115.2	82.6	74.9
	Control (no N)	66.9	52.1	51.0	38.7
	Early fall w/ inhibitors	111.1	99.5	68.5	66.6
	LSD (α = 0.05)[y]	-	-	-	-
Landscape position means					
High		120.9a	80.3	116.4a	123.6a
Low		101.6b	97.8	66.9b	65.2b
LSD (α = 0.10)		9.6	ns	43.7	na[z]
	Fertilization means				
	Early fall	116.8a	92.3a	85.1b	104.7a
	Mid fall	114.1a	98.8a	93.4ab	96.0a
	Late fall	124.3a	97.7a	100.9a	100.2a
	Spring	119.1a	101.4a	107.5a	100.5a
	Control (no N)	76.8b	52.2b	69.8c	68.6b
	Early fall w/ inhibitors	116.5a	91.8a	93.2ab	96.2a
	LSD (α = 0.05)	11.5	19.1	15.2	na[z]
ANOVA	df	$P > F$			
Landpos	1	0.0082*	0.3207	0.0703†	0.0008*
Trt	5	0.0001*	0.0001*	0.0004*	0.0007*
Landpos*Trt	5	0.198	0.7324	0.8339	0.5942
Block(Landpos)	6	0.0573*	0.0001*	0.0001*	0.0025*
Residual C.V. (%)		10.11	23.07	16.21	16.03

a-c Mean values followed by the same letter (within columns) are not significantly different.

[z] Brandon 2001/2002 had unbalanced data: therefore used LSMEANS which does not provide an LSD value.

[y] LSD for individual treatments within a landscape position is not reported b/c there was no Landpos*Trt interaction.

† Significant at $P < 0.10$ (used only for landscape position variables and interactions).

* Significant at $P < 0.05$.

Table F.5. Effect of landscape position, application date and inhibitors on grain N uptake (dry matter basis)

Treatment: Landscape position	Treatment: Fertilization	Site: Kane 2000/01[x]	Kane 2001/02	Rosser 2001/02	Brandon 2001/02
		(kg ha^{-1})			
High	Early fall	91.5	59.4	75.3	108.7
	Mid fall	87.4	67.1	80.1	104.2
	Late fall	91.1	64.3	84.5	96.5
	Spring	86.5	68.9	85.0	98.7
	Control (no N)	61.9	40.1	60.5	81.7
	Early fall w/ inhibitors	83.0	61.5	81.4	101.2
	LSD (α = 0.05)[y]	-	-	-	-
Low	Early fall	71.5	71.7	40.5	55.4
	Mid fall	73.3	74.8	41.5	48.0
	Late fall	83.1	74.6	49.4	61.7
	Spring	80.2	81.7	51.7	59.3
	Control (no N)	50.1	34.5	31.5	31.7
	Early fall w/ inhibitors	78.3	70.6	43.9	52.2
	LSD (α = 0.05)[y]	-	-	-	-
Landscape position means					
High		83.6a	60.2	77.8a	98.49a
Low		72.7b	68.0	43.1b	51.40b
LSD (α = 0.10)		6.2	ns	29.7	na[z]
	Fertilization means				
	Early fall	81.5a	65.6a	57.9b	82.1a
	Mid fall	80.4a	70.9a	60.8ab	76.1a
	Late fall	87.1a	69.5a	66.9ab	79.1a
	Spring	83.4a	75.3a	68.3a	79.0a
	Control (no N)	56.0b	37.3b	46.0c	56.7b
	Early fall w/ inhibitors	80.6a	66.1a	62.6ab	76.7a
	LSD (α = 0.05)	8.0	15.1	9.7	na[z]
ANOVA	df	$P > F$			
Landpos	1	0.0148*	0.5696	0.0633†	0.001*
Trt	5	0.0001*	0.0002*	0.0007*	0.0037*
Landpos*Trt	5	0.3994	0.8263	0.9346	0.4959
Block(Landpos)	6	0.0934†	0.0001*	0.0001*	0.0015*
Residual C.V. (%)		9.96	23.07	15.65	16.42

a-c Mean values followed by the same letter (within columns) are not significantly different.

[z] Brandon 2001/2002 had unbalanced data: therefore used LSMEANS which does not provide an LSD value.

[y] LSD for individual treatments within a landscape position is not reported b/c there was no Landpos*Trt interaction.

[x] Grain yields for Kane 2000/2001 were predicted from actual straw yields.

† Significant at $P < 0.10$ (used only for landscape position variables and interactions).

* Significant at $P < 0.05$.

Table F.6. Effect of landscape position, application date, and inhibitors on straw N uptake (dry matter basis)

Treatment		Site			
Landscape position	Fertilization	Kane 2000/01	Kane 2001/02	Rosser 2001/02	Brandon 2001/02
		(kg ha^{-1})			
High	Early fall	44.1a	21.0	34.9	30.3
	Mid fall	37.5a	23.8	42.5	25.2
	Late fall	39.1a	22.1	42.1	25.9
	Spring	39.4a	18.7	47.5	27.5
	Control (no N)	24.8b	12.2	28.0	16.7
	Early fall w/ inhibitors	39.0a	22.6	36.6	24.6
	LSD (α = 0.05)	na[w]	-[y]	-[y]	-[y]
Low	Early fall	26.5b	32.5	19.6	14.9
	Mid fall	29.9ab	32.0	22.6	14.4
	Late fall	35.3a	34.3	25.9	16.3
	Spring	32.1ab	33.4	30.9	15.5
	Control (no N)	16.8c	17.6	19.5	7.1
	Early fall w/ inhibitors	32.8ab	28.9	24.6	14.4
	LSD (α = 0.05)	na[w]	-[y]	-[y]	-[y]
Landscape position means					
High		37.3	20.1b	38.6	25.06a
Low		28.9	29.8a	23.9	13.76b
LSD (α = 0.10)		-[x]	6.9	ns	na[z]
	Fertilization means				
	Early fall	35.3	26.7a	27.2cd	22.6a
	Mid fall	33.7	27.9a	32.5bc	19.8a
	Late fall	37.2	28.2a	34.0ab	21.1a
	Spring	35.8	26.1a	39.1a	21.5a
	Control (no N)	20.8	14.9b	23.8d	11.9b
	Early fall w/ inhibitors	35.9	25.8a	30.6bc	19.5a
	LSD (α = 0.05)	-[x]	5.4	6.4	na[z]
ANOVA	df	$P > F$			
Landpos	1	0.0096*	0.034*	0.1028	0.0037*
Trt	5	0.0001*	0.0002**	0.0006*	0.0001*
Landpos*Trt	5	0.0919†	0.4656	0.5445	0.6611
Block(Landpos)	6	0.0255*	0.0007*	0.0001*	0.0019*
Residual C.V. (%)		13.92	21.29	20.03	20.07

a-d Mean values followed by the same letter (within columns) are not significantly different.

[z] Brandon 2001/2002 had unbalanced data: therefore used LSMEANS which does not provide an LSD value.

[y] LSD for individual treatments within a landscape position is not reported b/c there was no Landpos*Trt interaction.

[x] LSD is not reported b/c of Landpos*Trt interactions.

[w] Not applicable b/c used LSMEANS which does not provide an LSD value.

† Significant at $P < 0.10$ (used only for landscape position variables and interactions).

* Significant at $P < 0.05$.

Table F.7. Effect of landscape position, application date, and inhibitors on mean grain yield (dry matter basis) at all intensive sites, Red River Valley sites only and 2001/02 sites only

Treatment: Landscape position	Treatment: Fertilization	All intensive sites[z]	Red River Valley only[z]	2001/02 only
			(kg ha^{-1})	
High	Early fall	2528a	2298	2531
	Mid fall	2530a	2241	2591
	Late fall	2482a	2305	2486
	Spring	2446a	2201	2484
	Control (no N)	1917b	1688	1960
	Early fall w/ inhibitors	2448a	2218	2495
	LSD (α = 0.05)	na[y]	-[x]	-[x]
Low	Early fall	1939c	1920	1923
	Mid fall	1910c	1987	1857
	Late fall	2158ab	2151	2115
	Spring	2166a	2180	2154
	Control (no N)	1232d	1254	1178
	Early fall w/ inhibitors	1960bc	2005	1872
	LSD (α = 0.05)	na[y]	-[x]	-[x]
Landscape position means				
High		2392	2159	2425
Low		1894	1916	1850
LSD (α = 0.10)		-[w]	-[w]	-[w]
	Fertilization means			
	Early fall	2234	2109a	2227a
	Mid fall	2220	2114a	2224a
	Late fall	2320	2228a	2301a
	Spring	2306	2191a	2319a
	Control (no N)	1575	1471b	1569b
	Early fall w/ inhibitors	2204	2112a	2183a
	LSD (α = 0.05)	-[v]	162	na[y]

ANOVA	df	$P > F$	df	$P > F$	df	$P > F$
Site year	3	0.1106	2	0.4852	2	0.1053
Landpos	1	0.0051*	1	0.2286	1	0.0147*
Site year*Landpos	3	0.0028*	2	0.0167*	2	0.0059*
Trt	5	0.0001*	5	0.0001*	5	0.0001*
Site year*Trt	15	0.4885	10	0.1675	10	0.3342
Landpos*Trt	5	0.0330*	5	0.1392	5	0.8370
Site year*Landpos*Trt	15	0.6105	10	0.7032	10	0.5809
Block(Site year*Landpos)	24	0.0001*	18	0.0001*	18	0.0001*
Residual C.V. (%)		13.62		13.82		14.87

a-d Mean values followed by the same letter (within columns) are not significantly different.

[z] Grain yields for Kane 2000/2001 were predicted from actual straw yields.

[y] Not applicable b/c used LSMEANS which does not provide an LSD value.

[x] LSD for individual treatments within a landscape position is not reported b/c there was no Landpos*Trt interaction.

[w] LSD is not reported b/c of significant Site year*Landpos interaction.

[v] LSD is not reported b/c of significant Landpos*Trt interaction.

† Significant at $P < 0.10$ (used only for landscape position variables and interactions).

* Significant at $P < 0.05$.

Table F.8. Effect of landscape position, application date, and inhibitors on mean straw yield (dry matter basis) at all intensive sites, Red River Valley sites only and 2001/02 sites only

Treatment: Landscape position	Treatment: Fertilization	All intensive sites	Red River Valley only	2001/02 only
			(kg ha^{-1})	
High	Early fall	3242	3182	3040
	Mid fall	3231	3219	3122
	Late fall	3221	3304	3041
	Spring	3234	3213	3134
	Control (no N)	2303	2339	2195
	Early fall w/ inhibitors	3133	3122	3013
	LSD ($\alpha = 0.05$)[z]	-	-	-
Low	Early fall	2713	2883	2629
	Mid fall	2708	2945	2579
	Late fall	3069	3275	2937
	Spring	3070	3355	2986
	Control (no N)	1749	1975	1672
	Early fall w/ inhibitors	2707	2957	2491
	LSD ($\alpha = 0.05$)[z]	-	-	-
Landscape position means				
High		3061	3064	2924
Low		2669	2898	2549
LSD ($\alpha = 0.10$)		-[x]	-[x]	-[x]
	Fertilization means			
	Early fall	2978ab	3033b	2835ab
	Mid fall	2969ab	3082ab	2850ab
	Late fall	3145a	3289a	2989a
	Spring	3152a	3284a	3060a
	Control (no N)	2026c	2157c	1933c
	Early fall w/ inhibitors	2920b	3040b	2752b
	LSD ($\alpha = 0.05$)	-[y]	232	-[y]

ANOVA	df	$P > F$	df	$P > F$	df	$P > F$
Site year	3	0.1425	2	0.3334	2	0.5180
Landpos	1	0.083†	1	0.5361	1	0.2035
Site year*Landpos	3	0.0009*	2	0.002*	2	0.002*
Trt	5	0.0001*	5	0.0001*	5	0.0001*
Site year*Trt	15	0.2642	10	0.1818	10	0.2106
Landpos*Trt	5	0.1257	5	0.2614	5	0.2436
Site year*Landpos*Trt	15	0.4271	10	0.3183	10	0.4123
Block(Site year*Landpos)	24	0.0001*	18	0.0001*	18	0.0001*
Residual C.V. (%)		13.72		13.63		15.08

a-c Mean values followed by the same letter (within columns) are not significantly different.
[z] LSD for individual treatments within a landscape position is not reported b/c there was no Landpos*Trt interaction.
[y] Not applicable b/c used LSMEANS which does not provide an LSD value.
[x] LSD is not reported b/c of significant Site year*Landpos interaction.
† Significant at $P < 0.10$ (used only for landscape position variables and interactions).
* Significant at $P < 0.05$.

Table F.9. Effect of landscape position, application date, and inhibitors on mean total crop N uptake (dry matter basis) at all intensive sites, Red River Valley sites only and 2001/02 sites only

Treatment: Landscape position	Treatment: Fertilization	df	All intensive sites	df	Red River Valley only	df	2001/02 only
					(kg ha^{-1})		
High	Early fall		116.3		108.7		109.9
	Mid fall		117.0		112.8		114.3
	Late fall		116.4		114.4		111.8
	Spring		118.0		115.3		115.4
	Control (no N)		81.5		75.8		79.7
	Early fall w/ inhibitors		112.5		108.0		109.3
	LSD ($\alpha = 0.05$)^z		-		-		-
Low	Early fall		83.1		87.4		78.2
	Mid fall		84.1		91.4		77.8
	Late fall		95.2		100.9		87.4
	Spring		96.2		103.4		90.9
	Control (no N)		52.2		56.7		47.3
	Early fall w/ inhibitors		86.4		93.0		78.2
	LSD ($\alpha = 0.05$)^z		-		-		-
Landscape position means							
High			110.3		105.8		106.7
Low			82.9		88.8		76.6
LSD ($\alpha = 0.10$)			-^{x}		-^{x}		-^{x}
	Fertilization means						
	Early fall		99.7ab		98.1c		94.0a
	Mid fall		100.5ab		102.1abc		96.0a
	Late fall		105.8ab		107.6ab		99.6a
	Spring		107.1a		109.3a		103.1a
	Control (no N)		66.8c		66.2d		63.4b
	Early fall w/ inhibitors		99.4b		100.5bc		93.8a
	LSD ($\alpha = 0.05$)		na^y		8.7		na^y
ANOVA		**df**	**$P > F$**	**df**	**$P > F$**	**df**	**$P > F$**
Site year		3	0.1675	2	0.1358	2	0.9064
Landpos		1	0.0012*	1	0.0859†	1	0.0065*
Site year*Landpos		3	0.0059*	2	0.0306*	2	0.01*
Trt		5	0.0001*	5	0.0001*	5	0.0001*
Site year*Trt		15	0.4548	10	0.4238	10	0.3891
Landpos*Trt		5	0.4561	5	0.8231	5	0.7687
Site year*Landpos*Trt		15	0.8432	10	0.6035	10	0.807
Block(Site year*Landpos)		24	0.0001*	18	0.0001*	18	0.0001*
Residual C.V. (%)			15.75		15.66		18.01

a-d Mean values followed by the same letter (within columns) are not significantly different.

^{z} LSD for individual treatments within a landscape position is not reported b/c there was no Landpos*Trt interaction.

^{y} Not applicable b/c used LSMEANS which does not provide an LSD value.

^{x} LSD is not reported b/c of significant Site year*Landpos interaction.

† Significant at $P < 0.10$ (used only for landscape position variables and interactions).

* Significant at $P < 0.05$.

Table F.10. Effect of landscape position, application date, and inhibitors on mean grain N uptake (dry matter basis) at all intensive sites, Red River Valley sites only and 2001/02 sites only

Treatment			Red River Valley	
Landscape position	Fertilization	All intensive sites	only	2001/02 only
			(kg ha^{-1})	
High	Early fall	83.7	75.4	81.2
	Mid fall	84.7	78.2	83.8
	Late fall	84.1	79.9	81.7
	Spring	84.8	80.1	84.2
	Control (no N)	61.0	54.2	60.8
	Early fall w/ inhibitors	81.8	75.3	81.3
	LSD (α = 0.05)[z]	-	-	-
Low	Early fall	59.8	61.2	55.9
	Mid fall	59.4	63.2	54.8
	Late fall	67.2	69.0	61.9
	Spring	68.2	71.2	64.3
	Control (no N)	36.9	38.7	32.5
	Early fall w/ inhibitors	61.2	64.3	55.6
	LSD (α = 0.05)[z]	-	-	-
Landscape position means				
High		80.0	73.8	78.8
Low		58.8	61.3	54.2
LSD (α = 0.10)		-[x]	-[x]	-[x]
	Fertilization means			
	Early fall	71.8a	68.3b	68.5a
	Mid fall	72.1a	70.7ab	69.3a
	Late fall	75.6a	74.5ab	71.8a
	Spring	76.5a	75.7a	74.2a
	Control (no N)	49.0b	46.4c	46.7b
	Early fall w/ inhibitors	71.5a	69.8ab	68.5a
	LSD (α = 0.05)	na[y]	6.4	na[y]

ANOVA	df	*P* > F	df	*P* > F	df	*P* > F
Site year	3	0.0894	2	0.1054	1	0.2595
Landpos	1	0.0007*	1	0.0791†	1	0.0030*
Site year*Landpos	3	0.0075*	2	0.0595†	2	0.0151*
Trt	5	0.0001*	5	0.0001*	5	0.0001*
Site year*Trt	15	0.6557	10	0.512	10	0.5092
Landpos*Trt	5	0.4834	5	0.8843	5	0.6917
Site year*Landpos*Trt	15	0.928	10	0.8406	10	0.8715
Block(Site year*Landpos)	24	0.0001*	18	0.0001*	18	0.0001*
Residual C.V. (%)		16.42		16.41		18.64

a-c Mean values followed by the same letter (within columns) are not significantly different.
[z] LSD for individual treatments within a landscape position is not reported b/c there was no Landpos*Trt interaction.
[y] Not applicable b/c used LSMEANS which does not provide an LSD value.
[x] LSD is not reported b/c of significant Site year*Landpos interaction.
† Significant at P < 0.10 (used only for landscape position variables and interactions).
* Significant at P < 0.05.

Table F.11. Effect of landscape position, application date, and inhibitors on mean straw N uptake (dry matter basis) at all intensive sites, Red River Valley sites only and 2001/02 sites only

Treatment							
Landscape position	Fertilization		All intensive sites		Red River Valley only		2001/02 only
					(kg ha^{-1})		
High	Early fall		32.6		33.3		28.7
	Mid fall		32.3		34.6		30.5
	Late fall		32.3		34.4		30.0
	Spring		33.3		35.2		31.2
	Control (no N)		20.4		21.6		19.0
	Early fall w/ inhibitors		30.7		32.7		28.0
	LSD ($\alpha = 0.05$)^z		-		-		-
Low	Early fall		23.4		26.2		22.3
	Mid fall		24.7		28.2		23.0
	Late fall		28.0		31.8		25.5
	Spring		28.0		32.1		26.6
	Control (no N)		15.3		18.0		14.7
	Early fall w/ inhibitors		25.2		28.8		22.6
	LSD ($\alpha = 0.05$)^z		-		-		-
Landscape position means							
High			30.3		33.2		27.9
Low			24.1		27.5		22.5
LSD ($\alpha = 0.10$)			-^{x}		-^{x}		-^{x}
	Fertilization means						
	Early fall		28.0		29.8b		25.5b
	Mid fall		28.5		31.4ab		26.8ab
	Late fall		30.1		33.1a		27.8ab
	Spring		30.6		33.7a		28.9a
	Control (no N)		17.8		19.8c		16.8c
	Early fall w/ inhibitors		27.9		30.8ab		25.3b
	LSD ($\alpha = 0.05$)		-^{w}		3.1		na^y
ANOVA		df	$P > F$	df	$P > F$	df	$P > F$
Site year		3	0.0011*	2	0.0818	2	0.0150*
Landpos		1	0.0121*	1	0.1422	1	0.0815*
Site year*Landpos		3	0.004*	2	0.0083*	2	0.0063*
Trt		5	0.0001*	5	0.0001*	5	0.0001*
Site year*Trt		15	0.0386*	10	0.0518	10	0.0540
Landpos*Trt		5	0.4077	5	0.6191	5	0.8742
Site year*Landpos*Trt		15	0.3539	10	0.1928	10	0.4013
Block(Site year*Landpos)		24	0.0001*	18	0.0001*	18	0.0001*
Residual C.V. (%)			18.75		18.25		20.84

a-c Mean values followed by the same letter (within columns) are not significantly different.
^{z} LSD for individual treatments within a landscape position is not reported b/c there was no Landpos*Trt interaction.
^{y} Not applicable b/c used LSMEANS which does not provide an LSD value.
^{x} LSD is not reported b/c of significant Site year*Landpos interaction.
^{w} LSD is not reported b/c of significant Site year*Treatment interaction.
† Significant at $P < 0.10$ (used only for landscape position variables and interactions).
* Significant at $P < 0.05$.

Table F.12. Effect of landscape position, application date, and inhibitors on mean grain yield increase and fertilizer NUE at all intensive sites, Red River valley sites and 2001/2002 sites only

		All intensive sites				RR Valley intensive sites only				2001/02 sites only			
Treatment		Grain yield increase		Fertilizer NUE of the crop		Grain yield increase		Fertilizer NUE of the crop		Grain yield increase		Fertilizer NUE of the crop	
Landscape Position	Fertilization	(kg ha^{-1})	% of spring	% of applied	% of spring	(kg ha^{-1})	% of spring	% of applied	% of spring	(kg ha^{-1})	% of spring	% of applied	% of spring
High	Early fall	611a	117	43.5a	96	609	119	41.1	83	571	111	37.7	85
	Mid fall	613a	118	44.4a	98	553	108	46.2	94	631	123	43.3	98
	Late fall	565a	108	43.7a	96	616	120	48.2	98	526	102	40.1	91
	Spring	521a^z	100	45.5a^z	100	513	100	49.4	100	514^z	100	44.3^z	100
	Control (no N)	-	-	-	-	-	-	-	-	-	-	-	-
	Early fall w/ inhibitors	531a	102	38.8a	85	530	104	40.3	82	534	104	37.0	84
	LSD (α = 0.05)	na^w		na^w		-^{y}		-^{y}		ns		-^{y}	
Low	Early fall	707b	76	38.6b	70	666	72	38.4	66	745ab	76	38.6	71
	Mid fall	678b	73	39.9b	73	733	79	43.4	74	679b	70	38.1	70
	Late fall	926a	99	53.8a	98	898	97	55.3	95	937a	96	50.2	92
	Spring	934a	100	55.1a	100	927	100	58.4	100	976a	100	54.5	100
	Control (no N)	-	-	-	-	-	-	-	-	-	-	-	-
	Early fall w/ inhibitors	728b	78	42.8ab	78	751	81	45.5	78	694b	71	38.7	71
	LSD (α = 0.05)	na^w		na^w		-^{y}		-^{y}		na^w		-^{y}	
Landscape Position Means													
High		568		43.1		564	-	45.0	-	555	-	40.5	-
Low		794		46.0		795	-	48.2	-	806	-	44.0	-
LSD (α = 0.10)		-^{x}		ns		ns		ns		-^{x}		ns	
	Fertilization Means												
	Early fall	659	96	41.1	83	638	89	39.8c	74	658	88	38.2	77
	Mid fall	645	95	42.2	85	643	89	44.8abc	83	655	88	40.7	82
	Late fall	745	104	48.7	97	757	105	51.7ab	96	732	98	45.2	91
	Spring	727	100	50.3	100	720	100	53.9a	100	745	100	49.4	100
	Control (no N)	-	-	-	-	-	-	-	-	-	-	-	-
	Early fall w/ inhibitors	629	90	40.8	81	641	89	42.9bc	80	614	82	37.8	77
	LSD (α = 0.05)	-^{x}		ns		ns		10.5		-^{x}		ns	

ANOVA	df	$P > F$	$P > F$	df	$P > F$	$P > F$	df	$P > F$	$P > F$
Site year	3	0.1224	0.2026	2	0.0649	0.1688	2	0.0822	0.2075
Landpos	1	0.1313	0.7321	1	0.1821	0.7555	1	0.1722	0.734
Site year*Landpos	3	0.408	0.3209	2	0.2491	0.2124	2	0.2931	0.2341
Trt	4	0.3182	0.1176	4	0.3492	0.0436*	4	0.5078	0.2219
Site year*Trt	12	0.9565	0.6494	8	0.8283	0.7042	8	0.9208	0.538
Landpos*Trt	4	0.0363*	0.2984	4	0.1832	0.6928	4	0.0869†	0.6205
Site year*Landpos*Trt	12	0.6539	0.945	8	0.9629	0.8479	8	0.734	0.9711
Block(Site year*Landpos)	24	0.0001*	0.0001*	18	0.0001*	0.0001*	18	0.0001*	0.0001*
Residual C.V. (%)		39.93	41.01		37.41	39.01		42.9	46.3

a-c Mean values followed by the same letter (within columns) are not significantly different.

^{z} Brandon 2001/2002 had 1 missing spring sample in the high landscape position: therefore values estimated by SAS.

^{y} LSD for individual treatments within a landscape position was not run b/c there was no Landpos*Trt interaction.

^{x} LSD is not reported b/c of significant Landpos*Trt interaction.

^{w} Not applicable (na) because LSMEANS was used, which does not provide an LSD value.

† Significant at $P < 0.10$ (used only for landscape position variables and interactions).

* Significant at $P < 0.05$.

Appendix G

Analysis of Variance and LSDs for the Effects of Landscape Position, Application Date and Inhibitors on the Recovery of Soil Mineral N during the Fall, at Seeding, and at Harvest at Kane (2000/01)

Table G.1. Effect of landscape position, application date, and inhibitors on total 2M KCl + 5ppm PMA extractable inorganic N at Kane 2000/2001: 0-30cm soil depth

Treatment		Total inorganic N (kg ha^{-1})^{z}							
		Sampling date							
Landscape position	Fertilization		12/10/00		26/10/00		28/05/01		05/09/01
High	Early fall		91.7		109.5		92.1		72.3
	Mid fall		-		111.0		89.1		56.1
	Late fall		-		-		91.9		67.3
	Spring		-		-		-		57.8
	Control (no N)		49.2		79.1		55.5		69.8
	Early fall w/ inhibitors		94.7		113.9		97.6		62.2
	LSD (α = 0.05)^{y}		-		-		-		-
Low	Early fall		83.7		111.1		76.4		62.3
	Mid fall		-		126.1		82.7		32.5
	Late fall		-		-		85.5		80.2
	Spring		-		-		-		72.7
	Control (no N)		49.3		79.4		41.9		68.6
	Early fall w/ inhibitors		84.0		120.4		95.1		59.8
	LSD (α = 0.05)^{y}		-		-		-		-
Landscape position means									
High			78.5		103.4		85.2		64.2
Low			72.3		109.2		76.3		67.7
LSD (α = 0.10)			ns		ns		ns		ns
	Fertilization means								
	Early fall		87.7a		110.3b		84.3b		67.3
	Mid fall		-		118.5a		85.9b		59.3
	Late fall		-		-		88.7b		73.7
	Spring		-		-		-		65.3
	Control (no N)		49.3b		79.3c		48.7c		69.2
	Early fall w/ inhibitors		89.3a		117.1ab		96.3a		61.0
	LSD (α = 0.05)		7.1		8.2		7.6		ns
ANOVA		df	$P > F$	df	$P > F$	df	$P > F$	df	$P > F$
Landpos		1	0.131	1	0.2744	1	0.1556	1	0.6869
Trt		2	0.0001*	3	0.0001*	4	0.0001*	5	0.0840
Landpos*Trt		2	0.2611	3	0.2576	4	0.3702	5	0.1504
Block(Landpos)		6	0.1803	6	0.0288*	6	0.0010*	6	0.0001*
Residual C.V. (%)			8.59		7.35		9.13		10.24

a-c Mean values followed by the same letter (within columns) are not significantly different.

^{z} Assuming a bulk density of 1.24 g cm^{-3} for 0-15cm depth and 1.33 g cm^{-3} for 15-120cm.

^{y} LSD for individual treatments within a landscape position is not reported b/c there was no Landpos*Trt interaction.

† Significant at $P < 0.10$ (used only for landscape position variables and interactions).

* Significant at $P < 0.05$.

Table G.2. Effect of landscape position, application date, and inhibitors on total 2M KCl + 5ppm PMA extractable NH_4^+-N at Kane 2000/2001: 0-30cm soil depth

Treatment			Total extractable NH_4^+-N (kg ha^{-1})[z]						
			Sampling date						
Landscape position	Fertilization		12/10/00		26/10/00		28/05/01		05/09/01
High	Early fall		65.3		75.3		40.3		62.4
	Mid fall		-		79.2		37.8		45.3
	Late fall		-		-		37.9		58.2
	Spring		-		-		-		48.2
	Control (no N)		35.7		60.2		40.7		61.6
	Early fall w/ inhibitors		65.1		81.9		38.2		54.5
	LSD (α = 0.05)[y]		-		-		-		-
Low	Early fall		64.5		78.5		38.2		51.9
	Mid fall		-		96.8		34.9		53.4
	Late fall		-		-		38.8		68.5
	Spring		-		-		-		61.7
	Control (no N)		41.0		62.5		34.0		55.8
	Early fall w/ inhibitors		63.3		89.4		37.8		51.3
	LSD (α = 0.05)[y]								
Landscape position means									
High			55.4		74.1b		39.0		55.0
Low			56.3		81.8a		36.7		57.1
LSD (α = 0.10)			ns		5.7		ns		ns
	Fertilization means								
	Early fall		64.9a		76.9b		39.2		57.2
	Mid fall		-		88.0a		36.3		49.3
	Late fall		-		-		38.3		63.4
	Spring		-		-		-		55.0
	Control (no N)		38.4b		61.4c		37.4		58.7
	Early fall w/ inhibitors		64.2a		85.6a		38.0		52.9
	LSD (α = 0.05)		7.6		7.6		ns		ns
ANOVA		df	*P* > F	df	*P* > F	df	*P* > F	df	*P* > F
Landpos		1	0.8488	1	0.0399*	1	0.6440	1	0.7477
Trt		2	0.0001*	3	0.0001*	4	0.4122	5	0.1407
Landpos*Trt		2	0.5601	3	0.1721	4	0.1539	5	0.1291
Block(Landpos)		6	0.0706†	6	0.3063	6	0.0001*	6	0.0035*
Residual C.V. (%)			12.49		9.31		8.03		18.20

a-c Mean values followed by the same letter (within columns) are not significantly different.

[z] Assuming a bulk density of 1.24 g cm^{-3} for 0-15cm depth and 1.33 g cm^{-3} for 15-120cm.

[y] LSD for individual treatments within a landscape position is not reported b/c there was no Landpos*Trt interaction.

† Significant at $P < 0.10$ (used only for landscape position variables and interactions).

* Significant at $P < 0.05$.

Table G.3. Effect of landscape position, application date, and inhibitors on total 2M KCl + 5ppm PMA extractable NO_3^--N at Kane 2000/2001: 0-30cm soil depth

Treatment		Total extractable NO_3^--N (kg ha^{-1})[z]							
		Sampling date							
Landscape position	Fertilization		12/10/00		26/10/00		28/05/01		05/09/01
High	Early fall		25.3		32.5		51.8		9.3
	Mid fall		-		29.7		51.3		10.3
	Late fall		-		-		53.9		8.6
	Spring		-		-		-		8.9
	Control (no N)		12.7		17.4		14.8		7.9
	Early fall w/ inhibitors		28.7		30.4		59.4		7.1
	LSD ($\alpha = 0.05$)[y]		-		-		-		-
Low	Early fall		17.1		29.7		38.2		9.2
	Mid fall		-		26.0		47.9		7.6
	Late fall		-		-		46.7		9.9
	Spring		-		-		-		8.8
	Control (no N)		6.7		14.3		7.9		11.4
	Early fall w/ inhibitors		18.7		28.4		57.2		7.1
	LSD ($\alpha = 0.05$)[y]		-		-		-		-
Landscape position means									
High			22.2		27.5		46.3		8.7
Low			14.1		24.6		39.6		9.0
LSD ($\alpha = 0.10$)			ns		ns		ns		ns
	Fertilization means								
	Early fall		21.2a		31.1a		45.0b		9.3
	Mid fall		-		27.9a		49.6b		9.0
	Late fall		-		-		50.3ab		9.3
	Spring		-		-		-		8.8
	Control (no N)		9.7b		15.8b		11.4c		9.6
	Early fall w/ inhibitors		23.7a		29.4a		58.3a		7.1
	LSD ($\alpha = 0.05$)		5.6		4.0		8.1		ns
ANOVA		df	$P > F$	df	$P > F$	df	$P > F$	df	$P > F$
Landpos		1	0.1472	1	0.4893	1	0.2835	1	0.9175
Trt		2	0.0003*	3	0.0001*	4	0.0001*	5	0.2167
Landpos*Trt		2	0.728	3	0.9452	4	0.6371	5	0.1112
Block(Landpos)		6	0.0060*	6	0.0002*	6	0.0015*	6	0.0001*
Residual C.V. (%)			28.06		14.60		18.32		23.10

a-c Mean values followed by the same letter (within columns) are not significantly different.

[z] Assuming a bulk density of 1.24 g cm^{-3} for 0-15cm depth and 1.33 g cm^{-3} for 15-120cm.

[y] LSD for individual treatments within a landscape position is not reported b/c there was no Landpos*Trt interaction.

† Significant at $P < 0.10$ (used only for landscape position variables and interactions).

* Significant at $P < 0.05$.

Table G.4. Effect of landscape position, application date, and inhibitors on total 2M KCl + 5ppm PMA extractable NO_2^--N at Kane 2000/2001: 0-30cm soil depth

Treatment		Total extractable NO_2^--N ($kg\ ha^{-1}$)^z			
		Sampling date			
Landscape position	Fertilization	12/10/00	26/10/00	28/05/01	05/09/01
High	Early fall	1.10	1.76	0.00	0.50
	Mid fall	-	2.08	0.00	0.50
	Late fall	-	-	0.00	0.50
	Spring	-	-	-	0.73
	Control (no N)	0.88	1.57	0.00	0.25
	Early fall w/ inhibitors	0.89	1.64	0.00	0.50
	LSD ($\alpha = 0.05$)^y	-	-	-	-
Low	Early fall	2.13	2.94	0.00	1.23
	Mid fall	-	3.23	0.00	1.47
	Late fall	-	-	0.00	1.72
	Spring	-	-	-	2.18
	Control (no N)	1.58	2.59	0.00	1.47
	Early fall w/ inhibitors	1.98	2.62	0.00	1.47
	LSD ($\alpha = 0.05$)^y	-	-	-	-
Landscape position means					
High		0.95b	1.76b	0.00	0.50b
Low		1.90a	2.84a	0.00	1.59a
LSD ($\alpha = 0.10$)		0.39	0.73	ns	0.72
	Fertilization means				
	Early fall	1.61a	2.35ab	0.00	0.87b
	Mid fall	-	2.66a	0.00	0.98b
	Late fall	-	-	0.00	1.11ab
	Spring	-	-	-	1.46a
	Control (no N)	1.23b	2.08b	0.00	0.86b
	Early fall w/ inhibitors	1.44b	2.13b	0.00	0.98b
	LSD ($\alpha = 0.05$)	0.22	0.32	ns	0.37

ANOVA	df	$P > F$	df	$P > F$	df	$P > F$	df	$P > F$
Landpos	1	0.0034*	1	0.0285*	1	.	1	0.0263*
Trt	2	0.0104*	3	0.0059*	4	.	5	0.024*
Landpos*Trt	2	0.1846	3	0.8968	4	.	5	0.4458
Block(Landpos)	6	0.0052*	6	0.0001*	6	.	6	0.0001*
Residual C.V. (%)		14.49		13.43		.		34.57

a,b Mean values followed by the same letter (within columns) are not significantly different.

^{z} Assuming a bulk density of 1.24 $g\ cm^{-3}$ for 0-15cm depth and 1.33 $g\ cm^{-3}$ for 15-120cm.

^{y} LSD for individual treatments within a landscape position is not reported b/c there was no Landpos*Trt interaction.

† Significant at $P < 0.10$ (used only for landscape position variables and interactions).

* Significant at $P < 0.05$.

Table G.5. Effect of landscape position, application date, and inhibitors on total 2M KCl + 5ppm PMA extractable Urea-N at Kane 2000/2001: 0-30cm soil depth

Treatment		Total extractable Urea-N (kg ha^{-1})[z] Sampling date			
Landscape position	Fertilization	12/10/00	26/10/00	28/05/01	05/09/2001[x]
High	Early fall	0.7	0.3	0.3	0.0
	Mid fall	-	0.5	0.3	0.0
	Late fall	-	-	0.1	0.0
	Spring	-	-	-	0.0
	Control (no N)	0.5	0.0	0.0	0.0
	Early fall w/ inhibitors	6.7	1.1	0.1	0.0
	LSD (α = 0.05)[y]	-	-	-	-
Low	Early fall	0.6	0.5	1.3	0.0
	Mid fall	-	0.9	1.1	0.0
	Late fall	-	-	4.8	0.0
	Spring	-	-	-	0.0
	Control (no N)	0.3	0.0	2.2	0.0
	Early fall w/ inhibitors	2.3	0.9	2.0	0.0
	LSD (α = 0.05)[y]	-	-	-	-
Landscape position means					
High		2.6	0.5	0.1b	0.0
Low		1.1	0.6	2.3a	0.0
LSD (α = 0.10)		ns	ns	1.2	.
	Fertilization means				
	Early fall	0.6b	0.4bc	0.8	0.0
	Mid fall	-	0.7ab	0.7	0.0
	Late fall	-	-	2.4	0.0
	Spring	-	-	-	0.0
	Control (no N)	0.4b	0.0c	1.1	0.0
	Early fall w/ inhibitors	4.5a	1.0a	1.0	0.0
	LSD (α = 0.05)	3.2	0.4	ns	.

ANOVA	df	*P* > F	df	*P* > F	df	*P* > F	df	*P* > F
Landpos	1	0.3164	1	0.7592	1	0.0116*	1	.
Trt	2	0.0265*	3	0.0005*	4	0.4627	5	.
Landpos*Trt	2	0.2839	3	0.6138	4	0.3459	5	.
Block(Landpos)	6	0.2851	6	0.0350*	6	0.5308	6	.
Residual C.V. (%)		158.6		73.94		166.76		.

a-c Mean values followed by the same letter (within columns) are not significantly different.

[z] Assuming a bulk density of 1.24 g cm^{-3} for 0-15cm depth and 1.33 g cm^{-3} for 15-120cm.

[y] LSD for individual treatments within a landscape position is not reported b/c there was no Landpos*Trt interaction.

[x] Urea was not analyzed and assumed to be < 0.5 ppm

† Significant at P < 0.10 (used only for landscape position variables and interactions).

* Significant at P < 0.05.

Table G.6. Effect of landscape position, application date, and inhibitors on total 2M KCl + 5ppm PMA extractable N at Kane 2000/2001: 0-30cm soil depth

Treatment		Total extractable N (kg ha^{-1})^{z}			
		Sampling date			
Landscape position	Fertilization	12/10/00	26/10/00	28/05/01	05/09/01
High	Early fall	92.3	109.8	92.4	72.3
	Mid fall	-	111.6	89.4	56.1
	Late fall	-	-	91.9	67.3
	Spring	-	-	-	57.8
	Control (no N)	49.7	79.1	55.5	69.8
	Early fall w/ inhibitors	101.4	115.0	97.7	62.2
	LSD (α = 0.05)^{y}	-	-	-	-
Low	Early fall	84.2	111.6	77.7	62.3
	Mid fall	-	126.9	83.9	62.5
	Late fall	-	-	90.3	80.2
	Spring	-	-	-	72.7
	Control (no N)	49.6	79.4	44.1	68.6
	Early fall w/ inhibitors	86.3	121.3	97.1	59.8
	LSD (α = 0.05)^{y}	-	-	-	-
Landscape position means					
High		81.0	103.9	85.4	64.7
Low		73.4	109.8	79.0	64.2
LSD (α = 0.10)		ns	ns	ns	ns
	Fertilization means				
	Early fall	88.3a	110.7b	85.1b	67.3
	Mid fall	-	119.2a	86.7b	59.3
	Late fall	-	-	91.1ab	73.7
	Spring	-	-	-	65.3
	Control (no N)	49.7b	79.3c	49.8c	69.2
	Early fall w/ inhibitors	93.8a	118.1ab	97.4a	61.0
	LSD (α = 0.05)	8.1	8.4	7.6	ns

ANOVA	df	$P > F$	df	$P > F$	df	$P > F$	df	$P > F$
Landpos	1	0.1007	1	0.2622	1	0.2473	1	0.6869
Trt	2	0.0001*	3	0.0001*	4	0.0001*	5	0.0840
Landpos*Trt	2	0.1699	3	0.2586	4	0.2667	5	0.1504
Block(Landpos)	6	0.1906	6	0.0368*	6	0.0016*	6	0.0001*
Residual C.V. (%)		9.58		7.44		8.98		15.52

a-c Mean values followed by the same letter (within columns) are not significantly different.

^{z} Assuming a bulk density of 1.24 g cm^{-3} for 0-15cm depth and 1.33 g cm^{-3} for 15-120cm.

^{y} LSD for individual treatments within a landscape position is not reported b/c there was no Landpos*Trt interaction.

† Significant at $P < 0.10$ (used only for landscape position variables and interactions).

* Significant at $P < 0.05$.

Table G.7. Effect of landscape position, application date, and inhibitors on total 2M KCl + 5ppm PMA extractable inorganic N at Kane 2000/2001: 0-60cm soil depth

Treatment			Total inorganic N (kg ha^{-1})^{z}		
			Sampling date		
Landscape position	Fertilization		28/05/01		05/09/01
High	Early fall		191.1a		134.8
	Mid fall		186.1a		114.6
	Late fall		187.3a		120.3
	Spring		-		110.8
	Control (no N)		127.0b		123.8
	Early fall w/ inhibitors		187.6a		122.2
	LSD (α = 0.05)		na^{x}		-^{y}
Low	Early fall		131.9b		116.3
	Mid fall		165.2a		119.5
	Late fall		162.5a		148.6
	Spring		-		134.2
	Control (no N)		106.4c		123.1
	Early fall w/ inhibitors		176.1a		113.3
	LSD (α = 0.05)		na^{x}		-^{y}
Landscape position means					
High			175.8		121.1
Low			148.4		125.9
LSD (α = 0.10)			-^{w}		ns
	Fertilization means				
	Early fall		161.5		125.6
	Mid fall		175.7		117.1
	Late fall		174.9		134.5
	Spring		-		122.5
	Control (no N)		116.7		123.5
	Early fall w/ inhibitors		181.9		117.8
	LSD (α = 0.05)		-^{w}		ns
ANOVA		df	$P > F$	df	$P > F$
Landpos		1	0.1459	1	0.7563
Trt		4	0.0001*	5	0.4829
Landpos*Trt		4	0.0581†	5	0.125
Block(Landpos)		6	0.0001*	6	0.0001*
Residual C.V. (%)			9.88		15.15

a-c Mean values followed by the same letter (within columns) are not significantly different.

^{z} Assuming a bulk density of 1.24 g cm^{-3} for 0-15cm depth and 1.33 g cm^{-3} for 15-120cm.

^{y} LSD for individual treatments within a landscape position is not reported b/c there was no Landpos*Trt interaction.

^{x} Not applicable b/c used LSMEANS which does not provide an LSD value.

^{w} LSD is not reported b/c of significant Landpos*Trt interaction.

† Significant at $P < 0.10$ (used only for landscape position variables and interactions).

