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On-farm Nitrogen and Irrigation Management Strategies to Protect Groundwater Quality in the Bazile Groundwater Management Area

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ON-FARM NITROGEN AND IRRIGATION MANAGEMENT STRATEGIES TO PROTECT GROUNDWATER QUALITY IN THE BAZILE GROUNDWATER MANAGEMENT AREA

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ON-FARM NITROGEN AND IRRIGATION MANAGEMENT STRATEGIES TO PROTECT GROUNDWATER QUALITY IN THE BAZILE GROUNDWATER MANAGEMENT AREA

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Increasing groundwater nitrate (NO_3-N) contamination has raised significant environmental and health concerns in the irrigated sandy soils of Nebraska. Four studies were conducted to evaluate the impact the impact of 1) static (NE Yield Goal) vs. dynamic nitrogen (N) recommendations tools (Maize-N, Canopy Reflectance Sensing, Granular, and Adapt-N), 2) three N (optimum, suboptimum, and low) and irrigation rates (farmer's full irrigation (FIT), 80% FIT, and 60% FIT), 3) conventional N sources vs. enhanced efficiency fertilizers (EEFs), and 4) multiple N splits (2, 3, 4, and 5-N splits) on agronomic (maize yield), environmental (NO_3-N leaching), and economic returns (return to N (RTN) and RTN after considering environmental costs (RTN_{Env}). The first study indicated that the static Nebraska Yield Goal outperformed all the dynamic N tools by predicting the N rate and yield closer to EONR. At the same time, Maize-N recommended N above- and Canopy Reflectance Sensing, Granular, and Adapt-N below the EONR range. Environmentally, N tools did not significantly affect NO_3-N leaching. Economically, all tools were equally effective in determining RTN_{Env}. In the second study, a reduction in N rate by 25% in the suboptimum (202 kg ha^{-1}) and 50% in low N

rate (135 kg ha^{-1}) reduced NO_3-N leaching by 24% (7 kg NO_3-N ha^{-1}) and 51% (15 kg NO_3-N ha^{-1}), maize grain yield by 8% (14.5 Mg ha^{-1}) and 11% (14.0 Mg ha^{-1}), and RTN by \$215 ha^{-1} and \$298 ha^{-1}, respectively. The 80% FIT had significantly higher grain yield and RTN, and lower NO_3-N leaching by 13-21% than 60% FIT and FIT. In the third study, the use of EEFs (i.e., urea with urease and dual (urease and nitrification) inhibitors) in a single pre-plant application substantially decreased NO_3-N leaching with the levels approaching control treatments in both years, and had the same or better crop yield, and improved economic returns than conventional Urea-UAN split and pre-plant Urea. Lastly, we did not observe any benefit of increasing the number of in-season N-split applications in protecting groundwater quality or improving maize yield in a dry year. Overall, these findings will help producers and policymakers decide the right nitrogen recommendation tools, nitrogen source, and irrigation rates for improving agronomic, economic, and environmental performance.

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PREFACE

CHAPTER 2 is currently under preparation for submission to Soil Science Society of America Journal

Singh A., Rudnick, D., Snow, D., Proctor, C., & Iqbal, J. "*Agronomic, Environmental and Economic Performance of Static vs. Dynamic Nitrogen Recommendation Tools in Irrigated Sandy Soils of Northeast Nebraska*".

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Singh A., Rudnick, D., Snow, D., Proctor, C., & Iqbal, J. "*Tradeoffs Between Maize Yield, Economics, and Groundwater Quality in the Irrigated Sandy Soils of Bazile Groundwater Management Area in Nebraska*".

CHAPTER 4 is currently under preparation for submission to Soil Science Society of America Journal

Singh A., Rudnick, D., Snow, D., Proctor, C., & Iqbal, J. "*Enhanced Efficiency Fertilizers Improve Groundwater Water Quality in the Bazile Groundwater Management Area of Northeast Nebraska*".

CHAPTER 5 is currently under review in Agrosystems, Geosciences & Environment Journal

Singh A., Rudnick, D., Snow, D., Proctor, C., & Iqbal, J. "*Impact of split nitrogen applications on nitrate leaching and corn yield in irrigated loamy sand soils of Northeast Nebraska*".

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CHAPTER 1

GENERAL INTRODUCTION

Maize Production, Nitrogen Consumption And Losses

Nitrogen (N) is one of the critical crop nutrients needed for increased maize production worldwide. With the increasing population and expanding agricultural lands, N fertilizer consumption has dramatically increased. For example, agricultural use of N fertilizers increased from 11.4 Mega-tonnes (Mt) in 1961 to 107.7 Mt in 2019 (FAOSTAT, 2020) and is predicted to increase by two to three folds by 2050 (Tilman et al., 2002) to meet grain demand increase of 25-70% relative to 2014 (Hunter et al., 2017). When used excessively, N fertilizers lead to a range of environmental problems such as water contamination, biodiversity loss, and greenhouse gas emissions (Iqbal et al., 2013, 2015, 2018; Lin et al., 2012). Nitrogen loss through leaching and runoff deteriorates water resources, both belowground and surface, resulting in non-potable water supplies and eutrophication.

The US is one of the largest maize producers in the world (Hunt et al., 2020). Nebraska produces ~13% of the total maize in the US, with three-fifths of the state under irrigation. Producers in parts of the state commonly use excessive N and irrigation inputs to ensure higher crop yields. However, only 40-60% of the applied N fertilizer is recovered in the harvested crop product (Yan et al., 2014). This indicates low N use efficiency (NUE; the ratio of N recovered in harvested products relative to N inputs) and high potential N losses to the environment. The result of unrecovered N losses is evidenced in groundwater nitrate (NO_3-N) concentrations frequently exceeding the 10 mg L^{-1} EPA drinking water standard (Exner et al., 2014). For example, in the Bazile

Groundwater Management Area (BGMA), sandy soils with shallow depth to groundwater and extensive application of N fertilizer and irrigation water have resulted in a high level of NO_3-N contamination in the aquifer. This higher level of NO_3-N leaching to groundwater could be attributed to (1) poor synchrony between N fertilizer applications and crop N demand and (2) excessive N and irrigation inputs. Both result in the leaching of NO_3-N below the crop root zone. Improvements in NUE can be achieved by optimizing N and water inputs based on NO_3-N leaching. Optimized N and water inputs could help communities achieve cropping system goals such as increased crop production, profitability, enhanced environmental protection, and improved sustainability. The following strategies can help optimize nitrogen and water inputs in the irrigated maize cropping system of BGMA in Nebraska and elsewhere.

Maize Nitrogen Recommendation Tools

Excessive N fertilization in annual row crops potentially leads to excessive NO_3-N movement into the groundwater, affecting human health (Spalding et al., 2001), biodiversity, and groundwater-fed riverine systems (Hancock, 2002). On the other hand, reducing the N fertilizer rates decreases the NO_3-N movement and lowers the economic returns and profits to the farmers (Ruan et al., 2016). Therefore, it becomes mandatory to determine the optimum N fertilization rate that has the potential to maintain economically viable crop yields and provide environmental benefits such as reducing in N losses via nitrous oxide emissions and NO_3-N leaching, etc. Some of the factors that complicate the optimization of N include temporal and spatial variability of weather and soil (Archontoulis et al., 2020; Bastos, 2019; Mamo et al., 2003; Puntel et al., 2018, 2024;

Thompson et al., 2015) and poor correlation between optimum N rate and yield at optimum N rate (Thorburn et al., 2024).

Variable soil types, weather, and management practices result in under- and over-N application. Therefore, it would be worthwhile to pursue the variable N rate (VNR) application method for site-specific N applications (Mamo et al., 2003; Thompson et al., 2015, 2023). The VNR based on EONR can decrease N application up to 69 kg N ha^{-1} with little effect on grain yields and increase the profits by \$8-22 ha^{-1} than uniform N rate (Mamo et al., 2003). Other studies have reported that VNR can also increase N application upto 20 kg N ha^{-1} compared to uniform N rate with no differences in residual soil N Ferguson et al., 2002). Some earlier results have shown that EONR can typically be about 171-173 g N ha^{-1} in Nebraska. For example, 32 site-year research trials conducted on irrigated maize on farmer fields and research stations on diverse soils, tillage practices, and climate resulted in an average EONR of 171 kg N ha^{-1} in Nebraska (2002-2004) (Dobermann et al., 2011). In other 12 site-year research trials from 2004 to 2006, EONR was 173 kg N ha^{-1} in sandy soils (Alotaibi et al., 2018). Owing to factors such as weather and soil management at diverse temporal and spatial scales (Morris et al., 2018), no maize yield increase was observed to N application in silty clay loam soils from 156 to 234 (Pittelkow et al., 2017) and from 179 to 269 kg N ha^{-1} in silt loam soils of Illinois (Greer & Pittelkow, 2018); however, high variability for agronomic optimum N rate was observed for Nebraska, Missouri, and Illinois (Kaur et al., 2024). Furthermore, Puntel et al. (2016) observed higher optimum N rates during the years with above-normal spring precipitation, resulting in a reduction in the mineralization of soil organic matter leading to higher N losses (leaching and denitrification) and lower soil N availability for maize uptake. Similarly, Kaur et al. (2024) observed 80-160 kg N ha^{-1} higher optimum N rates and 50% lower grain yields in extremely wet climatic conditions than in normal years. Thompson et al. (2023) found that temporal variation was greater than spatial variation and was attributed mainly to inter-annual weather variation, leading to variation in yield.

Agricultural N recommendation tools are developed to optimize N and water inputs to maintain crop yields, reduce N losses, and extend the nutrient inputs to different soil types, seasonal weather variability, and varying management practices. However, the N tools can predict yield, but N rate predictions are highly uncertain (Thorburn et al., 2024). Broadly, two types of N tools exist: (i) static, and (ii) dynamic. The Nebraska yield goal (NE YG) is a static tool with a one-time N recommendation before the growing season (Iqbal et al., 2023). This tool's N recommendations are based on the Stanford yield goal approach that recommends N based on the mass balance equation driven by yield estimates, internal N cycling with soil type, and crop N uptake efficiency (Stanford, 1973). Furthermore, NE YG also possesses the unique features of requiring a wide range of inputs, such as NO_3-N in the maize root zone and irrigation water, N credits from soil organic matter, manure, and leguminous crop, and adjustments for N application timing and prices for yield and N etc, which makes it a successful tool for Nebraska conditions (Iqbal et al., 2023). However, NE YG does not consider annual weather variability for N rate recommendations. Limitations of this method have been described in the literature (Morris et al., 2018).

Meanwhile, other types of tools, known as dynamic N tools, consider annual weather variability in addition to soil and crop inputs, to recommend site-specific N rates

(Mandrini et al., 2021; Morris et al., 2018; Ransom et al., 2020). For example, Maize-N is a crop growth computer simulation model that recommends N based on the soil and crop processes, N transformations, crop N uptake, and soil N depletion (Setiyono et al., 2011). Adapt-N (Melkonian et al., 2008; Melkonian et al., 2005; Melkonian et al., 2007; van Es et al., 2007) and Granular (Gunzenhauser, 2023) are dynamic N tools that consider the site-specific soil and crop conditions, weather, and management inputs to optimize N inputs. Canopy reflectance sensing is another tool that uses active optimal canopy sensing of leaves to determine the leaves' darkness and quantify the in-season N needs using algorithms (Franzen et al., 2016; Holland & Schepers, 2010; Solari et al., 2008). The drawbacks of these dynamic N tools are the added costs of implementation, their accuracy, and their adaptability across diverse soil and weather conditions (Bean et al., 2021; Ransom et al., 2021). At the same time, previous research has shown no significant benefits of using dynamic N tools over static tools (Mandrini et al., 2021). For example, Puntel et al. (2018) reported that yield predictions using process-based models are reliable, but EONR predictions at the V6 maize developmental stage, even with known weather, are uncertain (R^2= 0.1). Similarly, no advantages of weather incorporation in EONR predictions were observed by Qin et al. (2018). Furthermore, Ransom et al. (2020) and Mandrini et al. (2021) also found that dynamic N tools do not consistently give better prediction of the EONR and N losses. However, Sela et al. (2017) found that Adapt-N increased farmer profit and improved EONR prediction compared to the Stanford-type maize nitrogen calculator in 14-site years of field trials in New York. Other examples of dynamic N tools include Agricultural Production Systems Simulator [APSIM; Keating et al. (2003)], Denitrification-Decomposition model [DNDC; Li et al.

(1992)], Hybrid-Maize (Yang et al., 2004), CERES-Maize (Jones & Kiniry, 1986), Decision Support System for Agrotechnology Transfer [DSSAT; Jones et al. (2003)], WOFOST (Van Diepen et al., 1989), and Root Zone Water Quality Model [RZWQM; Ahuja et al. (2000)], etc. All these dynamic N tools have varying water and nutrient use efficiencies. For example, N application based on chlorophyll meter readings saved >100 kg N/ha/year (Schepers et al., 1995). For the variable N fertilization levels, the APSIM, which accounts for N nutrition on crop water use, is likely more accurate (Manschadi et al., 2021). Puntel et al. (2018) predicted grain yield variability (77-81%) using historical weather data and current season growth stage specific weather data in APSIM model. For common fertilization rates, the simpler EVACROP seems appropriate (Vogeler et al., 2020). Results from EONR by RZWQM show that decreasing the N rate by 150 kg N /ha reduces N leaching by 18% (Thorp, 2007). Similarly, advancements in incorporating the historical weather and early season current year weather data help improve the irrigation scheduling and reduce the available N amount moving through the soil profile in the CERES-Maize model (Chen et al., 2020). Research is moving towards optimizing EONR to predict the maize yield gaps and available soil N supply to reduce N application while increasing economic and environmental profits (Morris et al., 2018; Puntel et al., 2018). Incorporation of weather and soil properties in existing maize N recommendation tools reduces the N rate recommendations when the N supply is sufficient whereas weather parameters incorporation leads to an increase in N recommendations (Ransom et al., 2021). Nevertheless, evaluation of static vs. dynamic N tools in high NO_3-N-contaminated areas in the Midwest is lacking. Moreover, most of the previous studies have reported the environmental impact of these models using simulations (e.g. Mandrini et al., 2021; Ransom et al. 2018), but not in-field NO_3-N leaching assessments.

Optimizing Irrigation And Nitrogen inputs

Nitrogen and water use significantly affect crop production and N dynamics at the soil-plant-water interface (Bhatti et al., 2022; Ferguson et al., 2012; Gunzenhauser et al., 2020; Irmak et al., 2022; Rudnick et al., 2017; Singh et al., 2021; Tarkalson et al., 2006). So, optimizing both factors based on NO_3-N leaching is necessary to achieve sustainable crop production in the Midwest maize-based cropping system.

Previous studies on N management in maize within Nebraska and neighboring states have primarily focused on N rate trials targeting optimizing N rate based on crop yield response, crop rotations, and soil textures (Banger et al., 2018; Cassman et al., 2003; Dinnes et al., 2002; Dobermann et al., 2011; Maharjan et al., 2016; Martin et al., 1994; Ransom et al., 2020; Rubin et al., 2016; Stanford, 1973; Struffert et al., 2016; Tubaña et al., 2008). However, very few studies have focused on N recommendations based on NO_3-N leaching in environmentally sensitive sites where groundwater NO_3-N contamination is a major concern (Sexton et al., 1998) This is in part because this type of research is often costly and requires intensive sampling for NO_3-N leaching measurements. Meanwhile, in other regions, researchers have suggested the use of suboptimal N rates to decrease NO_3-N leaching because maximizing the maize production with an economical optimum nitrogen rate comes with higher risks of N losses (Rose et al., 2018; Schröder et al., 1998). Moreover, the reduction of N input by half reduces the N losses by >50% (Ju et al., 2009; Vitousek et al., 2009; Quemada et al., 2013). For example, Schröder et al. (1998) in the Netherlands reported that applying N at a suboptimum N rate can reduce NO_3-N leaching risk with limited effect on maize yield. Similarly, Banger et al. (2020) in 270 distinct soil-climate regions in Canada, found that adjusting the N rate by 23-32% below the optimum N rate can significantly reduce NO_3-N leaching without impacting maize yield. However, Struffert et al. (2016) in Minnesota and Beaudoin et al. (2005) in Northern France reported that reducing N below the optimum level did not decrease NO_3-N leaching. These inconsistent effects of reduced N rates on NO_3-N leaching could be due to site-specific soil and climatic conditions (Li et al., 2023; Mzuku et al., 2005; Simmelsgaard & Djurhuus, 1998; Sogbedji et al., 2000; Zheng et al., 2020).

Similar to N, adjusting the amount of irrigation is another potential strategy to minimize NO_3-N leaching, as excessive irrigation leads to deep percolation below the root zone and results in higher NO_3-N leaching losses (Ferguson et al., 2013; Hergert, 1986; Quemada et al., 2013; Rudnick, 2013; Rudnick & Irmak, 2013, 2014). Sexton et al. (1998) found that even with optimum irrigation, significant NO_3-N leaching can occur when intensive summer thunderstorms happen soon after irrigation or fertilization. Similarly, Waddell et al. (2000) and Sexton et al. (1998) concluded that keeping deficit soil water levels between the irrigation events while maintaining soil water above the allowable depletion limit can significantly reduce NO_3-N leaching. In concurrence, increasing droughts, depleting groundwater levels in the high plain aquifer, and increasing water demands are creating deficit irrigation situations in the central great plains (Mieno et al., 2024; Rudnick et al., 2019; Tarkalson et al., 2006). These deficit irrigations could affect crop production and will need N fertilizer adjustments to meet crop N demand (Quemada et al., 2013). As such, farmers and policymakers are increasingly looking for alternative N and irrigation management strategies to efficiently use existing water resources to protect groundwater quality.

Enhanced Efficiency Fertilizers

Among the N management practices, N source plays a critical role in determining N use efficiency of crop production (Carneiro et al., 2012; Hussain et al., 2022; Neels et al., 2024; Struffert et al., 2016; Zaman et al., 2013). Because of the affordability and ease of application, granular urea and urea ammonium nitrate (UAN) are the most commonly used fertilizer for sandy soils in the region and the world. However, previous studies have shown that urea-based fertilizers have low NUE and high vulnerability for N losses through NH_3 volatilization, nitrous oxide emissions, and NO_3-N leaching (Dobermann et al., 2011; Drury et al., 2016; Woodley et al., 2020; Soares et al., 2023; Rochette et al., 2008; Maharjan et al., 2014; Venterea et al., 2021). Following surface application of urea, it quickly hydrolyzes within 1 or 2 days to NH_4-N, increasing soil pH and potential of NH_3-N volatilization losses in case precipitation or irrigation does not happen soon after application (Gioacchini et al., 2002; Zhengping et al., 1991). Moreover, subsequent nitrification of NH_4-N to NO_3-N in a short period increases the potential for NO_3-N leaching losses upto 80% in case of high precipitation, especially when the NO_3-N availability exceeds crop N uptake during the early season (Acutis et al., 2000; Adriaanse & Human, 1993; Di & Cameron, 2002). Therefore, stabilizing N availability, even with split N application, during the early growing season is critical to meet crop N needs and mitigate environmental N losses.

One possible technique to stabilize N is to slow down the N release by temporarily inhibiting the urease and nitrification (conversion of NH_4-N form of N to

NO_3-N) activity during the early growing season when crops do not take up much N from the applied N fertilizers. Broadly, the products delaying the N transformation can be categorized into two groups: (a) Urease inhibitors and (b) Nitrification inhibitors (Franzen, 2017):

Urease Inhibitors

The urease inhibitors are the chemical compounds that inhibit urease enzyme activity. The urease enzymes are commonly found in soil or plant residues. Along with water, these enzymes hydrolyze urea into NH_4-N through a process known as "urea hydrolysis". Urea hydrolysis can occur rapidly on the soil surface, depending on soil pH and plant residues. During this process, urea is converted into ammonia (NH_3) and lost into the air through NH_3 volatilization if not immediately incorporated by rain or irrigation into the soil. Urease inhibitors temporarily inhibit urea hydrolysis and keep the fertilizer in urea form. Inhibition of urea allows for the time for rainfall or irrigation that eventually incorporates the urea into the soil and thus minimizes the NH_3 volatilization during the urea hydrolysis process. One of the widely accepted and chemically stable chemical that inhibits urease is N-(n-butyl) thiophosphoric triamide (NBPT) (Drury et al., 2017; Mateo-Marín et al., 2020; Prakash et al., 1999; Zhengping et al., 1991).

Nitrification Inhibitors

Nitrification inhibitors are the products responsible for inhibiting nitrification, a process of converting NH_4-N to nitrite (NO_2-N) and then nitrate (NO_3-N). There are two groups of bacteria responsible for these conversions. The conversion of NH_4-N to NO_2-N occurs by *Nitrosomonas* spp., while conversion of NO_2-N to NO_3-N is carried out by *Nitrobacter* spp. Nitrification inhibitors temporarily delay NO_3-N production by depressing the activity of *Nitrosomonas* bacteria. The commonly used nitrification inhibitors are 2-chloro-6-(trichloromethyl)-pyridine (Nitrapyrin) (Wolt, 2000; Woodward et al., 2021; Zhou et al., 2020), Dicyandiamide (DCD) (Boy-Roura et al., 2016; Carneiro et al., 2012; Venterea et al., 2021), and 3,4-dimethylpyrazol-phosphate (DMPP) (Chaves et al., 2006; Díez-López et al., 2008; Dougherty et al., 2016), that can be found in variety of products with tradenames such as Centuro, SuperU, and ESN etc.

The increasing evidence have shown that the use of enhanced efficiency fertilizers (EEFs) including the urease and nitrification inhibitors can stabilize N and significantly reduce N losses without an impact on maize yield but higher economic returns at suboptimum (Allende-Montalbán et al., 2021; Rose et al., 2018), or optimal N rates (Díez-López et al., 2008; Nelson et al., 2008; Sanz-Cobena et al., 2012; Serna et al., 1994; Serna et al., 2000; Souza et al., 2020; Venterea et al., 2021). For example, Diez et al. (2010) found that a single pre-plant application of dicyandiamide (DCD) and 3,4-dimethylpyrazole phosphate (DMPP) nitrification inhibitors at the recommended N rate significantly decreased NO_3-N leaching by 29% without any impact on maize yield when compared to split N application in sandy loam soil of irrigated maize. They attributed NO_3-N leaching reduction to 30% lower soil NO_3-N production in the nitrification inhibitor plots than with no nitrification inhibitor. Similarly, Allende-Montalbán et al. (2021) found that single application of urease inhibitors was more effective in delaying urease activity, slowing N availability, and reducing potential N losses than the split application of urea with urease inhibitors in sandy soil in maize. In parallel, Rose et al. (2018) in a meta-analysis reported that the beneficial effects of EEFs in improving NUE and maize yield are more likely at suboptimal N rates.

Optimizing Number Of Nitrogen Splits

Choosing the right N application time is another effective strategy for better synchronizing soil N availability with crop N uptake. Generally, the N losses tend to be greater during the April-June period when soil N is available due to soil organic matter mineralization and fertilizer application but there is limited crop N uptake (Bowles et al., 2018). Meanwhile, narrowing the time between soil N application and crop N uptake can shorten the time for N losses (Nafziger & Rapp, 2020). Therefore, splitting the N application during the growing season is an effective strategy for synchronizing soil N availability with crop N needs (Chen et al., 2006; Ciampitti & Vyn, 2013), improving NUE (Lü et al., 2012; Olson et al., 1986) and reducing N losses (Preza-Fontes et al., 2022; Sitthaphanit et al., 2009). However, optimizing the number of N-splits to improve NUE during the growing season remains unclear. For example, Venterea & Coulter (2015) found that N application in three equal splits did not affect crop yield but increased nitrous oxide emissions more than early season N application in a silt loam soil. Similarly, no yield response to the late split-N application at the R1 maize growth stage in sandy loam soil was observed by Mueller et al. (2017). Other studies reported that delaying N application for too long until tasseling (Walsh et al., 2012) or silking (Silva et al., 2005) can decrease grain yields and NUE (Adriaanse & Human, 1993; Jung et al., 1972). However, some studies reported either a decrease (Binder et al., 2000; Sitthaphanit et al., 2009; Walsh et al., 2012) or no crop yield response (Jaynes & Colvin, 2006; Roberts et al., 2016; Scharf et al., 2002) with late split-N application. The authors of these studies attributed the yield decrease or no yield response to either irreversible yield loss with early season N stress or sufficient N availability early in the growing season, respectively.

In contrast, Lü et al. (2012) and Zhou et al. (2019) found that applying N in 3-splits (V6, V10, and R1) and 4-splits (preplant, V6, V12, and R1) increased grain yield than applying N at 2-N splits (preplant and V6). Nevertheless, optimizing the number of N-splits to improve NUE, increase crop yield, and decrease NO_3-N leaching risk, especially in sandy soils, remain unresolved as an approach to minimize groundwater contamination (Azad et al., 2020; Wang et al., 2016). Moreover, none of the studies have investigated the number of N-splits based on NO_3-N leaching in the Midwest, probably because this type of research is often costly and requires intensive sampling for NO_3-N leaching measurements. Meanwhile, in other regions, studies have reported either a decrease (Sitthaphanit et al., 2009) or no effect (Wang et al., 2016) with increasing the number of split-N applications on NO_3-N leaching in sandy soils. Rubin et al. (2016) recommended splitting the N application for irrigated sandy soils along with an economic optimum N rate to minimize NO_3-N leaching risk.

Research Objectives

The objectives of my research program were to investigate the impact of selective N management tools and practices on improving NUE and maximizing economic returns while protecting groundwater quality in the BGMA. The specific objectives by chapter were to:

1. Evaluate the agronomic, environmental, and economic performance of static (NE YG) vs. dynamic N tools (Maize-N, Canopy Reflectance Sensing, Adapt-N, Granular).

2. Determine the impact of deficit nitrogen and irrigation rates on NO_3-N leaching, grain yield, N use efficiencies (NUEs), N uptake, water use efficiencies (WUE), residual soil N, and economic profits.
3. Evaluate the impact of conventional nitrogen (N) split vs. pre-plant N application, with and without EEFs [Agrotain (urease inhibitor), SuperU (urease and nitrification inhibitor)] on NO_3-N leaching, maize yield, and return to N with (RTN_{Env}) and without environmental cost (RTN).
4. Optimize the number of N-splits based on crop yield, NO_3-N leaching losses, and profitability.

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CHAPTER 2

STATIC VS. DYNAMIC MAIZE NITROGEN RATE RECOMMENDATION TOOLS' PERFORMANCE

Abstract

The performance of static vs. dynamic maize nitrogen (N) recommendation tools has recently received much attention for improving N management in the Midwest maize production system. The objectives of this study were to evaluate the agronomic, environmental, and economic performance of a static NE yield goal vs. four dynamic nitrogen tools of Maize-N, Canopy Reflectance Sensing, Granular, and Adapt-N. The study included six N rates at an increment of 67 kg N ha^{-1} to calculate EONR, which was then compared to the N recommendations from N tools during the two study years (2021-2022) at a farmer's site in the Bazile Groundwater Management Area of Northeast Nebraska. Agronomically, the NE YG outperformed all the dynamic N tools by predicting N rate and yield closer to EONR. Maize-N recommended N above EONR but had grain yield within the EONR range. Other dynamic N tools (Canopy Reflectance Sensing, Granular, and Adapt-N) recommended N below EONR, resulting in a yield penalty (3-18 Mg ha^{-1}) more than half the time. Environmentally, nitrogen tools did not significantly affect nitrate leaching. However, three dynamic N tools (Canopy Reflectance Sensing, Granular, and Adapt-N) reduced nitrate leaching by 18% more than half the time. Economically, all tools were equally effective in determining economic returns when environmental costs of nitrate leaching (RTN_{Env}) were included. The findings of this study highlight a tradeoff of using static vs. dynamic N tools for agronomic, environmental, and economic benefits in groundwater-contaminated areas.

Policymakers and stakeholders need to identify priorities while using these N recommendation tools.

Introduction

Nitrogen (N) is the most limiting factor affecting crop production and has increasingly been used for maize production in the United States (Archontoulis et al., 2020; Ronald J Gehl et al., 2005; Puntel et al., 2024; Thorburn et al., 2024). At the same time, optimizing N is necessary to sustain agricultural production while protecting the environment. Researchers have spent decades of research predicting the most economical optimum N rate (Dobermann & Cassman, 2002; Mamo et al., 2003; Puntel et al., 2018; Thompson et al., 2015, 2023). However, no consensus has yet been reached on the methodology for finding a more accurate and site-specific N rate. This is partly due to complex biophysical N transformations occurring at spatial and temporal scales that induce error in determining the accurate specific-site N rate (Archontoulis et al., 2020; Mandrini et al., 2022; Puntel et al., 2016, 2024; Thompson et al., 2023; Thorburn et al., 2024; Sawyer et al., 2006). As a result, farmers either under or over-apply N fertilizer, resulting in a profit loss or degradation of the environment (Maharjan et al., 2014). Mostly, the farmers over-apply N to avoid the risk of profit loss, which eventually degrades the environment (Ferguson, 2015; Iqbal et al., 2018). In Nebraska, over application of N fertilizer is evidenced by groundwater NO_3-N levels far exceeding the Environmental Protection Agency (EPA) safe drinking water limit of 10 mg L^{-1} on about one million hectares of Nebraska (Exner et al., 2014; Juntakut et al., 2019). Simultaneously, more than 80% of Nebraska's rural population relies on groundwater for drinking purposes which results in adverse health effects in several Nebraska towns

(Ouattara, 2022). So, several Nebraska towns have to pay millions of dollars to treat the contaminated water (Pennino et al., 2020; Ray et al., 2022).

