The Effects of Split Nitrogen Application and Weather on the Profitability and Environmental Performance of Ontario Corn Production

by

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ABSTRACT

THE EFFECTS OF SPLIT NITROGEN APPLICATION AND WEATHER ON THE PROFITABILITY AND ENVIRONMENTAL PERFORMANCE OF ONTARIO CORN PRODUCTION

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The use of nitrogen (N) fertilizer is a ubiquitous management practice in conventional corn production in developed countries. Splitting N application timing strongly influences N losses and yield response. While the environmental and yield performance of split N application has been studied, the profitability is unknown. This thesis investigated the agronomic, environmental, and economic performance of such practice compared with traditional methods under alternative weather scenarios in Elora, Ontario. The DeNritrification and DeComposition (DNDC) was used to predict yield and N losses, and the profitability was determined through an enterprise budget. The results show that split application is environmentally viable under all weather scenarios, agronomically and economically viable under alternative weather scenarios. Adjusting the N rate generates higher benefits than adopting a single rate split or pre-plant application. This thesis implies that management practice has significant impacts on corn production's agronomic, economic, and environmental performance under alternative weather conditions.

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LIST OF ABBREVIATIONS AND NOTATIONS

BMP- Best Management Practices

C- Carbon

DNDC- DeNitrification and DeComposition

EORN- Economically Optimum Nitrogen Rates

GHG- Green House Gas

K- Potassium

MAP- Monoammonium Phosphate

mm- Millimetre

N- Nitrogen

NH_3- Ammonia

NO_3^- - Nitrate

N_2O- Nitrous Oxide

NRE- Nitrogen Recovery Efficiency

NUE- Nitrogen Use Efficiency

OMAFRA- Ontario Ministry of Agriculture, Food and Rural Affairs

P- Phosphorus

R(N)- Silking Stage of N

S- Sulphur

UAN- Urea-Ammonia-Nitrate

U.S.- United States

V(N)- Vegetation Stage of N

CHAPTER 1

INTRODUCTION

1.1 Background

World food production will need to be increased by 70% by 2050 to meet the expansion of the world's population (FAO, 2009). The required increase in crop production will be associated with an increase in fertilizer use and, with it, the environmental concerns about climate change, air quality, water quality and soil health (FAO, 2002). Overall, greenhouse gas (GHG) emissions in Canada rose by 20.9% between 1990 and 2018, with the increases particularly evident for nitrous oxide (N_2O), which is primarily associated with fertilizer management choices on croplands (Environment and Climate Change Canada, 2020). Similarly, water quality has deteriorated in the Great Lakes region due largely to flooding, soil erosion, and excess nutrient loading from agricultural practices (Carpenter et al., 2017; Kelly et al., 2017).

Efforts to reduce the environmental impact of fertilizer use in crop production include promoting 4R nutrient stewardship. The 4Rs refer to (1) right source, (2) right rate, (3) right time, and (4) right placement of fertilizer application (Bruulsema, 2018). In addition to reducing total nutrient losses, 4R fertilizer management has the potential to increase agricultural yields and profitability and ensure a sustainable production system.

The use of nitrogen (N) fertilizer is a universal management practice in corn production in developed countries. The efficiency of N use varies from farm-to-farm, and region-to-region due to the 4R management practices farmers choose to implement. Splitting the application time, farmers apply fertilizer twice or more during the growing season rather than applying before or at planting with a single application. The frequency and timing of N application(s) is one management factor that strongly influences environmental N losses and yield responses to fertilizer N. When fertilizer N resides in the soil profile, particularly without inhibitor products, it remains vulnerable to weather and edaphic factors, which can result in rapid and substantial losses via leaching, denitrification or volatilization (Burzoca et. Al., 2013; Nasielski et al., 2020; Thapa et al., 2016). Based on 4R principles (Reetz et al., 2015), an ideal N application time synchronizes the application of N with the uptake needs of the crop, minimizing residence time in the soil. For example, applying the majority of fertilizer N split, during periods of rapid crop growth, would reduce N residence time (Sebilo et al., 2013).

Corn uptakes the maximum amount of N during the silking stage (Ciampitti et al., 2011) and while delaying N application to the critical period is uncommon, split applications earlier in crop development (V3-V6) (Abendroth et al., 2011), but after planting, are common in eastern Canada (GFO 2020). In corn, several studies have found that the risk of weather-induced N losses decreases the closer N is applied to periods of rapid crop N uptake, as opposed to in the fall or early spring prior to planting. However, some studies found no significant impacts of N application timing on environmental or agronomic parameters in corn, a result of fewer N losses due to soil type, weather or other factors for a given site-year (Fernandez et al., 2020; Nasielski et al., 2020; Vyn et al., 2017; Blandino et al., 2015; Jaynes, 2013; An et al., 2020).

The benefit of split N application is that the N rate can be adjusted according to weather scenarios, which affect crop N uptake and soil N supply. The adjustment of N rate in split application allows farmers to tailor the N rate based on soil, crop, and weather variables in a given site-year. N rate adjustments, facilitated by N application timings that occur split, can reduce deleterious overapplications of N, which reduce the profitability and increase the environmental impact of N fertilizer use. Split N rates can be increased if N mineralization rates are low, if earlier N losses were high, or if yield potential of a crop is larger than expected.

Due to the availability of high-clearance equipment, farmers and researchers are interested in split applications. While there are several motivating factors, such as reduced labour requirements during the busy planting season, a major attraction of late N applications is the potential to increase net returns to fertilizer use by enhancing N-use efficiency, primarily via improvements in N recovery efficiency (e.g. reduced N losses, enhanced N uptake) and possibly by increasing N internal efficiency (e.g. by improving the harvest index).

1.2 Economic Problem

4R fertilizer BMPs have the potential to enhance environmental sustainability and economic feasibility. Therefore, farmers are interested in quantifying their agronomic, economic, and environmental benefits. Several studies investigated the effects of 4R practices, in combination or individually, on agronomic and environmental parameters; however, the research on the economic feasibility of adopting of 4Rs is limited (Successful Farming, 2020; Lesoing, 2014).

Although there are various ways to implement split N application, it can represent an interesting economic feasibility study as it potentially integrates one of the components of 4R management practices. It considers the N application’s time, the rate of application can be changed, the type of N used and the N placement method in the application can be different with split application. The benefit of adopting split application of N fertilizer is that rates can be adjusted to suit the demands of the crop instead of the traditional method of a single application at pre-planting. The improved matching of fertilizer supply to the crop demands should improve yields and/or reduce fertilizer use. However, the cost of fertilizer is a major variable cost for corn farmers, which encourages farmers to choose between management practices. Although farmers can adjust fertilizer cost by adjusting N rates in second application in response to weather, the cost of an application can be twice or more than pre-plant, depending on the time of the second application. The profitability of any management practice is a strong determinant of adoption, particularly for an innovation that can be easily tested (Weersink & Fulton, 2020). Thus, a profit evaluation of split N applications can potentially enhance farmers' decisions and potential initiatives taken by the government to induce adoption if there are environmental benefits compared to current practices. While a considerable amount of research has investigated the agronomic and environmental consequences of split N applications (Nasielski et al., 2020; Vyn et al., 2017; Blandino et al., 2015; Roy et al., 2014; Burzaco et al., 2013; Walsh et al., 2012), few studies have assessed the impact of N application timing on economic parameters (Successful Farming, 2020; Lesoing, 2014). However, the previous studies considered short-term field trials and weather data to evaluate the agronomic, economic and environmental impacts, which may inaccurately represent the underlying benefits of split N application. This thesis evaluates the profitability, along with yield and N losses in corn using long-term field trial and weather data at Elora, Ontario.

1.3 Research Problem

The research on the agronomic, environmental, and economic feasibility of split application of N in corn tends to be focused on one of the three aspects and typically for a single year at a single site. For example, in Indiana, Mueller et al. (2017) found that applying the last 45 kg N ha^{-1} at V12 increased nitrogen recovery efficiency (NRE) over the same N rate applied pre-plant, while, in Oklahoma, Walsh et al. (2012) found that NUE increased when N was split with 50% applied pre-plant and 50% applied at V10. Importantly, split-N applications never reduced yield relative to pre-plant applications in these studies. In Ontario, Nasielski and Deen (2019) found that delaying N applications to V13 could result in yield reductions due to reduced pollinated kernel numbers at R1 and reduced potential kernel weight at R2-R3. However, these N-stress related yield reductions could be avoided by providing a relatively small amount of N fertilizer around planting, although in one year, the entire N application could have been delayed to V13 without any reduction in yield (Nasielski & Deen 2019).

Similarly, DeBruin et al. (2018) in Illinois found that very severe N stress was required to irrevocably reduce kernel number prior to R1, suggesting that the majority of N fertilizer could be applied later than traditional timings, but prior to R1 with little risk of yield penalty. When N was delayed until R1, Mueller and Vyn (2018) in Indiana found that a V4 application of 55 kg N ha−1 prevented any yield reduction from the delayed application. Fernandez et al. (2020) conducted a meta-analysis of fourteen studies on late N applications, defined as when 50% or more of the N fertilizer was applied after V10. Overall, NRE increased by an average of 4% when N was applied at late N timings, a small but consistent increase over earlier N timings (Fernandez et al., 2020). Late N applications did not affect yield relative to the same N rate applied at an earlier time, although the impact of late N applications on yield depended on the environment. In environments where post-R1 N uptake was high, late N applications tended to increase yield, and in environments where post-silking N uptake was low, late N applications reduced yield (Fernandez et al., 2020). The authors suggest that because post-silking N uptake is related to soil water availability, corn response to late N applications will be poorer in drier environments, and better in wetter environments.

The University of Missouri Extension research team found that adopting split N application (delayed until V12-V16) in specific weather, e.g., wet spring, is profitable without yield penalty, based on the nitrogen deficiency level (Successful Farming, 2020). The team addresses the availability of machinery impedes split N application rather than biology of the crop (Successful Farming, 2020). Similarly, the University of Nebraska-Lincoln Extension also investigated the economic feasibility of split N application in a single year on-farm experiment (Lesoing, 2014). The study concluded that split N application might be profitable when the field has a high risk of N losses due to leaching and denitrification in the early season (Lesoing, 2014).

The mixed results on the impacts of split N application may be due to the limited number of weather conditions under which the studies were conducted. There may be economic and environmental benefits under specific weather scenarios from split N applications that were not experienced during the years of the short-term field trials in the previous studies. Using data from actual field trials limits the weather conditions that can be assessed. However, using a simulation model for a site allows for the evaluation of split N application to be conducted under multiple weather conditions. DNDC is a biogeochemical model that simulates crop growth, soil carbon, and nitrogen dynamics based on soil properties, climate, and farming practices (Li et al., 1992, 1994). This rain event-driven and process-orientated simulation model has already been calibrated and validated in corn production using field data from an 8-year N rate trial and actual weather data at the Elora Research Station in Elora, Ontario, Canada (Nasielski et al., 2020).

This thesis will investigate the yield, profitability, and environmental performance, e.g., nitrate (NO_3^-) leaching, nitrous oxide (N_2O) emissions and ammonia (NH_3) volatilization, of split N application by adjusting the N rate compared to traditional practice. The use of DNDC will permit the evaluation of the effect of adjusting N rates in corn production under alternative weather conditions.

1.4 Purpose

The purpose of this study is to jointly evaluate the agronomic, environmental, and economic performance of split N applications in corn relative to a traditional spring pre-plant N application timing under alternative weather scenarios. The specific objectives are:

1. To predict yield and N loss effects of different N management strategies across these weather scenarios using the DNDC model;
2. To evaluate the net returns using publicly available price data, including the additional costs associated with split N applications;
3. To evaluate the effect of adjusting N rates modestly in corn production under alternative weather conditions; and
4. To illustrate the trade-offs between profitability and environmental impacts of split application compared to the traditional approach of the pre-plant broadcast.

1.5 Outline

The thesis is organized into five chapters. Chapter 1 presents the background of split N application, the economic problem in adopting split N application, research gaps identified in previous studies, purpose, and an outline of the thesis. Chapter 2 provides an overview of 4R best management practices. This chapter briefly discusses the history of 4R, 4R N management practices (including each R), and the present scenario of 4R practices in Ontario, Canada. Chapter 3 determines the optimal N application rate associated with alternative scenarios in single and split N applications. Chapter 4 includes a paper on the evaluation of economic and environmental impacts from split N application and weather in Ontario corn production. This chapter introduces the materials and methods used in the thesis and presents the main results from the simulations. Chapter 5 concludes the thesis, including a summary, implications, and suggestions for further research.

CHAPTER 2

OVERVIEW OF 4R BEST MANAGEMENT PRACTICES (BMPs)

2.1 Introduction

The 4R nutrient stewardship framework was developed to sustainably maximize the economic, social, and environmental performance of fertilizer. The framework provides a system to achieve four goals: a) increased production, b) increased farmer profitability, c) enhanced environmental protection, and d) improved sustainability. To achieve these goals, farmers need the right fertilizer source at the right rate at the right time in the right place, which are the principles of 4R.

In this chapter, an overview of 4R best management practices for N fertilizer application on corn will be described. The chapter begins with a brief history of the development of 4R management. The next section describes each of the 4Rs (2.3.1 right source, 2.3.2 right rate, 2.3.3 right time, and 2.3.4 right placement) for the application of nitrogen to corn, including defining the management practices to be calculated in the subsequent chapters. Later, the chapter focuses on the 4Rs in a Canadian context and the profitability of adopting the 4Rs.

2.2 History of 4R Nutrient Management

Fertilizer Best Management Practices (BMPs) were first introduced by the Potash & Phosphate Institute (PPI) in 1988 (Roberts, 2007) to address the environmental impacts of agriculture, with nutrient efficiency as its core (Krauss et al., 2007; Chien et al., 2009). The nutrient management practices, including fertilizer BMPs, have proven effective and give ‘optimum production potential, input efficiency, and environmental protection’ (Roberts, 2007).

The principles of 4R, referred to as a fertilizer BMPs, are the Right source of fertilizer at the Right rate, at the Right time and the Right place (Roberts, 2007). The global '4R' nutrient stewardship framework was developed by the International Fertilizer Industry Association (IFA), aiming to develop fertilizer BMPs for economic, social, and environmental benefits (Roberts, 2007). The 4Rs integrate nutrient use BMPs with agronomic BMPs, thus increasing nutrient efficiency at the farm level, allowing the achievement of economic, social, and environmental goals for sustainable development (Roberts, 2007).

Fertilizer BMPs are site-specific and crop-specific, depend on soils, climatic conditions, crop and cropping history, and management expertise. Though fertilizer BMPs increase nutrient use efficiency, the primary goal is to use fertilizers efficiently and effectively in providing adequate nutrition for crops for achieving a sustainable and profitable yield.

2.3 4R Nitrogen Management Practices

2.3.1 Right Source

The 'Right source' of fertilizer means ensuring a balanced supply of essential nutrients according to crop needs. The key nutrients included in all the fertilizers are a) potassium (K), b) nitrogen (N), c) phosphorus (P), and d) sulphur (S). A balance between nutrients using the right types of fertilizer increases nutrient use efficiency. In corn production, N plays a significant role in plant growth and yield, depending on soil, crop, and climate conditions. The widely used N fertilizers in corn are anhydrous ammonia, urea, and urea ammonia nitrate (UAN), due to their lower prices, relative to other N sources like ammonium nitrate (Heffer and Prud'homme, 2016).

Urea contained fertilizers increases N losses due to volatilization (Jessica et al., 2016; Liu et al., 2019) if it is not injected (Beegle et al., 2003). Comparing urea and UAN in the pre-plant and split application, Abalos et al. (2016) found no significant impacts in reducing N_2O and increasing corn yield in the US and Canada. Applying UAN in split N application maximizes corn yield (Burzaco et al., 2013). On the contrary, applying ammonium nitrate in the late N application penalized 12% of corn yield (Binder et al., 2000).

2.3.2 Right Rate

The ‘Right rate’ of fertilizer is the threshold requirement of nutrients in the crop. Farmers decide the N rate depending on soil nutrient supply, plant demand, and environmental parameters. An excessive amount of fertilizer causes higher leaching and N losses to the environment, and an insufficient amount of fertilizer results in lower yield (Robert, 2007). The right rate depends on the soil, crop, and environmental parameters, specifically precipitation and temperature. A soil test is the means of assessing soil fertilizer availability to inform application rates.