* Significant at $P < 0.05$.

Table G.8. Effect of landscape position, application date, and inhibitors on total 2M KCl + 5ppm PMA extractable NH_4^+-N at Kane 2000/2001: 0-60cm soil depth

Treatment			Total extractable NH_4^+-N (kg ha^{-1})^z		
			Sampling date		
Landscape position	Fertilization		28/05/01		05/09/01
High	Early fall		89.3		113.9
	Mid fall		88.8		80.7
	Late fall		84.4		98.2
	Spring		-		90.7
	Control (no N)		85.2		109.6
	Early fall w/ inhibitors		83.2		104.1
	LSD ($\alpha = 0.05$)		-^{y}		ns
Low	Early fall		72.2		101.4b
	Mid fall		82.9		100.9b
	Late fall		87.8		129a
	Spring		-		115.7ab
	Control (no N)		80.5		105.3ab
	Early fall w/ inhibitors		84.8		97.3b
	LSD ($\alpha = 0.05$)		-^{y}		na^x
Landscape position means					
High			86.2		99.6
Low			81.6		108.3
LSD ($\alpha = 0.10$)			ns		-^{w}
	Fertilization means				
	Early fall		80.8		107.7
	Mid fall		85.9		90.8
	Late fall		86.1		113.6
	Spring				103.2
	Control (no N)		82.9		107.7
	Early fall w/ inhibitors		84.0		100.7
	LSD ($\alpha = 0.05$)		ns		-^{w}
ANOVA		df	*P* > F	df	*P* > F
Landpos		1	0.7364	1	0.5058
Trt		4	0.8436	5	0.1725
Landpos*Trt		4	0.3579	5	0.0596†
Block(Landpos)		6	0.0001*	6	0.0002*
Residual C.V. (%)			12.67		16.39

a,b Mean values followed by the same letter (within columns) are not significantly different.

^{z} Assuming a bulk density of 1.24 g cm^{-3} for 0-15cm depth and 1.33 g cm^{-3} for 15-120cm.

^{y} LSD for individual treatments within a landscape position is not reported b/c there was no Landpos*Trt interaction.

^{x} Not applicable b/c used LSMEANS which does not provide an LSD value.

^{w} LSD is not reported b/c of significant Landpos*Trt interaction.

† Significant at $P < 0.10$ (used only for landscape position variables and interactions).

* Significant at $P < 0.05$.

Table G.9. Effect of landscape position, application date, and inhibitors on total 2M KCl + 5ppm PMA extractable NO_3^--N at Kane 2000/2001: 0-60cm soil depth

Treatment			Total extractable NO_3^--N (kg ha^{-1})^z		
			Sampling date		
Landscape position	Fertilization		28/05/01		05/09/01
High	Early fall		101.8		19.31
	Mid fall		97.3		32.31
	Late fall		102.9		20.6
	Spring		-		18.4
	Control (no N)		41.8		13.4
	Early fall w/ inhibitors		104.4		16.6
	LSD ($\alpha = 0.05$)^y		-		-
Low	Early fall		59.2		11.7
	Mid fall		81.9		15.1
	Late fall		74.7		15.9
	Spring		-		14.3
	Control (no N)		25.4		14.4
	Early fall w/ inhibitors		91.2		12.6
	LSD ($\alpha = 0.05$)^y		-		-
Landscape position means					
High			89.6		20.1
Low			66.5		14.0
LSD ($\alpha = 0.10$)			ns		ns
	Fertilization means				
	Early fall		80.5b		15.5b
	Mid fall		89.6ab		23.7a
	Late fall		88.8ab		18.3ab
	Spring		-		16.3b
	Control (no N)		33.6c		15.5b
	Early fall w/ inhibitors		97.8a		14.6b
	LSD ($\alpha = 0.05$)		13.8		6.2
ANOVA		df	$P > F$	df	$P > F$
Landpos		1	0.1799	1	0.1967
Trt		4	0.0001*	5	0.0360*
Landpos*Trt		4	0.1832	5	0.1090
Block(Landpos)		6	0.0001*	6	0.0001*
Residual C.V. (%)			17.18		35.87

a-c Mean values followed by the same letter (within columns) are not significantly different.

^{z} Assuming a bulk density of 1.24 g cm^{-3} for 0-15cm depth and 1.33 g cm^{-3} for 15-120cm.

^{y} LSD for individual treatments within a landscape position is not reported b/c there was no Landpos*Trt interaction.

† Significant at $P < 0.10$ (used only for landscape position variables and interactions).

* Significant at $P < 0.05$.

Table G.10. Effect of landscape position, application date, and inhibitors on total 2M KCl + 5ppm PMA extractable inorganic N at Kane 2000/2001: 0-120cm soil depth

Treatment			Total inorganic N (kg ha^{-1})[z] Sampling date		
Landscape position	Fertilization		28/05/01		05/09/01
High	Early fall		300.1		260.3
	Mid fall		314.6		230.6
	Late fall		321.4		234.3
	Spring		-		233.3
	Control (no N)		239.5		230.3
	Early fall w/ inhibitors		311.6		242.2
	LSD ($\alpha = 0.05$)[y]		-		-
Low	Early fall		229.4		228.3
	Mid fall		274.2		226.0
	Late fall		277.5		274.2
	Spring		-		260.2
	Control (no N)		212.4		230.1
	Early fall w/ inhibitors		288.6		221.3
	LSD ($\alpha = 0.05$)[y]		-		-
Landscape position means					
High			297.4		238.5
Low			256.4		240.0
LSD ($\alpha = 0.10$)			ns		ns
	Fertilization means				
	Early fall		264.8b		244.3
	Mid fall		294.4a		228.3
	Late fall		299.4a		254.2
	Spring		-		246.8
	Control (no N)		226.0c		230.2
	Early fall w/ inhibitors		300.1a		231.8
	LSD ($\alpha = 0.05$)		26.4		ns
ANOVA		df	$P > F$	df	$P > F$
Landpos		1	0.3202	1	0.9631
Trt		4	0.0001*	5	0.5505
Landpos*Trt		4	0.3894	5	0.2688
Block(Landpos)		6	0.0001*	6	0.0001*
Residual C.V. (%)			9.23		13.94

a-c Mean values followed by the same letter (within columns) are not significantly different.

[z] Assuming a bulk density of 1.24 g cm^{-3} for 0-15cm depth and 1.33 g cm^{-3} for 15-120cm.

[y] LSD for individual treatments within a landscape position is not reported b/c there was no Landpos*Trt interaction.

† Significant at $P < 0.10$ (used only for landscape position variables and interactions).

* Significant at $P < 0.05$.

Table G.11. Effect of landscape position, application date, and inhibitors on total 2M KCl + 5ppm PMA extractable NH_4^+-N at Kane 2000/2001: 0-120cm soil depth

Treatment			Total extractable NH_4^+-N (kg ha^{-1})^z		
			Sampling date		
Landscape position	Fertilization		28/05/01		05/09/01
High	Early fall		163.8		217.9
	Mid fall		172.8		164.3
	Late fall		161.9		183.7
	Spring		-		178.7
	Control (no N)		167.7		199.6
	Early fall w/ inhibitors		154.2		197.0
	LSD (α = 0.05)		-^{y}		ns
Low	Early fall		152.2		207.4ab
	Mid fall		169.4		197.4b
	Late fall		181.3		243.5a
	Spring		-		230.3ab
	Control (no N)		169.0		203.3ab
	Early fall w/ inhibitors		174.8		195.8b
	LSD (α = 0.05)		-^{y}		na^x
Landscape position means					
High			164.1		190.2
Low			169.3		212.9
LSD (α = 0.10)			ns		-^{w}
	Fertilization means				
	Early fall		158.0		212.7
	Mid fall		171.1		180.8
	Late fall		171.6		213.6
	Spring		-		204.5
	Control (no N)		168.4		201.4
	Early fall w/ inhibitors		164.5		196.4
	LSD (α = 0.05)		ns		-^{w}
ANOVA		df	*P* > F	df	*P* > F
Landpos		1	0.8716	1	0.4153
Trt		4	0.5716	5	0.2274
Landpos*Trt		4	0.3403	5	0.0813†
Block(Landpos)		6	0.0001*	6	0.0001*
Residual C.V. (%)			11.06		13.99

a,b Mean values followed by the same letter (within columns) are not significantly different.

^{z} Assuming a bulk density of 1.24 g cm^{-3} for 0-15cm depth and 1.33 g cm^{-3} for 15-120cm.

^{y} LSD for individual treatments within a landscape position is not reported b/c there was no Landpos*Trt interaction.

^{x} Not applicable b/c used LSMEANS which does not provide an LSD value.

^{w} LSD is not reported b/c of significant Landpos*Trt interaction.

† Significant at $P < 0.10$ (used only for landscape position variables and interactions).

* Significant at $P < 0.05$.

Table G.12. Effect of landscape position, application date, and inhibitors on total 2M KCl + 5ppm PMA extractable NO_3^--N at Kane 2000/2001: 0-120cm soil depth

Treatment			Total extractable NO_3^--N (kg ha^{-1})^z		
			Sampling date		
Landscape position	Fertilization		28/05/01		05/09/01
High	Early fall		136.3		39.8
	Mid fall		141.8		63.8
	Late fall		159.4		48.1
	Spring		-		51.9
	Control (no N)		71.8		29.4
	Early fall w/ inhibitors		157.4		42.1
	LSD ($\alpha = 0.05$)^y		-		-
Low	Early fall		76.2		13.7
	Mid fall		103.4		21.1
	Late fall		96.2		23.4
	Spring		-		21.8
	Control (no N)		41.4		20.4
	Early fall w/ inhibitors		113.7		18.1
	LSD ($\alpha = 0.05$)^y		-		-
Landscape position means					
High			133.4		45.9a
Low			86.2		19.8b
LSD ($\alpha = 0.10$)			ns		21.8
	Fertilization means				
	Early fall		106.3b		26.8
	Mid fall		122.6ab		42.5
	Late fall		127.8a		35.8
	Spring		-		36.8
	Control (no N)		56.6c		24.9
	Early fall w/ inhibitors		135.6a		30.1
	LSD ($\alpha = 0.05$)		21.3		ns
ANOVA		df	$P > F$	df	$P > F$
Landpos		1	0.1322	1	0.0592†
Trt		4	0.0001*	5	0.1184
Landpos*Trt		4	0.4592	5	0.3045
Block(Landpos)		6	0.0001*	6	0.0001*
Residual C.V. (%)			18.79		41.61

a-c Mean values followed by the same letter (within columns) are not significantly different.

^{z} Assuming a bulk density of 1.24 g cm^{-3} for 0-15cm depth and 1.33 g cm^{-3} for 15-120cm.

^{y} LSD for individual treatments within a landscape position is not reported b/c there was no Landpos*Trt interaction.

† Significant at $P < 0.10$ (used only for landscape position variables and interactions).

* Significant at $P < 0.05$.

Appendix H

Analysis of Variance and LSDs for the Effects of Landscape Position, Application Date and Inhibitors on the Recovery of Soil Mineral N during the Fall, at Seeding, and at Harvest at Kane (2001/02)

Table H.1. Effect of landscape position, application date, and inhibitors on total 2M KCl + 5ppm PMA extractable inorganic N at Kane 2001/2002: 0-30cm soil depth

Treatment		Total inorganic N (kg ha^{-1})[z]				
		Sampling Date				
Landscape position	Fertilization	09/10/01	23/10/01	01/11/01	21/05/02	26/08/02
High	Early fall	120.9	124.7	109.4	117.4	64.1abc
	Mid fall	-	99.2	95.4	140.7	64.4abc
	Late fall	-	-	107.4	128.5	56.4b
	Spring	-	-	-	-	70.1ab
	Control (no N)	68.3	65.1	55.3	61.5	49.4c
	Early fall w/ inhibitors	110.8	101.8	110.5	113.8	74.9a
	LSD (α = 0.05)	-[y]	-[y]	-[y]	-[y]	na[x]
Low	Early fall	96.5	96.7	102.2	115.4	47.4
	Mid fall	-	97.1	121.0	152.8	38.7
	Late fall	-	-	95.7	119.9	45.3
	Spring	-	-	-	-	38.3
	Control (no N)	50.8	58.4	43.9	50.4	45.7
	Early fall w/ inhibitors	92.8	93.0	108.3	133.1	43.3
	LSD (α = 0.05)	-[y]	-[y]	-[y]	-[y]	ns
Landscape position means						
High		100.0a	97.7	95.6	112.4	63.2
Low		80b	86.3	94.2	114.3	43.1
LSD (α = 0.10)		10.3	ns	ns	ns	-[w]
	Fertilization means					
	Early fall	108.7a	110.7a	105.8a	116.4b	55.8
	Mid fall	-	98.1a	108.2a	146.7a	51.5
	Late fall	-	-	101.5a	124.2ab	50.8
	Spring	-	-	-	-	54.2
	Control (no N)	59.5b	61.7b	49.6b	56.0c	47.5
	Early fall w/ inhibitors	101.8a	97.4a	109.4a	123.5ab	59.1
	LSD (α = 0.05)	11.3	15.8	na[x]	27.4	-[w]

ANOVA	df	$P > F$	df	$P > F$	df	$P > F$	df	$P > F$	df	$P > F$
Landpos	1	0.0094*	1	0.2201	1	0.8287	1	0.8519	1	0.1700
Trt	2	0.0001*	3	0.0001*	4	0.0001*	4	0.0001*	5	0.3641
Landpos*Trt	2	0.7632	3	0.3554	4	0.1633	4	0.7368	5	0.0745†
Block(Landpos)	6	0.2385	6	0.0657†	6	0.2395	6	0.2557	6	0.0001*
Residual C.V. (%)		11.54		16.31		16.85		23.46		20.34

a-c Mean values followed by the same letter (within columns) are not significantly different.

[z] Assuming a bulk density of 1.24 g cm^{-3} for 0-15cm depth and 1.33 g cm^{-3} for 15-120cm.

[y] LSD for individual treatments within a landscape position is not reported b/c there was no Landpos*Trt interaction.

[x] Not applicable b/c used LSMEANS which does not provide an LSD value.

[w] LSD is not reported b/c of significant Landpos*Trt interaction.

† Significant at $P < 0.10$ (used only for landscape position variables and interactions).

* Significant at $P < 0.05$.

Table H.2. Effect of landscape position, application date, and inhibitors on total 2M KCl + 5ppm PMA extractable NH_4^+-N at Kane 2001/2002: 0-30cm soil depth

Treatment		Total extractable NH_4^+-N (kg ha^{-1})[z]				
		Sampling Date				
Landscape position	Fertilization	09/10/01	23/10/01	01/11/01	21/05/02	26/08/02
High	Early fall	70.3	62.8	45.4	25.5	34.5
	Mid fall	-	59.5	55.3	34.3	31.7
	Late fall	-	-	68.0	30.9	32.5
	Spring	-	-	-	-	27.2
	Control (no N)	31.7	28.0	18.1	19.1	29.5
	Early fall w/ inhibitors	64.3	54.3	49.3	33.3	30.2
	LSD ($\alpha = 0.05$)[y]	-	-	-	-	-
Low	Early fall	69.0	60.3	43.5	25.5	36.3
	Mid fall	-	67.0	70.8	37.9	31.3
	Late fall	-	-	67.0	33.5	35.5
	Spring	-	-	-	-	29.8
	Control (no N)	32.4	36.9	22.2	22.5	35.9
	Early fall w/ inhibitors	63.1	53.0	60.6	34.5	34.1
	LSD ($\alpha = 0.05$)[y]	-	-	-	-	-
Landscape position means						
High		55.5	51.2	47.2	28.6	30.9
Low		54.8	54.3	52.8	30.8	33.8
LSD ($\alpha = 0.10$)		ns	ns	ns	ns	ns
	Fertilization means					
	Early fall	69.6a	61.5a	44.4c	25.5bc	35.4
	Mid fall	-	63.3a	63.0ab	36.1a	31.5
	Late fall	-	-	67.5a	32.2ab	34.0
	Spring	-	-	-	-	28.5
	Control (no N)	32.1b	32.4b	20.1d	20.8c	32.7
	Early fall w/ inhibitors	63.7a	53.6a	54.9bc	33.9ab	32.1
	LSD ($\alpha = 0.05$)	6.7	11.8	na[x]	10.0	ns

ANOVA	df	$P > F$	df	$P > F$	df	$P > F$	df	$P > F$	df	$P > F$
Landpos	1	0.8528	1	0.3367	1	0.1466	1	0.6249	1	0.7090
Trt	2	0.0001*	3	0.0001*	4	0.0001*	4	0.0234*	5	0.3184
Landpos*Trt	2	0.9365	3	0.6594	4	0.3854	4	0.9950	5	0.9173
Block(Landpos)	6	0.2004	6	0.7618	6	0.4349	6	0.1299	6	0.0001*
Residual C.V. (%)		11.1		21.34		20.24		32.68		18.47

a-d Mean values followed by the same letter (within columns) are not significantly different.

[z] Assuming a bulk density of 1.24 g cm^{-3} for 0-15cm depth and 1.33 g cm^{-3} for 15-120cm.

[y] LSD for individual treatments within a landscape position is not reported b/c there was no Landpos*Trt interaction.

[x] Not applicable: 1 missing value therefore used LSMEANS which does not provide an LSD value.

† Significant at $P < 0.10$ (used only for landscape position variables and interactions).

* Significant at $P < 0.05$.

Table H.3. Effect of landscape position, application date, and inhibitors on total 2M KCl + 5ppm PMA extractable NO_3^--N at Kane 2001/2002: 0-30cm soil depth

Treatment		Total extractable NO_3^--N (kg ha^{-1})[z]				
		Sampling Date				
Landscape position	Fertilization	09/10/01	23/10/01	01/11/01	21/05/02	26/08/02
High	Early fall	49.2	58.7	60.6	91.5	28.7cd
	Mid fall	-	37.9	37.8	104.8	31.7bc
	Late fall	-	-	37.6	96.8	23.5cd
	Spring	-	-	-	-	42.4ab
	Control (no N)	36.5	37.0	37.2	42.4	19.2d
	Early fall w/ inhibitors	46.3	46.8	60.5	80.3	44.0a
	LSD (α = 0.05)	-[y]	-[y]	-[y]	-[y]	na[x]
Low	Early fall	25.7	34.5	54.9	89.9	10.9a
	Mid fall	-	28.4	45.7	114.7	7.1a
	Late fall	-	-	26.1	85.6	9.1a
	Spring	-	-	-	-	8.3a
	Control (no N)	18.4	21.6	20.7	27.9	9.7a
	Early fall w/ inhibitors	29.4	39.9	45.4	98.6	8.3a
	LSD (α = 0.05)	-[y]	-[y]	-[y]	-[y]	na[x]
Landscape position means						
High		44.0a	45.1	46.7	83.2	31.6
Low		24.5b	31.1	39.6	83.4	8.9
LSD (α = 0.10)		13.7	ns	ns	ns	-[w]
	Fertilization means					
	Early fall	37.4	46.6a	57.7a	90.7a	19.8
	Mid fall	-	33.1bc	41.8b	109.8a	19.4
	Late fall	-	-	31.8bc	91.2a	16.3
	Spring	-	-	-	-	25.4
	Control (no N)	27.5	29.3c	28.9c	35.2b	14.5
	Early fall w/ inhibitors	37.9	43.3ab	52.9a	89.5a	26.2
	LSD (α = 0.05)	ns	11.6	na[x]	21.1	-[w]

ANOVA	df	$P > F$	df	$P > F$	df	$P > F$	df	$P > F$	df	$P > F$
Landpos	1	0.0133*	1	0.1030	1	0.1399	1	0.9800	1	0.0193*
Trt	2	0.0893	3	0.0166*	4	0.0001*	4	0.0001*	5	0.0531
Landpos*Trt	2	0.7704	3	0.4260	4	0.1870	4	0.4687	5	0.0198*
Block(Landpos)	6	0.1384	6	0.0178*	6	0.1138	6	0.3745	6	0.0001*
Residual C.V. (%)		28.13		28.89		24.63		24.56		41.80

a-c Mean values followed by the same letter (within columns) are not significantly different.

[z] Assuming a bulk density of 1.24 g cm^{-3} for 0-15cm depth and 1.33 g cm^{-3} for 15-120cm.

[y] LSD for individual treatments within a landscape position is not reported b/c there was no Landpos*Trt interaction.

[x] Not applicable b/c used LSMEANS which does not provide an LSD value.

[w] LSD is not reported b/c of significant Landpos*Trt interaction.

† Significant at $P < 0.10$ (used only for landscape position variables and interactions).

* Significant at $P < 0.05$.

Table H.4. Effect of landscape position, application date, and inhibitors on total 2M KCl + 5ppm PMA extractable NO_2^--N at Kane 2001/2002: 0-30cm soil depth

Treatment		Total extractable NO_2^--N (kg ha^{-1})[z] Sampling Date				
Landscape position	Fertilization	09/10/01	23/10/01	01/11/01	21/05/02	26/08/02
High	Early fall	1.40	3.14	3.49a	0.35	0.98
	Mid fall	-	1.80	2.39b	1.58	0.98
	Late fall	-	-	1.80b	0.82	0.48
	Spring	-	-	-	-	0.48
	Control (no N)	0.00	0.00	0.00c	0.00	0.73
	Early fall w/ inhibitors	0.18	0.76	0.81c	0.17	0.73
	LSD (α = 0.05)	-[y]	-[y]	na[x]	-[y]	-[y]
Low	Early fall	1.86	1.98	3.76a	0.00	0.25
	Mid fall	-	1.75	4.47a	0.18	0.25
	Late fall	-	-	2.60b	0.76	0.75
	Spring	-	-	-	-	0.25
	Control (no N)	0.00	0.00	0.99c	0.00	0.00
	Early fall w/ inhibitors	0.23	0.17	2.34b	0.00	0.95
	LSD (α = 0.05)	-[y]	-[y]	na[x]	-[y]	-[y]
Landscape position means						
High		0.52	1.42	1.70	0.58a	0.73
Low		0.70	0.97	2.83	0.19b	0.41
LSD (α = 0.10)		ns	ns	-[w]	0.34	ns
	Fertilization means					
	Early fall	1.63a	2.56a	3.63	0.18bc	0.62
	Mid fall	-	1.77a	3.43	0.88a	0.62
	Late fall	-	-	2.20	0.79ab	0.62
	Spring	-	-	-	-	0.37
	Control (no N)	0.00b	0.00b	0.50	0.00c	0.37
	Early fall w/ inhibitors	0.20b	0.46b	1.58	0.09b	0.84
	LSD (α = 0.05)	0.38	0.99	-[w]	0.66	ns

ANOVA	df	$P > F$	df	$P > F$	df	$P > F$	df	$P > F$	df	$P > F$
Landpos	1	0.4024	1	0.3036	1	0.0206*	1	0.0621†	1	0.4663
Trt	2	0.0001*	3	0.0001*	4	0.0001*	4	0.0255*	5	0.7275
Landpos*Trt	2	0.3853	3	0.5822	4	0.0775†	4	0.1945	5	0.4367
Block(Landpos)	6	0.181	6	0.2471	6	0.0191*	6	0.6238	6	0.0022*
Residual C.V. (%)		57.59		78.19		27.13		165.70		119.12

a-c Mean values followed by the same letter (within columns) are not significantly different.

[z] Assuming a bulk density of 1.24 g cm^{-3} for 0-15cm depth and 1.33 g cm^{-3} for 15-120cm.

[y] LSD for individual treatments within a landscape position is not reported b/c there was no Landpos*Trt interaction.

[x] Not applicable b/c used LSMEANS which does not provide an LSD value.

[w] LSD is not reported b/c of significant Landpos*Trt interaction.

† Significant at $P < 0.10$ (used only for landscape position variables and interactions).

* Significant at $P < 0.05$.

Table H.5. Effect of landscape position, application date, and inhibitors on total 2M KCl + 5ppm PMA extractable Urea-N at Kane 2001/2002: 0-30cm soil depth

Treatment		Total extractable Urea-N (kg ha^{-1})^{z}				
		Sampling Date				
Landscape position	Fertilization	09/10/01	23/10/01	01/11/01	21/05/02	26/08/02
High	Early fall	0.9	3.2ab	6.0	0.9	0.5
	Mid fall	-	3.3ab	10.4	0.6	0.9
	Late fall	-	-	2.9	1.1	0.7
	Spring	-	-	-	-	0.3
	Control (no N)	0.9	3.1b	1.4	0.8	0.2
	Early fall w/ inhibitors	1.1	14.9a	2.6	0.2	0.7
	LSD (α = 0.05)	ns	na^{x}	-^{y}	-^{y}	-^{y}
Low	Early fall	1.2b	13.1	2.0	0.3	0.5
	Mid fall	-	4.2	10.5	2.3	2.7
	Late fall	-	-	3.4	0.2	0.2
	Spring	-	-	-	-	0
	Control (no N)	0.7b	8.7	3.8	0.0	0.2
	Early fall w/ inhibitors	6.4a	3.6	2.4	0.5	1.4
	LSD (α = 0.05)	na^{x}	ns	-^{y}	-^{y}	-^{y}
Landscape position means						
High		1.0	6.1	4.7	0.7	0.6
Low		2.8	7.4	4.4	0.7	0.8
LSD (α = 0.10)		-^{w}	-^{w}	ns	ns	1.1
	Fertilization means					
	Early fall	1.1	8.1	4.0	0.6	0.5
	Mid fall	-	3.8	10.5	1.5	1.8
	Late fall	-	-	3.2	0.6	0.5
	Spring	-	-	-	-	0.1
	Control (no N)	0.8	5.9	2.6	0.4	0.2
	Early fall w/ inhibitors	3.8	9.3	2.5	0.4	1.1
	LSD (α = 0.05)	-^{w}	-^{w}	ns	ns	ns

ANOVA	df	$P > F$	df	$P > F$	df	$P > F$	df	$P > F$	df	$P > F$
Landpos	1	0.0448*	1	0.7037	1	0.9057	1	0.9533	1	0.5331
Trt	2	0.0004*	3	0.5353	4	0.1749	4	0.4625	5	0.4824
Landpos*Trt	2	0.0006*	3	0.0783†	4	0.9384	4	0.3068	5	0.8587
Block(Landpos)	6	0.0963†	6	0.3093	6	0.5582	6	0.3108	6	0.6931
Residual C.V. (%)		60.66		116.9		160.71		195.68		271.71

a,b Mean values followed by the same letter (within columns) are not significantly different.

^{z} Assuming a bulk density of 1.24 g cm^{-3} for 0-15cm depth and 1.33 g cm^{-3} for 15-120cm.

^{y} LSD for individual treatments within a landscape position is not reported b/c there was no Landpos*Trt interaction.

^{x} Not applicable b/c used LSMEANS which does not provide an LSD value.

^{w} LSD is not reported b/c of significant Landpos*Trt interaction.

† Significant at $P < 0.10$ (used only for landscape position variables and interactions).

* Significant at $P < 0.05$.

Table H.6. Effect of landscape position, application date, and inhibitors on total 2M KCl + 5ppm PMA extractable N at Kane 2001/2002: 0-30cm soil depth

Treatment		Total extractable N (kg ha^{-1})^{z}				
		Sampling Date				
Landscape position	Fertilization	09/10/01	23/10/01	01/11/01	21/05/02	26/08/02
High	Early fall	121.8	127.8	115.4	118.3	64.6
	Mid fall	-	102.6	105.9	141.3	65.4
	Late fall	-	-	110.4	129.7	57.1
	Spring	-	-	-	-	70.4
	Control (no N)	69.2	68.2	56.7	62.3	49.7
	Early fall w/ inhibitors	111.9	116.7	113.1	113.9	75.6
	LSD ($\alpha = 0.05$)^{y}	-	-	-	-	-
Low	Early fall	97.7	109.8	104.2	115.8	47.9
	Mid fall	-	101.3	131.5	155.1	41.4
	Late fall	-	-	99.0	120.1	45.5
	Spring	-	-	-	-	38.3
	Control (no N)	51.5	67.2	47.7	50.4	45.9
	Early fall w/ inhibitors	99.2	96.7	110.7	133.7	44.7
	LSD ($\alpha = 0.05$)^{y}	-	-	-	-	-
Landscape position means						
High		101.0a	103.8	100.3	113.1	63.8
Low		82.8b	93.7	98.6	115.0	44.0
LSD ($\alpha = 0.10$)		9.4	ns	ns	ns	ns
	Fertilization means					
	Early fall	109.8a	118.8a	109.8a	117.0b	56.2
	Mid fall	-	101.9a	118.7a	148.2a	53.4
	Late fall	-	-	104.7a	124.9ab	51.3
	Spring	-	-	-	-	54.3
	Control (no N)	60.3b	67.6b	52.2b	56.3c	47.8
	Early fall w/ inhibitors	105.5a	106.7a	111.9a	123.8ab	60.2
	LSD ($\alpha = 0.05$)	11.4	19.2	na^{x}	27.7	ns

ANOVA	df	$P > F$	df	$P > F$	df	$P > F$	df	$P > F$	df	$P > F$
Landpos	1	0.0097*	1	0.3019	1	0.8007	1	0.8544	1	0.1728
Trt	2	0.0001*	3	0.0002*	4	0.0001*	4	0.0001*	5	0.3830
Landpos*Trt	2	0.5627	3	0.5956	4	0.3013	4	0.6969	5	0.1218
Block(Landpos)	6	0.3281	6	0.1333	6	0.4245	6	0.2645	6	0.0001*
Residual C.V. (%)		11.37		18.49		19.21		23.54		21.21

a-c Mean values followed by the same letter (within columns) are not significantly different.

^{z} Assuming a bulk density of 1.24 g cm^{-3} for 0-15cm depth and 1.33 g cm^{-3} for 15-120cm.

^{y} LSD for individual treatments within a landscape position is not reported b/c there was no Landpos*Trt interaction.

^{x} Not applicable b/c used LSMEANS which does not provide an LSD value.

† Significant at $P < 0.10$ (used only for landscape position variables and interactions).

* Significant at $P < 0.05$.

Table H.7. Effect of landscape position, application date, and inhibitors on total 2M KCl + 5ppm PMA extractable inorganic N at Kane 2001/2002: 0-60cm soil depth

Treatment			Total inorganic N (kg ha^{-1})^{z}		
			Sampling Date		
Landscape position	Fertilization		21/05/02		26/08/02
High	Early fall		185.4		134.1
	Mid fall		193.7		126.4
	Late fall		189.5		115.9
	Spring		-		132.1
	Control (no N)		115.0		103.4
	Early fall w/ inhibitors		171.7		129.4
	LSD (α = 0.05)^{y}		-		-
Low	Early fall		168.4		85.9
	Mid fall		207.3		74.2
	Late fall		169.9		85.3
	Spring		-		74.3
	Control (no N)		97.9		79.2
	Early fall w/ inhibitors		181.1		78.3
	LSD (α = 0.05)^{y}		-		-
Landscape position means					
High			171.1		123.6
Low			164.9		79.5
LSD (α = 0.10)			ns		ns
	Fertilization means				
	Early fall		176.9a		110.0
	Mid fall		200.5a		100.3
	Late fall		179.7a		100.6
	Spring		-		103.2
	Control (no N)		106.5b		91.3
	Early fall w/ inhibitors		176.5a		103.9
	LSD (α = 0.05)		34.8		ns
ANOVA		df	*P* > F	df	*P* > F
Landpos		1	0.7813	1	0.1665
Trt		4	0.0001*	5	0.6168
Landpos*Trt		4	0.7617	5	0.5234
Block(Landpos)		6	0.0067*	6	0.0001*
Residual C.V. (%)			20.05		20.17

a,b Mean values followed by the same letter (within columns) are not significantly different.

^{z} Assuming a bulk density of 1.24 g cm^{-3} for 0-15cm depth and 1.33 g cm^{-3} for 15-120cm.

^{y} LSD for individual treatments within a landscape position is not reported b/c there was no Landpos*Trt interaction.

† Significant at $P < 0.10$ (used only for landscape position variables and interactions).

* Significant at $P < 0.05$.

Table H.8. Effect of landscape position, application date, and inhibitors on total 2M KCl + 5ppm PMA extractable NH_4^+-N at Kane 2001/2002: 0-60cm soil depth

Treatment			Total extractable NH_4^+-N (kg ha^{-1})[z]		
			Sampling Date		
Landscape position	Fertilization		21/05/02		26/08/02
High	Early fall		42.0		64.5
	Mid fall		58.8		59.7
	Late fall		44.9		67.5
	Spring		-		54.7
	Control (no N)		37.6		59.5
	Early fall w/ inhibitors		48.8		54.7
	LSD ($\alpha = 0.05$)[y]		-		-
Low	Early fall		50.5		70.7
	Mid fall		65.9		62.8
	Late fall		57.0		71.5
	Spring		-		61.8
	Control (no N)		51.9		65.9
	Early fall w/ inhibitors		66.0		64.6
	LSD ($\alpha = 0.05$)[y]		-		-
Landscape position means					
High			46.4		60.1
Low			58.3		66.2
LSD ($\alpha = 0.10$)			ns		ns
	Fertilization means				
	Early fall		46.3c		67.6
	Mid fall		62.3a		61.3
	Late fall		51.0bc		69.5
	Spring		-		58.2
	Control (no N)		44.8c		62.7
	Early fall w/ inhibitors		57.4ab		59.6
	LSD ($\alpha = 0.05$)		9.0		ns
ANOVA		df	$P > F$	df	$P > F$
Landpos		1	0.1199	1	0.7239
Trt		4	0.0021*	5	0.4006
Landpos*Trt		4	0.7704	5	0.9955
Block(Landpos)		6	0.001*	6	0.0001*
Residual C.V. (%)			16.72		19.40

a-c Mean values followed by the same letter (within columns) are not significantly different.

[z] Assuming a bulk density of 1.24 g cm^{-3} for 0-15cm depth and 1.33 g cm^{-3} for 15-120cm.

[y] LSD for individual treatments within a landscape position is not reported b/c there was no Landpos*Trt interaction.

† Significant at $P < 0.10$ (used only for landscape position variables and interactions).

* Significant at $P < 0.05$.

Table H.9. Effect of landscape position, application date, and inhibitors on total 2M KCl + 5ppm PMA extractable NO_3^--N at Kane 2001/2002: 0-60cm soil depth

Treatment			Total extractable NO_3^--N (kg ha^{-1})^z		
			Sampling Date		
Landscape position	Fertilization		21/05/02		26/08/02
High	Early fall		143.0		67.7
	Mid fall		133.3		65.2
	Late fall		143.8		47.5
	Spring		-		75.9
	Control (no N)		77.4		42.2
	Early fall w/ inhibitors		122.8		73.0
	LSD ($\alpha = 0.05$)^y		-		-
Low	Early fall		117.9		13.4
	Mid fall		140.7		9.6
	Late fall		112.1		12.1
	Spring		-		11.3
	Control (no N)		45.4		12.7
	Early fall w/ inhibitors		114.6		12.3
	LSD ($\alpha = 0.05$)^y		-		-
Landscape position means					
High			124.1		61.9a
Low			106.2		11.9b
LSD ($\alpha = 0.10$)			ns		29.9
	Fertilization means				
	Early fall		130.5a		40.5
	Mid fall		137.0a		37.4
	Late fall		128.0a		29.7
	Spring		-		43.6
	Control (no N)		61.4b		27.4
	Early fall w/ inhibitors		118.7a		42.7
	LSD ($\alpha = 0.05$)		29.4		ns
ANOVA		df	$P > F$	df	$P > F$
Landpos		1	0.3035	1	0.0175*
Trt		4	0.0001*	5	0.3983
Landpos*Trt		4	0.5838	5	0.3492
Block(Landpos)		6	0.0207*	6	0.0001*
Residual C.V. (%)			24.73		50.54

a,b Mean values followed by the same letter (within columns) are not significantly different.

^{z} Assuming a bulk density of 1.24 g cm^{-3} for 0-15cm depth and 1.33 g cm^{-3} for 15-120cm.

^{y} LSD for individual treatments within a landscape position is not reported b/c there was no Landpos*Trt interaction.

† Significant at $P < 0.10$ (used only for landscape position variables and interactions).

* Significant at $P < 0.05$.

Table H.10. Effect of landscape position, application date, and inhibitors on total 2M KCl + 5ppm PMA extractable inorganic N at Kane 2001/2002: 0-120cm soil depth

Treatment			Total inorganic N (kg ha^{-1})^{z}		
			Sampling Date		
Landscape position	Fertilization		21/05/02		26/08/02
High	Early fall		258.9		203.1
	Mid fall		279.2		204.9
	Late fall		332.5		215.4
	Spring		-		210.6
	Control (no N)		188.0		187.4
	Early fall w/ inhibitors		240.3		216.4
	LSD (α = 0.05)^{y}		-		-
Low	Early fall		239.9		164.9
	Mid fall		270.3		155.2
	Late fall		235.4		174.3
	Spring		-		150.3
	Control (no N)		169.4		162.2
	Early fall w/ inhibitors		249.6		141.3
	LSD (α = 0.05)^{y}		-		-
Landscape position means					
High			259.8		206.3
Low			232.9		158.0
LSD (α = 0.10)			ns		ns
	Fertilization means				
	Early fall		249.4a		184.0
	Mid fall		274.7a		180.1
	Late fall		284.0a		194.9
	Spring		-		180.4
	Control (no N)		178.7b		174.8
	Early fall w/ inhibitors		245.0a		178.9
	LSD (α = 0.05)		58.7		ns
ANOVA		df	$P > F$	df	$P > F$
Landpos		1	0.386	1	0.3734
Trt		4	0.0102*	5	0.7652
Landpos*Trt		4	0.4102	5	0.5361
Block(Landpos)		6	0.0472*	6	0.0001*
Residual C.V. (%)			23.11		14.95

a,b Mean values followed by the same letter (within columns) are not significantly different.

^{z} Assuming a bulk density of 1.24 g cm^{-3} for 0-15cm depth and 1.33 g cm^{-3} for 15-120cm.

^{y} LSD for individual treatments within a landscape position is not reported b/c there was no Landpos*Trt interaction.

† Significant at $P < 0.10$ (used only for landscape position variables and interactions).

* Significant at $P < 0.05$.

Table H.11. Effect of landscape position, application date, and inhibitors on total 2M KCl + 5ppm PMA extractable NH_4^+-N at Kane 2001/2002: 0-120cm soil depth

Treatment			Total extractable NH_4^+-N (kg ha^{-1})[z]		
			Sampling Date		
Landscape position	Fertilization		21/05/02		26/08/02
High	Early fall		79.0		109.5
	Mid fall		103.8		113.2
	Late fall		106.4		132.0
	Spring		-		113.2
	Control (no N)		79.1		117.0
	Early fall w/ inhibitors		84.3		109.7
	LSD (α = 0.05)[y]		-		-
Low	Early fall		109.0		145.7
	Mid fall		116.4		139.8
	Late fall		110.0		156.5
	Spring		-		133.8
	Control (no N)		114.9		144.9
	Early fall w/ inhibitors		121.5		123.6
	LSD (α = 0.05)[y]		-		-
Landscape position means					
High			90.5		115.8
Low			114.4		140.7
LSD (α = 0.10)			ns		ns
	Fertilization means				
	Early fall		94.0		127.6
	Mid fall		110.1		126.5
	Late fall		108.2		144.2
	Spring		-		123.5
	Control (no N)		97.0		131.0
	Early fall w/ inhibitors		102.9		116.6
	LSD (α = 0.05)		ns		ns
ANOVA		df	$P > F$	df	$P > F$
Landpos		1	0.1584	1	0.4669
Trt		4	0.2702	5	0.1787
Landpos*Trt		4	0.2047	5	0.9240
Block(Landpos)		6	0.0001*	6	0.0001*
Residual C.V. (%)			16.3		15.83

[z] Assuming a bulk density of 1.24 g cm^{-3} for 0-15cm depth and 1.33 g cm^{-3} for 15-120cm.

[y] LSD for individual treatments within a landscape position is not reported b/c there was no Landpos*Trt interaction.

† Significant at $P < 0.10$ (used only for landscape position variables and interactions).

* Significant at $P < 0.05$.

Table H.12. Effect of landscape position, application date, and inhibitors on total 2M KCl + 5ppm PMA extractable NO_3^--N at Kane 2001/2002: 0-120cm soil depth

Treatment			Total extractable NO_3^--N (kg ha^{-1})^z Sampling Date		
Landscape position	Fertilization		21/05/02		26/08/02
High	Early fall		179.5		91.2
	Mid fall		173.8		89.7
	Late fall		225.3		82.0
	Spring		-		95.4
	Control (no N)		108.9		68.7
	Early fall w/ inhibitors		155.8		104.5
	LSD (α = 0.05)^y		-		-
Low	Early fall		130.9		16.9
	Mid fall		153.2		10.6
	Late fall		124.6		14.1
	Spring		-		14.3
	Control (no N)		53.9		15.7
	Early fall w/ inhibitors		127.6		15.3
	LSD (α = 0.05)^y		-		-
Landscape position means					
High			168.7		88.6a
Low			118.1		14.5b
LSD (α = 0.10)			32.8		47.9
	Fertilization means				
	Early fall		155.2a		54.0
	Mid fall		163.5a		50.2
	Late fall		175.0a		45.0
	Spring		-		54.9
	Control (no N)		81.4b		42.2
	Early fall w/ inhibitors		141.7a		59.9
	LSD (α = 0.05)		46.1		ns
ANOVA		df	*P* > F	df	*P* > F
Landpos		1	0.0240*	1	0.0239*
Trt		4	0.0030*	5	0.7443
Landpos*Trt		4	0.4342	5	0.7279
Block(Landpos)		6	0.2450	6	0.0001*
Residual C.V. (%)			31.15		45.91

a,b Mean values followed by the same letter (within columns) are not significantly different.

^{z} Assuming a bulk density of 1.24 g cm^{-3} for 0-15cm depth and 1.33 g cm^{-3} for 15-120cm.

^{y} LSD for individual treatments within a landscape position is not reported b/c there was no Landpos*Trt interaction.

† Significant at $P < 0.10$ (used only for landscape position variables and interactions).

* Significant at $P < 0.05$.

Appendix I

Analysis of Variance and LSDs for the Effects of Landscape Position, Application Date and Inhibitors on the Recovery of Soil Mineral N during the Fall, at Seeding, and at Harvest at Rosser (2001/02)

Table I.1. Effect of landscape position, application date, and inhibitors on total 2M KCl + 5ppm PMA extractable inorganic N at Rosser 2001/2002: 0-30cm soil depth

Treatment		Total inorganic N (kg ha^{-1})^{z}			
		Sampling Date			
Landscape position	Fertilization	02/10/01	30/10/01	27/05/02	29/08/02
High	Early fall	97.0	121.6ab	113.9	48.9
	Mid fall	-	133.2a	105.5	52.4
	Late fall	-	123.0ab	115.3	48.6
	Spring	-	-	-	63.9
	Control (no N)	48.6	58.0c	58.4	42.9
	Early fall w/ inhibitors	98.5	116.6b	107.9	57.1
	LSD (α = 0.05)	-^{y}	na^{x}	-^{y}	ns
Low	Early fall	101.0	107.3b	95.6	59.4bc
	Mid fall	-	111.3b	86.8	74.8ab
	Late fall	-	148.3a	91.0	81.9a
	Spring	-	-	-	51.7c
	Control (no N)	38.8	48.3c	59.0	60.1bc
	Early fall w/ inhibitors	86.2	104.9b	75.1	64.9a
	LSD (α = 0.05)	-^{y}	na^{x}	-^{y}	na^{x}
Landscape position means					
High		81.4	110.5	100.2	52.3
Low		75.3	104.0	81.5	65.5
LSD (α = 0.10)		ns	-^{w}	ns	-^{w}
	Fertilization means				
	Early fall	99.0a	114.4	104.8a	54.1
	Mid fall	-	122.3	96.2a	63.6
	Late fall	-	135.7	103.2a	65.2
	Spring	-	-	-	57.8
	Control (no N)	43.7b	53.1	58.7b	51.5
	Early fall w/ inhibitors	92.4a	110.7	91.5a	61.0
	LSD (α = 0.05)	14.1	-^{w}	14.8	-^{w}

ANOVA	df	$P > F$	df	$P > F$	df	$P > F$	df	$P > F$
Landpos	1	0.2961	1	0.2005	1	0.2799	1	0.2918
Trt	2	0.0001*	4	0.0001*	4	0.0001*	5	0.3998
Landpos*Trt	2	0.4247	4	0.0018*	4	0.2429	5	0.0844†
Block(Landpos)	6	0.4703	6	0.1475	6	0.0001*	6	0.0001*
Residual C.V. (%)		16.55		9.94		15.77		25.16

a-c Mean values followed by the same letter (within columns) are not significantly different.

