Optimum Nitrogen Management of Modern Corn Hybrids in Manitoba

by

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ABSTRACT

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Nitrogen (N) fertilizer applications are often necessary to achieve maximum profit in annual crop production. This research was meant to assist producers to achieve maximum profits by optimizing N application practices, as N is often a yield-limiting nutrient and also a significant cost of production. The research is focused on the 4Rs of nutrient stewardship to determine the right rate, right source, right timing, and right place of N fertilizer applications. Using 17 site-years of data collected from the 2018 and 2019 growing seasons, this research answers common questions such as how much N is required to produce a high-yielding corn crop, and are there benefits to split applying nitrogen. This research also investigates more technical questions such as are there advantages to using enhanced efficiency fertilizers (EEFs), and how consistent are in-season and post-season tests at evaluating crop N sufficiency. Thirteen of 17 site-years had a statistically significant response to N fertilizer application. Twelve of those sites (plus the 4 unresponsive sites) obtained their statistically greatest yield at fertilizer N application rates of 90 kg N ha^{-1} or less. According to quadratic response models for maximum return to nitrogen (MRTN) and accounting for spring soil nitrate, lower yielding sites (<8150 kg grain corn ha^{-1}) required 0.0298 kg N kg^{-1} corn produced and sites yielding >8150 kg of corn ha^{-1} were more efficient users of soil and fertilizer N, requiring 0.0224 kg N kg^{-1} corn. The source and placement comparisons showed no statistically significant differences in yield between three separate sources of EEF and conventional urea when applied at the same rate. Comparisons of application timings at planting, at V4, and V8 growth stage showed no significant yield increases by delaying N application and at sites with very small reserves of residual nitrate-N there was a yield penalty for delayed application. Results of the pre-side dress nitrate test, stalk nitrate test, and post-harvest soil test were within the range of the current decision guidelines for some site-years; however, across the site-years there was no consistency between the observed test values at the economic optimum fertilizer rates.

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FOREWORD

The guide to thesis preparation for graduate students in the Department of Soil Science (2018) was followed to prepare the thesis. Chapter one is an introduction to the literature, chapter two contains the results from the N rate portion of the study, and chapter three contains results from the timing, source, and placement treatments. This study had a larger number of site-years than most projects and so we tried to take advantage of that and collect as much data as possible to be used by future researchers. There is a collection of detailed soil, weather, observational, plant, harvest, and reflectance data that is not presented. In the future I hope that this data can be explored in detail.

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LIST OF ABBREVIATIONS

Abbreviation	Explanation
N	Nitrogen
MRTN	Maximum Return to Nitrogen
4R	Right time, Right rate, Right place, and Right source of fertilizer
EEF	Enhanced Efficiency Fertilizer
ESN™	Environmentally Smart Nitrogen
UAN	Urea Ammonium Nitrate fertilizer
V4	When the corn plant has 4 exposed leaf collars
V8	When the corn plant has 8 exposed leaf collars
PSNT	Pre-Side-dress Nitrate Test
CHU	Corn Heat Units
PSNT	Pre-Side dress Nitrate Test
ICP-OES	Inductively Coupled Plasma Optical Emission Spectroscopy
BD	Bulk Density
ANOVA	Analysis of Variance
PROC GLIMMIX	General Linear Mixed Model procedure
C.V.	Coefficient of Variation
Pr>F	Probability the dependent variable tested had no significant differences
LSmeans	Least Squares Means
Df	Degrees of Freedom

1. INTRODUCTION

1.1 Corn production in the Northern Great Plains

Corn is one of the most important crops in the world. In 2014-15, Canada and USA produced 37% of the corn worldwide on only 19% of the world's corn hectares (Omonode et al. 2017). Corn is a monocot crop with C4 photosynthesis that requires a warmer and longer growing season than most cereal crops to reach maturity. Therefore, historically, the cold continental climate in Manitoba has not been favourable for corn production, lacking the frost-free days, heat units, and rainfall required to reach maturity and produce high yields.

Over the last decade, much of the mid-west United States has stopped growing soybeans in favour of continuous corn (Fernandez et al. 2015). Genetic advances have led to the development of short-season corn hybrids suited to the Northern Great Plains. As a result, in North Dakota over the past 40 years, corn yields have more than doubled from 5000 kg ha^{-1} to expected yields of over 12 500 kg ha^{-1} (Franzen 2014). Genetic improvements have also led to an increased area of corn planted in Manitoba. In addition, grain corn production in Manitoba has increased to meet the demand for livestock feed and the ethanol industry (Manitoba Government 2012). As a result, in 2019 there were 168 500 ha of grain corn insured which is 59% above the 10 year average of 106 500 ha (MB Agriculture et al. 2020). In Manitoba, yields over 10 000 kg ha^{-1} are common in the Red River Valley region and the provincial average yield of grain corn was 9100 kg ha^{-1} in 2016 and 7900 kg ha^{-1} in 2019 (MB Agriculture et al. 2020).

Fertilizer management practices for corn are different from the practices for other crops grown in Manitoba because of corn's longer growing season and row crop production system. Currently, the efficiency of applied N fertilizer is approximately 42% for corn production in the United States; that is 42% of the applied N fertilizer is taken up by the corn crop during that growing season (Chim et al. 2016). Nitrogen efficiency can be maximized by supplying the right amount of N to the crop at the right place, time, and in the right form when the crop needs it, and to minimize N loss from the rooting zone of the crop (Sutton 2005). However, increasing N fertilizer application rates leads to decreasing N use efficiency in corn, because for each increment of fertilizer applied there are decreasing proportions of yield increase and N uptake (Burzaco et al. 2014). In modern corn hybrids there has been an increase in N use efficiency because dry matter yields have increased while plant N concentrations have decreased. From the 1960s to 2000s, N concentration in grain has decreased by 24% while grain yields have increased by 65% (Elmore et al. 2019). Slightly older research reported a 10% decrease in grain N from old era hybrids to new era hybrids; yields increased 1640 kg ha^{-1} and N requirements remained the same, at 140 kg ha^{-1} (Ciampitti and Vyn 2014).

1.2 Nitrogen fertilizer sources

Nitrogen fertilizer is required to maximize grain corn production and provide economic returns for grain corn producers (Sawyer et al. 2006). As the fertilizer industry is very important for enabling farmers to grow food, the fertilizer industry also recognizes the need for new practices and technologies to grow food with greater efficiency to sustain and improve our quality of life (Fixen and West 2002). In Canada, N fertilizer use has increased dramatically; in 1958-59 there were 56 300 tonnes of N used and by 1981-82 more than 15 times that, 862 000 tonnes was applied to crops (Tisdale et al. 1985). By 2010-11 over 2 million tonnes of N fertilizer was used in Canada (Dorff and Beaulieu 2014). In 2014-15 Canada and USA required 14.1 million tonnes of N fertilizer (Omonode et al. 2017). The increasing use of N fertilizer is a result of increasing N application rates, from 2015 to 2019 the average N application rate for canola in western Canada has increased from 112 to 145 kg N ha^{-1} and from 167 to 192 kg N ha^{-1} for grain corn in Ontario (Stratus Ag Research 2019).

Anhydrous ammonia has been a historically popular fertilizer in western Canada; however, ammonia use is slowly declining, partly due to safety concerns because this product is handled as a compressed gas. From 1981-91, approximately 31% of N fertilizer used in Saskatchewan was anhydrous ammonia (Campbell and Hnatowich 1990). However, anhydrous ammonia use on canola in western Canada has dropped from a market share of 32% in 2015 to 20% in 2019 (Stratus Ag Research 2019). Anhydrous ammonia remains popular in the mid-west United States, being the N source for 50% of the 2.5 million corn hectares in Indiana (Camberato 2016) and for 46% of the corn in Minnesota (Bierman et al. 2012). Benefits of anhydrous ammonia are the cost per unit of N is often less than other fertilizers and the N concentration of 82% makes for less product to handle.

Urea is a granular product and the most used N fertilizer around the world. Urea represented 47% of the N fertilizer used on western Canadian canola fields in 2019 (Stratus Ag Research 2019) and 45% of N fertilizer used for corn in Minnesota (Bierman et al. 2012). Urea-ammonium nitrate (UAN) is the least concentrated of the three common N fertilizers at 28% N, but UAN is popular for niche uses such as in-furrow or in-season N fertilizer. The advantages of UAN are that the product is composed of three types of N, providing 50% immediately plant available as nitrate and ammonium and 50% as urea which hydrolyses to become plant available. As a liquid product, UAN also provides ease of mixing with other liquid products, accurate metering, and uniform application (Mosaic 2021).

Enhanced efficiency fertilizers (EEFs) are N fertilizers that have additional technology intended to slow release and transformations of applied N fertilizer, reduce N losses, and increase N use efficiency. The types of additives in EEFs include nitrification inhibitors, urease inhibitors, and controlled release products. Nitrification inhibitors are substances that inhibit biological oxidation of ammonium N to nitrate N (Sutton 2005). Nitrification inhibitors delay the oxidation of ammonium to nitrite in the soil by controlling populations of nitrifying bacteria (Wood 2018, Sutton 2005). Delaying nitrification of ammonium and dissolution or hydrolysis of urea can reduce the risk of negative impacts of N fertilizer on the environment and will help to match plant available N in soil to the N demands of the crop. Nitrification inhibitors can be added to nearly any ammonical N fertilizer such as urea or anhydrous ammonia, or be incorporated during the manufacturing of the fertilizer such as SUPERU™. The two most common active ingredients for nitrification inhibitors in the marketplace are nitrapyrin (2-chloro-6-(trichloromethyl) pyridine) found in eNtrench™ and DCD (dicyandiamide) found in SuperU™(Fernandez 2016, Sutton 2005, Wood 2018).

Urease inhibitors are used to inhibit the hydrolysis of urea by the urease enzyme (Sutton 2005). When urea is surface applied, these inhibitors delay the creation of ammonia on the soil surface that leads to ammonia volatilization (Sutton 2005). The most common active ingredients for urease inhibitors in the marketplace are N-(n-butyl) thiophosphoric triamide (NBPT), N-(n-butyl) phosphoric triamide (NPPT), and thiophosphoryl triamide (Fernandez 2016, Sutton 2005, Wood 2018). The molecule NBPT is in the urease inhibitor available commercially as Agrotain™, which can be blended with urea or UAN. SuperU™ and AgrotainPlus™ are products that have both urease and nitrification inhibitors. When both nitrification and urease inhibitors are used together, the N is protected from volatilization, leaching, and denitrification (Sutton 2005).

A controlled release EEF does not chemically inhibit N fertilizer but instead uses a physical barrier. Application of controlled release fertilizer may be a best management practice to increase the efficiency of applied N by matching fertilizer N availability more closely to crop demand (Gagnon et al. 2012). When urea granules are polymer-coated the granule does not dissolve into the soil when exposed to water as it normally would. Instead, water diffuses into the granule and is contained for a period of time followed by slowly diffusing with urea into the soil solution (Fernandez 2016). The release of N is accelerated with increasing soil moisture and temperature (Fernandez 2016). Polymer-coated urea could be beneficial on soils with risk of leaching, volatilization, and denitrification due to excess moisture. An additional benefit of the polymer-coated fertilizer is the reduced risk of ammonia or salt toxicity when applied in furrow with seed (Nutrien 2022).

Yield responses to EEFs compared to conventional fertilizers have been sporadic. Recently in Manitoba, Wood (2018) reported that effects of EEF on yield or protein in spring wheat were minimal. Similarly, Grant et al. (2012) concluded that a blend of urea and polymer-coated urea applied to wheat, barley, and canola in field trials across the Canadian prairies increased grain yield compared to urea only in some situations. In Quebec, researchers found that during wet years controlled release and nitrification-inhibited urea increased grain corn yield compared to urea, and in dry years there were no differences in yield (Gagnon et al. 2012). A three year study in Illinois found no statistically significant differences in grain corn yield between anhydrous ammonia, urea, and polymer-coated urea as N sources (Fernandez et al. 2015). Under irrigated conditions in Arkansas and Colorado, polymer-coated urea had significantly greater corn grain yields over urea in 2 of 3 years (Halvorson and Bartolo 2013).

1.3 Nitrogen rates for corn

Recommending an appropriate rate of N requires knowledge of the difference between the upcoming crop's N requirement and mineral N reserves already present in the soil (Manitoba Agriculture 2007). On the Canadian prairies, a pre-plant nitrate-N test is used to quantify plant available soil mineral N reserves. Nitrogen requirement for the crop depends on crop species and yield goal, while actual crop N use and yield is dependent upon the growing season weather conditions such as precipitation and temperature, and the avoidance of destructive weather such a hail and frost. However, determination of the soil's total supply of N to a growing crop is more complicated than simply using the pre-plant nitrate-N test that is currently recommended. Mineralization of soil organic N can have a large influence on soil supply and mineralization is dependent upon many factors, including manure and legume history, soil organic matter, temperature, and precipitation (Schepers 2017). Research has developed methods to predict “potential” growing season mineralization; however, the methods are not consistently accurate in under field conditions (Mangin and Flaten 2017).

Soil and fertilizer N can be lost due to leaching, runoff, denitrification, and volatilization. Losses are dependent on soil texture, quantity and forms of soil N, precipitation, and temperature (Struffert et al. 2016). It is difficult to maintain enough plant available soil and fertilizer N to produce optimum crop yields while also reducing environmental impacts from fertilizer, because soil is an open system on the top and bottom (Sawyer 2015). Nitrogen rate, source, placement, and timing are all very important N management factors that can influence N recovery by the crop (Omonode et al. 2017).

There is no perfect tool for N rate recommendations; however, the refinement of models and combining individual tools such as soil tests, could lead to improved N management decisions (Ransom et al. 2020). Manitoba uses target yield to determine the appropriate rate of N application (Manitoba Agriculture 2007); the target yield is selected by the farmer and the amount of N recommended is determined from local research. Stanford (1966) was the first to publish and promote a yield goal-based recommendation for corn, developed using a linear yield response to N where 0.0214 kg N was required kg^{-1} grain corn based on research conducted from 1946-1960. Yield goal-based N recommendations provided a much needed rationale to lower N application rates in the 1970s when N fertilizer was inexpensive and N rates of 0.0354 kg N kg^{-1} grain corn were common (Fernandez et al. 2009). However, an evaluation of 31 corn N rate recommendation tools in the mid-west United States determined that yield goal-based N recommendations are very poor at predicting the maximum return to N application rate and on average, result in over-application of 58 kg N ha^{-1} (Ransom et al. 2020).

In Manitoba, the last study of corn N fertilization rates was conducted by the University of Manitoba in 1985. Those studies recommended that 227 kg N ha^{-1} should be applied to achieve a yield of 8175 kg ha^{-1} with 40 kg ha^{-1} of residual nitrate-N; or 0.0327 kg N kg^{-1} grain corn at a yield of 8175 kg ha^{-1} (Walley and Soper 1985). The Manitoba Soil Fertility Guide (Manitoba Agriculture 2007) provides N recommendations for corn yields to a maximum of 8150 kg ha^{-1}, which is less than yields currently achieved by some corn growers in Manitoba. The Soil Fertility Guide's N recommendation for growing 8150 kg^{-1} on soil with 34 kg residual nitrate-N ha^{-1} is to apply an additional 218 kg N ha^{-1} for a soil and fertilizer N supply rate of 0.0309 kg N kg^{-1} of corn. The Guide to Corn Production in Manitoba (Manitoba Corn Growers Association 2004) also has a N recommendation for growing 8150 kg ha^{-1}. To grow 8150 kg ha^{-1} on a field with 34 kg ha^{-1} of residual nitrate-N the Guide to Corn Production recommends applying 252 kg N fertilizer ha^{-1} for a total N supply of 0.0351 kg N kg^{-1} corn. Manitoba's guidelines for N fertilizer rates for corn are much greater than in the nearby U.S. In North Dakota, the AGVISE™ soil testing lab has recommendations for growing corn to a maximum yield of 15 680 kg ha^{-1} (AGVISE™ 2021). Targeting a yield of 7800 kg ha^{-1}, AGVISE™ recommends a total N supply of 168 kg N ha^{-1} or 0.0215 kg N kg^{-1} corn.

The rate of N for the maximum return to nitrogen (MRTN) is the rate at which the cost of one additional unit of N becomes equal to the revenue received for the additional corn produced, and applying N fertilizer beyond the MRTN rate would result in reduced net income. Response models or "curves" are often used to determine optimum economic rates of N where consideration is given to the cost of N fertilizer and price of corn. For example, Nafziger et al. (2004) used linear and quadratic equations to model N response data from multiple site-years to formulate optimum yield and N rates. Selecting the proper response curve is important and difficult. Cerrato and Blackmer (1990) compared linear plus plateau, quadratic plus plateau, quadratic, exponential, and square root models. The overall MRTN rate varied from 128 to 379 kg N ha^{-1} for \$0.0987 kg^{-1} N fertilizer and \$0.33 kg^{-1} corn, depending on which of the five models was used to portray the yield response data. Overall, the quadratic plus plateau model best described the observations, having recommended 184 kg N ha^{-1} in that analysis (Cerrato and Blackmer 1990). Quadratic, exponential, and square root models have a tendency to over-predict N requirements while a linear plus plateau would likely under predict N requirements (Cerrato and Blackmer 1990, Alotaibi et al. 2018).

The North Dakota State University's corn nitrogen calculator (NDSU 2020) uses typical yield ranges and additional information such as tillage system, soil organic matter, and prices for crop and fertilizer. Using criteria as similar to Manitoba as possible (Eastern ND, yield less than 10 035 kg ha^{-1}, 34 kg ha^{-1} residual nitrate-N) results in a recommendation to apply 134 kg ha^{-1} for our target of 8150 kg ha^{-1} resulting in a total N supply of 0.0206 kg N kg^{-1} corn.