To address the groundwater contamination risks, Natural Resource Districts (NRDs), a watershed-level government agency, passed legislation in 1987 and established groundwater management areas to set strategies for protecting groundwater quality. One of the major NO_3-N contaminated areas in the state (Juntakut et al., 2019) is the Bazile Groundwater Management Area (BGMA), which was developed by Nebraska in 1986 and accepted by the Environmental Protection Agency (EPA) in 2016 (Figure 2.1). BGMA comprises 1958 sq. km. area under sandy soil and lies within three counties (Antelope, Knox, Pierce) of the state. These sandy areas in BGMA are well above >10 mg NO_3-N L^{-1} (Figure 2.1) and provide drinking water to 7000 Nebraskans (Bartels, 2022). Though the shallow groundwater table depth in this area offers an inexpensive water supply to irrigate crops, it also results in a substantial NO_3-N leaching risk to the groundwater in the area (Gosselin, 1991; Hobza & Steele, 2020; Hou et al., 2023). To address the N management in BGMA and other groundwater management areas in Nebraska, NRDs set phase areas with increasing NO_3-N concentrations in the groundwater. i.e. Phase I: 0-5 mg NO_3-N L^{-1}, Phase II: 5.1-9.0 mg L^{-1}, Phase III: >9 mg NO_3-N L^{-1}, Phase IV – areas in Phase III for five years. In each phase management area, there are different N and irrigation regulations to improve the N use efficiency (NUE) and protect groundwater quality (Bartels, 2022; Exner et al., 2014). One of the major regulations is not to apply N before March 1st but to apply N in split during the growing season. Given that more than four-fifths of NO_3-N leaching occurs during maize early vegetative phase (March-May) due to high precipitation and N applications (Banger et al., 2018; Jin & Sands, 2003), the producers are recommended to split N at optimum N rate using the University of Nebraska-Lincoln Yield Goal Tool (NE YG).

The Nebraska yield goal (NE YG) is a static tool that gives a one-time N recommendation before the growing season (Iqbal et al., 2023). This tool's N recommendations are based on the Stanford yield goal approach that recommends N based on the mass balance equation driven by yield estimates, internal N cycling with soil type, and crop N uptake efficiency (Stanford, 1973). Furthermore, NE YG also possesses the unique features of requiring a wide range of inputs, such as NO_3-N in the maize root zone and irrigation water, N credits from soil organic matter, manure, and leguminous crop, and adjustments for N application timing and prices for yield and nitrogen etc., which makes it a successful tool for Nebraska conditions (Iqbal et al., 2023). However, NE YG does not consider annual weather variability for N rate recommendations. Limitations of this method has been described in the literature (Morris et al., 2018).

Meanwhile, other types of N recommendation tools, known as dynamic tools, consider annual weather variability in addition to soil and crop inputs, to recommend site-specific N rates (Mandrini et al., 2022; Morris et al., 2018; Ransom et al., 2021). For example, Maize-N is a crop growth computer simulation model that recommends N based on the soil and crop processes, N transformations, crop N uptake, and soil N depletion (Setiyono et al., 2011). Adapt-N (Melkonian et al., 2005; Moebius-Clune et al., 2013) and Granular (Gunzenhauser, 2023) are dynamic tools that consider the site-specific soil and crop conditions, weather, and management inputs to optimize N inputs. Canopy reflectance sensing is another tool that uses active optimal canopy sensing of leaves to determine the leaves' darkness and quantify the in-season N needs using algorithms (Franzen et al., 2016; Holland & Schepers, 2010; Solari et al., 2008). The drawbacks of these dynamic N tools are the added costs of implementation, their accuracy, and their adaptability across diverse soil and weather conditions (Ransom et al., 2021). At the same time, previous research has shown no significant benefits of using dynamic N tools over static N tools (Mandrini et al., 2021; Ransom, 2018). For example, Puntel et al., (2018) reported that yield predictions using process-based models are reliable, but economic optimum N rate (EONR) predictions at the V6 maize developmental stage, even with known weather, are uncertain ($R^2 = 0.1$). Similarly, no advantages of weather incorporation in EONR predictions were observed by Qin et al., (2018). Furthermore, Ransom et al. (2020) and Mandirini et al. (2021) found that dynamic N tools do not consistently give better prediction of the EONR and N losses. However, Sela et al. (2017) found that Adapt-N increased farmer profit and improved EONR prediction compared to the Stanford-type maize N calculator in 14-site years of field trials in New York.

Nevertheless, evaluation of static vs. dynamic N tools in high NO_3-N contaminated areas in the US Midwest is lacking. Moreover, most of the previous studies have reported the environmental impact of these models using simulations (e.g. Mandrini et al., 2021; Ransom, 2018), but not in-field NO_3-N leaching assessments. This study was conducted to evaluate the agronomic, environmental, and economic performance of static (NE YG) vs. dynamic N tools (Maize-N, Canopy Reflectance Sensing, Adapt-N, Granular) in the BGMA, an area with mounting NO_3-N leaching. Specific objectives of this study were to evaluate the impact of static vs. dynamic N tools on 1) prescribing N recommendation rate, and 2) evaluating their agronomic (grain yield, N use efficiencies), environmental (NO_3-N leaching *via* suction cup lysimeters), and economic performance (economic returns with and without including environmental costs) in the BGMA.

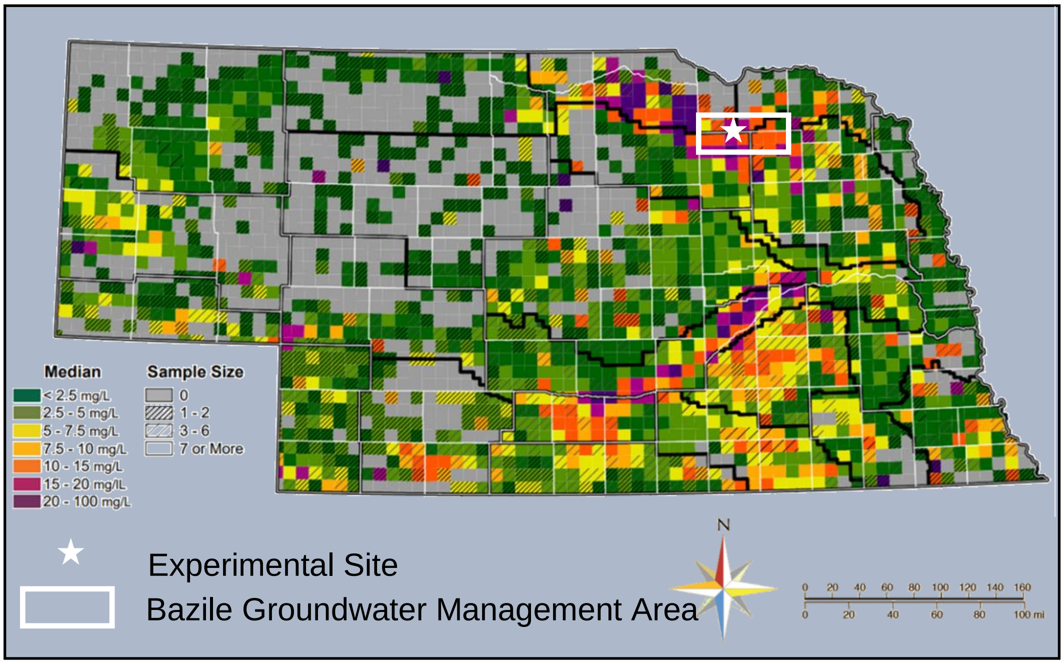

Figure 2.1 Median groundwater NO_3-N contamination for Nebraskan townships. The white rectangle in northeast Nebraska shows Bazile Groundwater Management Area (BGMA) and white star symbol shows the experimental site. (Adapted from NDEE, 2020).

Materials and Methods

Experimental Site

A two years (2021 and 2022) on-farm experiment was conducted near Creighton (lat. 42°25'02.3"N, long. 98°02'52.3"W, 568m elevation), Nebraska, United States. This site has an elevation of 568 m and is located in Phase III of the Bazile Groundwater Management Area (BGMA) in the Upper Elkhorn Natural Resource District (NRD). The climate at the study site is classified as humid (Singh et al., 2021), with an annual average precipitation of 714 mm and annual average temperature of 9.6^{0}C. The site has an excessively drained Thurman loamy sand soil, with 82.3% sand, 9.7% silt, and 8% clay.

A detailed description of the soil chemical and physical properties is provided in Table 2.1.

Table 2.1 Selected soil properties at the study site.

Soil property	Units	Value
Organic Matter	%	1.23
NO_3-N	mg kg^{-1}	2.46
Phosphorus	mg kg^{-1}	25.3
Potassium	mg kg^{-1}	157
Sulfate-S	mg kg^{-1}	6.36
Zinc	mg kg^{-1}	4.88
Iron	mg kg^{-1}	36.5
Manganese	mg kg^{-1}	5.27
Copper	mg kg^{-1}	0.28
Calcium	mg kg^{-1}	807
Magnesium	mg kg^{-1}	73.7
Sodium	mg kg^{-1}	8.43
Cation exchange capacity (CEC)	me 100g^{-1}	6.18
Bulk Density	g cm^{-3}	1.27

Experimental Design And Treatments

The experiment was conducted in a field with a center-pivot overhead sprinkler irrigation system. The outer two spans of the pivot were equipped with a variable rate irrigation (VRI) system (Valmont Industries, Valley, NE) and used to establish the experimental plots. The crop rotation was continuous maize. The treatments were applied to the same experimental plots in each study year. During 2021, maize was grown in a no-till field on May 12th. Due to high maize stubbles, the farmer tilled the field on April 14th, 2022, and planted maize on April 26th, 2022. Channel 20906 109 days mature maize variety was used during both years.

The treatments included six nitrogen rates from 0 to 336 kg N ha^{-1} with an increment of 67 kg N ha^{-1} and fertilizer-N rates from N tools (see Table 2.2 and 2.3) arranged in a randomized complete block design consisting of 24 m long and 36 m wide plots. The nitrogen at each rate was applied in 5-splits via pre-plant, sidedress at V4, and three fertigations at V8, V12, and VT. To minimize the ammonia (NH_3) volatilization losses at pre-plant, a urease inhibitor (AGROTAIN) from Koch Industries was used to coat urea at the recommended rate of 2.1 L AGROTAIN per ton Urea. The AGROTAIN-coated urea was surface broadcasted at pre-plant with a 3-m wide dry fertilizer drop spreader (Barber Engineering Co.). The side-dress N application with UAN (32%) was performed in furrows, using the 6-m wide liquid applicator at 4-leaf maize growth stage (V4). To minimize NH_3 volatilization losses, 19 mm irrigation was applied within 24 hours following side-dressing. The center pivot with variable rate sprinkler irrigation was used for irrigation and fertigation (with UAN 28%) purposes. The GPS-based irrigation and fertigation maps were uploaded before irrigation and/or fertigation events. During 2022, the application timing was adjusted by increasing early season N amounts (Table 2.2). We assume the differences in N application timing between the two years would not affect measured parameters, as the companion study showed no significant differences in N application timing on the parameters measured in this study, likely due to below than normal precipitation during both study years. A detailed description of the N application rate at different maize growth stages is provided in Table 2.2. To meet crop phosphorus requirements, the farmer applied Mono Ammonium Phosphate (MAP) before planting at 140 kg ha^{-1} (equivalent to 16 kg N ha^{-1}) and 105 kg ha^{-1} (equivalent to 12 kg N ha^{-1}) to the entire pivot field, including the experimental plots during 2021 and 2022, respectively. To meet potassium, magnesium, and sulfur needs, farmers broadcasted K-Mag from Mosaic at 86 kg K-Mag ha^{-1} (equivalent to 19 kg K_2O, 10 kg Mg, 19 kg S) to entire pivot field, including the experimental plots before planting maize each year. The management decisions such as crop hybrid selection, herbicide application, and irrigation scheduling were at the discretion of the farmer.

Table 2.2 Nitrogen rates (kg ha^{-1}) for the six N rate treatments during 2021 and 2022.

Total N	Preplant	Sidedress	Fertigation		
		V4*	V8	V12	VT
	Agrotain	UAN†			
		kg N ha^{-1}			
0 (0) ‡	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
67 (67)	22 (22)	11 (20)	11 (0)	11 (12)	11 (12)
135 (135)	45 (45)	11 (20)	11 (25)	33 (22)	33 (22)
202 (202)	67 (67)	35 (62)	33 (25)	33 (25)	33 (25)
269 (269)	90 (90)	78 (142)	33 (0)	33 (20)	33 (16)
336 (336)	112 (112)	123 (224)	33 (0)	33 (0)	33 (0)

† UAN, Urea NH_4-NO_3.
*V4, 4-leaf stage; V8, 8-leaf stage; V12, 12-leaf stage; VT, tasseling.
‡ indicate N input values in 2021 and 2022 (in parenthesis).

Crop Yield, Nitrogen Use Efficiencies, And Economic Return

At the physiological maturity in both years, the maize was hand-harvested from the middle two 3m rows per plot. The hand-harvested maize grain, and stover (stalk, leaves, cobs) were separated and analyzed for maize yield, and N uptake by maize. The stover was shredded using a portable woodchipper. Ears and subsamples of chopped maize stover were weighed and dried at 71°C to determine moisture content. Ears were shelled to separate grain and cobs. Grain and stover were milled and analyzed for total nitrogen using the dry combustion method at Ward Lab (Kearney, NE). Hand harvest grain yield at 15.5% moisture, nitrogen concentration in grain and stover, and plant population were used to calculate nitrogen uptake. Furthermore, different nitrogen use efficiency indicators (partial factor productivity (PFP, Eq. 2.1) and maize nitrogen use efficiency (NUE_{maize}; Eq. 2.2).) and net return to nitrogen (RTN; Eq. 2.3), and net return to nitrogen considering environmental costs (RTN_{Env} ; Eq. 2.4) were calculated as follows:

$$\mathrm{PFP}\ (\mathrm{kg\ kg^{-1}}) = \frac{\mathrm{Grain\ yield}}{\mathrm{Fertilizer\ N}} \quad \text{(Eq. 2.1)}$$

$$\mathrm{NUE_{maize}}(\mathrm{kg\ kg^{-1}}) = \frac{\mathrm{Grain\ N\ uptake}}{\mathrm{Fertilizer\ N}} \ \text{(Eq. 2.2)}$$

$$\mathrm{RTN} = (\mathrm{Yield_{Maize}\ x\ Price_{Maize}}) - (\mathrm{Input_N\ x\ Price_N}) \ \text{(Eq. 2.3)}$$

$$\mathrm{RTN_{Env}} = \mathrm{RTN} - (\mathrm{NO3} - \mathrm{N_{leached}}\ \mathrm{x}\ 18.54) \ \text{(Eq. 2.4)}$$

where 18.54 US$ kg^{-1} NO_3-N is the environmental cost associated with NO_3-N leached (Preza-Fontes et al., 2022; Sobota et al., 2015).

Nitrogen Recommendation Tools Investigated

Nebraska Yield Goal (YG)

Nitrogen recommendation (Eq. 2.5) using the static Nebraska YG (Iqbal et al., 2023) developed by the University of Nebraska-Lincoln was calculated as follows:

$$\mathrm{N_{rec}} = 1.12^{\dagger}\ \mathrm{x}\ \{[35 + (1.2\ \mathrm{x\ YG}) - (8\ \mathrm{x\ NO_3} - \mathrm{N_{(0-120cm)}}) - (0.14\ \mathrm{x\ YG\ x\ OM}) - \mathrm{other\ N\ credits}]\ \mathrm{x\ Time_{adj}\ x\ Price_{adj}}\}\ \text{(Eq. 2.5)}$$

where YG represents the yield goal calculated as the 105% of five-year yield average, $1.12^{\dagger}$ was the conversion factor from lb ac-1 to kg ha^{-1}, $NO_3 - N_{(0-120cm)}$ constitutes the average NO_3-N concentrations for the maize root zone (0-120 cm), OM stands for organic matter percentage, other N credits included NO_3-N concentrations from irrigation water, previous legume crop, manure, or any other N source, $Time_{adj}$ and $Price_{adj}$ were the adjustment factors for N application timing (fall, spring, split) and prices of maize and N, respectively.

Maize-N Crop Growth Model

Maize-N version 2018.4 was used to develop N recommendation. Maize-N, developed by the University of Nebraska-Lincoln, predicts the N recommendations using the long-term historical and in-season daily climate data input, soil data (soil organic carbon, soil texture, bulk density, soil NO_3-N in the maize root zone), water data (irrigation amounts, N credits from irrigation water), and crop and management inputs (type and timing of tillage, N application timing, N fertilizer price). The weather data was used from the nearest weather station of the High Plains Regional Climate Center. Maize-N uses the Hybrid-Maize for yield predictions (H. S. Yang et al., 2004). The full detail of Maize-N is provided by Setiyono et al. (2011)). Maize-N has been previously validated in many studies (Grassini et al., 2009; Ransom et al., 2021; Thompson et al., 2015). For year 2022, the N in the Maize-N model was accidentally applied in excess, therefore, the 2022 Maize-N treatment from here onwards would be called “Excess N”.

Canopy Reflectance Sensing

Canopy reflectance measurements were obtained for both years using the RapidSCAN CS-45 (Holland Scientific, Lincoln, NE) two days prior to split N application at V8 maize development stage. The Holland and Schepers algorithm (Holland & Schepers, 2010) was used to calculate an N fertilizer recommendation derived from these reflectance measurements. All plots associated with reflectance measurements received four N splits via pre-plant, and three fertigations at V8, V12, and VT. The treatment plots received 67 kg N ha^{-1} as preplant. Before fertigation at V8, NDRE values from sensing treatment plots were subtracted from NDRE obtained from the “reference N” plot i.e., 336 kg N ha^{-1} and called as sufficiency index (SI) (Eq. 2.6).

$$\mathrm{SI} = {}^{\mathrm{VI}_{67}}/_{\mathrm{VI}_{\mathrm{reference}}} \text{ (Eq. 2.6)}$$

where VI_{67} was the vegetation index obtained from all crop sensing treatment plots after averaging NDRE values that received 67 kg N ha^{-1} as preplant N application and $\mathrm{VI}_{\mathrm{reference}}$ was the vegetation index obtained from “reference N” plot i.e., 336 kg N ha^{-1}. The NDRE vegetative index (Eq. 2.7) was calculated as:

$$\mathrm{NDRE} = (\mathrm{NIR} - \mathrm{RE})/(\mathrm{NIR} + \mathrm{RE}) \text{ (Eq. 2.7)}$$

where RE and NIR represent red-edge (730 nm) and near-infrared (780 nm) wavelengths, respectively. Fertilizer N recommendations (Eq. 2.8) were then calculated as described by Holland and Schepers (2010) as shown below:

$$\mathrm{N}_{\mathrm{rec}} = \left(\mathrm{MZ}_{\mathrm{i}} \cdot \mathrm{N}_{\mathrm{Opt}} - \mathrm{N}_{\mathrm{PreFert}} - \mathrm{N}_{\mathrm{CRD}} + \mathrm{N}_{\mathrm{Comp}}\right) \text{ x } \sqrt{\frac{(1-\mathrm{SI})}{\Delta\mathrm{SI}}} \text{ (Eq. 2.8)}$$

where N_{rec} represents calculated N recommendation; MZ_i was considered scaling value ($0 \geq MZ_i \leq 2$) represents the adjustment of the N recommendation relative to high and low yielding areas and was kept 1 in our case; N_{Opt} means base N rate determined by producer and was kept as previous five-year average N rate applied by producer; $N_{PreFert}$ represents the N applied prior to sensing (i.e. 67 kg N ha^{-1} or VI_{67}); N_{CRD} consists of previous N credits similar to NE YG; N_{Comp} represents the compensation factor for growth-limiting conditions and is optional and was set to zero; SI means sufficiency index, and ΔSI represents the value defining the response range with recommended value of 0.30 that provides a response range for the measured vegetative index value between 0.70 and 1.00.

Adapt-N

Adapt-N, developed by Cornell University and recently acquired by Ever.Ag, is a web-based N recommendation tool (Ever.Ag; https://www.ever.ag/adapt-n-fieldalytics/) which was built around Precision Nitrogen Management (PNM) model (Melkonian et al., 2005; van Es et al., 2007), using an integrated and enhanced combination of the LEACHM model (Hutson, 2003), and a maize N uptake, growth, and yield model (Sinclair & Muchow, 1995). An important feature of Adapt-N is its dynamic access to gridded high-resolution (4 by 4 km) weather data. Importantly, the Adapt-N provides information regarding the maize N uptake and N losses depending on soil type, rooting depth, slope, and other factors. Adapt-N mostly provides in-season N recommendations at any crop growth stage. More details about the model can be found in Morris et al. (2018).

Granular

Granular Agronomy N Management, started as Encirca N Management in 2013, is a web-based, mechanistic, daily time-step crop growth model that uses weather, soil properties, management, and genetic information to estimate N requirements by simulating both aboveground and belowground processes. Nitrogen recommendations are provided based on the yield goal along with distinct decision zones, generated with spatial inputs such as soil water holding capacity, drainage, organic matter, irrigation etc. Granular uses historical, current, and 8-day forecast weather information for N recommendations and considers all N dynamics and losses (leaching, denitrification, nitrification, and volatilization). More details can be found in Gunzenhauser et al. (2023). The N recommendations from all N recommendation tools are provided in Table 2.3.

Table 2.3 Nitrogen rate recommendation from N recommendation tools during 2021 and 2022

N Recommendation tool	Recommended N	Applied N	Pre-plant	Sidedress V*4	Fertigation V8	Fertigation V12	Fertigation VT
	Agrotain				UAN†		
	kg N ha^{-1}						
Adapt-N	‡168 (189)	168 (200)	67 (67)	35 (111)	22 (0)	22 (11)	22 (11)
Granular	169 (222)	168 (242)	67 (67)	36 (175)	22 (0)	22 (0)	22 (0)
Canopy sensing	165 (177)	169 (169)	67 (67)	0 (0)	34 (34)	34 (34)	34 (34)
Maize-N (Excess-N)	268 (354)	268 (439)	67 (67)	99 (372)	34 (0)	34 (0)	34 (0)
NE YG	250 (239)	250 (242)	67 (67)	81 (142)	34 (11)	34 (11)	34 (11)

† UAN, Urea NH_4-NO_3.
*V4, 4-leaf stage; V8, 8-leaf stage; V12, 12-leaf stage; VT, tasseling.
‡ indicate N input values in 2021 and 2022 (in parenthesis).

Lysimeter Installation And Water Sampling

To monitor the pore water NO_3-N and NH_4-N concentration below the crop rootzone, two suction-cup lysimeters were installed approximately 30 m apart at 1.2 m soil depth in each experimental plot following the method described by Venterea et al. (2011) and Maharajan et al. (2014). The suction cup lysimeters were developed by the Irrometer Company Inc. (Model SSAT - Soil Solution Access Tube) and contained 100-kPa high flow ceramic cup attached to rubber tubing designed to apply the pressure and collect water samples at the soil surface. The suction cup lysimeters were installed using silica powder slurry to cover the ceramic cup at the bottom of the vertical hole bored with a soil probe. The soil from the hole was used to re-fill the hole around the lysimeter tube, followed by the placement of a finely powdered bentonite layer at the soil surface to prevent the preferential flow of water. Pore-water samples from the lysimeters were collected one to three times a week following rain or irrigation events from 20 May to 15 October of 2021 and 13 May to 17 September of 2022. To pull the pore water from the ceramic cup, a pressure of ~80 kpa was applied to the suction cup through the rubber tubes. After about 4 hours, the rubber tube line was opened to collect the pore-water sample with a 20 mL syringe and acidified with 0.1N HCl before transferring to the lab in a cooler. There were 23 and 26 water sample collection events during the years 2021 and 2022, respectively.

Water Balance And NO_3-N Leaching Calculations

A soil water balance equation (Eq. 2.9) was used to estimate the draining water via deep percolation below the root zone using the following approach (Djaman & Irmak, 2013):

$$DP_i = P_i + I_i - R_i - ET_i \pm \Delta S_i \text{ (Eq. 2.9)}$$

where DP is deep percolation, P is precipitation, I is irrigation, ET is evapotranspiration, ΔS is soil water storage in the root zone, and i is the current day. Units are mm day-1. The value of P was determined using High Plains Regional Climate Center (HPRCC) data collected at a weather station near the site, while I is the amount of irrigation applied in the field by the farmer. The ET values were calculated as a product of an alfalfa reference mean crop coefficient (K_{cr}) based on the stage of growing degree days (Lo et al., 2019) and the reference ET estimates incorporated with the daily weather data using the Penman-Monteith equation (Allen et al., 1998). The K_{cr} values for the curve were derived from the NDVI data collected during the R1 maize growth stage using the relationship [K_{cr} = 1.308*(NDVI) + 0.027] given by Singh & Irmak (2009) for irrigated maize in Nebraska. The water in the soil profile at the start of the growing season was assumed to be at field capacity. We estimated runoff for our experiment using the United States Department of Agriculture–Natural Resources Conservation Service (USDA NRCS) curve number method (USDA NRCS, 1985). Daily leaching amount of NO_3-N and NH_4-N were determined as the product of daily deep percolation and daily NO_3-N and NH_4-N concentration. The daily NO_3-N (Eq. 10) and NH_4-N amount from suction-cup lysimeters water sample were the product of (a) daily estimation(s) of deep percolation and (b) average of previous days pore water NO_3-N and NH_4-N concentrations after last deep percolation event occurred, and (c) 0.01 (kg ha^{-1}) unit conversion factor (Pawlick et al., 2019).

$$[\mathrm{NO_3-N}]_{\mathrm{leached}} = \frac{1}{n}\sum_{i=1}^{n}[NO_3 - N]_{120cm} \text{ x } DP_i \text{ x } 0.01 \text{ (Eq. 2.10)}$$

To calculate seasonal average pore water NO_3-N concentrations, the daily pore water NO_3-N concentrations were averaged across days in the maize growth stage. Sub-seasonal pore water NO_3-N concentrations were calculated based on the maize growth stages and the sampling dates between (i) planting and 8-leaf stage (early vegetative phase), (ii) 8-leaf to tasseling (late vegetative phase), and (iii) tasseling to physiological maturity (reproductive phase), derived and validated from field observations to compute the effect of treatments over time (Rudnick et al., 2017). For seasonal pore water concentrations, the average was performed across all dates while the daily NO_3-N amounts were summed up for area-scaled based seasonal NO_3-N leaching losses. Our data showed that >70% of NH_4-N values were below detection limit, therefore, ammonium data analysis was not performed.

Residual Soil NO_3-N And NH_4-N Analysis

In fall, six undisturbed deep core (0-120 cm) soil samples were collected after maize harvest from each experimental plot within non-trafficked rows. The truck mounted Giddings hydraulic probe (Giddings Machine Co., Fort Collins, CO) was used for sampling soil cores with a diameter of 44 mm. The intact cores were sliced at the following depth increments: 0-30, 30-60, 60-90, and 90-120 cm. The six soil cores per plot were composited by depth before transferring to the lab in a cooler. The soil samples were extracted with 2M KCl solution (5:1 solution to soil ratio) after shaking for 1 hr, followed by filtration through Whatman #1 filter paper. Soil extracts from deep core soil samples and lysimeter water samples were analyzed for NO_3-N and NH_4-N concentration using VCl_3/Griess method (Miranda et al., 2001) and the Berthelot reaction (Kandeler & Gerber, 1988), respectively.

Statistical Analysis

The maize yield was analyzed separately for each site-year to obtain EONR by fitting the yield to applied N rates using linear, quadratic, linear plateau and quadratic plateau models using the PROC NLIN procedure in SAS (Cerrato and Blackmer, 1990, Cho et al., 2023). We found that quadratic-plateau model performed better with higher coefficient of determination (R^2) and lower root mean square error (RMSE) than others. Our mode choice followed the von Liebig’s law of the minimum which states that plant growth occurs at a constant rate with nutrients contributing to grain production in a fixed proportion until some factors become limiting (Swanson, 1963). EONR range was calculated using the ±$2.47 ha^{-1} of the EONR (Greer & Pittelkow, 2018; Laboski et al., 2014; Morris et al., 2018; Curtis J Ransom et al., 2020; Sawyer & Sawyer, 2013; Sela et al., 2017). The recommendations of N tools outside the EONR range were considered significantly different. Another parameter used was the one-way analysis (ANOVA) for the maize yield, NO_3-N leaching, RTN, $RTN_{Env,}$ PFP, NUEcrop using PROC GLIMMIX with N tools as fixed factor and replications as random factors. Similarly, we performed two-way ANOVA with N tools, soil depth, and their interaction as fixed factors while replications and interaction of replications with N tools as random factors. For NO_3-N daily and sub-seasonal analysis, two-way repeated measures ANOVA was performed with date or sub season as repeated measure along with N tools, and their interaction as fixed factor but the replication was considered random factor. The significance threshold considered for all analysis was 0.05.