^{z} Assuming a bulk density of 1.24 g cm^{-3} for 0-15cm depth and 1.33 g cm^{-3} for 15-120cm.

^{y} LSD for individual treatments within a landscape position is not reported b/c there was no Landpos*Trt interaction.

^{x} Not applicable b/c used LSMEANS which does not provide an LSD value.

^{w} LSD is not reported b/c of significant Landpos*Trt interaction.

† Significant at $P < 0.10$ (used only for landscape position variables and interactions).

* Significant at $P < 0.05$.

Table I.2. Effect of landscape position, application date, and inhibitors on total 2M KCl + 5ppm PMA extractable NH_4^+-N at Rosser 2001/2002: 0-30cm soil depth

Treatment		Total extractable NH_4^+-N (kg ha^{-1})[z]							
		Sampling Date							
Landscape position	Fertilization		02/10/01		30/10/01		27/05/02		29/08/02
High	Early fall		52.2		46.3c		23.0		25.2
	Mid fall		-		70.9b		21.7		31.9
	Late fall		-		83.7a		30.1		24.1
	Spring		-		-		-		33.8
	Control (no N)		20.9		26.2d		18.4		25.2
	Early fall w/ inhibitors		64.6		56.2c		21.4		28.1
	LSD ($\alpha = 0.05$)		-[y]		na[x]		-[y]		-[y]
Low	Early fall		68.0		44.2c		24.3		38.7
	Mid fall		-		65.6b		26.4		37.7
	Late fall		-		116.9a		30.7		36.6
	Spring		-		-		-		31.9
	Control (no N)		24.5		26.9d		22.4		39.6
	Early fall w/ inhibitors		60.6		56.8b		23.9		34.1
	LSD ($\alpha = 0.05$)		-[y]		na[x]		-[y]		-[y]
Landscape position means									
High			45.9		56.7		22.9		28.0b
Low			51.1		62.1		25.5		36.4a
LSD ($\alpha = 0.10$)			ns		-[w]		ns		3.4
	Fertilization means								
	Early fall		60.1a		45.2		23.7b		31.9
	Mid fall		-		68.2		24.0b		34.8
	Late fall		-		100.3		30.4a		30.4
	Spring		-		-		-		32.8
	Control (no N)		22.7b		26.6		20.4b		32.4
	Early fall w/ inhibitors		62.6a		56.5		22.6b		31.1
	LSD ($\alpha = 0.05$)		9.8		-[w]		5.5		ns
ANOVA		df	$P > F$	df	$P > F$	df	$P > F$	df	$P > F$
Landpos		1	0.384	1	0.3457	1	0.3766	1	0.0029*
Trt		2	0.0001*	4	0.0001*	4	0.0134*	5	0.9323
Landpos*Trt		2	0.128	4	0.0007*	4	0.9298	5	0.3852
Block(Landpos)		6	0.1138	6	0.0067*	6	0.0373*	6	0.7984
Residual C.V. (%)			18.61		14.14		21.95		26.31

a-d Mean values followed by the same letter (within columns) are not significantly different.

[z] Assuming a bulk density of 1.24 g cm^{-3} for 0-15cm depth and 1.33 g cm^{-3} for 15-120cm.

[y] LSD for individual treatments within a landscape position is not reported b/c there was no Landpos*Trt interaction.

[x] Not applicable b/c used LSMEANS which does not provide an LSD value.

[w] LSD is not reported b/c of significant Landpos*Trt interaction.

† Significant at $P < 0.10$ (used only for landscape position variables and interactions).

* Significant at $P < 0.05$.

Table I.3. Effect of landscape position, application date, and inhibitors on total 2M KCl + 5ppm PMA extractable NO_3^--N at Rosser 2001/2002: 0-30cm soil depth

Treatment		Total extractable NO_3^--N (kg ha^{-1})[z]							
		Sampling Date							
Landscape position	Fertilization		02/10/01		30/10/01		27/05/02		29/08/02
High	Early fall		44.8		75.3		90.8a		23.7
	Mid fall		-		62.0		83.9a		20.6
	Late fall		-		39.2		85.2a		24.5
	Spring		-		-		-		30.2
	Control (no N)		27.7		31.5		40.0b		17.7
	Early fall w/ inhibitors		33.9		60.2		86.5a		29.1
	LSD ($\alpha = 0.05$)		-[y]		-[y]		na[x]		-[y]
Low	Early fall		33.0		63.0		71.3a		20.7
	Mid fall		-		45.7		60.4ab		37.1
	Late fall		-		31.3		60.3a		45.0
	Spring		-		-		-		19.8
	Control (no N)		14.2		21.4		36.6c		20.5
	Early fall w/ inhibitors		25.6		48.0		51.2bc		30.5
	LSD ($\alpha = 0.05$)		-[y]		-[y]		na[x]		-[y]
Landscape position means									
High			35.5		53.6a		77.3		24.3
Low			24.3		41.9b		56.0		28.9
LSD ($\alpha = 0.10$)			ns		5.5		-[w]		ns
	Fertilization means								
	Early fall		38.8a		69.2a		81.1a		22.2ab
	Mid fall		-		53.8b		72.1ab		28.9ab
	Late fall		-		35.3c		72.8ab		34.7a
	Spring		-		-		-		25.0ab
	Control (no N)		21.0b		26.4d		38.3c		19.1b
	Early fall w/ inhibitors		29.8ab		54.1b		68.9b		29.8ab
	LSD ($\alpha = 0.05$)		9.2		7.3		-[w]		15.3
ANOVA		df	$P > F$	df	$P > F$	df	$P > F$	df	$P > F$
Landpos		1	0.1984	1	0.006*	1	0.2480	1	0.7112
Trt		2	0.0041*	4	0.0001*	4	0.0001*	5	0.3574
Landpos*Trt		2	0.8238	4	0.8190	4	0.0946†	5	0.3161
Block(Landpos)		6	0.0083*	6	0.1927	6	0.0001*	6	0.0001*
Residual C.V. (%)			28.21		14.86		16.45		56.16

a-d Mean values followed by the same letter (within columns) are not significantly different.

[z] Assuming a bulk density of 1.24 g cm^{-3} for 0-15cm depth and 1.33 g cm^{-3} for 15-120cm.

[y] LSD for individual treatments within a landscape position is not reported b/c there was no Landpos*Trt interaction.

[x] Not applicable b/c used LSMEANS which does not provide an LSD value.

[w] LSD is not reported b/c of significant Landpos*Trt interaction.

† Significant at $P < 0.10$ (used only for landscape position variables and interactions).

* Significant at $P < 0.05$.

Table I.4. Effect of landscape position, application date, and inhibitors on total 2M KCl + 5ppm PMA extractable NO_2^--N at Rosser 2001/2002: 0-30cm soil depth

Treatment		Total extractable NO_2^--N (kg ha^{-1})[z]			
		Sampling Date			
Landscape position	Fertilization	02/10/01	30/10/01	27/05/02	29/08/02
High	Early fall	0.00	0.00	0.00	0.00
	Mid fall	-	0.38	0.00	0.00
	Late fall	-	0.06	0.00	0.00
	Spring	-	-	-	0.00
	Control (no N)	0.00	0.25	0.00	0.00
	Early fall w/ inhibitors	0.00	0.19	0.00	0.00
	LSD ($\alpha = 0.05$)[y]	-	-	-	-
Low	Early fall	0.00	0.12	0.00	0.00
	Mid fall	-	0.06	0.00	0.00
	Late fall	-	0.12	0.00	0.25
	Spring	-	-	-	0.00
	Control (no N)	0.00	0.00	0.00	0.00
	Early fall w/ inhibitors	0.00	0.00	0.00	0.25
	LSD ($\alpha = 0.05$)[y]	-	-	-	-
Landscape position means					
High		0.00	0.18	0.00	0.00
Low		0.00	0.06	0.00	0.08
LSD ($\alpha = 0.10$)		ns	ns	ns	ns
	Fertilization means				
	Early fall	0.00	0.06	0.00	0.00
	Mid fall	-	0.22	0.00	0.00
	Late fall	-	0.09	0.00	0.13
	Spring	-	-	-	0.00
	Control (no N)	0.00	0.13	0.00	0.00
	Early fall w/ inhibitors	0.00	0.09	0.00	0.13
	LSD ($\alpha = 0.05$)	ns	ns	ns	ns

ANOVA	df	$P > F$	df	$P > F$	df	$P > F$	df	$P > F$
Landpos	1	.	1	0.4288	1	.	1	0.1340
Trt	2	.	4	0.5561	4	.	5	0.5926
Landpos*Trt	2	.	4	0.1382	4	.	5	0.5926
Block(Landpos)	6	.	6	0.002*	6	.	6	0.7089
Residual C.V. (%)		.		167.27		.		505.96

[z] Assuming a bulk density of 1.24 g cm^{-3} for 0-15cm depth and 1.33 g cm^{-3} for 15-120cm.

[y] LSD for individual treatments within a landscape position is not reported b/c there was no Landpos*Trt interaction.

† Significant at $P < 0.10$ (used only for landscape position variables and interactions).

* Significant at $P < 0.05$.

Table I.5. Effect of landscape position, application date, and inhibitors on total 2M KCl + 5ppm PMA extractable Urea-N at Rosser 2001/2002: 0-30cm soil depth

Treatment			Total extractable Urea-N (kg ha^{-1})^{z}						
			Sampling Date						
Landscape position	Fertilization		02/10/01		30/10/01		27/05/02		29/08/02
High	Early fall		2.0		1.5		0.5		0.2
	Mid fall		-		1.0		1.1		1.4
	Late fall		-		3.3		0.9		0.7
	Spring		-		-		-		0.0
	Control (no N)		1.2		0.0		0.0		0.7
	Early fall w/ inhibitors		3.7		0.5		0.4		0.3
	LSD ($\alpha = 0.05$)^{y}		-		-		-		-
Low	Early fall		1.6		0.8		0.8		1.0
	Mid fall		-		1.8		0.7		0.2
	Late fall		-		5.0		0.4		0.2
	Spring		-		-		-		0.0
	Control (no N)		1.7		0.3		1.2		0.5
	Early fall w/ inhibitors		2.4		0.1		0.2		0.3
	LSD ($\alpha = 0.05$)^{y}		-		-		-		-
Landscape position means									
High			2.3		1.3		0.6		0.6
Low			1.9		1.6		0.6		0.4
LSD ($\alpha = 0.10$)			ns		ns		ns		ns
	Fertilization means								
	Early fall		1.8		1.1b		0.7		0.6
	Mid fall		-		1.4b		0.9		0.8
	Late fall		-		4.1a		0.6		0.5
	Spring		-		-		-		0.0
	Control (no N)		1.4		0.1b		0.6		0.6
	Early fall w/ inhibitors		3.1		0.3b		0.3		0.3
	LSD ($\alpha = 0.05$)		ns		2.0		ns		ns
ANOVA		df	$P > F$	df	$P > F$	df	$P > F$	df	$P > F$
Landpos		1	0.5414	1	0.6296	1	0.8732	1	0.3612
Trt		2	0.1918	4	0.0019*	4	0.5300	5	0.3285
Landpos*Trt		2	0.6177	4	0.7342	4	0.1149	5	0.2403
Block(Landpos)		6	0.6407	6	0.4122	6	0.1727	6	0.5677
Residual C.V. (%)			84.82		134.30		111.77		163.58

a,b Mean values followed by the same letter (within columns) are not significantly different.

^{z} Assuming a bulk density of 1.24 g cm^{-3} for 0-15cm depth and 1.33 g cm^{-3} for 15-120cm.

^{y} LSD for individual treatments within a landscape position is not reported b/c there was no Landpos*Trt interaction.

† Significant at $P < 0.10$ (used only for landscape position variables and interactions).

* Significant at $P < 0.05$.

Table I.6. Effect of landscape position, application date, and inhibitors on total 2M KCl + 5ppm PMA extractable N at Rosser 2001/2002: 0-30cm soil depth

Treatment		Total extractable N (kg ha^{-1})[z]			
		Sampling Date			
Landscape position	Fertilization	02/10/01	30/10/01	27/05/02	29/08/02
High	Early fall	99.0	123.1ab	114.4	49.1
	Mid fall	-	134.1a	106.6	53.9
	Late fall	-	126.3ab	116.2	49.3
	Spring	-	-	-	63.9
	Control (no N)	49.8	58.0c	58.4	43.6
	Early fall w/ inhibitors	102.3	117.1b	108.3	57.4
	LSD (α = 0.05)	-[y]	na[x]	-[y]	ns
Low	Early fall	102.5	108.1b	96.4	60.4bc
	Mid fall	-	113.1b	87.5	75.1ab
	Late fall	-	153.3a	91.4	82.1a
	Spring	-	-	-	51.7c
	Control (no N)	40.4	48.5c	60.2	60.6c
	Early fall w/ inhibitors	88.7	104.9b	75.3	65.1a
	LSD (α = 0.05)	-[y]	na[x]	-[y]	na[x]
Landscape position means					
High		83.7	111.7	100.8	52.9
Low		77.2	105.6	82.2	65.8
LSD (α = 0.10)		ns	-[w]	ns	-[w]
	Fertilization means				
	Early fall	100.7a	115.6	105.4a	54.7
	Mid fall	-	123.6	97.1a	64.5
	Late fall	-	139.8	103.8a	65.7
	Spring	-	-	-	57.8
	Control (no N)	45.1b	53.2	59.3b	52.1
	Early fall w/ inhibitors	95.5a	111.0	91.8a	61.3
	LSD (α = 0.05)	15.0	-[w]	15.0	-[w]

ANOVA	df	$P > F$	df	$P > F$	df	$P > F$	df	$P > F$
Landpos	1	0.2781	1	0.2300	1	0.2859	1	0.2977
Trt	2	0.0001*	4	0.0001*	4	0.0001*	5	0.4023
Landpos*Trt	2	0.4526	4	0.0021*	4	0.2148	5	0.098†
Block(Landpos)	6	0.5099	6	0.1660	6	0.0001*	6	0.0001*
Residual C.V. (%)		17.09		10.29		15.90		25.08

a-c Mean values followed by the same letter (within columns) are not significantly different.

[z] Assuming a bulk density of 1.24 g cm^{-3} for 0-15cm depth and 1.33 g cm^{-3} for 15-120cm.

[y] LSD for individual treatments within a landscape position is not reported b/c there was no Landpos*Trt interaction.

[x] Not applicable b/c used LSMEANS which does not provide an LSD value.

[w] LSD is not reported b/c of significant Landpos*Trt interaction.

† Significant at $P < 0.10$ (used only for landscape position variables and interactions).

* Significant at $P < 0.05$.

Table I.7. Effect of landscape position, application date, and inhibitors on total 2M KCl + 5ppm PMA extractable inorganic N at Rosser 2001/2002: 0-60cm soil depth

Treatment			Total inorganic N (kg ha^{-1})^{z} Sampling Date		
Landscape position	Fertilization		27/05/02		29/08/02
High	Early fall		156.9		88.9
	Mid fall		150.0		95.9
	Late fall		153.8		81.6
	Spring		-		105.4
	Control (no N)		94.4		73.4
	Early fall w/ inhibitors		161.4		92.1
	LSD (α = 0.05)^{y}		-		-
Low	Early fall		135.6		115.4
	Mid fall		123.8		136.8
	Late fall		123.5		147.9
	Spring		-		109.6
	Control (no N)		86.0		105.6
	Early fall w/ inhibitors		110.1		124.9
	LSD (α = 0.05)^{y}		-		
Landscape position means					
High			143.3		89.5
Low			115.8		123.4
LSD (α = 0.10)			ns		ns
	Fertilization means				
	Early fall		146.3a		102.1
	Mid fall		136.9a		116.4
	Late fall		138.7a		114.7
	Spring		-		107.5
	Control (no N)		90.2b		89.5
	Early fall w/ inhibitors		135.7a		108.5
	LSD (α = 0.05)		18.2		ns
ANOVA		df	$P > F$	df	$P > F$
Landpos		1	0.2088	1	0.2703
Trt		4	0.0001*	5	0.4183
Landpos*Trt		4	0.2142	5	0.3841
Block(Landpos)		6	0.0001*	6	0.0001*
Residual C.V. (%)			13.64		25.60

a,b Mean values followed by the same letter (within columns) are not significantly different.

^{z} Assuming a bulk density of 1.24 g cm^{-3} for 0-15cm depth and 1.33 g cm^{-3} for 15-120cm.

^{y} LSD for individual treatments within a landscape position is not reported b/c there was no Landpos*Trt interaction.

† Significant at P < 0.10 (used only for landscape position variables and interactions).

* Significant at P < 0.05.

Table I.8. Effect of landscape position, application date, and inhibitors on total 2M KCl + 5ppm PMA extractable NH_4^+-N at Rosser 2001/2002: 0-60cm soil depth

Treatment			Total extractable NH_4^+-N (kg ha^{-1})[z]		
			Sampling Date		
Landscape position	Fertilization		27/05/02		29/08/02
High	Early fall		40.6		52.2
	Mid fall		46.2		61.8
	Late fall		44.6		46.1
	Spring		-		56.3
	Control (no N)		36.9		48.7
	Early fall w/ inhibitors		41.9		50.6
	LSD ($\alpha = 0.05$)[y]		-		-
Low	Early fall		44.8		68.7
	Mid fall		48.9		71.7
	Late fall		50.7		73.6
	Spring		-		65.4
	Control (no N)		40.4		74.1
	Early fall w/ inhibitors		44.9		65.6
	LSD ($\alpha = 0.05$)[y]		-		-
Landscape position means					
High			42.0		52.6b
Low			45.9		69.9a
LSD ($\alpha = 0.10$)			ns		11.0
	Fertilization means				
	Early fall		42.7		60.4
	Mid fall		47.5		66.8
	Late fall		47.6		59.9
	Spring		-		60.8
	Control (no N)		38.6		61.4
	Early fall w/ inhibitors		43.4		58.1
	LSD ($\alpha = 0.05$)		ns		ns
ANOVA		df	$P > F$	df	$P > F$
Landpos		1	0.664	1	0.0224*
Trt		4	0.2338	5	0.8054
Landpos*Trt		4	0.9949	5	0.5662
Block(Landpos)		6	0.0001*	6	0.0420*
Residual C.V. (%)			19.78		20.07

[z] Assuming a bulk density of 1.24 g cm^{-3} for 0-15cm depth and 1.33 g cm^{-3} for 15-120cm.

[y] LSD for individual treatments within a landscape position is not reported b/c there was no Landpos*Trt interaction.

† Significant at $P < 0.10$ (used only for landscape position variables and interactions).

* Significant at $P < 0.05$.

Table I.9. Effect of landscape position, application date, and inhibitors on total 2M KCl + 5ppm PMA extractable NO_3^--N at Rosser 2001/2002: 0-60cm soil depth

Treatment			Total extractable NO_3^--N ($kg\ ha^{-1}$)[z]		
			Sampling Date		
Landscape position	Fertilization		27/05/02		29/08/02
High	Early fall		116.3a		35.7
	Mid fall		103.9a		33.1
	Late fall		109.2a		35.0
	Spring		-		48.6
	Control (no N)		57.5b		24.2
	Early fall w/ inhibitors		119.5a		41.0
	LSD (α = 0.05)		na[x]		-[y]
Low	Early fall		90.8a		46.7
	Mid fall		74.4ab		64.6
	Late fall		72.8ab		74.0
	Spring		-		43.8
	Control (no N)		45.6c		61.0
	Early fall w/ inhibitors		65.2b		59.0
	LSD (α = 0.05)		na[x]		-[y]
Landscape position means					
High			101.3		36.3
Low			69.7		53.2
LSD (α = 0.10)			-[w]		ns
	Fertilization means				
	Early fall		103.6		41.2ab
	Mid fall		89.1		48.9ab
	Late fall		91.0		54.5a
	Spring		-		46.2ab
	Control (no N)		51.6		27.6b
	Early fall w/ inhibitors		92.4		50.0ab
	LSD (α = 0.05)		-[w]		24.1
ANOVA		df	$P > F$	df	$P > F$
Landpos		1	0.1549	1	0.5928
Trt		4	0.0001*	5	0.2943
Landpos*Trt		4	0.0521†	5	0.4670
Block(Landpos)		6	0.0001*	6	0.0001*
Residual C.V. (%)			15.55		52.77

a-c Mean values followed by the same letter (within columns) are not significantly different.

[z] Assuming a bulk density of 1.24 g cm^{-3} for 0-15cm depth and 1.33 g cm^{-3} for 15-120cm.

[y] LSD for individual treatments within a landscape position is not reported b/c there was no Landpos*Trt interaction.

[x] Used LSMEANS which does not provide an LSD value.

[w] LSD is not reported b/c of significant Landpos*Trt interaction.

† Significant at $P < 0.10$ (used only for landscape position variables and interactions).

* Significant at $P < 0.05$.

Table I.10. Effect of landscape position, application date, and inhibitors on total 2M KCl + 5ppm PMA extractable inorganic N at Rosser 2001/2002: 0-120cm soil depth

Treatment			Total inorganic N ($kg\ ha^{-1}$)[z]		
			Sampling Date		
Landscape position	Fertilization		27/05/02		29/08/02
High	Early fall		214.4		164.9
	Mid fall		206.5		187.4
	Late fall		203.8		155.6
	Spring		-		176.4
	Control (no N)		151.9		133.9
	Early fall w/ inhibitors		226.9		158.1
	LSD ($\alpha = 0.05$)[y]		-		-
Low	Early fall		193.1		178.4
	Mid fall		177.8		230.8
	Late fall		177.5		227.9
	Spring		-		202.7
	Control (no N)		134.0		196.1
	Early fall w/ inhibitors		161.6		197.9
	LSD ($\alpha = 0.05$)[y]		-		-
Landscape position means					
High			200.7		162.7
Low			168.8		205.6
LSD ($\alpha = 0.10$)			ns		ns
	Fertilization means				
	Early fall		203.8a		171.6
	Mid fall		192.2a		209.1
	Late fall		190.7a		191.7
	Spring		-		189.5
	Control (no N)		142.9b		165.0
	Early fall w/ inhibitors		194.2a		178.0
	LSD ($\alpha = 0.05$)		21.7		ns
ANOVA		df	$P > F$	df	$P > F$
Landpos		1	0.2356	1	0.2117
Trt		4	0.0001*	5	0.1428
Landpos*Trt		4	0.1939	5	0.5285
Block(Landpos)		6	0.0001*	6	0.0001*
Residual C.V. (%)			11.41		18.25

a,b Mean values followed by the same letter (within columns) are not significantly different.

[z] Assuming a bulk density of 1.24 $g\ cm^{-3}$ for 0-15cm depth and 1.33 $g\ cm^{-3}$ for 15-120cm.

[y] LSD for individual treatments within a landscape position is not reported b/c there was no Landpos*Trt interaction.

† Significant at $P < 0.10$ (used only for landscape position variables and interactions).

* Significant at $P < 0.05$.

Table I.11. Effect of landscape position, application date, and inhibitors on total 2M KCl + 5ppm PMA extractable NH_4^+-N at Rosser 2001/2002: 0-120cm soil depth

Treatment			Total extractable NH_4^+-N (kg ha^{-1})^z		
			Sampling Date		
Landscape position	Fertilization		27/05/02		29/08/02
High	Early fall		78.0		109.2
	Mid fall		83.7		126.3
	Late fall		73.6		95.1
	Spring		-		100.8
	Control (no N)		77.9		92.7
	Early fall w/ inhibitors		82.9		98.6
	LSD (α = 0.05)^y		-		-
Low	Early fall		89.3		127.2
	Mid fall		89.4		144.2
	Late fall		95.2		143.1
	Spring		-		142.9
	Control (no N)		78.9		154.1
	Early fall w/ inhibitors		85.9		127.1
	LSD (α = 0.05)^y		-		-
Landscape position means					
High			79.2		103.8b
Low			87.7		139.8a
LSD (α = 0.10)			ns		23.4
	Fertilization means				
	Early fall		83.7		118.2
	Mid fall		86.5		135.3
	Late fall		84.4		119.1
	Spring		-		121.8
	Control (no N)		78.4		123.4
	Early fall w/ inhibitors		84.4		112.9
	LSD (α = 0.05)		ns		ns
ANOVA		df	$P > F$	df	$P > F$
Landpos		1	0.6372	1	0.0244*
Trt		4	0.8266	5	0.3426
Landpos*Trt		4	0.6060	5	0.1922
Block(Landpos)		6	0.0001*	6	0.0023*
Residual C.V. (%)			16.91		16.13

a,b Mean values followed by the same letter (within columns) are not significantly different.

^{z} Assuming a bulk density of 1.24 g cm^{-3} for 0-15cm depth and 1.33 g cm^{-3} for 15-120cm.

^{y} LSD for individual treatments within a landscape position is not reported b/c there was no Landpos*Trt interaction.

† Significant at $P < 0.10$ (used only for landscape position variables and interactions).

* Significant at $P < 0.05$.

Table I.12. Effect of landscape position, application date, and inhibitors on total 2M KCl + 5ppm PMA extractable NO_3^--N at Rosser 2001/2002: 0-120cm soil depth

Treatment		Total extractable NO_3^--N (kg ha^{-1})[z]			
		Sampling Date			
Landscape position	Fertilization		27/05/02		29/08/02
High	Early fall		136.3ab		54.7
	Mid fall		122.9b		59.6
	Late fall		130.2ab		59.5
	Spring		-		75.2
	Control (no N)		74.0c		40.2
	Early fall w/ inhibitors		144.0a		58.5
	LSD (α = 0.05)		na[x]		-[y]
Low	Early fall		103.8a		51.2
	Mid fall		87.9ab		86.1
	Late fall		82.3b		84.5
	Spring		-		59.3
	Control (no N)		55.1c		41.5
	Early fall w/ inhibitors		75.7bc		70.5
	LSD (α = 0.05)		na[x]		-[y]
Landscape position means					
High			121.5		57.9
Low			81.1		65.5
LSD (α = 0.10)			-[w]		ns
	Fertilization means				
	Early fall		120.1		52.9
	Mid fall		105.4		72.9
	Late fall		106.3		72.0
	Spring		-		67.2
	Control (no N)		64.6		40.8
	Early fall w/ inhibitors		109.9		64.5
	LSD (α = 0.05)		-[w]		ns
ANOVA		df	$P > F$	df	$P > F$
Landpos		1	0.1073	1	0.8474
Trt		4	0.0001*	5	0.1901
Landpos*Trt		4	0.0228*	5	0.6174
Block(Landpos)		6	0.0001*	6	0.0001*
Residual C.V. (%)			14.01		45.26

a-c Mean values followed by the same letter (within columns) are not significantly different.

[z] Assuming a bulk density of 1.24 g cm^{-3} for 0-15cm depth and 1.33 g cm^{-3} for 15-120cm.

[y] LSD for individual treatments within a landscape position is not reported b/c there was no Landpos*Trt interaction.

[x] Not applicable b/c used LSMEANS which does not provide an LSD value.

[w] LSD is not reported b/c of significant Landpos*Trt interaction.

† Significant at $P < 0.10$ (used only for landscape position variables and interactions).

* Significant at $P < 0.05$.

Appendix J

Analysis of Variance and LSDs for the Effects of Landscape Position, Application Date and Inhibitors on the Recovery of Soil Mineral N during the Fall, at Seeding, and at Harvest at Brandon (2001/02)

Table J.1. Effect of landscape position, application date, and inhibitors on total 2M KCl + 5ppm PMA extractable inorganic N at Brandon 2001/2002: 0-30cm soil depth

Treatment		Total inorganic N (kg ha^{-1})^{z}				
		Sampling Date				
Landscape position	Fertilization	1/10/01	15/10/01	1/11/01	20/5/02	20/9/02
High	Early fall	120.6	133.8	131.8b	152.9	37.8
	Mid fall	-	142.6	133.1b	136.2	46.0
	Late fall	-	-	182.6a	143.2	42.5
	Spring	-	-	-	-	39.3
	Control (no N)	40.8	45.6	35.6c	75.9	39.7
	Early fall w/ inhibitors	117.1	137.7	113.4b	126.3	34.5
	LSD (α = 0.05)	-^{y}	-^{y}	na^{x}	-^{y}	-^{y}
Low	Early fall	98.7	89.8	80.8a	88.3	25.3
	Mid fall	-	101.7	73.4a	78.7	21.4
	Late fall	-	-	89.9a	107.2	24.2
	Spring	-	-	-	-	24.4
	Control (no N)	15.6	17.6	15.1b	30.2	25.4
	Early fall w/ inhibitors	84.9	92.8	88.6a	77.5	27.2
	LSD (α = 0.05)	-^{y}	-^{y}	na^{x}	-^{y}	-^{y}
Landscape position means						
High		92.8a	114.9a	119.3	126.9a	40.0a
Low		66.4b	75.5b	69.5	76.4b	24.6b
LSD (α = 0.10)		23.7	29.0	-^{w}	16.1	10.5
	Fertilization means					
	Early fall	109.7a	111.8a	106.3	120.6ab	31.5
	Mid fall	-	122.2a	103.3	107.4ab	33.7
	Late fall	-	-	136.2	125.2a	33.3
	Spring	-	-	-	-	31.8
	Control (no N)	28.2b	31.6b	25.3	53.0c	32.6
	Early fall w/ inhibitors	101.0a	115.2a	101.0	101.9b	30.8
	LSD (α = 0.05)	16.3	30.1	-^{w}	22.5	ns

ANOVA	df	$P > F$	df	$P > F$	df	$P > F$	df	$P > F$	df	$P > F$
Landpos	1	0.0733†	1	0.0387*	1	0.0066*	1	0.0009*	1	0.0296*
Trt	2	0.0001*	3	0.0001*	4	0.0001*	4	0.0001*	5	0.9766
Landpos*Trt	2	0.7866	3	0.9288	4	0.0233*	4	0.7290	5	0.3964
Block(Landpos)	6	0.0199*	6	0.0933†	6	0.0244*	6	0.2396	6	0.0005*
Residual C.V. (%)		18.77		30.06		23.61		21.44		24.49

a-c Mean values followed by the same letter (within columns) are not significantly different.

^{z} Assuming a bulk density of 1.24 g cm^{-3} for 0-15cm depth and 1.33 g cm^{-3} for 15-120cm.

^{y} LSD for individual treatments within a landscape position is not reported b/c there was no Landpos*Trt interaction.

^{x} Not applicable because used LSMEANS which does not provide an LSD value.

^{w} LSD is not reported b/c of significant Landpos*Trt interaction.

† Significant at $P < 0.10$ (used only for landscape position variables and interactions).

* Significant at $P < 0.05$.

Table J.2. Effect of landscape position, application date, and inhibitors on total 2M KCl + 5ppm PMA extractable NH_4^+-N at Brandon 2001/2002: 0-30cm soil depth

Treatment		Total extractable NH_4^+-N (kg ha^{-1})^{z}				
		Sampling Date				
Landscape position	Fertilization	1/10/01	15/10/01	1/11/01	20/5/02	20/9/02
High	Early fall	70.8	32.5	23.4cd	21.2	8.5
	Mid fall	-	90.9	72.0b	18.2	8.5
	Late fall	-	-	141.9a	18.4	8.7
	Spring	-	-	-	-	8.7
	Control (no N)	9.5	10.9	10.6d	22.3	11.2
	Early fall w/ inhibitors	70.0	56.7	47.5bc	22.3	8.5
	LSD (α = 0.05)	-^{y}	-^{y}	na^{x}	-^{y}	-^{y}
Low	Early fall	57.3	23.1	11.5b	15.2	10.9
	Mid fall	-	68.8	38.7b	11.5	8.2
	Late fall	-	-	73.6a	17.2	11.6
	Spring	-	-	-	-	11.1
	Control (no N)	8.0	7.4	7.8b	15.1	12.6
	Early fall w/ inhibitors	53.0	42.3	36.7b	16.1	10.4
	LSD (α = 0.05)	-^{y}	-^{y}	na^{x}	-^{y}	-^{y}
Landscape position means						
High		50.1	47.8	59.1	20.5a	9.0
Low		39.4	35.4	33.7	15.0b	10.8
LSD (α = 0.10)		ns	ns	-^{w}	4.3	ns
	Fertilization means					
	Early fall	64.0a	27.8bc	17.5	18.2	9.7
	Mid fall	-	79.8a	55.4	14.9	8.3
	Late fall	-	-	107.8	17.8	10.1
	Spring	-	-	-	-	9.9
	Control (no N)	8.7b	9.2c	9.2	18.7	11.9
	Early fall w/ inhibitors	61.5a	49.5b	42.1	19.2	9.4
	LSD (α = 0.05)	13.6	28.0	-^{w}	ns	ns

ANOVA	df	$P > F$	df	$P > F$	df	$P > F$	df	$P > F$	df	$P > F$
Landpos	1	0.2933	1	0.3922	1	0.0144*	1	0.0499*	1	0.2948
Trt	2	0.0001*	3	0.0003*	4	0.0001*	4	0.2988	5	0.4692
Landpos*Trt	2	0.4528	3	0.9121	4	0.0559†	4	0.6217	5	0.9508
Block(Landpos)	6	0.0377*	6	0.1154	6	0.4095	6	0.0354*	6	0.0419*
Residual C.V. (%)		27.93		64.09		49.31		23.79		34.15

a-c Mean values followed by the same letter (within columns) are not significantly different.

^{z} Assuming a bulk density of 1.24 g cm^{-3} for 0-15cm depth and 1.33 g cm^{-3} for 15-120cm.

^{y} LSD for individual treatments within a landscape position is not reported b/c there was no Landpos*Trt interaction.

^{x} Not applicable b/c used LSMEANS which does not provide an LSD value.

^{w} LSD is not reported b/c of significant Landpos*Trt interaction.

† Significant at $P < 0.10$ (used only for landscape position variables and interactions).

* Significant at $P < 0.05$.

Table J.3. Effect of landscape position, application date, and inhibitors on total 2M KCl + 5ppm PMA extractable NO_3^--N at Brandon 2001/2002: 0-30cm soil depth

Treatment			Total extractable NO_3^--N (kg ha^{-1})[z]								
			Sampling Date								
Landscape position	Fertilization		1/10/01		15/10/01		1/11/01		20/5/02		20/9/02
High	Early fall		49.2		97.2		105.5		131.7		26.3
	Mid fall		-		51.3		59.7		118.0		37.5
	Late fall		-		-		40.6		124.9		33.8
	Spring		-		-		-		-		30.6
	Control (no N)		31.4		34.7		24.9		53.5		28.3
	Early fall w/ inhibitors		47.0		81.0		65.9		104.1		26.0
	LSD (α = 0.05)[y]		-		-		-		-		-
Low	Early fall		37.1		61.7		67.9		73.0		14.4
	Mid fall		-		29.7		31.8		67.1		13.2
	Late fall		-		-		14.9		89.8		12.6
	Spring		-		-		-		-		13.3
	Control (no N)		7.6		10.2		7.3		15.1		12.8
	Early fall w/ inhibitors		30.6		50.5		51.9		61.4		16.8
	LSD (α = 0.05)[y]		-		-		-		-		-
Landscape position means											
High			42.5a		66.1a		59.3a		106.4a		30.9a
Low			25.1b		38.0b		34.7b		61.3b		13.8b
LSD (α = 0.10)			9.3		11.6		12.8		15.7		9.6
	Fertilization means										
	Early fall		43.1a		79.5a		86.7a		102.3ab		21.8
	Mid fall		-		40.5b		45.7c		92.6ab		25.4
	Late fall		-		-		27.7d		107.3a		23.2
	Spring		-		-		-		-		21.9
	Control (no N)		19.5b		22.4c		16.1d		34.3c		20.6
	Early fall w/ inhibitors		38.8a		65.7a		58.9b		82.8b		21.4
	LSD (α = 0.05)		7.7		14.6		11.9		22.0		ns
ANOVA		df	$P > F$	df	$P > F$	df	$P > F$	df	$P > F$	df	$P > F$
Landpos		1	0.0109*	1	0.0033*	1	0.0097*	1	0.0014*	1	0.0134*
Trt		2	0.0001*	3	0.0001*	4	0.0001*	4	0.0001*	5	0.7740
Landpos*Trt		2	0.2858	3	0.7510	4	0.2966	4	0.8017	5	0.3315
Block(Landpos)		6	0.0616†	6	0.2474	6	0.0166*	6	0.2373	6	0.0002*
Residual C.V. (%)			20.78		26.76		24.44		25.38		30.28

a-d Mean values followed by the same letter (within columns) are not significantly different.

[z] Assuming a bulk density of 1.24 g cm^{-3} for 0-15cm depth and 1.33 g cm^{-3} for 15-120cm.

[y] LSD for individual treatments within a landscape position is not reported b/c there was no Landpos*Trt interaction.

† Significant at $P < 0.10$ (used only for landscape position variables and interactions).

* Significant at $P < 0.05$.

Table J.4. Effect of landscape position, application date, and inhibitors on total 2M KCl + 5ppm PMA extractable NO_2^--N at Brandon 2001/2002: 0-30cm soil depth

Treatment		Total extractable NO_2^--N (kg ha^{-1})[z]				
		Sampling Date				
Landscape position	Fertilization	1/10/01	15/10/01	1/11/01	20/5/02	20/9/02
High	Early fall	0.64	4.01	2.19	0.00	0.00
	Mid fall	-	0.41	1.34	0.00	0.00
	Late fall	-	-	0.06	0.00	0.00
	Spring	-	-	-	-	0.00
	Control (no N)	0.00	0.00	0.00	0.00	0.25
	Early fall w/ inhibitors	0.06	0.00	0.00	0.00	0.00
	LSD (α = 0.05)	ns	-[y]	-[y]	-[y]	-[y]
Low	Early fall	4.38a	5.07	1.34	0.06	0.00
	Mid fall	-	3.25	2.97	0.00	0.00
	Late fall	-	-	1.40	0.25	0.00
	Spring	-	-	-	-	0.00
	Control (no N)	0.00b	0.00	0.00	0.00	0.00
	Early fall w/ inhibitors	1.29b	0.00	0.00	0.00	0.00
	LSD (α = 0.05)	na[x]	-[y]	-[y]	-[y]	-[y]
Landscape position means						
High		0.23b	1.11	0.86	0.00	0.04
Low		1.89a	2.08	1.14	0.06	0.00
LSD (α = 0.10)		-[w]	ns	ns	ns	ns
	Fertilization means					
	Early fall	2.5	4.54a	2.13a	0.03	0.00
	Mid fall	-	1.83ab	2.16a	0.00	0.00
	Late fall	-	-	0.73ab	0.12	0.00
	Spring	-	-	-	-	0.00
	Control (no N)	0.00	0.00b	0.00b	0.00	0.13
	Early fall w/ inhibitors	0.67	0.00b	0.00b	0.00	0.00
	LSD (α = 0.05)	-[w]	3.02	1.51	ns	ns

ANOVA	df	$P > F$	df	$P > F$	df	$P > F$	df	$P > F$	df	$P > F$
Landpos	1	0.0241*	1	0.3373	1	0.6150	1	0.3559	1	0.3559
Trt	2	0.0008*	3	0.0162*	4	0.0087*	4	0.4269	5	0.4346
Landpos*Trt	2	0.0083*	3	0.7285	4	0.2264	4	0.4269	5	0.4346
Block(Landpos)	6	0.1721	6	0.5471	6	0.2976	6	0.1833	6	0.4435
Residual C.V. (%)		93.9		180.15		146.36		496.03		692.80

a,b Mean values followed by the same letter (within columns) are not significantly different.

[z] Assuming a bulk density of 1.24 g cm^{-3} for 0-15cm depth and 1.33 g cm^{-3} for 15-120cm.

[y] LSD for individual treatments within a landscape position is not reported b/c there was no Landpos*Trt interaction.

[x] Not applicable b/c used LSMEANS which does not provide an LSD value.

[w] LSD is not reported b/c of significant Landpos*Trt interaction.

† Significant at $P < 0.10$ (used only for landscape position variables and interactions).

* Significant at $P < 0.05$.

Table J.5. Effect of landscape position, application date, and inhibitors on total 2M KCl + 5ppm PMA extractable Urea-N at Brandon 2001/2002: 0-30cm soil depth

Treatment			Total extractable Urea-N (kg ha^{-1})^{z}								
			Sampling Date								
Landscape position	Fertilization		1/10/01		15/10/01		1/11/01		20/5/02		20/9/02
High	Early fall		12.0		4.5		7.1		2.6		1.2
	Mid fall		-		5.3		8.3		3.5		0.9
	Late fall		-		-		11.5		4.7		0.7
	Spring		-		-		-		-		0.7
	Control (no N)		2.6		7.9		3.1		2.4		0.7
	Early fall w/ inhibitors		5.8		5.7		5.5		2.0		0.5
	LSD (α = 0.05)^{y}		-		-		-		-		-
Low	Early fall		6.2		6.5		10.6		15.1		1.2
	Mid fall		-		8.7		14.1		6.1		0.7
	Late fall		-		-		14.5		12.7		0.2
	Spring		-		-		-		-		0.5
	Control (no N)		5.6		5.7		1.7		6.2		0.2
	Early fall w/ inhibitors		9.5		4.6		6.7		5.7		0.9
	LSD (α = 0.05)^{y}		-		-		-		-		-
Landscape position means											
High			6.8		5.9		7.1		3.0		0.8
Low			7.1		6.4		9.5		9.2		0.6
LSD (α = 0.10)			ns		ns		ns		ns		ns
	Fertilization means										
	Early fall		9.1		5.5		8.9ab		8.8		1.2
	Mid fall		-		7.0		11.2ab		4.8		0.8
	Late fall		-		-		13.0a		8.7		0.5
	Spring		-		-		-		-		0.6
	Control (no N)		4.1		6.8		2.4c		4.3		0.5
	Early fall w/ inhibitors		7.7		5.2		6.1bc		3.8		0.7
	LSD (α = 0.05)		ns		ns		5.8		ns		ns
ANOVA		df	$P > F$	df	$P > F$	df	$P > F$	df	$P > F$	df	$P > F$
Landpos		1	0.926	1	0.8578	1	0.2610	1	0.2101	1	0.7333
Trt		2	0.4998	3	0.8404	4	0.0080*	4	0.2918	5	0.6249
Landpos*Trt		2	0.474	3	0.6337	4	0.7692	4	0.4642	5	0.9162
Block(Landpos)		6	0.6177	6	0.0589†	6	0.3578	6	0.0014*	6	0.0244*
Residual C.V. (%)			120.85		80.00		68.12		99.25		132.23

a-c Mean values followed by the same letter (within columns) are not significantly different.