1.4 N fertilizer placement and timing for corn

Corn growers also have options for in-season or split applications, because approximately 75% of the N is taken up after 500 growing degree days or the V10 stage (Bender et al. 2013). Another reason why many corn growers use in-season applications of N fertilizer is because row crop production allows for in-season applications without damaging the growing crop. A Manitoba survey revealed that for grain corn 22% of N was applied as an in-crop application (Heard 2020). In Ontario, 30% of the N fertilizer applied to grain corn was applied in-crop (Stratus Ag Research 2019). Benefits of delaying N application into the growing season include the opportunity to evaluate yield potential before choosing the final N application rate and matching application timing closer to crop uptake, and reducing the period of time that N is susceptible to losses (Franzen 2013, Fernandez and Carlson 2020). For example, in Indiana, Burzaco et al. (2014) observed an increase of plant N uptake and N use efficiency for corn when the timing of N application was delayed from pre-plant to in-season application. Previous research across western Canada tested split N applications on canola, wheat, and barley found that in a few situations the split application led to yield increases but the economic analysis revealed the yield increase was never sufficient to cover additional costs (Khakbazan et al. 2013). On spring wheat in Manitoba, Mangin and Flaten (2018) measured a 220 kg ha^{-1} yield increase when N was split-applied at planting and stem elongation or flag leaf compared to equivalent N rates all at planting. Therefore, split application could be a best management practice for corn production in Manitoba, especially in soils or weather conditions that are at risk for N loss.

Side-dressing N at V4 growth stage or late June is an option for split application in corn. At the 4 leaf stage N fertilizer should be placed in subsurface bands between the rows (North Dakota State University n.d.). The V4 application is complementary to a starter rate of N fertilizer applied at planting in order to supply N until the V4 application. For in-season sub-surface banding of N fertilizer, application in every second row space is sufficient and slow- or controlled-release fertilizers should be avoided (North Dakota State University n.d.). In-season decision tools for N rate include a pre-side-dress nitrate test and canopy reflectance, while accumulated rainfall, heat units, and probabilities can be used for predicting yield and N requirements.

Mid-season N application when the crop is at V8-V10 growth stage is the second in-season N application strategy. However, all N should be applied while the plant is still growing to allow time for N to be taken up and metabolized; for corn, this means applying N before ears are set (The Fertilizer Institute n.d.). This later timing limits the application to high clearance machinery which is typically set up for handling liquid products. The advanced growth stage allows only surface placement of the N fertilizer which is susceptible to volatilization and so mid-season application is an opportunity to use urease inhibitors. There are still risks with V8 applications such as an N deficiency occurring in the crop before the in-season application occurs, or surface stranding of the applied N meaning that the fertilizer does not get leached from the soil surface into the rooting zone (The Fertilizer Institute n.d.). Applications that are "Y-dropped" use hoses to penetrate below the canopy and place fertilizer on the soil, adjacent to the corn rows. At the V8 stage, crop imagery can be used to predict the crop's N requirement and adjust rates accordingly. Forty-nine site years of field trials across eight Midwest states revealed that in 82% of the site-years, yields for N application at V7-V9 were similar to pre-plant N applications; in 14% of the site-years, split application out-yielded pre-plant N and in 4% of the site-years, there was a yield penalty for split application (Franzen and Carlson 2020). At Kansas State University, Sweeney and Ruiz Diaz (2021) reported that over a 3-year study the split N application treatments resulted in 15% greater yield compared to applying all 168 kg N ha^{-1} pre-plant.

1.5 Evaluating crop N status

Research has developed a number of instruments and methods to evaluate soil and plant N status and to predict yield in-season, as well as to evaluate the N fertilizer program near or after harvest. Soil pre-plant and pre-side-dress nitrate tests measure the amount of nitrate N in the soil and assist in determining N application rates (Reitsma et al. 2008). The post-harvest nitrate test is used after the growing season, where large amounts of residual nitrate-N can indicate over-fertilization and small amounts might indicate under-fertilization and soil depletion by the crop.

The corn stalk nitrate test is a quantitative measure of the nitrate-N in the base of the corn stalk at maturity (Blackmer and Mallarino 2000). Excess N within the plant that is not used for grain production is stored in the stalk as nitrate at maturity. By testing for nitrates in the stalk, corn growers can compare results to locally-developed thresholds to determine whether N within the plant was deficient, optimal, or excessive.

During the growing season, evaluating corn leaves' colour or reflectance can indicate N status of the plant. Leaf deficiency ratings are based on the premise that N is a mobile nutrient and therefore chlorosis due to N deficiency begins to show on lower leaves, and works its way from leaf margins to the base of the leaf. The severity of N deficiency can be estimated by the number and position of chlorotic leaves on the plant (Gelderman et al. 2009). Crop canopy reflectance is a more sophisticated evaluation of the leaves where canopy density and chlorophyll content are determined with sensors measuring light wavelengths (Kaiser 2016). Canopy reflectance is measured during vegetative growth stages, ideally while there is still opportunity to apply N based on the sensor measurements. Instrumentation can be handheld, mounted on equipment, or mounted on unmanned aerial vehicle (UAV or drone). However, canopy reflectance technology is not commonly used across Manitoba to determine N rates because the decision-making guidelines need to be investigated further before the data is useful for corn grown in Manitoba.

1.6 Objectives of the study

Research is required to develop best management practices for N fertilization of modern corn hybrids under Manitoba growing conditions. This study uses the 4R nutrient stewardship framework: right time, right rate, right place, and right source aimed at optimizing N use efficiency by evaluating advancements in fertilizer and application technology and addressing environmental concerns about excess N.

The primary objective was to determine appropriate N rates for high-yielding corn hybrids grown in Manitoba and to identify the amount of N required per unit of corn production. Secondly, this study was designed to evaluate combinations of new N fertilizer products and methods of application, to determine if new products and practices would consistently improve the agronomic and environmental management of N fertilizer. Improvements in N fertilizer management would be recognized as overall increased yields, improved N use efficiency (equivalent yields with reduced fertilizer application), and reduced environmental risk from N fertilizers. Reducing the environmental risk of N fertilizers can be achieved by decreasing the time period that high concentrations of nitrate are present in the soil before plant uptake, or reducing over-application of N fertilizer leading to elevated post-harvest soil nitrate-N concentrations.

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2. APPROPRIATE NITROGEN FERTILIZER RATES FOR MODERN CORN HYBRIDS IN MANITOBA

2.1 Abstract

Genetic improvements, rising input costs, advancements in technology, and environmental concerns have pushed for the further development of beneficial management practices for nitrogen (N) fertilization. As with most non-legume crops in Manitoba, corn has a large requirement for N, meaning that suboptimal rates will reduce yield; however, excessive application rates are an unnecessary expense for farmers and present risks to the environment. With corn acreage and yields in Manitoba increasing, this research targeted the most appropriate rate of N supply (from soil and fertilizer), and the most effective tools to measure soil and plant N status. This research used 17 site-years from 2018 and 2019 located across southern Manitoba with six N rates (0, 45, 90, 135, 180, and 225 kg N ha^{-1}). A global ANOVA of N fertilizer application rates revealed a statistically significant increase in yield as N fertilizer rates increased, a significant site-year effect, and a site-year*rate interaction. The Maximum Return to Nitrogen (MRTN), where N is defined as total N supply rate for fertilizer plus soil test nitrate-N, varied depending on the analysis method used. The average MRTN of 17 site-years at the medium fertilizer:corn price ratio was 192 kg N ha^{-1} using the numerically highest yielding treatment, and 202 kg N ha^{-1} using quadratic response equations. When site-years were split into two groups according to their maximum yield achieved, sites with lower maximum yields required more N per unit of corn production when compared to higher-yielding sites. Observed N mineralization was extremely variable across site-years, averaging 59 kg N ha^{-1} overall. Three

indicators of N sufficiency were evaluated; pre-side-dress nitrate test (PSNT), a stalk nitrate test, and a post-harvest soil nitrate test. Quantitative differences were noticeable across N rates within site-years; however, there was a lack of consistency across site-years to reliably use these tools as indicators of N sufficiency.

2.2 Introduction

2.2.1 Corn production in Manitoba

Corn is one of the most important crops grown around the world. In 2014-15, Canada and USA produced 37% of the corn worldwide on 19% of the world's corn hectares (Omonode et al. 2017). Traditionally, the cold continental climate in Manitoba has not been favourable for corn production, lacking the frost-free days and the rainfall required for corn to reach maturity and produce optimum yields. However, genetic and hybrid improvements have led to an increased area of corn production in Manitoba.

Managing N fertilizer efficiently has economic and environmental benefits. Overall, the greatest N efficiency can be achieved by supplying the right amount of N to the crop at the right place, time, and in the right form when the crop needs it, and by minimizing N loss from the rooting zone of the crop (Sutton 2005). However, fertilizing corn is different from most other crops grown in Manitoba because of its very high dry matter yields, longer growing season, and being grown as a row crop.

The effects of various fertilizer management practices for meeting the N demands of modern corn hybrids in Manitoba's climate and soil are unknown and this research aimed to develop best management practices for meeting those N demands. This research used the 4R nutrient stewardship framework: right time, right rate, right place, and right source to evaluate ways of optimizing N use efficiency and minimizing environmental concerns from excess N.

2.2.2 Determining N application rates

Currently, Manitoba uses target yield for determining the appropriate N rate to apply. The N rate recommended is equal to the difference between the upcoming crop's N requirement and the amount of pre-plant nitrate-N present in the soil (Manitoba Agriculture 2007). Predicted N requirement for the crop is based on typical historical yields and past soil fertility research, while actual crop N use and yield is dependent upon the genetic yield potential, the farmer's management practices, soil quality, and growing season weather conditions such as precipitation and temperature.

Stanford (1966) was the first to publish and promote a yield goal-based recommendation for corn, using a linear response where 0.0214 kg N was required kg^{-1} grain corn based on research conducted from 1946-1960 in southern United States. Yield goal-based N recommendations seemed logical and provided a much-needed rationale to lower N application rates in the 1970s when N fertilizer was inexpensive and N application rates of 0.0354 kg N kg^{-1} grain corn were common (Fernandez et al. n.d.). However, an evaluation of 31 corn N rate recommendation tools in the mid-west United States determined that yield goal-based N recommendations are very poor at predicting the maximum return to N application rate and result in over-application of 58 kg N ha^{-1} (Ransom et al. 2020).

Corn N rates at the University of Manitoba were last studied in 1985 and reported a recommendation that 227 kg N ha^{-1} should be applied to achieve a yield of 8175 kg ha^{-1} with 40 kg ha^{-1} of residual nitrate-N; or 0.0327 kg N kg^{-1} grain corn at a yield of 8175 kg ha^{-1} (Walley and Soper 1985). The Manitoba Soil Fertility Guide (Manitoba Agriculture 2007) provides N recommendations for corn yields to a maximum of 8150 kg ha^{-1}, which is less than the yields currently achieved by some corn growers in Manitoba. The Soil Fertility Guide's N recommendation for growing 8150 kg^{-1} on soil with 34 kg residual nitrate-N ha^{-1} is to apply an additional 218 kg N ha^{-1} for a soil and fertilizer N supply rate of 0.0309 kg N kg^{-1} of corn. To grow 8150 kg ha^{-1} on a field with 34 kg ha^{-1} of residual nitrate-N the Guide to Corn Production (Manitoba Corn Growers Association 2004) recommends applying 252 kg N fertilizer ha^{-1} for a total N supply of 0.0351 kg N kg^{-1} corn. In North Dakota, the AGVISE™ soil testing lab has recommendations for growing corn to a maximum yield of 15 680 kg ha^{-1} (AGVISE™ 2021). Targeting a yield of 7800 kg ha^{-1}, AGVISE™ recommends a total N supply of 168 kg N ha^{-1} or 0.0215 kg N kg^{-1} corn.

The North Dakota corn N calculator (NDSU 2020) uses typical yield ranges and additional information such as tillage system, soil organic matter, and prices for crop and fertilizer. Using criteria similar to Southern Manitoba (Eastern ND, yield less than 10 035 kg ha^{-1}, 34 kg ha^{-1} residual nitrate-N) results in a recommendation to apply 134 kg ha^{-1} for our target of 8150 kg ha^{-1}; this is a total N supply of 0.0206 kg N kg^{-1} corn.

2.2.3 Evaluating N application rates

Historical research has developed a number of instruments and methods to evaluate soil and plant N status, to predict yield in-season, and post-harvest evaluation of N fertilizer program. There is no N rate recommendation tool that performs perfectly; however, the refinement of crop growth models and combining with individual tools such as soil testing could lead to improved management decisions (Ransom et al. 2020). Nitrogen fertilizer response is most often modelled with non-linear models to summarize the N responses observed at field trials (Correndo et al. 2021). North Dakota State University's online corn nitrogen calculator is an example of using quadratic response curves from past N rate studies and inputting current commodity prices to determine the MRTN rate. Cerrato and Blackmer (1990), followed by Bullock and Bullock (1994), evaluated response models and determined that the quadratic-plateau model was most often the best fit to the data. At N application rates less than 150 kg N ha^{-1} the quadratic model has a tendency to under-predict yields, while at rates greater than 150 kg ha^{-1} the quadratic model will over-predict yield and economic optimum N rates (Cerrato and Blackmer 1990). Correndo et al. (2021) stated that there will always be an error when using a frequentist regression model because of the multiple crop, agronomic, soil, and weather interactions. Other statistical methods to evaluate response to fertilizer application are the probability of N sufficiency (Nafziger et al. 2004), an ANOVA test with least-square means (Bourns 2020), and the Bayesian approach (Correndo et al. 2021).

As mentioned previously, when determining N rates for crops in the Northern Great Plains, the soil's supply of nitrate-N should be considered. However, consideration should also be given to N mineralization, the N released during the decomposition of soil organic compounds that can supply inorganic N to the growing crop. The amount of N mineralized varies from year to year as it is dependent on biological activity which is influenced by soil moisture and temperature in the top 15 cm (Walley 2005). Additional management factors influence potential mineralization, such as type and amount of crop residue and its carbon:nitrogen ratio, manure and fertilizer history, and tillage.

Soil pre-plant and pre-side-dress nitrate tests (PSNT) measure the amount of nitrate-N in the soil and assist in determining N application rates (Reitsma et al. 2008). The post-harvest nitrate test is used after the growing season, where large amounts of residual nitrate-N can indicate over-fertilization and small amounts might indicate under-fertilization and soil depletion by the crop. The corn stalk nitrate test is a quantitative measure of the nitrate-N in the base of the corn stalk at harvest (Blackmer and Mallarino 2000). Excess N within the plant that is not used for grain production is stored in the stalk at maturity. Iowa State University (Blackmer and Mallarino 2000) reported that 250-700 mg kg^{-1} stalk nitrate indicates marginal N supply and that 700-2000 mg kg^{-1} is optimum; meanwhile AGVISE™ laboratories (Jenny, n.d.) interpret 250-1000 mg $kg^{-1}$of stalk nitrate to be sufficient (i.e., that plant available N did not limit grain yield).

The first objective of this study was to determine the optimum N application rate per unit of area (i.e., per hectare) and per unit of production (i.e., per kg of corn produced) because producers, agronomists, and researchers use both types of recommendations depending on preference and application. The second objective of this study was to evaluate current indicators of N sufficiency by determining the accuracy and consistency of strategies designed to either predict N required or determine if the crop N supply was sufficient or not.

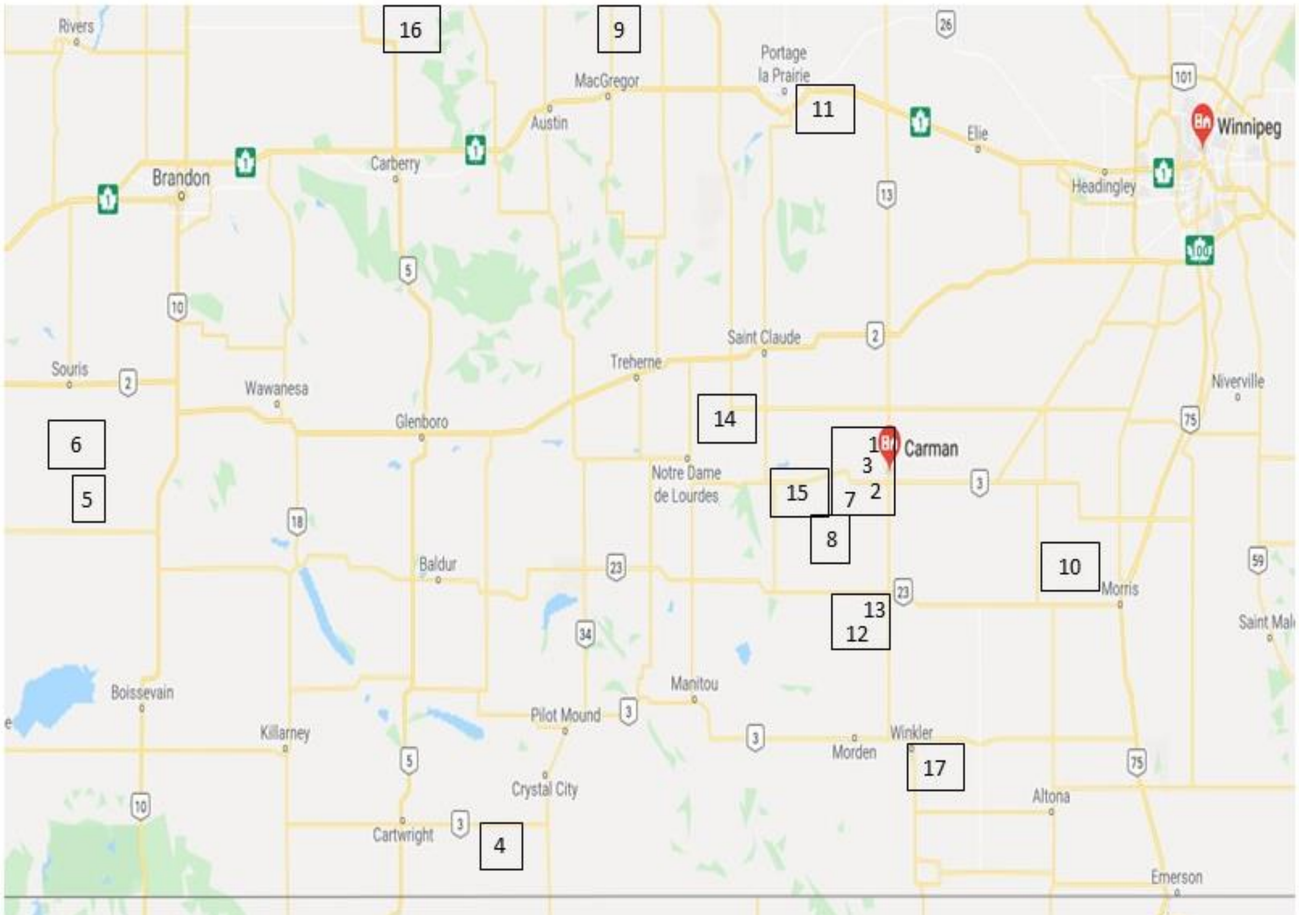
2.3 Materials and Methods

2.3.1 Field site descriptions

This study was conducted over 17 site-years located across southern Manitoba (Figure 2.1). Sites were named for their nearest town and their crop year, with the four "gold" level site-years being Graysville18, Stephenfield18, CarmanNorth19, and StClaude19 and numbered 1, 7, 14, and 15, respectively in Figure 2.1, Table 2.1, Table 2.2; the rest of the site-years were "silver" level sites. Exact geographical locations are listed in Appendix 1. The four "gold" level sites were managed entirely by the University of Manitoba and the 13 "silver" level site-years (7 in 2018, 6 in 2019) were located within commercial corn fields that were planted and maintained by the collaborating producer. Treatment differences for the "gold" and "silver" level site-years are described in Section 2.3.2 Experimental design and treatments.