Results

Weather Conditions

The growing season precipitation during 2021 (May through October; Figure 2.2a-c) and 2022 (April through September; Figure 2.3a-c) was 376 and 283 mm, respectively, which was 11 % and 25% lower than the last ten year's average growing season precipitation (424mm) at the site. The frequency of precipitation was different between the two years. In 2021, precipitation accounted for 15%, 49%, and 35% of the total growing season precipitation during the early vegetative, late vegetative, and reproductive phases, respectively. While in 2022, the precipitation accounted for 45%, 25%, and 28% of total growing season precipitation received during the early vegetative, late vegetative, and reproductive phases, respectively (Fig 2.3a-c). When total water inputs from precipitation and irrigation were considered, the water input in each phase differed from precipitation only. For example, in 2021, the higher total water input occurred in the reproductive phase (43%) and the late vegetative phase (43%) followed by early (14%) vegetative phase, respectively. While in 2022, the higher total water input occurred in the reproductive phase (46%), followed by the late (28 %) and early (25%) vegetative phases, respectively.

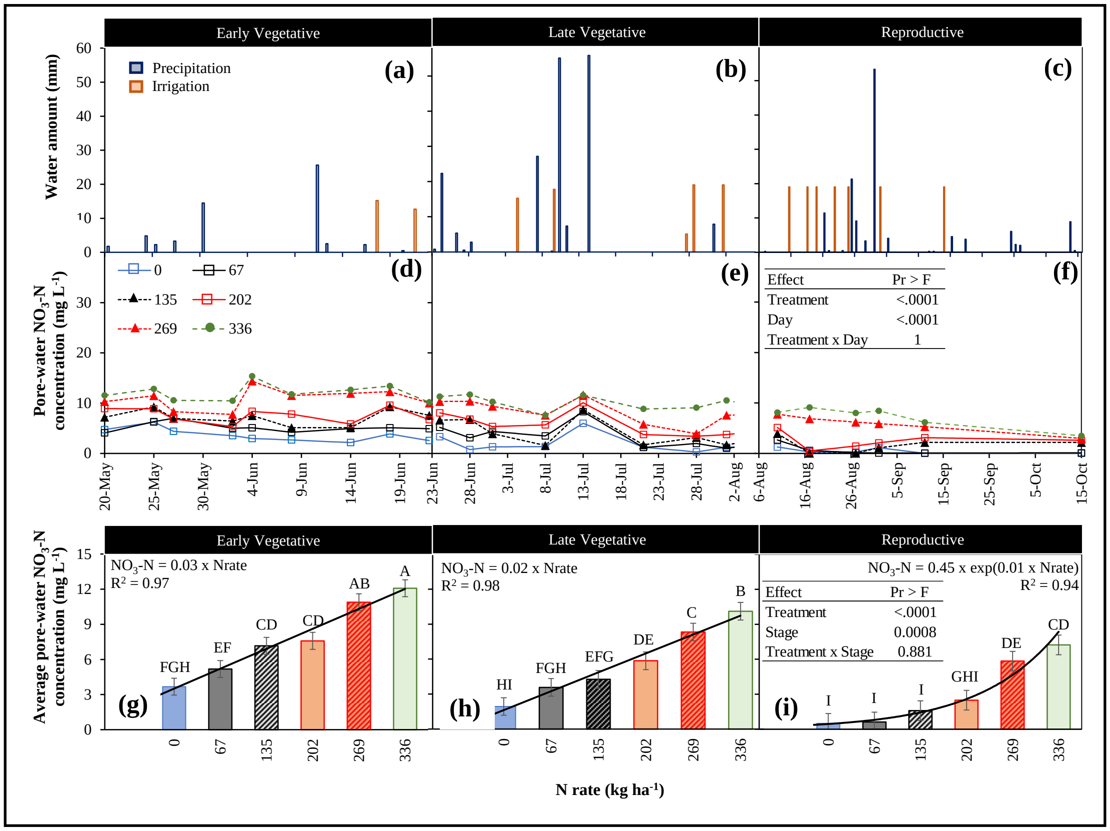

Figure 2.2 The upper panels (a-c) show water inputs (mm) for three maize growth phases – early vegetative (planting to V8), late vegetative (V8-VT) and reproductive phases (R1-R6), while daily and subseasonal pore water NO_3-N concentrations (mg L^{-1}) are shown in the middle panels (d-f) and lower panels (g-i), respectively in 2021.

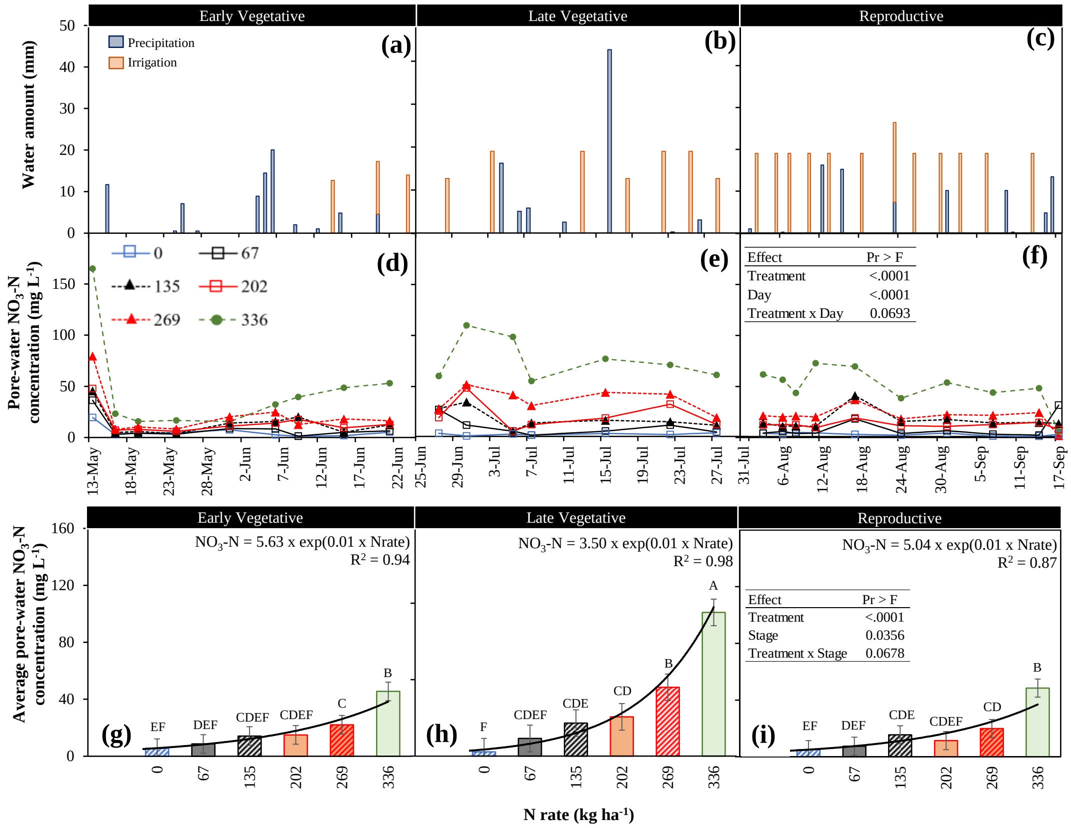

Figure 2.3 The upper panels (a-c) show water inputs (mm) for three maize growth phases – early vegetative (planting to V8), late vegetative (V8-VT) and reproductive phases (R1-R6), while daily and subseasonal pore water NO_3-N concentrations (mg L^{-1}) are shown in the middle panels (d-f) and lower panels (g-i), respectively in 2022.

NO_3-N Concentrations In Lysimeters

The pore-water samples from six N rates and N tool treatments were analyzed for NO_3-N concentrations following the 23 and 26 leaching events in 2021 and 2022, respectively (Figure 2.2, 2.3, and A1). Across all treatments, NO_3-N concentrations ranged from 0 to 20 mg L^{-1} in 2021 and from 0 to 257 mg L^{-1} in 2022. Among the six N rates, NO_3-N concentration increased with an increase in N rates during all maize growth stages. However, the increasing trend in NO_3-N concentration was different across two years. In 2021, NO_3-N concentrations increased linearly with increasing N rate for the early and late vegetative phases but exponentially during the reproductive phase (Figure

2.2 g-i). Moreover, the early vegetative phase (7.8 mg L^{-1}) had significantly higher NO_3-N concentrations, followed by the late vegetative (4.7 mg L^{-1}) and reproductive phase (1.04 mg L^{-1}). Over the entire 2021 season, there was a significant linear increase in average NO_3-N concentrations with increasing N rate (Figure 2.6).

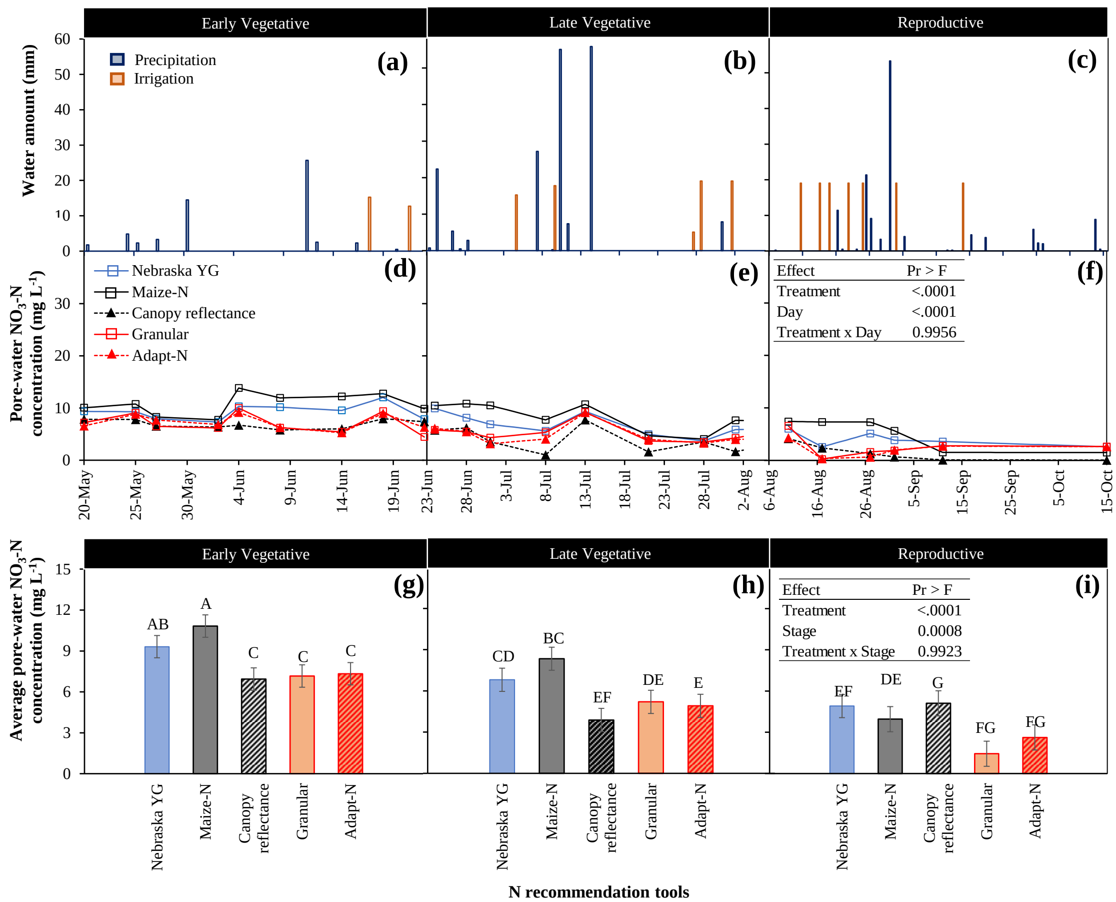

Figure 2.4 The upper panels (a-c) show water inputs (mm) for three maize growth phases – early vegetative (planting to V8), late vegetative (V8-VT) and reproductive phases (R1-R6), while daily and subseasonal pore water NO_3-N concentrations (mg L^{-1}) are shown in the middle panels (d-f) and lower panels (g-i), respectively in 2021.

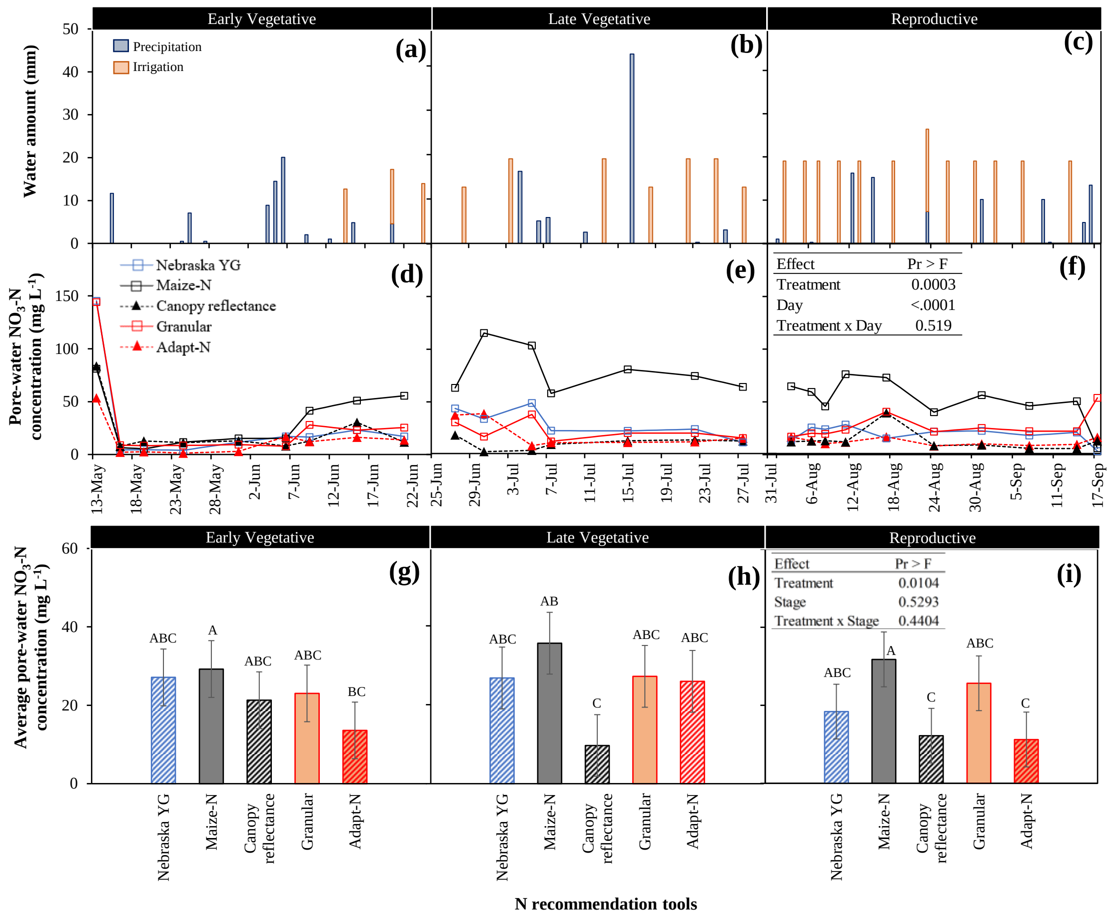

Figure 2.5 The upper panels (a-c) show water inputs (mm) for three maize growth phases – early vegetative (planting to V8), late vegetative (V8-VT) and reproductive phases (R1-R6), while daily and subseasonal pore water NO_3-N concentrations (mg L^{-1}) are shown in the middle panels (d-f) and lower panels (g-i), respectively in 2022.

Unlike 2021, NO_3-N concentration increased exponentially with an increasing N rate during all growth stages and the entire season in 2022 (Figure 2.7). Similar to 2021, the NO_3-N concentrations in 2022 were significantly higher in the early vegetative (27 mg L^{-1}) followed by the late vegetative (17 mg L^{-1}) and reproductive phases (16 mg L^{-1}). Across two years, average NO_3-N concentrations in 2022 were 3.8 times higher than in 2021. Like N rate treatments, N tool treatments had similar temporal trends for pore-water NO_3-N concentrations in both seasons (Figures 2.4 & 2.5).

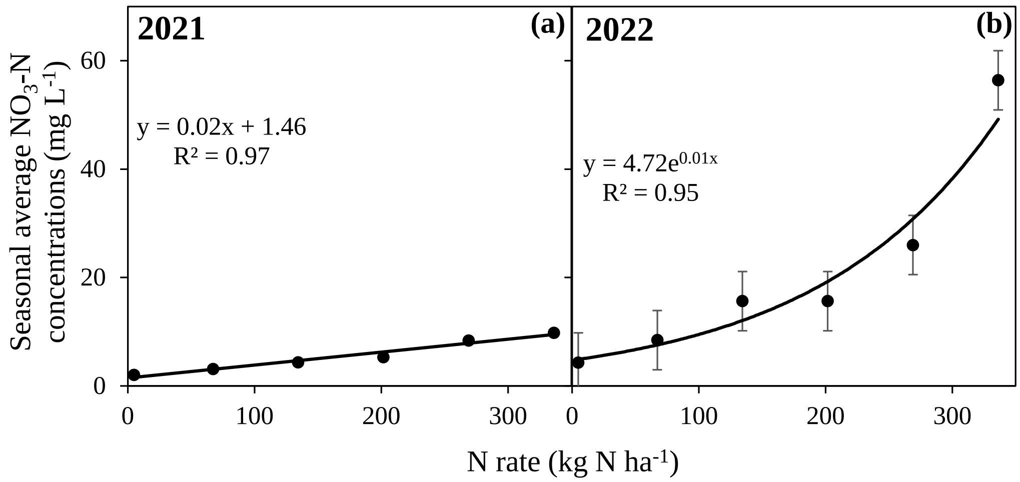

Figure 2.6 Seasonal average NO_3-N concentrations for N rates in (a) 2021 and (b) 2022.

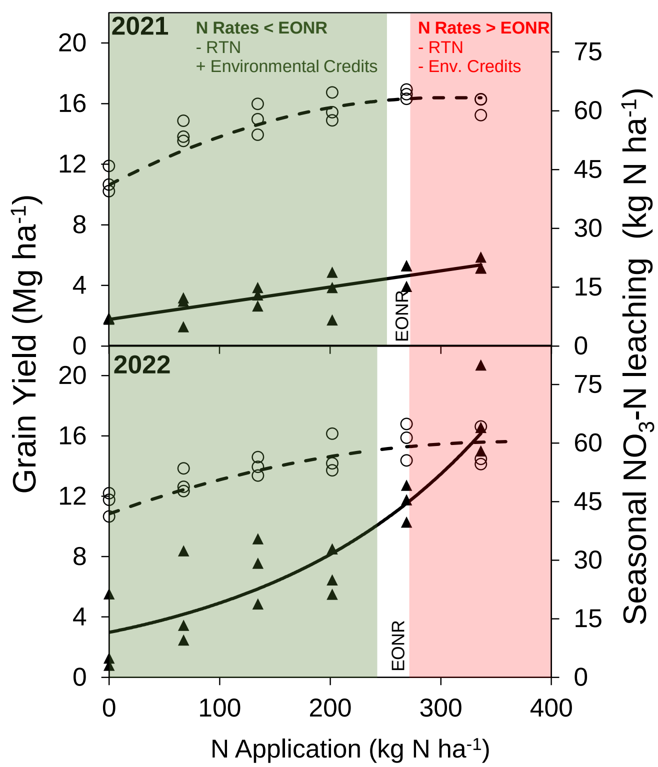

Figure 2.7 Maize yield (Mg ha^{-1}; dashed line with hollow circles) and NO_3-N leaching (kg ha^{-1}; solid line with filled triangles) response to N rates during (a) 2021 and (b) 2022. Green and red colors represent under and over-application than economic optimum N rate range (white shaded region), respectively.

Maize Yield And Nitrate Leaching Response To Nitrogen Rate

The maize yield and NO_3-N leaching response to applied N rates are shown in Figure 2.7. Nitrate leaching was calculated as a product of deep percolation and NO_3-N concentrations. Across two years, grain yield followed a similar response to the N rate.

However, NO_3-N leaching responded differently. In 2021, the maize yield ranged from 13 to 17 Mg ha^{-1} and increased with increasing N rate with a quadratic plateau response at EONR of 258 kg ha^{-1} (ranging from 247 to 271 kg ha^{-1}; R^2 = 0.97; RMSE = 7.4; p = 0.005) and corresponding yield of 16.26 Mg ha^{-1} (ranging from 16.19 to 16.33 Mg ha^{-1}). In contrast, NO_3-N leaching had a linear increase with an increase in N rate and averaged 17.4 kg NO_3-N ha^{-1} at EONR. Similar to 2021, in 2022, the maize yields (ranging from 12.5 Mg ha^{-1} to 15.3 Mg ha^{-1}) increased with an increase in N rate and followed a quadratic plateau response with EONR of 252 kg ha^{-1} (ranging from 241 to 270 kg N ha^{-1}) and a corresponding yield of 15.20 Mg ha^{-1} (ranging from 15.06 to 15.28 Mg ha^{-1}). Unlike 2021, in 2022, NO_3-N leaching increased exponentially with an increase in N rate and averaged 41 kg NO_3-N ha^{-1} at EONR. On the other hand, NO_3-N leaching was lower at a lower N rate and increased exponentially before the grain yield leveled off. Though EONR did not differ much by year, maize yield and NO_3-N leaching differed across years. At 2022 EONR, maize yield was 1.3 Mg ha^{-1} lower, and NO_3-N leaching was 2.3 times higher than at 2021 EONR.

Which Tools Gave Recommendations Close To EONR?

The average difference between the tool's N recommendation and EONR was used to evaluate the tool's performance in this study. Evaluating tools using this approach helped to determine which tools could best predict the EONR for each year. Across all N tools, the difference between N recommendation tools and EONR (dEONR) ranged from

-77 kg N ha^{-1} to + 13 kg N ha^{-1}. Among all tools, the static NE YG was the best predicting tool for this site as dEONR was within the EONR range and ranged from –5 to –10 kg N ha^{-1} across both years (Figure 2.8 a, d). Among the dynamic N tools, both the Canopy reflectance sensing and Adapt-N predicted lower N recommendations than EONR and had dEONR from -53 to - 77 kg N ha^{-1}. The Granular recommended lower N in 2021 (dEONR of -73 kg N ha^{-1}) but was in the EONR range in 2022 (dEONR of -10 kg N ha^{-1}). In contrast, Maize-N recommended N rates above the EONR range in both years with dEONR of +13 to +102 kg N ha^{-1}.

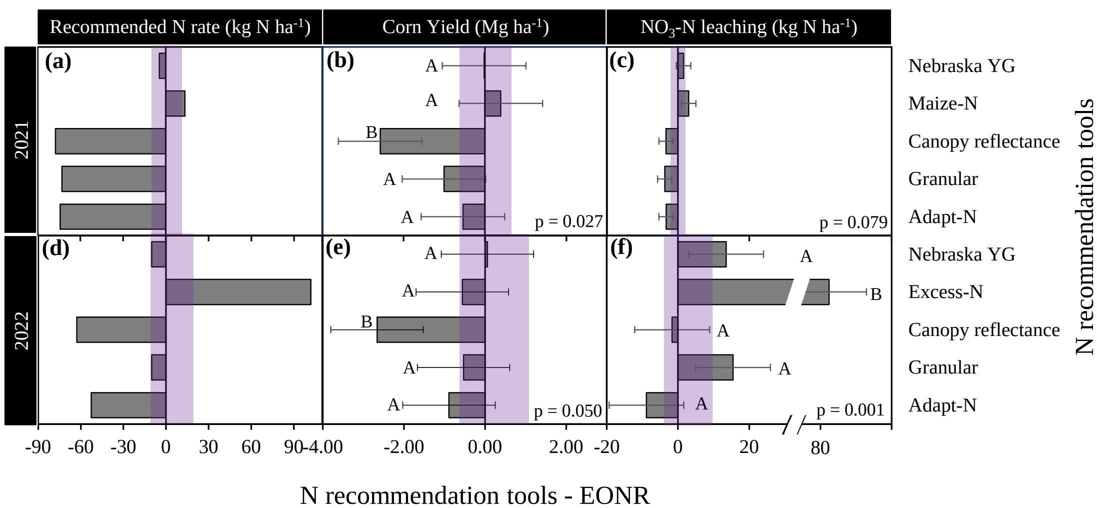

Figure 2.8 Comparison of N recommendation tool to EONR for N recommendation rate (kg ha^{-1}; a, d), maize yield (Mg ha^{-1}; b, e), and NO_3-N leaching (kg ha^{-1}; c, f) during the study years (2021, 2022).

Performance Of Tools For Agronomic, Environmental, And Economic Response

Two metrics, 1) dEONR and 2) ANOVA of dEONR, were used to test the agronomic, environmental, and economic performance of N tools. Across all tools, dEONR for grain yield ranged from 0 to -3 Mg ha^{-1}. Using the first metric, NE YG and Maize-N had grain yield dEONR within the EONR range in both years. Canopy reflectance sensing had grain yield dEONR (–2.6 to –2.7 Mg ha^{-1}) lower than the EONR range in both years. Granular and Adapt-N had variable responses in each year. Granular had grain yield dEONR below (-1 Mg ha^{-1}) and within the EONR range (-0.5 Mg ha^{-1}) in 2021 and 2022, respectively. Conversely, Adapt-N had grain yield dEONR within (-0.5 Mg ha^{-1}) and below (-0.9 Mg ha^{-1}) EONR range in 2021 and 2022, respectively. Using the 2nd metric of ANOVA resulted in significant grain yield differences among N tools. All tools had similar grain yield except Canopy reflectance sensing, which had significantly lower grain yield in both years (Figure 2.8 b, e).

Using both metrics, NO_3-N leaching significantly differed among the N tools. Using the dEONR metric for N tools, the direction of NO_3-N leaching followed the direction of N input 7 out of 10 times (Figure 2.8 c,f). The NE YG had NO_3-N leaching dEONR within (+2 kg NO_3-N ha^{-1}) and above (+14 kg NO_3-N ha^{-1}) EONR range in 2021 and 2022, respectively. In both years, Maize-N and Excess-N had NO_3-N leaching dEONR (+3 to + 42 kg NO_3-N ha^{-1}) above the EONR range. However, the three N tools, namely Canopy reflectance sensing, Granular and Adapt-N, had NO_3-N leaching dEONR (-2 to -9 kg NO_3-N ha^{-1}) below the EONR range in 5 out of 6 times. Using the 2nd metric of ANOVA resulted in an insignificant effect of NO_3-N leaching dEONR among N tools in 2021. While in 2022, Excess-N had significantly higher NO_3-N leaching dEONR than all other N tools (Figure 2.8 c, f).

All the N tools had negative RTN and RTN_{Env} values in both years (Figure 2.9). Across all tools, dEONR of RTN and RTN_{Env} ranged from -\$758 ha-1 to - \$8 ha-1 and -\$2035 ha-1 to -\$11 ha-1, respectively. Nebraska YG had RTN and RTN_{Env} dEONR closer to EONR in both years. Similarly, Maize-N had RTN and RTN_{Env} dEONR within the EONR range in 2021. However, Excess-N had both RTN and RTN_{Env} dEONR below the EONR range. In both years, Canopy reflectance sensing had RTN and RTN_{Env} dEONR below the EONR range. Conversely, Granular and Adapt-N had RTN dEONR below the EONR range in both years. However, among these two tools, the dEONR of RTN_{Env} was within the EONR range 3 out of 4 times in both years. Using the 2nd metric of ANOVA resulted in statistically similar values of RTN dEONR among N tools except Canopy reflectance sensing with lower values in 2021. However, no differences in RTN_{Env} among tools occurred in the same year. Conversely, in 2022, no differences in RTN occurred. However, RTN_{Env} dEONR was significantly lower in Excess-N than all other N tools.

Performance Of Tools For Nitrogen Use Efficiencies

Using the first metric, the dEONR of PFP was higher than the mean EONR and ranged from +1 to +33 kg grain kg-1 N during 2021 (Figure 2.10). However, in 2022, dEONR values were in either direction of the mean EONR and ranged from –27 to +7 kg grain kg^{-1} N. The NE YG and Maize-N had PFP dEONR within the EONR range. However, Excess-N had dEONR below the EONR range. Canopy reflectance sensing had dEONR above in 2021 but below the EONR range in 2022. Granular and Adapt-N had dEONR above the EONR range 3 out of 4 times. Using the 2nd metric of ANOVA resulted in significant differences of dEONR with lower values with NE YG and Maize-N than the other three tools in 2021. However, in 2022, there were no differences in dEONR among all tools except Excess-N, with significantly lower dEONR.