^{z} Assuming a bulk density of 1.24 g cm^{-3} for 0-15cm depth and 1.33 g cm^{-3} for 15-120cm.

^{y} LSD for individual treatments within a landscape position is not reported b/c there was no Landpos*Trt interaction.

† Significant at $P < 0.10$ (used only for landscape position variables and interactions).

* Significant at $P < 0.05$.

Table J.6. Effect of landscape position, application date, and inhibitors on total 2M KCl + 5ppm PMA extractable N at Brandon 2001/2002: 0-30cm soil depth

Treatment		Total extractable N (kg ha^{-1})^{z}				
		Sampling Date				
Landscape position	Fertilization	1/10/01	15/10/01	1/11/01	20/5/02	20/9/02
High	Early fall	132.6	138.3	138.9b	155.4	39.0
	Mid fall	-	147.8	141.4b	139.7	46.9
	Late fall	-	-	194.1a	147.9	43.2
	Spring	-	-	-	-	40.0
	Control (no N)	43.5	53.5	38.6c	78.2	40.5
	Early fall w/ inhibitors	122.9	143.4	118.9b	128.3	34.9
	LSD ($\alpha = 0.05$)	-^{y}	-^{y}	na^{x}	-^{y}	-^{y}
Low	Early fall	104.9	96.3	91.3a	103.4	26.5
	Mid fall	-	110.5	87.5a	84.8	22.1
	Late fall	-	-	104.4a	119.9	24.4
	Spring	-	-	-	-	24.8
	Control (no N)	21.2	23.3	16.7b	36.4	25.6
	Early fall w/ inhibitors	94.5	97.4	95.3a	83.3	28.1
	LSD ($\alpha = 0.05$)	-^{y}	-^{y}	na^{x}	-^{y}	-^{y}
Landscape position means						
High		99.7a	120.8a	126.4	129.9a	40.7a
Low		73.5b	81.9b	79.0	85.5b	25.3b
LSD ($\alpha = 0.10$)		21.1	31.8	-^{w}	19.4	11.1
	Fertilization means					
	Early fall	118.8a	117.3a	115.1	129.4ab	32.7
	Mid fall	-	129.2a	114.4	112.2ab	34.5
	Late fall	-	-	149.2	133.9a	33.8
	Spring	-	-	-	-	32.4
	Control (no N)	32.3b	38.4b	27.7	57.3	33.0
	Early fall w/ inhibitors	108.7a	120.3a	107.1	105.8b	31.5
	LSD ($\alpha = 0.05$)	18.7	31.6	-^{w}	23.8	ns

ANOVA	df	$P > F$	df	$P > F$	df	$P > F$	df	$P > F$	df	$P > F$
Landpos	1	0.053†	1	0.055†	1	0.0048*	1	0.0044*	1	0.0345*
Trt	2	0.0001*	3	0.0001*	4	0.0001*	4	0.0001*	5	0.9827
Landpos*Trt	2	0.9259	3	0.9583	4	0.035**	4	0.7955	5	0.3743
Block(Landpos)	6	0.0925†	6	0.0727†	6	0.0048*	6	0.1281	6	0.0003*
Residual C.V. (%)		19.82		29.67		21.64		21.43		24.47

a-c Mean values followed by the same letter (within columns) are not significantly different.

^{z} Assuming a bulk density of 1.24 g cm^{-3} for 0-15cm depth and 1.33 g cm^{-3} for 15-120cm.

^{y} LSD for individual treatments within a landscape position is not reported b/c there was no Landpos*Trt interaction.

^{x} Not applicable b/c used LSMEANS which does not provide an LSD value.

^{w} LSD is not reported b/c of significant Landpos*Trt interaction.

† Significant at $P < 0.10$ (used only for landscape position variables and interactions).

* Significant at $P < 0.05$.

Table J.7. Effect of landscape position, application date, and inhibitors on total 2M KCl + 5ppm PMA extractable inorganic N at Brandon 2001/2002: 0-60cm soil depth

Treatment			Total inorganic N (kg ha^{-1})^{z}		
			Sampling Date		
Landscape position	Fertilization		20/5/02		20/9/02
High	Early fall		202.4		52.8
	Mid fall		180.7		58.4
	Late fall		185.7		59.5
	Spring		-		57.3
	Control (no N)		112.3		53.2
	Early fall w/ inhibitors		180.8		55.4
	LSD ($\alpha = 0.05$)^{y}		-		-
Low	Early fall		119.3		45.3
	Mid fall		105.7		32.9
	Late fall		157.7		43.7
	Spring		-		40.9
	Control (no N)		51.2		42.4
	Early fall w/ inhibitors		98.0		39.2
	LSD ($\alpha = 0.05$)^{y}		-		-
Landscape position means					
High			172.4a		56.1
Low			106.4b		40.7
LSD ($\alpha = 0.10$)			28.0		ns
	Fertilization means				
	Early fall		160.8ab		49.0
	Mid fall		143.2ab		45.7
	Late fall		171.73a		51.6
	Spring		-		49.1
	Control (no N)		81.8c		47.8
	Early fall w/ inhibitors		139.4b		47.3
	LSD ($\alpha = 0.05$)		29.0		ns
ANOVA		df	*P* > F	df	*P* > F
Landpos		1	0.0038*	1	0.1465
Trt		4	0.0001*	5	0.9049
Landpos*Trt		4	0.2829	5	0.6105
Block(Landpos)		6	0.0421*	6	0.0001*
Residual C.V. (%)			20.17		21.02

a-c Mean values followed by the same letter (within columns) are not significantly different.

^{z} Assuming a bulk density of 1.24 g cm^{-3} for 0-15cm depth and 1.33 g cm^{-3} for 15-120cm.

^{y} LSD for individual treatments within a landscape position is not reported b/c there was no Landpos*Trt interaction.

† Significant at $P < 0.10$ (used only for landscape position variables and interactions).

* Significant at $P < 0.05$.

Table J.8. Effect of landscape position, application date, and inhibitors on total 2M KCl + 5ppm PMA extractable NH_4^+-N at Brandon 2001/2002: 0-60cm soil depth

Treatment			Total extractable NH_4^+-N (kg ha^{-1})[z]		
			Sampling Date		
Landscape position	Fertilization		20/5/02		20/9/02
High	Early fall		37.7		18.5
	Mid fall		36.7		17.0
	Late fall		34.9		18.2
	Spring		-		17.7
	Control (no N)		37.3		20.7
	Early fall w/ inhibitors		42.3		18.0
	LSD ($\alpha = 0.05$)[y]		-		-
Low	Early fall		28.2		28.4
	Mid fall		24.0		17.2
	Late fall		33.7		27.1
	Spring		-		25.1
	Control (no N)		29.6		26.0
	Early fall w/ inhibitors		25.6		19.9
	LSD ($\alpha = 0.05$)[y]		-		-
Landscape position means					
High			37.8a		18.3
Low			28.2b		23.9
LSD ($\alpha = 0.10$)			6.3		ns
	Fertilization means				
	Early fall		33.0		23.4
	Mid fall		30.4		17.1
	Late fall		34.3		22.7
	Spring		-		21.4
	Control (no N)		33.5		23.4
	Early fall w/ inhibitors		33.9		18.9
	LSD ($\alpha = 0.05$)		ns		ns
ANOVA		df	$P > F$	df	$P > F$
Landpos		1	0.0264*	1	0.1072
Trt		4	0.8479	5	0.5095
Landpos*Trt		4	0.3504	5	0.7862
Block(Landpos)		6	0.1328	6	0.1150
Residual C.V. (%)			22.95		37.25

a,b Mean values followed by the same letter (within columns) are not significantly different.

[z] Assuming a bulk density of 1.24 g cm^{-3} for 0-15cm depth and 1.33 g cm^{-3} for 15-120cm.

[y] LSD for individual treatments within a landscape position is not reported b/c there was no Landpos*Trt interaction.

† Significant at $P < 0.10$ (used only for landscape position variables and interactions).

* Significant at $P < 0.05$.

Table J.9. Effect of landscape position, application date, and inhibitors on total 2M KCl + 5ppm PMA extractable NO_3^--N at Brandon 2001/2002: 0-60cm soil depth

Treatment			Total extractable NO_3^--N (kg ha^{-1})^z		
			Sampling Date		
Landscape position	Fertilization		20/5/02		20/9/02
High	Early fall		164.7		34.3
	Mid fall		144.0		41.5
	Late fall		150.9		41.3
	Spring		-		39.6
	Control (no N)		75.0		31.8
	Early fall w/ inhibitors		138.6		37.5
	LSD (α = 0.05)^y		-		-
Low	Early fall		91.0		16.9
	Mid fall		81.6		15.7
	Late fall		123.8		16.6
	Spring		-		15.8
	Control (no N)		21.6		16.3
	Early fall w/ inhibitors		72.4		19.3
	LSD (α = 0.05)^y		-		-
Landscape position means					
High			134.6a		37.7a
Low			78.1b		16.8b
LSD (α = 0.10)			25.4		14.9
	Fertilization means				
	Early fall		127.8ab		25.6
	Mid fall		112.8ab		28.6
	Late fall		137.3a		28.9
	Spring		-		27.7
	Control (no N)		48.3c		24.1
	Early fall w/ inhibitors		105.5b		28.4
	LSD (α = 0.05)		27.8		ns
ANOVA		df	$P > F$	df	$P > F$
Landpos		1	0.005*	1	0.0345*
Trt		4	0.0001*	5	0.8237
Landpos*Trt		4	0.4839	5	0.7447
Block(Landpos)		6	0.063†	6	0.0001*
Residual C.V. (%)			25.36		30.97

a-c Mean values followed by the same letter (within columns) are not significantly different.

^{z} Assuming a bulk density of 1.24 g cm^{-3} for 0-15cm depth and 1.33 g cm^{-3} for 15-120cm.

^{y} LSD for individual treatments within a landscape position is not reported b/c there was no Landpos*Trt interaction.

† Significant at $P < 0.10$ (used only for landscape position variables and interactions).

* Significant at $P < 0.05$.

Table J.10. Effect of landscape position, application date, and inhibitors on total 2M KCl + 5ppm PMA extractable inorganic N at Brandon 2001/2002: 0-120cm soil depth

Treatment		Total inorganic N (kg ha^{-1})[z] Sampling Date	
Landscape position	Fertilization	20/5/02	20/9/02
High	Early fall	.[x]	138.3
	Mid fall	.	120.4
	Late fall	.	171.4
	Spring	.	142.8
	Control (no N)	.	134.7
	Early fall w/ inhibitors	.	181.9
	LSD (α = 0.05)[y]		-
Low	Early fall	.	94.8
	Mid fall	.	63.9
	Late fall	.	97.2
	Spring	.	90.5
	Control (no N)	.	85.9
	Early fall w/ inhibitors	.	73.7
	LSD (α = 0.05)[y]		-
Landscape position means			
High		.	148.3a
Low		.	84.4b
LSD (α = 0.10)			55.4
	Fertilization means		
	Early fall	.	116.5
	Mid fall	.	92.2
	Late fall	.	134.3
	Spring	.	116.8
	Control (no N)	.	110.3
	Early fall w/ inhibitors	.	127.8
	LSD (α = 0.05)		ns

ANOVA	df	$P > F$	df	$P > F$
Landpos	1	-	1	.0664†
Trt	4	-	5	0.1511
Landpos*Trt	4	-	5	0.3351
Block(Landpos)	6	-	6	0.0001*
Residual C.V. (%)		-		26.86

a,b Mean values followed by the same letter (within columns) are not significantly different.

[z] Assuming a bulk density of 1.24 g cm^{-3} for 0-15cm depth and 1.33 g cm^{-3} for 15-120cm.

[y] LSD for individual treatments within a landscape position is not reported b/c there was no Landpos*Trt interaction.

[x] No data analysis: missing numerous samples at depths greater than 60cm

† Significant at $P < 0.10$ (used only for landscape position variables and interactions).

* Significant at $P < 0.05$.

Table J.11. Effect of landscape position, application date, and inhibitors on total 2M KCl + 5ppm PMA extractable NH_4^+-N at Brandon 2001/2002: 0-120cm soil depth.

Treatment		Total extractable NH_4^+-N (kg ha^{-1})[z] Sampling Date			
Landscape position	Fertilization	20/5/02			20/9/02
High	Early fall	.[x]			45.5
	Mid fall	.			45.5
	Late fall	.			46.7
	Spring	.			39.2
	Control (no N)	.			48.2
	Early fall w/ inhibitors	.			47.5
	LSD (α = 0.05)[y]				-
Low	Early fall	.			68.4
	Mid fall	.			41.2
	Late fall	.			62.1
	Spring	.			63.1
	Control (no N)	.			58.0
	Early fall w/ inhibitors	.			44.9
	LSD (α = 0.05)[y]				-
Landscape position means					
High		.			45.4
Low		.			56.3
LSD (α = 0.10)					ns
	Fertilization means				
	Early fall	.			56.9
	Mid fall	.			43.3
	Late fall	.			54.4
	Spring	.			51.2
	Control (no N)	.			53.1
	Early fall w/ inhibitors	.			46.2
	LSD (α = 0.05)				ns
ANOVA		df	$P > F$	df	$P > F$
Landpos		1	-	1	0.1630
Trt		4	-	5	0.4718
Landpos*Trt		4	-	5	0.2856
Block(Landpos)		6	-	6	0.0467*
Residual C.V. (%)			-		29.66

[z] Assuming a bulk density of 1.24 g cm^{-3} for 0-15cm depth and 1.33 g cm^{-3} for 15-120cm.

[y] LSD for individual treatments within a landscape position is not reported b/c there was no Landpos*Trt interaction.

[x] No data analysis: missing numerous samples at depths greater than 60cm

† Significant at $P < 0.10$ (used only for landscape position variables and interactions).

* Significant at $P < 0.05$.

Table J.12. Effect of landscape position, application date, and inhibitors on total 2M KCl + 5ppm PMA extractable NO_3^--N at Brandon 2001/2002: 0-120cm soil depth

Treatment			Total extractable NO_3^--N (kg ha^{-1})[z]	
			Sampling Date	
Landscape position	Fertilization		20/5/02	20/9/02
High	Early fall		.[x]	92.8
	Mid fall		.	75.0
	Late fall		.	124.8
	Spring		.	103.6
	Control (no N)		.	85.3
	Early fall w/ inhibitors		.	134.5
	LSD ($\alpha = 0.05$)[y]			-
Low	Early fall		.	26.4
	Mid fall		.	22.7
	Late fall		.	35.1
	Spring		.	27.8
	Control (no N)		.	27.8
	Early fall w/ inhibitors		.	28.8
	LSD ($\alpha = 0.05$)[y]			-
Landscape position means				
High			.	102.7a
Low			.	28.1b
LSD ($\alpha = 0.10$)				51.4
	Fertilization means			
	Early fall		.	59.6
	Mid fall		.	48.9
	Late fall		.	79.9
	Spring		.	65.7
	Control (no N)		.	56.6
	Early fall w/ inhibitors		.	81.6
	LSD ($\alpha = 0.05$)			ns

ANOVA	df	$P > F$	df	$P > F$
Landpos	1	-	1	0.0303*
Trt	4	-	5	0.2423
Landpos*Trt	4	-	5	0.5230
Block(Landpos)	6	-	6	0.0001*
Residual C.V. (%)		-		47.46

a,b Mean values followed by the same letter (within columns) are not significantly different.

[z] Assuming a bulk density of 1.24 g cm^{-3} for 0-15cm depth and 1.33 g cm^{-3} for 15-120cm.

[y] LSD for individual treatments within a landscape position is not reported b/c there was no Landpos*Trt interaction.

[x] No data analysis: missing numerous samples at depths greater than 60cm

† Significant at $P < 0.10$ (used only for landscape position variables and interactions).

* Significant at $P < 0.05$.

Appendix K

Analysis of Variance and LSDs for the Effects of Landscape Position, Application Date and Inhibitors on the Mean Recovery of Soil Mineral N at Seeding (0-60cm) at All Intensive Sites, Red River Valley and 2001/2002 Sites Only

Table K.1. Effect of landscape position, application date, and inhibitors on the total extractable mineral N in the soil at seeding at all four intensive sites: 0-60 cm soil depth

Treatment: Landscape position	Treatment: Fertilization	Spring sampling date: Total NH_4^+-N (kg ha^{-1})^z	Total NO_3^--N (kg ha^{-1})^z	Total NO_2-N (kg ha^{-1})^z	Total inorganic N (kg ha^{-1})^z
High	Early fall	52.4	131.5	0.09	183.9
	Mid fall	57.6	119.6	0.40	177.6
	Late fall	52.2	126.7	0.20	179.1
	Spring	-	-	-	-
	Control (no N)	49.3	62.9	0.00	112.2
	Early fall w/ inhibitors	54.0	121.3	0.04	175.4
	LSD (α = 0.05)^y	-	-	-	-
Low	Early fall	48.9	89.7	0.14	138.8
	Mid fall	55.4	94.7	0.42	150.5
	Late fall	57.3	95.8	0.25	153.4
	Spring	-	-	-	-
	Control (no N)	50.6	34.5	0.25	85.4
	Early fall w/ inhibitors	55.3	85.9	0.13	141.3
	LSD (α = 0.05)^y	-	-	-	-
Landscape position means					
High		53.1	112.4a	0.15	165.6a
Low		53.5	80.1b	0.24	133.9b
LSD (α = 0.10)		ns	13.7	ns	15.5
	Fertilization means				
	Early fall	50.7bc	110.6a	0.11b	161.4a
	Mid fall	56.5a	107.2a	0.41a	164.1a
	Late fall	54.8ab	111.3a	0.23ab	166.3a
	Spring	-	-	-	-
	Control (no N)	49.9c	48.7b	0.13b	98.8b
	Early fall w/ inhibitors	54.7ab	103.6a	0.08b	158.4a
	LSD (α = 0.05)	4.5	10.8	0.23	12.4

ANOVA	df	$P > F$			
Site year	3	0.0001*	0.0105*	0.0118*	0.0178*
Landpos	1	0.9203	0.0005*	0.4199	0.0018*
Site year*Landpos	3	0.3276	0.3553	0.6551	0.1566
Trt	4	0.0154*	0.0001*	0.0433*	0.0001*
Site year*Trt	12	0.1524	0.0442*	0.105	0.0682*
Landpos*Trt	4	0.3479	0.5811	0.8729	0.4925
Site year*Landpos*Trt	12	0.8412	0.3038	0.2444	0.3023
Block(Site year*Landpos)	24	0.0001*	0.0001*	0.003*	0.0001*
Residual C.V. (%)		16.84	22.61	243.87	16.67

a-c Mean values followed by the same letter (within columns) are not significantly different.

^{z} Assuming a bulk density of 1.24 g cm^{-3} for 0-15 cm depth and 1.33 g cm^{-3} for 15-120 cm.

^{y} LSD for individual treatments within a landscape position is not reported b/c there was no Landpos*Trt interaction.

† Significant at P < 0.10 (used only for landscape position variables and interactions).

* Significant at P < 0.05.

Table K.2. Effect of landscape position, application date, and inhibitors on the total extractable mineral N in the soil at seeding at the intensive sites situated in the Red River Valley only: 0-60 cm soil depth

Treatment			Spring sampling date			
Landscape position	Fertilization		Total NH_4^+-N (kg ha^{-1})^z	Total NO_3^--N (kg ha^{-1})^z	Total NO_2-N (kg ha^{-1})^z	Total inorganic N (kg ha^{-1})^z
High	Early fall		57.3	120.4	0.12	177.8
	Mid fall		64.6	111.5	0.53	176.6
	Late fall		58.0	118.7	0.27	176.9
	Spring		-	-	-	-
	Control (no N)		53.2	58.9	0.00	112.1
	Early fall w/ inhibitors		57.9	115.6	0.06	173.6
	LSD (α = 0.05)^y		-	-	-	-
Low	Early fall		55.8	89.3	0.17	145.3
	Mid fall		65.9	99.0	0.56	165.4
	Late fall		65.2	86.5	0.25	152.0
	Spring		-	-	-	-
	Control (no N)		57.6	38.8	0.33	96.8
	Early fall w/ inhibitors		65.3	90.3	0.17	155.8
	LSD (α = 0.05)^y		-	-	-	-
Landscape position means						
High			62.0	105.0a	0.20	163.4a
Low			58.2	80.8b	0.30	143.1b
LSD (α = 0.10)			ns	17.0	ns	19.2
	Fertilization means					
	Early fall		56.6bc	104.9a	0.14b	161.6a
	Mid fall		65.2a	105.2a	0.54a	171.0a
	Late fall		61.6ab	102.6a	0.26ab	164.4a
	Spring		-	-	-	-
	Control (no N)		55.4c	48.9b	0.17b	104.4b
	Early fall w/ inhibitors		61.6ab	103.0a	0.11b	164.7a
	LSD (α = 0.05)		5.4	11.4	0.31	13.7
ANOVA		df		$P > F$		
Site year		2	0.0001*	0.0151*	0.0338*	0.0231*
Landpos		1	0.5122	0.0236*	0.4987	0.0823†
Site year*Landpos		2	0.504	0.8501	0.5504	0.6687
Trt		4	0.0030*	0.0001*	0.0422*	0.0001*
Site year*Trt		8	0.3367	0.1037	0.1783	0.1623
Landpos*Trt		4	0.422	0.4017	0.8067	0.5613
Site year*Landpos*Trt		8	0.8808	0.2784	0.23322	0.3613
Block(Site year*Landpos)		18	0.0001*	0.0001*	0.0079*	0.0001*
Residual C.V. (%)			15.65	21.23	217.03	15.54

a-c Mean values followed by the same letter (within columns) are not significantly different.

^{z} Assuming a bulk density of 1.24 g cm^{-3} for 0-15 cm depth and 1.33 g cm^{-3} for 15-120 cm.

^{y} LSD for individual treatments within a landscape position is not reported b/c there was no Landpos*Trt interaction.

† Significant at P < 0.10 (used only for landscape position variables and interactions).

* Significant at P < 0.05.

Table K.3. Effect of landscape position, application date, and inhibitors on the total extractable mineral N in the soil at seeding at the 2001/2002 intensive sites only: 0-60 cm soil depth

Treatment			Spring sampling date			
Landscape position	Fertilization		Total NH_4^+-N ($kg\ ha^{-1}$)[z]	Total NO_3^--N ($kg\ ha^{-1}$)[z]	Total NO_2-N ($kg\ ha^{-1}$)[z]	Total inorganic N ($kg\ ha^{-1}$)[z]
High	Early fall		40.1	141.4	0.12	181.5
	Mid fall		47.2	127.1	0.53	174.8
	Late fall		41.5	134.6	0.27	176.4
	Spring		-	-	-	-
	Control (no N)		37.3	70.0	0.00	107.3
	Early fall w/ inhibitors		44.3	127.0	0.06	171.3
	LSD ($\alpha = 0.05$)[y]		-	-	-	-
Low	Early fall		41.2	99.9	0.19	141.1
	Mid fall		46.3	98.9	0.39	145.6
	Late fall		47.2	102.9	0.34	150.4
	Spring		-	-	-	-
	Control (no N)		40.6	37.5	0.17	78.4
	Early fall w/ inhibitors		45.5	84.1	0.17	129.7
	LSD ($\alpha = 0.05$)[y]		-	-	-	-
Landscape position means						
High			42.1	120.0a	0.19	162.3
Low			44.2	84.7b	0.22	129.0
LSD ($\alpha = 0.10$)			-[x]	16.3	ns	-[x]
	Fertilization means					
	Early fall		40.6	120.6a	0.068b	161.3a
	Mid fall		46.7	113ab	0.46a	160.2a
	Late fall		44.3	118.8ab	0.30ab	163.4a
	Spring		-	-	-	-
	Control (no N)		40.0	53.8c	0.083b	92.8b
	Early fall w/ inhibitors		44.9	105.5b	0.11b	150.5a
	LSD ($\alpha = 0.05$)		-[w]	13.8	0.28	15.7
ANOVA		**df**	***P* > F**			
Site year		2	0.0021*	0.0533	0.0017*	0.0242*
Landpos		1	0.5858	0.0015*	0.8485	0.0063*
Site year*Landpos		2	0.0916†	0.2632	0.7972	0.0976†
Trt		4	0.0108*	0.0001*	0.0275*	0.0001*
Site year*Trt		8	0.0265*	0.1394	0.1502	0.1331
Landpos*Trt		4	0.699	0.7785	0.7838	0.7919
Site year*Landpos*Trt		8	0.868	0.265	0.2351	0.3219
Block(Site year*Landpos)		18	0.0001*	0.0001*	0.1303	0.0001*
Residual C.V. (%)			19.39	23.36	238.98	18.75

a-c Mean values followed by the same letter (within columns) are not significantly different.

[z] Assuming a bulk density of 1.24 g cm^{-3} for 0-15 cm depth and 1.33 g cm^{-3} for 15-120 cm.

[y] LSD for individual treatments within a landscape position is not reported b/c there was no Landpos*Trt interaction.

[x] LSD is not reported b/c of significant Site year *Landpos interaction.

[w] LSD is not reported b/c of significant Site year *Trt interaction.

† Significant at $P < 0.10$ (used only for landscape position variables and interactions).

* Significant at $P < 0.05$.

Appendix L

Analysis of Variance and LSDs for the Effects of Landscape Position, Application Date and Inhibitors on the Mean Recovery of Soil Mineral N at Harvest (0-120cm) at All Intensive Sites, Red River Valley and 2001/2002 Sites Only

Table L.1. Effect of landscape position, application date, and inhibitors on the total extractable mineral N at harvest at all four intensive sites: 0-120 cm soil depth

Treatment: Landscape position	Treatment: Fertilization	Harvest sampling date: Total NH_4^+-N ($kg\ ha^{-1}$)[z]	Total NO_3^--N ($kg\ ha^{-1}$)[z]	Total NO_2-N ($kg\ ha^{-1}$)[z]	Total inorganic N ($kg\ ha^{-1}$)[z]
High	Early fall	120.5	69.6	1.5	191.6
	Mid fall	112.3	72.0	1.5	185.8
	Late fall	114.4	78.6	1.2	194.2
	Spring	108.0	81.5	1.3	190.8
	Control (no N)	114.4	55.9	1.3	171.6
	Early fall w/ inhibitors	113.2	84.9	1.6	199.7
	LSD (α = 0.05)	ns	-[y]	-[y]	-[y]
Low	Early fall	137.2a	27.1	2.4	166.6
	Mid fall	130.7bc	35.1	3.2	169.0
	Late fall	151.3a	39.3	2.8	193.4
	Spring	142.5ab	30.8	2.7	176.0
	Control (no N)	140.1b	26.3	2.1	168.6
	Early fall w/ inhibitors	122.8c	33.2	2.5	158.6
	LSD (α = 0.05)	na[x]	-[y]	-[y]	-[y]
Landscape position means					
High		113.8	73.8a	1.4	189.0
Low		137.4	32.0b	2.6	172.0
LSD (α = 0.10)		-[v]	22.9	-[w]	ns
	Fertilization means				
	Early fall	128.8	48.3	1.9	179.1
	Mid fall	121.5	53.6	2.3	177.4
	Late fall	132.8	58.9	2.0	193.8
	Spring	125.2	56.2	2.0	183.4
	Control (no N)	127.2	41.1	1.7	170.1
	Early fall w/ inhibitors	118.0	59.0	2.0	179.1
	LSD (α = 0.05)	-[v]	10.6	ns	ns
ANOVA	**df**	**$P > F$**			
Site year	3	0.0001*	0.3342	0.0001*	0.009*
Landpos	1	0.0402*	0.0046*	0.0241*	0.3607
Site year*Landpos	3	0.8791	0.1099	0.0027*	0.1752
Trt	5	0.0877	0.0331*	0.4169	0.0855
Site year*Trt	15	0.2909	0.5424	0.2901	0.4258
Landpos*Trt	5	0.0819†	0.4667	0.4919	0.1202
Site year*Landpos*Trt	15	0.179	0.7548	0.5848	0.6383
Block(Site year*Landpos)	24	0.0001*	0.0001*	0.0001*	0.0001*
Residual C.V. (%)		16.99	47.19	56.52	17.44

a-c Mean values followed by the same letter (within columns) are not significantly different.

[z] Assuming a bulk density of 1.24 g cm^{-3} for 0-15 cm depth and 1.33 g cm^{-3} for 15-120 cm.

[y] LSD for individual treatments within a landscape position is not reported b/c there was no Landpos*Trt interaction.

[x] Not applicable b/c used LSMEANS which does not report an LSD value.

[w] LSD is not reported b/c of significant Site year*Landpos interaction.

[v] LSD is not reported b/c of significant Landpos*Trt interaction.

† Significant at $P < 0.10$ (used only for landscape position variables and interactions).

* Significant at $P < 0.05$.

Table L.2. Effect of landscape position, application date, and inhibitors on the total extractable mineral N at harvest at the intensive sites situated in the Red River Valley only: 0-120 cm soil depth

Treatment		Harvest sampling date			
Landscape position	Fertilization	Total NH_4^+-N ($kg\ ha^{-1}$)[z]	Total NO_3^--N ($kg\ ha^{-1}$)[z]	Total NO_2-N ($kg\ ha^{-1}$)[z]	Total inorganic N ($kg\ ha^{-1}$)[z]
High	Early fall	145.5	61.9	2.0	209.4
	Mid fall	134.6	71.0	2.0	207.6
	Late fall	136.9	63.2	1.7	201.8
	Spring	130.9	74.2	1.7	206.8
	Control (no N)	136.5	46.1	1.3	183.8
	Early fall w/ inhibitors	135.1	68.4	2.1	205.6
	LSD (α = 0.05)[y]	-	-	-	-
Low	Early fall	160.1	27.3	3.2	190.5
	Mid fall	160.5	39.3	4.2	204.0
	Late fall	181.0	40.7	3.7	225.4
	Spring	169.0	31.8	3.6	204.4
	Control (no N)	167.4	25.9	2.8	196.1
	Early fall w/ inhibitors	148.8	34.7	3.4	186.9
	LSD (α = 0.05)[y]	-	-	-	-
Landscape position means					
High		136.6b	64.1a	1.8	202.5
Low		164.5a	33.3b	3.5	201.2
LSD (α = 0.10)		24.9	26.9	-[x]	ns
	Fertilization means				
	Early fall	152.8	44.6ab	2.6	200.0
	Mid fall	147.5	55.2a	3.1	205.8
	Late fall	159.0	51.9a	2.7	213.6
	Spring	149.9	53.0a	2.7	205.6
	Control (no N)	151.9	36.0b	2.1	190.0
	Early fall w/ inhibitors	142.0	51.5a	2.7	196.2
	LSD (α = 0.05)	ns	12.9	ns	ns
ANOVA	df	$P > F$			
Site year	2	0.0004*	0.3261	0.0003*	0.0863
Landpos	1	0.0677†	0.0620†	0.0213*	0.9549
Site year*Landpos	2	0.9217	0.1253	0.0092*	0.2724
Trt	5	0.211	0.041*	0.1319	0.1525
Site year*Trt	10	0.1756	0.7545	0.5692	0.5936
Landpos*Trt	5	0.1393	0.5534	0.5938	0.138
Site year*Landpos*Trt	10	0.1637	0.7616	0.5053	0.7322
Block(Site year*Landpos)	18	0.0001*	0.0001*	0.0001*	0.0001*
Residual C.V. (%)		15.31	46.33	47.02	15.63

a,b Mean values followed by the same letter (within columns) are not significantly different.

[z] Assuming a bulk density of 1.24 g cm^{-3} for 0-15 cm depth and 1.33 g cm^{-3} for 15-120 cm.

[y] LSD for individual treatments within a landscape position is not reported b/c there was no Landpos*Trt interaction.

[x] LSD is not reported b/c of significant Site year*Landpos interaction.

† Significant at $P < 0.10$ (used only for landscape position variables and interactions).

* Significant at $P < 0.05$.

Table L.3. Effect of landscape position, application date, and inhibitors on the total extractable mineral N at harvest at the 2001/2002 intensive sites only: 0-120 cm soil depth

Treatment: Landscape position	Treatment: Fertilization		Harvest sampling date: Total NH_4^+-N ($kg\ ha^{-1}$)^z	Total NO_3^--N ($kg\ ha^{-1}$)^z	Total NO_2-N ($kg\ ha^{-1}$)^z	Total inorganic N ($kg\ ha^{-1}$)^z
High	Early fall		88.0	79.5	1.2	168.7
	Mid fall		95.0	74.8	1.2	170.9
	Late fall		91.3	88.7	0.8	180.8
	Spring		84.4	91.4	0.8	176.6
	Control (no N)		86.0	64.7	1.3	152.0
	Early fall w/ inhibitors		85.2	99.2	1.1	185.5
	LSD (α = 0.05)^y		-	-	-	-
Low	Early fall		113.8	31.5	0.8	146.0
	Mid fall		108.4	39.8	1.8	150.0
	Late fall		120.6	44.6	1.3	166.5
	Spring		113.2	33.8	0.9	147.9
	Control (no N)		119.0	28.3	0.7	148.0
	Early fall w/ inhibitors		98.5	38.2	0.9	137.6
	LSD (α = 0.05)^y		-	-	-	-
Landscape position means						
High			88.3b	83.1a	1.1	172.4
Low			112.3a	36.0b	1.1	149.3
LSD (α = 0.10)			20.2	30.2	ns	ns
	Fertilization means					
	Early fall		100.9	55.5	1.0	157.4
	Mid fall		101.7	57.3	1.5	160.5
	Late fall		105.9	66.6	1.1	173.6
	Spring		98.8	62.6	0.9	162.3
	Control (no N)		102.5	46.5	1.0	150.0
	Early fall w/ inhibitors		91.9	68.7	1.0	161.6
	LSD (α = 0.05)		ns	ns	ns	ns
ANOVA		df	$P > F$			
Site year		2	0.0001*	0.7998	0.0011*	0.0323*
Landpos		1	0.055†	0.0148*	0.98	0.3035
Site year*Landpos		2	0.6836	0.1143	0.3637	0.1255
Trt		5	0.1768	0.074	0.5853	0.1997
Site year*Trt		10	0.3124	0.5705	0.5221	0.1796
Landpos*Trt		5	0.2809	0.4849	0.3614	0.2397
Site year*Landpos*Trt		10	0.5712	0.7637	0.4148	0.6719
Block(Site year*Landpos)		18	0.0001*	0.0001*	0.0001*	0.0001*
Residual C.V. (%)			18.43	46.5	109.8	19.15

a,b Mean values followed by the same letter (within columns) are not significantly different.

^{z} Assuming a bulk density of 1.24 g cm^{-3} for 0-15 cm depth and 1.33 g cm^{-3} for 15-120 cm.

^{y} LSD for individual treatments within a landscape position is not reported b/c there was no Landpos*Trt interaction.

† Significant at $P < 0.10$ (used only for landscape position variables and interactions).

* Significant at $P < 0.05$.

Appendix M

Analysis of Variance and LSDs for the Effects of Landscape Position, Application Date and Inhibitors on the Mean Apparent Over-Winter Loss of Fertilizer N (0-60cm) at All Intensive Sites, Red River Valley and 2001/2002 Sites Only

Table M.1. Effect of landscape position, application date, and inhibitors on mean recovered mineral N at seeding and apparent over-winter loss of fertilizer N at all intensive sites: 0-60 cm soil depth

Treatment: Landscape Position	Treatment: Fertilization	Mean total NH_4^+-N (kg ha^{-1})[z]	Mean total NO_3^--N (kg ha^{-1})	Mean total inorganic N (kg ha^{-1})	Apparent recovered fertilizer N (kg ha^{-1})	Apparent overwinter loss of fertilizer N (kg ha^{-1})
High	Early fall	52.4	131.5	183.9	71.7	-8.3
	Mid fall	57.6	119.6	177.6	65.4	-14.6
	Late fall	52.2	126.7	179.1	66.9	-13.1
	Spring	-	-	-	-	-
	Control (no N)	49.3	62.9	112.2	-	-
	Early fall w/ inhibitors	54.0	121.3	175.4	63.2	-16.8
	LSD (α = 0.05)[y]	-	-	-	-	
Low	Early fall	48.9	89.7	138.8	53.4	-26.6
	Mid fall	55.4	94.7	150.5	65.1	-14.9
	Late fall	57.3	95.8	153.4	68.0	-12.0
	Spring	-	-	-	-	-
	Control (no N)	50.6	34.5	85.4	-	-
	Early fall w/ inhibitors	55.3	85.9	141.3	55.9	-24.1
	LSD (α = 0.05)[y]	-	-	-	-	
Landscape Position Means						
High		53.1	112.4a	165.6a	66.8	-13.2
Low		53.5	80.1b	133.9b	60.6	-19.4
LSD (α = 0.10)		ns	13.7	15.5	ns	
	Fertilization Means					
	Early fall	50.7bc	110.6	161.4a	62.6	-17.5
	Mid fall	56.5a	107.2	164.1a	65.3	-14.8
	Late fall	54.8ab	111.3	166.3a	67.5	-12.6
	Spring	-	-	-	-	-
	Control (no N)	49.9c	48.7	98.8b	-	-
	Early fall w/ inhibitors	54.7ab	103.6	158.4a	59.6	-20.5
	LSD (α = 0.05)	4.5	-[x]	12.4	ns	

ANOVA	df	$P > F$			df	$P > F$
Site year	3	0.0001*	0.011*	0.018*	3	0.21
Landpos	1	0.92	0.0005*	0.0018*	1	0.55
Site year*Landpos	3	0.33	0.36	0.16	3	0.63
Trt	5	0.015*	0.0001*	0.0001*	3	0.61
Site year*Trt	15	0.15	0.044*	0.07	9	0.08
Landpos*Trt	5	0.35	0.58	0.49	3	0.38
Site year*Landpos*Trt	15	0.84	0.30	0.30	9	0.20
Block(Site year*Landpos)	24	0.0001*	0.0001*	0.0001*	24	0.0001*
Residual C.V. (%)		16.8	22.6	16.7		38.8

a-c Mean values followed by the same letter (within columns) are not significantly different.

[z] Assuming a bulk density of 1.24 g cm^{-3} for 0-15 cm depth and 1.33 g cm^{-3} for 15-120 cm.

[y] LSD for individual treatments within a landscape position is not reported b/c there was no Landpos*Trt interaction.

[x] LSD is not reported b/c of significant Site year*Trt interaction.

† Significant at $P < 0.10$ (used only for landscape position variables and interactions).

* Significant at $P < 0.05$.

Table M.2. Effect of landscape position, application date, and inhibitors on mean recovered mineral N at seeding and apparent over-winter loss of fertilizer N at all Red River Valley sites only: 0-60 cm soil depth

Treatment		Mean total NH_4^+-N	Mean total NO_3^--N	Mean total inorganic N	Apparent recovered fertilizer N	Apparent overwinter loss of fertilizer N
Landscape position	Fertilization	($kg\ ha^{-1}$)[z]	($kg\ ha^{-1}$)	($kg\ ha^{-1}$)	($kg\ ha^{-1}$)	($kg\ ha^{-1}$)
High	Early fall	57.3	120.4	177.8	65.7	-14.3
	Mid fall	64.6	111.5	176.6	64.5	-15.5
	Late fall	58.0	118.7	176.9	64.8	-15.2
	Spring	-	-	-	-	-
	Control (no N)	53.2	58.9	112.1	-	-
	Early fall w/ inhibitors	57.9	115.6	173.6	61.5	-18.5
	LSD (α = 0.05)[y]	-	-	-	-	
Low	Early fall	55.8	89.3	145.3	48.5	-31.5
	Mid fall	65.9	99.0	165.4	68.6	-11.4
	Late fall	65.2	86.5	152.0	55.2	-24.8
	Spring	-	-	-	-	-
	Control (no N)	57.6	38.8	96.8	-	-
	Early fall w/ inhibitors	65.3	90.3	155.8	59.0	-21.0
	LSD (α = 0.05)[y]	-	-	-	-	
Landscape position means						
High		62.0	105.0a	163.4a	64.1	-15.9
Low		58.2	80.8b	143.1b	57.8	-22.2
LSD (α = 0.10)		ns	17.0	19.2	ns	
	Fertilization means					
	Early fall	56.6bc	104.9a	161.6a	57.1	-22.9
	Mid fall	65.2a	105.2a	171.0a	66.6	-13.5
	Late fall	61.6ab	102.6a	164.4a	60.0	-20.0
	Spring	-	-	-	-	-
	Control (no N)	55.4c	48.9b	104.4b	-	-
	Early fall w/ inhibitors	61.6ab	103.0a	164.7a	60.3	-19.8
	LSD (α = 0.05)	5.4	11.4	13.7	ns	

ANOVA	df	$P > F$			df	$P > F$
Site year	2	0.0001*	0.0151*	0.0231*	2	0.1353
Landpos	1	0.5122	0.0236*	0.0823†	1	0.5809
Site year*Landpos	2	0.504	0.8501	0.6687	2	0.396
Trt	4	0.0030*	0.0001*	0.0001*	4	0.5665
Site year*Trt	8	0.3367	0.1037	0.1623	8	0.2814
Landpos*Trt	4	0.422	0.4017	0.5613	4	0.4467
Site year*Landpos*Trt	8	0.8808	0.2784	0.3613	8	0.3368
Block(Site year*Landpos)	18	0.0001*	0.0001*	0.0001*	18	0.0001*
Residual C.V. (%)		15.65	21.23	15.54		38.85

a-c Mean values followed by the same letter (within columns) are not significantly different.

[z] Assuming a bulk density of 1.24 g cm^{-3} for 0-15 cm depth and 1.33 g cm^{-3} for 15-120 cm.

[y] LSD for individual treatments within a landscape position is not reported b/c there was no Landpos*Trt interaction.

† Significant at $P < 0.10$ (used only for landscape position variables and interactions).

* Significant at $P < 0.05$.

Table M.3. Effect of landscape position, application date, and inhibitors on mean recovered mineral N at seeding and apparent over-winter loss of fertilizer N at all 2001/2002 sites only: 0-60 cm soil depth

Treatment: Landscape position	Treatment: Fertilization	df	Mean total NH_4^+-N (kg ha^{-1})[z]	Mean total NO_3^--N (kg ha^{-1})	Mean total inorganic N (kg ha^{-1})	df	Apparent recovered fertilizer N (kg ha^{-1})	Apparent overwinter loss of fertilizer N (kg ha^{-1})
High	Early fall		40.1	141.4	181.5		74.2	-5.8
	Mid fall		47.2	127.1	174.8		67.5	-12.5
	Late fall		41.5	134.6	176.4		69.1	-10.9
	Spring		-	-	-		-	-
	Control (no N)		37.3	70.0	107.3		-	-
	Early fall w/ inhibitors		44.3	127.0	171.3		64.0	-16.0
	LSD (α = 0.05)[y]		-	-	-		-	
Low	Early fall		41.2	99.9	141.1		62.7	-17.3
	Mid fall		46.3	98.9	145.6		67.2	-12.8
	Late fall		47.2	102.9	150.4		72.0	-8.0
	Spring		-	-	-		-	-
	Control (no N)		40.6	37.5	78.4		-	-
	Early fall w/ inhibitors		45.5	84.1	129.7		51.3	-28.7
	LSD (α = 0.05)[y]		-	-	-		-	
Landscape position means								
High			42.1	120.0a	162.3		68.7	-11.3
Low			44.2	84.7b	129.0		63.3	-16.7
LSD (α = 0.10)			-[x]	16.3	-[x]		ns	
	Fertilization means							
	Early fall		40.6	120.6a	161.3a		68.5	-11.6
	Mid fall		46.7	113ab	160.2a		67.4	-12.7
	Late fall		44.3	118.8ab	163.4a		70.6	-9.4
	Spring		-	-	-		-	-
	Control (no N)		40.0	53.8c	92.8b		-	-
	Early fall w/ inhibitors		44.9	105.5b	150.5a		57.7	-22.4
	LSD (α = 0.05)		-[w]	13.8	15.7		ns	
ANOVA		df		$P > F$		df	$P > F$	
Site year		2	0.0021*	0.0533	0.0242*	2	0.2032	
Landpos		1	0.5858	0.0015*	0.0063*	1	0.6812	
Site year*Landpos		2	0.0916†	0.2632	0.0976†	2	0.507	
Trt		4	0.0108*	0.0001*	0.0001*	4	0.3682	
Site year*Trt		8	0.0265*	0.1394	0.1331	8	0.1709	
Landpos*Trt		4	0.699	0.7785	0.7919	4	0.6743	
Site year*Landpos*Trt		8	0.868	0.265	0.3219	8	0.2483	
Block(Site year*Landpos)		18	0.0001*	0.0001*	0.0001*	18	0.0001*	
Residual C.V. (%)			19.39	23.36	18.75		40.8	

a-c Mean values followed by the same letter (within columns) are not significantly different.