Field sites were selected on the basis of a variety of factors. The highest priorities were low concentrations of residual nitrate-N, proximity to other sites, uniform site area, corn as the surrounding commercial crop, and no recent history of livestock manure application. Many of the sites were located within the Red River Valley, where the majority of grain corn is grown in Manitoba; however, we also selected some sites in western Manitoba each year.

Background application of fertilizer across each entire site varied, depending upon the soil test and/or the host farmer's normal practice for that site-year (Table 2.1). All N that was applied as starter N fertilizer or with starter P or S fertilizers at planting was applied in or near the seed row. All sites received herbicide applications at appropriate rates and timings and were effective at controlling weeds.



1 **CarmanNorth19***
2 **CarmanSouth19**
3 **CarmanWest18**
4 **Clearwater19**
5 **Elgin18**
6 **Elgin19**
7 **Graysville18***
8 **Graysville19**
9 **MacGregor18**
10 **Morris19**
11 **Portage18**
12 **Rosebank18**
13 **Rosebank19**
14 **StClaude19***
15 **Stephenfield18***
16 **Wellwood18**
17 **Winkler18**
***Gold level site-years**

Figure 2.1 Map of southern Manitoba and legend showing the location of research site-years. Gold level site-years were managed entirely by the university. Silver level site-years were established and maintained on commercial corn fields in collaboration with farmers.

Table 2.1 Soil and crop characteristics of each site-year

	Site-year	Previous crop	Tillage	Soil texture 0-15 cm	Planting date	Hybrid	Plant count ha^{-1}	Background fertilizer[a] N	P_2O_5	K_2O	S
								kg ha^{-1}			
1	CarmanNorth19	Soybean	Conventional	Sand	May 9/19	DK33-78RIB	85109	0	76	45	22[b]
2	CarmanSouth19	Pinto bean	Zero till	Sandy Loam	May 8/19	P7940AM	74334	0	0	0	0
3	CarmanWest18	Soybean	Zero till	Sandy Loam	May 3/18	DK33-78RIB	73981	7	22	0	0
4	Clearwater19	Canola	Conventional	Loam	May 14/19	P7455R	84856	7[c]	22[c]	0[c]	0[c]
5	Elgin18	Canola	Conventional	Clay Loam	May 8/18	A4939G2RIB	63294	39	62	17	28
6	Elgin19	Wheat	Conventional	Clay Loam	May 2/19	A4939G2RIB	74530	12	50	18	0
7	Graysville18	Black Beans	Conventional	Sandy Loam	May 15/18	DK33-78RIB	91047	0	80	56	20
8	Graysville19	Canola	Zero till	Sandy Clay Loam	May 8/19	DK35-88RIB	68868	0	0	0	0
9	MacGregor18	Wheat	Zero till	Fine Sand	May 2/18	P7527AM	72749	5	18	1	0
10	Morris19	Soybean	Conventional	Clay	May 9/19	DK29-89RIB	75090	0	0	0	0
11	Portage18	Soybean	Conventional	Silty Clay	May 3/18	MZ1633DBR	85642	7	22	0	0
12	Rosebank18	Pinto bean	Conventional	Sandy Loam	May 5/18	DK33-78RIB	71378	5	18	0	0
13	Rosebank19	Edible bean	Conventional	Sandy Clay Loam	May 8/19	DK35-88RIB	71464	5	18	0	0
14	StClaude19	Corn	Conventional	Fine Sand	May 9/19	DK33-78RIB	81987	0	82	55	22
15	Stephenfield18	Corn	Conventional	Fine Sand	May 15/18	DK33-78RIB	85647	0	80	55	20
16	Wellwood18	Wheat	Conventional	Clay Loam	May 12/18	P7211AM	70694	10	34	0	0
17	Winkler18	Soybean	Conventional	Sandy Loam	May 3/18	P8387AM	70968	10	34	0	0

[a]Background fertilizer includes N applied as starter fertilizer banded in or near the seed row and any P, K, or S fertilizer applied across the entire site at planting

[b]plus 4 kg Zn and 2 kg Cu ha^{-1}

[c]plus 45, 90, 90, and 28 kg N, P_2O_5, K_2O and S ha^{-1} in fall 2018

Table 2.2 Early spring soil test analyses taken from 0 N plots at each site-year

	Site-year	Olsen P mg kg^{-1}	DTPA Cu mg kg^{-1}	EC dS m^{-1}	Exch. K mg kg^{-1}	OM %	pH	DTPA Zn mg kg^{-1}	SO_4-S kg ha^{-1}		NO_3-N kg ha^{-1}		
		0-15 cm							0-60 cm	0-120 cm	0-15 cm	0-60 cm	0-120 cm
1	CarmanNorth19	16	0.38	0.115	198	2.1	7.9	0.74	20	144	10	35	80
2	CarmanSouth19	39	0.53	0.130	145	3.2	7.5	0.93	171	1305	15	62	95
3	CarmanWest18	8	0.33	0.330	133	4.3	7.2	1.53	233	865	20	70	95
4	Clearwater19	25	1.07	0.424	283	5.8	6.7	1.60	3509	7761	56	139	198
5	Elgin18	17	0.89	0.573	270	5.4	6.6	1.02	113	295	46	123	190
6	Elgin19	5	1.02	0.239	405	6.2	6.7	2.20	60	165	19	50	69
7	Graysville18	17	0.73	0.341	193	4.4	6.3	1.53	198	1215	23	84	116
8	Graysville19	14	0.72	0.290	213	4.0	8.3	1.33	2698	6764	27	57	115
9	MacGregor18	23	0.28	0.170	97	1.5	6.9	0.64	128	164	11	55	150
10	Morris19	20	2.30	0.416	690	6.9	8.0	0.63	266	1184	43	108	142
11	Portage18	19	2.73	2.225	408	6.6	7.6	2.23	7596	16487	33	76	125
12	Rosebank18	21	0.59	0.626	163	3.4	7.5	0.93	226	965	32	117	195
13	Rosebank19	9	0.54	0.239	173	4.6	8.2	0.98	2068	5115	29	157	296
14	StClaude19	45	0.42	0.105	273	1.7	7.1	1.19	21	41	7	28	78
15	Stephenfield18	33	0.29	0.279	200	1.5	8.2	1.63	51	84	12	42	80
16	Wellwood18	54	1.98	0.371	413	5.9	5.9	5.65	43	73	18	51	67
17	Winkler18	13	0.67	0.465	193	2.6	8.0	1.80	167	502	16	56	93

Table 2.3 Close proximity weather data for each site-year growing season and long term averages (May 1 – Oct 31)

Site-year	Local Monthly Average Temp (°C) May	June	July	Aug	Sept	Oct	Mean	Corn Heat Units Growing season total	Local 30 year mean	% of 30 year mean
CarmanWest18, Graysville18 Stephenfield18, Rosebank18	15.6	19.7	20.4	19.3	11.0	3.1	14.9	2828	2821	100
Winkler18	15.9	20.1	20.6	19.8	11.5	3.5	15.2	2992	3022	99
Portage18	15.0	19.8	21.0	19.5	10.8	2.8	14.8	2926	2859	102
MacGregor18	14.4	19.2	20.0	18.3	10.2	2.3	14.1	2531	2644	96
Wellwood18	14.5	19.0	19.3	18.1	9.6	1.8	13.7	2531	2644	96
Elgin18	14.9	18.7	19.1	18.3	9.6	1.9	13.8	2722	2644	103
Morris19	10.3	18.0	20.0	18.2	13.4	3.3	13.9	2726	2821	97
CarmanNorth19 Graysville19 CarmanSouth19 Rosebank19	10.4	17.8	20.2	18.3	13.3	3.9	14.0	2647	2821	94
StClaude19	10.1	17.4	20.4	18.1	13.1	3.0	13.7	2647	2821	94
Clearwater19	9.5	16.6	19.1	16.9	12.4	1.9	12.7	2002	2711	74
Elgin19	9.7	16.7	19.2	16.7	12.5	2.0	12.8	2556	2644	97

Site-year	Local Monthly Precipitation (mm) May	June	July	Aug	Sept	Oct	Total	30 year mean	% of mean
CarmanWest18, Graysville18 Stephenfield18, Rosebank18	41.4	93.5	44.1	27.9	48.1	35.9	290.9	372	78
Winkler18	40.9	74.4	51.3	30.3	45.2	44.4	286.5	364	79
Portage18	22.3	110.9	39.7	19.2	90.2	35.7	318.0	370	86
MacGregor18	19.6	111.6	38.9	47.5	93.7	32.0	343.3	328	105
Wellwood18	31.0	100.4	78.6	34.0	100.4	48.0	392.4	328	120
Elgin18	19.9	101.9	62.9	24.5	76.3	20.1	305.6	328	93
Morris19	31.7	40.6	110.8	54.5	194.2	44.5	476.3	372	128
CarmanNorth19 Graysville19 CarmanSouth19 Rosebank19	40.4	41.4	61.8	64.1	149.9	37.1	394.7	372	106
StClaude19	46.7	31.8	103.3	32.6	152.5	30.0	396.9	372	107
Clearwater19	21.8	76.0	119.6	53.5	117.9	40.6	429.4	360	119
Elgin19	29.2	127.2	72.8	2.0	134.7	21.5	387.4	328	118

2.3.2 Experimental design and treatments

This study used two levels of experiments for 2018 and 2019 to determine optimum N rates. Each site was a randomized complete block design with four replicates; there was a total of 21 treatments at gold sites and 12 treatments at the silver sites, but only six treatments were used in this analysis of corn yield response to N rates. Nitrogen rates used were 0, 45, 90, 135, 180, and 225 kg N ha^{-1} applied in the spring, at or near planting. At gold level sites, the N rate treatments were applied as urea broadcast and incorporated immediately with a tandem disc 5-8 cm deep; sites were planted within five days of the treatment application. At silver sites, the N rates were applied as SuperU™ broadcast post-plant within 10 days of planting. All sites were planted on 76 cm rows except Portage18, Clearwater19, and Morris19 which were 51 or 56 cm row spacing depending on the cooperating producer's equipment. All plots were four rows wide and 8 m long with N treatments applied 1.5 m outside the front and back of each plot; only the centre two rows were used for measurements and data collection to minimize edge effects. All broadcasting of fertilizer was done by hand with pre-measured quantities and a minimum of two passes over the plot to apply fertilizer uniformly.

2.3.3 Sample collection and processing

Early spring soil samples were taken from each 0 N plot in late May or the first week of June and used to determine site background soil fertility and texture. To minimize the risk of including starter N fertilizer in the soil sample, soil samples were collected by hand with a Dutch auger midway between the planted rows. Each composite sample consisted of five cores from 0-15 cm, 15-30 cm, 30-60 cm, and three cores from 60-90 cm and 90-120 cm. Samples were kept refrigerated until dried and ground for analysis.

All soil fertility analyses were conducted by Farmers Edge Laboratories in Winnipeg, MB. Nitrate-N was extracted from 15 g of soil with 30 mL 0.01 M $CaCl_2$ placed on a reciprocating shaker for 30 minutes. The solution was put through filter paper and nitrate-N measured by automated colorimetry after reduction by hydrazine and complexing with n-(1-naphthyl)ethylenediamine dihydrochloride (Farmers Edge 2019). Results in the original analyses were reported as mg nitrate-N kg^{-1} of soil. The additional soil fertility analyses were completed for site characterization and are reported as site averages in Table 2.2. Soluble sulphur, assumed to be sulphate, was extracted from 15 g of soil with 30 mL 0.01 M $CaCl_2$ and measured by inductively coupled plasma optical emission spectroscopy (ICP-OES). Phosphorus was extracted by the Olsen method (0.5 M sodium bicarbonate) and reactive phosphate-phosphorus measured by automated colorimetry. Exchangeable potassium was extracted with 1.0 M ammonium acetate and measured by ICP-OES. Organic matter was determined by loss-on-ignition, after ashing at 375°C for two hours. Copper and zinc were extracted with DTPA-Sorbitol solution and measured by ICP-OES. Twenty-five grams of soil was agitated with 50 mL of deionized water for 30 minutes, and electrochemistry was used to measure pH and electrical conductivity.

Particle size analysis was completed in the University of Manitoba, Department of Soil Science labs. Two composite samples from each depth (0-15 cm, 15-30 cm, 30-60 cm, 60-90 cm, and 90-120 cm) at each site were analyzed for texture. Beginning with 10 grams of dried and ground soil, samples were treated with H_2O_2 to oxidize soil organic matter. After oxidation and dispersion, sand was collected with a #270 mesh screen that allowed silt and clay fractions to pass through. Silt and clay fractions were determined by oven-drying a portion of suspension solution taken by pipette at set time intervals (Carter and Gregorich 2008). Results of the particle size analysis for each site-year are listed in Appendix 1.

Reference values for soil bulk density (BD) in Prairie soils (University of Saskatchewan 1991) were used to calculate the amount of nutrient per ha in each sample depth at each site-year based upon the soil texture analyses. The estimated bulk densities from each depth at each site-year were used to convert lab concentrations of mg kg^{-1} into kilograms of nitrogen and sulphur per hectare. An example of the BD conversion calculation is as follows:

Table 2.4 Example of 0-15 cm texture analysis and reference bulk density values of each particle size fraction

Site	Depth	Sand	Silt	Clay
CarmanNorth19	0-15 cm	89%	4%	7%
Reference bulk density[a]		1.55 g cm^{-3}	1.15 g cm^{-3}	1.05 g cm^{-3}

[a]Reference bulk densities from University of Saskatchewan (1991) Basic Soil Science

Average bulk density of the depth, based on the proportion in each textural class:

$$Average\ bulk\ density = (0.89 * 1.55) + (0.04 * 1.15) + (0.07 * 1.05) = 1.50 \frac{g}{cm^3}$$

Determined kg of soil per hectare (ha) for 0-15 cm depth:

$$1.50 \frac{g}{cm^3} x \frac{\frac{1500000000\ cm^3}{15\ cm\ slice\ of\ a\ ha}}{\frac{1\ kg}{1000g}} = \frac{2250000\ kg\ soil}{15\ cm\ slice\ of\ a\ ha}$$

Since this sandy soil has an estimated 2,250,000 kg of soil 15 cm^{-1} slice ha^{-1}, the following formula converted lab analyses of mg kg^{-1} to kg ha^{-1}:

$$= \frac{lab\ mg\ of\ NO3 - N}{kg\ of\ soil} x \frac{2250000\ kg\ soil}{1000000} = \frac{kg\ nutrient}{15\ cm\ ha}$$

A pre-side-dress nitrate test (PSNT) was conducted on plots that received 45 kg ha^{-1} of N at planting time as SUPERU™ broadcast and which would be side-dressed with supplemental N at the V4 stage (see Chapter 3 for a full description of N source, placement, and timing treatments). Although these plots were not part of the N rate analysis, the PSNT values for these plots were investigated as a possible tool to identify sites where supplemental applications of N would not be required. Each PSNT soil sample was a composite of five cores from 0-30 cm taken randomly from between the corn rows, and samples were kept refrigerated until dried and ground and analyzed for nitrate-N using the same methods as for early spring samples.

Post-harvest soil sampling for nitrate-N was planned for all plots at all sites. However, poor weather in late fall resulted in delayed harvests and ground freezing before post-harvest soil sampling could be completed at several sites in both years. Sampling of all N rate plots to a depth of 120 cm occurred at only four of the sites; an additional four sites were soil sampled to 60 cm depth; five sites had only the 0 N plots soil sampled post-harvest; and four sites did not have any post-harvest soil samples taken. Post-harvest soil samples were taken with either a tractor-mounted hydraulic sampler or by hand with Dutch augers. All soil samples were taken mid-row, with four cores taken to 60 cm and two cores from 60 cm to 120 cm on each sampled plot. Soil samples were partitioned into 0-15 cm, 15-30 cm, 30-60 cm, 60-90 cm, and 90-120 cm depth increments and kept refrigerated until dried, ground, and analyzed for nitrate-N using the same method as for earlier samples. Nitrate-N concentrations in fall soil samples were converted to amounts of N per ha based on reference values for soil bulk densities, using the same method as for early spring soil samples.

Plant counts were completed post emergence at each site-year (Table 2.1). Plant counts were taken from a 2 rows by 4 m length on 25% of the plots at each site.

At maturity, stalk nitrate samples were collected from all research plots. Samples were collected after black layer formation on the ear and prior to harvest. Two stalks were collected from the front and rear of each harvest row, for a total of eight stalks per plot. Each section of stalk was 20 cm long, starting at 15 cm above the soil surface. Stalks were oven-dried at 65°C and ground to pass through a 1 mm screen before extraction. Nitrate-N was extracted from stalks with 2% acetic acid solution and the concentration determined with the cadmium reduction method (Benton Jones Jr 2001).