Applying N fertilizer below the crop N demand results in a yield penalty, whereas applying excess N fertilizer increases the intensity of N losses (Zebarth & Rosen, 2007). An increase in N rate from the optimum level rapidly increases water and air pollution through NO_3^- leaching and N_2O emissions (Van Es et al., 2002; Houles et al., 2004; Chantigny et al., 1998; Zebarth et al., 2008). Applying the economically optimum N rate (EORN), farmers can achieve both economic and environmental goals (Houles et al., 2004), but the rate is site-year specific, for example, in corn production (Scharf et al., 2005; Tremblay et al., 2007).

2.3.3 Right Time

The fertilizer application timing is significant for yields, reduction of nutrient losses and environmental damage, and increasing the efficient use of nutrients. The right timing is site-specific, based on the dynamics of crop uptake, local environmental conditions, and farm management practices. Crops need different nutrients at different stages of growth. Nutrient availability timing is influenced by application timing (e.g., pre-plant or split), controlled released technologies, stabilizers and inhibitors, and the right source of fertilizer (Robert, 2007).

The split application of fertilizer involves applying different rates at different times during the growing season, and the change in application time often requires different types of fertilizer placed at different spots for the crop. Thus, split N application potentially covers more than one component of 4R stewardship. The underlying premise of splitting the application of fertilizer, typically nitrogen, is that rates can be adjusted to suit the crop demands as opposed to the traditional method of a single application around planting. The needs of a crop for N will vary each year depending on temperature and precipitation; split application allows this rate to vary with the weather conditions for that year.

Roy et al. (2014) found that side-dress at the V8 stage significantly reduced N_2O emission without yield penalties in corn, applying UAN injected at the recommended rate (145 kg N ha^{-1}) during wet spring in Ontario. Split N application of 180 kg N ha^{-1} of UAN at V6 for corn maximized yield (Burzaco et al., 2013). When the precipitation was high, split application increased corn yield (Walsh et al., 2012). In contrast, several studies reported a corn yield penalty (Binder et al., 2000), or no significant impacts (Nasielski et al., 2020; Vyn et al., 2017; Blandino et al., 2015).

2.3.4 Right Placement

The ‘Right placement’ of nutrients means applying the fertilizer in a place where crops can uptake the required nutrients most effectively. Right placement manages spatial variability within the field to meet site-specific crop needs and limits potential losses from the field. The appropriate place for fertilizer application depends on crop types, management practices, and soil properties (Robert, 2007). There are two general methods to apply fertilizer- i) over the soil surface, referred to as broadcasting, and ii) deep into the soil and close to the seed, referred to as banding or injection.

Abalos et al. (2016) concluded that side-dress N application increased corn productivity compared to traditional pre-plant application. Applying urea as a side-dress reduced N_2O emission by 33% compared to pre-plant under conventional tillage in corn (Drury et al., 2012). However, Omonode et al. (2017) reported no influence of N placement on N_2O and NRE. Also, deep placement of N significantly reduced NH_3 volatilization and denitrification N losses in urea (Chien et al., 2009).

2.4. 4R Practice in Ontario, Canada

Canada has voluntarily adopted 4R nutrient stewardship through provincial and regional programs and initiatives. The Provincial governments of Alberta, Manitoba, Ontario, New Brunswick, and Prince Edward Island are practicing 4R Nutrient Stewardship (Fertilizer Canada, 2019). By 2020, 20 million acres, or 25% of Canadian croplands, should be implementing 4R nutrient stewardship programs (Fertilizer Canada, 2018). The Ontario agricultural industry recognized the problem of nutrient runoff in the Great Lakes region and embraced 4R nutrient stewardship to ensure sustainable agriculture and environment (Nutrient Stewardship).

In 2015, Fertilizer Canada, the Government of Ontario’s Ministry of Food Agriculture and Rural Affairs (OMAFRA), and the Ontario Agri-Business Association signed a Memorandum of Cooperation (MOC) to implement, maintain and evaluate the 4R Nutrient Stewardship programme across the province (Fertilizer Canada, 2019). Ontario has been preliminarily focused on Phosphorus use, which leads to the uncontrolled growth of bacteria called algae blooms in the great lakes (Environment and Climate Change Canada, 2017).

Roughly 67% of farmers in Ontario are voluntarily practicing some form of 4R nutrient stewardship (Fertilizer Canada, 2019). The combination of the 4Rs in Ontario corn production can reduce GHG emissions and water contamination, improve environmental sustainability and increase profitability (Fertilizer Canada, 2018). According to scientific findings, adopting the 4Rs in Ontario corn production can- i) decrease GHG emissions by 75% by applying UAN at the V8 stage of corn growth (right source and time); ii) decrease GHG emission between 40% and 60% under different weather conditions by applying urea or UAN (right source); iii) reduce ammonia losses and increase yield by 7% using injection (right placement); iv) increase yield by 20% in UAN injected compare to broadcast (right source and placement); and v) reduce P losses by 60% through surface banding (right placement) (Fertilizer Canada, 2018).

2.5. The profitability of the 4Rs

Although 4R BMPs integrate environmental sustainability and cropping system management goals, it is ultimately the profitability of such practices that will encourage farmers to change their current management practices on-farm voluntarily. Rather than achieving higher yield, it is also essential to determine how farmers can best invest in fertilizer BMPs to maximize agronomic, economic, and environmental benefits. Several studies investigated the effects of the 4Rs (individual or combined) on the agronomic and environmental parameters discussed above; however, the research on the economic feasibility of adopting the 4Rs is limited.

Particularly, an economic analysis on split N application is a striking focus in 4R management practice. The underlying premise of split application of fertilizer, typically nitrogen, is that rates can be adjusted to suit the crop demands as opposed to the traditional method of a single application around planting. The improved matching of fertilizer supply to the crop demands should improve yields and/or reduce fertilizer use. Thus, there is a potential reduction in the cost of fertilizer, a major variable cost that influences farmers' profitability. While a considerable amount of research has investigated the agronomic and environmental consequences of split N applications mentioned above, few studies have assessed the impact of N application timing on the economic parameters of N fertilizer application. However, the previous studies that do exist considered short-term field trial and weather data to evaluate the agronomic, economic and environmental impacts, which may not fully capture the underlying costs and benefits of split N application, like longer, more diverse trials, or simulation modelling.

2.5 Conclusion

4R nutrient stewardship is a science-based management framework to ensure adequate nutrients for crops while reducing the environmental impacts of fertilizer use. The 4Rs have the potential to generate higher yield, improve fertilizer use efficiency, and soil management decisions. Additionally, the 4Rs improve environmental sustainability by reducing water and air pollution. The agronomic and environmental performance of the 4Rs has been investigated in several studies. However, the economic performance of the 4Rs needs to be explored more for recommending specific BMPs to farmers. Split N application is a BMP in fertilizer that provides potential agronomic and environmental benefits. The next chapter will determine the optimal profit maximizing N application rate in single and split N applications.

CHAPTER 3

THEORETICAL MODEL

3.1. Introduction

The previous chapter reviewed each of the 4R fertilizer management systems. The focus of this thesis is on the timing of fertilizer application, although the other three are considered. This chapter will determine the optimal N application rate associated with alternative scenarios. It begins with deriving the conditions for the optimal rate to maximize profit, assuming full information and certainty at a single N rate. Later, this chapter introduces the optimal split N application rate assuming full information and certainty.

3.2. Optimal Single Application Rate with Certainty

Determining the optimal fertilizer rate to maximize profit begins with the yield response function for the crop to nitrogen fertilizer-

$$Y = F(N) \tag{1}$$

where Y is the yield in kg per hectare, N is the rate of nitrogen applied in kg per hectare, and $F(N)$ is the product function relating N to crop yield. The profit function for a farmer facing competitive input and output prices is

$$\pi = P_Y Y - P_N N \tag{2}$$

where π is the profit from crop production in dollars per hectare, P_Y is the crop price in dollars per kg, and P_N is the price of N per kg. The profit function can be expressed as a function of only the N rate by inserting the production function for crop yield (1) into (2).

$$\pi = P_Y F(N) - P_N N \tag{3}$$

At this stage, it is assumed all other inputs are fixed, and prices are known.

The N rate that maximizes profits is found by taking the first derivative of the profit function (3) with respect to N, setting it equal to zero, and solving N

$$\frac{\partial \pi}{\partial N} = P_Y \frac{\partial F(N)}{\partial N} - P_N = 0 \tag{4}$$

The profit maximizing condition given by (4) states that the incremental change in the crop value from applying an extra unit of N is equal to the cost of that extra unit of N (P_N). The marginal value product of N is the change in crop yield from applying the extra fertilizer or the marginal product ($\frac{\partial F(N)}{\partial N}$) multiplied by the crop price (P_Y).

An example of the derivation of the profit maximizing fertilizer rate can be illustrated by using a specific functional form for the crop yield response function (1). A quadratic is a commonly used functional form to capture the relationship between N use and corn yield. It implies that as the N rate increases, the yield response will increase until it reaches its maximum, then starts decreasing along with an increase in N rate (Mortensen & Beattie, 2005). The quadratic yield function is given by

$$Y = \alpha_0 + \alpha_1 N - \alpha_2 N^2 \tag{5}$$

The associated profit function with the assumption of a quadratic yield response function is

$$\pi = P_Y(\alpha_0 + \alpha_1 N - \alpha_2 N^2) - P_N N \tag{6}$$

Taking the first-order condition for N (as given by equation (4)) and then solving explicitly for N results in the profit maximizing N rate (N^*)

$$\frac{\partial \pi}{\partial N} = P_Y \alpha_1 - 2P_Y \alpha_2 N - P_N = 0$$

$$P_Y \alpha_1 - 2P_Y \alpha_2 N = P_N$$

$$\alpha_1 - 2\alpha_2 N = \frac{P_N}{P_Y}$$

$$2\alpha_2 N = \alpha_1 - \frac{P_N}{P_Y}$$

$$N^* = \frac{1}{2\alpha_2}(\alpha_1 - \frac{P_N}{P_Y}) \tag{7}$$

The optimal rate of N application that maximizes profit (N^*) is inversely related to the price of N (P_N), and positively associated with the corn price (P_Y) and the marginal product of N or the change in corn yield resulting from N ($\frac{\partial F(N)}{\partial N}$ = $(\alpha_1 - 2\alpha_2 N)$).

To illustrate the concept graphically, let us assume that price of corn (P_Y) is \$2 kg^{-1}, the price of N (P_N) is \$1.14 kg^{-1}, the fixed cost is \$850 ha^{-1}, the value of coefficients α_o, α_1 and α_2 are 900, 10 and 0.03 respectively resulting in the following yield response function for (5)

$$Y = 900 + 10N - 0.03N^2 \tag{5'}$$

The associated profit function (6) with the quadratic yield response function is

$$\pi = 2(900 + 10N - 0.03N^2) - 1.14N - 850 \tag{6'}$$

The profit-maximizing rate for this example is found by subbing in the parameters to (7)

$$N^* = \frac{1}{2*(.03)}\left(10 - \frac{1.14}{2}\right) = 157 \tag{7'}$$

The yield at the profit-maximizing rate is 1,731 kg ha^{-1} and is found by substituting N^*=157 into (5'). Similarly, the maximum potential profit for this example is \$2,432 ha^{-1}, calculated by substituting N=157 ha^{-1} into (6').

The marginal product of N or the change in corn yield resulting from N at the profit-maximizing N rate is

$$MP = \frac{\partial F(N)}{\partial N} = 10 - 2 * (0.03) * 157 = 0.58$$

The marginal product implies that if the farmer applies an extra unit of N, the yield will increase by 0.58 kg ha^{-1}, holding other factors constant. The rate that maximizes yield is where the marginal product is zero;

$$MP = 10 – 2*(0.03)*N = 0 \tag{8}$$

$$N^{Yield\ Max} = 10 / 2*(0.03) = 167 \tag{9}$$

Applying N at a rate of 167 ha^{-1} results in yield being maximized at 1,733 kg ha^{-1}. $N^{Yiel\ Max}$ is greater than N^* as expected since the objective of maximizing yield does not consider costs.

The quadratic curve in Figure 3.1 shows how a change in the N rate affects the total production. Yield increases with N rate until it reaches its maximum of 1,733 kg ha^{-1} at a N fertilizer rate of 167 kg N ha^{-1}. After achieving maximum yield, applying N above 167 kg N ha^{-1} decreases the yield. The yield function is concave and quadratic. Figure 3.1 shows that the profit maximizing yield (1,731 kg ha^{-1}) and N rate (157 kg N ha^{-1}) are lower than the maximum yield and yield maximizing N rate.

Figure 3.2 shows the total revenue, total cost, and profit associated with the profit maximizing optimal N rate. Total revenue (TR) is the value of output produced

$$TR = P_Y * Y = P_Y * F(N) \tag{10}$$

$$TR = 2 * (900 + 10N - 0.03N^2) \tag{10’}$$

The total revenue curve has the same shape as the yield response function. Total cost (TC) is a linear function of the N rate

$$TC = P_N * N - Fixed\ Cost \tag{11}$$

$$TC = 1.41 * N - 850 \tag{11’}$$

The difference between total revenue and the total cost is the payoff to applying N and is given by equation (6’) and illustrated in Figure 3.3 for different N rates. The profit increases with an increase in N rate until the maximum profit is achieved at the optimal N rate (157 kg N ha^{-1}). When the N rate increases more than the optimal rate, profit starts decreasing. As noted above, profits are lower for the yield maximizing N rate than at N^*.

An increase in the price of corn increases the value of output generated by N and the application rate. In the empirical example, the effect of an increase in P_Y can be found by taking the derivative of the equation for the optimal N^* (7) with respect to P_Y

$$\frac{\partial N*}{\partial P_Y} = \frac{P_N}{2\alpha_2}(P_Y)^{-2} \tag{12}$$

$$\frac{\partial N*}{\partial P_Y} = \frac{1.14}{0.06}(P_Y)^{-2} \tag{12'}$$

For example, if the price of corn doubles from \$2 to \$4, the profit maximizing application rate changes to 162 from 157 kg N ha^{-1}. The profit-maximizing N for alternative corn prices, assuming $P_N = 1.14$ is illustrated in Figure 3.4.

The demand for N can be determined by inserting the parameters into (7),

$$N^* = \frac{1}{2*(0.03)}\left(10 - \frac{P_N}{2}\right) = 1.67 - \frac{P_N}{2} \tag{13}$$

The demand curve for N is also illustrated in Figure 3.4. An increase in N price from 1.1.4 to 1.50 decreases N* from 157 to 154 kg N ha^{-1}. If P_N increases to \$20, then the demand for N falls to 0. Alternatively, if P_N falls to \$0, N is at the yield maximizing rate of 167. Figure 3.4 also shows how increasing the corn price to \$4 shifts the demand for N outwards.