[z] Assuming a bulk density of 1.24 g cm^{-3} for 0-15 cm depth and 1.33 g cm^{-3} for 15-120 cm.

[y] LSD for individual treatments within a landscape position is not reported b/c there was no Landpos*Trt interaction.

[x] LSD for is not reported b/c of significant Site year*Landpos interaction.

[w] LSD for is not reported b/c of significant Site year*Trt interaction.

† Significant at $P < 0.10$ (used only for landscape position variables and interactions).

* Significant at $P < 0.05$.

Appendix N

Analysis of Variance and LSDs for the Effects of Landscape Position, Application Date and Inhibitors on the Total Recovered N in the Crop and Soil (0-120 cm) and Overall N Budget at Harvest at the Individual Intensive Sites, All Intensive Sites, Red River Valley and 2001/2002 Sites Only

Table N.1. Effect of landscape position, application date, and inhibitors on total recovered N in the crop and soil and overall N budget at harvest at Kane 2000/2001

Treatment: Landscape position	Treatment: Fertilization	Total crop N uptake (kg ha^{-1})	Total inorganic soil N at harvest (0-120cm) (kg ha^{-1})	Total recovered N in crop and soil (0-120cm) (kg ha^{-1})	Apparent recovered fertilizer N (0-120cm) (kg ha^{-1})	Overall efficiency of recovered fertilizer N (%)
High	Early fall	135.6	260.3	395.9	78.9	99
	Mid fall	124.9	230.6	355.5	38.5	48
	Late fall	130.2	234.3	364.5	47.6	59
	Spring	125.9	233.3	359.2	42.3	53
	Control (no N)	86.7	230.3	317.0	-	-
	Early fall w/ inhibitors	122.0	242.2	364.2	47.2	59
	LSD (α = 0.05)[y]	-	-	-	-	
Low	Early fall	98.0	228.3	326.3	29.3	37
	Mid fall	103.3	226.0	329.2	32.2	40
	Late fall	118.4	274.2	392.5	95.5	119
	Spring	112.3	260.2	372.5	75.5	94
	Control (no N)	66.9	230.1	297.0	-	-
	Early fall w/ inhibitors	111.1	221.3	332.4	35.4	44
	LSD (α = 0.05)[y]	-	-	-	-	
Landscape position means						
High		120.9a	238.5	359.4	50.9	64
Low		101.6b	240.0	341.7	53.6	67
LSD (α = 0.10)		9.6	ns	ns	ns	
	Fertilization means					
	Early fall	116.8a	244.3	361.1a	54.1	68
	Mid fall	114.1a	228.3	342.4ab	35.4	44
	Late fall	124.3a	254.2	378.5a	71.5	89
	Spring	119.1a	246.8	365.9a	58.9	74
	Control (no N)	76.8b	230.2	307.0b	-	-
	Early fall w/ inhibitors	116.5a	231.8	348.3a	41.3	52
	LSD (α = 0.05)	11.5	ns	36.8	ns	

ANOVA	df		$P > F$		df	$P > F$
Landpos	1	0.0082*	0.9631	0.6188	1	0.8819
Trt	5	0.0001*	0.5505	0.0085*	4	0.3797
Landpos*Trt	5	0.198	0.2688	0.1328	4	0.1267
Block(Landpos)	6	0.0573†	0.0001*	0.0001*	6	0.1138
Residual C.V. (%)		10.11	13.94	10.28		74.14

a,b Mean values followed by the same letter (within columns) are not significantly different.

[y] LSD for individual treatments within a landscape position is not reported b/c there was no Landpos*Trt interaction.

† Significant at $P < 0.10$ (used only for landscape position variables and interactions).

* Significant at $P < 0.05$.

Table N.2. Effect of landscape position, application date, and inhibitors on total recovered N in the crop and soil and overall N budget at harvest at Kane 2001/2002

Treatment: Landscape position	Treatment: Fertilization	Total crop N uptake (kg ha^{-1})	Total inorganic soil N at harvest (0-120cm) (kg ha^{-1})	Total recovered N in crop and soil (0-120cm) (kg ha^{-1})	Apparent recovered fertilizer N (0-120cm) (kg ha^{-1})	Overall efficiency of recovered fertilizer N (%)
High	Early fall	80.4	203.1	283.5	43.9	55
	Mid fall	90.8	204.9	295.7	56.0	70
	Late fall	86.4	215.4	301.8	62.1	78
	Spring	87.6	210.6	298.2	58.5	73
	Control (no N)	52.3	187.4	239.7	-	-
	Early fall w/ inhibitors	84.1	216.4	300.5	60.8	76
	LSD (α = 0.05)[y]	-	-	-	-	
Low	Early fall	104.2	164.9	269.1	54.8	69
	Mid fall	106.8	155.2	262.0	47.7	60
	Late fall	109.0	174.3	283.3	69.0	86
	Spring	115.2	150.3	265.4	51.2	64
	Control (no N)	52.1	162.2	214.2	-	-
	Early fall w/ inhibitors	99.5	141.3	240.9	26.6	33
	LSD (α = 0.05)[y]	-	-	-	-	
Landscape position means						
High		80.3	206.3	286.6	56.3	70
Low		97.8	158.0	255.8	49.9	62
LSD (α = 0.10)		ns	ns	ns	ns	
	Fertilization means					
	Early fall	92.3a	184.0	276.3a	49.3	62
	Mid fall	98.8a	180.1	278.9a	51.9	65
	Late fall	97.7a	194.9	292.6a	65.6	82
	Spring	101.4a	180.4	281.8a	54.9	69
	Control (no N)	52.2b	174.8	227.0b	-	-
	Early fall w/ inhibitors	91.8a	178.9	270.7a	43.7	55
	LSD (α = 0.05)	19.1	ns	34.2	ns	

ANOVA	df		$P > F$		df	$P > F$
Landpos	1	0.3207	0.3734	0.5509	1	0.7108
Trt	5	0.0001*	0.7652	0.0096*	4	0.8020
Landpos*Trt	5	0.7324	0.5361	0.8024	4	0.7451
Block(Landpos)	6	0.0001*	0.0001*	0.0001*	6	0.0934†
Residual C.V. (%)		23.07	14.95	12.34		67.60

a,b Mean values followed by the same letter (within columns) are not significantly different.

[y] LSD for individual treatments within a landscape position is not reported b/c there was no Landpos*Trt interaction.

† Significant at $P < 0.10$ (used only for landscape position variables and interactions).

* Significant at $P < 0.05$.

Table N.3. Effect of landscape position, application date, and inhibitors on total recovered N in the crop and soil and overall N budget at harvest at Rosser 2001/2002

Treatment: Landscape position	Treatment: Fertilization	Total crop N uptake (kg ha^{-1})	Total inorganic soil N at harvest (0-120cm) (kg ha^{-1})	Total recovered N in crop and soil (0-120cm) (kg ha^{-1})	Apparent recovered fertilizer N (0-120cm) (kg ha^{-1})	Overall efficiency of recovered fertilizer N (%)
High	Early fall	110.2	164.9	275.0	52.7	66
	Mid fall	122.6	187.4	310.1	87.7	110
	Late fall	126.6	155.6	282.1	59.8	75
	Spring	132.4	176.4	308.9	86.5	108
	Control (no N)	88.5	133.9	222.4	-	-
	Early fall w/ inhibitors	118.0	158.1	276.1	53.7	67
	LSD (α = 0.05)[y]	-	-	-	-	
Low	Early fall	60.1	178.4	238.5	-8.6	-11
	Mid fall	64.1	230.8	294.9	47.8	60
	Late fall	75.3	227.9	303.2	56.1	70
	Spring	82.6	202.7	285.2	38.1	48
	Control (no N)	51.0	196.1	247.1	-	-
	Early fall w/ inhibitors	68.5	197.9	266.4	19.3	24
	LSD (α = 0.05)[y]	-	-	-	-	
Landscape position means						
High		116.4a	162.7	279.1	68.1	85
Low		66.9b	205.6	272.6	30.5	38
LSD (α = 0.10)		43.7	ns	ns	ns	
	Fertilization means					
	Early fall	85.1b	171.6	256.7bc	21.9	27
	Mid fall	93.4ab	209.1	302.5a	67.7	85
	Late fall	100.9a	191.7	292.6ab	57.8	72
	Spring	107.5a	189.5	297.0a	62.2	78
	Control (no N)	69.8c	165.0	234.8c	-	-
	Early fall w/ inhibitors	93.2ab	178.0	271.2abc	36.4	46
	LSD (α = 0.05)	15.2	ns	38.2	ns	

ANOVA	df		$P > F$		df	$P > F$
Landpos	1	0.0703†	0.2117	0.8931	1	0.3734
Trt	5	0.0004*	0.1428	0.0066*	4	0.0567
Landpos*Trt	5	0.8339	0.5285	0.5186	4	0.5225
Block(Landpos)	6	0.0001*	0.0001*	0.0001*	6	0.0001*
Residual C.V. (%)		16.21	18.25	13.58		67.83

a-c Mean values followed by the same letter (within columns) are not significantly different.

[y] LSD for individual treatments within a landscape position is not reported b/c there was no Landpos*Trt interaction.

† Significant at $P < 0.10$ (used only for landscape position variables and interactions).

* Significant at $P < 0.05$.

Table N.4. Effect of landscape position, application date, and inhibitors on total recovered N in the crop and soil and overall N budget at harvest at Brandon 2001/2002

Treatment: Landscape position	Treatment: Fertilization	Total crop N uptake (kg ha^{-1})	Total inorganic soil N at harvest (0-120cm) (kg ha^{-1})	Total recovered N in crop and soil (0-120cm) (kg ha^{-1})	Apparent recovered fertilizer N (0-120cm) (kg ha^{-1})	Overall efficiency of recovered fertilizer N (%)
High	Early fall	139.1	138.3	277.3	44.2	55
	Mid fall	129.5	120.4	249.9	16.8	21
	Late fall	122.4	171.4	293.9	60.8	76
	Spring	126.2^{z}	142.8	247.5^{z}	13.2^{z}	17
	Control (no N)	98.4	134.7	233.1	-	-
	Early fall w/ inhibitors	125.8	181.9	307.8	74.7	93
	LSD (α = 0.05)^{y}	-	-	-	-	
Low	Early fall	70.3	94.8	165.1	40.5	51
	Mid fall	62.5	63.9	126.4	1.8	2
	Late fall	78.0	97.2	175.2	50.6	63
	Spring	74.9	90.5	165.7	41.1	51
	Control (no N)	38.7	85.9	124.6	-	-
	Early fall w/ inhibitors	66.6	73.7	140.3	15.6	20
	LSD (α = 0.05)^{y}	-	-	-	-	
Landscape position means						
High		123.6a	148.3a	268.2a	41.9	52
Low		65.2b	84.4b	149.6b	29.9	37
LSD (α = 0.10)		na^{x}	55.4	na^{x}	ns	
	Fertilization means					
	Early fall	104.7a	116.5	221.2ab	42.3	53
	Mid fall	96.0a	92.2	188.2bc	9.3	12
	Late fall	100.2a	134.3	234.5a	55.6	70
	Spring	100.5a	116.8	206.6abc	27.2	34
	Control (no N)	68.6b	110.3	178.9c	-	-
	Early fall w/ inhibitors	96.2a	127.8	224.0ab	45.1	56
	LSD (α = 0.05)	na^{x}	ns	na^{x}	ns	

ANOVA	df	$P > F$			df	$P > F$
Landpos	1	0.0008*	0.0664†	0.0085*	1	0.6681
Trt	5	0.0007	0.1511	0.0314*	4	0.1461
Landpos*Trt	5	0.5942	0.3351	0.3734	4	0.2921
Block(Landpos)	6	0.0025*	0.0001*	0.0001*	6	0.002*
Residual C.V. (%)		16.03	26.90	17.42		99.90

a-c Mean values followed by the same letter (within columns) are not significantly different.

^{z}Brandon 2001/2002 had 1 missing spring sample in the high landscape position: therefore values estimated by SAS.

^{y} LSD for individual treatments within a landscape position is not reported b/c there was no Landpos*Trt interaction.

^{x} Not applicable becaused LSMEANS was used, which does not provide an LSD.

† Significant at P < 0.10 (used only for landscape position variables and interactions).

* Significant at P < 0.05.

Table N.5. Effect of landscape position, application date, and inhibitors on total recovered N in the crop and soil and overall N budget at harvest at all intensive sites

Treatment: Landscape position	Fertilization	Mean total crop N uptake (kg ha^{-1})	Mean total inorganic soil N at harvest (0-120cm) (kg ha^{-1})	Mean total recovered N in crop and soil (0-120cm) (kg ha^{-1})	Apparent recovered fertilizer N (0-120cm) (kg ha^{-1})	Overall efficiency of recovered fertilizer N (%)
High	Early fall	116.3	191.6	307.9a	54.8	69
	Mid fall	117.0	185.8	302.8a	49.7	62
	Late fall	116.4	194.2	310.6a	57.5	72
	Spring	118.0[v]	190.8	303.4a[v]	50.1[v]	63
	Control (no N)	81.5	171.6	253.1b	-	-
	Early fall w/ inhibitors	112.5	199.7	312.2a	59.1	74
	LSD (α = 0.05)	-[y]	-[y]	na[z]	ns	
Low	Early fall	83.1	166.6	249.7bc	28.9bc	36
	Mid fall	84.1	169.0	253.1bc	32.3bc	40
	Late fall	95.2	193.4	288.6a	67.8a	85
	Spring	96.2	176.0	272.2ab	51.4a	64
	Control (no N)	52.2	168.6	220.8d	-	-
	Early fall w/ inhibitors	86.4	158.6	245.0cd	24.2c	30
	LSD (α = 0.05)	-[y]	-[y]	na[z]	na[z]	
Landscape position means						
High		110.3a	189.0	298.3	54.3	68
Low		82.9b	172.0	254.9	40.9	51
LSD (α = 0.10)		-[x]	ns	-[w]	-[w]	
	Fertilization means					
	Early fall	99.7ab	179.1	278.8	41.9	52
	Mid fall	100.5ab	177.4	277.9	41.0	51
	Late fall	105.8ab	193.8	299.6	62.7	78
	Spring	107.1a	183.4	287.8	50.8	64
	Control (no N)	66.8c	170.1	236.9	-	-
	Early fall w/ inhibitors	99.4b	179.1	278.5	41.6	52
	LSD (α = 0.05)	na[z]	ns	-[w]	-[w]	

ANOVA	df	P > F	P > F	P > F	df	P > F
Site year	3	0.1675	0.0009*	0.0007*	3	0.7847
Landpos	1	0.0012*	0.3607	0.0437*	1	0.3237
Site year*Landpos	3	0.0059*	0.1752	0.2279	3	0.7337
Trt	5	0.0001*	0.0855	0.0001*	4	0.0848
Site year*Trt	15	0.4548	0.4258	0.3819	12	0.2629
Landpos*Trt	5	0.4561	0.1202	0.0954†	4	0.0835†
Site year*Landpos*Trt	15	0.8432	0.6383	0.6516	12	0.5359
Block(Site year*Landpos)	24	0.0001*	0.0001*	0.0001*	24	0.0001*
Residual C.V. (%)		15.75	17.44	12.95		75.66

a-c Mean values followed by the same letter (within columns) are not significantly different.

[z] Used LSMEANS which does not provide an LSD value.

[y] LSD for individual treatments within a landscape position is not reported b/c there was no Landpos*Trt interaction.

[x] LSD is not reported b/c of Site year*Landpos interaction.

[w] LSD is not reported b/c of Landpos*Trt interaction.

[v] Brandon 2001/2002 had 1 missing spring sample in the high landscape position: therefore values estimated by SAS.

† Significant at P < 0.10 (used only for landscape position variables and interactions).

* Significant at P < 0.05.

Table N.6. Effect of landscape position, application date, and inhibitors on total recovered N in the crop and soil and overall N budget at harvest at all Red River valley intensive sites only

Treatment: Landscape position	Treatment: Fertilization	Mean total crop N uptake ($kg\ ha^{-1}$)	Mean total inorganic soil N at harvest (0-120cm) ($kg\ ha^{-1}$)	Mean total recovered N in crop and soil (0-120cm) ($kg\ ha^{-1}$)	Apparent recovered fertilizer N (0-120cm) ($kg\ ha^{-1}$)	Overall efficiency of recovered fertilizer N (%)
High	Early fall	108.7	209.4	318.1	58.5	73
	Mid fall	112.8	207.6	320.4	60.8	76
	Late fall	114.4	201.8	316.2	56.6	71
	Spring	115.3	206.8	322.1	62.5	78
	Control (no N)	75.8	183.8	259.6	-	-
	Early fall w/ inhibitors	108.0	205.6	313.6	54.0	68
	LSD ($\alpha = 0.05$)[y]	-	-	-	-	
Low	Early fall	87.4	190.5	277.9	25.1	31
	Mid fall	91.4	204.0	295.4	42.6	53
	Late fall	100.9	225.4	326.3	73.5	92
	Spring	103.4	204.4	307.8	55.0	69
	Control (no N)	56.7	196.1	252.8	-	-
	Early fall w/ inhibitors	93.0	186.9	279.9	27.1	34
	LSD ($\alpha = 0.05$)[y]	-	-	-	-	
Landscape position means						
High		105.8	202.5	308.3	58.5	73
Low		88.8	201.2	290.0	44.7	56
LSD ($\alpha = 0.10$)		-[x]	ns	ns	ns	
	Fertilization means					
	Early fall	98.1c	200.0	298.1b	41.9	52
	Mid fall	102.1abc	205.8	307.9ab	51.7	65
	Late fall	107.6ab	213.6	321.2a	65.0	81
	Spring	109.3a	205.6	314.9ab	58.7	73
	Control (no N)	66.2d	190.0	256.2c	-	-
	Early fall w/ inhibitors	100.5bc	196.2	296.7b	40.5	51
	LSD ($\alpha = 0.05$)	8.7	ns	20.5	ns	

ANOVA	df	Mean total crop N uptake $P > F$	Mean total inorganic soil N $P > F$	Mean total recovered N $P > F$	df	Apparent recovered fertilizer N $P > F$
Site year	2	0.1358	0.0863	0.0322*	2	0.9776
Landpos	1	0.0859†	0.9549	0.4752	1	0.3781
Site year*Landpos	2	0.0306*	0.2724	0.9257	2	0.5389
Trt	5	0.0001*	0.1525	0.0001*	4	0.0938
Site year*Trt	10	0.4238	0.5936	0.6494	8	0.4849
Landpos*Trt	5	0.8231	0.138	0.163	4	0.1387
Site year*Landpos*Trt	10	0.6035	0.7322	0.6189	8	0.5636
Block(Site year*Landpos)	18	0.0001*	0.0001*	0.0001*	18	0.0001*
Residual C.V. (%)		15.66	15.63	11.93		70.01

a-d Mean values followed by the same letter (within columns) are not significantly different.

[y] LSD for individual treatments within a landscape position is not reported b/c there was no Landpos*Trt interaction.

[x] LSD is not reported b/c of Site year*Landpos interaction.

† Significant at $P < 0.10$ (used only for landscape position variables and interactions).

* Significant at $P < 0.05$.

Table N.7. Effect of landscape position, application date, and inhibitors on total recovered N in the crop and soil and overall N budget at harvest at all 2001/2002 intensive sites only

Treatment: Landscape position	Treatment: Fertilization	df	Mean total crop N uptake ($kg\ ha^{-1}$)	Mean total inorganic soil N at harvest (0-120cm) ($kg\ ha^{-1}$)	Mean total recovered N in crop and soil (0-120cm) ($kg\ ha^{-1}$)	df	Apparent recovered fertilizer N (0-120cm) ($kg\ ha^{-1}$)	Overall efficiency of recovered fertilizer N (%)
High	Early fall		109.9	168.7	278.6		46.9	59
	Mid fall		114.3	170.9	285.2		53.5	67
	Late fall		111.8	180.8	292.6		60.9	76
	Spring		115.4^{w}	176.6	284.8^{w}		52.7^{w}	66
	Control (no N)		79.7	152.0	231.7		-	-
	Early fall w/ inhibitors		109.3	185.5	294.8		63.1	79
	LSD ($\alpha = 0.05$)^{y}		-	-	-		-	
Low	Early fall		78.2	146.0	224.2		28.9	36
	Mid fall		77.8	150.0	227.8		32.5	41
	Late fall		87.4	166.5	253.9		58.6	73
	Spring		90.9	147.9	238.8		43.5	54
	Control (no N)		47.3	148.0	195.3		-	-
	Early fall w/ inhibitors		78.2	137.6	215.8		20.5	26
	LSD ($\alpha = 0.05$)^{y}		-	-	-		-	
Landscape position means								
High			106.7	172.4	278.0a		55.4	69
Low			76.6	149.3	225.9b		36.8	46
LSD ($\alpha = 0.10$)			$-^{x}$	ns	na^{z}		ns	
	Fertilization means							
	Early fall		94.0a	157.4	251.4b		38.0	48
	Mid fall		96.0a	160.5	256.5ab		43.1	54
	Late fall		99.6a	173.6	273.2a		59.8	75
	Spring		103.1a	162.3	261.8ab		48.1	60
	Control (no N)		63.4b	150.0	213.4c		-	-
	Early fall w/ inhibitors		93.8a	161.6	255.4ab		42.0	53
	LSD ($\alpha = 0.05$)		na^{z}	ns	na^{z}		ns	
ANOVA		df		$P > F$		df	$P > F$	
Site year		2	0.9064	0.0323*	0.075	2	0.6869	
Landpos		1	0.0065*	0.3035	0.0502†	1	0.2788	
Site year*Landpos		2	0.01*	0.1255	0.1824	2	0.7208	
Trt		5	0.0001*	0.1997	0.0001*	4	0.2554	
Site year*Trt		10	0.3891	0.1796	0.1784	8	0.1048	
Landpos*Trt		5	0.7687	0.2397	0.3456	4	0.3595	
Site year*Landpos*Trt		10	0.807	0.6719	0.7336	8	0.6054	
Block(Site year*Landpos)		18	0.0001*	0.0001*	0.0001*	18	0.0001*	
Residual C.V. (%)			18.01	19.15	14.189		76.14	

a-c Mean values followed by the same letter (within columns) are not significantly different.

^{z}Not applicable because used LSMEANS, which does not provide an LSD value.

^{y} LSD for individual treatments within a landscape position is not reported b/c there was no Landpos*Trt interaction.

^{x} LSD is not reported b/c of Site year*Landpos interaction.

^{w}Brandon 2001/2002 had 1 missing spring sample in the high landscape position: therefore values estimated by SAS.

† Significant at $P < 0.10$ (used only for landscape position variables and interactions).

* Significant at $P < 0.05$.

Appendix O

KANE (2000/01): BAND ZONE DATA (mg kg^{-1}): 0–15 cm

Table O.1. Effect of landscape position, application date, and inhibitors on soil pH at Kane 2000/2001: Bandrow (0-15 cm)

Treatment			pH		
			Sampling Date		
Landscape Position	Fertilization		10/12/00		10/26/00
High	Early fall		7.40		7.30
	Mid fall		-		7.33
	Late fall		-		-
	Spring		-		-
	Control (no N)		7.33		7.30
	Early fall w/ inhibitors		7.48		7.38
	LSD ($\alpha = 0.05$)[z]		-		-
Low	Early fall		7.80		7.62
	Mid fall		-		7.73
	Late fall		-		-
	Spring		-		-
	Control (no N)		7.80		7.73
	Early fall w/ inhibitors		7.78		7.68
	LSD ($\alpha = 0.05$)[z]		-		-
Landscape Position Means					
High			7.40b		7.33
Low			7.79a		7.69
LSD ($\alpha = 0.10$)			0.19		ns
	Fertilization Means				
	Early fall		7.63		7.48
	Mid fall		-		7.53
	Late fall		-		-
	Spring		-		-
	Control (no N)		7.56		7.51
	Early fall w/ inhibitors		7.63		7.53
	LSD ($\alpha = 0.05$)		ns		ns
ANOVA		df	$P > F$	df	$P > F$
Landpos		1	0.007*	1	0.1266
Trt		2	0.761	3	0.9369
Landpos*Trt		2	0.594	3	0.9037
Block(Landpos)		6	0.1421	6	0.0001*
Residual C.V. (%)			2.22		2.41

a-c Mean values followed by the same letter (within columns) are not significantly different.

[z] LSD for individual treatments in individual site years is not reported because there was no Landpos*Trt interaction.

† significant at $P < 0.10$ (used only for landscape position variables and interactions).

* significant at $P < 0.05$.

Table O.2. Effect of landscape position, application date, and inhibitors on soil EC at Kane 2000/2001: Bandrow (0-15 cm)

Treatment		EC (mS cm^{-1})			
		Sampling Date			
Landscape Position	Fertilization		10/12/00		10/26/00
High	Early fall		0.70		0.88
	Mid fall		-		0.60
	Late fall		-		-
	Spring		-		-
	Control (no N)		0.63		0.58
	Early fall w/ inhibitors		0.90		0.73
	LSD (α = 0.05)[z]		-		-
Low	Early fall		0.78		0.75
	Mid fall		-		0.65
	Late fall		-		-
	Spring		-		-
	Control (no N)		0.45		0.60
	Early fall w/ inhibitors		0.78		0.63
	LSD (α = 0.05)[z]		-		-
Landscape Position Means					
High			0.74		0.69
Low			0.67		0.65
LSD (α = 0.10)			ns		ns
	Fertilization Means				
	Early fall		0.74a		0.81a
	Mid fall		-		0.63b
	Late fall		-		-
	Spring		-		-
	Control (no N)		0.54b		0.59b
	Early fall w/ inhibitors		0.84a		0.68b
	LSD (α = 0.05)		0.18		0.13
ANOVA		df	*P* > F	df	*P* > F
Landpos		1	0.1055	1	0.6140
Trt		2	0.0114*	3	0.0126*
Landpos*Trt		2	0.3219	3	0.4362
Block(Landpos)		6	0.9074	6	0.0648†
Residual C.V. (%)			23.78		18.84

a,b Mean values followed by the same letter (within columns) are not significantly different.

[z] LSD for individual treatments in individual site years is not reported because there was no Landpos*Trt interaction.

† significant at $P < 0.10$ (used only for landscape position variables and interactions).

* significant at $P < 0.05$.

Table O.3. Total inorganic N in the bandrow at Kane 2000/2001: 0-15 cm soil depth

Treatment			Total inorganic-N (mg kg^{-1}) Sampling Date		
Landscape Position	Fertilization		10/12/00		10/26/00
High	Early fall		96.8		102.0
	Mid fall		-		103.5
	Late fall		-		-
	Spring		-		-
	Control (no N)		13.0		22.6
	Early fall w/ inhibitors		90.8		103.3
	LSD ($\alpha = 0.05$)[z]		-		-
Low	Early fall		73.3		90.0
	Mid fall		-		131.8
	Late fall		-		-
	Spring		-		-
	Control (no N)		15.3		23.2
	Early fall w/ inhibitors		79.0		109.5
	LSD ($\alpha = 0.05$)[z]		-		-
Landscape Position Means					
High			66.8		82.8
Low			55.8		88.6
LSD ($\alpha = 0.10$)			ns		ns
	Fertilization Means				
	Early fall		85.0a		96.0b
	Mid fall		-		117.6a
	Late fall		-		-
	Spring		-		-
	Control (no N)		14.1b		22.9c
	Early fall w/ inhibitors		84.9a		106.4ab
	LSD ($\alpha = 0.05$)		15.6		16.2
ANOVA		df	$P > F$	df	$P > F$
Landpos		1	0.2448	1	0.1913
Trt		2	0.0001*	3	0.0001*
Landpos*Trt		2	0.2379	3	0.1025
Block(Landpos)		6	0.1246	6	0.7837
Residual C.V. (%)			23.33		17.94

a-c Mean values followed by the same letter (within columns) are not significantly different.

[z] LSD for individual treatments in individual site years is not reported because there was no Landpos*Trt interaction.

† significant at $P < 0.10$ (used only for landscape position variables and interactions).

* significant at $P < 0.05$.

Table O.4. Total extractable NH_4^+-N in the bandrow at Kane 2000/2001: 0-15 cm soil depth

Treatment			Total extractable NH_4^+-N (mg kg^{-1})		
			Sampling Date		
Landscape Position	Fertilization		10/12/00		10/26/00
High	Early fall		72.5		61.8
	Mid fall		-		74.3
	Late fall		-		-
	Spring		-		-
	Control (no N)		9.3		16.5
	Early fall w/ inhibitors		70.3		74.0
	LSD (α = 0.05)[z]		-		-
Low	Early fall		52.5		51.8
	Mid fall		-		97.5
	Late fall		-		-
	Spring		-		-
	Control (no N)		12.7		17.8
	Early fall w/ inhibitors		59.0		75.0
	LSD (α = 0.05)[z]		-		-
Landscape Position Means					
High			50.7		56.6
Low			41.4		60.5
LSD (α = 0.10)			ns		ns
	Fertilization Means				
	Early fall		62.5a		56.8b
	Mid fall		-		85.9a
	Late fall		-		-
	Spring		-		-
	Control (no N)		11.0b		17.1c
	Early fall w/ inhibitors		62.5a		74.5a
	LSD (α = 0.05)		15.3		13.3
ANOVA		df	$P > F$	df	$P > F$
Landpos		1	0.3116	1	0.4054
Trt		2	0.0001*	3	0.0001*
Landpos*Trt		2	0.2826	3	0.1002
Block(Landpos)		6	0.1222	6	0.4962
Residual C.V. (%)			30.55		21.67

a-c Mean values followed by the same letter (within columns) are not significantly different.
[z] LSD for individual treatments in individual site years is not reported because there was no Landpos*Trt interaction.
† significant at $P < 0.10$ (used only for landscape position variables and interactions).
* significant at $P < 0.05$.

Table O.5. Total extractable NO_3^--N in the bandrow at Kane 2000/2001: 0-15 cm soil depth

Treatment			Total extractable NO_3^--N (mg kg^{-1})		
			Sampling Date		
Landscape Position	Fertilization		10/12/00		10/26/00
High	Early fall		23.6		39.7
	Mid fall		-		28.2
	Late fall		-		-
	Spring		-		-
	Control (no N)		3.5		5.8
	Early fall w/ inhibitors		20.2		28.9
	LSD ($\alpha = 0.05$)[z]		-		-
Low	Early fall		19.7		37.1
	Mid fall		-		32.0
	Late fall		-		-
	Spring		-		-
	Control (no N)		2.2		4.9
	Early fall w/ inhibitors		19.2		33.8
	LSD ($\alpha = 0.05$)[z]		-		-
Landscape Position Means					
High			15.8		25.6
Low			13.7		26.9
LSD ($\alpha = 0.10$)			ns		ns
	Fertilization Means				
	Early fall		21.6a		38.4a
	Mid fall		-		30.1b
	Late fall		-		-
	Spring		-		-
	Control (no N)		2.9b		5.4c
	Early fall w/ inhibitors		19.7a		30.1b
	LSD ($\alpha = 0.05$)		2.7		5.7
ANOVA		df	$P > F$	df	$P > F$
Landpos		1	0.1135	1	0.4080
Trt		2	0.0001*	3	0.0001*
Landpos*Trt		2	0.4505	3	0.4597
Block(Landpos)		6	0.3477	6	0.7306
Residual C.V. (%)			16.6		20.48

a-c Mean values followed by the same letter (within columns) are not significantly different.
[z] LSD for individual treatments in individual site years is not reported because there was no Landpos*Trt interaction.
† significant at $P < 0.10$ (used only for landscape position variables and interactions).
* significant at $P < 0.05$.

Table O.6. Total extractable NO_2^--N in the bandrow at Kane 2000/2001: 0-15 cm soil depth

Treatment			Total extractable NO_2^--N (mg kg^{-1})		
			Sampling Date		
Landscape Position	Fertilization		10/12/00		10/26/00
High	Early fall		0.70		0.59
	Mid fall		-		1.04
	Late fall		-		-
	Spring		-		-
	Control (no N)		0.14		0.25
	Early fall w/ inhibitors		0.32		0.38
	LSD ($\alpha = 0.05$)[z]		-		-
Low	Early fall		1.10		1.18
	Mid fall		-		2.21
	Late fall		-		-
	Spring		-		-
	Control (no N)		0.36		0.56
	Early fall w/ inhibitors		0.79		0.75
	LSD ($\alpha = 0.05$)[z]		-		-
Landscape Position Means					
High			0.75a		0.57
Low			0.38b		1.17
LSD ($\alpha = 0.10$)			0.31		ns
	Fertilization Means				
	Early fall		0.90a		0.88b
	Mid fall		-		1.63a
	Late fall		-		-
	Spring		-		-
	Control (no N)		0.25c		0.40b
	Early fall w/ inhibitors		0.55b		0.57b
	LSD ($\alpha = 0.05$)		0.31		0.54
ANOVA		df	$P > F$	df	$P > F$
Landpos		1	0.0593†	1	0.1318
Trt		2	0.0021*	3	0.0007*
Landpos*Trt		2	0.6634	3	0.3481
Block(Landpos)		6	0.1607	6	0.0142*
Residual C.V. (%)			49.5		58.79

a-c Mean values followed by the same letter (within columns) are not significantly different.

[z] LSD for individual treatments in individual site years is not reported because there was no Landpos*Trt interaction.

† significant at $P < 0.10$ (used only for landscape position variables and interactions).

* significant at $P < 0.05$.

Table O.7. Total extractable urea-N in the bandrow at Kane 2000/2001: 0-15 cm soil depth

Treatment			Total extractable urea-N (mg kg^{-1})		
			Sampling Date		
Landscape Position	Fertilization		10/12/00		10/26/00
High	Early fall		0.83		0.50b
	Mid fall		-		1.09b
	Late fall		-		-
	Spring		-		-
	Control (no N)		0.08		0.00c
	Early fall w/ inhibitors		14.33		2.34a
	LSD ($\alpha = 0.05$)		-^{z}		na^{y}
Low	Early fall		0.75		0.33
	Mid fall		-		0.34
	Late fall		-		-
	Spring		-		-
	Control (no N)		0.08		0.00
	Early fall w/ inhibitors		3.84		0.42
	LSD ($\alpha = 0.05$)		-^{z}		na^{y}
Landscape Position Means					
High			5.08		0.98
Low			1.56		0.27
LSD ($\alpha = 0.10$)			ns		-^{x}
	Fertilization Means				
	Early fall		0.79b		0.42
	Mid fall		-		0.71
	Late fall		-		-
	Spring		-		-
	Control (no N)		0.08b		0.00
	Early fall w/ inhibitors		9.09a		1.38
	LSD ($\alpha = 0.05$)		7.10		-^{x}
ANOVA		df	$P > F$	df	$P > F$
Landpos		1	0.2259	1	0.0019*
Trt		2	0.0307*	3	0.0001*
Landpos*Trt		2	0.2205	3	0.0007*
Block(Landpos)		6	0.4871	6	0.5302
Residual C.V. (%)			196.2		64.91

a-c Mean values followed by the same letter (within columns) are not significantly different.

^{z} LSD for individual treatments in individual site years is not reported because there was no Landpos*Trt interaction.

^{y} Not applicable (na) because used LSMEANS, which does not provide an LSD value.

^{x} LSD is not reported because of Landpos*Trt interaction.

† significant at $P < 0.10$ (used only for landscape position variables and interactions).

* significant at $P < 0.05$.

Appendix P

KANE (2000/01): BAND ZONE DATA (mg kg^{-1}): 15–30 cm

Table P.1. Effect of landscape position, application date, and inhibitors on soil pH at Kane 2000/2001: Bandrow (15-30 cm)

Treatment			pH		
			Sampling Date		
Landscape Position	Fertilization		10/12/00		10/26/00
High	Early fall		8.05		8.15
	Mid fall		-		8.10
	Late fall		-		-
	Spring		-		-
	Control (no N)		8.10		8.10
	Early fall w/ inhibitors		8.13		8.13
	LSD ($\alpha = 0.05$)[z]		-		-
Low	Early fall		8.23		8.28
	Mid fall		-		8.30
	Late fall		-		-
	Spring		-		-
	Control (no N)		8.35		8.28
	Early fall w/ inhibitors		8.28		8.30
	LSD ($\alpha = 0.05$)[z]		-		-
Landscape Position Means					
High			8.09b		8.12b
Low			8.28a		8.29a
LSD ($\alpha = 0.10$)			0.12		0.13
	Fertilization Means				
	Early fall		8.14		8.21
	Mid fall		-		8.20
	Late fall		-		-
	Spring		-		-
	Control (no N)		8.23		8.19
	Early fall w/ inhibitors		8.20		8.21
	LSD ($\alpha = 0.05$)		ns		ns
ANOVA		df	$P > F$	df	$P > F$
Landpos		1	0.0237*	1	0.0414*
Trt		2	0.1757	3	0.9013
Landpos*Trt		2	0.5287	3	0.8041
Block(Landpos)		6	0.049*	6	0.0019*
Residual C.V. (%)			1.10		0.94

a,b Mean values followed by the same letter (within columns) are not significantly different.

[z] LSD for individual treatments in individual site years is not reported because there was no Landpos*Trt interaction.

† significant at $P < 0.10$ (used only for landscape position variables and interactions).

* significant at $P < 0.05$.

Table P.2. Effect of landscape position, application date, and inhibitors on soil EC at Kane 2000/2001: Bandrow (15-30 cm)

Treatment			EC (mS cm^{-1})		
			Sampling Date		
Landscape Position	Fertilization		10/12/00		10/26/00
High	Early fall		1.00		0.58
	Mid fall		-		0.53
	Late fall		-		-
	Spring		-		-
	Control (no N)		0.55		0.58
	Early fall w/ inhibitors		0.85		0.60
	LSD ($\alpha = 0.05$)^z		-		-
Low	Early fall		1.08		0.63
	Mid fall		-		0.55
	Late fall		-		-
	Spring		-		-
	Control (no N)		0.43		0.70
	Early fall w/ inhibitors		0.88		0.48
	LSD ($\alpha = 0.05$)^z		-		-
Landscape Position Means					
High			14.37		0.57
Low			13.92		0.59
LSD ($\alpha = 0.10$)			ns		ns
	Fertilization Means				
	Early fall		1.04a		0.60
	Mid fall		-		0.54
	Late fall		-		-
	Spring		-		-
	Control (no N)		0.49b		0.64
	Early fall w/ inhibitors		0.86a		0.54
	LSD ($\alpha = 0.05$)		0.30		ns
ANOVA		df	$P > F$	df	$P > F$
Landpos		1	0.9583	1	0.8367
Trt		2	0.006*	3	0.5145
Landpos*Trt		2	0.7631	3	0.4638
Block(Landpos)		6	0.1834	6	0.0642†
Residual C.V. (%)			35.17		27.13

a,b Mean values followed by the same letter (within columns) are not significantly different.

^{z} LSD for individual treatments in individual site years is not reported because there was no Landpos*Trt interaction.

† significant at $P < 0.10$ (used only for landscape position variables and interactions).

* significant at $P < 0.05$.

Table P.3. Total inorganic N in the bandrow at Kane 2000/2001: 15-30 cm soil depth

Treatment			Total inorganic-N (mg kg^{-1})		
			Sampling Date		
Landscape Position	Fertilization		10/12/00		10/26/00
High	Early fall		15.7		18.1
	Mid fall		-		20.0
	Late fall		-		-
	Spring		-		-
	Control (no N)		12.5		18.6
	Early fall w/ inhibitors		14.7		18.4
	LSD ($\alpha = 0.05$)[z]		-		-
Low	Early fall		14.8		29.2
	Mid fall		-		20.7
	Late fall		-		-
	Spring		-		-
	Control (no N)		10.5		18.1
	Early fall w/ inhibitors		16.5		20.1
	LSD ($\alpha = 0.05$)[z]		-		-
Landscape Position Means					
High			14.4		18.8
Low			13.9		22.0
LSD ($\alpha = 0.10$)			ns		ns
	Fertilization Means				
	Early fall		15.3a		23.6
	Mid fall		-		20.3
	Late fall		-		-
	Spring		-		-
	Control (no N)		11.5b		18.3
	Early fall w/ inhibitors		15.7a		19.2
	LSD ($\alpha = 0.05$)		3.3		ns
ANOVA		df	$P > F$	df	$P > F$
Landpos		1	0.7313	1	0.3141
Trt		2	0.0317*	3	0.4929
Landpos*Trt		2	0.4924	3	0.3785
Block(Landpos)		6	0.466	6	0.2871
Residual C.V. (%)			21.33		35.19

a,b Mean values followed by the same letter (within columns) are not significantly different.

[z] LSD for individual treatments in individual site years is not reported because there was no Landpos*Trt interaction.

† significant at $P < 0.10$ (used only for landscape position variables and interactions).

* significant at $P < 0.05$.

Table P.4. Total extractable NH_4^+-N in the bandrow at Kane 2000/2001: 15-30 cm soil depth

Treatment		Total extractable NH_4^+-N (mg kg^{-1})			
		Sampling Date			
Landscape Position	Fertilization		10/12/00		10/26/00
High	Early fall		10.7		13.5
	Mid fall		-		14.8
	Late fall		-		-
	Spring		-		-
	Control (no N)		9.2		14.8
	Early fall w/ inhibitors		9.1		13.3
	LSD (α = 0.05)^z		-		-
Low	Early fall		11.9		22.8
	Mid fall		-		16.3
	Late fall		-		-
	Spring		-		-
	Control (no N)		8.7		14.8
	Early fall w/ inhibitors		12.1		15.8
	LSD (α = 0.05)^z		.		-
Landscape Position Means					
High			9.6		14.1b
Low			10.9		17.4a
LSD (α = 0.10)			ns		2.8
	Fertilization Means				
	Early fall		11.3		18.1
	Mid fall		-		15.5
	Late fall		-		-
	Spring		-		-
	Control (no N)		9.0		14.8
	Early fall w/ inhibitors		10.6		14.5
	LSD (α = 0.05)		ns		ns
ANOVA		df	$P > F$	df	$P > F$
Landpos		1	0.2584	1	0.0644†
Trt		2	0.1555	3	0.5354
Landpos*Trt		2	0.3578	3	0.3590
Block(Landpos)		6	0.386	6	0.7374
Residual C.V. (%)			22.43		34.43

a,b Mean values followed by the same letter (within columns) are not significantly different.

^{z} LSD for individual treatments in individual site years is not reported because there was no Landpos*Trt interaction.