Grain harvest was completed by one of two methods. The preferred method was a plot-scale combine harvest in the field and the secondary method was to hand pick and later stationary thresh ears. Nine of the 17 site-years were harvested directly with a 2-row plot combine; weights were obtained from the harvester and grain subsamples from each plot were oven-dried at 66°C until samples were no longer losing moisture. The ears were picked and bagged from a 4 m section of each harvest row at eight sites. Bags were placed in a drying room and later stationary threshed. Threshed corn was weighed to measure yield and subsamples were oven-dried to measure moisture. All grain yields were adjusted to 15.5% moisture.

Total above ground biomass was determined from 0 N plots at each site-year to determine plant N uptake for calculating mineralization. Immediately prior to grain harvest, consecutive plants from 1 m of each harvest row were cut at the soil surface and processed into separate samples for corn grain, corn cob, and stover material. For each sample we determined field weight before a sub-sample was taken for moisture determination, drying, grinding, and total N analysis. All samples were oven dried at 66°C until dry; stover was ground to fit through a 1 mm screen and grain was ground fine with a coffee bean grinder. Total N was determined by combustion analysis (Rapid N Cube analyzer, Elementar, Langenselbold, Germany). Mineralization was estimated based on the growing season change in soil nitrate-N and plant N uptake, where estimated mineralization = (post-harvest soil NO_3-N – early spring soil NO_3-N – starter N in background fertilizer) + above ground N uptake.

2.3.4 Data analysis

Collected data were entered into Excel (Microsoft Excel 2013, Microsoft Corporation) and Excel was used for all calculations and basic statistical analyses, including the generation of quadratic equations for yield response to total N supply. Statistical Analysis Software (SAS version 9.4, SAS Institute) was used to analyze treatment N rate effects on yield using PROC GLIMMIX, while PROC UNIVARIATE was used to determine the Coefficient of Variation (C.V.). A type III global analysis of variance is reported with degrees of freedom, *F*-value, and the *P*-value (*Pr>F*); which is the probability that N rate applied had no effect on yield and differences in yield were a result of random variation or other factors. Blocks were considered random but nested within each site-year. Site-years were also sliced to determine significant responses at individual sites. Treatment means were compared by least squares means (LSmeans) and Tukey's honest significant difference for multiple comparisons. An alpha of 0.05 was used as the *P* level to determine statistical significance.

2.3.5 Determining economic optimum N rate and N required per unit

The rate of N for maximum return to nitrogen (MRTN) was determined by using the response of grain corn yield to total N supply while considering the cost of N fertilizer applied and the price received for the corn. Mathematically, this is where revenue (yield x corn price) minus fertilizer cost (N application rate x cost of fertilizer) is maximized.

In this economic analysis, profitability was calculated using pre-set grain corn and fertilizer prices that represent a ratio between the cost of N fertilizer and price of grain corn. From 2000 to 2011, the market prices for grain corn averaged between \$0.10 and \$0.23 kg^{-1} annually, so \$0.18 kg^{-1} was selected as a reasonable target for corn (Manitoba Government 2020). Three fertilizer prices from \$0.77 to \$1.21 kg^{-1} N are used to represent the typical range of N fertilizer. The results of this analysis will hold true at market values that equal the ratios in Table 2.5.

Table 2.5 Fertilizer and corn prices and price ratios used for N profitability analysis

	Ratio of Price for Fertilizer N vs. Corn		
	Low N Price Ratio	Medium N Price Ratio	High N Price Ratio
Price of N fertilizer kg^{-1}	\$0.77	\$0.99	\$1.21
Price of corn kg^{-1}	\$0.18	\$0.18	\$0.18
Price ratio \$N:\$ corn	4.28:1	5.50:1	6.72:1

The first strategy for determining the MRTN was to identify the total N supply rate with the greatest numerical value for net economic return to N fertilizer at each site-year. The MRTN was determined using the mean yield of each rate treatment at each site-year with the corresponding fertilizer:corn price ratios applied to determine most profitable treatment. The second strategy was to develop a quadratic yield response model for each site-year and determine the MRTN supply rate for each fertilizer:corn price ratio. This strategy is similar to the traditional approach of developing a single response curve to fit data collected from all site-years (Nafziger et al. 2004), except that applying quadratic yield response models to individual site-years provides insight on the variability in N response across site-years. In this method, the MRTN supply rate is the point on the response curve where the cost of one additional unit of N becomes equal to the revenue received for the additional corn produced.

To determine N required per unit of corn produced at the optimum rate of N, the site-years were split into two groups, according to their maximum yield achieved. The site-years in this study were split according to whether the maximum yield was greater than or less than 8150 kg ha^{-1}. The threshold of 8150 kg ha^{-1} to separate site-years was chosen for two reasons. The first reason is that 8150 kg ha^{-1} is equivalent to the average yield of grain corn in Manitoba in 2020 (MB Agriculture et al. 2021); therefore, this threshold enabled a comparison between sites with yields above vs. below the Provincial average. Second, a visual evaluation of Figures 2.2 and 2.3 revealed that dividing the site-years at 8150 kg ha^{-1} would separate the cluster of high-yielding site-years from the low-yielding site-years.

Nitrogen required per unit of production at the MRTN rate for high- and low-yielding site-years was determined using three different methods. The first method was determined using the numerically optimum N rate at the medium cost:price ratio. The second and third determinations of N use per unit of production were from quadratic yield response models, the first being from the response model for each individual site-year and the second from two yield response models: one model for the entire group of all the low-yielding site-years and one model for the entire group of all the high-yielding site-years.

2.4 Results and Discussion

2.4.1 Effect of nitrogen rate on corn grain yield

A global ANOVA was performed to evaluate the effect of N fertilizer application rate on grain corn yield. As expected, we observed a statistically significant overall increase in yield as N fertilizer rates increased (Table 2.6). There was also a significant site-year effect and a site-year*treatment interaction. This means that although there was an overall response to N fertilizer application, the site-years did not respond uniformly to the rate of N fertilizer applied. Thirteen of the site-years had significant individual responses to N fertilizer application; three of the four site-years that did not respond to N fertilizer application had the highest values of baseline N supply (starter N fertilizer applied at planting, plus early spring soil test NO_3-N) being over 115 kg ha^{-1} and the fourth site had a baseline N supply of 62 kg N ha^{-1}. Of the thirteen sites that had significant yield responses, twelve of them reached the statistically highest means grouping of yields with N fertilizer applications of 90 kg N ha^{-1} or less.

The effect of treatment and site-year was highly variable. For example, at Elgin18 the yield differences among treatments were less than 500 kg ha^{-1}, while at CarmanNorth19 the yield differences among treatments were as large as 5500 kg ha^{-1}. Site mean yields varied from 3884 kg ha^{-1} at StClaude19 to 9602 kg ha^{-1} at CarmanSouth19 which is an example of the significant site-year effect due to site-specific growing conditions.

Table 2.6 Effect of N fertilizer application rate on corn grain yield

Site-year	*Pr>F*	Baseline N Supply[a] kg ha^{-1}	0 kg ha^{-1}		45 kg ha^{-1}		90 kg ha^{-1}		135 kg ha^{-1}		180 kg ha^{-1}		225 kg ha^{-1}		Site Mean[c]	
			Fertilizer N Rate — Yield (kg ha^{-1})[b]													
CarmanNorth19	<0.0001	35	3856	D	6053	C	7574	BC	8322	AB	8846	AB	9607	A	7376	cde
CarmanSouth19	0.3124	62	8881		9659		9553		9481		10195		9842		9602	ab
CarmanWest18	<0.0001	77	6553	B	8074	AB	8715	A	8987	A	9335	A	9319	A	8497	abc
Clearwater19	0.2482	146	9334		9247		10032		10285		9759		10306		9827	a
Elgin18	0.9630	162	7137		7590		7550		7365		7324		7560		7421	cde
Elgin19	<0.0001	62	4744	B	6052	AB	7347	A	6925	A	7325	A	7131	A	6587	def
Graysville18	0.0168	84	6715	B	8016	AB	8253	AB	8421	A	7363	AB	8301	AB	7845	bcd
Graysville19	0.0183	57	6961	B	8069	AB	8913	A	8445	AB	8505	AB	8207	AB	8183	abcd
MacGregor18	<0.0001	60	4551	C	8441	B	9279	AB	10391	A	9961	AB	9798	AB	8737	abc
Morris19	<0.0001	108	5505	B	7424	A	8100	A	7322	A	7723	A	7701	A	7296	cde
Portage18	<0.0001	83	5688	B	6980	AB	7659	A	8126	A	7064	AB	8163	A	7280	cde
Rosebank18	0.0118	122	7036	B	8482	AB	8305	AB	9143	A	8309	AB	8524	AB	8300	abcd
Rosebank19	0.2224	162	8757		9321		9625		9804		9927		10029		9577	ab
StClaude19	<0.0001	28	1181	B	2396	B	4143	A	5080	A	5196	A	5309	A	3884	g
Stephenfield18	<0.0001	42	1733	C	4584	B	6366	A	7806	A	7326	A	6890	A	5784	ef
Wellwood18	<0.0001	61	3064	B	4972	A	5989	A	4742	A	4930	A	5509	A	4868	fg
Winkler18	<0.0001	66	5595	C	8368	B	9889	AB	9745	AB	10045	A	9465	AB	8851	abc
Mean for all site-years	<0.0001	83	5723	C	7313	B	8100	A	8258	A	8148	A	8309	A		

Global ANOVA	df	*Pr>F*
Trt	5	<0.0001
Siteyr	16	<0.0001
Siteyr*Trt	80	<0.0001
C.V.		28%

[a]Baseline N supply includes early spring soil test NO_3-N to 60 cm plus starter N applied at planting
[b]Across fertilizer rates in each row, means followed by the same upper case letter are not significantly different at *P<0.05*
[c]Within the column for site means, means followed by the same lower case letter are not significantly different at *P<0.05*

The lack of fertilizer N response at sites with large amounts of soil N reserves illustrates the importance of accounting for N supplied from soil as well as fertilizer when determining the optimum rates of fertilizer N to apply. To evaluate the overall effect of total N supply on yield, baseline N supply (early spring soil nitrate-N plus starter N applied at planting across the entire site) plus N fertilizer applied as a treatment were added together for each site-year. This total N supply calculation is important in Manitoba because we use pre-plant soil nitrate concentrations to determine N fertilizer recommendations. This calculation accounted for the variation of spring soil nitrate concentrations and starter N applied across site-years. As a result, the values for total N supply rate at each rate of N fertilizer application were not consistent across site-years and are not suitable for a global ANOVA. However, the numerical relationships between total N supply and yield for each site-year are illustrated in Figures 2.2 and 2.3.

In 2018, at every site-year except Elgin18, corn yields responded positively to increasing total N supply rates until approximately 150 kg ha^{-1} of N supply. Site-specific factors such as heat and precipitation, soil conditions, and fertility outside of N could be responsible for sites plateauing at different maximum yields. In 2019, we observed similar results where the majority of the yield increase from N fertilizer was achieved by 150 kg N ha^{-1} total N supply, and yield increases above that N supply rate were small and infrequent. This visual interpretation of the data falls within the range of recommended N rates determined from corn fertilization studies in the mid-west U.S. where a 2012-2014 study found that maximum grain yield was achieved with 180 kg N ha^{-1} which was the highest N rate in that U.S. study (Burzaco et al. 2014). Another mid-west U.S. study conducted on 26 site-years from 1999-2003 determined that the optimum economic rate of N fertilizer was 140 kg ha^{-1}, yielding 11 000 kg ha^{-1} in a soybean corn rotation (Nafziger et al. 2004).

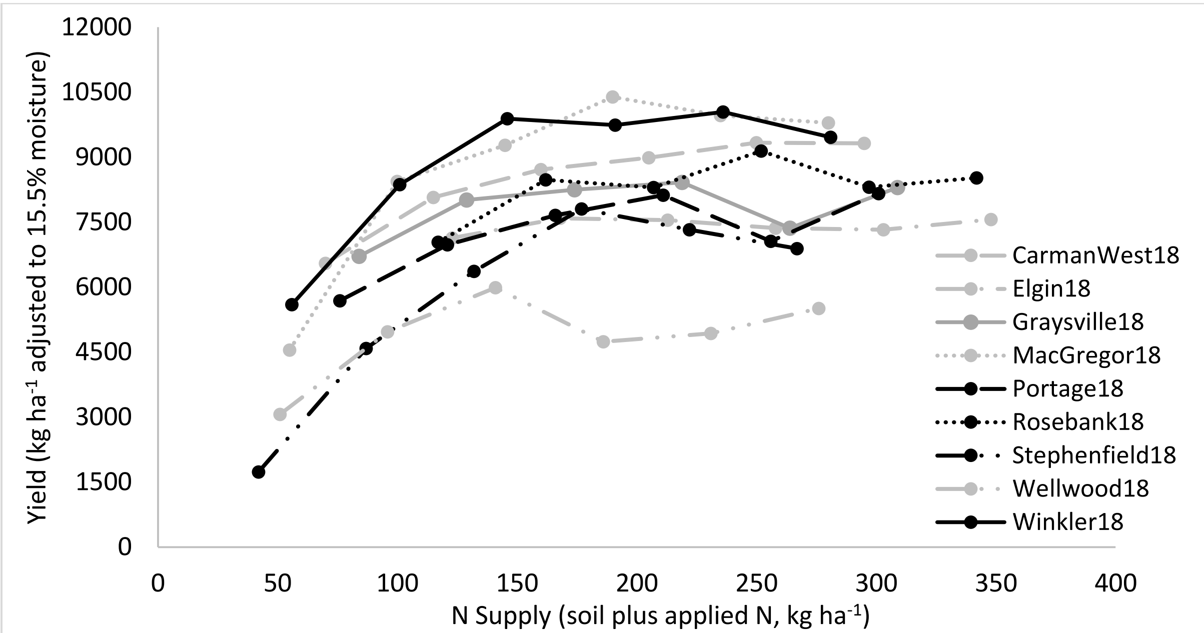


Figure 2.2 Effect of total N supply (baseline N supply plus fertilizer N) on corn grain yield at nine research sites in 2018

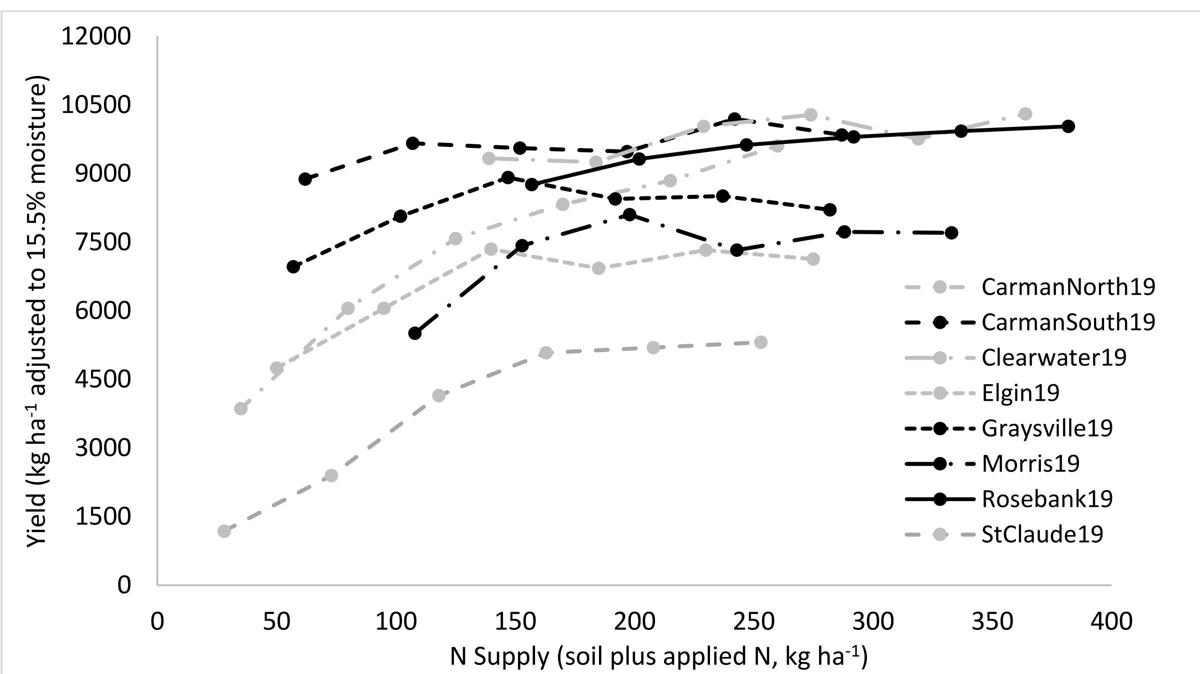


Figure 2.3 Effect of total N supply (baseline N supply plus fertilizer N) on corn grain yield at eight research sites in 2019

In Manitoba, the organic matter in soils can release a significant amount of plant-available N throughout the growing season. Therefore, depending on the growing season, the appearance of N (mineralization) is an important consideration for N fertilizer rate calculations. Approximately half of the site-years in this study experienced relatively dry summers in 2018 and 2019, likely reducing microbial activity and N mineralization. Therefore, some of our estimates of N mineralization might be less than expected.