3.3. Optimal Split Application Rate Under Certainty

Now farmers consider split N application in production. They know the initial N stock in soil, denoted by N_I and make fertilizer application decisions accordingly before crop planting, denoted by N_P. Farmers observe the N runoff or leaching from soil and decide whether to apply N in late spring (plant-growing period), denoted by N_{Split}. There is a threshold level of soil moisture. If soil moisture in late spring is less than the threshold level, then split application will be applied. Otherwise, it would be technically infeasible. The yield response function is

$$Y_{Split} = G(\gamma(N_I + N_P) + N_S) \tag{14}$$

where Y_{Split} is the yield response in kg per hectare in split application, N_S is the N applied in kg per hectare in split application, and γ is the proportion of N applied at pre-planting that is remaining at split time ($0 < \gamma < 1$). The yield response function is assumed to be continuous. The first derivative is assumed to be non-negative and the second to be non-positive. These assumptions imply that the marginal product is non-negative and non-increasing and encompasses diminishing marginal returns and a plateau with no returns from additional N. The profit function is

$$\pi_{Split} = P_Y Y_{Split} - (P_P N_P + P N_S) \tag{15}$$

where π_{Split} is the profit in dollar per hectare in split application, P_P is the cost of N application in dollar per kg at pre-planting, and P_S is the cost of split N in dollar per kg. The costs of pre-planting and split applications include the costs of inputs, labour, and machinery. Substituting the yield function into (15), the profit function can be written as

$$\pi_{Split} = P_Y G(\gamma(N_I + N_P) + N_S) - P_P N_P - P_S N_S \tag{16}$$

Assuming no field constraint can influence decisions about the applied N rate at split time and full information about weather, soil and N availability, the marginal conditions for the N rates that maximize profit are

$$\frac{\partial \pi}{\partial N_P} = \gamma P_Y G'(.) - P_P \leq 0, \ \left[\frac{\partial \pi}{\partial N_P}\right] N_P = 0 \tag{17}$$

$$\frac{\partial \pi}{\partial N_S} = \gamma P_Y G'(.) - P_S \leq 0, \ \left[\frac{\partial \pi}{\partial N_S}\right] N_S = 0 \tag{18}$$

The first term in each condition is the marginal product from applying N by the particular method. The marginal product is different in each application because their efficiencies in supplying N to the plant are not the same. Split application is more efficient than the pre-plant application because some proportion (γ) of the pre-plant application is lost before split application.

As split application is more expensive, the application costs are different in both methods. These conditions imply that N will be applied by a given method to the point at which the marginal product is equal to the cost of the method. The optimal result will be either the split or pre-plant application, but not a mix of both. Specifically, all N will be applied later unless

$$P_S \geq \frac{P_P}{\gamma} \tag{19}$$

If equation (17) holds as equality, then pre-plant or split applications are equally profitable, and any linear combination of N_P and N_S that satisfies equations (17) and (18) is optimal. If $P_S > P_P/\gamma$, then the pre-plant application is optimal. If $P_S < P_P/\gamma$, then the split application is optimal. While split is more profitable, the applied split N rate is lower to obtain a given yield than pre-plant application. The optimal split application may be greater than the profit-maximizing pre-plant application. The optimal N rates for pre-plant and split applications are found from the first derivative of profit function with respect to N

$$N_P^* = P_Y \gamma G_N - P_P \tag{20}$$

$$N_S^* = P_Y G_N - P_S \tag{21}$$

where N_P^* is the optimal N rate at pre-plant and N_S^* is the optimal N rate in split time.

3.4. Conclusion

In a single application under full information and certainty, the optimal rate of N that maximizes profit is less than the optimal N rate that maximizes yield. An excess N above profit maximizing N rate decreases the profit. The N rate is inversely related to the price of N and positively related to the corn price and the marginal product of N. In contrast, the marginal products of pre-plant and split applications are different because their efficiencies in supplying N to the plant differ. Split application is more efficient than pre-plant application when some proportion of N applied at the pre-planting stage is lost before second application time. The applied N rate during split is lower than pre-plant application to obtain a given yield. This thesis excludes the uncertainty and its impacts on the optimal N rate. Uncertainty in corn production can rise because of weather or soil moisture uncertainty at the time of N application (Babcock, 1992). If the marginal product of N function is convex (concave), increasing certainty will increase (decrease) the optimal N rate (Horan, 2017). However, as actual weather data are not available to estimate the yield response, this thesis used a process-based model called DNDC to integrate management practices, soil, and hypothetical weather data to predict yield under alternative N rates. The next chapter presents the DNDC model, the alternative weather scenarios, and the financial and environmental impacts of alternative N management strategies.

FIGURES

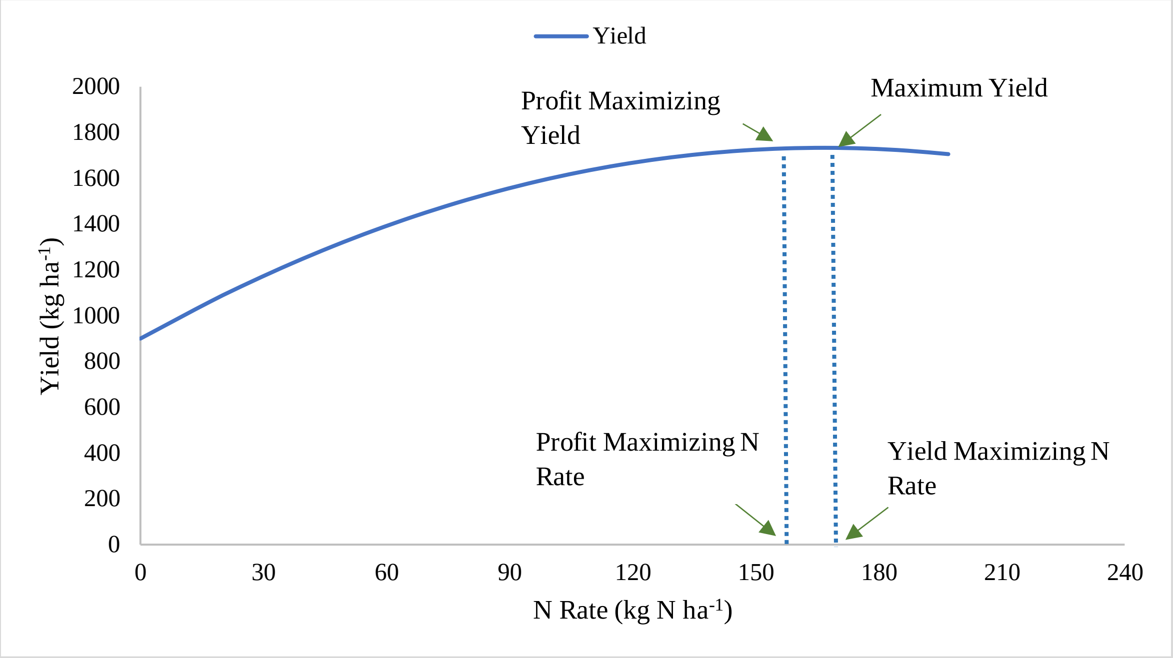

Figure 3. 1 Quadratic Yield Response Function Associated with Optimal N Rate shows a concave yield response function. Yield increases along with an increase in N rate until the maximum yield is achieved. Beyond maximum yield, an increase in the N rate decreases the yield. The yield response curve is flat because a change in the N rate causes a small change in yield.

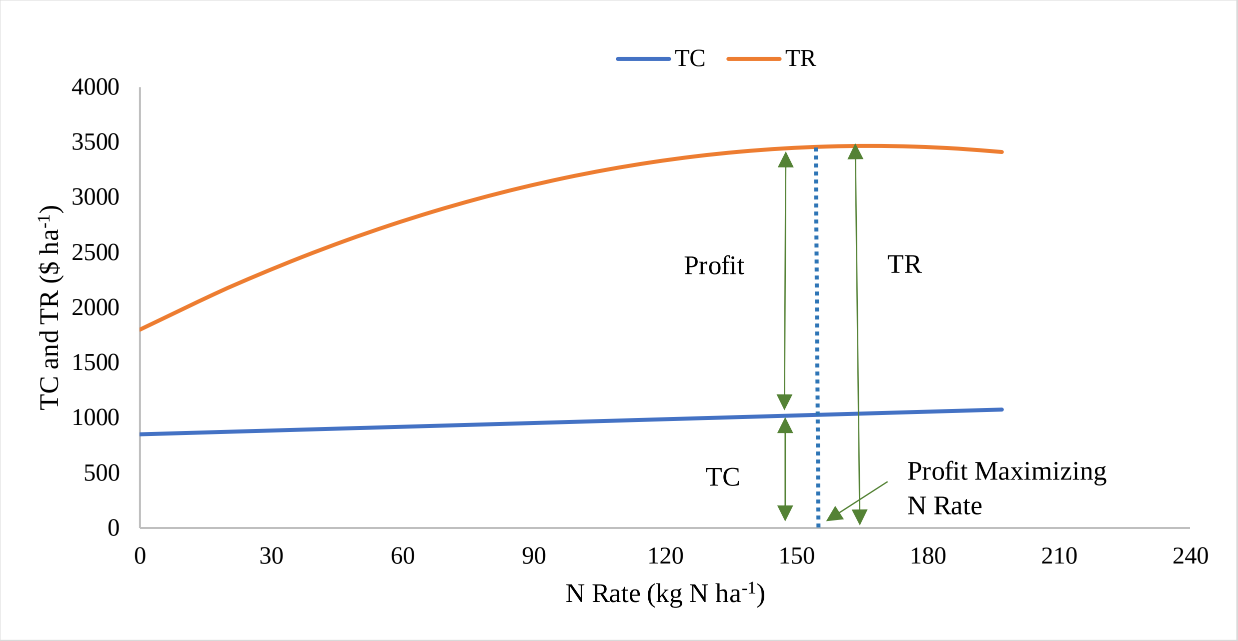

Figure 3. 2 Total Revenue (TR) and Total Cost (TC) Associated with N Rates shows that TC increases along with increased N rate, whereas, TR increases until profit maximizing optimal N rate is obtained. After achieving maximum TR, an increase above the optimal N rate decreases TR.

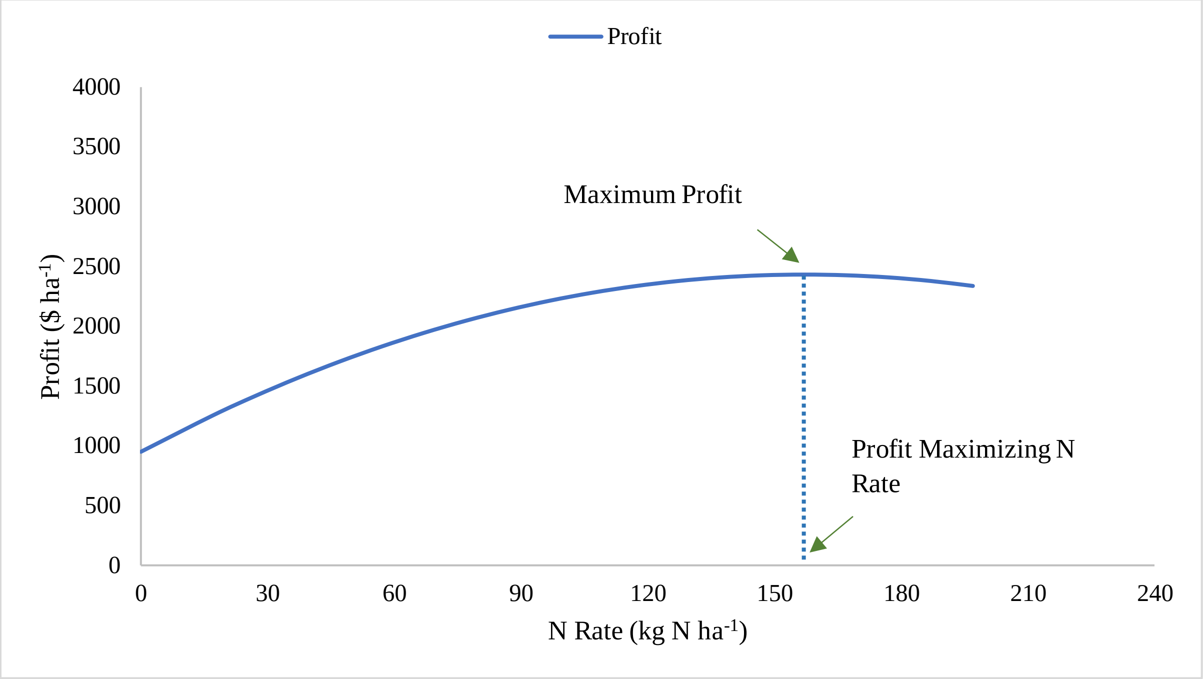

Figure 3. 3 Profit Associated N Rates is the difference between total revenue and total cost. As the N rate increases, the associated profit decreases until it reaches its maximum at the optimal N rate, and the profit decreases above the optimal N rate. However, the profit function for this example is concave.

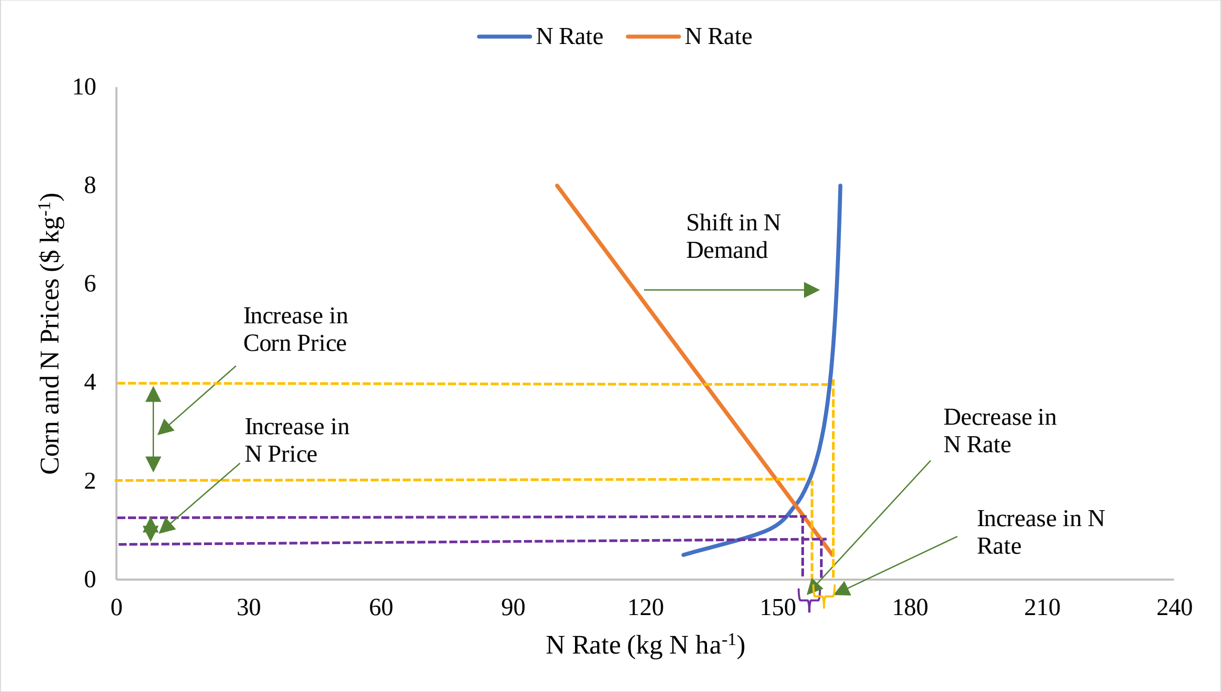

Figure 3. 4 Change in N Rate Associated with a Change in Corn and N Prices indicate that an increase in output (corn) price increases the input (N) demand (coloured blue), whereas, an increase in N price decreases the N demand (coloured orange) in corn production. Corn price is positively related to N demand, thus, upward-sloping demand curve. As N Rate is inversely related to its price, the demand curve is downward sloping. The change in N price moves the N rates along the demand curve, whereas, the change in corn price shifts the demand curve.

CHAPTER 4

THE EFFECTS OF SPLIT NITROGEN APPLICATION AND WEATHER ON THE PROFITABILITY AND ENVIRONMENTAL PERFORMANCE OF ONTARIO CORN PRODUCTION

4.1. Introduction

The use of fertilizer N is a nearly ubiquitous management practice in conventional corn production in developed countries, but the efficiency of N fertilizer use varies from farm-to-farm, and region-to-region due to the N management practices farmers choose to implement. The frequency and timing of N application(s) is one management factor that strongly influences environmental N losses and yield response to fertilizer N. When fertilizer N resides in the soil profile, particularly without inhibitor products, it remains vulnerable to weather and edaphic factors which can result in rapid and substantial losses via leaching, denitrification or volatilization. Based on 4R principles (Reetz et al., 2015), an ideal N application time synchronizes the application of N with the uptake needs of the crop, minimizing the residence time of N in the soil. This means that, ideally, the majority of fertilizer N is applied split during periods of rapid crop growth when N uptake rates are high and consequently, the residence time of fertilizer N in the soil is reduced (Sebilo et al., 2013).