† significant at $P < 0.10$ (used only for landscape position variables and interactions).

* significant at $P < 0.05$.

Table P.5. Total extractable NO_3^--N in the bandrow at Kane 2000/2001: 15-30 cm soil depth

Treatment			Total extractable NO_3^--N (mg kg^{-1})		
			Sampling Date		
Landscape Position	Fertilization		10/12/00		10/26/00
High	Early fall		4.7		4.0
	Mid fall		-		4.6
	Late fall		-		-
	Spring		-		-
	Control (no N)		3.0		3.3
	Early fall w/ inhibitors		5.5		4.6
	LSD ($\alpha = 0.05$)[z]		-		-
Low	Early fall		2.2		5.3
	Mid fall		-		3.7
	Late fall		-		-
	Spring		-		-
	Control (no N)		1.3		2.6
	Early fall w/ inhibitors		3.7		3.6
	LSD ($\alpha = 0.05$)[z]		-		-
Landscape Position Means					
High			4.4		4.1
Low			2.4		3.8
LSD ($\alpha = 0.10$)			ns		ns
	Fertilization Means				
	Early fall		3.4ab		4.6
	Mid fall		-		4.2
	Late fall		-		-
	Spring		-		-
	Control (no N)		2.2b		2.9
	Early fall w/ inhibitors		4.6a		4.1
	LSD ($\alpha = 0.05$)		ns		ns
ANOVA		df	$P > F$	df	$P > F$
Landpos		1	0.1873	1	0.8528
Trt		2	0.0268*	3	0.2708
Landpos*Trt		2	0.853	3	0.5007
Block(Landpos)		6	0.013*	6	0.0008*
Residual C.V. (%)			45.71		43.65

a,b Mean values followed by the same letter (within columns) are not significantly different.
[z] LSD for individual treatments in individual site years is not reported because there was no Landpos*Trt interaction.
† significant at $P < 0.10$ (used only for landscape position variables and interactions).
* significant at $P < 0.05$.

Table P.6. Total extractable NO_2^--N in the bandrow at Kane 2000/2001: 15-30 cm soil depth

Treatment			Total extractable NO_2^--N (mg kg^{-1})		
			Sampling Date		
Landscape Position	Fertilization		10/12/00		10/26/00
High	Early fall		0.29		0.64
	Mid fall		-		0.63
	Late fall		-		-
	Spring		-		-
	Control (no N)		0.31		0.55
	Early fall w/ inhibitors		0.33		0.60
	LSD ($\alpha = 0.05$)		ns		-^{z}
Low	Early fall		0.71a		1.13
	Mid fall		-		0.69
	Late fall		-		-
	Spring		-		-
	Control (no N)		0.46b		0.78
	Early fall w/ inhibitors		0.66a		0.75
	LSD ($\alpha = 0.05$)		na^y		-^{z}
Landscape Position Means					
High			0.31		0.61b
Low			0.61		0.84a
LSD ($\alpha = 0.10$)			-^{x}		0.21
	Fertilization Means				
	Early fall		0.50		0.88
	Mid fall		-		0.66
	Late fall		-		-
	Spring		-		-
	Control (no N)		0.38		0.66
	Early fall w/ inhibitors		0.49		0.68
	LSD ($\alpha = 0.05$)		-^{x}		ns
ANOVA		df	$P > F$	df	$P > F$
Landpos		1	0.0023*	1	0.0732†
Trt		2	0.0908	3	0.3475
Landpos*Trt		2	0.0771†	3	0.4878
Block(Landpos)		6	0.1908	6	0.3900
Residual C.V. (%)			23.57		39.26

a,b Mean values followed by the same letter (within columns) are not significantly different.

^{z} LSD for individual treatments in individual site years is not reported because there was no Landpos*Trt interaction.

^{y} Not applicable (na) because used LSMEANS, which does not provide an LSD value.

^{x} LSD is not reported because of Landpos*Trt interaction.

† significant at $P < 0.10$ (used only for landscape position variables and interactions).

* significant at $P < 0.05$.

Table P.7. Total extractable urea-N in the bandrow at Kane 2000/2001: 15-30 cm soil depth

Treatment			Total extractable urea-N (mg kg^{-1})		
			Sampling Date		
Landscape Position	Fertilization		10/12/00		10/26/00
High	Early fall		0.08		0.17
	Mid fall		-		0.08
	Late fall		-		-
	Spring		-		-
	Control (no N)		0.17		0.00
	Early fall w/ inhibitors		0.00		0.00
	LSD ($\alpha = 0.05$)[z]		-		-
Low	Early fall		0.17		0.17
	Mid fall		-		1.42
	Late fall		-		-
	Spring		-		-
	Control (no N)		0.08		0.00
	Early fall w/ inhibitors		0.33		1.43
	LSD ($\alpha = 0.05$)[z]		-		-
Landscape Position Means					
High			0.08		0.06
Low			0.19		0.75
LSD ($\alpha = 0.10$)			ns		ns
	Fertilization Means				
	Early fall		0.12		0.17
	Mid fall		-		0.75
	Late fall		-		-
	Spring		-		-
	Control (no N)		0.13		0.00
	Early fall w/ inhibitors		0.17		0.71
	LSD ($\alpha = 0.05$)		ns		ns
ANOVA		df	$P > F$	df	$P > F$
Landpos		1	0.1174	1	0.1818
Trt		2	0.9237	3	0.1864
Landpos*Trt		2	0.2607	3	0.1572
Block(Landpos)		6	0.8837	6	0.0558†
Residual C.V. (%)			174.97		197.86

[z] LSD for individual treatments in individual site years is not reported because there was no Landpos*Trt interaction.
† significant at $P < 0.10$ (used only for landscape position variables and interactions).
* significant at $P < 0.05$.

Appendix Q

KANE (2000/01): BETWEEN BAND ZONE DATA (mg kg^{-1}): 0–30 cm

Table Q.1. Total inorganic N between the bandrows at Kane 2000/2001: 0-30 cm soil depth

Treatment			Total inorganic-N (mg kg^{-1}) Sampling Date 10/12/00		Total inorganic-N (mg kg^{-1}) Sampling Date 10/26/00
Landscape Position	Fertilization		10/12/00		10/26/00
High	Early fall		27.1		36.7
	Mid fall		-		36.6
	Late fall		-		-
	Spring		-		-
	Control (no N)		25.5		41.2
	Early fall w/ inhibitors		31.3		39.3
	LSD ($\alpha = 0.05$)[z]		-		-
Low	Early fall		29.5		37.9
	Mid fall		-		37.8
	Late fall		-		-
	Spring		-		-
	Control (no N)		25.7		41.3
	Early fall w/ inhibitors		27.0		41.2
	LSD ($\alpha = 0.05$)[z]		-		-
Landscape Position Means					
High			27.9		38.4
Low			27.4		39.6
LSD ($\alpha = 0.10$)			ns		ns
	Fertilization Means				
	Early fall		28.3		37.3b
	Mid fall		-		37.2b
	Late fall		-		-
	Spring		-		-
	Control (no N)		25.6		41.2a
	Early fall w/ inhibitors		29.1		40.2ab
	LSD ($\alpha = 0.05$)		ns		3.2
ANOVA		df	$P > F$	df	$P > F$
Landpos		1	0.8699	1	0.5154
Trt		2	0.2402	3	0.0338*
Landpos*Trt		2	0.291	3	0.9514
Block(Landpos)		6	0.0370*	6	0.0845†
Residual C.V. (%)			14.78		7.86

a,b Mean values followed by the same letter (within columns) are not significantly different.

[z] LSD for individual treatments in individual site years is not reported because there was no Landpos*Trt interaction.

† significant at $P < 0.10$ (used only for landscape position variables and interactions).

* significant at $P < 0.05$.

Table Q.2. Total extractable NH_4^+-N between the bandrows at Kane 2000/2001: 0-30 cm soil depth

Treatment		Total extractable NH_4^+-N (mg kg^{-1})			
		Sampling Date			
Landscape Position	Fertilization		10/12/00		10/26/00
High	Early fall		17.9		27.5
	Mid fall		-		25.8
	Late fall		-		-
	Spring		-		-
	Control (no N)		18.5		31.3
	Early fall w/ inhibitors		19.4		28.3
	LSD ($\alpha = 0.05$)		ns		-[z]
Low	Early fall		23.8a		29.8
	Mid fall		-		30.0
	Late fall		-		-
	Spring		-		-
	Control (no N)		21.4b		32.5
	Early fall w/ inhibitors		21.7b		32.3
	LSD ($\alpha = 0.05$)		na[y]		-[z]
Landscape Position Means					
High			18.6		28.2b
Low			22.0		31.1a
LSD ($\alpha = 0.10$)			-[x]		2.4
	Fertilization Means				
	Early fall		20.8		28.6bc
	Mid fall		-		27.9c
	Late fall		-		-
	Spring		-		-
	Control (no N)		20.0		31.9a
	Early fall w/ inhibitors		20.0		30.3ab
	LSD ($\alpha = 0.05$)		-[x]		2.2
ANOVA		df	$P > F$	df	$P > F$
Landpos		1	0.0159*	1	0.0533†
Trt		2	0.4641	3	0.0056*
Landpos*Trt		2	0.0352*	3	0.4366
Block(Landpos)		6	0.0706†	6	0.0434*
Residual C.V. (%)			7.54		7.01

a-c Mean values followed by the same letter (within columns) are not significantly different.

[z] LSD for individual treatments in individual site years is not reported because there was no Landpos*Trt interaction.

[y] Not applicable (na) because used LSMEANS which does not provide an LSD value.

[x] LSD is not reported because of significant Landpos*Trt interaction.

† significant at $P < 0.10$ (used only for landscape position variables and interactions).

* significant at $P < 0.05$.

Table Q.3. Total extractable NO_3^--N between the bandrows at Kane 2000/2001: 0-30 cm soil depth

Treatment			Total extractable NO_3^--N (mg kg^{-1})		
			Sampling Date		
Landscape Position	Fertilization		10/12/00		10/26/00
High	Early fall		8.7		8.4
	Mid fall		-		10.0
	Late fall		-		-
	Spring		-		-
	Control (no N)		6.6		9.1
	Early fall w/ inhibitors		11.5		10.2
	LSD ($\alpha = 0.05$)[z]		-		-
Low	Early fall		4.9		6.9
	Mid fall		-		6.5
	Late fall		-		-
	Spring		-		-
	Control (no N)		3.5		7.5
	Early fall w/ inhibitors		5.4		7.7
	LSD ($\alpha = 0.05$)[z]		-		-
Landscape Position Means					
High			8.9		9.4
Low			4.6		7.1
LSD ($\alpha = 0.10$)			ns		ns
	Fertilization Means				
	Early fall		6.8		7.7
	Mid fall		-		8.2
	Late fall		-		-
	Spring		-		-
	Control (no N)		5.0		8.3
	Early fall w/ inhibitors		8.5		8.9
	LSD ($\alpha = 0.05$)		ns		ns
ANOVA		df	$P > F$	df	$P > F$
Landpos		1	0.1716	1	0.3218
Trt		2	0.1047	3	0.6323
Landpos*Trt		2	0.5862	3	0.7071
Block(Landpos)		6	0.0063*	6	0.0001*
Residual C.V. (%)			43.35		22.96

[z] LSD for individual treatments in individual site years is not reported because there was no Landpos*Trt interaction.
† significant at $P < 0.10$ (used only for landscape position variables and interactions).
* significant at $P < 0.05$.

Table Q.4. Total extractable NO_2^--N between the bandrows at Kane 2000/2001: 0-30 cm soil depth

Treatment			Total extractable NO_2^--N (mg kg^{-1})		
			Sampling Date		
Landscape Position	Fertilization		10/12/00		10/26/00
High	Early fall		0.45		0.80
	Mid fall		-		0.88
	Late fall		-		-
	Spring		-		-
	Control (no N)		0.45		0.80
	Early fall w/ inhibitors		0.40		0.79
	LSD (α = 0.05)[z]		-		-
Low	Early fall		0.88		1.26
	Mid fall		-		1.28
	Late fall		-		-
	Spring		-		-
	Control (no N)		0.82		1.33
	Early fall w/ inhibitors		0.88		1.30
	LSD (α = 0.05)[z]		-		-
Landscape Position Means					
High			0.43b		0.82b
Low			0.86a		1.29a
LSD (α = 0.10)			0.16		0.23
	Fertilization Means				
	Early fall		0.66		1.03
	Mid fall		-		0.08
	Late fall		-		-
	Spring		-		-
	Control (no N)		0.63		0.07
	Early fall w/ inhibitors		0.64		0.05
	LSD (α = 0.05)		ns		ns
ANOVA		df	$P > F$	df	$P > F$
Landpos		1	0.0018*	1	0.0074*
Trt		2	0.761	3	0.7504
Landpos*Trt		2	0.4984	3	0.5501
Block(Landpos)		6	0.009*	6	0.0001*
Residual C.V. (%)			13.74		9.17

a,b Mean values followed by the same letter (within columns) are not significantly different.

[z] LSD for individual treatments in individual site years is not reported because there was no Landpos*Trt interaction.

† significant at $P < 0.10$ (used only for landscape position variables and interactions).

* significant at $P < 0.05$.

Table Q.5. Total extractable urea-N between the bandrows at Kane 2000/2001: 0-30 cm soil depth

Treatment			Total extractable urea-N (mg kg^{-1}) Sampling Date		
Landscape Position	Fertilization		10/12/00		10/26/00
High	Early fall		0.17		0.00
	Mid fall		-		0.00
	Late fall		-		-
	Spring		-		-
	Control (no N)		0.25		0.00
	Early fall w/ inhibitors		0.00		0.00
	LSD (α = 0.05)^z		-		-
Low	Early fall		0.08		0.17
	Mid fall		-		0.00
	Late fall		-		-
	Spring		-		-
	Control (no N)		0.17		0.00
	Early fall w/ inhibitors		0.25		0.00
	LSD (α = 0.05)^z		-		-
Landscape Position Means					
High			0.14		0.00
Low			0.17		0.04
LSD (α = 0.10)			ns		ns
	Fertilization Means				
	Early fall		0.13		0.08
	Mid fall		-		0.00
	Late fall		-		-
	Spring		-		-
	Control (no N)		0.21		0.00
	Early fall w/ inhibitors		0.13		0.00
	LSD (α = 0.05)		ns		ns
ANOVA		df	$P > F$	df	$P > F$
Landpos		1	0.8803	1	0.3559
Trt		2	0.7348	3	0.4155
Landpos*Trt		2	3198	3	0.4155
Block(Landpos)		6	0.0447*	6	0.4552
Residual C.V. (%)			159.03		565.68

^{z} LSD for individual treatments in individual site years is not reported because there was no Landpos*Trt interaction.

† significant at $P < 0.10$ (used only for landscape position variables and interactions).

* significant at $P < 0.05$.

Appendix R

KANE (2001/02): BAND ZONE DATA (mg kg^{-1}): 0–15 cm

Table R.1. Effect of landscape position, application date, and inhibitors on soil pH at Kane 2001/2002: Bandrow (0-15 cm)

Treatment			pH				
			Sampling Date				
Landscape Position	Fertilization		10/09/01		10/23/01		11/01/01
High	Early fall		7.99		7.93		7.93
	Mid fall		-		8.02		7.90
	Late fall		-		-		7.96
	Spring		-		-		-
	Control (no N)		7.92		7.98		7.88
	Early fall w/ inhibitors		7.96		7.91		7.85
	LSD (α = 0.05)[z]		-		-		-
Low	Early fall		8.09		7.94		7.85
	Mid fall		-		7.90		7.95
	Late fall		-		-		7.94
	Spring		-		-		-
	Control (no N)		8.03		8.01		7.96
	Early fall w/ inhibitors		8.07		7.88		7.88
	LSD (α = 0.05)[z]		-		-		-
Landscape Position Means							
High			7.95		7.96		7.88
Low			8.06		7.93		7.91
LSD (α = 0.10)			ns		ns		ns
	Fertilization Means						
	Early fall		8.04		7.93		7.84
	Mid fall		-		7.96		7.92
	Late fall		-		-		7.95
	Spring		-		-		-
	Control (no N)		7.98		7.99		7.92
	Early fall w/ inhibitors		8.01		7.89		7.86
	LSD (α = 0.05)		ns		ns		ns
ANOVA		df	$P > F$	df	$P > F$	df	$P > F$
Landpos		1	0.1011	1	0.6216	1	0.5915
Trt		2	0.4019	3	0.1986	4	0.1693
Landpos*Trt		2	0.9933	3	0.4676	4	0.8589
Block(Landpos)		6	0.0935†	6	0.0384*	6	0.0228*
Residual C.V. (%)			1.07		1.16		1.21

a-c Mean values followed by the same letter (within columns) are not significantly different.

[z] LSD for individual treatments in individual site years is not reported because there was no Landpos*Trt interaction.

† significant at $P < 0.10$ (used only for landscape position variables and interactions).

* significant at $P < 0.05$.

Table R.2. Effect of landscape position, application date, and inhibitors on soil EC at Kane 2001/2002: Bandrow (0-15 cm)

Treatment			EC (mS cm^{-1}) Sampling Date				
Landscape Position	Fertilization		10/09/01		10/23/01		11/01/01
High	Early fall		1.62		1.97		1.90
	Mid fall		-		2.03		2.48
	Late fall		-		-		2.90
	Spring		-		-		-
	Control (no N)		2.75		3.01		2.98
	Early fall w/ inhibitors		2.89		3.05		2.21
	LSD (α = 0.05)[z]		-		-		-
Low	Early fall		1.13		1.49		2.21
	Mid fall		-		1.47		1.43
	Late fall		-		-		1.35
	Spring		-		-		-
	Control (no N)		1.02		1.19		1.19
	Early fall w/ inhibitors		1.26		1.60		1.38
	LSD (α = 0.05)[z]		-		-		-
Landscape Position Means							
High			2.42a		2.51		2.49a
Low			1.14b		1.43		1.51b
LSD (α = 0.10)			1.15		ns		0.94
	Fertilization Means						
	Early fall		1.37		1.73		2.05
	Mid fall		-		1.75		1.95
	Late fall		-		-		2.12
	Spring		-		-		-
	Control (no N)		1.88		2.10		2.08
	Early fall w/ inhibitors		2.08		2.32		1.79
	LSD (α = 0.05)		ns		ns		ns
ANOVA		df	$P > F$	df	$P > F$	df	$P > F$
Landpos		1	0.0736†	1	0.1275	1	0.09†
Trt		2	0.1584	3	0.2389	4	0.9515
Landpos*Trt		2	0.1856	3	0.1452	4	0.1983
Block(Landpos)		6	0.0155	6	0.0006*	6	0.0297*
Residual C.V. (%)			39.42		33.22		45.31

a,b Mean values followed by the same letter (within columns) are not significantly different.

[z] LSD for individual treatments in individual site years is not reported because there was no Landpos*Trt interaction.

† significant at $P < 0.10$ (used only for landscape position variables and interactions).

* significant at $P < 0.05$.

Table R.3. Total inorganic N in the bandrow at Kane 2001/2002: 0-15 cm soil depth

Treatment			Total inorganic N (mg kg^{-1})				
			Sampling Date				
Landscape Position	Fertilization		10/09/01		10/23/01		11/01/01
High	Early fall		134.0		112.6		118.3
	Mid fall		-		93.3		106.5
	Late fall		-		-		132.8
	Spring		-		-		-
	Control (no N)		19.5		17.5		16.0
	Early fall w/ inhibitors		106.0		88.1		113.5
	LSD (α = 0.05)[z]		-		-		-
Low	Early fall		120.3		92.0		123.5
	Mid fall		-		103.6		119.4
	Late fall		-		-		119.3
	Spring		-		-		-
	Control (no N)		17.5		18.4		15.9
	Early fall w/ inhibitors		95.4		80.6		129.5
	LSD (α = 0.05)[z]		-		-		-
Landscape Position Means							
High			86.5		77.9		97.4
Low			77.7		73.7		101.5
LSD (α = 0.10)			ns		ns		ns
	Fertilization Means						
	Early fall		127.1a		102.3a		120.9a
	Mid fall		-		98.4a		112.9a
	Late fall		-		-		126.0a
	Spring		-		-		-
	Control (no N)		18.5c		17.9b		15.9b
	Early fall w/ inhibitors		100.7b		84.4a		121.5a
	LSD (α = 0.05)		14.4		30.3		27.0
ANOVA		df	$P > F$	df	$P > F$	df	$P > F$
Landpos		1	0.1627	1	0.5067	1	0.5563
Trt		2	0.0001*	3	0.0001*	4	0.0001*
Landpos*Trt		2	0.664	3	0.7430	4	0.8065
Block(Landpos)		6	0.4425	6	0.9040	6	0.7022
Residual C.V. (%)			16.1		38.02		26.30

a-c Mean values followed by the same letter (within columns) are not significantly different.

[z] LSD for individual treatments in individual site years is not reported because there was no Landpos*Trt interaction.

† significant at $P < 0.10$ (used only for landscape position variables and interactions).

* significant at $P < 0.05$.

Table R.4. Total extractable NH_4^+-N in the bandrow at Kane 2001/2002: 0-15 cm soil depth

Treatment			Total extractable NH_4^+-N (mg kg^{-1})				
			Sampling Date				
Landscape Position	Fertilization		10/09/01		10/23/01		11/01/01
High	Early fall		99.6		66.1		57.3
	Mid fall		-		73.1		76.4
	Late fall		-		-		107.5
	Spring		-		-		-
	Control (no N)		9.0		6.9		4.6
	Early fall w/ inhibitors		80.5		57.5		69.4
	LSD ($\alpha = 0.05$)[z]		-		-		-
Low	Early fall		89.8		54.1		47.9
	Mid fall		-		76.9		75.8
	Late fall		-		-		94.1
	Spring		-		-		-
	Control (no N)		9.8		10.0		6.6
	Early fall w/ inhibitors		72.1		47.8		80.4
	LSD ($\alpha = 0.05$)[z]		-		-		-
Landscape Position Means							
High			63.0		50.9		63.0
Low			57.2		47.2		61.0
LSD ($\alpha = 0.10$)			ns		ns		ns
	Fertilization Means						
	Early fall		94.7a		60.1a		52.6b
	Mid fall		-		75.0a		76.1b
	Late fall		-		-		100.8a
	Spring		-		-		-
	Control (no N)		9.4c		8.4b		5.6c
	Early fall w/ inhibitors		76.3b		52.6a		74.9b
	LSD ($\alpha = 0.05$)		14.1		25.0		24.4
ANOVA		df	*P* > F	df	*P* > F	df	*P* > F
Landpos		1	0.3417	1	0.4724	1	0.6742
Trt		2	0.0001*	3	0.0002*	4	0.0001*
Landpos*Trt		2	0.6836	3	0.8636	4	0.8542
Block(Landpos)		6	0.3983	6	0.9103	6	0.8752
Residual C.V. (%)			21.58		48.43		38.16

a-c Mean values followed by the same letter (within columns) are not significantly different.

[z] LSD for individual treatments in individual site years is not reported because there was no Landpos*Trt interaction.

† significant at $P < 0.10$ (used only for landscape position variables and interactions).

* significant at $P < 0.05$.

Table R.5. Total extractable NO_3^--N in the bandrow at Kane 2001/2002: 0-15 cm soil depth

Treatment			Total extractable NO_3^--N ($mg\ kg^{-1}$)				
			Sampling Date				
Landscape Position	Fertilization		10/09/01		10/23/01		11/01/01
High	Early fall		31.4		41.3		53.5
	Mid fall		-		16.6		25.1
	Late fall		-		-		21.4
	Spring		-		-		-
	Control (no N)		10.5		10.6		11.4
	Early fall w/ inhibitors		25.1		29.4		42.4
	LSD ($\alpha = 0.05$)[z]		-		-		-
Low	Early fall		26.5		34.0		69.9
	Mid fall		-		23.0		39.0
	Late fall		-		-		21.9
	Spring		-		-		-
	Control (no N)		7.8		8.4		8.9
	Early fall w/ inhibitors		22.8		32.5		47.8
	LSD ($\alpha = 0.05$)[z]		-		-		-
Landscape Position Means							
High			22.3		24.5		30.8
Low			19.0		24.5		37.5
LSD ($\alpha = 0.10$)			ns		ns		ns
	Fertilization Means						
	Early fall		28.9a		37.6a		61.7a
	Mid fall		-		19.8b		32.1c
	Late fall		-		-		21.6d
	Spring		-		-		-
	Control (no N)		9.1b		9.5c		10.1e
	Early fall w/ inhibitors		23.9a		30.9a		45.1b
	LSD ($\alpha = 0.05$)		6.2		9.1		9.7
ANOVA		df	$P > F$	df	$P > F$	df	$P > F$
Landpos		1	0.1978	1	1.0000	1	0.1700
Trt		2	0.0001*	3	0.0001*	4	0.0001*
Landpos*Trt		2	0.8941	3	0.4352	4	0.2281
Block(Landpos)		6	0.4744	6	0.5385	6	0.0915†
Residual C.V. (%)			27.44		35.49		27.63

a-e Mean values followed by the same letter (within columns) are not significantly different.

[z] LSD for individual treatments in individual site years is not reported because there was no Landpos*Trt interaction.

† significant at $P < 0.10$ (used only for landscape position variables and interactions).

* significant at $P < 0.05$.

Table R.6. Total extractable NO_2^--N in the bandrow at Kane 2001/2002: 0-15 cm soil depth

Treatment		Total extractable NO_2^--N (mg kg^{-1})					
		Sampling Date					
Landscape Position	Fertilization		10/09/01		10/23/01		11/01/01
High	Early fall		3.00		5.3		7.50
	Mid fall		-		3.5		5.00
	Late fall		-		-		3.88
	Spring		-		-		-
	Control (no N)		0.00		0.0		0.00
	Early fall w/ inhibitors		0.38		1.3		1.75
	LSD ($\alpha = 0.05$)[z]		-		-		-
Low	Early fall		4.00		3.9		5.75
	Mid fall		-		3.8		4.63
	Late fall		-		-		3.25
	Spring		-		-		-
	Control (no N)		0.00		0.0		0.38
	Early fall w/ inhibitors		0.50		0.4		1.38
	LSD ($\alpha = 0.05$)[z]		-		-		-
Landscape Position Means							
High			1.13		2.50		3.63
Low			1.50		2.00		3.08
LSD ($\alpha = 0.10$)			ns		ns		ns
	Fertilization Means						
	Early fall		3.5a		4.56a		6.63a
	Mid fall		-		3.63a		4.81b
	Late fall		-		-		3.56b
	Spring		-		-		-
	Control (no N)		0.0b		0.00b		0.19d
	Early fall w/ inhibitors		0.44b		0.81b		1.56c
	LSD ($\alpha = 0.05$)		0.83		1.55		1.28
ANOVA		df	*P* > F	df	*P* > F	df	*P* > F
Landpos		1	0.4021	1	0.4680	1	0.3102
Trt		2	0.0001*	3	0.0001*	4	0.0001*
Landpos*Trt		2	0.3885	3	0.6693	4	0.5541
Block(Landpos)		6	0.1839	6	0.2237	6	0.1878
Residual C.V. (%)			58.02		65.53		36.93

a-d Mean values followed by the same letter (within columns) are not significantly different.
[z] LSD for individual treatments in individual site years is not reported because there was no Landpos*Trt interaction.
† significant at $P < 0.10$ (used only for landscape position variables and interactions).
* significant at $P < 0.05$.

Table R.7. Total extractable urea-N in the bandrow at Kane 2001/2002: 0-15 cm soil depth

Treatment		Total extractable urea-N (mg kg^{-1})		
		Sampling Date		
Landscape Position	Fertilization	10/09/01	10/23/01	11/01/01
High	Early fall	0.38	1.38	2.50
	Mid fall	-	2.38	1.63
	Late fall	-	-	3.13
	Spring	-	-	-
	Control (no N)	0.50	1.00	0.38
	Early fall w/ inhibitors	0.63	5.75	1.50
	LSD ($\alpha = 0.05$)[z]	-	-	-
Low	Early fall	2.13	3.13	1.25
	Mid fall	-	1.63	2.00
	Late fall	-	-	3.00
	Spring	-	-	-
	Control (no N)	0.38	3.75	0.63
	Early fall w/ inhibitors	3.75	1.13	1.25
	LSD ($\alpha = 0.05$)[z]	-	-	-
Landscape Position Means				
High		0.50b	2.63	1.83
Low		2.08a	2.41	1.63
LSD ($\alpha = 0.10$)		1.24	ns	ns
	Fertilization Means			
	Early fall	1.25	2.25	1.88ab
	Mid fall	-	2.00	1.81abc
	Late fall	-	-	3.06a
	Spring	-	-	-
	Control (no N)	0.44	2.38	0.50c
	Early fall w/ inhibitors	2.19	3.44	1.38bc
	LSD ($\alpha = 0.05$)	1.79	ns	1.32

ANOVA	df	$P > F$	df	$P > F$	df	$P > F$
Landpos	1	0.0482*	1	0.8973	1	0.6622
Trt	2	0.1445	3	0.8600	4	0.0102*
Landpos*Trt	2	0.1806	3	0.2068	4	0.7353
Block(Landpos)	6	0.5168	6	0.1927	6	0.3620
Residual C.V. (%)		126.9		142.49		74.25

a-c Mean values followed by the same letter (within columns) are not significantly different.

[z] LSD for individual treatments in individual site years is not reported because there was no Landpos*Trt interaction.

† significant at $P < 0.10$ (used only for landscape position variables and interactions).

* significant at $P < 0.05$.

Appendix S

KANE (2001/02): BAND ZONE DATA (mg kg^{-1}): 15–30 cm

Table S.1. Effect of landscape position, application date, and inhibitors on soil pH at Kane 2001/2002: Bandrow (15-30 cm)

Treatment		pH		
		Sampling Date		
Landscape Position	Fertilization	10/09/01	10/23/01	11/01/01
High	Early fall	7.91	7.92	7.92
	Mid fall	-	7.93	7.81
	Late fall	-	-	7.91
	Spring	-	-	-
	Control (no N)	7.96	7.96	7.88
	Early fall w/ inhibitors	7.93	7.92	7.78
	LSD (α = 0.05)[z]	-	-	-
Low	Early fall	8.22	8.16	8.13
	Mid fall	-	8.08	8.12
	Late fall	-	-	7.86
	Spring	-	-	-
	Control (no N)	8.19	8.06	7.78
	Early fall w/ inhibitors	8.18	8.11	8.08
	LSD (α = 0.05)[z]	-	-	-
Landscape Position Means				
High		7.93b	7.93b	7.84b
Low		8.20a	8.10a	7.99a
LSD (α = 0.10)		0.16	0.11	na[y]
	Fertilization Means			
	Early fall	8.06	8.04	7.97
	Mid fall	-	8.00	7.97
	Late fall	-	-	7.89
	Spring	-	-	-
	Control (no N)	8.07	8.01	7.83
	Early fall w/ inhibitors	8.06	8.02	7.93
	LSD (α = 0.05)	ns	ns	ns

ANOVA	df	$P > F$	df	$P > F$	df	$P > F$
Landpos	1	0.0174*	1	0.0239*	1	0.0251*
Trt	2	0.8366	3	0.8436	4	0.8078
Landpos*Trt	2	0.3463	3	0.4202	4	0.3212
Block(Landpos)	6	0.0002*	6	0.0148*	6	0.8567
Residual C.V. (%)		0.72		1.06		3.17

a,b Mean values followed by the same letter (within columns) are not significantly different.

[z] LSD for individual treatments in individual site years is not reported because there was no Landpos*Trt interaction.

[y] Not applicable (na) because used LSMEANS (missing sample), which does not provide an LSD value.

† significant at $P < 0.10$ (used only for landscape position variables and interactions).

* significant at $P < 0.05$.

Table S.2. Effect of landscape position, application date, and inhibitors on soil EC at Kane 2001/2002: Bandrow (15-30 cm)

Treatment			EC (mS cm^{-1})			
			Sampling Date			
Landscape Position	Fertilization		10/09/01		10/23/01	11/01/01
High	Early fall		4.42		5.52	4.93
	Mid fall		-		5.85	5.39
	Late fall		-		-	3.80
	Spring		-		-	-
	Control (no N)		5.79		5.74	6.28
	Early fall w/ inhibitors		5.84		6.26	6.53
	LSD (α = 0.05)[z]		-		-	-
Low	Early fall		1.13		1.32	1.03
	Mid fall		-		1.67	1.26
	Late fall		-		-	1.33
	Spring		-		-	-
	Control (no N)		1.31		1.40	1.38
	Early fall w/ inhibitors		1.49		1.39	1.26
	LSD (α = 0.05)[z]		-		-	-
Landscape Position Means						
High			5.35a		5.84a	5.38a
Low			1.31b		1.44b	1.25b
LSD (α = 0.10)			3.09		3.22	na[y]
	Fertilization Means					
	Early fall		2.77		3.42	2.98
	Mid fall		-		3.76	9.92
	Late fall		-		-	2.56
	Spring		-		-	-
	Control (no N)		3.55		3.57	3.83
	Early fall w/ inhibitors		3.67		3.82	3.89
	LSD (α = 0.05)		ns		ns	ns

ANOVA	df	$P > F$	df	$P > F$	df	$P > F$
Landpos	1	0.0442*	1	0.038*	1	0.0408*
Trt	2	0.3752	3	0.8400	4	0.1380
Landpos*Trt	2	0.6327	3	0.8899	4	0.1619
Block(Landpos)	6	0.0009*	6	0.0001*	6	0.0001*
Residual C.V. (%)		40.00		27.27		33.55

a,b Mean values followed by the same letter (within columns) are not significantly different.

[z] LSD for individual treatments in individual site years is not reported because there was no Landpos*Trt interaction.

[y] Not applicable (na) because used LSMEANS (missing sample), which does not provide an LSD value.

† significant at $P < 0.10$ (used only for landscape position variables and interactions).

* significant at $P < 0.05$.

Table S.3. Total inorganic N in the bandrow at Kane 2001/2002: 15-30 cm soil depth

Treatment		Total inorganic N (mg kg^{-1})					
		Sampling Date					
Landscape Position	Fertilization		10/09/01		10/23/01		11/01/01
High	Early fall		17.1		22.8a		13.3
	Mid fall		-		15.8b		17.9
	Late fall		-		-		13.3
	Spring		-		-		-
	Control (no N)		16.0		16.3b		12.8
	Early fall w/ inhibitors		15.5		19.4ab		20.4
	LSD (α = 0.05)		-[y]		na[z]		-[y]
Low	Early fall		9.8		11.6		9.6
	Mid fall		-		12.6		13.8
	Late fall		-		-		8.8
	Spring		-		-		-
	Control (no N)		9.1		12.1		9.0
	Early fall w/ inhibitors		9.9		15.5		9.6
	LSD (α = 0.05)		-[y]		ns		-[y]
Landscape Position Means			16.2a		18.5		15.5a
High			9.6b		13.0		10.2b
Low			3.7		-[x]		na[w]
LSD (α = 0.10)							
	Fertilization Means						
	Early fall		13.4		17.2		11.4
	Mid fall		-		14.2		15.8
	Late fall		-		-		11.0
	Spring		-		-		-
	Control (no N)		12.6		14.2		10.9
	Early fall w/ inhibitors		12.7		17.4		15.0
	LSD (α = 0.05)		ns		-[x]		ns
ANOVA		df	$P > F$	df	$P > F$	df	$P > F$
Landpos		1	0.0129*	1	0.0349*	1	0.0647†
Trt		2	0.758	3	0.0431*	4	0.3529
Landpos*Trt		2	0.7774	3	0.0355*	4	0.7483
Block(Landpos)		6	0.0334*	6	0.0075*	6	0.2457
Residual C.V. (%)			19.49		17.80		47.50

a,b Mean values followed by the same letter (within columns) are not significantly different.
[z] Not applicable (na) because used LSMEANS, which does not provide an LSD value.
[y] LSD for individual treatments in individual site years is not reported because there was no Landpos*Trt interaction.
[x] LSD is not reported because of Landpos*Trt interaction.
[w] Not applicable (na) because used LSMEANS (missing sample), which does not provide an LSD value.
† significant at $P < 0.10$ (used only for landscape position variables and interactions).
* significant at $P < 0.05$.

Table S.4. Total extractable NH_4^+-N in the bandrow at Kane 2001/2002: 15-30 cm soil depth

Treatment			Total extractable NH_4^+-N (mg kg^{-1})				
			Sampling Date				
Landscape Position	Fertilization		10/09/01		10/23/01		11/01/01
High	Early fall		7.6		11.1		5.8
	Mid fall		-		8.6		11.0
	Late fall		-		-		6.0
	Spring		-		-		-
	Control (no N)		7.5		7.6		4.8
	Early fall w/ inhibitors		5.9		9.1		5.8
	LSD ($\alpha = 0.05$)[z]		-		-		-
Low	Early fall		7.9		9.3		6.8
	Mid fall		-		9.9		10.3
	Late fall		-		-		6.6
	Spring		-		-		-
	Control (no N)		7.1		9.1		6.5
	Early fall w/ inhibitors		7.4		10.4		6.3
	LSD ($\alpha = 0.05$)[z]		-		-		-
Landscape Position Means							
High			7.0		9.1		6.7
Low			7.5		9.7		7.3
LSD ($\alpha = 0.10$)			ns		ns		ns
	Fertilization Means						
	Early fall		7.8		10.2		6.3
	Mid fall		-		9.3		10.6
	Late fall		-		-		6.3
	Spring		-		-		-
	Control (no N)		7.3		8.4		5.6
	Early fall w/ inhibitors		6.6		9.8		6.0
	LSD ($\alpha = 0.05$)		ns		ns		ns
ANOVA		df	$P > F$	df	$P > F$	df	$P > F$
Landpos		1	0.4782	1	0.2609	1	0.7364
Trt		2	0.13	3	0.3332	4	0.1911
Landpos*Trt		2	0.2202	3	0.3057	4	0.9890
Block(Landpos)		6	0.1317	6	0.8899	6	0.2303
Residual C.V. (%)			14.24		21.26		64.14

[z] LSD for individual treatments in individual site years is not reported because there was no Landpos*Trt interaction.
† significant at $P < 0.10$ (used only for landscape position variables and interactions).
* significant at $P < 0.05$.

Table S.5. Total extractable NO_3^--N in the bandrow at Kane 2001/2002: 15-30 cm soil depth

Treatment			Total extractable NO_3^--N (mg kg^{-1})				
			Sampling Date				
Landscape Position	Fertilization		10/09/01		10/23/01		11/01/01
High	Early fall		9.5		11.6		7.5
	Mid fall		-		7.1		6.8
	Late fall		-		-		7.3
	Spring		-		-		-
	Control (no N)		8.5		8.6		8.0
	Early fall w/ inhibitors		9.6		10.3		14.6
	LSD ($\alpha = 0.05$)[z]		-		-		-
Low	Early fall		1.9		2.4		2.5
	Mid fall		-		2.8		3.1
	Late fall		-		-		1.8
	Spring		-		-		-
	Control (no N)		2.0		3.0		2.3
	Early fall w/ inhibitors		2.5		5.1		2.9
	LSD ($\alpha = 0.05$)[z]		-		-		-
Landscape Position Means			9.2a		9.4a		8.8a
High			2.1b		3.3b		2.5b
Low			4.6		4.2		na[y]
LSD ($\alpha = 0.10$)							
	Fertilization Means						
	Early fall		5.7		7.0		5.0
	Mid fall		-		4.9		4.9
	Late fall		-		-		4.5
	Spring		-		-		-
	Control (no N)		5.3		5.8		5.2
	Early fall w/ inhibitors		6.1		7.7		8.8
	LSD ($\alpha = 0.05$)		ns		ns		ns
ANOVA		df	$P > F$	df	$P > F$	df	$P > F$
Landpos		1	0.0239*	1	0.0309	1	0.001*
Trt		2	0.7428	3	0.1176	4	0.1486
Landpos*Trt		2	0.8653	3	0.1908	4	0.2246
Block(Landpos)		6	0.0015*	6	0.0005*	6	0.5355
Residual C.V. (%)			36.76		36.31		62.26

a,b Mean values followed by the same letter (within columns) are not significantly different.
[z] LSD for individual treatments in individual site years is not reported because there was no Landpos*Trt interaction.
[y] Not applicable (na) because used LSMEANS (missing sample), which does not provide an LSD value.
† significant at $P < 0.10$ (used only for landscape position variables and interactions).
* significant at $P < 0.05$.

Table S.6. Total extractable NO_2^--N in the bandrow at Kane 2001/2002: 15-30 cm soil depth

Treatment		Total extractable NO_2^--N (mg kg^{-1})					
		Sampling Date					
Landscape Position	Fertilization		10/09/01		10/23/01		11/01/01
High	Early fall		0.00		0.00		0.00
	Mid fall		-		0.00		0.13
	Late fall		-		-		0.00
	Spring		-		-		-
	Control (no N)		0.00		0.00		0.00
	Early fall w/ inhibitors		0.00		0.00		0.00
	LSD (α = 0.05)[z]		-		-		-
Low	Early fall		0.00		0.00		0.38
	Mid fall		-		0.00		0.38
	Late fall		-		-		0.38
	Spring		-		-		-
	Control (no N)		0.00		0.00		0.24
	Early fall w/ inhibitors		0.00		0.00		0.50
	LSD (α = 0.05)[z]		-		-		-
Landscape Position Means							
High			0.00		0.00		0.03b
Low			0.00		0.00		0.37a
LSD (α = 0.10)			ns		ns		na[y]
	Fertilization Means						
	Early fall		0.00		0.00		0.19
	Mid fall		-		0.00		0.25
	Late fall		-		-		0.19
	Spring		-		-		-
	Control (no N)		0.00		0.00		0.12
	Early fall w/ inhibitors		0.00		0.00		0.25
	LSD (α = 0.05)		ns		ns		ns
ANOVA		df	*P* > F	df	*P* > F	df	*P* > F
Landpos		1	.	1	.	1	0.0092*
Trt		2	.	3	.	4	0.3573
Landpos*Trt		2	.	3	.	4	0.3422
Block(Landpos)		6	.	6	.	6	0.0039*
Residual C.V. (%)			.		.		66.19

a,b Mean values followed by the same letter (within columns) are not significantly different.
[z] LSD for individual treatments in individual site years is not reported because there was no Landpos*Trt interaction.
[y] Not applicable (na) because used LSMEANS (missing sample), which does not provide an LSD value.
† significant at $P < 0.10$ (used only for landscape position variables and interactions).
* significant at $P < 0.05$.

Table S.7. Total extractable urea-N in the bandrow at Kane 2001/2002: 15-30 cm soil depth

Treatment			Total extractable urea-N (mg kg^{-1})			
			Sampling Date			
Landscape Position	Fertilization		10/09/01		10/23/01		11/01/01
High	Early fall		0.00		0.75		0.38
	Mid fall		-		0.50		1.13
	Late fall		-		-		0.13
	Spring		-		-		-
	Control (no N)		0.00		0.63		0.38
	Early fall w/ inhibitors		0.13		0.63		0.50
	LSD (α = 0.05)[z]		-		-		-
Low	Early fall		0.50		1.13		0.75
	Mid fall		-		1.00		0.75
	Late fall		-		-		0.38
	Spring		-		-		-
	Control (no N)		0.00		0.88		0.44
	Early fall w/ inhibitors		0.38		0.50		0.38
	LSD (α = 0.05)[z]		-		-		-
Landscape Position Means							
High			0.04b		0.63		0.50
Low			0.29a		0.88		0.54
LSD (α = 0.10)			0.22		ns		ns
	Fertilization Means						
	Early fall		0.25		0.94		0.56
	Mid fall		-		0.75		0.94
	Late fall		-		-		0.25
	Spring		-		-		-
	Control (no N)		0.00		0.75		0.41
	Early fall w/ inhibitors		0.25		0.56		0.44
	LSD (α = 0.05)		ns		ns		ns
ANOVA		df	$P > F$	df	$P > F$	df	$P > F$
Landpos		1	0.0686†	1	0.2231	1	0.8388
Trt		2	0.1555	3	0.8176	4	0.4507
Landpos*Trt		2	0.2353	3	0.8663	4	0.8623
Block(Landpos)		6	0.4682	6	0.8368	6	0.7770
Residual C.V. (%)			165.83		103.64		142.13

a,b Mean values followed by the same letter (within columns) are not significantly different.
[z] LSD for individual treatments in individual site years is not reported because there was no Landpos*Trt interaction.
† significant at $P < 0.10$ (used only for landscape position variables and interactions).
* significant at $P < 0.05$.