Table 2.7 Observed plant N uptake and mineralization from 0 N treatment at each site-year

Site-year	Baseline N Supply[a]	Plant N uptake	Post-harvest NO_3^- N to 60 cm	Estimated Mineralization
	———	——— kg ha^{-1}	———	———
CarmanNorth19	35	73	15	53
CarmanSouth19	62	140	28	106
CarmanWest18[b]	77	117	59	99
Clearwater19[b]	146	160	33	47
Elgin18[bc]	162	148		
Elgin19[b]	62	93	34	65
Graysville18	84	116	33	65
Graysville19	57	108	24	75
MacGregor18[b]	60	95	22	57
Morris19	108	92	35	19
Portage18[bc]	83	97		
Rosebank18[b]	122	166	58	102
Rosebank19[b]	162	154	34	26
StClaude19	28	45	20	37
Stephenfield18	42	44	12	14
Wellwood18[bc]	61	63		
Winkler18[bc]	66	108		
Mean	83	107	31	59

[a]Baseline N supply includes spring NO_3-N to 60 cm plus starter N applied at planting
[b]Additional starter N applied at planting as a baseline application to all plots at these sites was accounted for in the calculation for estimated mineralization
[c]Post-harvest soil samples were not collected from these sites due to frozen soils; therefore, estimated mineralization could not be calculated

As shown in Table 2.7, N mineralization was extremely variable across site-years. In 2018 the greatest observed mineralization was at Rosebank with 102 kg ha^{-1} and the least was at Stephenfield with 14 kg ha^{-1}; these sites were approximately 30 km apart but on very different soil textures. In 2019, the amount of mineralization at CarmanNorth was estimated at 53 kg N ha^{-1} and CarmanSouth at 106 kg ha^{-1}; these sites were within 15 km of each other. Mangin and Flaten (2018) found that mineralization in Manitoba varied between 39 and 145 kg ha^{-1} and averaged 74 kg ha^{-1} across eight spring wheat sites. These Manitoba results align with Walley (2005) who reported between 43 and 97 kg N ha^{-1} can be potentially mineralized in the black soil zone in Saskatchewan.

2.4.2 Economic optimum nitrogen rate

In Table 2.8 the MRTN was determined numerically using the mean yield of each rate treatment at each site-year, while in Table 2.9 the strategy was to fit a quadratic yield response model to each site-year. The quadratic equations and R^2 for the quadratic equation at each site-year in Table 2.9 are listed in Appendix 2.

Table 2.8 Total N supply (baseline N plus fertilizer N) for the numerically highest yielding treatment and numerically greatest economic return to N fertilizer at each fertilizer:corn price ratio for each site-year

Site-year	For maximum Yield	For maximum return to N fertilizer		
		Low price ratio[a]	Medium price ratio	High price ratio
	Total N supply (kg N ha^{-1})			
CarmanNorth19	260	260	260	260
CarmanSouth19	242	107	107	107
CarmanWest18	257	257	257	167
Clearwater19	371	281	281	146
Elgin18	207	207	207	207
Elgin19	152	152	152	152
Graysville18	219	174	129	129
Graysville19	147	147	147	147
MacGregor18	195	195	195	195
Morris19	198	195	198	198
Portage18	308	218	218	218
Rosebank18	257	257	257	167
Rosebank19	252	207	207	207
StClaude19	253	163	163	163
Stephenfield18	177	177	177	177
Wellwood18	151	151	151	151
Winkler18	246	156	156	156
Mean	227	194	192	171

[a]Fertilizer:corn price ratios are defined in Table 2.5

Although the quadratic model was used for our second method of determining MRTN, U.S. studies by Cerrato and Blackmer (1990) and Bullock and Bullock (1994) reported that the quadratic-plateau model fit corn N response data more accurately than the quadratic or linear-plateau model. Bullock and Bullock (1994) reported that at some site-years the MRTN rate was significantly greater for the quadratic than the quadratic-plateau model and at others the difference was minimal. In Quebec, Alotaibi et al. (2018) reported that, averaged across several sites of varying soil texture, the quadratic model predicted an optimum economic N rate 18% higher than the quadratic-plateau method and 40% higher than a linear-plateau model.

Therefore, some of our calculations for MRTN based on quadratic responses are likely overestimated.

Table 2.9 Total N supply (baseline N plus fertilizer N) for the maximum yield and maximum greatest return to N fertilizer at each fertilizer:corn price ratio as determined by quadratic response equations for each individual site-year

Site-year	For maximum Yield	For maximum return to N fertilizer		
		Low price ratio[a]	Medium price ratio	High price ratio
	Total N supply (kg N ha^{-1})			
CarmanNorth19	270	248	242	235
CarmanSouth19	271	168	139	110
CarmanWest18	255	228	220	212
Clearwater19	367	250	217	183
Elgin18	na[b]	na[b]	na[b]	na[b]
Elgin19	212	190	184	178
Graysville18	228	193	184	174
Graysville19	195	171	164	157
MacGregor18	213	203	201	198
Morris19	257	235	229	222
Portage18	248	217	209	200
Rosebank18	261	234	226	218
Rosebank19	369	289	266	243
StClaude19	230	210	204	199
Stephenfield18	205	195	192	190
Wellwood18	203	178	171	164
Winkler18	198	188	185	182
Mean	249	212	202	192

[a]Fertilizer:corn price ratios are defined in Table 2.5
[b]No response to N fertilizer at Elgin18, so the quadratic response model did not fit well (R^2=0.21)

Using the numerical greatest return to N, the average total N supply rate to achieve maximum yield across all site-years was 227 kg ha^{-1}. When a quadratic response curve was applied to model each site-year's response, the average total N supply rate for maximum yield increased by 22 kg ha^{-1}, to 249 kg N ha^{-1}. At the medium price ratio for fertilizer:corn, the MRTN recommendations from each method are only 10 kg ha^{-1} apart (192 and 202 kg N ha^{-1}). These rates are similar to the optimum N rate studies in Quebec from 45 site-years between 2002 and

2010 which was 195 kg N ha^{-1} (Kablan et al. 2017). However, the optimum rates in our study are slightly greater than those in another Quebec study (Alotaibi et al. 2018), which determined the MRTN rate ranged from 163 to 190 kg N ha^{-1} depending on soil texture.

The direct numerical evaluation of N responses identified 11 site-years where the same N application rate resulted in maximum yield and MRTN at the medium fertilizer:corn price ratio; that concurrence was probably due to the coarse (45 kg ha^{-1}) increments in N rate treatments. With the capacity to interpolate between the increments in N rate treatments, the quadratic response models revealed more differences in total N supply rates for maximum yield vs. MRTN. The quadratic models indicated that N supply should be reduced by 47 kg ha^{-1} (to 202 kg ha^{-1}) when targeting MRTN at the medium fertilizer:corn price ratio, compared to targeting the absolute maximum yield (249 kg N ha^{-1}). Across individual site-years, the total N supply rates for maximum yield were between 12 and 150 kg N ha^{-1} greater than for MRTN at the medium price ratio.

Sawyer et al. (2006) used individual site-year response curves for corn N trials in a soy-corn rotation across four U.S. states. The average MRTN rates for each state were Illinois 182 kg ha^{-1}, Iowa 138 kg ha^{-1}, Wisconsin 119 kg ha^{-1}, and Minnesota 113 kg ha^{-1}. Those recommendations are less than those in Table 2.9 where 202 kg ha^{-1} was the mean MRTN supply rate in our study; however, our values for total N supply include baseline N supply at planting in addition to the applied fertilizer N. Therefore, after subtracting the baseline N supply (an average of 83 kg ha^{-1}), the overall average MRTN fertilizer N application rate of 119 kg ha^{-1} in our study would be similar to those in Wisconsin and Minnesota. A 2016 Minnesota study reported that the MRTN rate in a corn-soy rotation was 201 kg ha^{-1}, which was much higher than all other N rates reported (Rubin et al. 2016). However, the sites in the study by Rubin et al. were irrigated and had soil textures of loamy sand and sandy loam making them higher-yielding and more prone to N loss and with lower ability to supply N, compared to other studies in Minnesota.

The three fertilizer:corn price ratios had some effect on MRTN application rates. Using the numerically most profitable treatment, the overall average N rate recommendation was reduced by 23 kg ha^{-1} as the fertilizer:corn price ratio increased from low to high. The average quadratic response-based MRTN rate recommendations developed for each individual site-year were 212 kg ha^{-1} at the low fertilizer:corn price ratio, 202 kg ha^{-1} at the medium ratio, and 192 kg ha^{-1} at the high ratio. The similar reduction in N rates (10 kg) for each increase in N prices (22 cents kg^{-1}) indicates that the yield response to N fertilizer is quite linear in that segment of the quadratic response model.

2.4.3 MRTN and N required per unit of corn production for high- and low-yielding site-years

Figures 2.2 and 2.3 demonstrate that similar amounts of total N supply resulted in very large differences in maximum yields at each site-year. With such a range of maximum yields, the result is that site-years with lower maximum yields tended to require more N per unit of corn produced when compared to higher yielding site-years.

The first method to determine N required per unit of production was using the numerically optimum N rate for each site-year (Table 2.10). The second method was to develop quadratic response models for each individual site-year (Table 2.11) and a third method was to develop two quadratic response models, one model for the high-yielding group of site-years and one model for the low-yielding group of site-years (Figure 2.4 and Table 2.12).

Table 2.10 Total N supply and N required per kilogram of corn yield at the numerically optimum economic N rate for site-years and grouped by high and low yield potential

Site-year	Baseline N Supply[a] kg N ha^{-1}	Total N supply at MRTN[b] kg N ha^{-1}	Corn yield at MRTN[b] kg ha^{-1}	Total N supply $unit^{-1}$ kg N kg^{-1} grain corn
	Low yield potential site-years (yield potential <8150 kg ha^{-1})			
Elgin18	162	207	7590	0.0273
Elgin19	62	152	7347	0.0207
Morris19	108	198	8100	0.0244
StClaude19	28	163	5080	0.0321
Stephenfield18	42	177	7806	0.0227
Wellwood18	61	151	5989	0.0252
Mean	77	175	6985	0.0254
	High yield potential site-years (yield potential ≥8150 kg ha^{-1})			
CarmanNorth19	35	260	9607	0.0271
CarmanSouth19	62	107	9659	0.0111
CarmanWest18	77	257	9335	0.0275
Clearwater19	146	281	10285	0.0272
Graysville18	84	129	8016	0.0161
Graysville19	57	147	8913	0.0165
MacGregor18	60	195	10391	0.0188
Portage18	83	218	8126	0.0268
Rosebank18	122	257	9143	0.0281
Rosebank19	162	207	9625	0.0262
Winkler18	66	156	9889	0.0158
Mean	87	210	9363	0.0219

[a]Baseline N supply includes early spring NO_3-N to 60 cm and background N applied
[b]MRTN, maximum return to nitrogen, the numerically most profitable total N supply rate using the medium fertilizer:corn price ratio in Table 2.5

Table 2.11 Total N supply and N required per kilogram of corn yield determined by a quadratic response model for individual site-years and grouped by high and low yield potential

Site-year	Baseline N Supply[a] kg N ha^{-1}	Total N supply at MRTN[b] kg N ha^{-1}	Corn yield at MRTN[b] kg ha^{-1}	Total N supply $unit^{-1}$ kg N kg^{-1} grain corn
	Low yield potential site-years (yield potential <8150 kg ha^{-1})			
Elgin18	162	na[c]	na[c]	na[c]
Elgin19	62	184	7330	0.0251
Morris19	108	229	7910	0.0290
StClaude19	28	204	5293	0.0385
Stephenfield18	42	192	7641	0.0251
Wellwood18	61	171	5435	0.0315
Mean	77	196	6722	0.0298
	High yield potential site-years (yield potential ≥8150 kg ha^{-1})			
CarmanNorth19	35	242	9350	0.0259
CarmanSouth19	62	139	9558	0.0145
CarmanWest18	77	220	9274	0.0237
Clearwater19	146	217	9765	0.0222
Graysville18	84	184	8148	0.0226
Graysville19	57	164	8685	0.0189
MacGregor18	60	201	10482	0.0192
Portage18	83	209	7832	0.0267
Rosebank18	122	226	8738	0.0259
Rosebank19	162	266	9716	0.0274
Winkler18	66	194	10249	0.0189
Mean	87	206	9254	0.0224

[a]Baseline N supply includes early spring NO_3-N to 60 cm and background N applied

[b]MRTN, maximum return to nitrogen, most profitable total N supply rate according to the quadratic response using the medium fertilizer:corn price ratio in Table 2.5

[c]No response to N fertilizer at Elgin18, so the quadratic response model did not fit well (R^2=0.21)

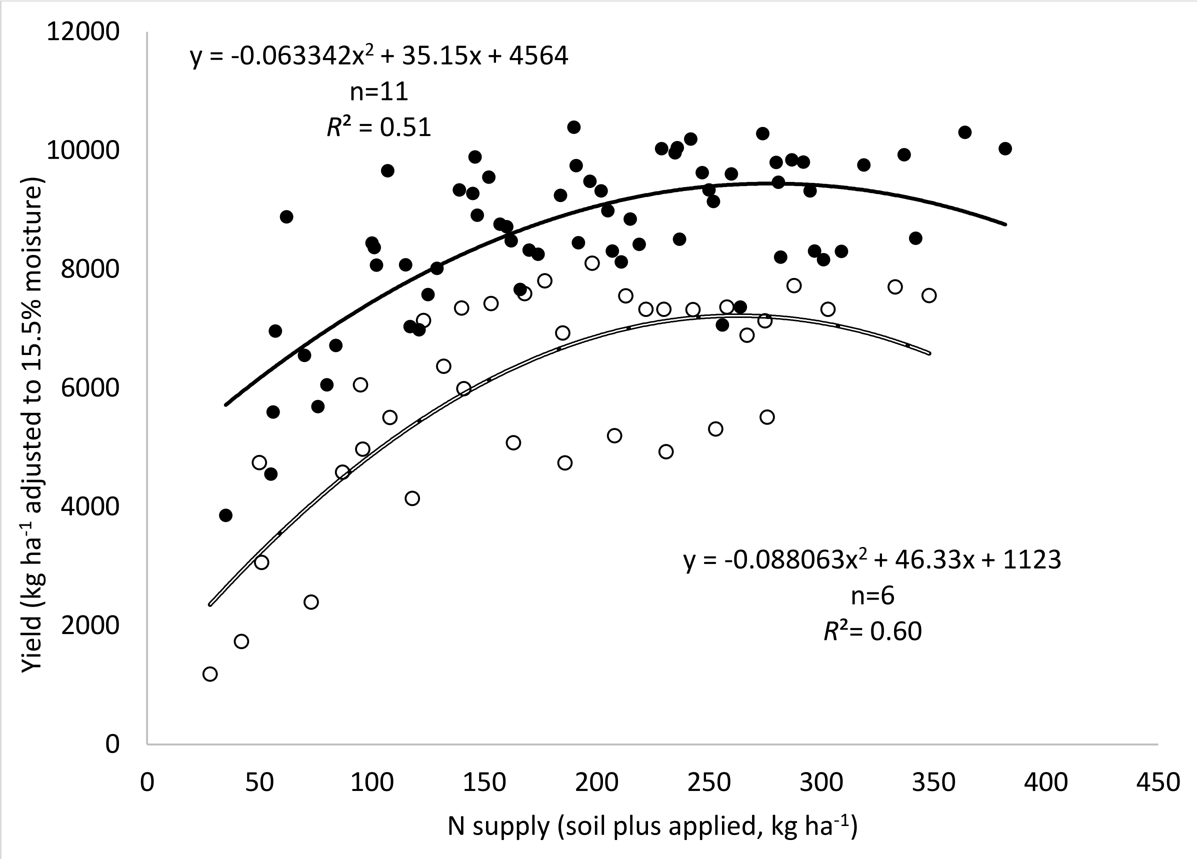


Figure 2.4 Quadratic response models for grain corn yield response to total N supply for site-years grouped with yield potential greater or less than 8150 kg ha^{-1}

Table 2.12 Total N supply and N required per kilogram of corn yield determined from a quadratic response model where site-years are grouped by high and low yield potential

Site-year group	Baseline N Supply[a]	Total N supply at MRTN[b]	Yield at MRTN[b]	Total N supply kg^{-1} of grain corn
		kg ha^{-1}		kg N
Low yield potential <8150 kg ha^{-1}	77	232	7133	0.0325
High yield potential ≥8150 kg ha^{-1}	87	234	9324	0.0251

[a]Baseline N supply includes early spring NO_3-N to 60 cm and background N applied
[b]MRTN, maximum return to nitrogen, most profitable total N supply rate according to the quadratic response using the medium fertilizer:corn price ratio in Table 2.5

The recommendations developed by the two quadratic models for the two yield groups in Table 2.12 are nearly identical, with values of 232 kg N ha^{-1} for low- and 234 kg ha^{-1} for high-yielding sites and much greater than the average N recommendations developed from quadratic responses at individual site-years, which averaged 196 kg ha^{-1} and 206 kg ha^{-1} for low- and high-yielding sites respectively. Nevertheless, within each strategy where quadratic response models were used the optimum N rates were very similar for low- and high-yielding sites. These results are similar to those published by Nafziger et al. (2004), who also found that optimum N rate does not change significantly with differing yield potential for corn. However, creating the single quadratic response curve for a large group of sites (Figure 2.4) can be misleading because it can easily be influenced by non-typical data and does not provide information about the true variance of yields and N response across site-years. Therefore, we are more confident in the MRTN values generated by the averages of response models for individual site-years than those generated by a single response model for a group of site-years. Furthermore, as mentioned previously, quadratic response models in particular are prone to over-estimating the rate of N required for optimum economic yield (Cerrato and Blackmer 1990; Bullock and Bullock 1994). Therefore, it was not surprising that using the numerically optimum N rate analysis resulted in lower overall recommendations of N per unit of corn production than the recommendations from the two quadratic methods.

All methods of analysis identified greater N use efficiency at higher yielding sites than at lower yielding sites. At the numerically optimum MRTN rate, low-yielding sites required 0.0035 kg more N kg^{-1} corn than high-yielding sites; however, at the MRTN rate determined from the quadratic analysis of individual site-years, low-yielding sites required an average of 0.0074 kg more N kg^{-1} corn than high-yielding sites. Nitrogen requirement per kg corn production was also variable between sites with the same yield potential. For example, in Table 2.11

CarmanNorth19 and CarmanSouth19 were similar in soil type, weather, and yield but had very different N requirements of 0.0259 and 0.0145 kg N kg^{-1} grain corn, respectively, at optimum yield.