In corn, N uptake rates reach a maximum during the critical period bracketing silking (Ciampitti et al., 2011), and while delaying N applications to the critical period is uncommon, split applications earlier in crop development (V3-V6; Abendroth et al., 2011) are common in eastern Canada. In corn, several studies have found that the risk of weather-induced N losses decreases the closer N is applied to periods of rapid crop N uptake, as opposed to in the fall or early spring prior to planting. However, in studies where soil type, weather, or other factors make N losses less likely for a given site-year, N application timing does not strongly influence environmental N losses or agronomic parameters in corn. Some studies found no yield impact on corn from split application (Fernandez et al., 2020; Nasielski et al., 2020; Vyn et al., 2017; Blandino et al., 2015) and N loss (Jaynes, 2013; An et al., 2020).

A concomitant benefit to N applications made split is that the N rate can be adjusted based on variables known to affect crop N demand and indigenous soil N supply, such as weather. The amount of N fertilizer required to ensure that yield is not N-limited will depend on soil, crop, and weather variables that may be more reliably estimated split, as opposed to prior to planting, allowing for farmers to tailor N rates to a given field and growing season. N rate adjustments, facilitated by N application timings that occur split, can reduce deleterious overapplications of N, increase profitability and minimize the environmental impact of N fertilizer use. Split N rates can be increased if N mineralization rates are low, if earlier N losses were high, or if the yield potential of a crop is larger than expected.

Enabled by the increasing availability of high-clearance equipment, there is growing interest in N management strategies from farmers and researchers where the bulk of fertilizer N is applied much later split than typical, closer to silking. While there are several motivating factors, such as reduced labour requirements during the busy planting season, a major benefit of late N applications is the potential to increase net returns to fertilizer use by enhancing N-use efficiency primarily through improvements in N recovery efficiency (e.g., reduced N losses, enhanced N uptake) and possibly by increasing N internal efficiency (e.g., by improving the harvest index). In Indiana, Mueller et al. (2017) found that applying the last 45 kg N ha^{-1} at vegetation stage of 12 (V12) increased NRE over the same N rate applied pre-plant, while, in Oklahoma, Walsh et al. (2012) found that NUE increased when N was split with 50% applied pre-plant and 50% applied at V10. Importantly, split-N applications never reduced yield relative to pre-plant applications in these studies. In the province of Ontario in Canada, Nasielski and Deen (2019) found that delaying N applications to V13 could result in yield reductions due to reduced pollinated kernel numbers at the silking stage, R1, and reduced potential kernel weight established at early grain-filling stages, R2 - R3. However, these N-stress related yield reductions could be avoided by providing a relatively small amount of N fertilizer around planting, although in one year, the entire N application could have been delayed to V13 without any reduction in yield (Nasielski & Deen 2019).

Similarly, DeBruin et al. (2018) in Illinois found that very severe N stress was required to irrevocably reduce kernel numbers prior to R1, suggesting that the majority of N fertilizer could be applied later than traditional timings, but prior to R1 with little risk of yield penalty. When N was delayed until R1, Mueller and Vyn (2018) in Indiana found that a vegetation stage of 4 (V4) application of 55 kg N ha^{-1} prevented any yield reduction from the delayed application. Fernandez et al. (2020) conducted a meta-analysis of fourteen studies on late N applications, defined as when 50% or more of the N fertilizer applied after V10. Overall, NRE increased by an average of 4% when N was applied at late N timings, a small but consistent increase over earlier N timings (Fernandez et al., 2020). Late N applications did not affect yield relative to the same N rate applied at an earlier time. However, the impact of late N applications on yield depended on the environment. In environments where post-R1 N uptake was high, late N applications tended to increase yield, and in environments where post-silking N uptake was low, late N applications reduced yield (Fernandez et al., 2020). The authors suggest that because post-silking N uptake is related to soil water availability, corn response to late N applications will be poorer in drier environments, and better in wetter environments.

While a considerable amount of research has investigated the agronomic and environmental consequences of split N applications made at typical timings between planting and V6, and at later application timings closer to R1, few studies have investigated the impact of N application timing on the net returns to fertilizer N. The University of Missouri Extension research team claimed that adopting split N application (delayed until V12-V16) increased profitability in wet spring with no effect on yield, based on nitrogen deficiency levels (Successful Farming, 2020). The team addresses the availability of machinery impeding split N application rather than the biology of the crop (Successful Farming, 2020). Likewise, the University of Nebraska-Lincoln Extension also investigated the economic feasibility of split N application in a single year on-farm experiment (Lesoing, 2014). The study concluded that split N application is profitable when the field has a high risk of N losses due to leaching and denitrification in the early season (Lesoing, 2014). Since N fertilizer is one of the largest variable costs corn farmers face, choices of management practices related to N can have a significant influence on financial returns to the farm operation. Although farmers can adjust fertilizer costs by adjusting the N rate in split application, the fertilizer application cost goes up in split application, two or more depending on the time of the second application. The profitability of management practice is a strong determinant of adoption, particularly for an innovation that can be easily tested (Weersink & Fulton, 2020). Evaluating the profitability of split N applications can potentially provide valuable information to farmers about the cost and benefits of such practice. However, government support may be needed to induce adoption if there are environmental benefits compared to current practices.

The purpose of this study is to jointly evaluate the agronomic, environmental, and financial performance of split-N applications in corn relative to a traditional spring pre-plant N application timing under alternative weather scenarios using the DNDC model. The DNDC model was previously calibrated and validated using field data from an 8-year N rate trial at the Elora Research Station in Elora, Ontario, Canada (Nasielski et al., 2020). Using 19-year weather records from the Elora Research Station to compute standard deviation values for mean daily precipitation and temperature, nine hypothetical weather scenarios were constructed varying in mean seasonal temperature and precipitation. DNDC was then used to jointly predict yield and N loss effects of different N management strategies across these weather scenarios. Specifically, a pre-plant N application wcompared with a split-N strategy of applying 50% of the N fertilizer pre-plant and the remaining 50% at either V6 or V13 (Abendroth et al., 2011). Net returns were calculated using publicly available price data, including the additional costs, e.g., fertilizer application costs associated with split N applications. The N rate was modestly increased/decreased to evaluate the effect of adjusting N rates in corn production under alternative weather conditions.

4.2. Materials and Methods

4.2.1 Overview

The flowchart in Figure 4.1 illustrates the empirical method used to evaluate the effects of split application on corn yields and the environment compared to traditional pre-plant broadcast. The inputs and outputs into the models are delineated by the orange and black parallelograms, respectively. The blue rectangles give the simulation models (i.e., processes), and the green diamond illustrates the outputs of these models. The arrows are connectors that show the relationship between the shapes in the flowchart.

The input data used to parameterize the DNDC model were collected at a long-term N rate field trial at the Elora Research Sation located in Elora, ON, Canada, described by Deen et al. (2015). The trial was initiated in 2010 to measure the short and long-term effects of the N fertilizer application rate on corn productivity and soil health. From 2005, a continuous corn rotation was maintained with all management factors held constant except for the N application rate. N application rate changed on a per-plot basis, varying from 30 kg N ha^{-1} to 260 kg N ha^{-1}. Soil properties and crop management practices inputted into DNDC were based on actual field data and management practices, except for N application rate and timing. The DNDC model was calibrated and validated by Nasielski et al. (2020) using data from this field trial, and this calibrated model served as the basis for the present study. DNDC simulated crop yield and nitrogen application strategies are combined with prices within an enterprise budget to estimate the financial net returns for the practice. To calculate the profit-scaled N losses, the net returns are divided by total N losses for each scenario. For evaluating the benefits of adjusting the N rate, the N rate is increased/decreased in the DNDC model in response to the weather. The process is then repeated for each N management practice and different weather scenarios. Details of the components are discussed further below.

4.2.2 Field Management Practices

Corn is the crop grown and the management of nitrogen is the practice of concern. It is assumed the production practices are the same across all three fertilizer practices. The study considers grain corn at 79,040 plants ha^{-1} a typical seeding rate in Ontario (OMAFRA, 2020) for budget analysis. To control annual grasses and broadleaf weeds, a typical herbicide program is used for calculating the enterprise budget (OMAFRA, 2020). The tillage method is assumed to be a conventional system two times (May 3 and December 7) in a year for the DNDC model and budget analysis. The long-term N rate study specifies the average dates of pre-plant tillage, planting, crop phenology (V6 and V13), and harvests, which were May 2, May 7, June 21, July 17, and October 28, respectively (Nasielski et al., 2020). For the simulation in the DNDC model, the study considers ploughing with disk or chisel into 10 cm depth in both tillages. The crops are produced in a continuous corn system, with DNDC simulating a 10-year spin-up using corn-barley-soybean in the simulation ((Nasielski et al., 2020). Soil properties inputted in the DNDC model were based on field data. The soil was classified as a silt loam with pH 7.7, silt 48%, clay 20%, and soil organic carbon (SOC) 4.5% (Nasielski et al., 2020).

A total of 169 kg N ha^{-1} is applied according to the recommendation of OMAFRA (OMAFRA, 2020), referred to as a moderate N rate in the study. This study adjusts the N rates modestly (+/-20 and 40 kg N ha^{-1}) in the split application time. Three nitrogen application practices are examined in this study for simulation and budget analysis: one traditional pre-plant application and two split applications. For each, 34 kg N ha^{-1} is applied as Monoammonium Phosphate (MAP) at planting as a starter, which is 20% of the moderate N rate. Starter fertilizer has been shown to increase yield and reduce maturity time, particularly in cool soil temperatures, by increasing nutrient availability early in the season (Vossenkemper et al., 2017) and is a recommended practice in Ontario (OMAFRA, 2020).

The traditional method broadcasts 135 kg N ha^{-1} of urea prior to planting, followed by tillage to incorporate urea to a 10 cm depth. No fertilizer is applied after planting, resulting in a total assumed rate of 169 kg N ha^{-1}. In the two split applications, five different N rates (129, 149, 169,189 and 209 kg N ha^{-1}) are applied. In addition to the 34 kg N ha^{-1} of MAP used as a starter at planting, 67.5 kg N ha^{-1} of urea is broadcast prior to planting, resulting in 101.5 kg N ha^{-1} applied by planting. The remaining N is injected (banded) as UAN in mid-row at a 7 cm depth at either the V6 or V13 stage (Abendroth et al., 2011). For corn, banding UAN mid-row is effective because the plant gets access to fertilizer with minimal damage. In dry weather conditions, injected UAN maximizes corn yield rather than broadcasting fertilizer on the surface (Russell et al., 2018). However, different fertilizer N rates and sources incorporate to the DNDC model for yield and environmental impact prediction. In contrast, the cost of different sources of N associated with different N rates is included in the budget analysis.

4.2.3 Weather Scenarios

Corn yield is directly related to the change in mean and variability of air temperature and soil moisture. Nine weather scenarios are developed using the standard deviation of annual temperatures and rainfall calculated from 19 years (1999-2018) of weather data collected at the Elora Research Station. One standard deviation from the mean temperature (cool and warm) and precipitation (wet and dry) and two standard deviations (cold and hot; very wet and very dry) are applied to daily average values over the 19 years. The nine scenarios are given in Table 4.1. The average daily maximum and minimum temperature in cold, cool, moderate, warm, and hot weather conditions are 10^{o} and 0.3^{o}, 10.8^{o} and 1.1^{o}, 11.6^{o} and 1.9^{o}, 12.4^{o} and 2.6^{o}, and 13.2^{o} and 3.4^{o}. The average daily precipitation in very dry, dry, moderate, wet, and very wet weather conditions is 0.173 mm, 0.214 mm, 0.255 mm, 0.295 mm, and 0.336 mm, respectively. Wind speed, solar irradiance, and relative humidity are kept at their daily dataset mean values. Overall average wind speed, solar irradiance, and relative humidity are 3.5 mph, 13.3 Wm^{-2}, and 79.4%, respectively. The weather parameters are used by the DNDC model to simulate yield and environmental performance under the nine weather scenarios. However, the combination of moderate temperature and precipitation is considered normal or base weather conditions in this study.

4.2.4 The DNDC Model

DNDC is a biogeochemical model that simulates crop growth, soil carbon, and nitrogen dynamics based on soil properties, climate, and farming practices (Li et al., 1992, 1994). The DNDC model was introduced by Li et al. (1992) as a rain event-driven, process-orientated simulation model for the emission of trace gases from agricultural soils in the U.S. The DNDC model measures the impacts of ecological drivers and soil environmental variables on trace gas-related geochemical or biochemical reactions.

The DNDC model takes climate (weather data), soil (properties, structures, profiles, etc.) and management practices (crop, tillage, fertilization, irrigation, etc.) as inputs. The model executes in daily sequence till the last day of the year. On the last day of the year, the DNDC model generates the annual summary report of crop production, carbon pools and fluxes, nitrogen and water for that simulated year.

Model calibration is a process to predict the explanatory variables based on known dependent variables. Nasielski et al. (2020) calibrated the DNDC model for Elora, Ontario, Canada, over eight years (2009-2016). They used a modified version (version 9.5 v.CAN) developed for Canada. The purpose of the calibration was to optimize the model fit of EORN, yield, N uptake, and soil mineral N by making a realistic adjustment to crop and soil data. A simple algorithm was used to scale corn yield sensitivity to water stress based on the growth stage, with sensitivity increasing around R1. For the study purpose, we used their calibrated model and modified N fertilizer management practices to predict yield response, NO_3^- leaching, N_2O emissions, and NH_3 volatilization to the environment. While DNDC normally holds crop C:N ratios constant, a simple algorithm was developed to dynamically adjust C:N ratios based on N stress in a manner that is consistent with the literature (Nasielski et al., 2020). In the model, an 11-year spin-up of corn-barley-soybean rotation was run using weather data (average daily precipitation, maximum and minimum temperatures, wind speed, relative humidity, and solar radiation), soil parameters (pH, silt, clay, and SOM) and management practices (crop types and rotation, fertilizer types, rates and placement, tillage methods and dates, and average dates of pre-planting, planting, V6, V13, and harvesting). The simulated last year generated the corn data, including yield, NO_3^- leaching, N_2O emissions, and NH_3 volatilization. Overall, 99 simulations (three application practices, under nine weather conditions and one N rate in pre-plant broadcast and five N rates in split applications) were performed in the process.

4.2.5. Profit-Scaled N Losses

Profit-scaled N loss is measured by dividing total N losses (leaching, emissions, and volatilization) by profit in a particular scenario, which varies for different management practices at different N rates under different weather scenarios. Profit-scaled N losses illustrate a scenario of N losses associated with profitability.

4.2.6. Budget Analysis

The Ontario Ministry of Agriculture, Food and Rural Affairs (OMAFRA) annually assemble field crop budgets as a management tool for farmers to estimate break-even values for yields/prices and to evaluate alternative farm enterprises and practices (OMAFRA, 2020). The budgets for each crop provide prices and quantities typical for the province that can be used as a base scenario and can be modified for individual use. The input prices in the budget are survey outcomes conducted in Ontario (U of G, 2019). The same fertilizer prices in the 2020 field crop budget are used here: \$0.557 kg^{-1} for MAP (11-52-0), \$0.454 kg^{-1} for urea (46-0-0), and \$0.275

kg^{-1} for UAN (28-0-0). Corn price is assumed to be \$0.22 kg^{-1} for southwestern/central Ontario (OMAFRA, 2020).

The OMAFRA enterprise budget for growing corn in 2020 has been summarized in Table 4.2. To evaluate the profitability of adopting split N application, only the costs and returns that are directly attributable to the different fertilizer management practices are considered, and other costs that are unchanged regardless of the N application method are fixed and grouped together. In the resulting budget analysis, the cost of fertilizer changed with the N source, placement, and rate.

The cost of fertilizer application in pre-plant broadcast is assumed to be \$29.64 ha^{-1}, which is the value given in Publication 60 (OMAFRA, 2020). The cost of applying fertilizer in split application of injecting N at V6 and V13 is assumed to be \$59.3 ha^{-1}. The labour cost (\$37.8 ha^{-1}; self or hired) is assumed to be fixed for all practices. Some costs will vary with yields, such as crop removal, marketing board and grain financial protection fees, trucking, drying, and storage. The study also considers the cost of a seeding rate of 79,040 plants ha^{-1}, given in Publication 60 (OMAFRA, 2020). All the associated expenses and revenue are based on the conventional tillage system provided in Publication 60 (OMAFRA, 2020).