Appendix T

KANE (2001/02): BETWEEN BAND ZONE DATA (mg kg^{-1}): 0–30 cm

Table T.1. Total inorganic N between the bandrows at Kane 2001/2002: 0-30 cm soil depth

Treatment			Total inorganic N (mg kg^{-1})			
			Sampling Date			
Landscape Position	Fertilization		10/09/01		10/23/01	11/01/01
High	Early fall		34.6		42.3	33.3
	Mid fall		-		33.3	25.8
	Late fall		-		-	27.1
	Spring		-		-	-
	Control (no N)		35.5		33.8	28.8
	Early fall w/ inhibitors		37.3		35.4	32.9
	LSD (α = 0.05)		-[z]		-[z]	ns
Low	Early fall		24.9		33.6	28.0b
	Mid fall		-		29.6	41.3a
	Late fall		-		-	25.0b
	Spring		-		-	-
	Control (no N)		26.6		30.5	23.8b
	Early fall w/ inhibitors		30.4		33.3	30.3b
	LSD (α = 0.05)		-[z]		-[z]	na[y]
Landscape Position Means						
High			65.8a		36.2	29.6
Low			27.3b		31.8	29.7
LSD (α = 0.10)			3.2		ns	-[x]
	Fertilization Means					
	Early fall		29.8		37.9	30.6
	Mid fall		-		31.4	33.5
	Late fall		-		-	26.1
	Spring		-		-	-
	Control (no N)		31.1		32.1	26.3
	Early fall w/ inhibitors		33.8		34.3	31.6
	LSD (α = 0.05)		ns		ns	-[x]

ANOVA	df	$P > F$	df	$P > F$	df	$P > F$
Landpos	1	0.002*	1	0.3071	1	0.9743
Trt	2	0.4916	3	0.1519	4	0.1580
Landpos*Trt	2	0.9098	3	0.6983	4	0.0288*
Block(Landpos)	6	0.8969	6	0.0156*	6	0.0487*
Residual C.V. (%)		21.41		17.28		22.62

a,b Mean values followed by the same letter (within columns) are not significantly different.

[z] LSD for individual treatments in individual site years is not reported because there was no Landpos*Trt interaction.

[y] Not applicable (na) because used LSMEANS which does not provide an LSD value.

[x] LSD is not reported because of significant Landpos*Trt interaction.

† significant at $P < 0.10$ (used only for landscape position variables and interactions).

* significant at $P < 0.05$.

Table T.2. Total extractable NH_4^+-N between the bandrows at Kane 2001/2002: 0-30 cm soil depth

Treatment			Total extractable NH_4^+-N (mg kg^{-1})				
			Sampling Date				
Landscape Position	Fertilization		10/09/01		10/23/01		11/01/01
High	Early fall		14.0		18.4		11.0
	Mid fall		-		14.6		9.9
	Late fall		-		-		10.4
	Spring		-		-		-
	Control (no N)		16.5		14.5		9.4
	Early fall w/ inhibitors		16.6		15.9		9.8
	LSD (α = 0.05)		-[z]		-[z]		ns
Low	Early fall		16.1		21.1		12.4b
	Mid fall		-		18.1		21.3a
	Late fall		-		-		13.8b
	Spring		-		-		-
	Control (no N)		15.9		19.1		12.4b
	Early fall w/ inhibitors		18.0		17.6		13.9b
	LSD (α = 0.05)		-[z]		-[z]		na[y]
Landscape Position Means							
High			15.7		15.8b		10.1
Low			17.0		19.0a		14.7
LSD (α = 0.10)			ns		1.1		-[x]
	Fertilization Means						
	Early fall		15.1		19.7a		11.7
	Mid fall		-		16.4b		15.6
	Late fall		-		-		12.1
	Spring		-		-		-
	Control (no N)		16.7		16.8b		10.9
	Early fall w/ inhibitors		17.3		16.8b		11.8
	LSD (α = 0.05)		ns		2.3		-[x]
ANOVA		df	$P > F$	df	$P > F$	df	$P > F$
Landpos		1	0.3365	1	0.0017*	1	0.0105*
Trt		2	0.1687	3	0.0239*	4	0.0035*
Landpos*Trt		2	0.7491	3	0.6213	4	0.0016*
Block(Landpos)		6	0.19	6	0.7560	6	0.0192*
Residual C.V. (%)			13.95		12.68		17.70

a,b Mean values followed by the same letter (within columns) are not significantly different.

[z] LSD for individual treatments in individual site years is not reported because there was no Landpos*Trt interaction.

[y] Not applicable (na) because used LSMEANS which does not provide an LSD value.

[x] LSD is not reported because of significant Landpos*Trt interaction.

† significant at $P < 0.10$ (used only for landscape position variables and interactions).

* significant at $P < 0.05$.

Table T.3. Total extractable NO_3^--N between the bandrows at Kane 2001/2002: 0-30 cm soil depth

Treatment			Total extractable NO_3^--N (mg kg^{-1})				
			Sampling Date				
Landscape Position	Fertilization		10/09/01		10/23/01		11/01/01
High	Early fall		20.6		23.4		22.3
	Mid fall		-		18.5		15.9
	Late fall		-		-		16.8
	Spring		-		-		-
	Control (no N)		19.0		19.3		19.4
	Early fall w/ inhibitors		20.6		19.4		23.1
	LSD ($\alpha = 0.05$)[z]		-		-		-
Low	Early fall		8.8		12.4		15.0
	Mid fall		-		11.5		18.5
	Late fall		-		-		10.6
	Spring		-		-		-
	Control (no N)		9.8		11.4		11.0
	Early fall w/ inhibitors		12.4		15.6		15.4
	LSD ($\alpha = 0.05$)[z]		-		-		-
Landscape Position Means							
High			20.1a		20.1a		19.5a
Low			10.3b		12.7b		14.1b
LSD ($\alpha = 0.10$)			5.1		7.0		na[y]
	Fertilization Means						
	Early fall		14.7		17.9		18.6
	Mid fall		-		15.0		17.2
	Late fall		-		-		13.7
	Spring		-		-		-
	Control (no N)		14.4		15.3		15.2
	Early fall w/ inhibitors		16.5		17.5		19.3
	LSD ($\alpha = 0.05$)		ns		ns		ns
ANOVA		df	$P > F$	df	$P > F$	df	$P > F$
Landpos		1	0.0095*	1	0.0845†	1	0.0577†
Trt		2	0.6674	3	0.6113	4	0.2834
Landpos*Trt		2	0.7617	3	0.6032	4	0.3067
Block(Landpos)		6	0.2239	6	0.0148*	6	0.1905
Residual C.V. (%)			33.04		32.27		33.19

a,b Mean values followed by the same letter (within columns) are not significantly different.

[z] LSD for individual treatments in individual site years is not reported because there was no Landpos*Trt interaction.

[y] Not applicable (na) because used LSMEANS (missing sample), which does not provide an LSD value.

† significant at $P < 0.10$ (used only for landscape position variables and interactions).

* significant at $P < 0.05$.

Table T.4. Total extractable NO_2^--N between the bandrows at Kane 2001/2002: 0-30 cm soil depth

Treatment			Total extractable NO_2^--N (mg kg^{-1})				
			Sampling Date				
Landscape Position	Fertilization		10/09/01		10/23/01		11/01/01
High	Early fall		0.00		0.50		0.00
	Mid fall		-		0.13		0.00
	Late fall		-		-		0.00
	Spring		-		-		-
	Control (no N)		0.00		0.00		0.00
	Early fall w/ inhibitors		0.00		0.13		0.00
	LSD ($\alpha = 0.05$)[z]		-		-		-
Low	Early fall		0.00		0.13		0.63
	Mid fall		-		0.00		1.50
	Late fall		-		-		0.63
	Spring		-		-		-
	Control (no N)		0.00		0.00		0.44
	Early fall w/ inhibitors		0.00		0.00		1.00
	LSD ($\alpha = 0.05$)[z]		-		-		-
Landscape Position Means							
High			0.00		0.19		0.00b
Low			0.00		0.03		0.84a
LSD ($\alpha = 0.10$)			ns		ns		na[y]
	Fertilization Means						
	Early fall		0.00		0.31		0.31
	Mid fall		-		0.06		0.75
	Late fall		-		-		0.31
	Spring		-		-		-
	Control (no N)		0.00		0.00		0.21
	Early fall w/ inhibitors		0.00		0.06		0.50
	LSD ($\alpha = 0.05$)		ns		ns		ns
ANOVA		df	*P* > F	df	*P* > F	df	*P* > F
Landpos		1	.	1	0.3437	1	0.0099*
Trt		2	.	3	0.3644	4	0.1005
Landpos*Trt		2	.	3	0.7804	4	0.1005
Block(Landpos)		6	.	6	0.2843	6	0.0208*
Residual C.V. (%)			.		337.52		90.60

a,b Mean values followed by the same letter (within columns) are not significantly different.
[z] LSD for individual treatments in individual site years is not reported because there was no Landpos*Trt interaction.
[y] Not applicable (na) because used LSMEANS (missing sample), which does not provide an LSD value.
† significant at $P < 0.10$ (used only for landscape position variables and interactions).
* significant at $P < 0.05$.

Table T.5. Total extractable urea-N between the bandrows at Kane 2001/2002: 0-30 cm soil depth

Treatment		Total extractable urea-N (mg kg^{-1})					
		Sampling Date					
Landscape Position	Fertilization		10/09/01		10/23/01		11/01/01
High	Early fall		0.50		1.50		3.25
	Mid fall		-		1.38		6.38
	Late fall		-		-		1.00
	Spring		-		-		-
	Control (no N)		0.50		1.63		0.75
	Early fall w/ inhibitors		0.50		8.50		1.13
	LSD (α = 0.05)		ns		-^{z}		-^{z}
Low	Early fall		0.00b		7.88		0.75
	Mid fall		-		2.13		6.38
	Late fall		-		-		1.25
	Spring		-		-		-
	Control (no N)		0.38b		4.63		2.17
	Early fall w/ inhibitors		3.13a		2.00		1.13
	LSD (α = 0.05)		na^{y}		-^{z}		-^{z}
Landscape Position Means							
High			0.50		3.25		2.50
Low			1.17		4.16		2.33
LSD (α = 0.10)			-^{x}		ns		ns
	Fertilization Means						
	Early fall		0.25		4.69		2.00
	Mid fall		-		1.75		6.38
	Late fall		-		-		1.13
	Spring		-		-		-
	Control (no N)		0.44		3.13		1.46
	Early fall w/ inhibitors		1.81		5.25		1.13
	LSD (α = 0.05)		-^{x}		ns		ns
ANOVA		df	$P > F$	df	$P > F$	df	$P > F$
Landpos		1	0.103	1	0.6794	1	0.9012
Trt		2	0.0029*	3	0.5967	4	0.1845
Landpos*Trt		2	0.0029*	3	0.1639	4	0.9541
Block(Landpos)		6	0.3564	6	0.3892	6	0.6693
Residual C.V. (%)			91.92		150.59		206.45

a,b Mean values followed by the same letter (within columns) are not significantly different.

^{z} LSD for individual treatments in individual site years is not reported because there was no Landpos*Trt interaction.

^{y} Not applicable (na) because used LSMEANS which does not provide an LSD value.

^{x} LSD is not reported because of significant Landpos*Trt interaction.

† significant at $P < 0.10$ (used only for landscape position variables and interactions).

* significant at $P < 0.05$.

Appendix U

ROSSER (2001/02): BAND ZONE DATA (mg kg^{-1}): 0–15 cm

Table U.1. Effect of landscape position, application date, and inhibitors on soil pH at Rosser 2001/2002: Bandrow (0-15 cm)

Treatment		pH	
		Sampling Date	
Landscape Position	Fertilization	10/02/01	10/30/01
High	Early fall	7.16ab	6.93b
	Mid fall	-	6.96b
	Late fall	-	7.18a
	Spring	-	-
	Control (no N)	7.03b	6.92b
	Early fall w/ inhibitors	7.24a	6.79b
	LSD (α = 0.05)	na[z]	na[z]
Low	Early fall	7.27b	7.11c
	Mid fall	-	7.45ab
	Late fall	-	7.51a
	Spring	-	-
	Control (no N)	7.39ab	7.31b
	Early fall w/ inhibitors	7.45a	7.34ab
	LSD (α = 0.05)	na[z]	na[z]
Landscape Position Means			
High		7.14	6.96
Low		7.37	7.34
LSD (α = 0.10)		-[x]	-[x]
	Fertilization Means		
	Early fall	7.21	7.02
	Mid fall	-	7.20
	Late fall	-	7.34
	Spring	-	-
	Control (no N)	7.21	7.11
	Early fall w/ inhibitors	7.34	7.07
	LSD (α = 0.05)	-[x]	-[x]

ANOVA	df	$P > F$	df	$P > F$
Landpos	1	0.1562	1	0.0596†
Trt	2	0.0308*	4	0.0001*
Landpos*Trt	2	0.0785†	4	0.0381*
Block(Landpos)	6	0.0002*	6	0.0001*
Residual C.V. (%)		1.39		1.68

a-c Mean values followed by the same letter (within columns) are not significantly different.

[z] Not applicable (na) because used LSMEANS, which does not provide an LSD value.

[y] LSD for individual treatments in individual site years is not reported because there was no Landpos*Trt interaction.

[x] LSD is not reported because of Landpos*Trt interaction.

† significant at $P < 0.10$ (used only for landscape position variables and interactions).

* significant at $P < 0.05$.

Table U.2. Effect of landscape position, application date, and inhibitors on soil EC at Rosser 2001/2002: Bandrow (0-15 cm)

Treatment			EC (mS cm^{-1}) Sampling Date		
Landscape Position	Fertilization		10/02/01		10/30/01
High	Early fall		1.58		1.89
	Mid fall		-		1.39
	Late fall		-		1.44
	Spring		-		-
	Control (no N)		1.29		1.26
	Early fall w/ inhibitors		1.45		1.37
	LSD (α = 0.05)[z]		-		-
Low	Early fall		1.39		1.63
	Mid fall		-		1.25
	Late fall		-		1.36
	Spring		-		-
	Control (no N)		1.26		1.22
	Early fall w/ inhibitors		1.51		1.56
	LSD (α = 0.05)[z]		-		-
Landscape Position Means					
High			1.44		1.47
Low			1.39		1.40
LSD (α = 0.10)			ns		ns
	Fertilization Means				
	Early fall		1.48a		1.76a
	Mid fall		-		1.32bc
	Late fall		-		1.40bc
	Spring		-		-
	Control (no N)		1.27b		1.24c
	Early fall w/ inhibitors		1.48a		1.46b
	LSD (α = 0.05)		0.18		0.22
ANOVA		df	$P > F$	df	$P > F$
Landpos		1	0.8111	1	0.7085
Trt		2	0.0379*	4	0.0008*
Landpos*Trt		2	0.3573	4	0.3434
Block(Landpos)		6	0.0006*	6	0.0005*
Residual C.V. (%)			11.72		14.81

a-c Mean values followed by the same letter (within columns) are not significantly different.

[z] LSD for individual treatments in individual site years is not reported because there was no Landpos*Trt interaction.

† significant at $P < 0.10$ (used only for landscape position variables and interactions).

* significant at $P < 0.05$.

Table U.3. Total inorganic N in the bandrow at Rosser 2001/2002: 0-15 cm soil depth

Treatment			Total inorganic N (mg kg^{-1}) Sampling Date		
Landscape Position	Fertilization		10/02/01		10/30/01
High	Early fall		123.0		123.6
	Mid fall		-		150.0
	Late fall		-		154.8
	Spring		-		-
	Control (no N)		17.1		19.8
	Early fall w/ inhibitors		121.9		118.9
	LSD (α = 0.05)[z]		-		-
Low	Early fall		135.4		119.9
	Mid fall		-		129.3
	Late fall		-		175.3
	Spring		-		-
	Control (no N)		12.5		16.0
	Early fall w/ inhibitors		102.9		95.4
	LSD (α = 0.05)[z]		-		-
Landscape Position Means					
High			87.3		113.4
Low			83.6		107.2
LSD (α = 0.10)			ns		ns
	Fertilization Means				
	Early fall		129.2a		121.8b
	Mid fall		-		139.6b
	Late fall		-		165.0a
	Spring		-		-
	Control (no N)		14.8b		17.9d
	Early fall w/ inhibitors		112.4a		107.1c
	LSD (α = 0.05)		22.5		20.0
ANOVA		df	$P > F$	df	$P > F$
Landpos		1	0.5485	1	0.5405
Trt		2	0.0001*	4	0.0001*
Landpos*Trt		2	0.3483	4	0.1938
Block(Landpos)		6	0.8052	6	0.0519†
Residual C.V. (%)			24.2		17.53

a-d Mean values followed by the same letter (within columns) are not significantly different.
[z] LSD for individual treatments in individual site years is not reported because there was no Landpos*Trt interaction.
† significant at $P < 0.10$ (used only for landscape position variables and interactions).
* significant at $P < 0.05$.

Table U.4. Total extractable NH_4^+-N in the bandrow at Rosser 2001/2002: 0-15 cm soil depth

Treatment			Total extractable NH_4^+-N (mg kg^{-1})		
			Sampling Date		
Landscape Position	Fertilization		10/02/01		10/30/01
High	Early fall		73.4		44.6
	Mid fall		-		97.4
	Late fall		-		128.5
	Spring		-		-
	Control (no N)		6.0		7.1
	Early fall w/ inhibitors		92.3		67.0
	LSD (α = 0.05)[z]		-		-
Low	Early fall		100.4		48.6
	Mid fall		-		84.8
	Late fall		-		154.1
	Spring		-		-
	Control (no N)		6.9		7.8
	Early fall w/ inhibitors		80.8		57.5
	LSD (α = 0.05)[z]		-		-
Landscape Position Means					
High			57.2		68.9
Low			62.7		70.6
LSD (α = 0.10)			ns		ns
	Fertilization Means				
	Early fall		86.9a		46.6c
	Mid fall		-		91.1b
	Late fall		-		141.3a
	Spring		-		-
	Control (no N)		6.4b		7.4d
	Early fall w/ inhibitors		86.5a		62.3c
	LSD (α = 0.05)		19.7		20.1
ANOVA		df	$P > F$	df	$P > F$
Landpos		1	0.5893	1	0.8775
Trt		2	0.0001*	4	0.0001*
Landpos*Trt		2	0.1372	4	0.3348
Block(Landpos)		6	0.2101	6	0.0378*
Residual C.V. (%)			30.23		27.87

a-d Mean values followed by the same letter (within columns) are not significantly different.
[z] LSD for individual treatments in individual site years is not reported because there was no Landpos*Trt interaction.
† significant at $P < 0.10$ (used only for landscape position variables and interactions).
* significant at $P < 0.05$.

Table U.5. Total extractable NO_3^--N in the bandrow at Rosser 2001/2002: 0-15 cm soil depth

Treatment			Total extractable NO_3^--N ($mg\ kg^{-1}$)		
			Sampling Date		
Landscape Position	Fertilization		10/02/01		10/30/01
High	Early fall		49.6		79.0
	Mid fall		-		52.6
	Late fall		-		26.3
	Spring		-		-
	Control (no N)		11.1		12.6
	Early fall w/ inhibitors		29.6		51.9
	LSD ($\alpha = 0.05$)[z]		-		-
Low	Early fall		35.0		71.0
	Mid fall		-		44.4
	Late fall		-		21.0
	Spring		-		-
	Control (no N)		5.6		8.3
	Early fall w/ inhibitors		22.1		37.9
	LSD ($\alpha = 0.05$)[z]		-		-
Landscape Position Means					
High			30.1		44.5a
Low			20.9		36.5b
LSD ($\alpha = 0.10$)			ns		7.3
	Fertilization Means				
	Early fall		42.3a		75.0a
	Mid fall		-		48.5b
	Late fall		-		23.6c
	Spring		-		-
	Control (no N)		8.4c		10.4d
	Early fall w/ inhibitors		25.9b		44.9b
	LSD ($\alpha = 0.05$)		10.0		8.3
ANOVA		df	$P > F$	df	$P > F$
Landpos		1	0.1802	1	0.0780†
Trt		2	0.0001*	4	0.0001*
Landpos*Trt		2	0.59	4	0.7812
Block(Landpos)		6	0.071†	6	0.0820†
Residual C.V. (%)			35.79		19.92

a-d Mean values followed by the same letter (within columns) are not significantly different.

[z] LSD for individual treatments in individual site years is not reported because there was no Landpos*Trt interaction.

† significant at $P < 0.10$ (used only for landscape position variables and interactions).

* significant at $P < 0.05$.

Table U.6. Total extractable NO_2^--N in the bandrow at Rosser 2001/2002: 0-15 cm soil depth

Treatment		Total extractable NO_2^--N (mg kg^{-1})			
		Sampling Date			
Landscape Position	Fertilization		10/02/01		10/30/01
High	Early fall		0.00		0.00
	Mid fall		-		0.00
	Late fall		-		0.00
	Spring		-		-
	Control (no N)		0.00		0.00
	Early fall w/ inhibitors		0.00		0.00
	LSD ($\alpha = 0.05$)[z]		-		-
Low	Early fall		0.00		0.25
	Mid fall		-		0.13
	Late fall		-		0.13
	Spring		-		-
	Control (no N)		0.00		0.00
	Early fall w/ inhibitors		0.00		0.00
	LSD ($\alpha = 0.05$)[z]		-		-
Landscape Position Means					
High			0.00		0.00
Low			0.00		0.10
LSD ($\alpha = 0.10$)			ns		ns
	Fertilization Means				
	Early fall		0.00		0.13a
	Mid fall		-		0.06ab
	Late fall		-		0.06ab
	Spring		-		-
	Control (no N)		0.00		0.00b
	Early fall w/ inhibitors		0.00		0.00b
	LSD ($\alpha = 0.05$)		ns		0.12
ANOVA		df	$P > F$	df	$P > F$
Landpos		1	.	1	0.2070
Trt		2	.	4	0.2029
Landpos*Trt		2	.	4	0.2029
Block(Landpos)		6	.	6	0.0097
Residual C.V. (%)			.		232.70

a,b Mean values followed by the same letter (within columns) are not significantly different.

[z] LSD for individual treatments in individual site years is not reported because there was no Landpos*Trt interaction.

† significant at $P < 0.10$ (used only for landscape position variables and interactions).

* significant at $P < 0.05$.

Table U.7. Total extractable urea-N in the bandrow at Rosser 2001/2002: 0-15 cm soil depth

Treatment		Total extractable urea-N (mg kg^{-1})	
		Sampling Date	
Landscape Position	Fertilization	10/02/01	10/30/01
High	Early fall	0.75	2.00
	Mid fall	-	1.00
	Late fall	-	6.13
	Spring	-	-
	Control (no N)	0.50	0.00
	Early fall w/ inhibitors	5.00	0.25
	LSD ($\alpha = 0.05$)[z]	-	-
Low	Early fall	0.88	0.50
	Mid fall	-	1.75
	Late fall	-	8.63
	Spring	-	-
	Control (no N)	0.50	0.00
	Early fall w/ inhibitors	1.50	0.13
	LSD ($\alpha = 0.05$)[z]	-	-
Landscape Position Means			
High		2.10	1.88
Low		0.96	2.20
LSD ($\alpha = 0.10$)		ns	ns
	Fertilization Means		
	Early fall	0.80	1.25b
	Mid fall	-	1.38b
	Late fall	-	7.38a
	Spring	-	-
	Control (no N)	0.50	0.00b
	Early fall w/ inhibitors	3.25	0.19b
	LSD ($\alpha = 0.05$)	ns	4.14

ANOVA	df	$P > F$	df	$P > F$
Landpos	1	0.4305	1	0.7968
Trt	2	0.2344	4	0.0067*
Landpos*Trt	2	0.4862	4	0.8975
Block(Landpos)	6	0.4892	6	0.5088
Residual C.V. (%)		218.59		197.11

a,b Mean values followed by the same letter (within columns) are not significantly different.

[z] LSD for individual treatments in individual site years is not reported because there was no Landpos*Trt interaction.

† significant at $P < 0.10$ (used only for landscape position variables and interactions).

* significant at $P < 0.05$.

Appendix V

ROSSER (2001/02): BAND ZONE DATA (mg kg^{-1}): 15–30 cm

Table V.1. Effect of landscape position, application date, and inhibitors on soil pH at Rosser 2001/2002: Bandrow (15-30 cm)

Treatment			pH		
			Sampling Date		
Landscape Position	Fertilization		10/02/01		10/30/01
High	Early fall		7.78		7.77
	Mid fall		-		7.77
	Late fall		-		7.78
	Spring		-		-
	Control (no N)		7.67		7.77
	Early fall w/ inhibitors		7.81		7.67
	LSD ($\alpha = 0.05$)		-		-
Low	Early fall		7.85		7.94
	Mid fall		-		7.91
	Late fall		-		7.95
	Spring		-		-
	Control (no N)		7.97		7.93
	Early fall w/ inhibitors		7.94		7.97
	LSD ($\alpha = 0.05$)		-		-
Landscape Position Means					
High			7.75b		7.75b
Low			7.92a		7.94a
LSD ($\alpha = 0.10$)			0.12		0.17
	Fertilization Means				
	Early fall		7.82		7.85
	Mid fall		-		7.83
	Late fall		-		7.86
	Spring		-		-
	Control (no N)		7.82		7.85
	Early fall w/ inhibitors		7.87		7.82
	LSD ($\alpha = 0.05$)		ns		ns
ANOVA		df	$P > F$	df	$P > F$
Landpos		1	0.039*	1	0.0764†
Trt		2	0.4491	4	0.8900
Landpos*Trt		2	0.1072	4	0.4500
Block(Landpos)		6	0.0964†	6	0.0001*
Residual C.V. (%)			1.28		1.24

a,b Mean values followed by the same letter (within columns) are not significantly different.

[z] LSD for individual treatments in individual site years is not reported because there was no Landpos*Trt interaction.

† significant at $P < 0.10$ (used only for landscape position variables and interactions).

* significant at $P < 0.05$.

Table V.2. Effect of landscape position, application date, and inhibitors on soil EC at Rosser 2001/2002: Bandrow (15-30 cm)

Treatment			EC (mS cm^{-1})		
			Sampling Date		
Landscape Position	Fertilization		10/02/01		10/30/01
High	Early fall		1.18		1.60
	Mid fall		-		1.46
	Late fall		-		1.73
	Spring		-		-
	Control (no N)		1.38		1.30
	Early fall w/ inhibitors		1.57		1.36
	LSD ($\alpha = 0.05$)[z]		-		-
Low	Early fall		1.45		1.45
	Mid fall		-		1.78
	Late fall		-		1.34
	Spring		-		-
	Control (no N)		1.48		1.44
	Early fall w/ inhibitors		1.63		1.50
	LSD ($\alpha = 0.05$)[z]		-		-
Landscape Position Means					
High			1.37		1.49
Low			1.52		1.50
LSD ($\alpha = 0.10$)			ns		ns
	Fertilization Means				
	Early fall		1.31		1.53
	Mid fall		-		1.62
	Late fall		-		1.54
	Spring		-		-
	Control (no N)		1.43		1.37
	Early fall w/ inhibitors		1.60		1.43
	LSD ($\alpha = 0.05$)		ns		ns
ANOVA		df	$P > F$	df	$P > F$
Landpos		1	0.8016	1	0.9813
Trt		2	0.2271	4	0.6195
Landpos*Trt		2	0.7725	4	0.2753
Block(Landpos)		6	0.0001*	6	0.0001*
Residual C.V. (%)			21.62		22.57

[z] LSD for individual treatments in individual site years is not reported because there was no Landpos*Trt interaction.

† significant at $P < 0.10$ (used only for landscape position variables and interactions).

* significant at $P < 0.05$.

Table V.3. Total inorganic N in the bandrow at Rosser 2001/2002: 15-30 cm soil depth

Treatment			Total inorganic N (mg kg^{-1})		
			Sampling Date		
Landscape Position	Fertilization		10/02/01		10/30/01
High	Early fall		9.1		16.9
	Mid fall		-		14.4
	Late fall		-		10.9
	Spring		-		-
	Control (no N)		8.4		10.6
	Early fall w/ inhibitors		8.6		16.1
	LSD ($\alpha = 0.05$)[z]		-		-
Low	Early fall		10.1		13.4
	Mid fall		-		13.9
	Late fall		-		14.3
	Spring		-		-
	Control (no N)		7.8		9.3
	Early fall w/ inhibitors		9.4		11.5
	LSD ($\alpha = 0.05$)[z]		-		-
Landscape Position Means					
High			8.7		13.8
Low			9.1		12.5
LSD ($\alpha = 0.10$)			ns		ns
	Fertilization Means				
	Early fall		9.6		15.1
	Mid fall		-		14.1
	Late fall		-		12.6
	Spring		-		-
	Control (no N)		8.1		9.9
	Early fall w/ inhibitors		9.0		13.8
	LSD ($\alpha = 0.05$)		ns		ns
ANOVA		df	$P > F$	df	$P > F$
Landpos		1	0.6946	1	0.2981
Trt		2	0.1616	4	0.033*
Landpos*Trt		2	0.535	4	0.1454
Block(Landpos)		6	0.1236	6	0.2824
Residual C.V. (%)			17.13		24.32

a-c Mean values followed by the same letter (within columns) are not significantly different.

[z] LSD for individual treatments in individual site years is not reported because there was no Landpos*Trt interaction.

† significant at $P < 0.10$ (used only for landscape position variables and interactions).

* significant at $P < 0.05$.

Table V.4. Total extractable NH_4^+-N in the bandrow at Rosser 2001/2002: 15-30 cm soil depth

Treatment			Total extractable NH_4^+-N (mg kg^{-1})		
			Sampling Date		
Landscape Position	Fertilization		10/02/01		10/30/01
High	Early fall		5.9		8.1
	Mid fall		-		7.9
	Late fall		-		6.8
	Spring		-		-
	Control (no N)		4.9		6.5
	Early fall w/ inhibitors		5.9		7.9
	LSD ($\alpha = 0.05$)		-[y]		na[z]
Low	Early fall		7.0		6.8b
	Mid fall		-		7.9ab
	Late fall		-		9.8a
	Spring		-		-
	Control (no N)		5.9		6.3b
	Early fall w/ inhibitors		7.1		6.3b
	LSD ($\alpha = 0.05$)		-[y]		na[z]
Landscape Position Means					
High			5.5b		7.4
Low			6.7a		7.4
LSD ($\alpha = 0.10$)			0.7		-[x]
	Fertilization Means				
	Early fall		6.4		7.4
	Mid fall		-		7.9
	Late fall		-		8.3
	Spring		-		-
	Control (no N)		5.4		6.4
	Early fall w/ inhibitors		6.5		7.1
	LSD ($\alpha = 0.05$)		ns		-[x]
ANOVA		df	$P > F$	df	$P > F$
Landpos		1	0.0256*	1	0.9527
Trt		2	0.0666	4	0.2717
Landpos*Trt		2	0.9672	4	0.0981†
Block(Landpos)		6	0.506	6	0.0868†
Residual C.V. (%)			15.83		23.68

a,b Mean values followed by the same letter (within columns) are not significantly different.

[z] Not applicable (na) because used LSMEANS, which does not provide an LSD value.

[y] LSD for individual treatments in individual site years is not reported because there was no Landpos*Trt interaction.

[x] LSD is not reported because of Landpos*Trt interaction.

† significant at $P < 0.10$ (used only for landscape position variables and interactions).

* significant at $P < 0.05$.

Table V.5. Total extractable NO_3^--N in the bandrow at Rosser 2001/2002: 15-30 cm soil depth

Treatment			Total extractable NO_3^--N (mg kg^{-1})		
			Sampling Date		
Landscape Position	Fertilization		10/02/01		10/30/01
High	Early fall		3.3		8.8
	Mid fall		-		6.5
	Late fall		-		4.0
	Spring		-		-
	Control (no N)		3.5		4.0
	Early fall w/ inhibitors		2.8		8.3
	LSD ($\alpha = 0.05$)[z]		-		-
Low	Early fall		3.1		6.6
	Mid fall		-		6.0
	Late fall		-		4.4
	Spring		-		-
	Control (no N)		1.9		3.0
	Early fall w/ inhibitors		2.3		5.3
	LSD ($\alpha = 0.05$)[z]		-		-
Landscape Position Means					
High			3.2		6.3
Low			2.4		5.1
LSD ($\alpha = 0.10$)			ns		ns
	Fertilization Means				
	Early fall		3.2		7.7a
	Mid fall		-		6.3ab
	Late fall		-		4.2bc
	Spring		-		-
	Control (no N)		2.7		3.5c
	Early fall w/ inhibitors		2.5		6.8a
	LSD ($\alpha = 0.05$)		ns		2.1
ANOVA		df	$P > F$	df	$P > F$
Landpos		1	0.4752	1	0.1637
Trt		2	0.3544	4	0.0021*
Landpos*Trt		2	0.2921	4	0.5231
Block(Landpos)		6	0.003*	6	0.2403
Residual C.V. (%)			33.84		36.57

a-c Mean values followed by the same letter (within columns) are not significantly different.

[z] LSD for individual treatments in individual site years is not reported because there was no Landpos*Trt interaction.

† significant at $P < 0.10$ (used only for landscape position variables and interactions).

* significant at $P < 0.05$.

Table V.6. Total extractable NO_2^--N in the bandrow at Rosser 2001/2002: 15-30 cm soil depth

Treatment			Total extractable NO_2^--N (mg kg^{-1})		
			Sampling Date		
Landscape Position	Fertilization		10/02/01		10/30/01
High	Early fall		0.00		0.00
	Mid fall		-		0.00
	Late fall		-		0.13
	Spring		-		-
	Control (no N)		0.00		0.13
	Early fall w/ inhibitors		0.00		0.00
	LSD (α = 0.05)[z]		-		-
Low	Early fall		0.00		0.00
	Mid fall		-		0.00
	Late fall		-		0.13
	Spring		-		-
	Control (no N)		0.00		0.00
	Early fall w/ inhibitors		0.00		0.00
	LSD (α = 0.05)[z]		-		-
Landscape Position Means					
High			0.00		0.05
Low			0.00		0.03
LSD (α = 0.10)			ns		ns
	Fertilization Means				
	Early fall		0.00		0.00
	Mid fall		-		0.00
	Late fall		-		0.13
	Spring		-		-
	Control (no N)		0.00		0.06
	Early fall w/ inhibitors		0.00		0.00
	LSD (α = 0.05)		ns		ns
ANOVA		df	$P > F$	df	$P > F$
Landpos		1	.	1	0.6704
Trt		2	.	4	0.2067
Landpos*Trt		2	.	4	0.8067
Block(Landpos)		6	.	6	0.1053
Residual C.V. (%)			.		333.33

[z] LSD for individual treatments in individual site years is not reported because there was no Landpos*Trt interaction.
† significant at $P < 0.10$ (used only for landscape position variables and interactions).
* significant at $P < 0.05$.

Table V.7. Total extractable urea-N in the bandrow at Rosser 2001/2002: 15-30 cm soil depth

Treatment		Total extractable urea-N (mg kg^{-1}) Sampling Date			
Landscape Position	Fertilization		10/02/01		10/30/01
High	Early fall		0.38		0.75
	Mid fall		-		0.25
	Late fall		-		0.25
	Spring		-		-
	Control (no N)		0.13		0.00
	Early fall w/ inhibitors		0.25		0.00
	LSD ($\alpha = 0.05$)[z]		-		-
Low	Early fall		0.13		0.38
	Mid fall		-		0.13
	Late fall		-		0.13
	Spring		-		-
	Control (no N)		0.38		0.13
	Early fall w/ inhibitors		0.63		0.00
	LSD ($\alpha = 0.05$)[z]		-		-
Landscape Position Means					
High			0.25		0.25
Low			0.38		0.15
LSD ($\alpha = 0.10$)			ns		ns
	Fertilization Means				
	Early fall		0.25		0.56
	Mid fall		-		0.19
	Late fall		-		0.19
	Spring		-		-
	Control (no N)		0.25		0.06
	Early fall w/ inhibitors		0.44		0.00
	LSD ($\alpha = 0.05$)		ns		ns
ANOVA		df	$P > F$	df	$P > F$
Landpos		1	0.3867	1	0.5060
Trt		2	0.5903	4	0.0774
Landpos*Trt		2	0.3119	4	0.7825
Block(Landpos)		6	0.7025	6	0.3109
Residual C.V. (%)			131.99		198.96

[z] LSD for individual treatments in individual site years is not reported because there was no Landpos*Trt interaction.
† significant at $P < 0.10$ (used only for landscape position variables and interactions).
* significant at $P < 0.05$.

Appendix W

ROSSER (2001/02): BETWEEN BAND ZONE DATA (mg kg^{-1}): 0–30 cm

Table W.1. Total inorganic N between the bandrows at Rosser 2001/2002: 0-30 cm soil depth

Treatment		Total inorganic N (mg kg^{-1})			
		Sampling Date			
Landscape Position	Fertilization		10/02/01		10/30/01
High	Early fall		24.6		39.0
	Mid fall		-		39.4
	Late fall		-		31.9
	Spring		-		-
	Control (no N)		25.5		30.4
	Early fall w/ inhibitors		26.3		37.3
	LSD ($\alpha = 0.05$)^z		-		-
Low	Early fall		23.0		31.4
	Mid fall		-		30.9
	Late fall		-		42.0
	Spring		-		-
	Control (no N)		20.3		25.3
	Early fall w/ inhibitors		23.5		38.5
	LSD ($\alpha = 0.05$)^z		-		-
Landscape Position Means					
High			25.5		35.6
Low			22.3		33.6
LSD ($\alpha = 0.10$)			ns		ns
	Fertilization Means				
	Early fall		23.8		35.2
	Mid fall		-		35.1
	Late fall		-		36.9
	Spring		-		-
	Control (no N)		22.9		27.8
	Early fall w/ inhibitors		24.9		37.9
	LSD ($\alpha = 0.05$)		ns		ns
ANOVA		df	$P > F$	df	$P > F$
Landpos		1	0.3165	1	0.1533
Trt		2	0.6237	4	0.2568
Landpos*Trt		2	0.665	4	0.2756
Block(Landpos)		6	0.0420*	6	0.9836
Residual C.V. (%)			16.93		27.18

^{z} LSD for individual treatments in individual site years is not reported because there was no Landpos*Trt interaction.
† significant at $P < 0.10$ (used only for landscape position variables and interactions).
* significant at $P < 0.05$.

Table W.2. Total extractable NH_4^+-N between the bandrows at Rosser 2001/2002: 0-30 cm soil depth

Treatment		Total extractable NH_4^+-N (mg kg^{-1})			
		Sampling Date			
Landscape Position	Fertilization		10/02/01		10/30/01
High	Early fall		10.5		14.9
	Mid fall		-		15.0
	Late fall		-		14.3
	Spring		-		-
	Control (no N)		10.9		13.6
	Early fall w/ inhibitors		13.0		14.6
	LSD ($\alpha = 0.05$)		-		-
Low	Early fall		12.4		12.6
	Mid fall		-		15.4
	Late fall		-		28.4
	Spring		-		-
	Control (no N)		12.8		14.0
	Early fall w/ inhibitors		13.5		18.9
	LSD ($\alpha = 0.05$)		-		-
Landscape Position Means					
High			11.5		14.5b
Low			12.9		17.9a
LSD ($\alpha = 0.10$)			ns		2.6
	Fertilization Means				
	Early fall		11.4b		13.8
	Mid fall		-		15.2
	Late fall		-		21.3
	Spring		-		-
	Control (no N)		11.8b		13.8
	Early fall w/ inhibitors		13.3a		16.8
	LSD ($\alpha = 0.05$)		1.3		ns
ANOVA		df	$P > F$	df	$P > F$
Landpos		1	0.2439	1	0.0431*
Trt		2	0.0215*	4	0.2302
Landpos*Trt		2	0.4227	4	0.2062
Block(Landpos)		6	0.0069*	6	0.9109
Residual C.V. (%)			9.59		44.53

a,b Mean values followed by the same letter (within columns) are not significantly different.

[z] LSD for individual treatments in individual site years is not reported because there was no Landpos*Trt interaction.

† significant at $P < 0.10$ (used only for landscape position variables and interactions).

* significant at $P < 0.05$.

Table W.3. Total extractable NO_3^--N between the bandrows at Rosser 2001/2002: 0-30 cm soil depth

Treatment			Total extractable NO_3^--N (mg kg^{-1})		
			Sampling Date		
Landscape Position	Fertilization		10/02/01		10/30/01
High	Early fall		14.1		24.1
	Mid fall		-		24.1
	Late fall		-		17.6
	Spring		-		-
	Control (no N)		14.6		16.6
	Early fall w/ inhibitors		13.3		22.5
	LSD ($\alpha = 0.05$)[z]		-		-
Low	Early fall		10.6		18.8
	Mid fall		-		15.5
	Late fall		-		13.6
	Spring		-		-
	Control (no N)		7.5		11.3
	Early fall w/ inhibitors		10.0		19.6
	LSD ($\alpha = 0.05$)[z]		-		-
Landscape Position Means					
High			14.0		21.0a
Low			9.4		15.8b
LSD ($\alpha = 0.10$)			ns		1.8
	Fertilization Means				
	Early fall		12.4		21.4a
	Mid fall		-		19.8ab
	Late fall		-		15.6bc
	Spring		-		-
	Control (no N)		11.1		13.9c
	Early fall w/ inhibitors		11.6		21.1a
	LSD ($\alpha = 0.05$)		ns		4.6
ANOVA		df	$P > F$	df	$P > F$
Landpos		1	0.2022	1	0.0012*
Trt		2	0.7678	4	0.0064*
Landpos*Trt		2	0.501	4	0.7562
Block(Landpos)		6	0.0096*	6	0.8568
Residual C.V. (%)			30.66		24.19

a-c Mean values followed by the same letter (within columns) are not significantly different.

[z] LSD for individual treatments in individual site years is not reported because there was no Landpos*Trt interaction.

† significant at $P < 0.10$ (used only for landscape position variables and interactions).

* significant at $P < 0.05$.