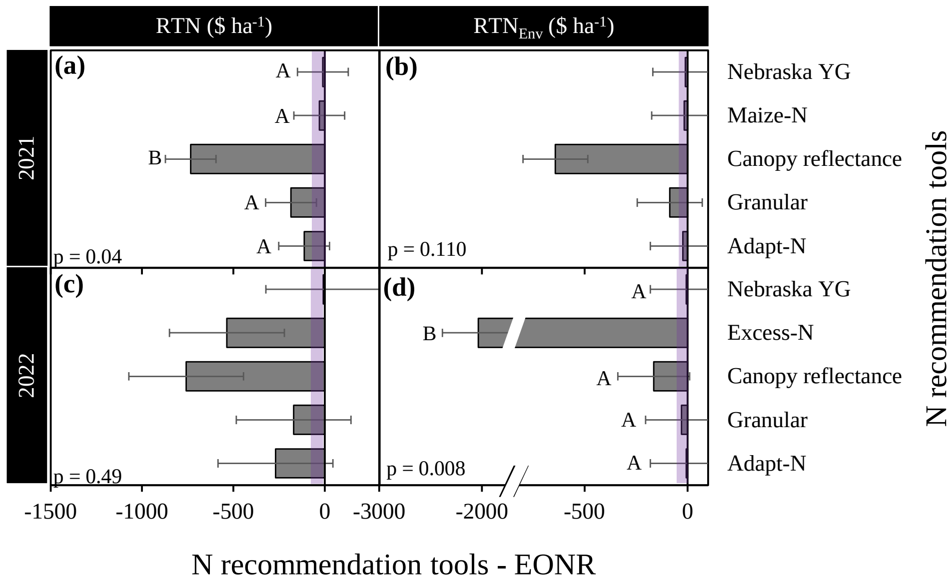

Figure 2.9 RTN and RTN_{Env} ($ ha^{-1}) are compared for N recommendation tools against EONR for 2021 (a and c) and 2022 (b and d), respectively. Significant differences at alpha = 0.05 are shown in different letters.

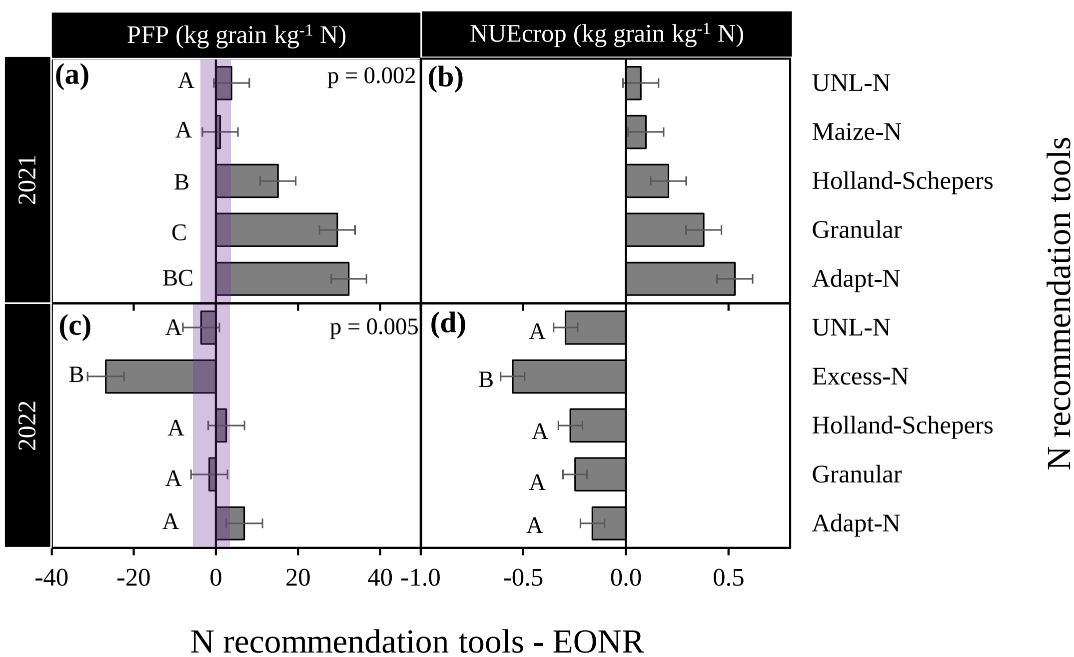

Figure 2.10 Partial Factor Productivity and Nitrogen Use Efficiency (kg grain kg^{-1} N) are compared for N recommendation tools against EONR for 2021 (a and c) and 2022 (b and d), respectively. Significant differences at alpha = 0.05 are shown in different letters.

In 2021, NUE_{crop} dEONR values were positive and above EONR in all the N tools and ranged from +0.1 to +0.5 kg grain kg^{-1} N (Figure 2.10) in 2021. In contrast, in 2022, NUE_{crop} dEONR values were negative and below EONR in all tools and ranged from – 0.5 to – 0.2 kg grain kg^{-1} N. Using the 2nd metric of ANOVA resulted in significant differences of dEONR with lower values with NE YG and Maize-N than the other three tools in 2021. However, in 2022, there were no differences in dEONR among all tools except Excess-N, with significantly lower dEONR.

Residual Soil N For N Recommendation Tools

No main or interactive effect of N-tools and soil depth on residual soil NO_3-N and NH_4-N occurred in 2021 (Table 2.4). When averaged across depths, the residual soil NO_3-N and NH_4-N ranged from 0.02 to 1.21 kg ha^{-1} and 4.31 to 8.84 kg N ha^{-1} among all N tools, respectively. In 2022, there were no main effects of N-tools and N-tools-depth interaction. However, soil depth significantly affected residual soil NO_3-N and NH_4-N. Among all N tools, the residual soil NO_3-N and soil NH_4-N ranged from 2.56 to 7.76 kg ha^{-1} and 11.06 to 14.55 kg N ha^{-1}, respectively. Residual soil NO_3-N was higher in the lower 90-120 cm depth than in the Upper three depths at 0-90 cm. Similarly, residual soil NH_4-N increased with soil depth with significantly higher values at the lower than the Upper soil depths. Overall, 2022 had three times higher (9 kg N ha^{-1}) residual soil N than in 2021. Interestingly, residual soil NH_4-N was three times and nine times higher than the residual soil NO_3-N in 2021 and 2022, respectively.

Table 2.4 Residual soil NO_3-N and NH_4-N from the N recommendation models

Source of Effect	2021		2022	
	NO_3-N	NH_4-N	NO_3-N	NH_4-N
N recommendation tools				
Adapt-N	0.02	4.69	6.24	13.86
Granular	0.25	5.51	7.76	14.55
Holland-Schepers	1.21	5.48	2.58	13.40
Maize-N	0.10	8.84	-	-
UNL-N	0.55	4.31	6.95	11.06
Depth (cm)				
0-30	0.62	4.27	5.71ab	10.65b
30-60	0.06	3.59	3.25b	12.99ab
60-90	0.46	9.71	4.53b	13.56a
90-120	0.56	5.50	10.04a	15.66a
SE	0.57	2.33	1.72	1.11
Significance	Pr>F			
N tools	0.566	0.800	0.194	0.172
Depth	0.424	0.242	**0.028**	**0.014**
N-tools x Depth	0.291	0.604	0.483	0.268

Discussion

Maize Yield And NO_3-N Leaching Response To Nitrogen Rate

A need to link maize productivity to environmental N losses has been well-highlighted in the past (Eagle et al., 2017; Puntel et al., 2016; Sela et al., 2017). Meanwhile, the associated consequence of high N application rates to groundwater quality is of concern (Exner et al., 2014; Saint-Fort et al., 1991; Schepers et al., 1995; Spalding et al., 2001). To our knowledge, no previous studies have reported agronomic, economic and NO_3-N leaching response with environmental cost to N rate and N recommendations from N tools. This study explored these responses and found the variable effect of the N rates and N recommendation tools on these responses.

Though the EONR was not much different between the two years in this study, maize grain yield, nitrate leaching, RTN, and RTN_{Env} were considerably different at EONR between years, indicating the importance of yearly weather and management impacts on agronomic, environmental, and economic performance. The quadratic plateau maize yield response observed in this study was similar to the observation in previous studies (Kaur et al., 2024; Manevski et al., 2016; Yang et al., 2017). However, in this study, both linear and exponential nitrate leaching responses in 2021 and 2022 were inconsistent with earlier findings with either linear (Vogeler et al., 2020) or exponential nitrate leaching responses with N rates (Delin & Stenberg, 2014). Interestingly, a linear increase above or below EONR in 2021 was accompanied by relatively lower NO_3-N leaching, indicating less potential for N losses. Conversely, the exponential increase in NO_3-N leaching above and below EONR in 2022 reflected a higher potential for NO_3-N leaching losses. These results were consistent with the findings of Delin & Stenberg (2014) who found an exponential increase in NO_3-N leaching and attributed that to lower grain yield in their study. Similarly, the higher NO_3-N leaching in 2022 of this study were also reflected by the lower grain yield, PFP, and NUE_{crop} than in 2021. The higher NO_3-N leaching in 2022 could partly be due to disk tillage by farmer in 2022 than no-till in 2021, as rainfall intensification has been shown to increase NO_3-N leaching from tilled cropping systems compared to no-till cropping system (Hess et al., 2020; Ritter et al., 1993). Although we applied slightly higher N during the early season in 2022 than in 2021, we assume the differences in N application amounts across times between the two years would not impact NO_3-N leaching in the study years, as the companion study showed no differences in NO_3-N leaching between 2-N vs. 3N vs. 4N vs. 5N splits, likely because of dry year with below than normal early and total seasonal precipitation (Singh et al., under review).

Agronomic Performance Of N Tools

The recognition of the best N recommendation tool can be site-specific or regional based on the goal of either crop productivity or environmental N losses or both, but available static and dynamic N tools do have some limitations on their performance (Asseng et al., 2013; Banger et al., 2018; Brilli et al., 2017). In this study, static and dynamic N tools had a wide range of responses in predicting EONR, NO_3-N leaching, RTN, $RTN_{Env,}$ and N use efficiency under the same weather conditions and soil type. This was not surprising as static and dynamic N tools use different input parameters to recommend EONR (Morris et al., 2018). However, it was surprising that despite not accounting for local weather conditions, static NE YG succeeded in both years in predicting an N rate close to EONR than all the dynamic N tools that account for site-specific soil and weather conditions (Morris et al., 2018). Discussion on the agronomic performance of each tool is given below:

Nebraska Yield Goal

Ransom et al. (2020) reported that NE YG was among the best performing tools among 31 evaluated N-tools and underestimated the N rate by only 12 kg N ha^{-1} at planting and by 27 kg N ha^{-1} during split-N (preplant and V8 side-dress) application but was within the EONR range of ±30 kg N ha^{-1}. Similarly, this study found that NE YG was successful in recommending the N rate within the EONR range in the irrigated sandy soils. This was in contrast with previous studies that reported a weak correlation of yield goal tools to EONR (Oglesby et al., 2023; Vanotti & Bundy, 1994). However, Nebraska

YG is well-known for possessing the unique features of requiring a wide range of inputs, such as NO_3-N in the maize root zone and irrigation water, nitrogen credit from soil organic matter and leguminous crop, and adjustments for N application timing and prices for yield and nitrogen etc, which makes it a successful model for Nebraska conditions (Iqbal et al., 2023). Moreover, NE YG recommends 5% less N for in-season N application than the pre-plant N rates, which generally improves its performance (Ransom et al., 2020).

Maize-N

Among all tools, Maize-N was the only model that recommended an N rate above EONR (13 to 102 kg N ha^{-1}) in both years (Figure 2.8). Similar to the results of this study, Thompson et al. (2015) found that Maize-N had 61 kg N ha^{-1} higher N recommendations compared to Canopy reflectance sensing on 9 out of 11 sites in the US Midwest. High N recommendations from Maize-N partially could be due to a lower estimation of N from mineralization (Thomspon et al., 2015) as lower soil organic matter generally translates to lower mineralized N (Myrold and Bottomley, 2008) and subsequently a lower estimation of soil N availability for crop uptake. Although Maize-N currently possesses the ability to respond to in-season growing conditions of weather variability impacting N mineralization while combining Hybrid-Maize for yield estimations and considering the response of maize yield to N (Setiyono et al., 2011; Thompson et al., 2015; Yang et al., 2004), it still needs to incorporate the denitrification estimation algorithms (Banger et al. 2018; Morris et al., 2018). Moreover, many of the model coefficients in Maize-N are simplified estimates of genetics, management, and soil characteristics and could be altered to better match crop N needs (Ransom et al., 2020).

Canopy Reflectance Sensing

Canopy reflectance sensing using Holland-Schepers algorithm did not perform well and underestimated N recommendation by 63-77 kg N ha^{-1} than EONR, resulting in a 2.6-2.7 Mg ha^{-1} yield penalty across both years. Previous studies have reported variable results with no differences (Barker & Sawyer, 2012), under prediction (Bean et al., 2018; Ransom et al., 2020) or over prediction of N (Thompson et al., 2015) with the canopy reflectance sensing than EONR, indicating a non-linearity of N recommendations to EONR across a wide range of environments (Ransom et al., 2020). At our site, the Canopy reflectance sensing tool might not have performed well because of the early season N stress as N was sidedressed at the V4 growth stage at all other N tools except Canopy reflectance sensing, which might have caused irreversible yield loss (Sitthaphanit et al., 2009; Walsh et al., 2012). The N stress in the Canopy reflectance sensing during the early season could have also resulted from the observed higher NO_3-N leaching losses from the pre-plant N during the early vegetative phase (Figure 2.5) as sandy soils possess greater NO_3-N leaching risk to groundwater due to high soil porosity, hydraulic conductivity, and lower water holding capacity, compared to clay soils (Silva et al., 2005). Therefore, a continuous supply of N in multiple N splits during the early season could be necessary to ensure adequate N supply without a yield loss (Gehl et al., 2005; Jung et al., 1972). The poor performance of the Canopy reflectance sensing with lack of sidedress N application at V4 was also evidenced by relatively lower maize yield by this N tool (13.7 Mg ha^{-1}) than the Granular (15.3 Mg ha^{-1}) that received the same seasonal total N rate as Canopy reflectance sensing but with sidedress N application at V4.

Granular and Adapt-N

Granular and Adapt-N recommended 10-74 kg N ha^{-1} lower N than EONR for the three site-years, resulting in maize yield loss of 0.5-1.0 Mg ha^{-1}. Previous studies have reported variable performance of these tools. For example, Sela et al. (2016) found that compared to farmer's N rate, Adapt-N reduced N recommendation by 34%, with no difference in maize yield observed in 113 on-farm trials in Iowa and New York. However, in N-rate trials of North Carolina, Adapt-N under- and over-estimated N up to 68 and 225 kg N ha^{-1} than agronomic optimum N rate, respectively. The differences in N recommendation across the sites could be due to variations in weather conditions (Puntel et al., 2018) which let the model provide wide ranges (up to 138 kg N ha^{-1}) of N recommendations after preplant spring application (Sela & van Es, 2018). Moreover, both N tools simulate the nitrification, denitrification, NO_3-N leaching, and NH_3 volatilization losses using daily weather data, and soil properties from the Soil Survey Geographic Database (SSURGO) (Morris et al., 2018; Gunzenhauser, 2023) which can have erroneous boundaries (Sangwan & Merwade, 2015) and might lead to variation in N recommendation. In addition, in our study, a considerable amount of N was credited from irrigation water (55-57 kg N ha^{-1}), which might have led to an underestimation of N from these tools. Therefore, improvement in N utilization estimates from areas with high NO_3-N concentration irrigation water might improve these tools' performance.

Environmental And Economic Performance of Tools

Despite a wide range of differences in N recommendations among the N tools, ANOVA did not result in statistical differences in NO_3-N leaching among all the tools except Excess N with higher NO_3-N leaching of 94 kg NO_3-N ha^{-1} than EONR. In general, the direction of NO_3-N leaching followed the direction of N recommendation 7 out of 10 times among all N tools. The lack of significant effect of NO_3-N leaching among the majority of the N tools was consistent with the findings of Delin and Stenberg (2014) who found that N fertilizer application did not significantly affect NO_3-N leaching when each extra kg resulted in 10 kg grain yield increase and beyond that level, the NO_3-N leaching increased exponentially. In fact, the pattern of higher NO_3-N leaching from the Excess-N and no differences of NO_3-N leaching around or below EONR was consistent with the higher NO_3-N leaching above EONR than below EONR in 2022 NO_3-N leaching response curve in this study (Figure 2.7). Moreover, the results were aligned with Hong et al. (2007), who reported no differences in potential N loss (i.e. residual NO_3-N) until the N rate exceeded 30 kg N ha^{-1}. Interestingly, this was similar to insignificant differences in residual NO_3-N among all N tools except Excess-N, with significantly higher residual NO_3-N in this study (Table 2.4). Despite insignificant differences, three dynamic N tools decreased NO_3-N leaching by 18% (5 out of 6 times) in both years, indicating a trend of decreased NO_3-N leaching with the dynamic N tools. ANOVA resulted in no statistical differences in RTN among all tools except the Canopy reflectance sensing with lower RTN, which could be explained by the lower grain yield. However, the significantly lower RTN from the canopy reflectance turned into insignificant lower RTN_{Env} effects due to NO_3-N leaching reduction with lower N rate from the Canopy reflectance sensing (Figure 2.9). Conversely, despite the wide range of RTN (-\$758 to -\$8 ha^{-1}), there were no significant effects among tools on RTN in 2022. However, higher NO_3-N leaching in the Excess N model resulted in significantly lower RTN_{Env} from Excess N than all other tools, indicating negative implications of higher N application on groundwater and profitability.

Overall, all N tools (excluding Excess-N) were equally effective in determining economic returns when environmental costs of NO_3-N leaching (RTN_{Env}) were included. Despite having multiple in-season inputs from the dynamic N tools with added costs of implementation, no significant improvement in agronomic, environmental, and economic performance questions the adaptability of these tools in improving RTN_{Env} in high NO_3-N contaminated areas. In fact, dynamics N tools are expected to perform better as they require more soil and crop information and implementation costs than the dynamic N tools (Ransom et al., 2020; Mandirini et al., 2021). Nevertheless, three dynamic N tools (Canopy Reflectance Sensing, Granular, and Adapt-N) reduced NO_3-N leaching by 18% more than half of the time, suggesting the potential for environmental benefits using these tools. On the other hand, static NE YG performed better in predicting EONR and yield but did not provide environmental benefits. State stakeholders need to priorities their agronomic and environmental goals using these N recommendation tools. Furthermore, future research can focus on refining and integrating positive aspects of multiple N tools to provide better N recommendations.

Conclusion

Higher groundwater NO_3-N contamination in the sandy soils of the BGMA poses a high risk to the environment and human health. Identifying and evaluating the best N recommendation tools are critical to sustaining crop production with minimal impact on water quality in this area. This study assessed the agronomic, environmental, and economic performance of static NE YG vs. multiple dynamic N tools. The results showed that the static NE YG tool was more effective in predicting EONR and grain yield than the dynamic N tools. Furthermore, dynamic N tools predicted nitrogen rates below

EONR, resulting in yield penalties more than half of the time. However, three dynamic N tools (Canopy Reflectance Sensing, Granular, and Adapt-N) reduced nitrate leaching by 18% more than half of the time, suggesting the potential for environmental benefits using these tools. Economically, all N tools were equally effective in determining economic returns when environmental costs of NO_3-N leaching (RTN_{Env}) were included. These results highlight challenges in adopting dynamic N tools as these provide some environmental benefits but with yield penalties and no economic benefits. On the other hand, the static NE YG can provide agronomic and economic benefits but no environmental benefits. Policymakers and farmers need to prioritize environmental or economic benefits while preferring any of these N recommendation tools.

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CHAPTER 3

TRADEOFFS OF NITROGEN AND IRRIGATION MANAGEMENT FOR MAIZE YIELD, ECONOMICS, AND GROUNDWATER QUALITY

Abstract

Increasing groundwater nitrate (NO_3-N) contamination has raised significant environmental and health concerns in the irrigated sandy soils of Nebraska. The objectives of this study were to evaluate the impact of nitrogen (N) and irrigation rates on NO_3-N leaching (measured via suction cup lysimeters), crop yield, agronomic indicators, and return to nitrogen with (RTN_{Env}) and without environmental cost (RTN). The two-year on-farm study included a factorial combination of three N rates (optimum, suboptimum, and low) and three irrigation rates (farmer's full irrigation (FIT), 80% of FIT, and 60% of FIT,) in continuous maize and irrigated sandy soils of Bazile Groundwater Management Area of Nebraska. The results showed that a reduction in N rate by 25% in the suboptimum (202 kg ha^{-1}) and 50% in low N rate (135 kg ha^{-1}) reduced NO_3-N leaching by 24% (7 kg NO_3-N ha^{-1}) and 51% (15 kg NO_3-N ha^{-1}), maize grain yield by 8% (14.5 Mg ha^{-1}) and 11% (14.0 Mg ha^{-1}), and RTN by \$215 ha^{-1} and \$298 ha^{-1}, respectively. However, reduced N rates did not affect RTN_{Env} . The 80% FIT had significantly higher grain yield and RTN, and lower NO_3-N leaching by 13-21% than 60% FIT and FIT. Furthermore, the year had a significant effect on most measured parameters. The year 2021 with an 8% higher grain yield, and 64% lower NO_3-N leaching (explained by 38% lower irrigation, 37% higher grain N uptake and 74% lower residual N), resulted in \$214 more RTN and \$587 more RTN_{Env} than in 2022. These findings highlight a tradeoff of adjusting N below the optimum N rate and decreasing

irrigation rates. While this approach substantially reduced NO_3-N leaching, it also reduced yield and had a higher RTN_{Env} in the groundwater contaminated area.

Introduction

Groundwater NO_3-N contamination has raised significant environmental and health concerns in the Midwestern United States (Exner et al., 2014; Ferguson et al., 1991; Juntakut et al., 2019, 2020; Mittelstet et al., 2019; Ouattara, 2022; Pennino et al., 2020; Ransom et al., 2022). In Nebraska, more than 80% of the population relies on groundwater for drinking (Skipton et al., 2011; NDEE, 2024). At the same time, increasing NO_3-N levels as observed in the Nebraska groundwater has caused adverse health effects such as birth defects, cancer, and methemoglobinemia (Ziebarth, 1991; Ouattara, 2022). These higher NO_3-N levels in groundwater are closely associated with excessive nitrogen (N) fertilizer use, especially in coarse-textured soils, as these soils possess greater NO_3-N leaching risk to groundwater due to high soil porosity, hydraulic conductivity, and lower water holding capacity (Ferguson et al., 2015; Owens et al., 1995; Silva et al., 2005). A recent report from the Nebraska Department of Environment and Energy showed that groundwater NO_3-N concentration frequently exceeded drinking water quality limits of 10 mg L^{-1} in several wellhead protection areas of Nebraska (NDEE 2023; See Figure 2.1). To address the increasing groundwater NO_3-N contamination, Natural Resource Districts (NRDs) of Nebraska, serving as watershed-based government entities, passed legislation in 1987 to establish groundwater management areas and set some regulatory strategies to protect groundwater quality (Ferguson et al., 2015).

One of the major NO_3-N contaminated areas in the state (Juntakut et al., 2019) is the Bazile Groundwater Management Area (BGMA), which was developed by Nebraska in 1986 and accepted by the Environmental Protection Agency (EPA) in 2016 (Figure 2.1). BGMA comprises 1958 sq. km. area under sandy soil and lies within three Nebraska counties (Antelope, Knox, Pierce). These sandy areas in BGMA are well above the EPA maximum contaminant level (MCL) of 10 mg NO_3-N L^{-1} and provide drinking water to more than 7,000 Nebraskans (Bartels, 2022; Figure 2.1). Though the shallow groundwater table depth in this area offers an inexpensive water supply to irrigate crops, it also results in a substantial NO_3-N leaching risk to the groundwater in the area (Gosselin, 1991; Hobza & Steele, 2020; Hou et al., 2023). Consequently, NRDs set phase areas with increasing NO_3-N concentrations in the BGMA and other groundwater management areas of Nebraska, i.e. Phase I: 0-5 mg NO_3-N L^{-1}, Phase II: 5.1-9.0 mg L^{-1}, Phase III: >9 mg NO_3-N L^{-1}, and Phase IV – areas in Phase III for five years. In each phase management area, there are different N and irrigation regulations set to improve NUE and decrease NO_3-N leaching (Bartels, 2022; Exner et al., 2014). For example, producers in all phases cannot apply N fertilizer during fall and before March 1st on sandy soils. In addition, producers in Phases II, III, and IV must report planted crops, expected yields, water and soil tests, and N credits, and conduct annual deep soil NO_3-N and groundwater NO_3-N analysis. Despite all these conservative efforts, NO_3-N levels in the groundwater are not showing a decreasing trend (Cannia et al., 2017; Hobza & Steele, 2020). Thus, the NRDs are looking for alternative N and water management efforts to protect groundwater quality without an economic impact.

Previous studies on N management in maize within Nebraska and neighboring states have mostly focused on N rate trials targeting optimizing N rate based on crop yield response, crop rotations, and soil textures (Banger et al., 2018; Cassman et al., 2003; Dinnes et al., 2002; Dobermann et al., 2011; Maharjan et al., 2016; Martin et al., 1994; Ransom et al., 2020; Rubin et al., 2016; Stanford, 1973; Struffert et al., 2016; Tubaña et al., 2008). However, very few studies have focused on N recommendations based on NO_3-N leaching in environmentally sensitive sites where groundwater NO_3-N contamination is a major concern (Sexton et al., 1998) This is in part because this type of research is often costly and requires intensive sampling for NO_3-N leaching measurements. Meanwhile, in other regions, researchers have suggested to use suboptimal N rates to decrease NO_3-N leaching because maximizing the maize production with an economical optimum nitrogen rate comes with higher risks of N losses (Rose et al., 2018; Schröder et al., 1998). Moreover, the reduction of N input by half reduces the N losses by >50% (Ju et al., 2009; Vitousek et al., 2009; Quemada et al., 2013). For example, Schroder et al. (1998) in the Netherland reported that applying nitrogen at a suboptimum N rate can reduce NO_3-N leaching risk with limited effect on maize yield. Similarly, Banger et al. (2020) in 270 distinct soil-climate regions in Canada, found that adjusting the nitrogen rate by 23-32% below the optimum N rate can significantly reduce NO_3-N leaching without impacting maize yield. However, Struffert et al. (2016) in Minnesota and Beaudoin et al. (2005) in Northern France reported that reducing N below the optimum level did not decrease NO_3-N leaching. These inconsistent effects of reduced N rates on NO_3-N leaching could be due to site-specific soil and climatic conditions (Li et al., 2023; Mzuku et al., 2005; Simmelsgaard & Djurhuus, 1998; Sogbedji et al., 2000; Zheng et al., 2020).

Similar to N, adjusting the amount of irrigation is another potential strategy to minimize NO_3-N leaching, as excessive irrigation leads to deep percolation below the root zone and results in higher NO_3-N leaching losses (Ferguson et al., 2013; Hergert, 1986; Quemada et al., 2013; Rudnick, 2013; Rudnick & Irmak, 2013, 2014). Sexton et al. (1998) found that even with optimum irrigation, significant NO_3-N leaching can occur when intensive summer thunderstorms happen soon after irrigation or fertilization. Similarly, Waddell et al. (2000) and Sexton et al. (1998) concluded that keeping deficit soil water levels between the irrigation events while maintaining soil water above the allowable depletion limit, can significantly reduce NO_3-N leaching. In concurrence, increasing droughts, depleting groundwater levels in the high plain aquifer, and increasing water demands are creating deficit irrigation situations in the central great plains (Mieno et al., 2024; Rudnick et al., 2019; Tarkalson et al., 2006). These deficit irrigations could affect crop production and will need N fertilizer adjustments to meet crop N demand (Quemada et al., 2013). As such, farmers and policymakers are increasingly looking for alternative N and irrigation management strategies to efficiently use existing water resources to protect groundwater quality.

Given the need to find alternative N and irrigation management strategies, there is an immediate need to assess the impact of reduced N and water inputs on crop production while minimizing NO_3-N leaching in the groundwater management areas. However, there is limited real-time data on the interactive effects of N and water inputs on both maize gain yield and NO_3-N leaching in Midwest sandy soils. This study assessed the impacts of suboptimal nitrogen (optimum. vs. suboptimum vs. low) and deficit irrigation (farmer's full irrigation (FIT), 80% of FIT vs. 60% of FIT) under split-N application on NO_3-N leaching and grain yield in irrigated maize of the BGMA. The specific objectives of this study were to evaluate the impacts of the above-mentioned N and irrigation rates on the maize grain yield, NO_3-N leaching, nitrogen recovery, agronomic indicators, residual soil N, and economic returns.

Materials And Methods

Experimental Conditions

The on-farm research experiment was conducted for two years (2021-2022) near Creighton, Nebraska, USA (42°25'02.3"N, 98°02'52.3"W). This site has an elevation of 568 m and is located in Phase III of the Bazile Groundwater Management Area (BGMA) in the Upper Elkhorn Natural Resource District (NRD). The site has a sub-humid climate (Li et al., 2023; Singh et al., 2021) with long-term annual average precipitation of ~700 mm, and air temperature of 9.6^0C (HPRCC, 2023). During the study years, the average annual temperature and precipitation were 10.5°C and 376 mm in 2021 and 9.3°C and 284 mm in 2022, respectively. Prior to the start of the experiment in the fall of 2020, the groundwater table depth at the site was around 12 meters. The predominant soil at the site is Thurman loamy sand (Soil Survey, 2022) with a 0-2% slope, 82.3% sand, 9.67% silt, and 8% clay. Before the treatment establishment, soil samples were collected at 0-20 cm depth and analyzed for soil physical and chemical properties listed in Table 2.1.