4.3. Results and Discussion

4.3.1 Impact of weather and N Management Practices on Yield

Soil moisture played a significant role in regulating corn yield. A lack of rainfall in extremely dry weather reduced the yield significantly in all management practices. For example, corn yield was highest at 12.1 t ha^{-1} for the conventional N practice under wet and warm growing conditions but dropped to approximately 9 t ha^{-1} under very dry conditions. The air temperature also influenced the impact of precipitation. In dry or very dry conditions, yield benefitted slightly from cool or cold air temperatures. Conversely, in wet or very wet conditions, the yield was higher than warm and hot weather.

For a given N rate, the overall yield slightly changed in split application compared to pre-plant broadcast under drier conditions but increased in wetter conditions (Table 4.3). There were slightly fewer or no changes in yield under very dry weather conditions in split applications. Application of 129 kg N ha^{-1} in split application at V6 and V13 generally increased yield compared to the traditional application approach, particularly under dry weather conditions for which split V13 generated the highest yields. Under normal conditions, yields for V6 were 1.2% lower and for V13 0.8% lower compared to the pre-plant broadcast yield of 11.6 t ha^{-1}.

The yields with the moderate and high split application rates were higher than the pre-plant broadcast method in wetter conditions. Under wet conditions, split V13 at a higher N rate (189 kg N ha^{-1}) generated yields that were 3.3% higher with warm weather and 6.1% higher with cool weather than pre-plant broadcast yields. In very wet conditions, split application at a higher N rate (209 kg N ha^{-1}) increased yield by more than 9% in hot temperature from the pre-plant broadcast yield of 12.0 t ha^{-1}, whereas, in cold temperatures, moderate split application rate at the V6 stage increased yield by 3.4% compared to the base yield of 11.1 t ha^{-1}. When weather was wet, warm temperatures increased yield, whereas, under dry, cooler temperatures, yield increased. In conclusion, pre-plant broadcast generates higher yields under normal weather conditions. In contrast, split application, with or without N rate adjustment, maximizes yield under dry, wet, and very wet weather conditions.

4.3.2. Impact on Profitability

The percentage change in returns from pre-plant broadcast incurred with split applications at different N rates under different weather conditions is presented in Table 4.4.

Returns to the traditional system are \$724 ha^{-1} in average weather conditions. Returns drop significantly with decreases in rainfall and especially as temperature increases. For example, returns fall to \$284 ha^{-1} under very dry and hot weather for pre-plant broadcast. In contrast, the net returns increase with precipitation highlighting the importance of water as a limiting resource for current corn varieties in Ontario. Profits for pre-plant broadcast are highest under warm and wet conditions (\$800 ha^{-1}) and the next highest (\$794 ha^{-1}) for hot and very wet weather.

However, the profits increase under extreme weather scenarios with a move from pre-plant broadcast to split application and an adjustment of N rates in split N application. For example, profit for split V6 is highest at 209 kg N ha^{-1} under very wet and hot conditions, 14.5% higher than pre-plant broadcast (\$794 ha^{-1}). In split V13, the profit is highest at 129 kg N ha^{-1} under dry and cool conditions, 10.6% higher than pre-plant broadcast (\$533 ha^{-1}). At the moderate N rate, the profit increases (compared to pre-plant broadcast) in split application under wet, very wet, and cold conditions. For example, the highest increases are 5.6% in both applications from pre-plant broadcast under wet and cool conditions. On the other hand, the profits decrease under very dry, dry, and moderate conditions. The highest reductions are 14.2% (split V6) and 10.3% (split V13) under very dry and hot conditions.

Overall, fertilizer costs associated with adjusting N rates depict sensitiveness in profit generated in split applications (Table 4.4). Lowering the N rate (149 kg N ha^{-1}) in split applications decreased the profits from pre-plant broadcast in all weather conditions. For example, the highest profit reductions are 7.4% (split V6) under very dry and hot conditions and 4.1% (split V13) under very wet and hot. On the contrary, increasing the N rate (189 kg N ha^{-1}) in split application shows mixed results. For example, the profits increase (compared to pre-plant) up to 11.1% in both split applications under very wet and hot conditions. When the precipitation is high, higher N rates generate more profits than pre-plant broadcast. In contrast to dryer weather, higher N rates reduce profits significantly from the pre-plant broadcast. For example, the profit reductions are up to 21.2% (split V6) and 17.3% (split V13) under very dry and hot, a sharp fall from the pre-plant broadcast.

Adjusting N rate illustrates that a modest change in N rate changes the profit in split application, a result of a change in N cost. When N rate is adjusted at 129 kg N ha^{-1}, the highest profit increases (compared to pre-plant broadcast) are 9.2% (split V6) and 10.6% (split V13) under dry and cool conditions. Though profits in split V13 increase in dry conditions only, split V13 is more profitable in both very dry and dry conditions, than pre-plant broadcast. In the rest of the weather conditions, profit reductions at 129 kg N ha^{-1} are up to 19% (split V6) and 17.1% (split V13) under very wet and cold conditions, a significant reduction from the pre-plant broadcast. On the contrary, adjusting the N rate at 209 kg N ha^{-1} in split application increases the profits under wet and cool, and very wet and hot conditions. For example, the highest increases are 14.5% (split V6) and 13.9% (split V13) under very wet and hot conditions. But the profits decrease up to 24.2% (split V6) and 28.1% (split V13) under very dry and hot conditions, a sharp fall from the pre-plant broadcast.

Table 4.4 compares profits under different management practices at different N rates of profit-maximizing practices under different weather conditions (Table 4.4). Split application results in higher profit under extreme weather conditions compared to pre-plant broadcast. When the weather was very dry and dry, split V13 at 129 kg N ha^{-1} generates higher profit, a range of 3.1% to 10.6%, compared to the traditional method. In wet weather conditions, applying 189 kg N ha^{-1} at V13 generates higher profit, a range of 1.9% to 9.0%, than pre-plant broadcast. When the weather is very wet and hot, 209 kg N ha^{-1} at split V6 shows higher profit (14.5%) than pre-plant broadcast. Applying the moderate N rate at the V6 stage results in higher profit (5.1%) than pre-plant broadcast under very wet and cold conditions. The traditional pre-plant broadcast method is the most profitable (\$724 ha^{-1}) only in normal conditions.

4.3.3. N Losses

4.3.3.1. Weather Effects on N Loss Pathways

NO_3^- Leaching

Leaching N loss is strongly influenced by precipitation, being greater in wet or very wet scenarios (Table 4.5). The wetter the weather scenario, the higher the soil moisture from higher rainfall, the higher the N losses in management practices and the greater the N concentrations in surface and drainage water. Leaching is also slightly increased in cool and cold scenarios. For example, the maximum leaching occurs under very wet and cold conditions in all practices, (35.6 kg N ha^{-1}) in the pre-plant broadcast. The minimum leaching is observed in very dry and hot conditions, 12.8 kg N ha^{-1} in the pre-plant broadcast. Thus, the combination of high (low) precipitation and low (high) temperature results in maximum (minimum) leaching.

N_2O Emissions

The N_2O emissions are generally higher in higher temperatures, regardless of management practices (Table 4.6). For example, the maximum emissions occur in very wet and hot conditions, 0.84 kg N ha^{-1} in the pre-plant broadcast. The minimum emissions are observed under very dry and cold conditions, 0.51 kg N ha^{-1} in the pre-plant broadcast. It seems that precipitation does not show any pattern in emission changes.

NH_3 Volatilization

NH_3 volatilization is generally higher in higher temperatures and lower precipitation regardless of management practices (Table 4.7). For example, the maximum volatilization is under very dry and hot conditions, 41.5 kg N ha^{-1} in the pre-plant broadcast. The minimum volatilization is under very wet and cold conditions, 21.0 kg N ha^{-1} in the pre-plant broadcast. Thus, the combination of high (low) precipitation and lower (high) temperature results in minimum (maximum) volatilization losses.

4.3.3.2 N Management Effects on N loss Pathways

NO_3^- *Leaching*

Adopting split application significantly reduces leaching almost under all weather conditions compared to pre-plant broadcast. For example, leaching is 21.2 kg N ha^{-1} in pre-plant broadcast under normal conditions, falls by 19.3% (split V6) and 21.3% (split V13) at 169 kg N ha^{-1} rate. The highest reductions in split applications are 22.7% (split V6) and 23.8% (split V13) under dry and warm and very wet and cold conditions, while leaching is 16.9 and 35.6 kg N ha^{-1} in pre-plant. Split application reduces leaching from pre-plant broadcast under all scenarios at a moderate rate (169 kg N ha^{-1}). The maximum reduction is 12.8% in split V6 and 19.4% in split V13 from 28.5 kg N ha^{-1} (pre-plant) under very wet and hot conditions, whereas the minimum reduction is 4.0% in split V6 from 14.2 kg N ha^{-1} (pre-plant) and 8.3% in split V13 from 12.8 kg N ha^{-1} (pre-plant) under very dry and hot conditions.

Adjusting the N rates in split applications shows mixed results in the simulation (Table 4.5). Applying 149 kg N ha^{-1} at V6 and V13 significantly reduces the leaching from the traditional method. For example, when the leaching is 27.4 kg N ha^{-1} in pre-plant broadcast, adopting split application reduces the leaching by 16% (split V6) and 20% (split V13) under wet and cool conditions. The maximum reductions are 17.4% in split V6 and 21.4% in split V13 from 35.6 kg N ha^{-1} (pre-plant) under very wet and cold conditions, whereas the minimum reductions are 12.5% in split V6 and 15.5% in split V13 from 12.8 (pre-plant) under very dry and hot conditions.

Applying 189 kg N ha^{-1}, the leaching increases under very dry and dry conditions but decreases under normal, wet, and very wet conditions in split V6, compared to pre-plant broadcast. For example, leaching rises to 3.7% from 12.8 kg N ha^{-1} (pre-plant) under very dry and hot conditions, while falls up to 9.5% from 28.5 kg N ha^{-1} (pre-plant) under very wet and hot conditions. Applying a high N rate at V16 incurs less leaching than pre-plant broadcasting under all scenarios. For example, the maximum and minimum reductions are 0.7% from 12.8 kg N ha^{-1} (pre-plant) under very dry and hot conditions and 17.8% from 28.5 kg N ha^{-1} (pre-plant) under very wet and hot conditions.

The leaching in split application is significantly decreasing from pre-plant broadcast at 129 kg N ha^{-1}. For example, minimum reductions are 19.2% in split V6 and 21.2% in split V13 from 24.9 kg N ha^{-1} (pre-plant) under wet and warm conditions. 209 kg N ha^{-1} at V6 increases the leaching from pre-plant broadcast under all conditions except very wet and hot conditions, 5.4% less than pre-plant broadcast. On the contrary, split V6 at 209 kg N ha^{-1} increases leaching up to 12.6% from 16.9 kg N ha^{-1}(pre-plant) under dry and warm conditions. Split V13 at 209 kg N ha^{-1} results in higher leaching under very dry and dry conditions and lower leaching under moderate, wet, and very wet conditions. The maximum increase is 6% from 12.8 kg N ha^{-1}(pre-plant) under very dry and hot conditions, whereas minimum reduction is 16.2% from 28.5 kg N ha^{-1} (pre-plant) under very wet and hot conditions.

Applying lower and moderate rates of N at V6 and V13 stage significantly decreased NO_3^- leaching in different weather conditions compared to the traditional method. Although 189 kg N ha^{-1} at V13 stage reduced NO_3^- leaching in different scenarios, split V6 increased leaching in very dry and dry conditions. Applying 209 kg N ha^{-1} in split application shows mixed results in leaching. Comparing the different management practices and N rates, adjusting the N rate at split V13 induces the lowest NO_3^- leaching in different weather conditions, resulting in an environmentally win practice.

N_2O Emissions

Adopting split application shows mixed results in emissions associated with different N rates under different weather conditions compared to pre-plant broadcast (Table 4.6). For example, the maximum reductions in emissions are 14.9% in split V6 and 24.3% in split V13 at 129 kg N ha^{-1} from 0.74 kg N ha^{-1}(pre-plant) under very dry and hot conditions. While the maximum increase in emissions is 52.7% in split V6 from 0.55 kg N ha^{-1}(pre-plant) under very wet and cold conditions and 35.6% in split V13 from 0.51 kg N ha^{-1}(pre-plant) under very dry and cold conditions. At moderate N rate (169 kg N ha^{-1}), split V6 increases under all scenarios, a range of 5.4% to 27.3% from the pre-plant broadcast.

Adjusting the N rate also illustrates mixed results in split applications. At 149 kg N ha^{-1}, split V6 increased the emissions level from pre-plant broadcast under all weather scenarios except hot conditions. For example, the maximum rise in emission is 7.8% from 0.51 kg N ha^{-1} (pre-plant) under very dry and cold conditions, whereas 2.7% reduction from 0.74 kg N ha^{-1} (pre-plant) is the maximum under very dry and hot conditions. However, the emission levels reduce in split V13 at 149 kg N ha^{-1} under all weather conditions than pre-plant broadcast, a range of 2% to 18.9%. At high N rate, emissions increase under all weather scenarios in split application except in split V13 under very dry and hot conditions. The highest levels of increase are 41.8% in split V6 and 21.8% in split V13 from 0.55 kg N ha^{-1} (pre-plant) under very wet and cold conditions.

At 129 kg N ha^{-1}, split application incurs lower emissions than the traditional method in a range of 5.5% to 14.9% in split V6 and 12.7% to 24.3% in split V13. At 209 kg N ha^{-1}, the emission level increases under all weather conditions in split application, in a range of 27% to 52.7% in split V6 and 2.7% to 35.3% in split V13.

Applying 129 kg N ha^{-1} in split application generates less N_2O emissions under different weather scenarios, than pre-plant broadcast. The higher the N rates in different weather conditions, the higher the N_2O emissions. The comparison between management practices demonstrates that adjusting N rate (129 kg N ha^{-1}) at the V13 stage significantly reduces emissions than the pre-plant broadcast in different weather conditions, resulting in an environmentally win practice.

NH_3 Volatilization

The simulated results in volatilization present that the N loss is significantly higher in pre-plant broadcast than split application under all scenarios except in split V13 at 209 kg N ha^{-1} rate under wet and very wet conditions (Table 4.7). For example, when the volatilization in pre-plant broadcast is 39.1 kg N ha^{-1} under very dry and cold conditions, a move to split application decreases the N loss up to 47.5% in split V6 and split V13 at 129 kg N ha^{-1}. Moderate N rate (169 kg N ha^{-1}) reduces the volatilization losses in a range of 32.4% to 54.5% in split V6 and 33.3% to 44.7% in split V13. At 149 kg N ha^{-1}, the volatilization reduction rates from the pre-plant broadcast are 47.5% to 54.5% in split V6 and 44.6% to 54.7% in split V13. But the reduction rates reduce as 189 kg N ha^{-1} is applied at V6 or V13 stage. For example, applying 189 kg N ha^{-1} at splitting time decreases volatilization losses between 22.7% and 47.4% in split V6 and 7.8% and 24.4% in split V13 under different weather conditions.

At 129 kg N ha^{-1}, volatilization shows a similar pattern as observed at 149 kg N ha^{-1} in split application. The reduction rates in split V6 at 129 kg N ha^{-1} from the pre-plant broadcast are unchanged under all weather conditions. However, results remain the same as 149 kg N ha^{-1} in split 13 under very dry and dry conditions. In the rest of the scenarios, the N losses reduce in a range of 47.8% to 54.7% in split V13. Split V6 at 209 kg N ha^{-1} results in lower N losses from pre-plant broadcast, a range of 8.1% to 22.6% under different weather conditions. Applying 209 kg N ha^{-1} at the V13 stage reduces the N losses in lower precipitation but increases in higher precipitation. For example, the higher N losses reduction is 10.6% from 39.1 kg N ha^{-1} (pre-plant) under very dry and cold conditions, whereas the higher increases in N losses are 15.6% from 28.3 kg N ha^{-1} (pre-plant) under very wet and hot conditions.