In the literature, total N required per kg of corn production has a pattern of decreasing with more recent research. As mentioned earlier, for yields similar to 8150 kg ha^{-1}, early research in Manitoba recommended 0.0327 kg N kg^{-1} corn (Walley and Soper 1985); Manitoba's Corn Production Guide recommends 0.0351 kg N kg^{-1} corn (Manitoba Corn Growers Association 2004); Manitoba's Soil Fertility Guide recommends 0.0309 kg N kg^{-1} corn (Manitoba Agriculture 2007); AGVISE™ recommends a total N supply rate of 0.0215 kg N kg^{-1} corn (AGVISE 2021); and a typical recommendation from the North Dakota corn N calculator would be 0.0206 kg N kg^{-1} corn (NDSU 2020). Our study's average recommendations from individual quadratic responses for each site-year (0.0298 kg N kg^{-1} corn for low-yielding sites and 0.0224 kg N kg^{-1} corn for high-yielding sites) are slightly greater than the current values used in North Dakota, but less than past recommendations in Manitoba. Our study's average recommendation from individual quadratic responses at high-yielding sites is also similar to those based on quadratic response models developed by researchers at the University of Illinois, who recommended 0.0220 kg N kg^{-1} corn (Bullock and Bullock 1994). This value from Illinois is also nearly identical to the average value of 0.0219 kg N kg^{-1} corn determined using the numerically optimum approach for high-yielding site-years in our study.

2.4.4 Indicators of N sufficiency

Three indicators of N sufficiency were evaluated: a pre-side-dress nitrate test (PSNT), a stalk nitrate test, and a post-harvest soil nitrate test. Each of these methods have been studied and reported in other crops or regions and the purpose in this study was to evaluate their effectiveness for corn grown in Manitoba. Manitoba's short growing season, with less CHU and precipitation than other climates, may affect the effectiveness of these tools, as the early maturing hybrids' requirements change rapidly through an accelerated growing season. Additionally, Manitoba has diverse soils which can mineralize varying amounts of N depending on weather conditions; and mineralized N will influence soil nitrate tests that are being taken to characterize soil N status.

The purpose of the PSNT is to allow corn growers to adjust the rate of N that they would normally apply at or after the V4 stage. This soil test accounts for any changes in plant available soil N that would have occurred since the early spring nitrate test, in response to soil and weather conditions (e.g., loss of N due to plant uptake, leaching, and denitrification, as well as the gain of plant available N due to mineralization).

Table 2.13 Average measured pre-side-dress nitrate test (PSNT) concentrations (0-30 cm) and yields for plots that received 45 kg N ha^{-1} at planting and no additional fertilizer after PSNT sampling, compared to yields from plots that received 225 kg N ha^{-1} at planting

Site-year	Mean PSNT 0-30 cm mg kg^{-1}	% of high N rate yield	Yield at 45 kg N ha^{-1}	Yield at 225 kg N ha^{-1}	Tukey's HSD difference in yield
			——kg ha^{-1}——		
Stephenfield18	11.5	67	4584	6890	yes
MacGregor18	13.5	86	8441	9798	no
CarmanNorth19	17.5	63	6053	9607	yes
StClaude19	18.9	45	2396	5309	yes
Elgin19	19.8	85	6052	7131	no
Wellwood18	20.0	90	4972	5509	no
Winkler18	22.0	88	8368	9465	no
Clearwater19	26.4	90	9247	10306	no
CarmanWest18	29.0	87	8074	9319	no
CarmanSouth19	29.2	98	9659	9842	no
Graysville18	30.0	97	8016	8301	no
Rosebank19	32.7	93	9321	10029	no
Graysville19	35.2	98	8069	8207	no
Rosebank18	37.1	100	8482	8524	no
Morris19	54.8	96	7424	7701	no

All sites where PSNT concentrations were 20 mg kg^{-1} or greater achieved 87% or more of the yield of the highest rate of fertilizer N, with no additional N added beyond the 45 kg N ha^{-1} applied at planting (Table 2.13). The five sites that tested >30 mg kg^{-1} all yielded within 7% of the high N rate plots. The recommendation in Ontario is that no additional N should be side-dressed when PSNT is ≥27.5 mg kg^{-1} and the expected yield is 10 500 kg ha^{-1} or less (Ontario Ministry of Agriculture, Food and Rural Affairs 2021). Only three of the fifteen site-years had statistically significant yield increases from the 45 kg N ha^{-1} to the 225 kg N ha^{-1} fertilizer application rate. None of the three sites that had significant yield increases had PSNT values greater than 20 mg kg^{-1}, indicating that at PSNT concentrations >20 mg kg^{-1} significant yield increases from additional applications of N are unlikely. In Ontario the long term average for PSNT is 12 mg kg^{-1} which is near the lowest value that we observed from these site-years

(Ontario Ministry of Agriculture, Food and Rural Affairs 2021). Brouder and Mengel (2003) found the critical PSNT nitrate concentration where additional N should be applied is 24 mg kg^{-1}, as anything over 20 mg kg^{-1} indicates nearly sufficient and typical PSNT concentrations are 11-15 mg kg^{-1} for a soy-corn rotation. The Illinois Agronomy Handbook recommends no additional N is needed if PSNT is greater than 25 mg kg^{-1}, and a full rate of N is required if PSNT levels are below 10 mg kg^{-1} (Fernández et al. n.d.). Therefore, our study's critical threshold of 20 mg kg^{-1} is slightly less than the thresholds in these other corn growing areas.

Samples of the corn stalk were taken pre-harvest for nitrate concentration analysis to determine if there was an accumulation of nitrates within the plant. Excess nitrates in the corn stalk would indicate that the crop was over-fertilized with N. Overall, the mean stalk nitrate concentration tended to increase as N application rates increased (Table 2.14).

However, the stalk nitrate concentrations at the rate of N supply for MRTN were very inconsistent across site-years. For example, at the numerically-determined MRTN rate, stalk nitrate concentrations varied between 42 and 3566 mg kg^{-1}. Furthermore, these stalk nitrate concentrations at our fertilizer rates for MRTN did not match the stalk nitrate concentration range of 700-2000 mg kg^{-1} that Iowa State University (Blackmer and Mallarino 2000) regarded as an indicator of N sufficiency. According to the Iowa guidelines, only 5 of the 17 sites had optimal N status at the numerically-determined MRTN rate; four sites indicated an excess of stalk nitrates at the numerically-determined MRTN rate (2494 to 3566 mg kg^{-1}), while eight sites indicated low or marginal N status rate (42 to 636 mg kg^{-1}). However, AGVISE™ Laboratories (Jenny, n.d.) interprets a stalk nitrate test of 250-2000 mg kg^{-1} to indicate sufficient N supply for the corn crop which, using the numerically-determined MRTN rate, would move four more site-years into the category of sufficient N supply according to their stalk nitrate thresholds. Studies in Minnesota by Rubin et al. (2016) reported that an average stalk N concentration of 2527 mg kg^{-1} was required to achieve optimum yield, which is greater than the 700-2000 mg kg^{-1} recommended by Iowa State University. Therefore, although the stalk nitrate concentrations were generally able to detect increasing amounts of N supply at each site-year in our study, the stalk nitrate values were highly variable across site-years and sufficiency thresholds for Iowa do not seem to be appropriate for indicating N sufficiency in corn grown under Manitoba conditions.

Table 2.14 Corn stalk nitrate concentrations at maturity, by site-year and N fertilizer rate

Site-year	0 kg N ha^{-1}	45 kg N ha^{-1}	90 kg N ha^{-1}	135 kg N ha^{-1}	180 kg N ha^{-1}	225 kg N ha^{-1}	site-year mean
	stalk NO_3 concentration (mg kg^{-1})[a]						
CarmanNorth19	64	46	196	644	1267	1937[b]	692
CarmanSouth19	229	313	467	1818	2021	2222	1178
CarmanWest18	44	36	164	742	1571	1642	700
Clearwater19	203	576	2698	3566	4743	4819	2767
Elgin18	226	336	645	742	699	992	607
Elgin19	107	58	409	1133	2879	2933	1253
Graysville18	80	66	801	2039	2522	3110	1436
Graysville19	123	573	2819	4677	5580	4408	3030
MacGregor18	83	167	553	1173	1475	2108	926
Morris19	83	236	1045	4186	8222	9191	3827
Portage18	42	59	242	824	3905	5783	1809
Rosebank18	656	661	1809	2494	3918	4181	2286
Rosebank19	870	1913	2678	3213	3938	4585	2866
StClaude19	138	80	136	158	151	545	201
Stephenfield18	43	18	22	55	392	789	220
Wellwood18	98	665	636	3012	4941	6691	2674
Winkler18	45	41	42	364	1257	2140	648
Mean	184	344	903	1814	2910	3416	

[a]Cells are coloured according to the Iowa State University guidelines for the stalk nitrate test to evaluate the crop's late season N status (see below)
[b]Underlined stalk NO_3 concentrations indicate the N treatment that was identified to be the numerically-determined MRTN rate for the medium fertilizer:corn price ratio in Table 2.5

Iowa State University interpretation guidelines

Stalk NO_3^- concentration (mg kg^{-1})	N status interpretation
<250 mg kg^{-1}	Low
250-700 mg kg^{-1}	Marginal
700-2000 mg kg^{-1}	Optimal
>2000 mg kg^{-1}	Excess

Post-harvest fall nitrate-N tests are commonly used on the prairies to determine N fertilizer requirements for the next crop. The post-harvest soil test can also be used to evaluate the fertility management for the crop recently harvested; for example, high concentrations of residual soil nitrate could indicate excessive rates of N application. To test this tool for corn grown in Manitoba, post-harvest soil nitrate-N to 60 cm was measured on N rate treatments at eight of the site-years and soil tests for check plots (0 N) at an additional five sites.

Overall, the average residual nitrate-N on check plots was 35 kg ha^{-1} and residual N did not begin to increase until the 135 kg ha^{-1} treatment, where an average of 44 kg N ha^{-1} remained (Table 2.15). At the numerically-determined MRTN rate, residual nitrate-N ranged from 17 kg ha^{-1} at StClaude19 to 98 kg ha^{-1} at Rosebank18, while the average residual N was 40 kg N ha^{-1}. However, the amount of residual nitrate-N at Rosebank18 was unusually large, since none of the other seven site-years had more than 45 kg nitrate-N ha^{-1} at their numerically-determined MRTN rates. The range of post-harvest nitrate-N at a recent wheat study in Manitoba (Mangin and Flaten 2018) was 24 to 59 kg ha^{-1} nitrate-N to 60 cm, the residual N range from that wheat study fell within the residual N range of this corn study. In our study, given that the amount of residual N at the MRTN rate for Rosebank18 was more than double the equivalent amounts at any of the other site-years, amounts of post-harvest residual nitrate-N greater than 50-60 kg ha^{-1} probably indicate that the N supply to the corn crop exceeded the optimum economic rate of N.

Although post-harvest residual nitrate-N may indicate excessive rates of N application, this soil test does not appear to be a reliable indicator of insufficient rates of N application. There was a very small difference between the residual nitrate-N at MRTN rates and at 0 N fertilizer rates, a difference of only 5 kg N ha^{-1}. This small difference indicates that at the MRTN rate the corn crop had nearly depleted all soil N reserves that it was capable of and, therefore, post-harvest nitrate-N may not be a reliable indicator of insufficient N application rates. Nevertheless, the lowest residual N values were measured at CarmanNorth19 (18 kg ha^{-1}) and at StClaude19 (19 kg ha^{-1}) where the 0 N plots displayed signs of extreme N deficiency indicating that the crop was unable to deplete soil N below those concentrations.

Table 2.15 Effect of fertilizer N rate on post-harvest mean residual soil nitrate-N

	Rate of fertilizer N applied (kg N ha^{-1})					
	0	45	90	135	180	225
Site-year	Residual soil NO_3-N after harvest ——kg N ha^{-1} to 60cm ——					
CarmanNorth19	18	17	17	21	20	26*
CarmanSouth19	27	31*	28	41	42	61
CarmanWest18[a]	59				*	
Clearwater19[a]	33			*		
Elgin19a	34		*			
Graysville18	53	45*	41	73	108	133
Graysville19	26	46	39*	37	35	38
MacGregor18[a]	22			*		
Morris19[a]	35		*			
Rosebank18	66	42	64	98*	136	130
Rosebank19	33	40*	43	41	46	40
StClaude19	19	17	19	17*	18	22
Stephenfield18	25	22	21	26*	31	31
Mean	35	33	34	44	55	60

[a]Post-harvest NO_3-N was not measured at across all N treatments due to frozen soil
*Indicates the N treatment that was identified to be the numerically-determined MRTN rate for the medium fertilizer:corn price ratio in Table 2.7

The variability of the results across site-years for these three tests could be due to the diverse crop rotations, land use practices, and weather conditions within our field trials. Similar factors may also account for the differences between the results for our field trials in Manitoba and those in the mid-west United States.

2.5 Conclusions

There are several challenges to predicting the MRTN application rate for growing a corn crop. Dhital and Raun (2016) said that maximum corn grain yield and the response to N are independent; however, they both influence N demand, so the optimum rate of N fertilizer at a location will differ every year. The challenge is made greater by temporal and spatial variability in N mineralization, which is often a substantial contribution to the crop's N supply, e.g., researchers in Minnesota reported that in a corn-soybean rotation an average of 71% of MRTN yield was achieved with no N fertilizer (Fernandez 2017). Gao et al. (2018) studied N response in Manitoba on potatoes and reported that site-years all differed in response to N fertilizer, suggesting that soil and climate differences impact fertilizer N efficiency and potential for environmental N loss.

In our study, the MRTN supply rate for corn grown in Manitoba with a fertilizer price of 99 cents kg^{-1} N and corn price of 18 cents kg^{-1} was between 175 and 210 kg total N supply ha^{-1} using mean MRTN values from the numerical and quadratic analyses of individual site-years averaged across all site-years or for low- and high-yielding groups of site-years. This relatively narrow range of optimum rates of N excludes the MRTN values for the quadratic analyses where one response equation was developed for each entire yield group, which were relatively high for reasons mentioned earlier.

Unlike most other literature values for corn's economically optimum N supply, our N supply rate accounts for the soil's pre-plant reserves of soil nitrate-N, treatment and starter fertilizer N applied. Therefore, soil nitrate-N soil concentrations at planting should be subtracted from our study's range of MRTN rates to determine the optimum rate of fertilizer N application. Kablan et al. (2017) found that the MRTN rate is greatly affected by soil texture and rainfall; such information may also be true in our dataset and could be explored with further data analysis.

Evaluation of the soil and stalk nitrate tests that are used elsewhere for determining and evaluating N rates produced mixed results. The pre-side-dress nitrate test revealed that a crop is unlikely to respond to additional N if PSNT concentrations are greater than 20 mg kg^{-1}. The stalk nitrate analyses revealed that the optimum range of nitrate in the stalk is more variable here than in other regions where the test is used and may not be a reliable indicator of N sufficiency. Post-harvest soil tests are useful to identify excess N in the soil (e.g., > 50-60 kg nitrate-N ha^{-1}), but the difference in soil residual N between crops with deficient or optimum N supplies is not easily distinguishable.

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3. NITROGEN FERTILIZER SOURCE, TIME, AND PLACEMENT FOR PRODUCTION OF MODERN CORN HYBRIDS IN MANITOBA

3.1 Abstract

A two-year field experiment was conducted in Manitoba to evaluate nitrogen fertilizer sources (inhibitor technology) and application timings to improve N use efficiency by reducing the exposure of applied N losses. To evaluate enhanced efficiency fertilizers (EEFs), five N source treatments were applied at two N application rates each and compared to each other and to the standard practice of pre-plant urea broadcast and incorporated. There were no significant differences among any N source treatments at the same application rate using a global ANOVA for comparisons. For split N applications, one method tested was to apply a portion of the N requirement at planting to meet the early season N requirements and follow with an in-season N application by side-dressing (mid-row banding) at the V4 stage. The other strategy tested for in-season corn fertilization was to split N between planting and surface Y-drop application at the V8 growth stage with and without urease inhibitor. Statistical analyses showed no yield advantage to split-applying N fertilizer when compared to all N being spring-applied and at three site-years there was a yield penalty to delaying N application. There was also no yield increase from adding a urease inhibitor to the UAN when dribble banded on the soil surface at the V8 stage.

3.2 Introduction

3.2.1 Corn production in Manitoba

Corn is one of the most important crops grown around the world. In 2014-15, Canada and USA produced 37% of the corn worldwide on 19% of the world's corn hectares (Omonode et al. 2017). Traditionally, the cold continental climate in Manitoba has not been favourable for corn production, lacking the frost-free days and the rainfall required for corn to reach maturity and produce optimum yields. However, genetic improvements have led to an increased area of corn production in Manitoba.

Managing N fertilizer efficiently has economic and environmental benefits. Improving N use efficiency increases the proportion of applied fertilizer taken up by the crop in that year. Obtaining the greatest N use efficiency can be achieved by supplying the right amount of N to the crop at the right place, time, and in the right form when the crop needs it while minimizing N loss from the rooting zone (Sutton 2005).

3.2.2 Nitrogen Fertilizer Sources

Urea is a granular product and the most commonly used N fertilizer around the world; urea represented 47% of the N fertilizer used on western Canadian canola fields in 2019 (Stratus Ag Research 2019) and 45% of N fertilizer used for corn in Minnesota (Bierman et al. 2012). Urea-ammonium nitrate (UAN) is a liquid N fertilizer and the least concentrated of common N fertilizers at 28% N, but UAN is popular for niche uses such as in-furrow or in-season N fertilizer.

Enhanced efficiency fertilizers are nitrogen fertilizers that have additional technology intended to slow soil transformations of applied N fertilizer and increase N use efficiency. Delaying the transformation of N in soil from the fertilizer form temporarily reduces the risk of fertilizer causing negative environmental impacts and matches the timing of plant-available N to the N demands of the crop. The types of EEF are nitrification inhibitors, urease inhibitors, and controlled release products.