Experimental Design And Treatments

The experiment was conducted in a field with a center-pivot overhead sprinkler irrigation system. The outer two spans of the pivot were equipped with a variable rate irrigation (VRI) system (Valmont Industries, Valley, NE) and used to establish the experimental plots. The experimental design was a randomized complete block design with a factorial combination of three nitrogen (low, suboptimum, optimum) and three irrigation rates (Farmer’s full irrigation (FIT), 80% of FIT, 60% of FIT) and a zero-nitrogen control with three replications. Individual plots were 24 m long and 36 m wide.

The crop rotation was continuous maize. The treatments were applied to the same experimental plots in each study year. During 2021, maize was grown in a no-till field on May 12th. Due to high maize stubbles, the farmer tilled the field on April 14th, 2022, and planted maize on April 26th, 2022. Channel 20906 109 days mature maize variety was used during both years.

The three nitrogen treatments included a low N rate of 134 kg N ha^{-1}, suboptimum rate of 202 kg N ha^{-1}, and an optimum rate of 269 kg N ha^{-1}. The nitrogen at each rate was applied in 5-splits via pre-plant, sidedress at V4, and three fertigations at V8, V12, and VT. To minimize the ammonia volatilization losses at pre-plant, a urease inhibitor (AGROTAIN) from Koch Industries was used to coat urea at the recommended rate of 2.1 L AGROTAIN per ton Urea. The AGROTAIN-coated urea was surface broadcasted at pre-plant with a 3-m wide dry fertilizer drop spreader (Barber Engineering Co.). The side-dress N application with UAN (32%) was performed in furrows, using the 6-m wide liquid applicator at 4-leaf maize growth stage (V4). To minimize NH_3 volatilization losses, 19.05 mm irrigation was applied within 24 hours following side-dressing. The center pivot with variable rate sprinkler irrigation was used for irrigation and fertigation (with UAN 28%) purposes. The GPS-based irrigation and fertigation maps were uploaded before irrigation and/or fertigation events. During 2022, the application timing was adjusted by increasing early season N amounts. We assume the differences in N application timing between the two years would not affect measured parameters, as the companion study showed no significant differences in N application timing on the parameters measured in this study, likely due to below than normal precipitation during both study years. A detailed description of the N application rate at different maize growth stages is provided in Table 3.1.

Table 3.1 Nitrogen fertilizer inputs at the study site during 2021 and 2022.

Irrigation	Total Nitrogen (excluding MAP)	Preplant	Side-dress	Fertigation		
			V*4	V8	V12	VT
		Urea-AGROTAIN	UAN†			
			kg N ha^{-1}			
60% FIT	§134 (134)	45 (45)	11 (22)	11 (22)	34 (22)	34 (22)
	202 (202)	67 (67)	34 (67)	34 (22)	34 (22)	34 (22)
	269 (269)	90 (90)	78 (157)	34 (0)	34 (11)	34 (11)
80% FIT	134 (134)	45 (45)	11 (22)	11 (22)	34 (22)	34 (22)
	202 (202)	67 (67)	34 (67)	34 (22)	34 (22)	34 (22)
	269 (269)	90 (90)	78 (157)	34 (0)	34 (11)	34 (11)
FIT	134 (134)	45 (45)	11 (22)	11 (22)	34 (22)	34 (22)
	202 (202)	67 (67)	34 (67)	34 (22)	34 (22)	34 (22)
	269 (269)	90 (90)	78 (157)	34 (0)	34 (11)	34 (11)

§indicate N input values in 2021 and 2022 (in parenthesis).
† UAN, Urea Ammonium NO_3-N.
*V, maize stage, V4, 4-leaf stage; V8, 8-leaf stage; V12, 12-leaf stage; VT, tasseling.

To meet crop phosphorus requirements, the farmer applied Mono Ammonium Phosphate (MAP) before planting at 140 kg ha^{-1} (equivalent to 16 kg N ha^{-1}) and 105 kg ha^{-1} (equivalent to 12 kg N ha^{-1}) to the entire pivot field, including the experimental plots during 2021 and 2022, respectively. To meet potassium, magnesium, and sulfur needs, farmers broadcasted K-Mag from Mosaic at 86 kg K-Mag ha^{-1} (equivalent to 19 kg K_2O, 10 kg Mg, 19 kg S) to entire pivot field, including the experimental plots before planting maize each year.

The irrigation treatments included a farmer's full irrigation rate (FIT) (close to field capacity as measured by the soil moisture sensors), 80% of farmer's full irrigation (80% FIT), and 60% of farmer's full irrigation (60% FIT). During 2021, the total irrigation applied during the growing season for 60% FIT, 80% FIT, and FIT with 14 irrigation events was 143, 190, and 237 mm, respectively. While in 2022, the total irrigation applied during the growing season for 60% FIT, 80% FIT, and FIT with 22 irrigation events was 229, 306, and 382 mm, respectively. The management decisions such as crop hybrid selection, herbicide application, and irrigation scheduling were at the discretion of the farmer. The handheld canopy sensors were used to calculate the vegetation indices namely, normalized difference vegetation index (NDVI) and normalized difference red edge index (NDRE) to quantify vegetation greenness and measure the amount of chlorophyll in plants at the R1 maize growth stage, respectively.

Crop Yield, Nitrogen And Water Use Efficiencies, And Economic Return

At the end of the season, the middle two 3-meter rows were hand-harvested and separated into maize grain, and stover (stalk, leaves, cobs). The stover was shredded using a portable woodchipper. Ears and subsamples of chopped maize stover were weighed and dried at 71°C to determine moisture content. Ears were shelled to separate grain and cobs. Grain and stover were milled and analyzed for total nitrogen using the dry combustion method at Ward Laboratories, Inc. (Kearney, NE). Hand harvest grain yield at 15.5% moisture, nitrogen concentration in grain and stover, and plant population were used to calculate total aboveground biomass, harvest index, nitrogen uptake by grain, plant, and nitrogen harvest index. Furthermore, different nitrogen and water use efficiency indicators (Congreves et al., 2021; Rudnick & Irmak, 2013) including partial factor productivity (PFP, Eq. 3.1), maize nitrogen use efficiency (NUE_{maize}; Eq. 3.2), agronomic efficiency (AE; Eq. 3.3), nitrogen recovery efficiency (NRE; Eq. 3.4), nitrogen utilization efficiency (NUtE; Eq. 3.5), crop water use efficiency (CWUE; Eq.

3.6), net return to nitrogen (RTN; Eq. 3.7), and net return to nitrogen considering environmental costs (RTN_{Env} ; Eq. 3.8) were calculated as follows:

$$\mathrm{PFP}\ (\mathrm{kg\ kg^{-1}}) = \frac{\text{Grain yield}}{\text{Fertilizer N}} \quad \text{(Eq. 3.1)}$$

$$\mathrm{NUE_{maize}}(\mathrm{kg\ kg^{-1}}) = \frac{\text{Grain N uptake}}{\text{Fertilizer N}} \ \text{(Eq. 3.2)}$$

$$\mathrm{AE}\ (\mathrm{kg\ kg^{-1}}) = \frac{\text{Yield}_{\text{trt}} - \text{Yield}_{\text{control}}}{\text{Fertilizer N}} \quad \text{(Eq. 3.3)}$$

$$\mathrm{NRE}\ (\%) = \frac{\text{Plant N uptake}_{\text{trt}} - \text{Plant N uptake}_{\text{control}}}{\text{Fertilizer N}} \times 100 \ \text{(Eq. 3.4)}$$

$$\mathrm{NUtE}\ (\mathrm{kg\ kg^{-1}}) = \frac{\text{Grain Yield}}{\text{Plant N uptake}} \qquad \text{(Eq. 3.5)}$$

$$\mathrm{CWUE}\ (\mathrm{kg\ m^{-3}}) = \frac{\text{Grain Yield}}{\text{Crop Evapotranspiration}} \ \text{(Eq. 3.6)}$$

$$\mathrm{RTN} = (\mathrm{Yield_{Maize}} \text{ x } \mathrm{Price_{Maize}}) - (\mathrm{Input_N} \text{ x } \mathrm{Price_N}) \ \text{(Eq. 3.7)}$$

$$\mathrm{RTN_{Env}} = \mathrm{RTN} - (\mathrm{NO3} - \mathrm{N_{leached}} \text{ x } 18.54) \ \text{(Eq. 3.8)}$$

where 18.54 US$ kg^{-1} NO_3-N is the environmental cost associated with NO_3-N leached (Preza-Fontes et al., 2022; Sobota et al., 2015).

Lysimeter Installation And Water Sampling

To monitor the pore-water NO_3-N and NH_4-N concentration below the crop rootzone, two suction-cup lysimeters were installed approximately 30 m apart in the middle rows at 1.2 m soil depth in each experimental plot following the method described by Venterea et al. (2011) and Maharjan et al. (2014). The suction cup lysimeters were developed by the Irrometer Company Inc. (Model SSAT - Soil Solution Access Tube) and contained 100-kPa high flow ceramic cup attached to rubber tubing designed to apply the pressure and collect water samples at the soil surface. The suction cup lysimeters were installed using silica powder slurry to cover the ceramic cup at the bottom of the vertical hole bored with a soil probe. The soil from the hole was used to re-fill the hole around the lysimeter tube, followed by the placement of a finely powdered bentonite layer at the soil surface to prevent the preferential flow of water. Pore-water samples from the lysimeters were collected one to three times a week following rain or irrigation events from 20 May to 15 October 2021 and 13 May to 17 September 2022. To pull the pore water from the ceramic cup, a pressure of ~80 kpa was applied to the suction cup through the rubber tubes. After about 4 hours, the rubber tube line was opened to collect the pore-water sample with a 20 ml syringe and acidified with 0.1N HCl before transferring it to the lab in a cooler. There were 23 and 26 water sample collection events during 2021 and 2022, respectively.

Water Balance And NO_3-N Leaching Calculations

A soil water balance equation (Eq. 3.9) was used to estimate the draining water *via* deep percolation below the root zone using the following approach (Djaman & Irmak, 2013) :

$$DP_i = P_i + I_i - R_i - ET_i \pm \Delta S_i \text{ (Eq. 3.9)}$$

where DP is deep percolation, P is precipitation, I is irrigation, ET is evapotranspiration, ΔS is change in soil water storage in the root zone, and i is current day. Units are mm day^{-1}. The value of P was determined using High Plains Regional Climate Center (HPRCC) data collected at a weather station near the site, while I is the amount of irrigation applied. The ET values were calculated as a product of an alfalfa reference mean crop coefficient (K_s and K_{cr}) based on the stage of growing degree days (Lo et al., 2019) and the potential ET estimates incorporated with the daily weather data using the Penman-Monteith equation (Allen, 2000; Allen et al., 1998). The K_{cr} values for the curve were derived from the NDVI data collected during the R_1 maize growth stage using the relationship [K_{cr} = 1.308*(NDVI) + 0.027] given by Singh & Irmak (2009) for irrigated maize in Nebraska. The water in the soil profile at the start of the growing season was assumed to be at field capacity. We estimated runoff for our experiment using the United States Department of Agriculture–Natural Resources Conservation Service (USDA NRCS) curve number method (USDA-NRCS, 1985). Daily leaching mass of NO_3-N and NH_4-N were determined as the product of daily deep percolation and daily NO_3-N and NH_4-N concentration. The daily NO_3-N (Eq. 3.10) and NH_4-N mass from suction-cup lysimeters water sample concentrations were the product of (a) daily estimation(s) of deep percolation, (b) average of previous days pore water NO_3-N and NH_4-N concentrations after the last deep percolation event occurred, and (c) 0.01 (kg ha^{-1}) unit conversion factor (Pawlick et al., 2019).

$$[\mathrm{NO_3-N}]_{\mathrm{leached}} = \frac{1}{n}\sum_{i=1}^{n}[NO_3 - N]_{120cm}\ \mathrm{x}\ DP_i\ \mathrm{x}\ 0.01\ (\mathrm{Eq.}\,10)(\mathrm{Eq.}\ 3.10)$$

To calculate seasonal average pore water NO_3-N concentrations, the daily pore water NO_3-N concentrations were averaged across days for each maize growth stage. Sub-seasonal pore water NO_3-N concentrations were calculated based on the maize growth stages and the sampling dates between (i) planting and 8-leaf stage (early vegetative phase), (ii) 8-leaf to tasseling (late vegetative phase), and (iii) tasseling to physiological maturity (reproductive phase), and derived and validated from field observations to compute the effect of treatments over time (Rudnick et al., 2017; Singh et al., 2021). For seasonal pore water concentrations, the average was performed across all dates while the daily NO_3-N mass was summed up for area-scaled based seasonal NO_3-N leaching losses. Our data showed that >70% of ammonium values were below the detection limit, therefore, ammonium data analysis was not performed.

Residual Soil NO_3-N And NH_4-N Analysis

After harvest each year, six undisturbed deep core (0-120 cm) soil samples were collected after maize harvest from each experimental plot within non-trafficked rows. The truck mounted Giddings hydraulic probe (Giddings Machine Co., Fort Collins, CO) was used for sampling soil cores with a diameter of 44 mm. The intact cores were sliced at the following depth increments: 0-30, 30-60, 60-90, and 90-120 cm. The six soil cores per plot were composited by depth before being transported to the lab in a cooler. The soil samples were extracted with 2M KCl solution (5:1 solution to soil ratio) after shaking for 1 hr and filtered through Whatman # 1 filter paper. Soil extracts from deep core soil samples and lysimeter water samples were analyzed for NO_3-N and NH_4-N concentration using VCl_3/Griess method (Miranda et al., 2001) and the Berthelot reaction (Kandeler & Gerber, 1988), respectively.

Statistical Analysis

The data was checked for normality assumptions using the Shapiro-Wilk test with PROC UNIVARIATE function in SAS and verified with “dplyr” package in R software. The rest of the analysis was conducted using SAS statistical analysis version 9.4. In each year, daily and sub-seasonal pore water NO_3-N concentration analysis was performed with three-way repeated measures analysis of variance (ANOVA) using PROC GLIMMIX in SAS with nitrogen, irrigation, day/stage (repeated factor), and their interactions as fixed factors while replication and all interactions with replication as random factor. The treatment effect on response variables (NO_3-N leaching, grain yield, biomass yield, grain N uptake, plant N uptake, harvest index, nitrogen harvest index, partial factor productivity, nitrogen use efficiency of maize, agronomic efficiency N recovery efficiency, nitrogen utilization efficiency, crop water use efficiency, return to N

(RTN), and RTN_{Env}) were evaluated using three-way ANOVA considering nitrogen rate, irrigation rate, and year as fixed effects, and blocks, and all interactions of blocks with other factors as a random effect. The year was considered as a fixed effect to evaluate the effects of irrigation and precipitation between the two growing seasons (Bohman et al., 2020; Maharjan et al., 2016). For residual soil N (both NO_3-N and NH_4-N) analysis, the four-way repeated measures ANOVA was performed with nitrogen, irrigation, year, depth (as repeated factor), and their interactions for residual soil N as fixed factors while the replication and interaction between replication, year, irrigation and nitrogen were considered random factors. We used least square means estimates to analyze the differences among treatments. The significance was calculated at the 0.05 probability level.

Results

Weather Conditions

The growing season precipitation during 2021 (May through October) and 2022 (April through September) was 376 and 283 mm, respectively, which was 11.49% and 24.56% lower than the last ten year's average growing season precipitation (424 mm) at the site. The frequency of precipitation was different between the two years (Figure 3.1 & 3.2). In the year 2021, precipitation accounted for 15%, 49%, and 35% of the total growing season precipitation during the early vegetative, late vegetative, and reproductive phases, respectively. In 2022, precipitation accounted for 45%, 25%, and 28% of total growing season precipitation received during the early vegetative, late vegetative, and reproductive phases, respectively. When total water inputs from precipitation and irrigation were considered, the water input in each growth stage differed from precipitation only. For example, in 2021, the higher total water input occurred in the reproductive phase (43%) and late vegetative phase (43%), followed by early (14%) vegetative phase, respectively. While, in 2022, the higher total water input occurred in the reproductive phase (46%) followed by the late (28%) and early (25%) vegetative phase, respectively.

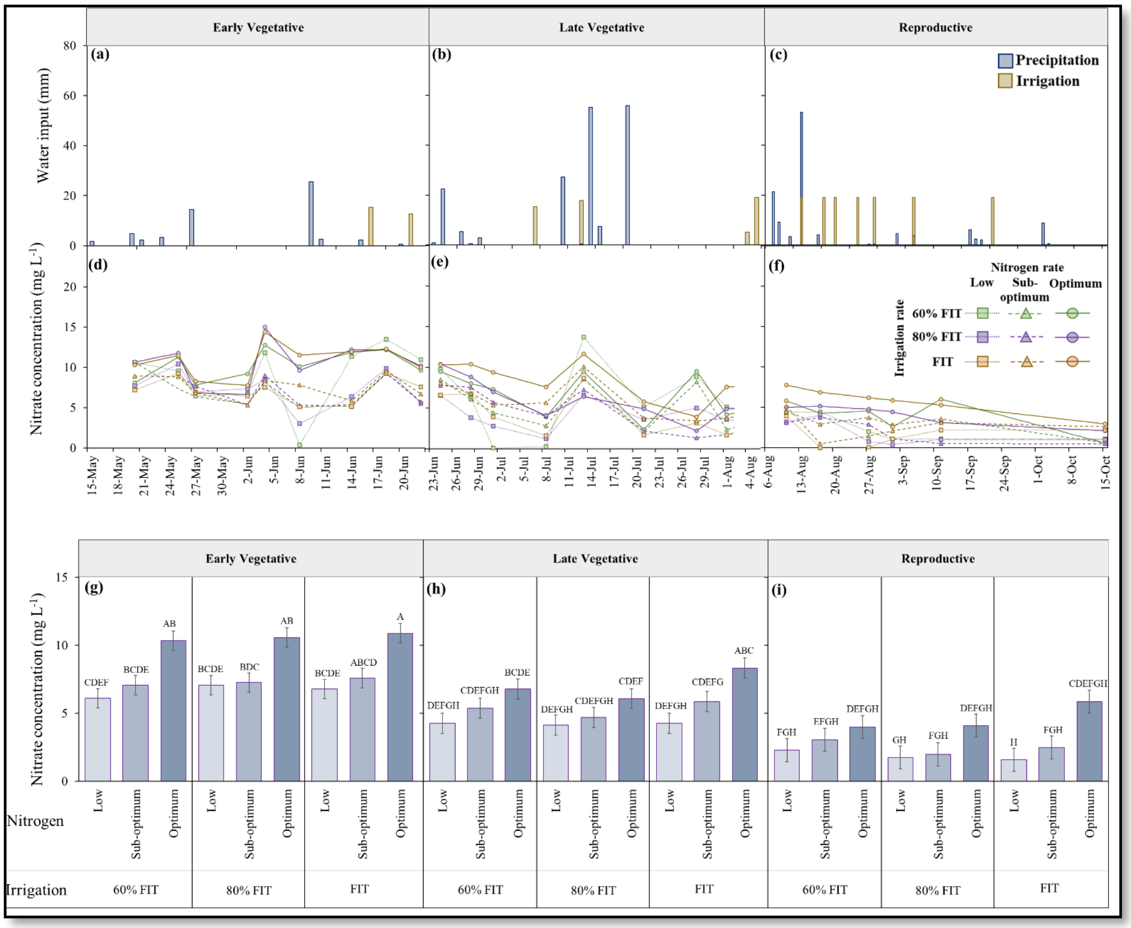

Figure 3.1 The upper panels (a-c) show water inputs (mm) for three maize growth phases – early vegetative (planting to V8), late vegetative (V8-VT) and reproductive phases (R1-R6), while daily and subseasonal pore water NO_3-N concentrations (mg L^{-1}) are shown in the middle panels (d-f) and lower panels (g-i), respectively in 2021.

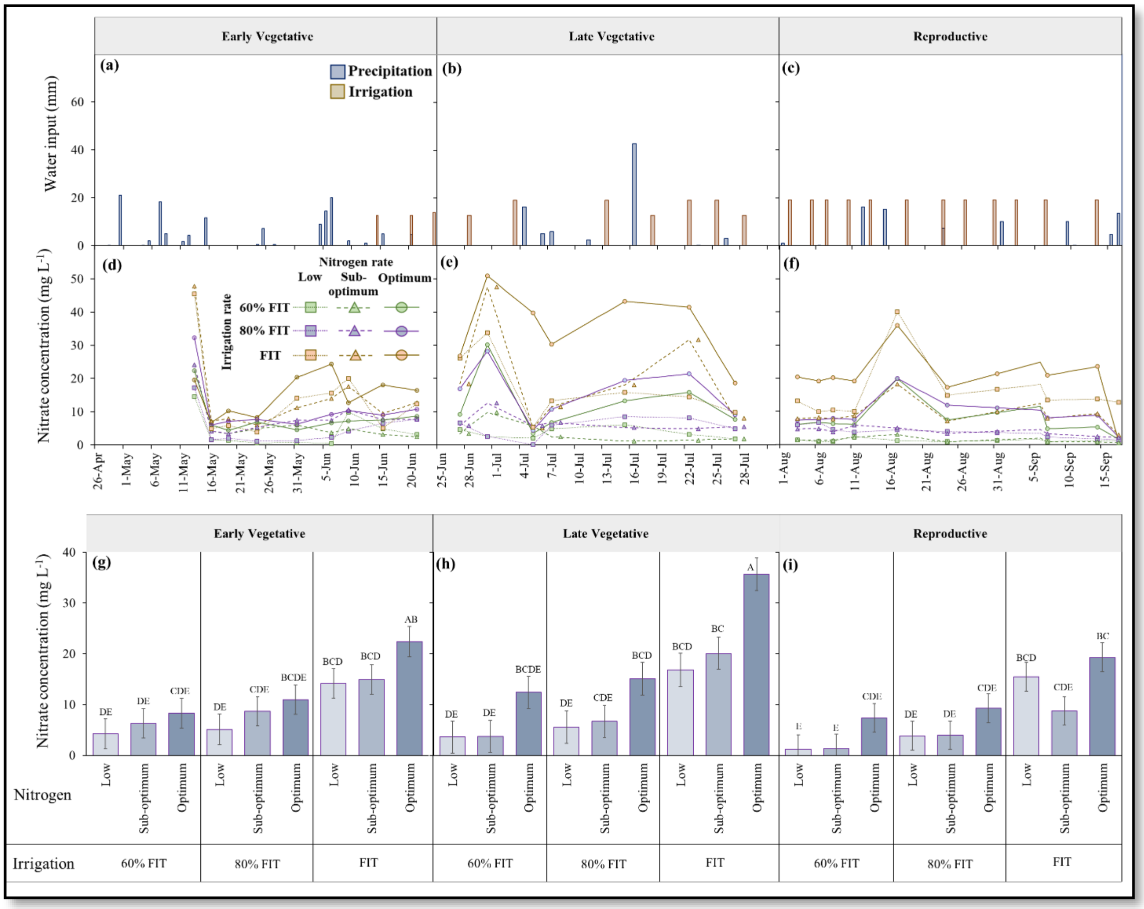

Figure 3.2 The upper panels (a-c) show the water inputs (mm) for three maize growth phases – early vegetative (planting to V8), late vegetative (V8-VT) and reproductive phases (R1-R6), while daily and subseasonal pore water NO_3-N concentrations (mg L^{-1}) are shown in the middle panels (d-f) and lower panels (g-i), respectively in 2022.

NO_3-N Concentration In Lysimeters

Across both years, the NO_3-N concentration in pore-water from the suction cup lysimeters was generally higher in the early to mid-growing season and decreased till the end of the growing season (Figures 3.1 and 3.2). For both growing seasons, there were no interactions among N, irrigation, and crop growth stage on pore-water NO_3-N concentration except for significant nitrogen and crop growth stage interactions in 2022 (Table 3.2). In 2021, N rates and growth stage significantly affected the pore water NO_3-N concentrations, but the irrigation rate had no effect (Table 3.2).

Table 3.2 Means and probability values for the main effect of nitrogen rate, irrigation rate, crop growth stage, and their interaction on pore-water NO_3-N concentrations during 2021 and 2022.

Source of effects	2021	2022
Nitrogen (N)		
Low	4.25b§	7.78b
Suboptimum	5.04b	8.26b
Optimum	7.43a	15.6a
Irrigation (I)		
60% FIT	5.47	5.39b
80% FIT	5.29	7.67b
FIT	5.96	18.6a
Stage (S) †		
EV	8.18a	10.6ab
LV	5.53b	13.3a
R	3.01c	7.83b
SE¶	0.3	1.9
Significance	ANOVA (Pr>F)	
N	**<.0001**	**<.0001**
I	0.134	**<.0001**
S	**<.0001**	**0.048**
N x S	0.334	**0.052**
N x I	0.307	0.184
I x S	0.606	0.069
N x I x S	0.966	0.797

§ Least significant difference at the 95% confidence level by PROC GLIMMIX-SAS treatment means followed by the same letter are not significantly different. Columns that do not contain letters indicate no significant difference between treatments. The bold numbers are significant at 0.05.
† The stages EV, LV, and R stands for early vegetative, late vegetative, and reproductive phases, respectively.
¶ SE, standard error of the mean.

Pore-water NO_3-N concentration in the optimum N rate was 48% and 75% higher than the sub-optimum and low N rates. Though non-significant, 80% FIT had 3% and 11% lower NO_3-N concentration than 60% FIT, and FIT, respectively. The pore-water NO_3-N concentration was highest during the early vegetative phase (8.18 mg L^{-1}), followed by late vegetative (5.53 mg L^{-1}), and reproductive phase (3.01 mg L^{-1}). During the 2022 growing season, N, irrigation, and growth stage had significant main effects on pore-water NO_3-N concentration. Optimum N rates had 47% and 50% higher pore-water NO_3-N concentrations than the suboptimum and low N rates. The 60% FIT and 80% FIT had 41% and 29% lower pore-water NO_3-N concentrations than the FIT. Moreover, pore-water NO_3-N concentration was highest during the late vegetative phase (13.3 mg mg L^{-1}), followed by early vegetative (10.6 mg L^{-1}), and reproductive phase (7.8 mg L^{-1}). Among all treatment combinations, high N rates with FIT had the highest pore-water NO_3-N concentration. In contrast, the lowest N rates with 60% FIT had the lowest pore-water NO_3-N concentration.

Seasonal NO_3-N Leaching

Total seasonal NO_3-N leaching was calculated from the pore-water NO_3-N concentration and deep percolation below the maize root zone depth. Across both years, no significant N, irrigation, and year interaction effect on NO_3-N leaching existed. However, year and N rate had a significant main effect on NO_3-N leaching. The NO_3-N leaching in 2022 (31.6 kg N ha^{-1}) was significantly higher than in 2021 (11.5 N ha^{-1}) (Table 3.3).

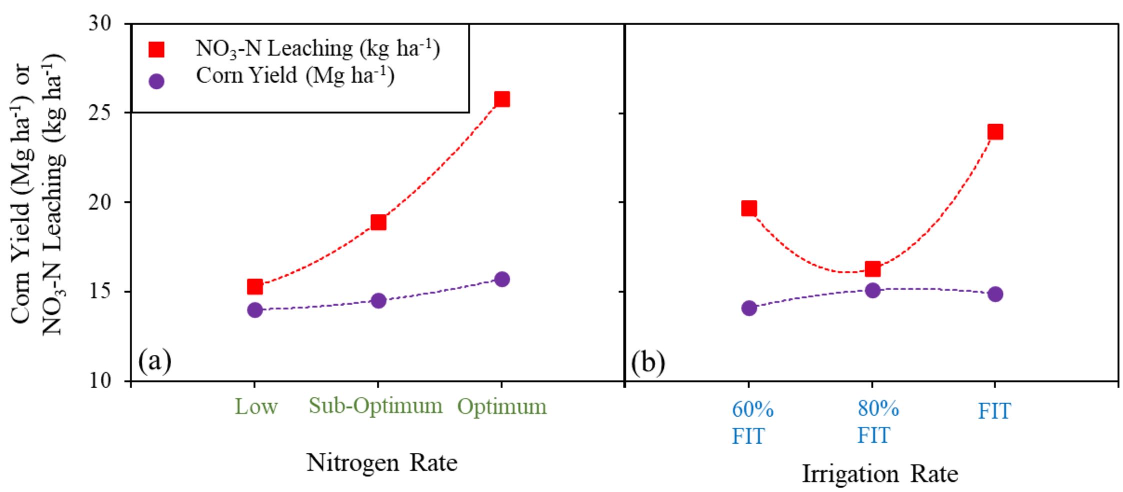

Figure 3.3 Relationships of maize yield and NO_3-N leaching across two study years for nitrogen (a) and irrigation rates (b).

Table 3.3 Treatment means and significance of NO_3-N leaching, grain yield, biomass yield, harvest index, grain-N uptake, plant-N uptake, N harvest index, vegetation indices, and ear leaf nitrogen concentration (ELNC) as affected by nitrogen rate, irrigation rate, year and their interactions in 2021 and 2022 at Creighton, NE.