As the N rates increases in split applications, the volatilization losses increase accordingly. The environmental performance of NH_3 losses is better in split application than the pre-plant broadcast under different weather scenarios. An exception was followed at 209 kg N ha^{-1} in split V13, likely due to higher precipitation during the season. Greater reduction in NH_3 losses was observed in split V13 at 129 kg N ha^{-1} compared to the traditional method under all weather conditions. If the temperature is low, split V13 would also lessen NH_3 loss at 129 kg N ha^{-1}. However, the lower NH_3 loss in split application results from applying UAN injected in corn production.

Profit-Scaled N loss

Profit-scaled N loss shows total N losses to the environment for every $100 of profit in each scenario (Table 4.8). Profit-scaled N losses are generally higher in higher temperatures except in very wet and hot conditions. Also, profit-scaled N losses increase with higher N rates under different weather scenarios. The results in split application indicate mixed conclusions in profit-scaled N losses. Profit-scaled N losses are generally higher in pre-plant broadcast than split applications under certain scenarios. For example, while pre-plant broadcast incurs the maximum profit-scaled N loss (19.4 kg N $\$^{-1}$) under very dry and hot conditions, a move to split application generates lower profit-scaled N loss, 11.3 kg N $\$^{-1}$ in split V6 and 10.8 kg N $\$^{-1}$ in split V13 at 129 kg N ha^{-1}. At a moderate N rate (169 kg N ha^{-1}), the profit-scaled N losses in split applications are between 5.0 kg N $\$^{-1}$ and 16.8 kg N $\$^{-1}$ in split V6 and 5.0 kg N $\$^{-1}$ and 15.7 kg N $\$^{-1}$ in split V13 under different weather scenarios.

Lowering the N rate causes significant decreases in profit-scaled N losses in split application. For example, at 149 kg N ha^{-1}, split application decreases profit-scaled N losses, between 4.6 kg N $\$^{-1}$ and 12.7 kg N $\$^{-1}$ in split V6, and 4.7 kg N $\$^{-1}$ and 12.6 kg N $\$^{-1}$ in split V13, under different weather conditions. On the contrary, at 189 kg N ha^{-1}, split application reduces the losses under all weather conditions except under very dry and hot conditions; however, the losses are between 20.6 kg N ha^{-1} and 5.3 kg N ha^{-1} in split V6 and 19.6 kg N ha^{-1} and 5.6 kg N ha^{-1} in split V13.

Although applying 129 kg ha^{-1} of N significantly reduces profit-scaled N losses in all scenarios in split application, 209 kg ha^{-1} of N application generally increases the losses than pre-plant broadcast under very dry, dry and moderate conditions. While split application decreases profit-scaled N losses at 209 kg N ha^{-1} in a range of 5.9 kg N ha^{-1} to 6.5 kg N ha^{-1} in split V6, and 6.4 kg N ha^{-1} to 6.9 kg N ha^{-1} in split V13, under wet and very wet and hot conditions, it also increases the N losses up to 25.8 kg N ha^{-1} in split V6, and 24.8 kg N ha^{-1} in split V13, under very dry and hot conditions.

In normal and alternative weather conditions (i.e., very dry, dry and very wet and cold) applying 209 kg ha^{-1} of N in split application increases profit-scaled N losses, whereas, at 189 kg

N ha^{-1}, split application increases profit-scaled N losses only in the very dry and hot weather scenario. Profit maximizing practices minimized profit-scaled N losses in very dry and dry weather conditions. Although profit-maximizing practices did not minimize profit-scaled N losses in the rest of the weather scenarios, the losses are significantly lower than pre-plant broadcast. Under normal condition, the profit-maximizing practice (pre-plant broadcast) generated lower profit-scaled N losses than split application at 209 kg ha^{-1} of N rate.

4.3.4. Trade-off Between Profitability and Environmental Impacts

This study tends to prioritize economic indicators (i.e., profitability) at the cost of the environment (i.e., NO_3^- leaching, N_2O emission, and NH_3 volatilization) under certain weather conditions. Tables 4.5, 4.6, and 4.7 show the trade-off between profit and environmental impacts under different weather conditions. The tables illustrate that profit-maximizing management practices could not pursue maximum economic and environmental benefits simultaneously without compromising on either. The higher the profit, as desirable to farmers, the less the environmental protection in some specific weather conditions (Table 4.5, 4.6, and 4.7). The economic and environmental trade-off turned into a win-win in some weather conditions. In very dry and dry weather conditions, the trade-off between profit and environmental parameters turned into a win-win, whereas in other weather conditions, it was win-loss. Thus, the debate between profit maximization and environmental protection arose while adopting split application from traditional application.

Although profit-maximizing management practices did not induce maximum environmental protection, the environmental losses were higher in pre-plant broadcast than in split V6 and split V13. Tables 4.5, 4.6, and 4.7 show the percentage change in environmental losses while moving from pre-plant broadcast to maximum environmental and economic benefits. If the farmers choose maximum environmental protection, they can reduce NO_3^- leaching by 23.3% to 24.4% in different weather conditions compared to the traditional method. Conversely, if profit maximization is the farmers' objective, they can reduce NO_3^- leaching in a range of 0% to 16.3% in different weather conditions compared to the traditional method. Farmers can reduce N_2O emissions in a range of 15.7% to 24.3% by moving towards maximum environmental protection in different weather conditions compared to the traditional method. The profit-maximizing practices do not emerge maximum environmental benefits in N_2O emissions like NO_3^- leaching but can reduce emissions in a range of 0% to 19% in split application. The trade-off scenario in NH_3 volatilization is similar to leaching and emissions. Environmentally maximized practices can reduce volatilization losses by 44.6% to 48.6% compared to the traditional method. Conversely, profit-maximizing practices can reduce such losses by 0% to 54.5%. Noted, profit-maximizing management practices induced no environmental benefits in normal conditions. The comparison between traditional and split applications indicates that split application is a better method for gaining maximum economic and environmental benefits in some specific weather conditions. However, the change in the magnitude of environmental impacts depends on the N rate adjustment according to different weather conditions.

4.4. Conclusion

This study has found that management practices have significant impacts on the agronomic, economic, and environmental performance of corn production. Split N applications maximized yield under dry, wet and very wet weather conditions, whereas, pre-plant broadcast generated higher yields under normal weather conditions. Farmers would remain indifferent between pre-plant broadcast and split V13 under very dry conditions. Split N application was more profitable than traditional pre-plant broadcast under alternative weather conditions.

Adjusting N rate showed that profitability depends on adjusting the split rate when adopting split application instead of pre-plant broadcast. Split V6 was profitable under very wet weather conditions, whereas split V13 led to higher profit under very dry, dry and wet weather conditions. 129 kg N ha^{-1} at V13 stage induced greater profit under very dry and dry conditions, while increasing N rate (189 kg N ha^{-1} and 209 kg N ha^{-1}) at V13 and V6 stages under wet and very wet and hot conditions induced greater profit. Split V6 at moderate N rates enhanced profit under very wet and cold conditions. Split N application emerged more environmental benefits in all weather conditions assessed in the study. However, economically recommended farming management practices did not always imply a win-win case for economic and environmental aspects. Although applying 189 kg N ha^{-1} in wet and very wet weather conditions led to maximum profit; the environmental losses increased along with an increase in N rate. Yet, split N application generated higher profit and lessened water and air pollution by reducing NO_3^- leaching, N_2O emissions and NH_3 volatilization in the environment compared to the traditional method. Adjusting the N rate influenced the yield response, profitability, environmental impacts, and profit-scaled N losses under different weather conditions, thus changing management recommendation for economic, agronomic, and environmental benefits.

The analysis is conducted by creating hypothetical weather scenarios using the weather data of Elora, Ontario. The incorporation of actual weather data may vary the results in different regions under various crop types, weather, and soil conditions. The study considered smooth rainfall and excluded extreme weather events (e.g., 30 mm of rainfall on one day) from the simulation. Such point events appear to cause considerable N losses, especially earlier in the growing season, thereby leaving some N losses unaccounted. Including extreme weather events may change the simulated N losses. The study excluded uncertainty concerns that arise with weather or soil moisture at the time of N application. Such uncertainties affect the optimal N rate (Babcock, 1992), which results in a change in yield, profitability, and environmental impacts. The study also excluded the demand, supply, and price effects under extreme weather conditions. Such effects may have significant impacts on decisions taken by farmers under extreme weather scenarios. The study incorporated similar custom costs in the V6 and V13 stages. Delayed N application requires high-clearance equipment to apply the fertilizer. Thus, the cost of applying fertilizer at V6 is different from the cost of applying at V13. The study did not address the feasibility of adopting split application, especially delayed until V13, when the custom cost changes, for a small-scale farmer. 4R is promoted to adopt voluntarily in management practices; thus, the willingness to adopt split application under alternative weather conditions can be an area for further research. Finally, more field experimental data on split applications in different regions under alternate climate and soil conditions are required for a robust conclusion on the agronomic, environmental and economic performance of split N application.

TABLES

Table 4. 1 Different Weather Scenarios under Precipitation and Temperature is created by 19 years (1999-2018) of average daily precipitation, maximum and minimum temperatures at Elora, Ontario. One standard deviation from the mean temperature (cool and warm) and precipitation (wet and dry) and two standard deviations (cold and hot; very wet and very dry) are applied to daily average values over the 19 years.

Precipitation (mm)	**Temperature (^{O}C)**				
	Cold	Cool	Moderate	Warm	Hot
Very Dry	0.173 max 10^{O}/ min 0.3^{O}				0.173 max 12.4^{O} / min 2.6^{O}
Dry		0.214 max 10.8^{O}/ min 1.1^{O}		0.214 max 12.4^{O} / min 2.6^{O}	
Moderate			0.255 max 11.6^{O} / min 1.9^{O}		
Wet		0.295 max 10.8^{O}/ min 1.1^{O}		0.295 max 12.4^{O} / min 2.6^{O}	
Very Wet	0.336 max 10^{O}/ min 0.3^{O}				0.336 max 12.4^{O} / min 2.6^{O}

Table 4. 2 Enterprise Budget in Different Management Practices allows farmers to evaluate the profitability in different management practices at different N rates under alternative weather conditions.

Operating Expenses (Costs based on yield of kg/ha)			**Pre-plant Broadcast ($/ha)**	**Split V6 ($/ha)**	**Split V13 ($/ha)**
Seed (average costs of 3 hybrids)	79,040 kernels-treated-multi-trait		299.61	299.61	299.61
Insecticide seed treatment, if required			3.95	crea3.95	3.95
Fertilizer (169 kg/ha N)	Starter- MAP (11-52-0)				
	Preplant-Urea (46-0-0)				
	Split-UAN (28-0-0)				
	Total Cost				
	crop removal	80 kg/ha P2O2 (7.25 kg/tonne removal rate)	86.7	86.7	86.7
		54 kg/ha K2O (4.9 kg/tonne removal rate)	46.9	46.9	46.9
Herbicide	annual grass and broadleaf weed		65.2	65.2	65.2
Tractor and machine expenses	fuel (34 L conventional) and lubricant		93.5	93.5	93.5
	Repairs and maintenance		68.7	68.7	68.7
Marketing board and Grain Financial Protection Fees ($/kg)			4.5	4.5	4.5
Production insurance			28.7	28.7	28.7
Risk Management Program			21.7	21.7	21.7
Custom Work	fertilizer application, mixing and delivery		29.6	59.3	59.3
	pesticide applications		27.17	27.17	27.17
Trucking ($/kg)			98.4	98.4	98.4
Drying ($/kg, 8 points)			229.3	229.3	229.3
Land rent			-	-	-
Operator Labour (self or hired)			37.8	37.8	37.8

Storage ($/kg/month* 4 months)		102.8	102.8	102.8
Interest on operating		35.2	35.2	35.2
	Total Operating Expenses			
Revenue				
Expected Yield (kg/ha)				
Expected Price ($/ha)				
	Total Market Revenue (yield*price)			
	Contribution Margin (Revenue-Operating Expenses)			
Overhead Expenses				
Machinery	Depreciation	101.64	101.64	101.64
	interest on investment	34.46	34.46	34.46
Land		-	-	-
Other overhead		14.33	14.33	14.33
	Total Expenses			
	Net Return			

Notes:

1. The N rate is based on the nitrogen N rate calculator and is recommended for corn grown in southwestern/central Ontario, 2800 heat units clay loam soil, following wheat with straw removed, with projected corn yield of 10.95 t/ha, nitrogen cost of $1.25/kg and corn price of $195/t (OMAFRA, 2020).
2. The costs shaded by green color changes according a change in management practices and N rates.
3. The costs shaded by blue color changes according to a change in yield.

Table 4. 3 Comparison of Yield Response Associated with Different Practices under Different Weather Conditions shows that not only adopting split N application but also adjusting the N rate during the growing stage generates higher yield under certain weather conditions.

Weather		**Pre-plant Broadcast** (t/ha)	**Split V6** (%)					**Split V13 (%)**				
			Low (129 kg N ha^{-1})	**Low** (149 kg N ha^{-1})	**Moderate** (169 kg N ha^{-1})	**High** (189 kg N ha^{-1})	**High** (209 kg N ha^{-1})	**Low** (129 kg N ha^{-1})	**Low** (149 kg N ha^{-1})	**Moderate** (169 kg N ha^{-1})	**High** (189 kg N ha^{-1})	**High** (209 kg N ha^{-1})
Very Dry	Hot	8.9	↓ 0.8	↓ 0.8	↓ 0.8	↓ 0.8	↓ 0.8	0.0	0.0	0.0	0.0	0.0
	Cold	9.1	↓ 0.7	↓ 0.7	↓ 0.7	↓ 0.7	↓ 0.7	0.0	0.0	0.0	0.0	0.0
Dry	Warm	10.1	↑ 0.6	↓ 0.7	↓ 0.7	↓ 0.7	↓ 0.7	↑ 1.5	0.0	0.0	0.0	0.0
	Cool	10.4	↑ 2.3	↓ 0.5	↓ 0.5	↓ 0.5	↓ 0.5	↑ 2.8	0.0	0.0	0.0	0.0
Moderate	Moderate	11.6	↓ 1.8	↓ 0.4	↓ 1.2	↓ 1.2	↓ 1.2	↓ 1.4	↓ 0.1	↓ 0.8	↓ 0.8	↓ 0.8
Wet	Warm	12.1	↓ 5.8	↓ 0.3	↑ 2.0	↑ 2.8	↑ 2.8	↓ 5.5	↓ 0.6	↑ 2.1	↑ 3.3	↑ 3.0
	Cool	11.8	↓ 7.5	↓ 1.6	↑ 3.7	↑ 5.3	↑ 5.3	↓ 7.1	↓ 1.0	↑ 3.7	↑ 6.1	↑ 5.5
Very Wet	Hot	12.0	↓ 7.0	↓ 0.8	↑ 3.7	↑ 7.0	↑ 9.4	↓ 6.6	↓ 1.2	↑ 2.9	↑ 7.0	↑ 9.1
	Cold	11.1	↓ 7.3	↓ 1.2	↑ 3.4	↑ 2.3	↑ 2.3	↓ 6.6	↓ 0.8	↑ 3.4	↑ 2.3	↑ 2.3

Notes:

1. The percentage change in split V6 and Split V13 shows the deviation from the pre-plant broadcast.
2. The cells shaded by blue colour indicate the best practices for maximizing yield.

Table 4. 4 Comparison of Profits in Different Management Practices under Different Weather Conditions illustrates that split N application is more profitable under alternative weather conditions than pre-plant broadcast. Adjusting the N rate in the second application emerges higher profit than adopting split N application over pre-plant broadcast.