Table W.4. Total extractable NO_2^--N between the bandrows at Rosser 2001/2002: 0-30 cm soil depth

Treatment		Total extractable NO_2^--N (mg kg^{-1})			
		Sampling Date			
Landscape Position	Fertilization		10/02/01		10/30/01
High	Early fall		0.00		0.00
	Mid fall		-		0.25
	Late fall		-		0.00
	Spring		-		-
	Control (no N)		0.00		0.13
	Early fall w/ inhibitors		0.00		0.13
	LSD (α = 0.05)[z]		-		-
Low	Early fall		0.00		0.00
	Mid fall		-		0.00
	Late fall		-		0.00
	Spring		-		-
	Control (no N)		0.00		0.00
	Early fall w/ inhibitors		0.00		0.00
	LSD (α = 0.05)[z]		-		-
Landscape Position Means					
High			0.00		0.10
Low			0.00		0.00
LSD (α = 0.10)			ns		ns
	Fertilization Means				
	Early fall		0.00		0.00
	Mid fall		-		0.13
	Late fall		-		0.00
	Spring		-		-
	Control (no N)		0.00		0.06
	Early fall w/ inhibitors		0.00		0.06
	LSD (α = 0.05)		ns		ns
ANOVA		df	$P > F$	df	$P > F$
Landpos		1	.	1	0.2070
Trt		2	.	4	0.2029
Landpos*Trt		2	.	4	0.2029
Block(Landpos)		6	.	6	0.0097*
Residual C.V. (%)			.		232.74

[z] LSD for individual treatments in individual site years is not reported because there was no Landpos*Trt interaction.
† significant at $P < 0.10$ (used only for landscape position variables and interactions).
* significant at $P < 0.05$.

Table W.5. Total extractable urea-N between the bandrows at Rosser 2001/2002: 0-30 cm soil depth

Treatment			Total extractable urea-N (mg kg^{-1})		
			Sampling Date		
Landscape Position	Fertilization		10/02/01		10/30/01
High	Early fall		1.00		0.13
	Mid fall		-		0.25
	Late fall		-		0.25
	Spring		-		-
	Control (no N)		0.63		0.00
	Early fall w/ inhibitors		0.88		0.25
	LSD ($\alpha = 0.05$)[z]		-		-
Low	Early fall		0.75		0.25
	Mid fall		-		0.63
	Late fall		-		0.63
	Spring		-		-
	Control (no N)		0.88		0.13
	Early fall w/ inhibitors		1.00		0.00
	LSD ($\alpha = 0.05$)[z]		-		-
Landscape Position Means					
High			0.83		0.18
Low			0.88		0.33
LSD ($\alpha = 0.10$)			ns		ns
	Fertilization Means				
	Early fall		0.88		0.19
	Mid fall		-		0.44
	Late fall		-		0.44
	Spring		-		-
	Control (no N)		0.75		0.06
	Early fall w/ inhibitors		0.94		0.13
	LSD ($\alpha = 0.05$)		ns		ns
ANOVA		df	$P > F$	df	$P > F$
Landpos		1	0.7502	1	0.3053
Trt		2	0.7334	4	0.3533
Landpos*Trt		2	0.5692	4	0.6603
Block(Landpos)		6	0.8592	6	0.5578
Residual C.V. (%)			56.04		185.74

[z] LSD for individual treatments in individual site years is not reported because there was no Landpos*Trt interaction.

† significant at $P < 0.10$ (used only for landscape position variables and interactions).

* significant at $P < 0.05$.

Appendix X

BRANDON (2001/02): BAND ZONE DATA (mg kg^{-1}): 0–15 cm

Table X.1. Effect of landscape position, application date, and inhibitors on soil pH at Brandon 2001/2002: Bandrow (0-15 cm)

Treatment			pH				
			Sampling Date				
Landscape Position	Fertilization		10/01/01		10/15/01		11/01/01
High	Early fall		7.65		7.38b		7.39
	Mid fall		-		7.59a		7.52
	Late fall		-		-		7.70
	Spring		-		-		-
	Control (no N)		7.63		7.59a		7.52
	Early fall w/ inhibitors		7.62		7.59a		7.50
	LSD ($\alpha = 0.05$)		-[z]		na[y]		-[z]
Low	Early fall		8.01		7.93		7.91
	Mid fall		-		7.90		7.96
	Late fall		-		-		8.01
	Spring		-		-		-
	Control (no N)		8.01		7.98		8.00
	Early fall w/ inhibitors		8.01		7.89		7.95
	LSD ($\alpha = 0.05$)		-[z]		ns		-[z]
Landscape Position Means							
High			7.36b		7.54b		7.52b
Low			8.01a		7.92a		7.98a
LSD ($\alpha = 0.10$)			0.25		-[x]		0.19
	Fertilization Means						
	Early fall		7.83		7.65		7.65c
	Mid fall		-		7.75		7.74b
	Late fall		-		-		7.89a
	Spring		-		-		-
	Control (no N)		7.82		7.79		7.76b
	Early fall w/ inhibitors		7.81		7.73		7.72bc
	LSD ($\alpha = 0.05$)		ns		-[x]		0.08
ANOVA		df	$P > F$	df	$P > F$	df	$P > F$
Landpos		1	0.0254*	1	0.0105*	1	0.0039*
Trt		2	0.9752	3	0.1386	4	0.0001*
Landpos*Trt		2	0.9531	3	0.0854†	4	0.4978
Block(Landpos)		6	0.0119*	6	0.0004*	6	0.0001*
Residual C.V. (%)			1.87		1.39		1.02

a-c Mean values followed by the same letter (within columns) are not significantly different.

[z] LSD for individual treatments in individual site years is not reported because there was no Landpos*Trt interaction.

[y] Not applicable (na) because used LSMEANS, which does not provide an LSD value.

[x] LSD is not reported because of Landpos*Trt interaction.

† significant at $P < 0.10$ (used only for landscape position variables and interactions).

* significant at $P < 0.05$.

Table X.2. Effect of landscape position, application date, and inhibitors on soil EC at Brandon 2001/2002: Bandrow (0-15 cm)

Treatment			EC (mS cm^{-1})			
			Sampling Date			
Landscape Position	Fertilization		10/01/01	10/15/01		11/01/01
High	Early fall		0.90	1.63		1.82
	Mid fall		-	0.99		1.21
	Late fall		-	-		1.02
	Spring		-	-		-
	Control (no N)		0.83	0.70		0.70
	Early fall w/ inhibitors		0.97	1.13		1.27
	LSD ($\alpha = 0.05$)[z]		-	-		-
Low	Early fall		5.36	4.30		4.39
	Mid fall		-	4.28		4.54
	Late fall		-	-		4.63
	Spring		-	-		-
	Control (no N)		4.29	4.38		4.38
	Early fall w/ inhibitors		4.46	3.83		3.40
	LSD ($\alpha = 0.05$)[z]		-	-		-
Landscape Position Means			0.9b	1.11		1.20
High			4.7a	4.20		4.26
Low			3.06	ns		ns
LSD ($\alpha = 0.10$)						
	Fertilization Means					
	Early fall		3.13	2.97		3.10
	Mid fall		-	2.63		2.87
	Late fall		-	-		2.82
	Spring		-	-		-
	Control (no N)		2.56	2.54		2.54
	Early fall w/ inhibitors		2.71	2.48		2.33
	LSD ($\alpha = 0.05$)		ns	ns		ns

ANOVA	df	$P > F$	df	$P > F$	df	$P > F$
Landpos	1	0.0525†	1	0.2064	1	0.1480
Trt	2	0.5126	3	0.4614	4	0.5059
Landpos*Trt	2	0.5315	3	0.3593	4	0.3763
Block(Landpos)	6	0.0001*	6	0.0001*	6	0.0001*
Residual C.V. (%)		35.32		24.41		33.70

a-c Mean values followed by the same letter (within columns) are not significantly different.

[z] LSD for individual treatments in individual site years is not reported because there was no Landpos*Trt interaction.

† significant at $P < 0.10$ (used only for landscape position variables and interactions).

* significant at $P < 0.05$.

Table X.3. Total inorganic N in the bandrow at Brandon 2001/2002: 0-15 cm soil depth

Treatment			Total inorganic N (mg kg^{-1})			
			Sampling Date			
Landscape Position	Fertilization		10/01/01		10/15/01		11/01/01
High	Early fall		176.3		182.4		184.1b
	Mid fall		-		217.4		203.4b
	Late fall		-		-		297.4a
	Spring		-		-		-
	Control (no N)		15.6		17.0		13.8c
	Early fall w/ inhibitors		166.4		149.3		155.3b
	LSD (α = 0.05)		-[z]		-[z]		na[y]
Low	Early fall		159.6		147.4		119.6a
	Mid fall		-		182.9		99.8a
	Late fall		-		-		155.9a
	Spring		-		-		-
	Control (no N)		4.6		6.1		3.1b
	Early fall w/ inhibitors		130.3		152.9		120.8a
	LSD (α = 0.05)		-[z]		-[z]		na[y]
Landscape Position Means							
High			119.4		141.5		170.8
Low			98.2		122.3		99.8
LSD (α = 0.10)			ns		ns		-[x]
	Fertilization Means						
	Early fall		167.9a		164.9a		151.9
	Mid fall		-		200.1a		151.6
	Late fall		-		-		226.6
	Spring		-		-		-
	Control (no N)		10.1b		11.6b		8.4
	Early fall w/ inhibitors		148.3a		151.1a		138.0
	LSD (α = 0.05)		29.6		67.2		-[x]
ANOVA		df	$P > F$	df	$P > F$	df	$P > F$
Landpos		1	0.2964	1	0.5970	1	0.0089*
Trt		2	0.0001*	3	0.0001*	4	0.0001*
Landpos*Trt		2	0.6346	3	0.9121	4	0.0703†
Block(Landpos)		6	0.0599†	6	0.079†	6	0.2009
Residual C.V. (%)			24.94		48.53		34.83

a-c Mean values followed by the same letter (within columns) are not significantly different.

[z] LSD for individual treatments in individual site years is not reported because there was no Landpos*Trt interaction.

[y] Not applicable (na) because used LSMEANS, which does not provide an LSD value.

[x] LSD is not reported because of Landpos*Trt interaction.

† significant at $P < 0.10$ (used only for landscape position variables and interactions).

* significant at $P < 0.05$.

Table X.4. Total extractable NH_4^+-N in the bandrow at Brandon 2001/2002: 0-15 cm soil depth

Treatment			Total extractable NH_4^+-N (mg kg^{-1})			
			Sampling Date			
Landscape Position	Fertilization		10/01/01	10/15/01		11/01/01
High	Early fall		127.3	48.1		31.3cd
	Mid fall		-	176.1		133.3b
	Late fall		-	-		272.3a
	Spring		-	-		-
	Control (no N)		2.1	2.3		2.6d
	Early fall w/ inhibitors		124.3	86.8		80.1bc
	LSD ($\alpha = 0.05$)		-[z]	-[z]		na[y]
Low	Early fall		101.1	33.1		5.6b
	Mid fall		-	133.8		53.5b
	Late fall		-	-		138.5a
	Spring		-	-		-
	Control (no N)		2.0	2.3		1.5b
	Early fall w/ inhibitors		87.6	75.0		57.1b
	LSD ($\alpha = 0.05$)		-[z]	-[z]		na[y]
Landscape Position Means						
High			84.5	78.3		103.9
Low			63.6	61.0		51.3
LSD ($\alpha = 0.10$)			ns	ns		-[x]
	Fertilization Means					
	Early fall		114.2a	40.6bc		18.4
	Mid fall		-	154.9a		93.4
	Late fall		-	-		205.4
	Spring		-	-		-
	Control (no N)		2.1b	2.3c		2.1
	Early fall w/ inhibitors		105.9a	80.9b		68.6
	LSD ($\alpha = 0.05$)		28.9	59.7		-[x]

ANOVA	df	$P > F$	df	$P > F$	df	$P > F$
Landpos	1	0.2849	1	0.5910	1	0.0084*
Trt	2	0.0001*	3	0.0003*	4	0.0001*
Landpos*Trt	2	0.3958	3	0.8957	4	0.0644†
Block(Landpos)	6	0.0666†	6	0.0801†	6	0.5627
Residual C.V. (%)		35.84		81.56		61.27

a-d Mean values followed by the same letter (within columns) are not significantly different.

[z] LSD for individual treatments in individual site years is not reported because there was no Landpos*Trt interaction.

[y] Not applicable (na) because used LSMEANS, which does not provide an LSD value.

[x] LSD is not reported because of Landpos*Trt interaction.

† significant at $P < 0.10$ (used only for landscape position variables and interactions).

* significant at $P < 0.05$.

Table X.5. Total extractable NO_3^--N in the bandrow at Brandon 2001/2002: 0-15 cm soil depth

Treatment			Total extractable NO_3^--N (mg kg^{-1})				
			Sampling Date				
Landscape Position	Fertilization		10/01/01		10/15/01		11/01/01
High	Early fall		47.6		125.6		146.8
	Mid fall		-		40.4		67.3
	Late fall		-		-		25.0
	Spring		-		-		-
	Control (no N)		13.5		14.8		11.1
	Early fall w/ inhibitors		42.0		62.5		75.1
	LSD ($\alpha = 0.05$)[z]		-		-		-
Low	Early fall		49.8		103.8		111.1
	Mid fall		-		42.1		40.1
	Late fall		-		-		14.4
	Spring		-		-		-
	Control (no N)		2.6		3.9		1.6
	Early fall w/ inhibitors		40.0		77.9		63.6
	LSD ($\alpha = 0.05$)[z]		-		-		-
Landscape Position Means							
High			34.4		60.8		65.1a
Low			30.8		56.9		46.2b
LSD ($\alpha = 0.10$)			ns		ns		14.0
	Fertilization Means						
	Early fall		48.7a		114.7a		128.9a
	Mid fall		-		41.3c		53.7b
	Late fall		-		-		19.7b
	Spring		-		-		-
	Control (no N)		8.1b		9.3d		6.4c
	Early fall w/ inhibitors		41.0a		70.2b		69.4b
	LSD ($\alpha = 0.05$)		7.9		23.3		16.7
ANOVA		df	$P > F$	df	$P > F$	df	$P > F$
Landpos		1	0.3211	1	0.6056	1	0.0396*
Trt		2	0.0001*	3	0.0001*	4	0.0001*
Landpos*Trt		2	0.2261	3	0.3939	4	0.3948
Block(Landpos)		6	0.3445	6	0.5571	6	0.1083
Residual C.V. (%)			22.2		37.66		29.11

a-d Mean values followed by the same letter (within columns) are not significantly different.

[z] LSD for individual treatments in individual site years is not reported because there was no Landpos*Trt interaction.

† significant at $P < 0.10$ (used only for landscape position variables and interactions).

* significant at $P < 0.05$.

Table X.6. Total extractable NO_2^--N in the bandrow at Brandon 2001/2002: 0-15 cm soil depth

Treatment			Total extractable NO_2^--N (mg kg^{-1})				
			Sampling Date				
Landscape Position	Fertilization		10/01/01		10/15/01		11/01/01
High	Early fall		1.38		8.63		6.13
	Mid fall		-		0.88		2.88
	Late fall		-		-		0.13
	Spring		-		-		-
	Control (no N)		0.00		0.00		0.00
	Early fall w/ inhibitors		0.13		0.00		0.00
	LSD ($\alpha = 0.05$)		ns		-[z]		-[z]
Low	Early fall		8.75a		10.50		2.88
	Mid fall		-		7.00		6.13
	Late fall		-		-		3.00
	Spring		-		-		-
	Control (no N)		0.00b		0.00		0.00
	Early fall w/ inhibitors		2.63b		0.00		0.00
	LSD ($\alpha = 0.05$)		na[y]		-[z]		-[z]
Landscape Position Means							
High			0.50		2.38		2.40
Low			3.80		4.38		1.83
LSD ($\alpha = 0.10$)			-[x]		ns		ns
	Fertilization Means						
	Early fall		5.10		9.56a		4.50a
	Mid fall		-		3.94ab		4.50a
	Late fall		-		-		1.56ab
	Spring		-		-		-
	Control (no N)		0.00		0.00b		0.00b
	Early fall w/ inhibitors		1.40		0.00b		0.00b
	LSD ($\alpha = 0.05$)		-[x]		6.56		3.25
ANOVA		df	$P > F$	df	$P > F$	df	$P > F$
Landpos		1	0.0257*	1	0.3664	1	0.6257
Trt		2	0.0009*	3	0.0203*	4	0.0109*
Landpos*Trt		2	0.0101*	3	0.7351	4	0.2669
Block(Landpos)		6	0.1745	6	0.5413	6	0.3141
Residual C.V. (%)			94.09		184.92		149.48

a,b Mean values followed by the same letter (within columns) are not significantly different.

[z] LSD for individual treatments in individual site years is not reported because there was no Landpos*Trt interaction.

[y] Not applicable (na) because used LSMEANS, which does not provide an LSD value.

[x] LSD is not reported because of Landpos*Trt interaction.

† significant at $P < 0.10$ (used only for landscape position variables and interactions).

* significant at $P < 0.05$.

Table X.7. Total extractable urea-N in the bandrow at Brandon 2001/2002: 0-15 cm soil depth

Treatment			Total extractable urea-N (mg kg^{-1})			
			Sampling Date			
Landscape Position	Fertilization		10/01/01		10/15/01		11/01/01
High	Early fall		2.00		0.88		4.00
	Mid fall		-		3.13		3.00
	Late fall		-		-		9.00
	Spring		-		-		-
	Control (no N)		0.75		0.63		1.38
	Early fall w/ inhibitors		3.75		1.75		5.13
	LSD ($\alpha = 0.05$)[z]		-		-		-
Low	Early fall		2.00		1.38		2.50
	Mid fall		-		3.50		3.25
	Late fall		-		-		15.25
	Spring		-		-		-
	Control (no N)		2.75		2.50		0.63
	Early fall w/ inhibitors		11.38		2.38		4.13
	LSD ($\alpha = 0.05$)[z]		-		-		-
Landscape Position Means							
High			5.38		1.59		4.50
Low			2.17		2.44		5.15
LSD ($\alpha = 0.10$)			ns		ns		ns
	Fertilization Means						
	Early fall		2.00		1.13		3.25b
	Mid fall		-		3.31		3.13b
	Late fall		-		-		12.13a
	Spring		-		-		-
	Control (no N)		1.75		1.56		1.00a
	Early fall w/ inhibitors		7.56		2.06		4.63b
	LSD ($\alpha = 0.05$)		ns		ns		5.47
ANOVA		df	$P > F$	df	$P > F$	df	$P > F$
Landpos		1	0.1257	1	0.2362	1	0.6089
Trt		2	0.0871	3	0.2288	4	0.0036*
Landpos*Trt		2	0.3674	3	0.8857	4	0.5831
Block(Landpos)		6	0.6684	6	0.6339	6	0.7905
Residual C.V. (%)			142.03		105.54		109.93

a,b Mean values followed by the same letter (within columns) are not significantly different.

[z] LSD for individual treatments in individual site years is not reported because there was no Landpos*Trt interaction.

† significant at $P < 0.10$ (used only for landscape position variables and interactions).

* significant at $P < 0.05$.

Appendix Y

BRANDON (2001/02): BAND ZONE DATA (mg kg^{-1}): 15–30 cm

Table Y.1. Effect of landscape position, application date, and inhibitors on soil pH at Brandon 2001/2002: Bandrow (15-30 cm)

Treatment		pH					
		Sampling Date					
Landscape Position	Fertilization		10/01/01		10/15/01		11/01/01
High	Early fall		7.95		8.03a		7.87
	Mid fall		-		7.85b		7.81
	Late fall		-		-		7.89
	Spring		-		-		-
	Control (no N)		7.72		7.94ab		7.80
	Early fall w/ inhibitors		7.88		7.98a		7.89
	LSD ($\alpha = 0.05$)		-[y]		na[z]		-
Low	Early fall		8.28		8.43a		8.39
	Mid fall		-		8.09b		8.12
	Late fall		-		-		8.35
	Spring		-		-		-
	Control (no N)		8.26		8.17b		8.32
	Early fall w/ inhibitors		8.27		8.43a		8.25
	LSD ($\alpha = 0.05$)		-[y]		na[z]		-
Landscape Position Means							
High			7.9b		7.95		7.85b
Low			8.3a		8.28		8.28a
LSD ($\alpha = 0.10$)			0.25		-[x]		0.20
	Fertilization Means						
	Early fall		8.12		8.23		8.13
	Mid fall		-		7.97		7.96
	Late fall		-		-		8.12
	Spring		-		-		-
	Control (no N)		7.99		8.05		8.06
	Early fall w/ inhibitors		8.07		8.20		8.07
	LSD ($\alpha = 0.05$)		ns		-[x]		ns
ANOVA		df	$P > F$	df	$P > F$	df	$P > F$
Landpos		1	0.0175*	1	0.0029*	1	0.0054*
Trt		2	0.5408	3	0.0001*	4	0.2381
Landpos*Trt		2	0.6129	3	0.0346*	4	0.5500
Block(Landpos)		6	0.1377	6	0.0023*	6	0.0038*
Residual C.V. (%)			2.74		1.03		1.90

a,b Mean values followed by the same letter (within columns) are not significantly different.

[z] LSD for individual treatments in individual site years is not reported because there was no Landpos*Trt interaction.

[y] Not applicable (na) because used LSMEANS, which does not provide an LSD value.

[x] LSD is not reported because of Landpos*Trt interaction.

† significant at $P < 0.10$ (used only for landscape position variables and interactions).

* significant at $P < 0.05$.

Table Y.2. Effect of landscape position, application date, and inhibitors on soil EC at Brandon 2001/2002: Bandrow (15-30 cm)

Treatment			EC (mS cm^{-1}) Sampling Date			
Landscape Position	Fertilization		10/01/01		10/15/01		11/01/01
High	Early fall		0.59		0.59		0.88
	Mid fall		-		0.93		0.93
	Late fall		-		-		0.74
	Spring		-		-		-
	Control (no N)		1.34		1.20		1.19
	Early fall w/ inhibitors		0.72		0.56		0.88
	LSD ($\alpha = 0.05$)[z]		-		-		-
Low	Early fall		3.29		2.42		2.82
	Mid fall		-		2.65		2.46
	Late fall		-		-		2.14
	Spring		-		-		-
	Control (no N)		2.52		3.14		3.20
	Early fall w/ inhibitors		3.29		2.42		2.95
	LSD ($\alpha = 0.05$)[z]		-		-		-
Landscape Position Means							
High			0.88b		0.82		0.92
Low			3.03a		2.66		2.71
LSD ($\alpha = 0.10$)			1.57		ns		ns
	Fertilization Means						
	Early fall		1.94		1.51		1.85
	Mid fall		-		1.79		1.69
	Late fall		-		-		1.44
	Spring		-		-		-
	Control (no N)		1.93		2.17		2.19
	Early fall w/ inhibitors		2.00		1.49		1.91
	LSD ($\alpha = 0.05$)		ns		ns		ns
ANOVA		df	$P > F$	df	$P > F$	df	$P > F$
Landpos		1	0.0376*	1	0.2548	1	0.1587
Trt		2	0.9872	3	0.1185	4	0.5258
Landpos*Trt		2	0.2663	3	0.9859	4	0.9105
Block(Landpos)		6	0.0181*	6	0.0001*	6	0.0001*
Residual C.V. (%)			49.96		34.74		47.87

a,b Mean values followed by the same letter (within columns) are not significantly different.

[z] LSD for individual treatments in individual site years is not reported because there was no Landpos*Trt interaction.

† significant at $P < 0.10$ (used only for landscape position variables and interactions).

* significant at $P < 0.05$.

Table Y.3. Total inorganic N in the bandrow at Brandon 2001/2002: 15-30 cm soil depth							
			Total inorganic N (mg kg^{-1})				
Treatment			Sampling Date				
Landscape Position	Fertilization		10/01/01		10/15/01		11/01/01
High	Early fall		6.8		9.5		8.4
	Mid fall		-		7.3		8.9
	Late fall		-		-		6.4
	Spring		-		-		-
	Control (no N)		5.9		7.0		5.0
	Early fall w/ inhibitors		7.3		9.4		6.9
	LSD (α = 0.05)^z		-		-		-
Low	Early fall		14.9		4.8		8.5
	Mid fall		-		4.4		17.8
	Late fall		-		-		4.9
	Spring		-		-		-
	Control (no N)		3.5		3.7		4.6
	Early fall w/ inhibitors		14.1		4.5		19.8
	LSD (α = 0.05)^z		-		-		-
Landscape Position Means							
High			6.6		8.3a		7.7
Low			10.8		4.2b		11.1
LSD (α = 0.10)			ns		1.6		ns
	Fertilization Means						
	Early fall		10.8		7.1a		8.4
	Mid fall		-		5.8ab		13.3
	Late fall		-		-		5.6
	Spring		-		-		-
	Control (no N)		10.7		6.9a		4.8
	Early fall w/ inhibitors		4.7		5.1b		13.3
	LSD (α = 0.05)		ns		1.5		ns
ANOVA		df	P > F	df	P > F	df	P > F
Landpos		1	0.1321	1	0.0023*	1	0.1597
Trt		2	0.1292	3	0.0247*	4	0.5470
Landpos*Trt		2	0.2353	3	0.4605	4	0.7412
Block(Landpos)		6	0.5434	6	0.0458*	6	0.8928
Residual C.V. (%)			72.64		22.15		143.04

a,b Mean values followed by the same letter (within columns) are not significantly different.

^{z} LSD for individual treatments in individual site years is not reported because there was no Landpos*Trt interaction.

† significant at P < 0.10 (used only for landscape position variables and interactions).

* significant at P < 0.05.

Table Y.4. Total extractable NH_4^+-N in the bandrow at Brandon 2001/2002: 15-30 cm soil depth

Treatment			Total extractable NH_4^+-N (mg kg^{-1})				
			Sampling Date				
Landscape Position	Fertilization		10/01/01		10/15/01		11/01/01
High	Early fall		2.9		3.6		3.1
	Mid fall		-		3.1		4.5
	Late fall		-		-		3.4
	Spring		-		-		-
	Control (no N)		2.8		3.4		2.9
	Early fall w/ inhibitors		3.1		3.6		3.1
	LSD ($\alpha = 0.05$)[z]		-		-		-
Low	Early fall		5.8		2.0		2.6
	Mid fall		-		2.3		10.6
	Late fall		-		-		3.1
	Spring		-		-		-
	Control (no N)		2.1		1.6		2.5
	Early fall w/ inhibitors		6.0		2.1		6.5
	LSD ($\alpha = 0.05$)[z]		-		-		-
Landscape Position Means							
High			2.9b		3.4a		3.4
Low			4.6a		2.0b		5.1
LSD ($\alpha = 0.10$)			ns		0.5		ns
	Fertilization Means						
	Early fall		4.3		2.8		2.9
	Mid fall		-		2.7		7.6
	Late fall		-		-		3.3
	Spring		-		-		-
	Control (no N)		2.4		2.5		2.7
	Early fall w/ inhibitors		4.6		2.9		4.8
	LSD ($\alpha = 0.05$)		ns		ns		ns
ANOVA		df	$P > F$	df	$P > F$	df	$P > F$
Landpos		1	0.0194*	1	0.002*	1	0.2949
Trt		2	0.1814	3	0.8260	4	0.4111
Landpos*Trt		2	0.2633	3	0.7461	4	0.7019
Block(Landpos)		6	0.9143	6	0.5561	6	0.6811
Residual C.V. (%)			62.00		31.48		133.93

a,b Mean values followed by the same letter (within columns) are not significantly different.

[z] LSD for individual treatments in individual site years is not reported because there was no Landpos*Trt interaction.

† significant at $P < 0.10$ (used only for landscape position variables and interactions).

* significant at $P < 0.05$.

Table Y.5. Total extractable NO_3^--N in the bandrow at Brandon 2001/2002: 15-30 cm soil depth

Treatment			Total extractable NO_3^--N (mg kg^{-1})			
			Sampling Date			
Landscape Position	Fertilization		10/01/01		10/15/01	11/01/01
High	Early fall		3.9		5.9	5.1
	Mid fall		-		4.1	4.4
	Late fall		-		-	3.0
	Spring		-		-	-
	Control (no N)		3.1		3.6	2.1
	Early fall w/ inhibitors		4.1		5.8	3.8
	LSD ($\alpha = 0.05$)[z]		-		-	-
Low	Early fall		8.5		2.8	5.9
	Mid fall		-		2.1	6.9
	Late fall		-		-	1.8
	Spring		-		-	-
	Control (no N)		1.4		1.5	2.1
	Early fall w/ inhibitors		8.0		2.4	13.3
	LSD ($\alpha = 0.05$)[z]		-		-	-
Landscape Position Means						
High			3.7		4.8a	3.7
Low			6.0		2.2b	6.0
LSD ($\alpha = 0.10$)			ns		1.3	ns
	Fertilization Means					
	Early fall		6.2		4.3a	5.5
	Mid fall		-		3.1bc	5.6
	Late fall		-		-	2.4
	Spring		-		-	-
	Control (no N)		2.3		2.6c	2.1
	Early fall w/ inhibitors		6.1		4.1ab	8.5
	LSD ($\alpha = 0.05$)		ns		1.2	ns

ANOVA	df	$P > F$	df	$P > F$	df	$P > F$
Landpos	1	0.2847	1	0.0086*	1	0.1503
Trt	2	0.1189	3	0.0178*	4	0.4643
Landpos*Trt	2	0.2521	3	0.5140	4	0.6661
Block(Landpos)	6	0.2897	6	0.0275*	6	0.9180
Residual C.V. (%)		81.92		34.41		160.70

a-c Mean values followed by the same letter (within columns) are not significantly different.
[z] LSD for individual treatments in individual site years is not reported because there was no Landpos*Trt interaction.
† significant at $P < 0.10$ (used only for landscape position variables and interactions).
* significant at $P < 0.05$.

Table Y.6. Total extractable NO_2^--N in the bandrow at Brandon 2001/2002: 15-30 cm soil depth

Treatment			Total extractable NO_2^--N (mg kg^{-1})			
			Sampling Date			
Landscape Position	Fertilization		10/01/01		10/15/01		11/01/01
High	Early fall		0.00		0.00		0.13
	Mid fall		-		0.00		0.00
	Late fall		-		-		0.00
	Spring		-		-		-
	Control (no N)		0.00		0.00		0.00
	Early fall w/ inhibitors		0.00		0.00		0.00
	LSD ($\alpha = 0.05$)[z]		-		-		-
Low	Early fall		0.63		0.00		0.00
	Mid fall		-		0.00		0.25
	Late fall		-		-		0.00
	Spring		-		-		-
	Control (no N)		0.00		0.00		0.00
	Early fall w/ inhibitors		0.13		0.00		0.00
	LSD ($\alpha = 0.05$)[z]		-		-		-
Landscape Position Means							
High			0.00		0.00		0.03
Low			0.25		0.00		0.05
LSD ($\alpha = 0.10$)			ns		ns		ns
	Fertilization Means						
	Early fall		0.31		0.00		0.06
	Mid fall		-		0.00		0.13
	Late fall		-		-		0.00
	Spring		-		-		-
	Control (no N)		0.00		0.00		0.00
	Early fall w/ inhibitors		0.06		0.00		0.00
	LSD ($\alpha = 0.05$)		ns		ns		ns
ANOVA		df	$P > F$	df	$P > F$	df	$P > F$
Landpos		1	0.134	1	.	1	0.6704
Trt		2	0.1393	3	.	4	0.5371
Landpos*Trt		2	0.1393	3	.	4	0.3365
Block(Landpos)		6	0.3154	6	.	6	0.4481
Residual C.V. (%)			244.95		.		471.40

[z] LSD for individual treatments in individual site years is not reported because there was no Landpos*Trt interaction.
† significant at $P < 0.10$ (used only for landscape position variables and interactions).
* significant at $P < 0.05$.

Table Y.7. Total extractable urea-N in the bandrow at Brandon 2001/2002: 15-30 cm soil depth

Treatment			Total extractable urea-N (mg kg^{-1})				
			Sampling Date				
Landscape Position	Fertilization		10/01/01		10/15/01		11/01/01
High	Early fall		0.25		0.25		1.25
	Mid fall		-		0.63		4.25
	Late fall		-		-		0.38
	Spring		-		-		-
	Control (no N)		0.63		3.38		0.25
	Early fall w/ inhibitors		1.00		0.38		1.00
	LSD (α = 0.05)^z		-		-		-
Low	Early fall		0.88		1.25		3.13
	Mid fall		-		4.25		3.75
	Late fall		-		-		1.25
	Spring		-		-		-
	Control (no N)		0.25		0.50		0.25
	Early fall w/ inhibitors		4.13		1.25		1.50
	LSD (α = 0.05)^z		-		-		-
Landscape Position Means							
High			0.63		1.16		1.43
Low			1.75		1.81		1.98
LSD (α = 0.10)			ns		ns		ns
	Fertilization Means						
	Early fall		0.56		0.75		2.19b
	Mid fall		-		2.40		4.00a
	Late fall		-		-		0.81bc
	Spring		-		-		-
	Control (no N)		0.44		1.94		0.25c
	Early fall w/ inhibitors		2.56		0.81		1.25bc
	LSD (α = 0.05)		ns		ns		1.72
ANOVA		df	$P > F$	df	$P > F$	df	$P > F$
Landpos		1	0.2144	1	0.5478	1	0.4948
Trt		2	0.0894	3	0.5190	4	0.0015*
Landpos*Trt		2	0.2241	3	0.1510	4	0.6762
Block(Landpos)		6	0.4521	6	0.3577	6	0.0975†
Residual C.V. (%)			164.73		180.40		98.28

a-c Mean values followed by the same letter (within columns) are not significantly different.

^{z} LSD for individual treatments in individual site years is not reported because there was no Landpos*Trt interaction.

† significant at P < 0.10 (used only for landscape position variables and interactions).

* significant at P < 0.05.

Appendix Z

BRANDON (2001/02): BETWEEN BAND ZONE DATA (mg kg^{-1}): 0–30 cm

Table Z.1. Total inorganic N between the bandrows at Brandon 2001/2002: 0-30 cm soil depth

Treatment			Total inorganic N (mg kg^{-1})				
			Sampling Date				
Landscape Position	Fertilization		10/01/01		10/15/01		11/01/01
High	Early fall		24.6		30.5		29.6
	Mid fall		-		26.6		24.0
	Late fall		-		-		29.0
	Spring		-		-		-
	Control (no N)		21.5		24.0		18.8
	Early fall w/ inhibitors		25.1		45.0		26.5
	LSD (α = 0.05)[z]		-		-		-
Low	Early fall		11.9		13.3		14.5
	Mid fall		-		10.1		12.6
	Late fall		-		-		10.4
	Spring		-		-		-
	Control (no N)		8.1		9.3		7.8
	Early fall w/ inhibitors		12.0		13.6		15.9
	LSD (α = 0.05)[z]		-		-		-
Landscape Position Means							
High			23.8a		31.5a		25.6a
Low			10.7b		11.6b		12.2b
LSD (α = 0.10)			6.0		4.8		5.3
	Fertilization Means						
	Early fall		18.3		21.9		22.1a
	Mid fall		-		18.4		18.3ab
	Late fall		-		-		19.7a
	Spring		-		-		-
	Control (no N)		14.8		16.6		13.3b
	Early fall w/ inhibitors		18.6		29.3		21.2a
	LSD (α = 0.05)		ns		ns		5.6
ANOVA		df	$P > F$	df	$P > F$	df	$P > F$
Landpos		1	0.0054*	1	0.0002*	1	0.0028*
Trt		2	0.0608	3	0.1813	4	0.0288*
Landpos*Trt		2	0.9799	3	0.4871	4	0.5320
Block(Landpos)		6	0.0047*	6	0.9042	6	0.0487*
Residual C.V. (%)			18.11		54.81		28.78

a,b Mean values followed by the same letter (within columns) are not significantly different.
[z] LSD for individual treatments in individual site years is not reported because there was no Landpos*Trt interaction.
† significant at $P < 0.10$ (used only for landscape position variables and interactions).
* significant at $P < 0.05$.

Table Z.2. Total extractable NH_4^+-N between the bandrows at Brandon 2001/2002: 0-30 cm soil depth

Treatment			Total extractable NH_4^+-N (mg kg^{-1})				
			Sampling Date				
Landscape Position	Fertilization		10/01/01		10/15/01		11/01/01
High	Early fall		7.0		5.8		5.0
	Mid fall		-		5.1		5.4
	Late fall		-		-		9.5
	Spring		-		-		-
	Control (no N)		4.9		5.6		5.5
	Early fall w/ inhibitors		7.4		10.3		6.0
	LSD ($\alpha = 0.05$)[z]		-		-		-
Low	Early fall		5.1		4.6		5.3
	Mid fall		-		3.8		5.9
	Late fall		-		-		5.3
	Spring		-		-		-
	Control (no N)		4.1		3.9		4.0
	Early fall w/ inhibitors		6.4		4.4		4.8
	LSD ($\alpha = 0.05$)[z]		-		-		-
Landscape Position Means							
High			6.4		6.7		6.3
Low			5.2		4.2		5.0
LSD ($\alpha = 0.10$)			ns		ns		ns
	Fertilization Means						
	Early fall		6.1a		5.2		5.1
	Mid fall		-		4.4		5.6
	Late fall		-		-		7.4
	Spring		-		-		-
	Control (no N)		4.5b		4.8		4.8
	Early fall w/ inhibitors		6.9a		7.3		5.4
	LSD ($\alpha = 0.05$)		1.0		ns		ns
ANOVA		df	$P > F$	df	$P > F$	df	$P > F$
Landpos		1	0.1588	1	0.1056	1	0.2432
Trt		2	0.0008*	3	0.4957	4	0.2870
Landpos*Trt		2	0.4608	3	0.6117	4	0.3545
Block(Landpos)		6	0.0195*	6	0.5359	6	0.2202
Residual C.V. (%)			15.80		74.39		44.12

[z] LSD for individual treatments in individual site years is not reported because there was no Landpos*Trt interaction.
† significant at $P < 0.10$ (used only for landscape position variables and interactions).
* significant at $P < 0.05$.

Table Z.3. Total extractable NO_3^--N between the bandrows at Brandon 2001/2002: 0-30 cm soil depth

Treatment			Total extractable NO_3^--N ($mg\ kg^{-1}$)				
			Sampling Date				
Landscape Position	Fertilization		10/01/01		10/15/01		11/01/01
High	Early fall		17.6		24.8		24.6
	Mid fall		-		21.5		18.6
	Late fall		-		-		19.5
	Spring		-		-		-
	Control (no N)		16.6		18.4		13.3
	Early fall w/ inhibitors		17.8		34.8		20.5
	LSD ($\alpha = 0.05$)[z]		-		-		-
Low	Early fall		6.8		8.5		9.3
	Mid fall		-		6.4		6.8
	Late fall		-		-		5.1
	Spring		-		-		-
	Control (no N)		4.0		5.4		3.8
	Early fall w/ inhibitors		5.6		9.3		11.1
	LSD ($\alpha = 0.05$)[z]		-		-		-
Landscape Position Means							
High			17.3a		24.8a		19.3a
Low			5.5b		7.4b		7.2b
LSD ($\alpha = 0.10$)			5.0		4.4		5.2
	Fertilization Means						
	Early fall		12.2		16.6		16.9a
	Mid fall		-		13.9		12.7ab
	Late fall		-		-		12.3ab
	Spring		-		-		-
	Control (no N)		10.3		11.9		8.5b
	Early fall w/ inhibitors		11.7		22.0		15.8ab
	LSD ($\alpha = 0.05$)		ns		ns		4.9
ANOVA		df	$P > F$	df	$P > F$	df	$P > F$
Landpos		1	0.0036*	1	0.0002*	1	0.004*
Trt		2	0.4798	3	0.1564	4	0.0132*
Landpos*Trt		2	0.847	3	0.5219	4	0.6129
Block(Landpos)		6	0.0177*	6	0.7916	6	0.0184*
Residual C.V. (%)			27.26		54.98		35.54

a,b Mean values followed by the same letter (within columns) are not significantly different.

[z] LSD for individual treatments in individual site years is not reported because there was no Landpos*Trt interaction.

† significant at $P < 0.10$ (used only for landscape position variables and interactions).

* significant at $P < 0.05$.

Table Z.4. Total extractable NO_2^--N between the bandrows at Brandon 2001/2002: 0-30 cm soil depth

Treatment			Total extractable NO_2^--N (mg kg^{-1})				
			Sampling Date				
Landscape Position	Fertilization		10/01/01		10/15/01		11/01/01
High	Early fall		0.00		0.00		0.00
	Mid fall		-		0.00		-
	Late fall		-		-		-
	Spring		-		-		-
	Control (no N)		0.00		0.00		0.00
	Early fall w/ inhibitors		0.00		0.00		0.00
	LSD (α = 0.05)[z]		-		-		-
Low	Early fall		0.00		0.13		0.00
	Mid fall		-		0.00		-
	Late fall		-		-		-
	Spring		-		-		-
	Control (no N)		0.00		0.00		0.00
	Early fall w/ inhibitors		0.00		0.00		0.00
	LSD (α = 0.05)[z]		-		-		-
Landscape Position Means							
High			0.00		0.00		0.00
Low			0.00		0.03		0.00
LSD (α = 0.10)			ns		ns		ns
	Fertilization Means						
	Early fall		0.00		0.06		0.00
	Mid fall		-		0.00		0.00
	Late fall		-		-		0.00
	Spring		-		-		-
	Control (no N)		0.00		0.00		0.00
	Early fall w/ inhibitors		0.00		0.00		0.00
	LSD (α = 0.05)		ns		ns		ns
ANOVA		df	$P > F$	df	$P > F$	df	$P > F$
Landpos		1	.	1	0.3559	1	.
Trt		2	.	3	0.4155	4	.
Landpos*Trt		2	.	3	0.4155	4	.
Block(Landpos)		6	.	6	0.4552	6	.
Residual C.V. (%)			.		565.69		.

[z] LSD for individual treatments in individual site years is not reported because there was no Landpos*Trt interaction.
† significant at $P < 0.10$ (used only for landscape position variables and interactions).
* significant at $P < 0.05$.

Table Z.5. Total extractable urea-N between the bandrows at Brandon 2001/2002: 0-30 cm soil depth							
		Total extractable urea-N (mg kg^{-1})					
Treatment		Sampling Date					
Landscape Position	Fertilization		10/01/01		10/15/01		11/01/01
High	Early fall		7.38		2.75		3.25
	Mid fall		-		2.38		3.25
	Late fall		-		-		4.88
	Spring		-		-		-
	Control (no N)		1.38		4.00		1.63
	Early fall w/ inhibitors		2.50		3.38		1.88
	LSD (α = 0.05)^z		-		-		-
Low	Early fall		3.38		3.63		5.38
	Mid fall		-		3.38		7.38
	Late fall		-		-		4.63
	Spring		-		-		-
	Control (no N)		3.00		3.00		0.88
	Early fall w/ inhibitors		1.50		2.00		2.75
	LSD (α = 0.05)^z		-		-		-
Landscape Position Means							
High			3.75		3.13		2.98
Low			2.63		3.00		4.20
LSD (α = 0.10)			ns		ns		ns
	Fertilization Means						
	Early fall		5.40		3.20		4.31ab
	Mid fall		-		2.88		5.31a
	Late fall		-		-		4.75ab
	Spring		-		-		-
	Control (no N)		2.20		3.50		1.25c
	Early fall w/ inhibitors		2.00		2.69		2.31bc
	LSD (α = 0.05)		ns		ns		2.78
ANOVA		df	P > F	df	P > F	df	P > F
Landpos		1	0.6096	1	0.9390	1	0.3354
Trt		2	0.3408	3	0.9412	4	0.0275*
Landpos*Trt		2	0.5399	3	0.7621	4	0.3959
Block(Landpos)		6	0.4298	6	0.0617†	6	0.1241
Residual C.V. (%)			155.00		91.59		75.04

a-c Mean values followed by the same letter (within columns) are not significantly different.
^{z} LSD for individual treatments in individual site years is not reported because there was no Landpos*Trt interaction.
† significant at P < 0.10 (used only for landscape position variables and interactions).
* significant at P < 0.05.