Source of	NO_3-N leaching	Yield ($Mg\ ha^{-1}$)			N uptake ($kg\ ha^{-1}$)			R1 maize growth stage		
effects	($kg\ ha^{-1}$)	Grain	Biomass	HI	Grain	Plant‡	NHI	NDRE	NDVI	ELNC (%)
Nitrogen (N)										
Low	14.0b§	13.9b	21.8	0.66	206b	366b	0.60	0.68b	0.92b	2.60b
Suboptimum	21.8ab	14.4b	23.0	0.65	208b	371b	0.59	0.70a	0.93a	2.88a
Optimum	28.7a	15.6a	23.7	0.68	240a	433a	0.59	0.71a	0.93a	3.04a
Irrigation (I)										
60% FIT	21.7	14.1b	21.4b	0.67	213	369	0.61	0.69	0.93	2.91
80% FIT	19.0	15.1a	23.5a	0.66	217	397	0.60	0.69	0.93	2.70
FIT	23.9	14.8a	23.6a	0.65	216	403	0.58	0.69	0.93	2.92
Year (Y)										
2021	11.5b	15.2a	19.4b	0.78a	249a	309a	0.80a	0.64b	0.91b	2.67b
2022	31.6a	14.1b	26.3a	0.54b	181b	471b	0.39b	0.74a	0.94a	3.01a
SE¶	4.75	0.41	1.18	0.01	5.3	16.8	0.01	0.00	0.001	0.07
					ANOVA (Pr > F)					
N	**0.053**	**0.001**	0.138	0.167	**<.001**	**0.003**	0.772	**<.0001**	**0.007**	**0.003**
I	0.694	**0.034**	**0.043**	0.395	0.852	0.214	0.105	0.913	0.805	0.159
Y	**0.0001**	**0.001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**0.002**
N x I	0.413	0.257	0.292	0.689	0.106	0.111	0.527	0.764	0.720	0.242
N x Y	0.212	0.608	0.793	0.629	0.070	0.235	0.819	0.278	0.732	0.088
I x Y	0.514	0.229	0.069	0.267	0.094	0.149	0.881	0.139	0.061	0.354
N x I x Y	0.359	0.378	0.872	0.383	0.397	0.634	0.729	0.773	0.701	0.718

‡ Plant N uptake is the sum of grain and stover N uptake.

§ Least significant difference at the 95% confidence level by PROC GLIMMIX-SAS treatment means followed by the same letter are not significantly different. Columns that do not contain letters indicate no significant difference between treatments. The bold numbers are significant at 0.05.

¶ SE, standard error of the mean.

Averaged across both years, NO_3-N leaching significantly increased with increasing N rate with a quadratic response (Figure 3.3a). The low and suboptimum N rates had 51% (7 kg ha^{-1}) and 24% (15 kg N ha^{-1}) lower NO_3-N leaching than the optimum N rate (29 kg N ha^{-1}; Table 3.3). Though the irrigation rate did not significantly affect NO_3-N leaching, it had a curvilinear response with the lowest NO_3-N leaching at 80% FIT (Figure 3.3b). On the other hand, the 80% FIT had 14% (3 kg ha^{-1}) and 26% (5 kg ha^{-1}) lower NO_3-N leaching than the 60% FIT and FIT, respectively.

Grain Yield And Aboveground Biomass

There were no three-way or two-way interactions of N, irrigation, and year on grain yield and aboveground biomass (Table 3.3). However, year, N, and irrigation rate had significant main effects on grain yield and the aboveground biomass (Table 3.3). The grain yield was significantly higher in 2021 (15.2 Mg ha^{-1}) than in 2022 (14.1 Mg ha^{-1}). Across both years, grain yield responded positively to N rates and increased from 13.9 Mg ha^{-1} at a low N rate to 15.6 Mg ha^{-1} at an optimum N rate with a quadratic response (Figure 3.3a). Each additional N input of 1 kg N ha^{-1} increased grain yield by 0.014 Mg ha^{-1}. On the other hand, low to suboptimum N rates significantly increased grain yield by 3.5%, while suboptimum to optimum N rates increased grain yield by 7.7% (Table 3.3). Although irrigation had a significant main effect on grain yield, increasing irrigation rates did not increase grain yield across irrigation rates; rather, it had a curvilinear response (Figure 3.3). There were no differences in grain yield between 80% FIT and FIT. However, decreasing the water input to 60% FIT reduced grain yield by 7% (1.0 Mg ha^{-1}) and 5% (0.7 Mg ha^{-1}) compared to 80% FIT, and FIT, respectively (Table 3.3).

Similar to the grain yield, aboveground maize biomass had an increasing trend with an increase in N rate but it was not significant (Table 3.3). However, irrigation had a significant effect on the aboveground biomass. Corresponding to the irrigation effect on grain yield, 80% FIT and FIT had statistically similar but higher biomass than the 60% FIT. Moreover, 2022 had significantly higher aboveground biomass compared to 2021.

Crop N Uptake And Other Agronomic Traits

There were no three-way or two-way interactions of N, irrigation, and year on crop N uptake and other agronomic traits (Table 3.3). However, year and N rate had a significant main effect on crop N uptake and other agronomic traits. Corresponding to grain yield, grain N uptake and N harvest index were significantly higher in 2021 than in 2022 (Table 3.3). In contrast, plant N uptake was higher in 2022 than in 2021. Similar to grain yield, there were significant responses of grain and plant N uptake to N rate. Adding 1 kg N ha^{-1} as N input increased grain and plant N uptake by 0.31 and 0.50 kg N ha^{-1}, respectively. No significant differences among irrigation rates for grain and plant N uptake were observed. However, the 80% FIT and FIT had similar grain N uptake (~217 kg N ha^{-1}), which was ~4 kg N ha^{-1} higher than the 60% FIT. Although not significantly different, the plant N uptake increased from 369 kg N ha^{-1} at 60% FIT to 403 kg N ha^{-1} at FIT. The N and irrigation rates did not significantly affect nitrogen harvest index (NHI) and harvest index (HI) (Table 3.3). However, the year 2021 had a significantly higher HI than the year 2022.

Nitrogen, irrigation, and year did not interact to affect NDVI, NDRE, and ear leaf N concentration (ELNC) (Table 3.3). However, N rate and year had a significant main effect on NDRE, NDVI, and ELNC (Table 3.3). The NDRE, NDVI, and ELNC were significantly higher in 2022 than in 2021 (Table 3.3). Moreover, optimum and suboptimum N rates had significantly higher NDRE, NDVI, and ELNC compared to low nitrogen rate. However, the irrigation rate did not affect NDRE, NDVI, and ELNC (Table 3.3).

Resource (Nitrogen And Water) Use Efficiencies

No significant three- or two-way interactions between N, irrigation, and year were observed for partial factor productivity (PFP), agronomic efficiency (AE), nitrogen recovery efficiency (NRE), and crop water use efficiency (CWUE). However, there were significant N and year interaction effects on NUE_{maize} and NUtE (Table 3.4). In 2021, NUE_{maize} decreased from 1.6 kg grain kg^{-1} N in low to 1.0 kg grain kg^{-1} N^{-1} in both optimum and sub-optimum N rates. However, there was a decreasing trend, from low to optimum N rates, for NUE_{maize} (NUE_{maize} = 0.22*(N rate) + 1.35; R^2= 0.95) in 2022. There was a significant increase in NUtE at sub-optimum N rate compared to optimum and low N rates in 2021 whereas no significant differences were observed in 2022. Furthermore, the N rate and year had a significant main effect on PFP, AE, NRE, and CWUE. The year 2021 had significantly higher PFP, AE, and CWUE compared to the year 2022 (Table 3.4). Low N rate had higher PFP, AE, NRE, and lower CWUE compared to suboptimum and optimum N rates (Table 3.4). Irrigation rates did not significantly affect all agronomic parameters except CWUE. The FIT had significantly lower CWUE than 60% FIT and 80% FIT (Table 3.4).

Economics

Considering the economic and environmental importance of N use, we computed the net returns to N (RTN) and economic returns after considering the environmental costs associated with NO_3-N leaching (RTN_{Env}). The N, irrigation, and year had no significant interaction on RTN and RTN_{Env} . However, N, irrigation, and year had significant main effects on RTN. The year 2021 had \$214 ha^{-1} higher RTN than 2022.

Table 3.4 Treatment means and significance of partial factor productivity (PFP), maize nitrogen use efficiency (NUE_{maize}), agronomic efficiency (AE), nitrogen utilization efficiency (NUtE), nitrogen recovery efficiency (NRE), crop water use efficiency (CWUE), return to N (RTN), and RTN considering environmental costs (RTN_{Env}) as affected by nitrogen rate, irrigation rate, year and their interactions in 2021 and 2022 at Creighton, NE

Source of effects	PFP	NUE_{maize}	AE	NUtE	NRE	CWUE	RTN	RTN_{Env}
	kg grain kg^{-1} N^{-1}				%	kg m^{-3}	\$ ha^{-1}	
Nitrogen (N)								
Low	94.1ab§	1.39a	32.6a	40.3ab	108a	2.26b	609b	504
Medium	67.1b	0.92b	24.2b	42.7ab	75.0b	2.34b	692b	442
High	55.4c	0.84b	22.6b	38.1b	79.3b	2.53a	907a	529
Irrigation (I)								
60% FIT	69.4	1.05	23.5	40.5	78.2	2.42a	620b	373
80% FIT	74.6	1.07	29.1	41.1	94.6	2.42a	817b	621
100% FIT	72.6	1.04	26.8	39.6	90	2.28b	771a	482
Year (Y)								
2021	74.1a	1.21a	30.0a	50.2a	56.0b	2.72a	843a	785a
2022	70.3b	0.89b	23.0b	30.6b	119a	2.03b	629b	198b
SE¶	2.16	0.03	2.86	1.34	15.2	0.06	95	152
Significance	ANOVA (Pr > F)							
N	**<.0001**	**<.0001**	**0.0006**	**0.046**	**0.015**	**0.0004**	**0.008**	0.655
I	0.067	0.779	0.093	0.689	0.378	**0.054**	**0.024**	0.168
Y	**0.038**	**<.0001**	**0.001**	**<.001**	**<.001**	**<.0001**	**<.001**	**0.001**
N x I	0.295	0.188	0.347	0.463	0.185	0.333	0.289	0.228
N x Y	0.925	**0.002**	0.912	**0.024**	0.294	0.334	0.966	0.431
I x Y	0.209	0.09	0.252	0.53	0.117	0.445	0.124	0.145
N x I x Y	0.376	0.22	0.434	0.515	0.345	0.382	0.406	0.613

§ Least significant difference at the 95% confidence level by PROC GLIMMIX-SAS treatment means followed by the same letter are not significantly different. Columns that do not contain letters indicate no significant difference between treatments. The bold numbers are significant at 0.05.
¶ SE, standard error of the mean.

The RTN responded positively to increasing N rate (Table 3.4). The optimum N rate had significantly higher \$215 ha^{-1} and \$298 ha^{-1} RTN than the suboptimum and low

N rate, respectively. Meanwhile, the 80% deficit irrigation had \$46 ha^{-1} (5.6%) and \$197 ha^{-1} (24.1%) higher RTN compared to FIT and 60% FIT, respectively. However, after accounting for the environmental cost of NO_3-N leaching, significant irrigation and N effects of RTN changed into insignificant RTN_{Env} effects for irrigation and N treatments (Table 3.4). However, 2021 still had \$587 ha^{-1} higher RTN_{Env} than 2022.

Residual Soil Nitrogen

Across two years, no significant interactions existed between N, irrigation, depth, and year on residual soil NO_3-N and NH_4-N at 0-1.2 m soil depth (Table 3.5). However, the year significantly affected residual soil NO_3-N and NH_4-N ($p<0.001$). Compared to 2021, 2022 had 22 times and 3 times higher soil NO_3-N and NH_4-N, respectively. The N rate significantly affected residual soil NO_3-N in 2021 only (Table 3.5). Compared to the optimum nitrogen rate (5.26 kg ha^{-1}), soil NO_3-N decreased by 73% and 51% in the low (1.40 kg ha^{-1}) and suboptimum rate (2.56 kg ha^{-1}), respectively. In contrast, the irrigation and depth did not affect soil NO_3-N and NH_4-N. It was interesting to observe >3 times higher residual soil NH_4-N than residual soil NO_3-N across both years.

Table 3.5 Treatment means and significance of post-harvest soil NO_3-N (a) and NH_4-N (b) at 0-1.2 m soil depth as affected by nitrogen rate, irrigation rate, year and their interactions in 2021 and 2022 at Creighton, NE

Source of effects	Residual soil N (kg ha^{-1})	
	NO_3-N	NH_4-N
Nitrogen (N)		
Low	1.40b§	8.69
Suboptimum	2.56ab	9.05
Optimum	5.23a	9.13
SE¶	1.15	0.70
Irrigation (I)		
60% FIT	4.10	8.51
80% FIT	2.35	8.71
FIT	2.73	9.64
SE	1.15	0.70

Year (Y)		
2021	0.26b	4.79b
2022	5.86a	13.1a
SE	0.99	0.57
Depth (D)		
0-0.3m	4.49	8.26
0.3-0.6m	2.11	9.29
0.6-0.9m	2.20	8.86
0.9-1.2m	3.45	9.41
SE	1.07	0.61
Significance	Pr>F	
N	**0.035**	0.888
I	0.448	0.472
Y	**<.0001**	**<.0001**
D	0.131	0.377
NxI	0.984	0.220
IxY	0.571	0.839
IxY	0.209	0.359
NxD	0.945	0.661
IxD	0.158	0.778
YxD	0.215	0.900
NxIxD	0.750	0.091
NxYxD	0.887	0.252
IxYxD	0.223	0.203
NxIxYxD	0.943	0.353

§ Least significant difference at the 95% confidence level by PROC GLIMMIX-SAS treatment means followed by the same letter are not significantly different. Columns that do not contain letters indicate no significant difference between treatments. The bold numbers are significant at 0.05.
¶ SE, standard error of the mean.

Discussion

NO_3-N Leaching

NO_3-N leaching in sandy soils is often driven by water inputs across years and generally increases with increasing precipitation or irrigation (Bowles et al., 2018; Martin et al., 1994; Mohseni et al., 2021; Preza-Fontes et al., 2021). In this study, although 2022 had less precipitation than 2021, higher irrigation amounts and total water input in 2022 corresponded to higher NO_3-N leaching in 2022 (31.6 kg ha^{-1}) than in 2021 (11.5 kg ha^{-1}). These results were consistent with previous studies that reported higher NO_3-N leaching with higher irrigation amounts (Bowles et al., 2018; Quemada et al., 2013). For example, Waddell et al. (2000) showed increased NO_3-N leaching (6, 15, and 40 kg N ha^{-1}) with increasing irrigation rates (73, 191, and 154 mm) and deep percolation (29, 74, and 114 mm) in sandy loam soils of Minnesota. Moreover, it must be noted that, in this study, higher NO_3-N leaching in 2022 could also be due to a combination of higher irrigation water nitrogen input and disk tillage by farmer in 2022 than no-till in 2021, as rainfall intensification has been shown to increase NO_3-N leaching from tilled cropping systems compared to no-till cropping system (Hess et al., 2020; Ritter et al., 1993). Although, 2022 had a different timing of N fertilizer with more being applied early season, we assume the differences in N application amounts across times between the two years would not impact NO_3-N leaching in the study years as the companion study showed no differences in NO_3-N leaching between 2N vs. 3N vs. 4N vs. 5N splits, likely because of dry year with below than normal early season and total seasonal precipitation (Singh et al., under review).

The results of the N fertilizer and irrigation treatments within the two growing seasons indicated that N rates impacted seasonal NO_3-N leaching more than the irrigation rates. Though the deep percolation mass were not different between the N fertilizer treatments (76.70, 76.40, 76.39 mm for low, suboptimum, and optimum rates, respectively), seasonal NO_3-N leaching in these treatments was mainly driven by the pore-water NO_3-N concentration as the optimum N rate had significantly higher pore-water NO_3-N concentration and NO_3-N leaching than the suboptimum and low N rates in both years (Table 3.2; Figure 3.2). This incremental increase in seasonal NO_3-N leaching with increasing N rate was consistent with the earlier studies (Gheysari et al., 2009; Gholamhoseini et al., 2013; Liang et al., 2011; Sexton et al., 1998). In the present study, reducing N rate by 135 kg ha^{-1} and 67 kg ha^{-1} in the low and suboptimum N rate reduced NO_3-N leaching by 51% (15 kg ha^{-1}) and 24% (7 kg ha^{-1}). This was consistent with previous studies that reported substantially lower NO_3-N leaching when N rates were adjusted below the optimum N rate (Banger et al., 2020; Schröder et al., 1998a). The lower losses in the reduced N rates are generally attributable to higher PFP, NUE_{maize}, and AE at lower rates as observed in this (Table 3.4) and previous studies (Dobermann, 2005; Gao et al., 2012; Morris et al., 2018; Schröder et al., 1998).

Reducing irrigation generally decreases deep percolation and seasonal NO_3-N leaching (Bowles et al., 2018; Quemada et al., 2013). For example, Saffigna et al. (1977) observed that reduced irrigation (435 to 245 mm) resulted in less deep percolation (465 to 275) and NO_3-N leaching (208 to 128 kg N ha^{-1}) in loamy sand soils of Wisconsin. In agreement with previous findings, the results from this study showed that decreasing irrigation by 20% (80% FIT) and 40% (60% FIT) reduced percolation by 4% (77 mm) and 8% (73 mm), compared to FIT (80 mm), respectively. However, the decreasing percolation did not correspond to decreasing NO_3-N leaching across these irrigation rates. This was likely because of variations in NO_3-N concentrations of pore-water from lysimeters, indicating that the pore-water NO_3-N concentration was the primary driver of NO_3-N leaching (Bohman et al., 2019, 2020; Ochsner et al., 2018; Venterea et al., 2011). Despite this observation, 80% FIT had 14% (3 kg ha^{-1}) and 26% (5 kg ha^{-1}) lower NO_3-N leaching than 60% FIT and FIT (Table 3.3; Figure 3.2). Compared to 80% FIT, relatively higher NO_3-N leaching in 60% FIT could be due to water stress leading to less N uptake and grain yield, resulting in more leftover N for leaching. In contrast, over-irrigation in famer's conventional irrigation could have resulted in more available water than the plant requirement, that combined with higher irrigation water NO_3-N concentration, led to higher NO_3-N leaching. On the other hand, the 80% FIT might have provided optimum levels of available water to the crop, resulting in optimum crop N uptake and lower NO_3-N leaching than the FIT. This was evidenced by the similar grain yield, crop biomass, and crop N uptake between the 80% FIT and FIT (Table 3.3). Correspondingly, 80% FIT had \$46 ha^{-1} higher RTN and \$139 ha^{-1} higher RTN_{Env} than FIT, indicating higher profitability when irrigation is reduced by 20%. Future work should further explore optimizing irrigation water inputs through irrigation scheduling methods to better match crop water requirements, reduce deep percolation, and minimize NO_3-N leaching (Singh et al., 2023; Tarkalson et al., 2006).

Regardless of N and irrigation treatments, the NO_3-N leaching losses from our study were lower than those reported in previous studies in Nebraska (Klocke et al., 1999; Spalding et al., 2001). Earlier studies have reported 53 to 75 mg L^{-1} of NO_3-N concentrations and 91 to 146 kg ha^{-1} of NO_3-N leaching (Klocke et al., 1999; Hergert et al., 1986). The pore-water NO_3-N concentration in our study was lower than the earlier studies and within the range of 6 to 35 mg NO_3-N L^{-1} pore-water NO_3-N concentration reported by Spalding et al. (2001) in the Central Platte Valley of Nebraska during 1993-1996. Furthermore, the seasonal NO_3-N leaching in this study, ranging from 11.5 to 31.6 kg NO_3-N ha^{-1} was quite lower than the five-year annual average NO_3-N leaching losses of 52 to 91 kg NO_3-N ha^{-1} reported at the West Central Research and Extension Center

(WCREC) of Nebraska (Klocke et al., 1999). Though the N rates in this study were from a low to higher range (135 to 269 kg ha^{-1}) than WCREC study (202 kg N ha^{-1}), the lower NO_3-N leaching across all N rates in our study was likely due to use of AGROTAIN N stabilizer at pre-plant and multiple split application of N from pre-plant to R1 growth stage compared to all the N application at fourth to sixth leaf stage of maize at WCREC. Furthermore, total water application in this study in both years was lower than water inputs at the WCREC study (523 to 858 mm/season), indicating relatively improved rainfall or irrigation water adjustments to meet crop water demands in the present study. The lower NO_3-N leaching in this study than in the earlier studies (Gehl et al., 2005; Klocke et al., 1999; Shrestha et al., 2023) indicates considerable progress toward adopting best management practices in reducing NO_3-N leaching in sandy soils of Nebraska. However, the results of this study must be referred to and used in the context of dry years, since the study had lower than normal precipitation in both years. Further refinement of crop water use through accurate irrigation scheduling methods and N use through process-based models must be considered under variable weather conditions, as precipitation and N inputs are the key drivers for determining the magnitude and timing of NO_3-N leaching (Bohman et al., 2020).

Crop Yield, Nitrogen Uptake, And Net Return To Nitrogen

Nitrogen rates and irrigation water inputs are the driving factors of maize grain yield (Bhatti et al., 2020; Lo et al., 2019; Puntel et al., 2016, 2018; Rudnick et al., 2017; Rudnick & Irmak, 2013). So, the optimum levels of N and irrigation rates are desired to optimize maize grain yield, increase NUE and economic returns, and decrease N losses (Sexton et al., 1998). In this study, across both years, optimum N rate had the highest grain yield and RTN compared to suboptimum and low N rates, which was in agreement with the previous studies in the literature (Iqbal et al., 2015; Kaur et al., 2024; Yan et al., 2021). The higher maize grain yield with optimum N rates could be explained by higher values of grain and plant N uptake, NDRE, NDVI, ELNC, and CWUE compared to lower N rates (Tables 4 and 5). As expected, lower N rates had higher PFP, NUE_{maize}, AE, NUtE, and NRE, as crops with low N rates have a higher ability to utilize N efficiently (Montemurro et al., 2006; Rubin et al., 2016; Van Dijk et al., 2020). It is worth noting that the optimum N rate (269 kg N ha^{-1}) used in this study was close to the economic optimum nitrogen (EONR) of 257 kg N ha^{-1} and within the EONR range (247-271 kg N ha^{-1}) found in the companion study. Thus, increased maize yield and economic returns at optimum than suboptimum and lower N rates in this study can be explained by high N availability and crop N uptake (Table 3.3). Interestingly, there were no differences in N rate on RTN_{Env} after the inclusion of NO_3-N leaching cost, indicating tradeoffs between N rates, NO_3-N- leaching, and economic returns with the environmental costs. This was similar to a study in the Netherlands where Schroder et al. (1998) reported that adjusting the N rate below the optimum rate substantially reduced NO_3-N leaching with a limited impact on maize yield. Similarly, in 270 distinct soil climate regions of Canada, Banger et al. (2020) found that reducing N by 23 to 32% below the optimum N rate significantly reduced NO_3-N leaching without impacting maize yield. Furthermore, it is worth noting that compared to the optimum N rate used in this study, the companion study showed a similar or slightly higher grain yield (15.9 to 17.0 Mg ha^{-1}) at the same suboptimum N rate used in this study when the N stabilizer products such as SUPERU and AGROTAIN were used to meet entire season crop N demand. Furthermore, in the companion study, enhanced efficiency fertilizers reduced NO_3-N leaching by 50 to 78% at the suboptimum rate. This clearly indicates that using alternative N fertilizer sources could mitigate the negative yield effect at suboptimum N rates and still substantially reduce NO_3-N leaching.

Across both years, unlike the N rate, higher irrigation rates did not necessarily increase grain yield (Table 3.3; Figure 3.2), which was the opposite of the general understanding that increasing irrigation increases grain yield (Vaux & Pruitt, 1983). Compared to FIT, 60% FIT significantly decreased grain yield, grain and crop N uptake, stalk N, NDRE, crop biomass, and RTN, which was similar to previous studies that reported a decrease in grain yield with a reduction in irrigation input (Gheysari et al., 2009; Pandey et al., 2000; Bennett et al., 1989). However, in this study, 80% of FIT had similar grain yield, crop biomass, RTN, and higher CWUE than FIT. These results suggest that 80% of FIT likely met the crop water demand, and additional water input did not provide yield and economic benefits. These results were similar to findings from some other studies that reported no significant grain yield response when the irrigation amount was increased from 80% to 100% ET-based irrigation (Bohman et al., 2020; El-Hendawy & Schmidhalter, 2010; Guo et al., 2022; Liu et al., 2002). In fact, in this study, 80% FIT, with relatively lower NO_3-N leaching, led to fairly higher RTN_{Env} than the other two irrigation rates. These results suggest that adjusting irrigation rates below field capacity (FIT could) decrease NO_3-N leaching without impacting maize yield. Future work should further explore optimizing irrigation water inputs through irrigation scheduling methods to better match crop water requirements and minimize NO_3-N leaching (Tarkalson et al., 2006).

Though the N and irrigation effects on maize yield and other agronomic parameters did not differ between the two study years, these parameters had significant year effects across all treatments. The 2022 had lower grain yield than 2021, likely because of more irrigation and NO_3-N leaching in 2022 than in 2021. Furthermore, there was much lower N uptake, HI, and NHI in 2022 than in 2021, presumably indicating N limitation for crop uptake in 2022. The lower grain yield in 2022 could also be explained by lower NUE_{maize}, AE, NutE, and CWUE in 2022 than in 2021. These results strongly support the previous convention of decreased crop yield and increased NO_3-N leaching when comparatively higher irrigation rates are applied (Bowles et al., 2018; Preza-Fontes et al., 2021; Long and Sun, 2012). Moreover, these findings indicate that irrigation rates in some years can be more critical in determining NO_3-N leaching than rainfall, as despite having low rainfall, 2022 had higher NO_3-N leaching due to more irrigation than 2021. Interestingly, with lower grain yield and higher NO_3-N leaching losses in 2022, 2022 had \$214 ha^{-1} lower RTN and \$593 ha^{-1} lower RTN_{Env} than 2021. These results clearly demonstrate that year-year variability in N losses and grain yield can significantly impact yearly NO_3-N leaching losses and economic returns. Therefore, optimizing yearly irrigation rates can be critical in achieving water quality and farm profit goals.

Residual Soil Nitrogen

Nitrogen leftover in the soil after harvest has the potential to increase NO_3-N leaching during the off-growing season in the mid-west (Iqbal et al., 2017; Syswerda et al., 2012). In this study, the optimum N rates had higher residual NO_3-N, corresponding to increased NO_3-N leaching with optimum N rate during the growing season. These results suggest that despite multiple N splits, optimum N inputs could still leave high NO_3-N at the end of the growing season and increase the risk of NO_3-N leaching during winter. On the other hand, suboptimum and low N rates left approximately half of residual soil NO_3-N than the optimum N rate. The cumulative residual NO_3-N across all treatments at 0-1.2m depth (12.3 kg N ha^{-1}) from this study was lower than the generally reported residual NO_3-N value of 25 kg NO_3-N ha^{-1} at 1 meter depth in sandy soils of Nebraska (Shapiro et al., 2016). One reason for the lower residual NO_3-N could be the optimum or lower N rates that, with multiple N-splits, resulted in higher crop N uptake (Table 3.3) and left relatively lower NO_3-N after the crop harvest. However, compared to cumulative soil NO_3-N (12.3 kg NO_3-N ha^{-1}), it was interesting to observe three times higher cumulative residual soil NH_4-N (35.8 kg NH_4-N ha^{-1}), likely originating from fertilizer or mineralization of soil organic matter. This relatively higher NH_4-N than NO_3-N was similar to our recent study, where we found a significant amount of residual NH_4-N in silty clay loam soil in Central Nebraska (Neels et al., 2023). These results suggest that N recommendations for the next season crop could be refined using N credits from NO_3-N and NH_4-N, decreasing N fertilizer inputs, and further reducing the NO_3-N leaching risks. The irrigation rates did not affect residual soil NO_3-N or NH_4-N, indicating that irrigation rate mainly affected the N movement in the soil during the growing season and had less impact on soil N movement during the off-growing season. Compared to irrigation and N rate, year had a more pronounced effect on soil NO_3-N and NH_4-N as these values were significantly higher in 2022 than in 2021. The higher residual N in 2022 could be due to a combination of high inputs (water and nitrogen) and disk tillage by farmer in 2022 that likely increased the soil organic matter mineralization (Cassman & Munns, 1980; Contosta et al., 2011; McPherson, 2022). Notably, the higher residual N in 2022 also corresponded to higher NO_3-N leaching in 2022. Furthermore, when averaged across all treatments, cumulative residual N at 0-1.2 m depth (5 kg N ha^{-1} in 2021, 19 kg N ha^{-1} in 2022) was 40-56% of NO_3-N leaching load during each growing season, indicating risk for NO_3-N leaching during the off-growing season. This was supported by previous studies that reported that a significant portion of NO_3-N leaching occurred during the off-growing season of November – April in the region (Basso & Ritchie, 2005; Power et al., 2001; Syswerda et al., 2012). Nevertheless, the result from this study indicates that only in-season N management might not be enough to reduce NO_3-N leaching, but off-season N management practices need to be adopted to better provide a whole-year approach for reducing the NO_3-N leaching.