Weather		**Pre-plant Broadcast** ($/ha)	**Split V6** (%)					**Split V13** (%)				
			Low (129 kg N ha^{-1})	**Low** (149 kg N ha^{-1})	**Moderate** (169 kg N ha^{-1})	**High** (189 kg N ha^{-1})	**High** (209 kg N ha^{-1})	**Low** (129 kg N ha^{-1})	**Low** (149 kg N ha^{-1})	**Moderate** (169 kg N ha^{-1})	**High** (189 kg N ha^{-1})	**High** (209 kg N ha^{-1})
Very Dry	Hot	284	↓ 0.4	↓ 7.4	↓ 14.2	↓ 21.2	↓ 28.1	↑ 3.5	↓ 3.5	↓ 10.3	↓ 17.3	↓ 24.2
	Cold	312	↓ 0.2	↓ 6.6	↓ 12.8	↓ 19.1	↓ 25.4	↑ 3.2	↓ 3.2	↓ 9.4	↓ 15.7	↓ 22.0
Dry	Warm	487	↑ 4.0	↓ 4.4	↓ 8.4	↓ 12.4	↓ 16.4	↑ 7.1	↓ 2.0	↓ 6.0	↓ 10.1	↓ 14.1
	Cool	533	↑ 9.2	↓ 3.4	↓ 7.0	↓ 10.7	↓ 14.4	↑ 10.6	↓ 1.8	↓ 5.5	↓ 9.2	↓ 12.9
Moderate	Moderate	724	↓ 3.3	↓ 2.3	↓ 7.1	↓ 9.9	↓ 12.6	↓ 2.2	↓ 1.6	↓ 6.1	↓ 8.8	↓ 11.5
Wet	Warm	800	↓ 13.0	↓ 2.0	↑ 1.3	↑ 0.8	↓ 1.7	↓ 12.3	↓ 2.7	↑ 1.6	↑ 1.9	↓ 1.1
	Cool	758	↓ 17.8	↓ 5.3	↑ 5.6	↑ 7.1	↑ 4.5	↓ 16.8	↓ 3.9	↑ 5.6	↑ 9.0	↑ 4.9
Very Wet	Hot	794	↓ 16.0	↓ 3.1	↑ 5.4	↑ 11.1	↑ 14.5	↓ 15.1	↓ 4.1	↑ 3.5	↑ 11.1	↑ 13.9
	Cold	646	↓ 19.0	↓ 4.8	↑ 5.1	↓ 1.1	↓ 4.2	↓ 17.1	↓ 3.8	↑ 5.0	↓ 1.1	↓ 4.2

Notes:

1. The percentage change in split V6 and Split V13 shows the deviation from the pre-plant broadcast.
2. The cells shaded by blue colour indicate the best practices for maximizing profit.

Table 4. 5 Comparison of NO_3^- Leaching Associated with Different Practices under Different Weather Conditions shows adjusting N rate split emerges minimum N losses than adopting split N application over pre-plant broadcast. Also, split N application is economically and environmentally win-win practice under certain weather scenarios.

Weather		**Pre-plant Broadcast** (kgN/ha)	**Split V6** (%)					**Split V13** (%)				
			Low (129 kg N ha^{-1})	**Low** (149 kg N ha^{-1})	**Moderate** (169 kg N ha^{-1})	**High** (189 kg N ha^{-1})	**High** (209 kg N ha^{-1})	**Low** (129 kg N ha^{-1})	**Low** (149 kg N ha^{-1})	**Moderate** (169 kg N ha^{-1})	**High** (189 kg N ha^{-1})	**High** (209 kg N ha^{-1})
Very Dry	Hot	12.8	⬇ 22.2	⬇ 12.5	⬇ 5.2	⬆ 3.7	⬆ 11.9	⬇ 23.3	⬇ 15.5	⬇ 8.3	⬇ 0.7	⬆ 6.0
	Cold	14.2	⬇ 22.4	⬇ 13.8	⬇ 4.0	⬆ 3.7	⬆ 11.9	⬇ 23.7	⬇ 16.6	⬇ 9.4	⬇ 3.3	⬆ 3.3
Dry	Warm	16.9	⬇ 22.7	⬇ 15.1	⬇ 5.9	⬆ 2.6	⬆ 12.6	⬇ 24.4	⬇ 18.9	⬇ 12.3	⬇ 4.8	⬆ 2.5
	Cool	18.0	⬇ 21.9	⬇ 15.8	⬇ 6.1	⬆ 2.0	⬆ 11.4	⬇ 23.6	⬇ 19.3	⬇ 12.7	⬇ 6.1	⬆ 1.2
Moderate	Moderate	21.2	⬇ 19.3	⬇ 15.2	⬇ 8.2	⬇ 0.1	⬆ 10.0	⬇ 21.3	⬇ 19.3	⬇ 15.9	⬇ 9.4	⬇ 1.8
Wet	Warm	24.9	⬇ 19.2	⬇ 15.6	⬇ 11.3	⬇ 7.0	⬆ 2.7	⬇ 21.2	⬇ 19.8	⬇ 18.2	⬇ 16.2	⬇ 9.9
	Cool	27.4	⬇ 20.2	⬇ 16.0	⬇ 11.2	⬇ 4.5	⬆ 3.6	⬇ 22.3	⬇ 20.0	⬇ 17.7	⬇ 15.0	⬇ 7.5
Very Wet	Hot	28.5	⬇ 19.4	⬇ 16.4	⬇ 12.8	⬇ 9.5	⬇ 5.4	⬇ 21.5	⬇ 20.2	⬇ 19.4	⬇ 17.8	⬇ 16.2
	Cold	35.6	⬇ 21.7	⬇ 17.4	⬇ 11.8	⬇ 1.8	⬆ 6.6	⬇ 23.8	⬇ 21.4	⬇ 18.0	⬇ 11.8	⬇ 5.0

Notes:

1. The percentage change in split V6 and Split V13 shows the deviation from the pre-plant broadcast.
2. The cells shaded by orange, green and blue colours indicate the environmentally and economically win-win, environmentally win, and economically win practices.

Table 4. 6 Comparison of N_2O Emission Associated with Different Practices under Different Weather Conditions similarly shows that adjusting N rate split emerges minimum N losses than adopting split N application over pre-plant broadcast. Also, split N application is economically and environmentally win-win practice under certain weather scenarios.

Weather		**Pre-plant Broadcast** (kgN/ha)	**Split V6** (%)					**Split V13** (%)				
			Low (129 kg N ha^{-1})	**Low** (149 kg N ha^{-1})	**Moderate** (169 kg N ha^{-1})	**High** (189 kg N ha^{-1})	**High** (209 kg N ha^{-1})	**Low** (129 kg N ha^{-1})	**Low** (149 kg N ha^{-1})	**Moderate** (169 kg N ha^{-1})	**High** (189 kg N ha^{-1})	**High** (209 kg N ha^{-1})
Very Dry	Hot	0.74	↓ 14.9	↓ 2.7	↑ 5.4	↑ 16.2	↑ 27.0	↓ 24.3	↓ 18.9	↓ 12.2	↓ 4.1	↑ 2.7
	Cold	0.51	↓ 7.8	↑ 7.8	↑ 25.5	↑ 37.3	↑ 51.0	↓ 15.7	↓ 2.0	↑ 9.8	↑ 21.6	↑ 35.3
Dry	Warm	0.72	↓ 11.1	↑ 0.0	↑ 12.5	↑ 22.2	↑ 33.3	↓ 20.8	↓ 13.9	↓ 5.6	↑ 4.2	↑ 13.9
	Cool	0.6	↓ 10.0	↑ 3.3	↑ 18.3	↑ 30.0	↑ 43.3	↓ 18.3	↓ 6.7	↑ 3.3	↑ 15.0	↑ 28.3
Moderate	Moderate	0.68	↓ 11.8	↑ 4.4	↑ 17.6	↑ 26.5	↑ 38.2	↓ 20.6	↓ 8.8	0.0	↑ 8.8	↑ 19.1
Wet	Warm	0.75	↓ 12.0	↑ 2.7	↑ 17.3	↑ 26.7	↑ 38.7	↓ 20.0	↓ 12.0	↓ 1.3	↑ 8.0	↑ 16.0
	Cool	0.62	↓ 9.7	↑ 4.8	↑ 21.0	↑ 35.5	↑ 46.8	↓ 16.1	↓ 6.5	↑ 6.5	↑ 16.1	↑ 27.4
Very Wet	Hot	0.84	↓ 14.3	↓ 2.4	↑ 10.7	↑ 19.0	↑ 31.0	↓ 22.6	↓ 15.5	↓ 8.3	↑ 1.2	↑ 10.7
	Cold	0.55	↓ 5.5	↑ 9.1	↑ 27.3	↑ 41.8	↑ 52.7	↓ 12.7	↓ 1.8	↑ 10.9	↑ 21.8	↑ 32.7

Notes:

1. The percentage change in split V6 and Split V13 shows the deviation from the pre-plant broadcast.
2. The cells shaded by orange, green and blue colours indicate the environmentally and economically win-win, environmentally win, and economically win practices.

Table 4. 7 Comparison of NH_3 Volatilization in Different Management Practices under Different Weather Conditions presents that adjusting N rate split induces minimum N losses than adopting split N application over pre-plant broadcast. Also, split N application is economically and environmentally win-win practice under certain weather scenarios.

Weather		**Pre-plant Broadcast** (kgN/ha)	**Split V6** (%)					**Split V13** (%)				
			Low (129 kg N ha^{-1})	**Low** (149 kg N ha^{-1})	**Moderate** (169 kg N ha^{-1})	**High** (189 kg N ha^{-1})	**High** (209 kg N ha^{-1})	**Low** (129 kg N ha^{-1})	**Low** (149 kg N ha^{-1})	**Moderate** (169 kg N ha^{-1})	**High** (189 kg N ha^{-1})	**High** (209 kg N ha^{-1})
Very Dry	Hot	41.5	↓ 48.4	↓ 48.4	↓ 32.4	↓ 22.7	↓ 9.7	↓ 48.6	↓ 44.6	↓ 33.3	↓ 21.6	↓ 5.7
	Cold	39.1	↓ 47.5	↓ 47.5	↓ 47.5	↓ 33.7	↓ 22.6	↓ 47.7	↓ 47.7	↓ 40.6	↓ 24.4	↓ 10.6
Dry	Warm	36.5	↓ 47.5	↓ 47.5	↓ 40.4	↓ 25.0	↓ 16.6	↓ 47.7	↓ 44.5	↓ 31.5	↓ 18.9	↓ 2.7
	Cool	34.2	↓ 44.4	↓ 44.4	↓ 44.4	↓ 28.7	↓ 19.3	↓ 44.6	↓ 44.6	↓ 34.8	↓ 18.8	↓ 5.0
Moderate	Moderate	32.4	↓ 50.9	↓ 50.9	↓ 50.9	↓ 33.5	↓ 21.9	↓ 51.1	↓ 48.7	↓ 36.0	↓ 20.5	↓ 3.6
Wet	Warm	29.8	↓ 52.5	↓ 52.5	↓ 52.5	↓ 30.0	↓ 19.3	↓ 52.6	↓ 47.3	↓ 33.4	↓ 16.3	↑ 4.7
	Cool	26.7	↓ 47.7	↓ 47.7	↓ 47.7	↓ 40.4	↓ 17.7	↓ 47.8	↓ 47.8	↓ 38.0	↓ 16.8	↑ 0.6
Very Wet	Hot	28.3	↓ 50.8	↓ 50.8	↓ 42.5	↓ 20.8	↓ 8.1	↓ 51.0	↓ 43.5	↓ 26.7	↓ 7.8	↑ 15.6
	Cold	21.0	↓ 54.5	↓ 54.5	↓ 54.5	↓ 47.4	↓ 23.3	↓ 54.7	↓ 54.7	↓ 44.7	↓ 15.3	↑ 12.1

Notes:

1. The percentage change in split V6 and Split V13 shows the deviation from the pre-plant broadcast.
2. The cells shaded by orange, green and blue colours indicate the environmentally and economically win-win, environmentally win, and economically win practices.

Table 4. 8 Profit-Scaled N Loss Associated with Different Management Practices under Different Weather Conditions shows that profit maximizing management practices generate low profit-scaled N losses compare to the pre-plant broadcast method.

Weather		**Pre-plant Broadcast (kgN/$)**	**Split V6 (kgN/$)**					**Split V13 (kgN/$)**				
			Low (129 kg N ha^{-1})	**Low** (149 kg N ha^{-1})	**Moderate** (169 kg N ha^{-1})	**High** (189 kg N ha^{-1})	**High** (209 kg N ha^{-1})	**Low** (129 kg N ha^{-1})	**Low** (149 kg N ha^{-1})	**Moderate** (169 kg N ha^{-1})	**High** (189 kg N ha^{-1})	**High** (209 kg N ha^{-1})
Very Dry	Hot	19.4	11.3	12.7	16.8	20.6	25.8	10.8	12.6	15.7	19.6	24.8
	Cold	17.2	10.3	11.4	12.8	16.3	20.1	9.8	10.8	12.9	16.7	20.6
Dry	Warm	1.1	6.5	7.3	8.6	10.7	12.4	6.2	7.2	8.9	10.6	12.8
	Cool	9.9	5.8	6.8	7.4	9.1	10.6	5.6	6.5	7.7	9.4	11.1
Moderate	Moderate	7.5	4.8	4.9	5.4	6.7	7.8	4.7	4.8	5.8	6.9	8.3
Wet	Warm	6.9	5.0	4.6	4.6	5.6	6.4	4.9	4.7	5.0	5.7	6.9
	Cool	7.2	5.8	5.2	4.9	5.3	6.5	5.7	5.0	5.0	5.6	6.7
Very Wet	Hot	7.3	5.6	5.0	5.0	5.6	5.9	5.5	5.2	5.4	5.7	6.4
	Cold	8.9	7.3	6.4	6.1	7.3	8.9	6.9	6.1	6.1	7.8	9.4

Notes:

1. The cells shaded by blue colours indicate the economically win practices.

FIGURE

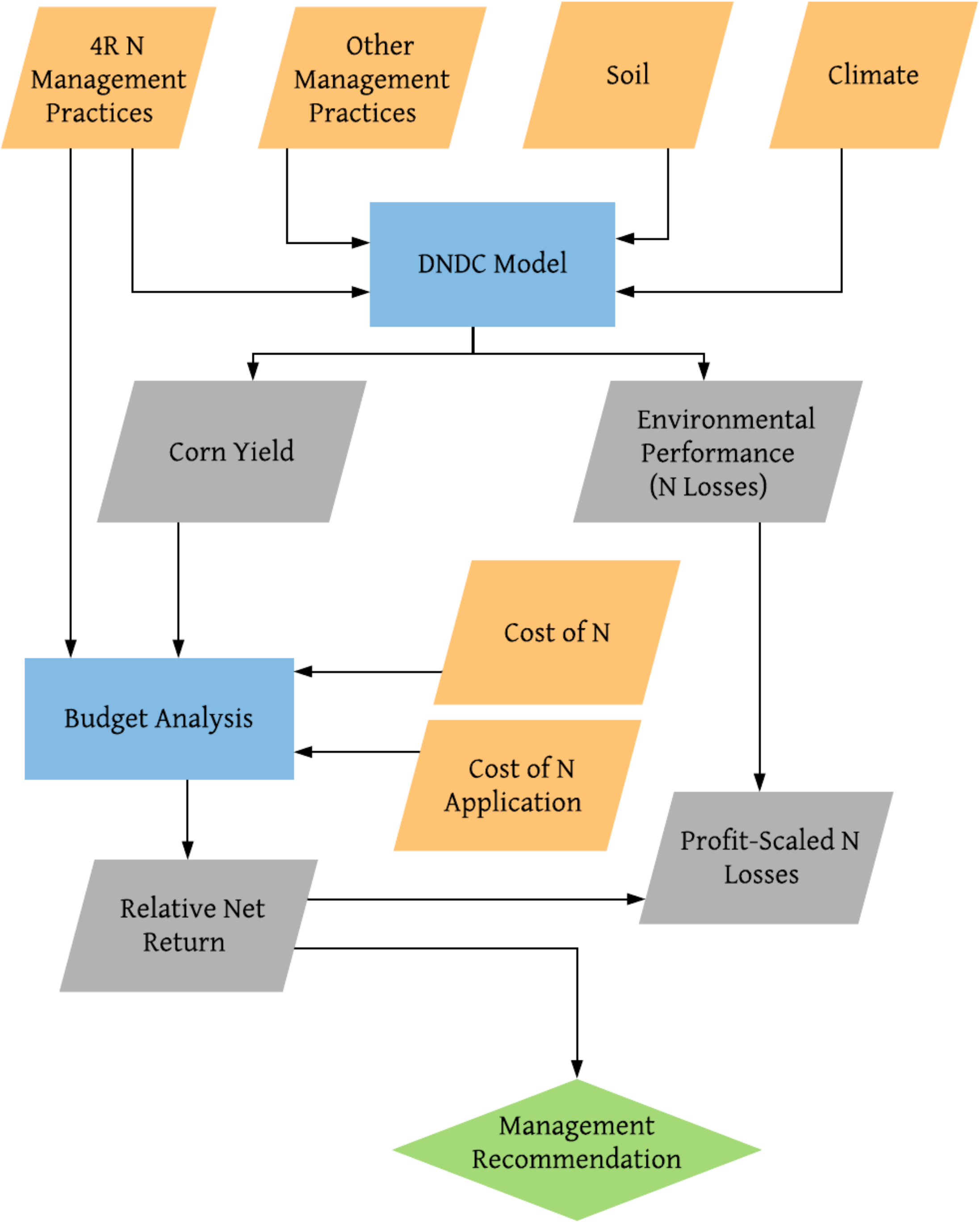

Figure 4. 1 The Flowchart of Empirical Model presents the method used to evaluate the effect of split N application on corn yield and environmental parameters using management practices, weather and soil data.