Nitrification inhibitors inhibit the biological oxidation of ammonium N to nitrate N (Sutton 2005). Three site-years of corn research in Indiana showed that nitrification inhibitors increased N use efficiency by 17% (Burzaco et al. 2014). Urease inhibitors are used to inhibit the hydrolysis of urea by the urease enzyme (Sutton 2005). When urea is surface-applied, these inhibitors can reduce the accumulation of ammonium and ammonia on the soil surface that leads to ammonia volatilization (Sutton 2005). Controlled release EEFs do not chemically inhibit N fertilizer but, instead, use a physical barrier. When urea granules are polymer-coated the granule does not dissolve into the soil when exposed to water as it normally would; instead, water diffuses into the granule and is contained for a period of time, followed by slowly diffusing into the soil solution (Fernandez 2016). The release period of polymer-coated urea is 60-90 days, depending on soil temperature (Grant et al. 2012).

3.2.3 Nitrogen Fertilizer Timing & Placement

Split application of N fertilizer is the application of a portion of fertilizer at planting and the remainder during crop growth (Grant et al. 2012). Split application options for timing and placement of N fertilizer could be especially suited to corn because approximately 75% of the N is taken up after 500 growing degree days or the V10 stage (Bender et al. 2013) and corn is a row crop that allows for in-season application without damaging the plants. Benefits of delaying N application into the growing season include the opportunity to evaluate yield potential before choosing the final N application rate, matching application timing closer to crop uptake, and reducing the period of time that N is susceptible to losses such as leaching and denitrification. Splitting N applications between planting and V5 growth stage or later can reduce the total N needed to achieve maximum yield. For example, researchers at the University of Guelph found it more profitable to split N application and adjust the in-season application rate compared to applying all N at planting (Brown et al. 2009). However, in Minnesota, there was no significant corn yield difference between pre-plant or split-applied N (Venterea and Coulter 2014) and no reported difference of corn grain yields in Iowa with in-season N applications at the V2, V6, or V12 growth stage (Jaynes 2013).

Side-dressing N at V4 growth stage or late June is an option for split application. The N fertilizer can be banded sub-surface which is optimum placement, and the overall N application rate can still be adjusted for growing conditions. At planting, a partial rate of N is applied to supply N until the V4 application; the starter rate depends on producer preference and pre-plant soil residual nitrate. As the growing season progresses, more information is available, allowing the final N application rate to be determined with greater confidence. In-season decision tools for determining the appropriate N rate include a pre-side-dress nitrate test and canopy reflectance; accumulated rainfall, heat units, and long term probabilities can also be used for predicting N requirement and potential yield.

Mid-season N application when the crop is at the V8-V10 growth stage is another in-season N application strategy. This later-season timing limits the application to high clearance machinery which is typically set up for handling liquid products; however, granular fertilizer could also be applied. The advanced growth stage allows only surface placement of the N fertilizer, leaving it susceptible to volatilization; therefore, this could be a good opportunity to use urease inhibitors. Additional risks with V8 applications are an N deficiency occurring in the crop before the in-season application occurs or dry weather causing surface stranding of the applied N, meaning the fertilizer does not get leached from the soil surface into the rooting zone. Applications that are "Y-dropped" use hoses to apply fertilizer below the canopy and place fertilizer in bands on the soil surface adjacent to the corn rows. At these later crop stages, canopy reflectance can also be useful to quantify the crop's N status and determine an appropriate rate for N application. However, canopy sensors cannot predict grain yield or optimum N rate required until the V8 growth stage and are more accurate at V12 growth stage (Paiao et al. 2020).

Fertilizing corn is different from fertilizing most other crops grown in Manitoba because of its very high dry matter yields, longer growing season, and row crop production system. The best methods for meeting the unique demands of modern corn hybrids for N in Manitoba's climate and soil are unknown. Therefore, this research aimed to develop best management practices for supplying N to corn crops, evaluating N sources, along with combinations of timings and placement within the 4R nutrient stewardship framework.

3.3 Materials and Methods

3.3.1 Field site descriptions

This study was conducted across 17 site-years in southern Manitoba, the same site-years described in Chapter 2. Site locations, soil characteristics, background fertilizations, general agronomic practices, and growing season weather conditions are described in Chapter 2.

3.3.2 Experimental design and treatments

Two levels of experiments were used in this study for 2018 and 2019 to determine optimum N fertilizer sources and timing of application. The study on N sources and timing was embedded within a larger experiment, which had a randomized complete block design with 4 replicates; 21 treatments at gold sites and 12 treatments at the silver sites that included the N rate study discussed in Chapter 2. Table 3.1 provides a list of treatments used in this analysis.

The four gold level sites contained treatments for comparison of N fertilizer sources and N timings, while the silver sites contained only timing comparisons. At gold sites only, four sources of N were applied at 90 and 135 kg N ha^{-1}: urea, urea treated with eNtrench™, urea:ESN™ blend, and SUPERU™; all sources were broadcast before planting and incorporated immediately with a tandem disc 5-8 cm deep while another SUPERU™ treatment was broadcast post-plant. The urea:ESN™ blend was mixed at a 1:1 ratio and the eNtrench™ was treated within 14 days of field application at the label-recommended rate of 2.7 L ha^{-1}. All fertilizer products and inhibitors were obtained from local retailers. Sites were planted within five days of the pre-plant fertilizer treatment application.

Treatments for comparing N application timing were the same at gold and silver level sites. There were three timing treatments: all N applied at planting, split application of N at planting and at the V4 growth stage, or split application at planting and V8 stage. The applications at planting were SUPERU™ broadcast by hand within 10 days of planting, while in-season treatments at the V4 stage (plants between 20 and 40 cm tall) were applied with a tractor-drawn toolbar, and in-season treatments at V8 were applied with a modified electrically-powered backpack sprayer tank and pump to simulate commercial Y-drop application.

For V4 side-dress application at sites with 76 cm row spacing, the tractor-drawn toolbar applicator had three shanks at 76 cm spacing with two cm-wide knife openers. Nitrogen was band-applied midway between corn rows and 5 cm deep within the four rows in each plot with drag chains to close furrows. Half rates of N fertilizer were applied as a surface dribble band adjacent to the guard rows for each plot to minimize edge effects. For two site-years that did not have 76 cm row spacing, the early season application of N at V4 consisted of a surface application of UAN mid-row applied with the backpack applicator (Clearwater19, Morris19). For the V8 application at all sites, the modified backpack applicator was used to dribble band UAN fertilizer on the surface of the soil on both sides of each corn row. The backpack applicator's rate of application was controlled by selecting orifices, adjusting pressure, and walking at specific speeds. For V8 treatments that included urease inhibitor, Agrotain Ultra™ was mixed at the label-recommended rate of 1.6 L per tonne of UAN immediately prior to application.

Table 3.1 N fertilizer source and timing comparison treatments applied at gold and silver site-years, eNt (eNtrench™ nitrification inhibitor-treated urea), ESN™ (polymer-coated, controlled release urea), SPU (SuperU™ urease and nitrification-inhibited urea), UAN (urea-ammonium nitrate), Bct (broadcast application), Inc (incorporated after application), Sdr (side-dress midrow band placement), Ydr (dribble-banded adjacent to rows at V4 or V8 leaf stage).

N Applications at Planting			In-Season N Applications		
N rate kg ha^{-1}	Source	Placement & Timing	N rate kg ha^{-1}	Source	Placement & timing
		Gold sites			
90	Urea	Pre-plant Bct&Inc			
90	Urea&eNt	Pre-plant Bct&Inc			
90	Urea&ESN™	Pre-plant Bct&Inc			
90	SPU	Pre-plant Bct&Inc			
90	SPU	Post-plant Bct			
135	Urea	Pre-plant Bct&Inc			
135	Urea&eNt	Pre-plant Bct&Inc			
135	Urea&ESN™	Pre-plant Bct&Inc			
135	SPU	Pre-plant Bct&Inc			
135	SPU	Post-plant Bct			
45	SPU	Post-plant Bct	45	UAN	Sdr @ V4
45	SPU	Post-plant Bct	45 or 59[a]	UAN	Ydr @ V8
45	SPU	Post-plant Bct	45 or 59[a]	UAN&Agrotain	Ydr @ V8
45	SPU	Post-plant Bct	90	UAN	Sdr @ V4
45	SPU	Post-plant Bct	90 or 119[b]	UAN	Ydr @ V8
45	SPU	Post-plant Bct	90 or 119[b]	UAN&Agrotain	Ydr @ V8
		Silver sites			
90	SPU	Post-plant Bct			
135	SPU	Post-plant Bct			
45	SPU	Post-plant Bct	45	UAN	Sdr @ V4
45	SPU	Post-plant Bct	45 or 59[a]	UAN	Ydr @ V8
45	SPU	Post-plant Bct	45 or 59[a]	UAN&Agrotain	Ydr @ V8
45	SPU	Post-plant Bct	90	UAN	Sdr @ V4
45	SPU	Post-plant Bct	90 or 119[b]	UAN	Ydr @ V8
45	SPU	Post-plant Bct	90 or 119[b]	UAN&Agrotain	Ydr @ V8

[a]The rate of N applied at V8 was 59 kg ha^{-1} in 2018 and 45 kg ha^{-1} in 2019
[b]The rate of N applied at V8 was 119 kg ha^{-1} in 2018 and 90 kg ha^{-1} in 2019

3.3.3 Sample collection and processing

Grain yield at harvest was completed by one of two methods; the preferred method was to mechanically harvest by combine in the field and the secondary method was to hand pick and later stationary thresh corn ears. Nine of the 17 site-years were harvested directly with a two-row plot combine; plot harvest weights were obtained from the harvester and grain subsamples from each plot were oven-dried at 66°C to obtain moisture content. The ears were picked and bagged from a four-meter section of each harvest row at eight sites. Bags were placed in a drying room and later stationary threshed. Threshed corn was weighed to measure yield and subsamples were oven-dried to measure moisture. All grain yields were adjusted to 15.5% moisture.

3.3.4 Data analysis

Collected data were entered into Excel (Microsoft Excel 2013, Microsoft Corporation) and Excel was used for all calculations and basic statistical analyses. Statistical Analysis Software (SAS version 9.4, SAS Institute) was used to analyze treatment source and timing effects on yield using PROC GLIMMIX, while PROC UNIVARIATE was used to determine the Coefficient of Variation (C.V.). A type III global analysis of variance is reported with degrees of freedom, *F*-value, and the *P*-value (*Pr>F*); which is the probability that observed differences were due to random variability and not the treatment applied. Blocks were considered random but nested within each site-year. Site-years were also sliced to determine significant responses at individual sites. Treatment means were compared by least squares means (LSmeans) and

Tukey's honest significant difference for multiple comparisons. An alpha threshold of 0.05 was used as the *P* level to determine statistical significance.

3.4 Results and Discussion

3.4.1 Comparison of enhanced efficiency fertilizers applied pre-plant

Across the four gold site-years there were no significant differences in corn grain yield for different sources and placements of N fertilizer when applied at the same rates of either 90 or 135 kg N ha^{-1} (Table 3.2). These results are not surprising because nitrification and urease inhibitors were designed to and have been shown to slow the transformations of fertilizer in soil, but yield response to EEFs is highly variable (Reitsma et al. 2008), with little or no yield increase from polymer-coated or urease-inhibited fertilizer compared to conventional fertilizer, especially if growing conditions are relatively dry and not conducive to N losses (Grant et al. 2012, Grant 2014). Growing season precipitation at the gold sites was significantly (22%) below average in 2018 and slightly (6-7%) above average in 2019 (Table 2.3). Precipitation can have an effect on the benefits of EEFs. Gagnon et al. (2012) determined that in wet years, controlled release urea and nitrification-inhibited urea resulted in greater yields over standard N fertilizer; however, yields were not significantly different in dry years. Since weather conditions at our sites, especially during the early to middle part of the growing season, were not particularly wet, substantial benefits of EEFs would not be expected. Another reason why the lack of statistically significant differences between N sources was not surprising was because only one of these site-years had a significant yield increase at N application rates greater than 90 kg ha^{-1} in the rate portion of this study (Chapter 1).

Even though there were no differences between N sources applied at the same rate, the yield for SUPERU™ broadcast post-plant at 90 kg ha^{-1} was the only treatment at this rate that was statistically similar to the five 135 kg ha^{-1} treatments, while urea was the only treatment at 135 kg ha^{-1} with a yield that was statistically similar to the five 90 kg ha^{-1} treatments. As stated earlier, these numerically small, statistically insignificant differences between N sources could be expected under the relatively dry conditions in our study. Other N research in Manitoba with five site-years also on a long season crop (potatoes) found no yield increase with ESN™ or SuperU™ EEF compared to urea (Gao et al. 2018). Furthermore, even under wet lower-mainland conditions in British Columbia, Grant et al. (2012) reported that broadcast urea at planting was as at least as effective as any type of controlled release fertilizer for increasing corn dry matter yields. However, experiments across the U.S. Midwest measured an average corn yield increase of 270 kg ha^{-1} when Agrotain™ was used with urea (Fernández et al. 2009.). In another trial in the mid-west United States applied 165 kg N ha^{-1} at planting as nine different combinations of N sources (six were EEFs) over three consecutive years, ammonia with nitrification inhibitor was numerically lowest yielding and SuperU™ broadcast was highest yielding; however, statistically, most N sources produced similar yields and all sources yielded between 13863 and 14365 kg grain corn ha^{-1} when applied at planting (Nafziger 2018).

Table 3.2 Effects of N fertilizer sources and placements applied at planting on corn grain yield at gold level site-years

Global ANOVA	df	*Pr>F*
Trt	9	<.0001
Site-year	3	0.0002
Site-year*Trt	27	0.1216
C.V.		27%

Site-year	Early spring NO_3-N kg ha^{-1}	mean yield kg ha^{-1}[a]
Graysville18	84	8505 A
Stephenfield18	42	7524 A
CarmanNorth19	35	8333 A
StClaude19	28	4846 B

Site-year	90 kg N ha^{-1} Urea Bct[b]&Inc	90 kg N ha^{-1} Urea&eNt Bct&Inc	90 kg N ha^{-1} Urea&ESN Bct&Inc	90 kg N ha^{-1} SPU Bct&Inc	90 kg N ha^{-1} SPU Bct	135 kg N ha^{-1} Urea Bct&Inc	135 kg N ha^{-1} Urea&eNt Bct&Inc	135 kg N ha^{-1} Urea&ESN Bct&Inc	135 kg N ha^{-1} SPU Bct&Inc	135 kg N ha^{-1} SPU Bct
	Yield kg ha^{-1}									
Graysville18	8253	8206	8578	8175	8874	8421	8845	9064	8812	7821
Stephenfield18	6366	6929	6611	6921	6454	7806	8626	8959	7776	8788
CarmanNorth19	7574	7001	7652	8197	8874	8322	8705	8662	8989	9359
StClaude19	4143	4261	3601	4030	5804	5080	5126	5274	5750	5386
Mean	6584 C	6599 C	6610 C	6831 BC	7501 ABC	7407 ABC	7825 AB	7990 A	7832 AB	7839 AB

[a]Means within a column or row followed by the same letter are not statistically different (*P*<0.05)

[b]Abbreviations are defined in Table 3.1

3.4.2 Comparison of nitrogen application timings

Split application of N fertilizer was evaluated using three timing treatments with total N application rates of 90 or 135 kg ha^{-1} for each timing. There was some variability of crop staging across the 17 site-years when in-season applications were made; however, the concept was maintained and applications were grouped to the targeted V4 and V8 stages.

The global analysis indicated significant differences across timing treatments, site-years, and a site-year*treatment interaction (Table 3.3). The interaction revealed that only 3 of the 17 site-years had significant yield differences between applying a full rate of N at planting and using a split application. At Stephenfield18, the 135 kg ha^{-1} SUPERU™ applied entirely at planting yielded significantly more than split applications of the same N rate and more than every 90 kg N ha^{-1} treatment. At CarmanNorth19 every N rate and timing treatment belonged to the top yielding group except for one split application, the low rate of N split-applied at the late timing (45 kg N ha^{-1} at planting plus 45 kg N ha^{-1} at V8), which yielded significantly less than when the full rate of N was applied at planting. At StClaude19, any treatment applied early (all at planting or split between planting and V4) was able to achieve yields equivalent to the highest yielding group; while split treatments applied at V8 stage yielded significantly less than treatments where the full rate of N was applied at planting.

There were no situations in this study where split application of N yielded more than full rate N applications at planting; however, there were several situations where split application yielded less. Although greater than 75% of plant N uptake occurs after the V6 stage (Bender et al. 2013), early season N deficiency before V6 appears to have lasting, detrimental effects on yield even if ample quantities of N are supplied later on. Similarly, after compiling research on corn fertilization across seven states in the U.S. corn belt, Nafziger (2018) reported that not having sufficient amounts of N available early in the season can sometimes cause lower yields even when substantial amounts of N are added later. Also, in another comprehensive study with 136 site-years of experiments across Iowa, Minnesota, and Wisconsin from 1987-1992, Bundy (2006) showed that split application rarely (7% of the time) yielded more than pre-plant N.

In our study, the three sites that demonstrated yield loss from split application had relatively low concentrations of early spring soil residual nitrate-N, indicating that the 45 kg ha^{-1} we applied at planting was not sufficient to carry the crop through to in-season application. That risk could be mitigated by increasing the N rate at planting or by applying the split-application before V4 stage. Also, these results do not rule out potential benefits of split application such as cost savings by lowering N rates in years with poorer yield potential, spreading out the growing season workload, or reducing environmental N losses when wet conditions are conducive to N loss. Other research in the more moist environment of the U.S. Midwest identified greater yields and improved N recovery with split application on coarse-textured soils whereas those benefits were not observed on the fine-textured soils (Bundy 2006).

Other researchers have also observed that grain corn yield is primarily affected by the N application rate, while timing and source were not as important (Burzaco et al. 2014). Our study supports that observation. So, in Manitoba, a yield increase should not be expected from a split-application of N fertilizer when compared to applying all N fertilizer in the spring at planting, and instead there should be greater emphasis on applying the correct N rate at planting.