Conclusion

High groundwater NO_3-N contamination in the sandy soils undermines the sustainability of growing row crops in vulnerable areas, including the Bazile Groundwater Management Area. So, evaluating and adopting efficient nutrient and water management practices are crucial to ensure acceptable crop production with soil and water protection. This study demonstrated that using multiple N-splits at optimum or reduced N rates can substantially reduce NO_3-N leaching in vulnerable sandy soils. Though 25% and 50% reductions in N fertilizer decreased maize yield by 8% and 11%, this reduction in N rates substantially reduced NO_3-N leaching by 24 and 51% and RTN_{Env} by \$87 ha^{-1} and \$25 ha^{-1}, respectively. These results highlight a tradeoff between reduced grain yield, reduced NO_3-N leaching, and societal economic returns in the groundwater NO_3-N contaminated areas. Furthermore, higher maize grain yield, RTN, and relatively lower NO_3-N leaching from 80% FIT indicate that reducing irrigation can minimize NO_3-N leaching without impacting maize yield and economic returns.

Compared to N and irrigation management within the growing season, it was interesting to observe that yearly variation in irrigation and grain yield had a higher impact on determining NO_3-N leaching and economic returns i.e. despite having lower irrigation and total water inputs, 2021 had higher grain yield, lower NO_3-N leaching, lower residual NO_3-N and NH_4-N, and higher RTN than 2022. These results demonstrate that adjusting irrigation and N rates could substantially reduce NO_3-N leaching without impacting RTN_{Env} in the groundwater NO_3-N contaminated areas. Future research should explore irrigation scheduling and N rate models to better optimize the irrigation and NO_3-N inputs to reduce NO_3-N leaching.

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CHAPTER 4

IMPACT OF ENHANCED EFFICIENCY FERTILIZERS ON THE GROUNDWATER WATER QUALITY

Abstract

The increasing groundwater nitrate (NO_3-N) contamination in irrigated sandy soils poses significant economic, environmental, and health threats. The objectives of this study were to evaluate the impact of conventional nitrogen (N) split vs. pre-plant N application, with and without enhanced efficiency fertilizers (EEFs) [i.e., (a) urease inhibitor (UI), and (b) urease and nitrification inhibitor (UI+NI)] on NO_3-N leaching, maize yield, and return to N with (RTN_{Env}) and without environmental cost (RTN) in irrigated sandy soils of Bazile Groundwater Management Area in Nebraska. The two-year (2021-2022) on-farm study included a zero N check treatment and following six treatments at a sub-optimal N rate of 202 kg N ha^{-1}: 1) Urea applied as preplant (U_{PP}), 2) and in split with conventional Urea-urea ammonium-nitrate (UAN) (U_{split}), 3) urea with UI applied as preplant ($(U+UI)_{PP}$), 4) and split with UAN ($(U+UI)_{split}$), 5) urea with UI+NI applied as pre-plant ($(U+UI+NI)_{PP}$), and 6) split with UAN ($(U+UI+NI)_{split}$). Compared to conventional U_{split}, $(U+UI)_{PP}$ and $(U+UI+NI)_{PP}$ decreased nitrate leaching by 75% (by 27 kg NO_3-N ha^{-1}) and increased RTN_{Env} by \$537 ha^{-1} but had no considerable effect on maize yield. There were no significant differences between U_{split} and U_{PP} on NO_3-N leaching, maize yield, and RTN. Furthermore, $(U+UI)_{split}$ + $(U+UI+NI)_{split}$ significantly reduced NO_3-N leaching by 31% (by 20 kg NO_3-N ha^{-1}) and increased grain yield by 9.6% than the U_{PP} in 2021. However, $(U+UI)_{split}$ + $(U+UI+NI)_{split}$ (29.1 kg NO_3-N ha^{-1}) significantly increased NO_3-N leaching by 139%

(2.4 times) than $(U+UI)_{PP}$ and $(U+UI+NI)_{PP}$ (12.2 kg NO_3-N ha^{-1}) with no effect on grain yield in both years. Notably, in both years, NO_3-N leaching from $(U+UI)_{PP}$ and $(U+UI+NI)_{PP}$ had similar NO_3-N leaching as the check treatment. These findings suggest that pre-plant application of EEFs can substantially reduce nitrate leaching without impacting maize yield but with higher economic returns in groundwater-contaminated areas.

Introduction

For the last six decades, maize production in Nebraska has increased from 39 to 100 million acres (USDA NASS, 2023). Nationally, Nebraska ranks third in maize production, producing 1.45 billion bushels of grains and 5.37 million tons of silage from 9.6 million acres of maize production in 2022 (USDA NASS, 2023). Increased crop production generally increases nitrogen (N) consumption (Sawyer et al., 2016), and so does it increase the potential of nitrate (NO_3-N) leaching losses to groundwater (Mittelstet et al., 2019; Zelt & Munn, 2009). The increase in NO_3-N contamination is evidenced by groundwater NO_3-N levels far exceeding the Environmental Protection Agency (EPA) safe drinking water limit of 10 mg L^{-1} on about one million hectares of Nebraska (Juntakut et al., 2019; NDEE, 2020). At the same time, more than 80% of Nebraska's rural population relies on groundwater for drinking purposes, which resulted in adverse health effects in several Nebraskan towns (Ouattara, 2022). Meanwhile, several Nebraska towns are paying millions of dollars to treat the contaminated water (Exner et al., 2014; Pennino et al., 2017, 2020; Ray et al., 2022). To address the groundwater contamination risks, Natural Resource Districts (NRDs), a watershed-level government agency, passed legislation in 1987 and established groundwater management areas to set strategies for protecting groundwater quality.

One of the major NO_3-N contaminated areas in the state (Juntakut et al., 2019) is the Bazile Groundwater Management Area (BGMA), which was developed by Nebraska in 1986 and accepted by the Environmental Protection Agency (EPA) in 2016 (Figure 2.1). BGMA comprises 1958 sq. km. area under sandy soil and lies within three counties (Antelope, Knox, Pierce) of the state. These sandy areas in BGMA are well above >10 mg NO_3-N L^{-1} (Figure 2.1) and provide drinking water to 7000 Nebraskans (Bartels, 2022). Though the shallow groundwater table depth in this area provides an inexpensive water supply to irrigate crops, it also results in a substantial NO_3-N leaching risk to the groundwater in the area (Gosselin, 1991; Hobza & Steele, 2020; Hou et al., 2023). To address the N management in BGMA and other groundwater management areas in Nebraska, NRDs set phase areas with increasing NO_3-N concentrations in the groundwater. i.e. Phase I: 0-5 mg NO_3-N L^{-1}, Phase II: 5.1-9.0 mg L^{-1}, Phase III: >9 mg NO_3-N L^{-1}, Phase IV – areas in Phase III for five years. In each phase management area, there are different nitrogen and irrigation regulations to improve N use efficiency (NUE) and protect groundwater quality (Bartels, 2022; Exner et al., 2014). One of the major regulations is not to apply N before March 1st but to apply N in split during the growing season. Though the producers are recommended to use the optimum N rate using the University of Nebraska-Lincoln N recommendations, they have no set limits for total N use in these phase areas.

Despite the set regulations, NO_3-N levels are not showing a decreasing trend of groundwater NO_3-N contaminants (Cannia et al., 2017; Hobza & Steele, 2020), so NRDs are increasingly looking for alternative best management practices to reduce NO_3-N leaching. Meanwhile, researchers have shown that despite adopting best N management practices, only 40-60% of applied N is recovered by the crop, while the rest is lost into the environment (Dobermann & Cassman, 2002; Hirel et al., 2007; Zhang et al., 2015). Moreover, in a recent water quality research review, Christianson & Harmel (2015) suggested that optimizing the N rate will remain a key for research and regulations. Other researchers pointed to using suboptimal N rates to decrease NO_3-N leaching because maximizing the maize production with an economically optimum N rate comes with higher risks of N losses (Schröder et al., 1998). In the other regions, the researchers found that the reduction of N input by half reduces the N losses by >50% (Ju et al., 2009; Vitousek et al., 2009; Quemada et al., 2013). For example, Schroder et al. (1998) in the Netherlands reported that applying N at suboptimum N rate can reduce NO_3-N leaching risk with limited effect on maize yield. Similarly, Banger et al., (2020) in 270 distinct soil-climate regions in Canada, found that adjusting the N rate by 23-32% below the optimum N rate significantly reduced NO_3-N leaching without impacting corn yield. However, Struffert et al. (2016) in Minnesota and Beaudoin et al. (2005) in Northern France reported that reducing N below the optimum level did not decrease NO_3-N leaching. These inconsistent effects of reduced N rates on NO_3-N leaching could be due to site-specific soil and climatic conditions and N sources (Bhatti et al., 2020; Ferguson et al., 2002; Hussain et al., 2022; Pawlick et al., 2019; Silva et al., 2005).

Because of the affordability and ease of application, granular urea and urea ammonium nitrate (UAN) are the most commonly used fertilizer for sandy soils in the region and the world. However, previous studies have shown that urea-based fertilizers have low NUE and high vulnerability for N losses through NH_3 volatilization, nitrous oxide emissions and NO_3-N leaching (Dobermann et al., 2011; Drury et al., 2016; Woodley et al., 2020; Soares et al., 2023; Rochette et al., 2008; Maharjan et al., 2014; Venterea et al., 2021). Following surface application of urea, it is quickly hydrolyzed within 1 or 2 days to NH_4-N, increasing soil pH, and potential of NH_3-N volatilization losses in case precipitation or irrigation does not happen soon after application (Overrein & Moe, 1967; Zambelli et al., 2011; Zhengping et al., 1991). Moreover, subsequent nitrification of NH_4-N to NO_3-N in a short period increases the potential for NO_3-N leaching losses upto 80% in case of high precipitation, especially when the NO_3-N availability exceeds crop N uptake during the early season (Paul and Clark, 1996; Di and Cameron 2002; Parfitt et al., 2006). Therefore, stabilizing N availability, even with split N application, during the early growing season is critical to meet crop N needs and mitigate environmental N losses. Increasing the NUE of synthetic N fertilizers also helps to meet the demands of the Kyoto Protocol (Protocol, 1997).

Meanwhile, increasing evidence has shown that the use of enhanced efficiency fertilizers (EEFs), including the urease and nitrification inhibitors, can stabilize N and significantly reduce N losses without an impact on corn yield but higher economic returns at suboptimum N rate (Allende-Montalbán et al., 2021; Rose et al., 2018), or optimal N rates (Díez-López et al., 2008; Nelson et al., 2008; Souza et al., 2019; Wilson et al., 2010). For example, Diez et al. (2010) found that a single pre-plant application of dicyandiamide (DCD) and 3,4-dimethylpyrazole phosphate (DMPP) nitrification inhibitors at the recommended N rate significantly decreased NO_3-N leaching by 29% without any impact on corn yield when compared to split N application in sandy loam soil of irrigated corn. They attributed NO_3-N leaching reduction to 30% lower soil NO_3-N production in the nitrification inhibitor plots than with no nitrification inhibitor. Similarly, Allende-Motalban et al. (2021) found that a single application of urease inhibitors was more effective in delaying urease activity, slowing N availability, and reducing potential N losses than the split application of urea with urease inhibitors in sandy soil in corn. In parallel, Rose et al. (2018) in a meta-analysis reported that the beneficial effects of EEFs in improving NUE and corn yield are more likely at suboptimal N rates.

To our knowledge, no study has reported the use of EEFs with either single or split application at suboptimal N rates to reduce NO_3-N leaching (possibly no yield difference or higher economic effects), especially in groundwater management areas where NO_3-N contamination poses a substantial environmental and health concerns. Moreover, only a few studies have attempted to optimize the N management for corn based on NO_3-N leaching in the sandy soils of the US Midwest (Maharjan et al., 2016; Struffert et al., 2016), as research is costly and requires intensive sampling for NO_3-N leaching measurements. Understanding that using EEFs could profoundly influence the NO_3-N leaching in the area, this study aimed to investigate the impact of EEFs in single or split applications on NO_3-N leaching, corn yield, and economic returns. Using the suboptimal N rates, the objectives of this study were to evaluate the effects of 1) conventional U_{split} (U_{split}) vs. one-time application of urea coated with N-(n-butyl) thiophosphoric triamide (NBPT) urease inhibitor ($(U+UI)_{PP}$), urea coated with NBPT + DCD ($(U+UI+NI)_{PP}$), and regular urea (U_{PP}), and 2) split application of Agrotain with UAN ($(U+UI)_{split}$) and SuperU with UAN ($(U+UI+NI)_{split}$) vs. conventional U_{split},

$(U+UI)_{PP}$, $(U+UI+NI)_{PP}$, and U_{PP}, on NO_3-N leaching, corn yield, nitrogen use efficiency, residual N, and economic returns.

Materials And Methods

Experimental Conditions

The on-farm research experiment was conducted for two years (2021-2022) near Creighton, Nebraska, USA (42°25'02.3"N, 98°02'52.3"W). This site has an elevation of 568 m and is located in Phase III of the Bazile Groundwater Management Area (BGMA) in the Upper Elkhorn Natural Resource District (NRD). The site has a sub-humid climate (Li et al., 2023; Singh et al., 2021) with long-term annual average precipitation of ~700 mm, and air temperature of 9.6^{0}C. During the study years, the average annual temperature and precipitation were 10.5°C and 376 mm in 2021 and 9.3°C and 284 mm in 2022, respectively. Prior to the start of the experiment in the fall of 2020, the groundwater table depth at the site was around 12 meters. The predominant soil at the site is Thurman loamy sand (Soil Survey, 2022) with a 0-2% slope, 82.3% sand, 9.67% silt, and 8% clay. Before the treatment establishment, soil samples were collected at 0-20 cm depth and analyzed for soil physical and chemical properties listed in Table 2.1.

Site Description, Experimental Design, And Crop Management

The experiment was conducted in a field with a center-pivot overhead sprinkler irrigation system. The outer two spans of the pivot were equipped with a variable rate irrigation (VRI) system (Valmont Industries, Valley, NE) and used to establish the experimental plots. The experimental design was a randomized complete block design with a combination of nitrogen sources and application timing and a zero-nitrogen control (check treatment) with three replications. Individual plots were 24 m long and 36 m wide. The crop rotation was continuous maize. The treatments were applied to the same experimental plots in each study year. During 2021, maize was grown in a no-till field on May 12th. Due to high maize stubbles, the farmer tilled the field on April 14th, 2022, and planted maize on April 26th, 2022. Channel 20906 maize variety, matures in 109 days, was used during both years.

In addition to a zero-N check treatment, the study included the following six treatments with a combination of nitrogen sources with and without EEFs and N application timing (pre-plant vs. split): (i) single preplant application of regular Urea (U_{PP}), (ii) conventional 5-N split of Urea and UAN (U_{split}) (iii) single preplant application of urea coated with N-(n-butyl) thiophosphoric triamide (NBPT) urease inhibitor ($(U+UI)_{PP}$), (iv) 5-N split of Agrotain coated urea with UAN ($(U+UI)_{split}$), (v) single preplant application of urea coated with NBPT + DCD ($(U+UI+NI)_{PP}$) and (vi) 5-N split of SuperU with UAN ($(U+UI+NI)_{split}$). Due to logistics issues, U_{split} was implemented in 2022 only. All N fertilizer treatments were applied at a single rate of 202 kg N ha^{-1} in 2021 and 2022. More details about the N rates and timing are provided in Table 2. The EFFS products, including Agrotain and SuperU, were both acquired from the Koch Industries. Agrotain was used to coat urea at the recommended rate of 2.1 L Agrotain per ton Urea, while SuperU was applied as received.

The preplant N application was surface broadcasted with a 3-m wide dry fertilizer drop spreader (Barber Engineering Co.). For split applications, one-third N was applied with or without inhibitor as preplant while two-third of the N application was applied with Urea Ammonium Nitrate (UAN; 32% N) via a side-dress and three fertigations. The side-dress N application with UAN (32%) was performed in furrows, using the 6-m wide liquid applicator at 4-leaf maize growth stage (V4). To minimize NH_3 volatilization losses, 19.05 mm irrigation was applied within 24 hours following side-dressing. The center pivot with variable rate sprinkler irrigation was used for irrigation and fertigation (with UAN 28%) purposes. The GPS-based irrigation and fertigation maps were uploaded before irrigation and/or fertigation events. A detailed description of the N application rate and timing is provided in Table 4.1.

Table 4.1 Timing of N application for various N sources at the study site in the year 2021 and 2022.

N timing*	Total N	Preplant application with N source	UAN†			
			V4	V8	V12	VT
N method			Side-dress	fertigation		
N source	kg N ha^{-1}					
U_{PP}	202 (202)‡	202 (202)	0 (0)	0 (0)	0 (0)	0 (0)
U_{split}	0 (202)	0 (68)	0 (68)	0 (22)	0 (22)	0 (22)
$(U+UI)_{PP}$	202 (202)	202 (202)	0 (0)	0 (0)	0 (0)	0 (0)
$(U+UI)_{split}$	202 (202)	67 (68)	33 (68)	34 (22)	34 (22)	34 (22)
$(U+UI+NI)_{PP}$	264 (202)	264 (202)	0 (0)	0 (0)	0 (0)	0 (0)
$(U+UI+NI)_{split}$	264 (202)	88 (68)	74 (68)	34 (22)	34 (22)	34 (22)
Check	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)

† UAN, Urea NH_4-NO_3.
*V4, 4-leaf stage; V8, 8-leaf stage; V12, 12-leaf stage; VT, tasseling.
‡ indicate N input values in 2021 and 2022 (in parenthesis).

To meet crop phosphorus requirements, the farmer applied Mono Ammonium Phosphate (MAP) before planting at 140 kg ha^{-1} (equivalent to 16 kg N ha^{-1}) and 105 kg ha^{-1} (equivalent to 12 kg N ha^{-1}) to the entire pivot field, including the experimental plots during 2021 and 2022, respectively. To meet potassium, magnesium, and sulfur needs, farmers broadcasted K-Mag from Mosaic at 86 kg K-Mag ha^{-1} (equivalent to 19 kg K_2O, 10 kg Mg, 19 kg S) to entire pivot field, including the experimental plots before planting maize each year. The management decisions such as crop hybrid selection, herbicide application, and irrigation scheduling were at the discretion of the farmer.

Crop Yield, Nitrogen Use Efficiencies, And Economic Return

At the end of the season, the middle two 3-meter rows were hand-harvested and separated into maize grain, and stover (stalk, leaves, cobs). The stover was shredded using a portable woodchipper. Ears and subsamples of chopped maize stover were weighed and dried at 71°C to determine moisture content. Ears were shelled to separate grain and cobs. Grain and stover were milled and analyzed for total nitrogen using the dry combustion method at Ward Laboratories, Inc. (Kearney, NE). Hand harvest grain yield at 15.5% moisture, nitrogen concentration in grain and stover, and plant population were used to calculate total aboveground biomass, harvest index, nitrogen uptake by grain, plant, and nitrogen harvest index. Furthermore, several nitrogen use efficiency indicators (Congreves et al., 2021) including partial factor productivity (PFP, Eq. 4.1), agronomic efficiency (AE, Eq. 4.2), nitrogen recovery efficiency (NRE, Eq. 4.3), and economic returns including the net return to nitrogen (RTN; Eq. 4.4), and net return to nitrogen considering environmental costs (RTN_{Env}; Eq. 4.5) were calculated as follows:

$$\text{PFP (kg kg}^{-1}) = \frac{\text{Grain yield}}{\text{Fertilizer N}} \quad \text{(Eq. 4.1)}$$

$$\text{AE (kg kg}^{-1}) = \frac{\text{Yield}_{\text{trt}} - \text{Yield}_{\text{control}}}{\text{Fertilizer N}} \quad \text{(Eq. 4.2)}$$

$$\text{NRE (\%)} = \frac{\text{Plant N uptake}_{\text{trt}} - \text{Plant N uptake}_{\text{control}}}{\text{Fertilizer N}} \text{ x } 100 \text{ (Eq. 4.3)}$$

$$\text{RTN} = (\text{Yield}_{\text{Corn}} \text{ x } \text{Price}_{\text{Corn}}) - (\text{Input}_{\text{N}} \text{ x } \text{Price}_{\text{N}}) \text{ (Eq. 4.4)}$$

$$\text{RTN}_{\text{Env}} = \text{RTN} - (\text{NO}_3{-}\text{N}_{\text{leached}} \text{ x } 18.54^{*}) \text{ (Eq. 4.5)}$$

*18.54 US$ kg^{-1} NO_3-N was the environmental cost associated with NO_3-N leaching (Preza-Fontes et al., 2023; Sobota et al., 2015).

Lysimeter Installation And Water Sampling

To monitor the pore water NO_3-N and NH_4-N concentration below the crop rootzone, two suction-cup lysimeters were installed approximately 30m apart at 1.2 m soil depth in each experimental plot following the method described by Venterea et al., (2011) and Maharjan et al. (2014). The suction cup lysimeters were developed by the Irrometer Company Inc. (Model SSAT - Soil Solution Access Tube) and contained 100-kPa high flow ceramic cup attached to rubber tubing designed to apply the pressure and collect water samples at the soil surface. The suction cup lysimeters were installed using silica powder slurry to cover the ceramic cup at the bottom of the vertical hole bored with a soil probe. The soil from the hole was used to re-fill the hole around the lysimeter tube, followed by the placement of a finely powdered bentonite layer at the soil surface to prevent the preferential flow of water. Pore-water samples from the lysimeters were collected one to three times a week following rain or irrigation events from 20 May to 15 October of 2021 and 13 May to 17 September of 2022. To pull the pore water from the ceramic cup, a pressure of ~80 kpa was applied to the suction cup through the rubber tubes. After about 4 hours, the rubber tube line was opened to collect the pore-water sample with a 20 ml syringe and acidified with 0.1N HCl before transferring to the lab in a cooler. There were 23 and 26 water sample collection events during the years 2021 and 2022, respectively.

Water Balance And NO_3-N Leaching Calculations

A soil water balance equation (Eq. 4.6) was used to estimate the draining water via deep percolation below the root zone using the following approach (Djaman & Irmak, 2013):

$$DP_i = P_i + I_i - R_i - ET_i \pm \Delta S_i \text{ (Eq. 4.6)}$$

where DP is deep percolation, P is precipitation, I is irrigation, ET is evapotranspiration, ΔS is soil water storage in the root zone, and i is current day. Units are mm day^{-1}. The value of P was determined using High Plains Regional Climate Center (HPRCC) data collected at a weather station near the site, while I is the amount of irrigation applied in the field by the farmer. The ET values were calculated as a product of an alfalfa reference mean crop coefficient (Kcr) based on the stage of growing degree days (Lo et al., 2019) and the reference ET estimates incorporated with the daily weather data using the Penman-Monteith equation (Allen et al., 1998, 2000). The Kcr values for the curve were derived from the NDVI data collected during the R1 corn growth stage using the relationship [K_{cr} = 1.308*(NDVI) + 0.027] given by Singh & Irmak (2009) for irrigated corn in Nebraska. The water in the soil profile at the start of the growing season was assumed to be at field capacity. We estimated runoff for our experiment using the United States Department of Agriculture–Natural Resources Conservation Service (USDA NRCS) curve number method (USDA NRCS, 1985). Daily leaching amount of NO_3-N and NH_4-N were determined as the product of daily deep percolation and daily NO_3-N and NH_4-N concentration. The daily NO_3-N (Eq. 4.7) and NH_4-N amount from suction-cup lysimeters water sample were the product of (a) daily estimation(s) of deep percolation and (b) average of previous days pore water NO_3-N and NH_4-N concentrations after last deep percolation event occurred, and (c) 0.01 (kg ha^{-1}) unit conversion factor (Pawlick et al., 2019).

$$[\mathrm{NO_3-N}]_{\mathrm{leached}} = \frac{1}{n}\sum_{i=1}^{n}[NO_3-N]_{120cm} \text{ x } DP_i \text{ x } 0.01 \text{ (Eq. 7)(Eq. 4.7)}$$

Seasonal average pore water NO_3-N concentrations use daily pore water NO_3 concentrations were averaged across days in the corn growth stage. Sub-seasonal pore water NO_3-N concentrations were calculated based on the corn growth stages and the sampling dates between (i) planting and 8-leaf stage (early vegetative phase), (ii) 8-leaf to tasseling (late vegetative phase), and (iii) tasseling to physiological maturity (reproductive phase), derived and validated from field observations to compute the effect of treatments over time (Rudnick et al., 2017; Singh et al., 2021). For seasonal pore water concentrations, the average was performed across all dates while the daily NO_3-N amounts were summed up for area-scaled based seasonal NO_3-N leaching losses. Our data showed that >70% of ammonium values were below detection limit, therefore, ammonium data analysis was not performed.

Residual Soil NO_3-N And NH_4-N Analysis

In fall, six undisturbed deep core (0-120 cm) soil samples were collected after corn harvest from each experimental plot within non-trafficked rows. The truck mounted Giddings hydraulic probe (Giddings Machine Co., Fort Collins, CO) was used for sampling soil cores with a diameter of 44 mm. The intact cores were sliced at the following depth increments: 0-30, 30-60, 60-90, and 90-120 cm. The six soil cores per plot were composited by depth before being transported to the lab in a cooler. The soil samples were extracted with 2M KCl solution (5:1 solution to soil ratio) after shaking for 1 hr, followed by filtration through Whatman #1 filter paper. Soil extracts from deep core soil samples and lysimeter water samples were analyzed for NO_3-N and NH_4-N concentration using VCl_3/Griess method (Miranda et al., 2001) and the Berthelot reaction (Kandeler & Gerber, 1988), respectively.

Statistical Analysis

Two-way repeated measures analysis of variance (ANOVA) was performed using PROC GLIMMIX with replication as a random factor, treatment as a fixed factor, and crop growth stage and/or date as a repeated fixed factor using the autoregressive (1) structure for the residuals (Singh et al., 2023), for analyzing the differences between (i) sub-seasonal, and (ii) daily pore water NO_3-N concentrations. One way ANOVA was performed with replication as a random factor and treatment as a fixed factor to analyze the differences among treatments for grain yield, biomass yield, grain N uptake, plant N uptake, harvest index, nitrogen harvest index, NO_3-N leaching, partial factor productivity, agronomic efficiency, N recovery efficiency, return to N, and return to N considering environmental costs. The least square means estimates were used to analyze the differences among treatments. Furthermore, the following contrasts were performed for agronomic and economic variables: "check vs. others", "U_{split} vs. $(U+UI)_{PP}$ + $(U+UI+NI)_{PP}$", "$(U+UI)_{split}$ + $(U+UI+NI)_{split}$ vs. U_{split}", "$(U+UI)_{split}$ + $(U+UI+NI)_{split}$ vs. U_{PP}", "$(U+UI)_{split}$ + $(U+UI+NI)_{split}$ vs. $(U+UI)_{PP}$ + $(U+UI+NI)_{PP}$", "$(U+UI)_{PP}$ + $(U+UI+NI)_{PP}$ vs. U_{PP}". Two-way repeated measures ANOVA was performed each year using PROC GLIMMIX with replication as a random factor, treatment as a fixed factor, and depth as a repeated fixed factor for residual soil N (NO_3-N and NH_4-N). A contrast of "$(U+UI)_{PP}$ vs. others" was performed for residual soil N. The significance was calculated at the 0.1 probability level.

Results

Weather Conditions

The growing season precipitation during 2021 (May through October; Figure 4.1a-c) and 2022 (April through September; Figure 4.1a-c) was 376 and 283 mm, respectively, which was 11 % and 25% lower than the last ten year's average growing season precipitation (424mm) at the site. The frequency of precipitation was different between the two years. In 2021, precipitation accounted for 15%, 49%, and 35% of the total growing season precipitation during the early vegetative, late vegetative, and reproductive phases, respectively (Figure 4.2). In 2022, the precipitation accounted for 45%, 25%, and 28% of total growing season precipitation received during the early vegetative, late vegetative, and reproductive phases, respectively. When total water inputs from precipitation and irrigation were considered, the water input in each growth stage differed from precipitation only. For example, in 2021, the higher total water input occurred in the reproductive phase (43%) and the late vegetative phase (43%) followed by early (14%) vegetative phase, respectively. While in 2022, the higher total water input occurred in the reproductive phase (46%) followed by the late (28 %) and early (25%) vegetative phase, respectively.

NO_3-N Concentration In Lysimeters

The NO_3-N concentrations were analyzed from the water samples collected from the 23 and 26 leaching events following the precipitation and irrigation events during 2021 and 2022, respectively. Daily changes in pore-water NO_3-N concentrations are shown in Figures 4.1 (d-f) and 4.2 (d-f). During both years, pore-water nitrate concentration significantly varied over time, ranging from 0.01-18.30 mg L^{-1} in 2021 and 0.23-393.44 mg L^{-1} in 2022. In both years, significant treatment and crop growth stage interactions existed on pore-water NO_3-N concentration. In 2021, all EEF treatments including single and split applications had significantly lower pore-water NO_3-N concentrations than U_{PP} during early vegetative phases. However, these significant differences changed into marginally significant differences during the late vegetative phases. During late vegetative phases, pore-water NO_3-N concentration in $(U+UI)_{split}$ and $(U+UI+NI)_{PP}$ were significantly higher than U_{PP}, $(U+UI)_{PP}$, and $(U+UI+NI)_{split}$. During all growth stage, the check treatment had significantly lower pore-water NO_3-N concentration than all N-fertilized treatments.