CHAPTER 5

CONCLUSION

5.1 Summary

4R nutrient stewardship is a site-based program due to environmental factors (such as soil and climate conditions), crops, and management practices. Split N application synchronizes the supply of N fertilizer with the demand of the crop, by minimizing the residence time of N in the soil and ensuring crop N demands are met during rapid growth. The benefits of split N application are that the N rate can be adjusted based on crop N demand, soil N supply, and weather scenarios. The impediment of adopting split N application is a lack of evidence of profitability compared to traditional practices. Thus, the purpose of the thesis is to evaluate the agronomic, environmental, and economic performance of split N application in corn relative to a traditional pre-plant broadcast under alternative weather scenarios. The study simulates the yield and environmental parameters of different management practices using DNDC and analyzes budgets to evaluate profit-maximizing management practices under alternative weather conditions. Also, to evaluate the effect of adjusting N rates in split application, the N rate is modestly increased or decreased in the second application.

The study has found that management practices have significant impacts on the agronomic, economic and environmental performance of corn production. Adjusting N rates during the growing season generates greater profit than adopting single rate split N application or pre-plant broadcast. Split N applications maximized yield under dry, wet, and very wet weather conditions, whereas pre-plant broadcast generated higher yields under normal weather conditions. Farmers would remain indifferent between pre-plant broadcast and split V13 under very dry conditions. Split N application was more profitable than traditional pre-plant broadcast under alternative weather conditions when N rates were adjusted. Split V6 was profitable under very wet weather conditions, whereas split V13 led to higher profit under very dry, dry and wet weather conditions. 129 kg N ha^{-1} in split application induced greater profit under very dry and dry conditions, while higher N rates (189 kg N ha^{-1} and 209 kg N ha^{-1}) under wet and very wet and hot conditions induced higher profit. Moderate rate (169 kg N ha^{-1}) in split application was profitable only under very wet and cold conditions. Split N application reduced environmental impacts in all weather conditions. However, economically recommended farming management practices did not always imply a win-win case for economic and environmental aspects. Although a high N rate in wet and very wet weather conditions led to maximum profit, the environmental losses increased along with an increase in N rate. However, split N application generated higher profit and lessened water and air pollution by reducing NO_3^- leaching, N_2O emissions, and NH_3 volatilization compared to the traditional method.

Adjusting N rates changed the management decisions for yield response, profitability, environmental impacts, and profit-scaled N losses under certain weather conditions. For example, applying 129 kg N ha^{-1} and 209 kg N ha^{-1} changed the management decisions for yield in dry and very wet and hot weather conditions. Adjusting N rates during the season maximized the yield under dry, wet, and very wet and hot conditions. Applying 129 kg ha^{-1} of N in split application increased profit under very dry and dry weather conditions but decreased them in normal, wet, and very wet conditions. At 209 kg N ha^{-1}, profit decreased under all weather conditions except very wet and hot. When leaching and emissions in split applications were maximum at 209 kg N ha^{-1}, both were minimum at 129 kg N ha^{-1} under different weather conditions. The volatilization losses at 129 kg N ha^{-1} in split V6 remained unchanged but increased with 209 kg N ha^{-1}. On the other hand, volatilization losses were unchanged in split V13 at 129 kg N ha^{-1} when the temperature was low but increased at 209 kg N ha^{-1}. Profit-scaled N losses showed positive, negative or no changes in 129 kg N ha^{-1} in split application N rates. In contrast, at 209 kg N ha^{-1}, the profit-scaled N losses increased under different weather scenarios.

5.2 Contributions and Implications of Research

For current ongoing research on the economic feasibility of split N application, this thesis provides evidence of higher agronomic, economic, and environmental benefits with split N application over the traditional pre-plant broadcast method, depending on weather scenarios. The method used in the study also provides researchers with examples of integrated predictions of yield and N losses in crop production. The trade-off between the environment and profitability implies that split application has higher net returns and lower N losses for farmers, ensuring sustainable agricultural practices. It is evident from the study that split N application enhances not only the quality and quantity of crop production for farmers but also reduces N losses. Adjusting N rates during the growing season allows farmers to provide required N for crops in rapid growth stages and adjust fertilizer costs accordingly under certain weather conditions. As split N application has environmental gains with increased profit, by promoting such practices, the government can balance economic and environmental benefits to promote sustainable agriculture.

As a fertilizer BMP, split N application with a second application made in season is a practical management practice to mitigate N losses to the environment. The thesis concludes split N application maximizes net return under extreme weather scenarios, which is a major concern for farmers while adopting new management practices. This thesis implies that the magnitude of change in net return under certain weather conditions allows farmers to make decisions about management practices and N rates in corn production. Also, if the goal is to minimize the environmental impacts, the magnitude of change in environmental parameters allows farmers to choose split N application during all weather conditions.

5.3 Suggestions for Further Research

In the analysis, hypothetical weather scenarios were created using the weather data of Elora, Ontario. The results might vary with real weather scenarios in different regions under various crop types, weather, and soil conditions. Weather scenarios were assumed to have smooth rainfall, leaving extreme weather events (e.g., 30 mm of rainfall on one day) excluded from the simulation. These point events appear to cause considerable N losses, especially earlier in the growing season, thereby leaving some N losses unaccounted. Further research should consider more realistic weather scenarios and extreme weather events. The study excluded uncertainty concerns, e.g., weather or soil moisture at the time of N application. Uncertainty in corn production increases or decreases the optimal N rate for farmers, depending on the convexity of the marginal product of N function (Babcock, 1992). Thus, the values of yield, profitability, and environmental impacts will change. The study also assumed no effect of demand, supply and prices of inputs and outputs under extreme weather conditions. Further research is suggested to focus on the drivers of demand, supply, and price changes and how they influence the decision of management practices for farmers under alternative weather scenarios. The study also assumed the similar custom costs for split V6 and split V13. Delaying N application requires high-clearance equipment to apply the fertilizer, which may vary at the V13 stage. Further research is suggested to investigate the real custom cost or additional costs associated with split V13. The study did not address the feasibility of adopting split application for a small-scale farmer, especially delayed until V13 when the custom cost changes or custom work is unavailable. 4R is promoted to adopt voluntarily in management practices, thus, the willingness to adopt split application under alternative weather conditions can be an area for further research. Finally, more field experimental data on split applications in different regions under different weather and soil conditions are required for a robust and transferrable result about the agronomic, environmental and economic performance of this 4R nutrient management practice.

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APPENDICES

Table A. 1 Simulated Yield Response Associated with Different Practices under Different Weather Conditions

Weather		**Pre-plant Broadcast (t/ha)**	**Split V6 (t/ha)**					**Split V13 (t/ha)**				
			Low (129 kg N ha^{-1})	**Low** (149 kg N ha^{-1})	**Moderate** (169 kg N ha^{-1})	**High** (189 kg N ha^{-1})	**High** (209 kg N ha^{-1})	**Low** (129 kg N ha^{-1})	**Low** (149 kg N ha^{-1})	**Moderate** (169 kg N ha^{-1})	**High** (189 kg N ha^{-1})	**High** (209 kg N ha^{-1})
Very Dry	Hot	8.9	8.8	8.8	8.8	8.8	8.8	8.9	8.9	8.9	8.9	8.9
	Cold	9.1	9.0	9.0	9.0	9.0	9.0	9.1	9.1	9.1	9.1	9.1
Dry	Warm	10.1	10.2	10.1	10.1	10.1	10.1	10.3	10.1	10.1	10.1	10.1
	Cool	10.4	10.7	10.4	10.4	10.4	10.4	10.7	10.4	10.4	10.4	10.4
Moderate	Moderate	11.6	11.4	11.6	11.5	11.5	11.5	11.4	11.6	11.5	11.5	11.5
Wet	Warm	12.1	11.4	12.0	12.3	12.4	12.4	11.4	12.0	12.3	12.5	12.4
	Cool	11.8	10.9	11.6	12.2	12.4	12.4	11.0	11.7	12.2	12.5	12.5
Very Wet	Hot	12.0	11.2	11.9	12.5	12.9	13.2	11.2	11.9	12.4	12.9	13.1
	Cold	11.1	10.3	11.0	11.5	11.4	11.4	10.4	11.0	11.5	11.4	11.4

Table A. 2 Simulated Profits in Different Management Practices under Different Weather Conditions

Weather		**Pre-plant Broadcast ($/ha)**	**Split V6 ($/ha)**					**Split V13 ($/ha)**				
			Low (129 kg N ha^{-1})	**Low** (149 kg N ha^{-1})	**Moderate** (169 kg N ha^{-1})	**High** (189 kg N ha^{-1})	**High** (209 kg N ha^{-1})	**Low** (129 kg N ha^{-1})	**Low** (149 kg N ha^{-1})	**Moderate** (169 kg N ha^{-1})	**High** (189 kg N ha^{-1})	**High** (209 kg N ha^{-1})
Very Dry	Hot	284	283	263	244	224	204	294	274	255	235	215
	Cold	312	312	292	272	253	233	322	302	283	263	244
Dry	Warm	487	506	466	446	426	407	521	477	457	438	418
	Cool	533	583	515	496	476	457	590	524	504	484	465
Moderate	Moderate	724	700	707	672	653	633	708	712	680	660	641
Wet	Warm	800	696	784	810	806	786	702	778	813	816	791
	Cool	758	623	717	801	812	792	631	728	801	826	795
Very Wet	Hot	794	667	769	837	882	909	674	761	822	882	904
	Cold	646	523	615	678	638	618	535	621	677	638	618

Table A. 3 Simulated NO_3 Leaching Associated with Different Practices under Different Weather Conditions

Weather		**Pre-plant Broadcast** (kgN/ha)	**Split V6 (kgN/ha)**					**Split V13 (kgN/ha)**				
			Low (129 kg N ha^{-1})	**Low** (149 kg N ha^{-1})	**Moderate** (169 kg N ha^{-1})	**High** (189 kg N ha^{-1})	**High** (209 kg N ha^{-1})	**Low** (129 kg N ha^{-1})	**Low** (149 kg N ha^{-1})	**Moderate** (169 kg N ha^{-1})	**High** (189 kg N ha^{-1})	**High** (209 kg N ha^{-1})
Very Dry	Hot	12.8	10.0	11.2	12.2	13.3	14.4	9.8	10.8	11.8	12.7	13.6
	Cold	14.2	11.0	12.3	13.6	14.7	15.9	10.8	11.9	12.9	13.7	14.7
Dry	Warm	16.9	13.0	14.3	15.9	17.3	19.0	12.7	13.7	14.8	16.0	17.3
	Cool	18.0	14.1	15.2	16.9	18.4	20.0	13.7	14.5	15.7	16.9	18.2
Moderate	Moderate	21.2	17.2	18.0	19.5	21.2	23.4	16.7	17.1	17.9	19.3	20.9
Wet	Warm	24.9	20.2	21.1	22.1	23.2	25.6	19.7	20.0	20.4	20.9	22.5
	Cool	27.4	21.9	23.0	24.3	26.2	28.4	21.3	21.9	22.5	23.3	25.3
Very Wet	Hot	28.5	23.0	23.9	24.9	25.8	27.0	22.4	22.8	23.0	23.4	23.9
	Cold	35.6	27.9	29.5	31.4	35.0	38.0	27.2	28.0	29.2	31.5	33.9

Table A. 4 Simulated N_2O Emissions Associated with Different Practices under Different Weather Conditions

Weather		Pre-plant Broadcast (kgN/ha)	Split V6 (kgN/ha)					Split V13 (kgN/ha)				
			Low (129 kg N ha^{-1})	**Low** (149 kg N ha^{-1})	**Moderate** (169 kg N ha^{-1})	**High** (189 kg N ha^{-1})	**High** (209 kg N ha^{-1})	**Low** (129 kg N ha^{-1})	**Low** (149 kg N ha^{-1})	**Moderate** (169 kg N ha^{-1})	**High** (189 kg N ha^{-1})	**High** (209 kg N ha^{-1})
Very Dry	Hot	0.74	0.63	0.72	0.78	0.86	0.94	0.56	0.60	0.65	0.71	0.76
	Cold	0.51	0.47	0.55	0.64	0.70	0.77	0.43	0.50	0.56	0.62	0.69
Dry	Warm	0.72	0.64	0.72	0.81	0.88	0.96	0.57	0.62	0.68	0.75	0.82
	Cool	0.60	0.54	0.62	0.71	0.78	0.86	0.49	0.56	0.62	0.69	0.77
Moderate	Moderate	0.68	0.6	0.71	0.80	0.86	0.94	0.54	0.62	0.68	0.74	0.81
Wet	Warm	0.75	0.66	0.77	0.88	0.95	1.04	0.60	0.66	0.74	0.81	0.87
	Cool	0.62	0.56	0.65	0.75	0.84	0.91	0.52	0.58	0.66	0.72	0.79
Very Wet	Hot	0.84	0.72	0.82	0.93	1.00	1.10	0.65	0.71	0.77	0.85	0.93
	Cold	0.55	0.52	0.60	0.70	0.78	0.84	0.48	0.54	0.61	0.67	0.73

Table A. 5 NH_3 Volatilization in Different Management Practices under Different Weather Conditions

Weather		**Pre-plant Broadcast (kgN/ha)**	**Split V6 (kgN/ha)**					**Split V13 (kgN/ha)**				
			Low (129 kg N ha^{-1})	**Low** (149 kg N ha^{-1})	**Moderate** (169 kg N ha^{-1})	**High** (189 kg N ha^{-1})	**High** (209 kg N ha^{-1})	**Low** (129 kg N ha^{-1})	**Low** (149 kg N ha^{-1})	**Moderate** (169 kg N ha^{-1})	**High** (189 kg N ha^{-1})	**High** (209 kg N ha^{-1})
Very Dry	Hot	41.5	21.4	21.4	28.0	32.1	37.4	21.3	23.0	27.7	32.5	39.1
	Cold	39.1	20.5	20.5	20.5	25.9	30.2	20.4	20.4	23.2	29.5	34.9
Dry	Warm	36.5	19.2	19.2	21.8	27.4	30.5	19.1	20.3	25.0	29.7	35.6
	Cool	34.2	19.0	19.0	19.0	24.4	27.6	19.0	19.0	22.3	27.8	32.5
Moderate	Moderate	32.4	15.9	15.9	15.9	21.6	25.3	15.9	16.6	20.7	25.8	31.3
Wet	Warm	29.8	14.1	14.1	14.1	20.8	24.0	14.1	15.7	19.8	24.9	31.2
	Cool	26.7	13.9	13.9	13.9	15.9	21.9	13.9	13.9	16.5	22.2	26.8
Very Wet	Hot	28.3	13.9	13.9	16.2	22.4	26.0	13.8	16.0	20.7	26.1	32.7
	Cold	21.0	9.6	9.6	9.6	11.1	16.1	9.5	9.5	11.6	17.8	23.6