Table 3.3 Effect of N fertilizer application timing on grain corn yield

Site-year	*Pr>f*	df	90 kg N ha^{-1} @planting	45 kg N ha^{-1} @planting +45 kg N ha^{-1} @V4	45 kg N ha^{-1} @planting +45 or 59 kg N ha^{-1} @V8[a]	135 kg N ha^{-1} @planting	45 kg N ha^{-1} @planting +90 kg N ha^{-1} @V4	45 kg N ha^{-1} @planting +90 or 119 kg N ha-^{1} @V8[a]
			Yield kg ha^{-1}[b]					
CarmanWest18	0.3333	5	8715	8414	8752	8987	9724	8959
Elgin18	0.5684	3	7550	na[c]	7043	7365	na[c]	7851
Graysville18	0.5527	5	8874	8158	8188	7821	8463	8564
MacGregor18	0.1800	5	9279	9369	8986	10391	9287	8995
Portage18	0.8312	3	7659	na[c]	7648	8126	na[c]	7812
Rosebank18	0.1419	5	8305	9818	9007	9143	8496	9009
Stephenfield18	<0.0001	5	6454 B	5870 B	5804 B	8788 A	5593 B	6198 B
Wellwood18	0.0594	5	5989	4855	4690	4742	5735	5834
Winkler18	0.7200	5	9889	9176	9084	9745	9494	9503
CarmanNorth19	<0.0001	5	8874 A	7772 AB	6274 B	9359 A	9107 A	7957 A
CarmanSouth19	0.7031	5	9553	9649	9381	9481	10355	9852
Clearwater19	0.7602	5	10032	9869[d]	10400	10285	10064[d]	9569
Elgin19	0.5888	5	7347	7135	6997	6925	7428	6436
Graysville19	0.7485	5	8913	8879	8334	8445	8270	8879
Morris19	0.3353	5	8100	7394[d]	7647	7322	7687[d]	6782
Rosebank19	0.4237	5	10029	10519	10731	9804	10623	9861
StClaude19	0.0002	5	5804 A	4826 ABC	3879 BC	5386 AB	5677 A	3634 C
Mean			8316	8114	7815	8360	8400	7982
Global ANOVA		df	*Pr>f*					
Trt		5	0.0002					
Siteyr		16	<.0001					
Siteyr*Trt		76	0.0001					
C.V.			23%					

[a]In 2018 the N rate at V8 was 59 or 119 kg ha^{-1}; in 2019 the N rate was 45 or 90 kg ha^{-1}

[b]Means within the same row that are followed by the same letter are not statistically different *(P*<0.05*)*

[c]At this site, the V4 treatment was not applied because the crop row spacing was not compatible with the side-dressing toolbar

[d]At these sites, the V4 treatment was surface-applied rather than injected

3.4.3 Comparison of enhanced efficiency fertilizers applied mid-season

Late season (V8) application of N fertilizer is limited to surface application. Therefore, urea or UAN applied at this stage is susceptible to volatilization losses, and using a urease inhibitor could increase the fertilizer's effectiveness. To address this, our study had four treatments that included UAN applied at a high and low rate of N fertilizer, with or without the addition of Agrotain™. Within this section of the study there was no effect of fertilizer rate or source. The average yields across all four treatments were nearly identical across and within N rates; there was no yield advantage to adding a urease inhibitor such as Agrotain™ when mid-season UAN was surface applied. The only statistical significant effect was site-year, because the mean yield of some site-years was significantly different from others (Table 3.4). However, as mentioned before, there was very little yield response to fertilizer rates above 90 kg ha^{-1} of applied N in the N rate portion of our study. Therefore, adding Agrotain™ to the UAN was not likely to increase yields because the untreated UAN provided sufficient N to achieve near maximum yields.

Table 3.4 Effect of supplemental mid-season N application source and rate on grain corn yield at each site-year. All treatments also received 45 kg N ha^{-1} as SuperU™ broadcast at planting

Site-year	*Pr>f*	df	45 or 59 kg N ha^{-1} as UAN @V8[a]	45 or 59 kg N ha^{-1} as UAN with Agrotain™ @V8[a]	90 or 119 kg N ha^{-1} as UAN @V8[a]	90 or 119 kg N ha^{-1} as UAN with Agrotain™ @V8[a]	Mean[b]	
			Yield kg ha^{-1}					
CarmanWest18	0.7887	3	8752	9218	8959	9202	9033	ABC
Elgin18	0.0418	3	7043	6991	7851	6319	7051	DEF
Graysville18	0.3937	3	8188	7879	8564	8708	8335	BCD
MacGregor18	0.9787	3	8986	9137	9009	9187	9080	ABC
Portage18	0.5014	3	7648	7185	7812	7949	7649	CDE
Rosebank18	0.8706	3	9007	9016	9009	9375	9102	ABC
Stephenfield18	0.8311	3	5804	5943	6198	5742	5922	EF
Wellwood18	0.0263	3	4690	5273	5834	6214	5502	FG
Winkler18	0.3605	3	9084	9465	9503	10126	9545	AB
CarmanNorth19	0.0004	3	6274	6252	7957	7827	7078	DEF
CarmanSouth19	0.6996	3	9381	9896	9852	9486	9654	AB
Clearwater19	0.3086	3	10400	10437	9569	9951	10089	AB
Elgin19	0.4401	3	6997	7204	6436	6587	6806	DEF
Graysville19	0.6773	3	8334	8603	8879	8311	8532	ABCD
Morris19	0.4131	3	7647	7166	6782	7391	7246	CDEF
Rosebank19	0.1451	3	10731	9713	9861	10566	10218	A
StClaude19	0.0489	3	3880	3200	3634	4661	3844	G
Mean			7815	7799	7983	8094		

Global ANOVA	df	*Pr>F*
Trt	3	0.0701
Siteyr	16	<.0001
Siteyr*Trt	48	0.0660
C.V.		25%

[a]In 2018 the N rate at V8 was 59 or 119 kg ha^{-1}, in 2019 the N rate was 45 or 90 kg ha^{-1}

[b]Means within the same column that are followed by the same letter are not statistically different *($P<0.05$)*

3.5 Conclusions

Under the field conditions for this study, there were few differences in corn yield for various N source and timing treatments. Overall, when comparing within the same total rate of N applied, yields from applications of EEFs were equal to those from applications of conventional urea N at planting; and yields from split applications of N fertilizers were equal to or less than N applied at planting. The EEF study had indirect comparisons suggesting that SUPERU™ might have been slightly superior to urea. At several sites where early spring reserves of residual nitrate-N were very low, applying all N at planting or split-applying some N at planting and some at V4 was superior to split applications where the in-season application was delayed until V8. These situations were at risk of shorting the crop of N during vegetative stages when delaying N application. Similar to the results for EEFs applied at planting, the comparison of surface applications of UAN at V8 with and without urease inhibitor showed similar treatment means for similar N application rates.

There was no consistent agronomic benefit from using EEFs or split application timings when compared to spring-applied conventional fertilizer. The small and infrequent effects of N application sources and timings aligns with most of the cited research that had been conducted on corn and other crops in Canada and the mid-west United States. However, the conditions for our studies were not wet enough to encourage in-season N losses by leaching and denitrification and the N rates used for the source and timing treatments were near the optimum rates for yield, making differences in N efficiency very difficult to detect. Also, this research did not evaluate the potential logistical and environmental benefits of EEFs or split N applications.

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4. OVERALL SYNTHESIS

This thesis addresses the 4Rs for N fertilization of modern, short-season corn hybrids in Manitoba - applying N fertilizer at the right rate, right source, right place, and right time. The first objective of the research project was to determine the N fertilizer rate for maximum return to nitrogen (MRTN) and overall N required per unit of grain production at the optimum economic rate of N. The second focus from this research was to evaluate enhanced efficiency fertilizers (EEFs) and alternative combinations of fertilizer application timings and placement. Together, the results will help Manitoba farmers and agronomists to identify fertilizer management strategies that will lead to optimum economic returns to N fertilizer.

For corn production in Manitoba the main focus should remain on determining the MRTN rate; the analysis in chapter two revealed how the MRTN rate varied among site-years and among methods of determining the MRTN. The research presented in Chapter 3 demonstrates that corn growers who experience conditions similar to those in this study, where dry weather resulted in low risk of N losses, do not need to utilize EEF sources or in-season N applications to achieve maximum potential yields. Although not directly evaluated in this research, fertilizer best management practices for timing and placement are probably still important; such as spring over fall application, and subsurface placement. Overall, the conclusions from this research are similar to other studies in North America; however, it was important to repeat those studies in Manitoba.

4.1 Weather impact on the study

Overall, Manitoba has one of the shortest and driest growing season climates for corn production in North America. It is also important to recognize, especially in dryland field crop production, that every site-year has a unique set of weather conditions and soil characteristics leading to results that will not be repeated. However, further research could isolate which weather parameters at specific crop growth stages have the greatest effect on yield potential and response to N rate, source, placement, and timing.

The site-years in this experiment experienced a variety of weather conditions which affected the maximum yield and the response to N fertilization. In 2018 we experienced a hot and dry summer with precipitation occurring on the shoulders of the growing season. The Carman region received less than 28 mm of rain in July but 93.5 mm in June and 48.1 mm in September. The accumulated growing season corn heat units (CHU) were between 96 and 103% of the local 30 year average at each site-year. Precipitation was between 78 and 120% of normal at site-years. However, the area that received only 78% of normal precipitation was in the Red River Valley region where grain corn production and the sites were primarily located. Growing seasons in the Red River Valley region when moisture is not limiting can produce yields greater than what we observed. Increased growing season precipitation would lead to increased potential for N losses from the rooting zone as leaching and denitrification, while also increasing the crop N uptake due to increased yield potential. Nitrogen mineralization would also be expected to increase with additional May-August rainfall. Expected observations from additional rainfall are dependent upon soil type as sandy soils are more prone to leaching while clay soils would be more likely to experience denitrification.

In 2019 the accumulated heat units at every site were less than the long term normal, with Clearwater19 experiencing 74% of normal and the other 7 sites at 94% to 97%. The most common hybrid in the study was DK 33078RIB which is rated at 2450 CHU and every site-year received over 2600 CHU between May 1 and October 31. With fewer heat units than normal in 2019 the expected impact is that our yield potential was less than normal. Lower yield potential may have reduced the crop's N demand, meaning that in a year of high yields the MRTN rates could be greater than reported here. In the 2019 growing season precipitation at all sites was 106% to 128% of normal with September and June being the months with greatest rainfall. Yield benefits from EEF or in-season N application treatments are more likely to occur in growing seasons with above average May-July rainfall causing N loss from the soil before N is utilized up by the crop. Therefore, the conclusions from this research may not be the same as in growing seasons with above-average rainfall in May-July; those situations may show benefits of EEF and split N applications that were not realized in our study.

One concern with growing corn in Manitoba is that an early fall frost before physiological maturity can have a large negative impact on yield, but our sites did not have frost until they were at or near physiological maturity. The greatest weather impact was rain and snow storms in the late fall which resulted in a reduced field access and the number of working days for harvesting and post-harvest soil sampling.

Overall, the growing conditions experienced at these site-years were within the expected climate for Manitoba; the greatest standout is accumulated precipitation in September, which is not as detrimental for corn as it would be for other cereal crops.

4.2 Observations

Observations from the study indicated that cultural practices such as seed bed preparation and planting are very important to have high yield potential; poor seed placement and uneven emergence can reduce maximum yield before N supply becomes a factor. A potential benefit to the in-season applications are that a farmer can evaluate the plant stand before applying the full N rate. Depending on the site-year there are different factors determine maximum yield. Therefore, the N requirement and likelihood of observing an N deficiency is different for each site-year.

In our study, there was a lack of consistency across the site-years when comparing tests that are designed to evaluate the corn crop's N status during or after the growing season. We were not able to identify a test that consistently distinguished between N deficiency and sufficiency at maturity; however, the stalk nitrate and soil nitrate tests could identify when a large excess of N was present. Post-harvest soil nitrate tests revealed that each site-year had different absolute minimum residual soil nitrate concentrations after the crop matured. Meanwhile, the pre-side dress nitrate test was able to detect when there was sufficient supply of N in the soil to achieve equivalent yields to the maximum N application rate; and that was at ≥20 mg kg^{-1} nitrate-N.

4.3 Future

There are two areas arising from this project that could be expanded. The first is to compile all data from recent corn N trials in Manitoba to further strengthen and improve recommendations. A meta-analysis could provide more information about factors affecting corn response to N fertilizer and provide more information to determine the optimum rate of N application at each site-year.

Second, there is plenty of opportunity to explore data that was collected but not presented in this thesis. We collected extensive data to be used towards characterizing and estimating the release of plant available N from soil organic N. Mineralization is credited for producing high yields that required little fertilizer N and being able to predict mineralization would result in substantial economic and environmental gains. Site-year soil and weather data could also be used to determine what parameters are the most important contributors to yield, and what is limiting the maximum yield at some years. Canopy reflectance data was collected with multiple instruments at multiple timings from each site-year to be utilized for calibrating sensors to differentiate between N deficiency and N sufficiency of vegetative corn in Manitoba. Nitrogen concentration in the grain has also been collected to calculate N use efficiency across treatments and site-years to determine if hybrids are more efficient users of N when lower N rates are applied, and to investigate the observation that site-years with a lower maximum yield also produced less corn kg^{-1} N.

4.4 Recommendations

My recommendations from this research are that corn growers in Manitoba presently do not need to adopt new fertilizer application strategies to achieve maximum potential yields with modern, short-season hybrids. This research was conducted on soils with a wide range in texture, including clay and very sandy soils. However, we did not experience above-average precipitation which would create conditions more suitable for N loss and for the benefits of EEFs and split-applications to be realized.

Another limitation of this study was that the rate increments were 45 kg N ha^{-1}, which is relatively coarse for detecting subtle differences in the performance of fertilizer management practices. Therefore I cannot conclude if N application rates could be slightly reduced when using EEF or in-season N applications and still achieve maximum yield.

5. Appendices

Appendix 1 Geographic location and soil texture for research sites

Site-year	Latitude	Longitude	Textural class	% silt	% clay
			0-15 cm		
CarmanNorth19	49.548043	-98.018946	Sand	4	6
CarmanSouth19	49.486331	-98.076623	Sandy Loam	7	12
CarmanWest18	49.516362	-98.059604	Sandy Loam	11	11
Clearwater19	49.071927	-99.043731	Loam	29	24
Elgin18	49.502254	-100.199636	Clay Loam	41	27
Elgin19	49.518464	-100.226046	Clay Loam	41	28
Graysville18	49.47971	-98.112385	Sandy Loam	16	17
Graysville19	49.446486	-98.138439	Sandy Clay Loam	11	22
MacGregor18	50.01298	-98.745334	Fine Sand	3	4
Morris19	49.384025	-97.564765	Clay	23	72
Portage18	49.949494	-98.200054	Silty Clay	48	51
Rosebank18	49.335728	-98.111329	Sandy Loam	10	18
Rosebank19	49.34478	-98.091102	Sandy Clay Loam	14	21
StClaude19	49.576123	-98.440686	Fine Sand	4	5
Stephenfield18	49.499393	-98.229081	Fine Sand	1	5
Wellwood18	50.048441	-99.353196	Clay Loam	35	32
Winkler18	49.147625	-97.866052	Sandy Loam	11	17

Appendix 2 Quadratic response equations, maximum yield, and MRTN rates for each individual site-year and for grouped yield responses

Site-year	Second order polynomial response equations[a]	R^2 value	Maximum yield (vertex)	N supply at maximum yield	Yield at MRTN medium ratio	N supply at MRTN medium N price	N supply at MRTN low N price	N supply at MRTN high N price
			kg ha^{-1}					
CarmanNorth19	$y = -0.098483x^2 + 53.1046x + 2267.69$	0.9897	9427	270	9350	242	248	235
CarmanSouth19	$y = -0.020943x^2 + 11.3353x + 8385.25$	0.6757	9919	271	9558	139	168	110
CarmanWest18	$y = -0.078104x^2 + 39.8635x + 4284.72$	0.9786	9371	255	9274	220	228	212
Clearwater19	$y = -0.018289x^2 + 13.4210x + 7716.62$	0.6409	10179	367	9765	217	250	183
Elgin18	$y = -0.009603x^2 + 5.2418x + 6775.86$	0.2055	7491	273	6704	-13	50	-77
Elgin19	$y = -0.097795x^2 + 41.5181x + 3000.65$	0.9246	7407	212	7330	184	190	178
Graysville18	$y = -0.061684x^2 + 28.1397x + 5061.47$	0.4993	8271	228	8148	184	193	174
Graysville19	$y = -0.089647x^2 + 34.8793x + 5376.35$	0.8789	8769	195	8685	164	171	157
MacGregor18	$y = -0.223430x^2 + 95.1075x + 394.56$	0.9536	10516	213	10482	201	203	198
Morris19	$y = -0.095282x^2 + 49.0664x + 1672.09$	0.7468	7989	257	7910	229	235	222
Portage18	$y = -0.069920x^2 + 34.6737x + 3641.40$	0.7419	7940	248	7832	209	217	200
Rosebank18	$y = -0.077451x^2 + 40.4765x + 3547.29$	0.7435	8836	261	8738	226	234	218
Rosebank19	$y = -0.026754x^2 + 19.7268x + 6362.00$	0.9899	9998	369	9716	266	289	243
StClaude19	$y = -0.106119x^2 + 48.8527x - 258.03$	0.9858	5364	230	5293	204	210	199
Stephenfield18	$y = -0.224717x^2 + 91.9463x - 1730.23$	0.9924	7675	205	7641	192	195	190
Wellwood18	$y = -0.087839x^2 + 35.6136x + 1911.78$	0.5782	5522	203	5435	171	178	164
Winkler18	$y = -0.190908x^2 + 75.9064x + 2743.58$	0.9626	10289	199	10249	184	188	181
Grouped sites with yield potential <8150 kg ha^{-1}	$y = -0.065718x^2 + 41.1282x + 931.85$	0.6808	7367	313	7252	271	280	262
Grouped sites with yield potential >8150 kg ha^{-1}	$y = -0.060543x^2 + 34.5309x + 4481.37$	0.4850	9405	285	9280	240	250	230

[a] y is equal to the expected grain corn yield kg ha^{-1} adjusted to 15.5% moisture, and x is equal to N supply (soil plus applied) kg ha^{-1}