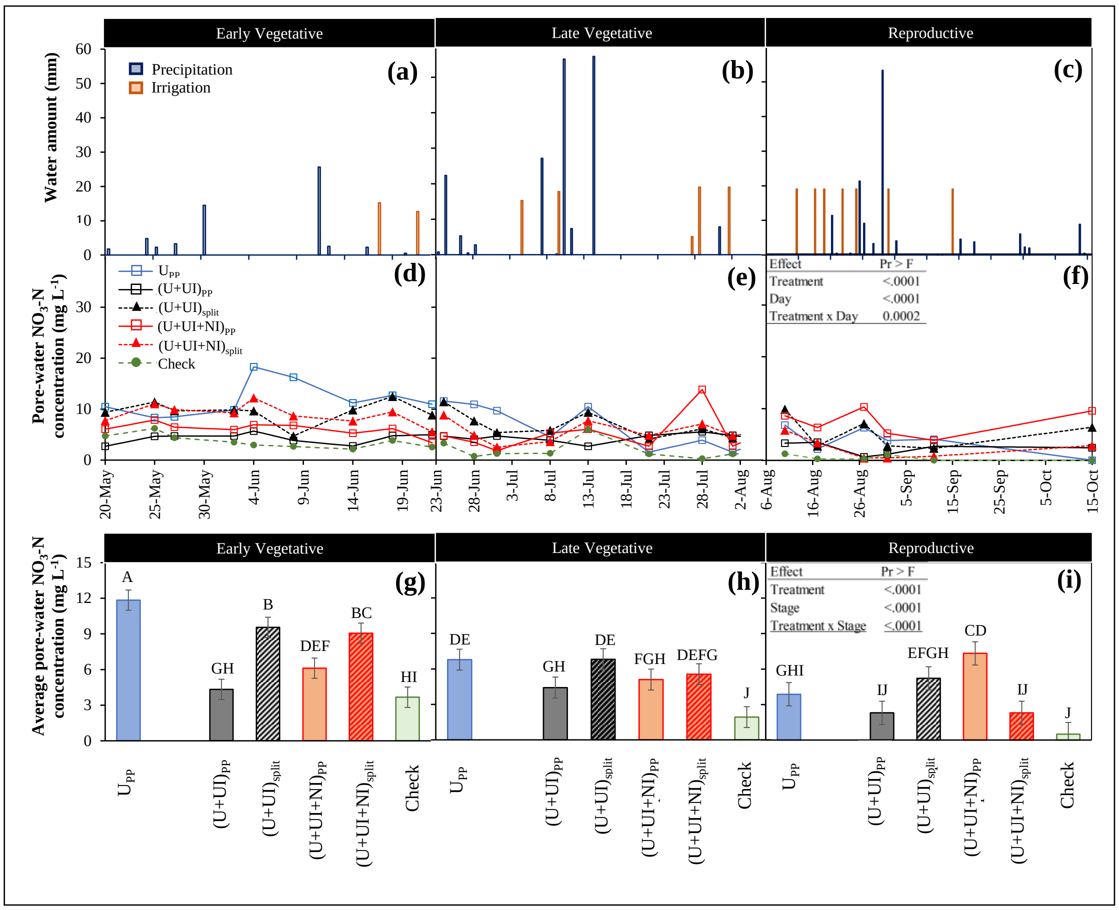

Figure 4.1 The upper panels (a-c) show water inputs (mm) for three maize growth phases – early vegetative (planting to V8), late vegetative (V8-VT) and reproductive phases (R1-R6), while daily and subseasonal pore water NO_3-N concentrations (mg L^{-1}) are shown in the middle panels (d-f) and lower panels (g-i), respectively in 2021.

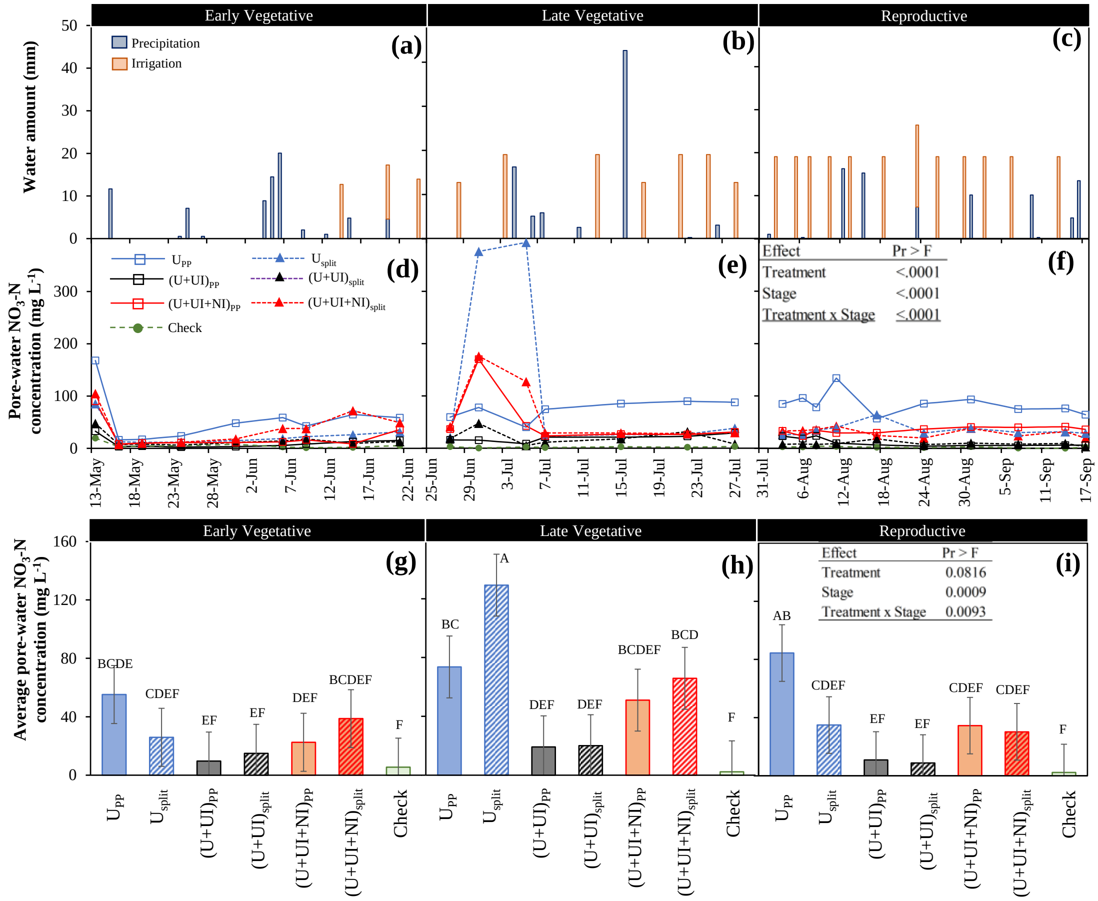

Figure 4.2 The upper panels (a-c) show water inputs (mm) for three maize growth phases – early vegetative (planting to V8), late vegetative (V8-VT) and reproductive phases (R1-R6), while daily and subseasonal pore water NO_3-N concentrations (mg L^{-1}) are shown in the middle panels (d-f) and lower panels (g-i), respectively in 2022.

In 2022, there were no statistical differences in pore-water NO_3-N concentration among all N-fertilized treatments during early reproductive phases. However, during the late vegetative phase, significant differences among N-fertilized treatments occurred due to pore-water NO_3-N concentration peaks for U_{split}, and $(U+UI+NI)_{split}$ treatments following UAN sidedressing. Conventional U_{split} had significantly higher pore-water NO_3-N concentration than all other N fertilizer treatments. $(U+UI)_{split}$ had significantly lower pore-water NO_3-N concentration than U_{PP} and U_{split}. While $(U+UI+NI)_{split}$ had a lower pore-water NO_3-N concentration than U_{split}, it had no differences with other N-fertilized treatments. There were no differences in pore-water NO_3-N concentration during reproductive phases among all N fertilizer treatments except U_{PP}, with significantly higher pore-water NO_3-N concentration. Like 2021, check had significantly lower pore-water NO_3-N concentration than N fertilized treatments during all crop growth stages.

When averaged across the entire season, there were significant treatment effect on pore-water NO_3-N concentration in both years (Figure 4.3). Pore-water NO_3-N concentrations from all the N fertilized treatments were significantly higher by 3-11 times than the check in both years. The $(U+UI)_{PP}$ (12.7 mg L^{-1}) and $(U+UI+NI)_{PP}$ (34.8 mg L^{-1}) decreased pore-water NO_3-N concentration by 78% and 39% than the conventional U_{split} (57.2 mg L^{-1}), respectively. Contrast analysis revealed that $(U+UI)_{PP}$ + $(U+UI+NI)_{PP}$ (14.3 mg L^{-1}) had significantly lower average pore-water NO_3-N concentration by 64% than U_{PP} (39.5 mg L^{-1}) in both years. $(U+UI)_{split}$ + $(U+UI+NI)_{split}$ (17.4 mg L^{-1}) had significantly lower pore-water NO_3-N concentration by 56% than the U_{PP}, but had significantly higher pore-water NO_3-N concentration by 21% than $(U+UI)_{PP}$ + $(U+UI+NI)_{PP}$ (14.3 mg L^{-1}) in both years. When averaged across all N fertilizer treatments, pore-water NO_3-N concentrations were six times higher in 2022 than in 2021.

Table 4.2 Means, probability values, and contrast analysis for the effect of N treatments on NO_3-N concentrations and NO_3-N leaching during 2021 and 2022.

Source of effects	2021				2022			
	ET‡	DP†	NO_3-N concentration	NO_3-N leaching	ET‡	DP†	NO_3-N concentration	NO_3-N leaching
	mm		mg L^{-1}	kg ha^{-1}	mm		mg L^{-1}	kg ha^{-1}
U_{PP}	583	85	7.5a§	20.9a	691	75	71a	63a
U_{split}	-	-	-	-	687	76	57ab	43ab
$(U+UI)_{PP}$	590	84	3.7c	7.4b	697	74	13cd	14b
$(U+UI)_{split}$	590	84	7.2a	13.5ab	664	74	14cd	26ab
$(U+UI+NI)_{PP}$	588	84	6.2b	10.3ab	695	74	35bc	17b
$(U+UI+NI)_{split}$	586	85	5.6b	15.9ab	693	75	43b	61a
Check	579	86	2.0d	7.0b	657	76	3.4d	10b
SE¶	-	-	0.7	2.7	-	-	8	14
	Significance (Pr>F)							
ANOVA	-	-	**<.0001**	**0.010**	-	-	**<.0001**	**0.059**
Check vs. Others	-	-	**<.0002**	**0.025**	-	-	**<.0001**	**0.078**
U_{split} vs. EEF_{PP}	-	-	-	-	-	-	**0.001**	0.121
U_{split} vs. EEF_{split}	-	-	-	-	-	-	**0.005**	0.956
EEF_{split} vs. U_{PP}	-	-	**0.039**	**0.048**	-	-	**<.0001**	0.242
EEF_{split} vs. EEF_{PP}	-	-	**0.001**	**0.028**	-	-	0.579	**0.056**
EEF_{PP} vs. U_{PP}	-	-	**<.0001**	**0.002**	-	-	**<.0001**	**0.012**

‡ ET, Evapotranspiration.
† DP, Deep Percolation.
§ Least significant difference at the 90% confidence level by PROC GLIMMIX-SAS treatment means followed by the same letter are not significantly different. Columns that do not contain letters indicate no significant difference between treatments. The bold represents significant p-values at 0.10.
SE, standard error

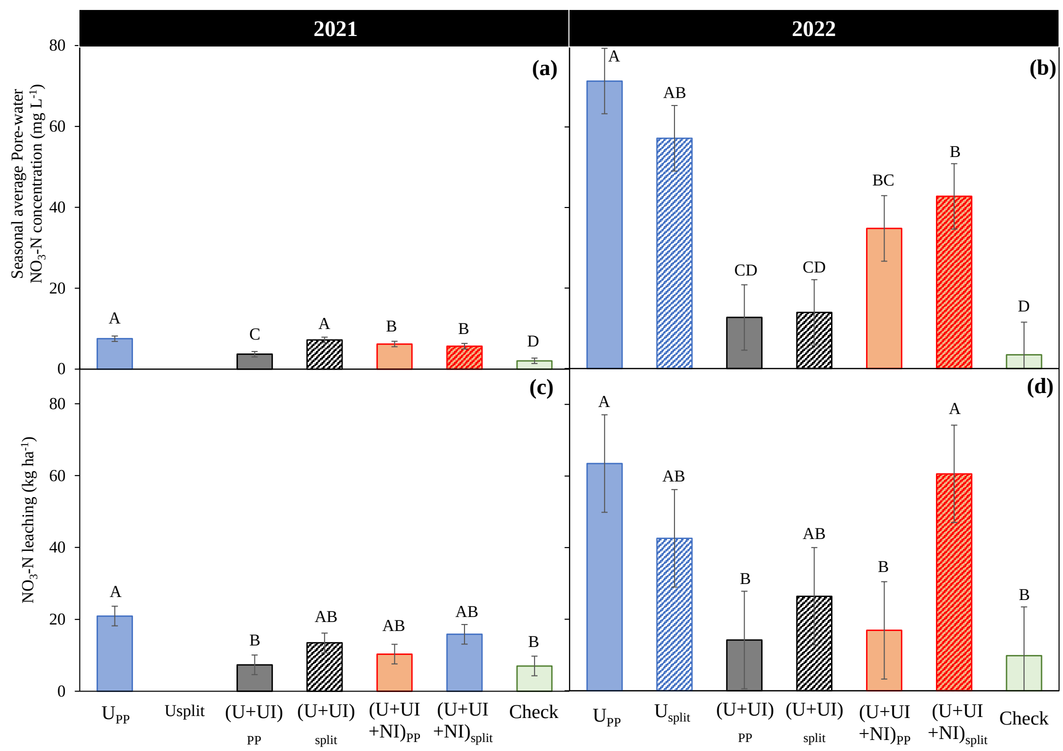

Figure 4.3 Seasonal average pore water NO_3-N concentrations (mg L^{-1}; a, b) and NO_3-N leaching (kg ha^{-1}; c, d) as affected by N treatments in 2021 and 2022.

Seasonal NO_3-N leaching

Total seasonal NO_3-N leaching was calculated from the pore-water NO_3-N concentration and deep percolation below the corn root zone depth. Averaged across the entire season, there were significant treatment effects on NO_3-N leaching in both years. Nitrate leaching from all the N fertilized treatments was significantly higher by three times (202%) than the check treatment in both years. Though not significantly different, $(U+UI)_{PP}$ (14 kg ha^{-1}) and $(U+UI+NI)_{PP}$ (17 kg ha^{-1}) decreased NO_3-N leaching by 67% and 60% than conventional U_{split} (64 kg ha^{-1}), respectively, in 2022. Contrast analysis showed both $(U+UI)_{PP}$ + $(U+UI+NI)_{PP}$ (12 kg ha^{-1}) decreased NO_3-N leaching by 74% and 68% than U_{PP} (42 kg ha^{-1}) in 2021 and 2022, respectively. $(U+UI)_{split}$ had significantly lower NO_3-N leaching than conventional U_{split}, however, there were no significant differences between $(U+UI+NI)_{split}$ (17 kg ha^{-1}) and conventional U_{split} (43 kg ha^{-1}) in 2022. $(U+UI)_{split}$ + $(U+UI+NI)_{split}$ (15 kg ha^{-1}) had significantly lower NO_3-N leaching by 35% than the U_{PP} (21 kg ha^{-1}) in 2021, but $(U+UI)_{split}$ + $(U+UI+NI)_{split}$ (29 kg ha^{-1}) had significantly higher NO_3-N leaching by 138% than $(U+UI)_{PP}$ + $(U+UI+NI)_{PP}$ (12 kg ha^{-1}) in both years. When averaged across all N fertilizer treatments, NO_3-N leaching was 2.7 times higher in 2022 than in 2021.

Grain Yield And Other Agronomic Parameters

There were significant treatment effects on grain and biomass yield in both years (Table 4.3). Contrast analysis revealed that all the N fertilized treatments had significantly higher grain and biomass yield than the check treatment in both years. However, there were no significant treatment differences in grain yield among N fertilizer treatments in 2022. Despite insignificant yield differences, there were 2.0-2.4 Mg ha^{-1} higher grain yield in Agrotain and $(U+UI+NI)_{split}$ than other fertilized treatments in 2022. In 2021, $(U+UI)_{PP}$ + $(U+UI+NI)_{PP}$ (16.8 Mg ha^{-1}) significantly increased corn grain yield by 15% than U_{PP} (14.6 Mg ha^{-1}). Similarly, $(U+UI)_{split}$ + $(U+UI+NI)_{split}$ (16.1 Mg ha^{-1}) significantly increased grain yield by 10% than U_{PP} (14.6 Mg ha^{-1}). Though there was a tendency for higher grain yield with a single application of EEFs, EEFs applied as pre-plant were statistically insignificant than when used in a split application (i.e., $(U+UI)_{split}$ + $(U+UI+NI)_{split}$). When averaged across all N fertilizer treatments, grain yield was 56% (9.1 Mg ha^{-1}) higher in 2021 than in 2022. There were significant treatment differences in grain and plant N uptake in both years. Contrast analysis revealed that all the N-fertilized treatments had significantly higher grain and plant N uptake than the check in both years. Unlike grain yield, N fertilizer treatments had an inconsistent effect on grain and plant N uptake in both years. In 2021, N fertilizer treatment did not affect grain and plant N uptake except for significantly higher grain N uptake with $(U+UI)_{PP}$ + $(U+UI+NI)_{PP}$ than the $(U+UI)_{split}$ + $(U+UI+NI)_{split}$. Likewise, in 2022, N fertilizer treatments had no significant effect on grain and plant N uptake, except significantly higher plant N uptake in $(U+UI)_{PP}$ + $(U+UI+NI)_{PP}$ and $(U+UI)_{split}$ + $(U+UI+NI)_{split}$ than in U_{PP} (Table 4.3).

For PFP, there was a trend of higher PFP values with the use of EEFs either in single or split application than the U_{PP} and conventional U_{split} treatments with significant effects in 2021 only (Table 4.4). A similar trend was observed for AE. Though there was no significant effect of N fertilizer treatments on NRE in both years, EEF treatments including both preplant and split N application had significantly higher NRE than the U_{PP} in 2022.

Economics

Considering the economic and environmental importance of N use, we computed the net returns to N (RTN) and economic returns after considering the environmental costs associated with NO_3-N leaching (RTN_{Env}). Treatments had a variable effect on RTN and RTN_{Env} across both years. There were more significant N fertilizer treatment effects on RTN and RTN_{Env} in 2021 than in 2022. The contrast analysis revealed \$415 ha^{-1} and \$639 ha^{-1} higher RTN and RTN_{Env} in $(U+UI)_{PP}$ + $(U+UI+NI)_{PP}$ than the U_{PP} in 2021. Similarly, RTN and RTN_{Env} were \$268 ha^{-1} and \$384 ha^{-1} higher in $(U+UI)_{split}$ + $(U+UI+NI)_{split}$ than in the U_{PP} in 2021. Moreover, $(U+UI)_{PP}$ + $(U+UI+NI)_{PP}$ had \$255 ha^{-1} higher RTN_{Env} than $(U+UI)_{split}$ + $(U+UI+NI)_{split}$ in 2021 (Table 4.4). While in 2022, $(U+UI)_{PP}$ + $(U+UI+NI)_{PP}$ had \$1114 ha^{-1} and \$537 ha^{-1} higher RTN_{Env} than the U_{PP} and conventional U_{split}, respectively. When averaged across all N fertilizer treatments, RTN and RTN_{Env} were \$351 ha^{-1} and \$408 ha^{-1} higher in 2021 than 2022, respectively.

Table 4.3 Treatment means, significance, and contrast analysis of grain yield, biomass yield, grain-N uptake, plant-N uptake, vegetation indices, and ear leaf nitrogen concentration (ELNC) as affected by treatments in 2021 and 2022 at Creighton, NE.

Source of effects	2021						2022					
	Yield (Mg ha^{-1})		N uptake (kg ha^{-1})		NDRE	ELNC	Yield (Mg ha^{-1})		N uptake (kg ha^{-1})		NDRE	ELNC
	Grain	Biomass	Grain	Plant‡		%	Grain	Biomass	Grain	Plant‡		%
U_{PP}	14.6 b§	18.7 a	258 a	321 a	0.7 a	2.71 a	13.5 ab	21.0 bc	160 ab	352 ab	0.71 ab	2.85 ab
U_{split}	-	-	-	-	-	-	13.3 ab	22.7 abc	171 ab	413 ab	0.75 a	3.00 a
$(U+UI)_{PP}$	17.0 a	21.2 a	296 a	363 a	0.7 a	2.89 a	15.9 a	25.8 ab	201 a	473 a	0.75 a	2.98 ab
$(U+UI)_{split}$	15.7 ab	19.7 a	222 ab	279 ab	0.6 a	2.88 a	13.8 ab	29.1 a	176 ab	488 a	0.76 a	2.96 ab
$(U+UI+NI)_{PP}$	16.7 a	20.6 a	255 ab	305 ab	0.6 a	3.02 a	13.7 ab	24.7 ab	166 ab	430 ab	0.73 ab	2.96 ab
$(U+UI+NI)_{split}$	16.5 ab	20.9 a	251 a	323 a	0.6 a	3.09 a	15.6 a	27.6 ab	193 a	460 a	0.75 a	2.92 ab
Check	9.4 c	12.3 b	158 b	200 b	0.5 b	2.10 b	10.5 b	16.8 c	116 b	250 b	0.67 b	2.67 b
SE¶	0.5	0.6	19	25	0.01	0.10	1.0	1.8	17	45	0.01	0.08
	Significance (Pr>F)											
ANOVA	**<.001**	**<.001**	**0.01**	**0.01**	**<.001**	**0.01**	**0.019**	**0.002**	**0.015**	**0.008**	**0.006**	**0.105**

Check vs. Others	**<.001**	**<.001**	**0.01**	**0.01**	**<.001**	**<.001**	**0.002**	**0.000**	**0.001**	**0.001**	**0.000**	**0.006**
U_{split} vs. EEF_{PP}	-	-	-	-	-	-	0.185	0.195	0.435	0.413	0.355	0.729
U_{split} vs. EEF_{split}	-	-	-	-	-	-	0.222	**0.011**	0.421	0.207	0.965	0.525
EEF_{split} vs. U_{PP}	**0.02**	**0.04**	0.312	0.503	**0.015**	**0.039**	0.291	**0.002**	0.162	**0.020**	**0.031**	0.367
EEF_{split} vs. EEF_{PP}	0.119	0.292	**0.039**	0.192	0.190	0.785	0.889	**0.069**	0.976	0.562	0.283	0.719
EEF_{PP} vs. U_{PP}	**0.002**	**0.009**	0.404	0.663	0.108	**0.057**	0.245	**0.045**	0.168	**0.049**	0.151	0.239

‡ Plant N uptake is the sum of grain and stover N uptake.

§ Least significant difference at the 90% confidence level by PROC GLIMMIX-SAS treatment means followed by the same letter are not significantly different. Columns that do not contain letters indicate no significant difference between treatments. The bold represents significant p-values at 0.10.

¶ SE, standard error of the mean.

Table 4.4 Treatment means, significance, and contrast analysis of partial factor productivity (PFP), agronomic efficiency (AE), nitrogen recovery efficiency (NRE), return to N (RTN), and RTN considering environmental costs (RTN_{Env}) as affected by treatments in 2021 and 2022 at Creighton, NE

Source of effects	2021					2022				
	PFP	AE	NRE (%)	RTN	RTN_{Env}	PFP	AE	NRE (%)	RTN	RTN_{Env}
	kg kg^{-1}			\$ ha^{-1}		kg kg^{-1}			\$ ha^{-1}	
U_{PP}	72b§	26b	60	915b	528c	63	15	51	621	-131
U_{split}						62	14	81	568	445
$(U+UI)_{PP}$	84a	37a	81	1365a	1229a	74	27	111	1284	1203
$(U+UI)_{split}$	78ab	31ab	39	1116ab	866b	64	16	118	700	393
$(U+UI+NI)_{PP}$	83a	36a	52	1295a	1104ab	64	16	89	651	763
$(U+UI+NI)_{split}$	82a	35a	58	1250a	956b	73	25	104	1199	499
SE	2.5	2.5	13	100	120	5	8	19	269	304
					Significance (Pr>F)					
ANOVA	**0.039**	**0.039**	0.223	**0.051**	**0.003**	0.149	0.145	0.230	0.150	0.121
U_{split} vs. EEF_{PP}	-	-	-	-	-	0.145	0.141	0.431	0.167	0.161
U_{split} vs. EEF_{split}	-	-	-	-	-	0.178	0.174	0.225	0.186	0.998
EEF_{split} vs. U_{PP}	**0.030**	**0.030**	0.433	**0.043**	**0.006**	0.243	0.246	**0.027**	0.250	0.135
EEF_{split} vs. EEF_{PP}	0.161	0.161	0.153	0.145	**0.016**	0.875	0.871	0.576	0.936	**0.094**
EEF_{PP} vs. U_{PP}	**0.005**	**0.005**	0.654	**0.006**	**0.001**	0.200	0.198	**0.060**	0.226	**0.011**

§ Least significant difference at the 90% confidence level by PROC GLIMMIX-SAS treatment means followed by the same letter are not significantly different. Columns that do not contain letters indicate no significant difference between treatments. The bold represents significant p-values at 0.10.

¶ SE, standard error of the mean.

Table 4.5 Treatment means, significance, and contrast analysis for post-harvest soil NO_3-N and NH_4-N at 0-1.2 m soil depth as affected by treatments in 2021 and 2022 at Creighton, NE

Source of effects	Residual soil N (kg ha^{-1})			
	2021		2022	
Treatment	NO_3-N	NH_4-N	NO_3-N	NH_4-N
U_{PP}	0.17	3.79	4.04cd	14.78ab
U_{split}	-	-	9.93ab	13.47ab
$(U+UI)_{PP}$	0.57	17.43	10.79a	15.44a
$(U+UI)_{split}$	0.01	5.90	5.04bcd	15.66a
$(U+UI+NI)_{PP}$	0.65	4.58	7.96abc	13.50ab
$(U+UI+NI)_{split}$	0.18	6.03	3.39d	13.20ab
Check	0.00	4.13	1.89d	11.15b
SE¶	0.30	6.51	1.74	1.86
Depth (cm)				
0-30	0.21b§	12.29	7.43a	12.49b
30-60	0.15b	4.76	3.40b	13.40ab
60-90	0.06b	5.04	3.48b	14.77a
90-120	0.63a	5.82	9.71a	14.87a
SE	0.23	4.88	1.12	1.4
ANOVA ($Pr > F$)				
Treatment	0.415	0.631	**0.046**	**0.094**
Depth	**0.063**	0.535	**0.001**	**0.063**
Treatment x Depth	0.115	0.719	0.595	0.529
Contrast analysis				
Others vs. Check	0.312	**0.001**	**0.002**	**0.009**
U_{split} vs. EEF_{PP}	-	-	0.797	0.440
U_{split} vs. EEF Split	-	-	**0.008**	0.460
EEF Split vs. U_{PP}	0.854	0.824	0.924	0.643
EEF split vs. EEF_{PP}	**0.080**	0.441	**0.001**	0.968
EEF_{PP} vs. U_{PP}	0.327	0.464	**0.004**	0.620
$(U+UI)_{PP}$ vs. others	0.216	**0.093**	**0.001**	**0.083**

§ Least significant difference at the 90% confidence level by PROC GLIMMIX-SAS treatment means followed by the same letter are not significantly different. Columns that do not contain letters indicate no significant difference between treatments.

¶ SE, standard error of the mean.

Residual Soil Nitrogen

Across both years, no significant interactions existed between treatment and soil depth on residual soil NO_3-N and NH_4-N (Table 4.5). In 2021, treatments did not affect soil NO_3-N and NH_4-N; however, soil depth significantly affected soil NO_3-N. Soil NO_3-N was considerably higher at the lower 90-120cm (0.63 kg N ha^{-1}) than the Upper soil depths (0.06-0.21 kg N ha^{-1}). Though not significant, NH_4-N was four times higher in $(U+UI)_{PP}$ (17 kg N ha^{-1}) than in check (4 kg N ha^{-1}) and 3 to 5 times higher than all N fertilized treatments (4-6 kg N ha^{-1}) in 2021.

In 2022, both treatments and depth significantly affected soil NO_3-N and soil NH_4-N (Table 4.5). Both soil residual NO_3-N and NH_4-N increased with soil depth. Most N-fertilized treatments had significantly higher soil NO_3-N and NH_4-N than the check. Within N fertilized treatments, soil residual NO_3-N ranged from 3.4-11 kg N ha^{-1} with the highest soil residual NO_3-N in $(U+UI)_{PP}$ (11 kg N ha^{-1}) and lowest in $(U+UI+NI)_{split}$ (3.4 kg N ha^{-1}). In 2022, residual NH_4-N ranged from 13.2-15.7 kg N ha^{-1} and had the highest NH_4-N concentration in the $(U+UI)_{PP}$ (15.4 kg N ha^{-1}) and $(U+UI)_{split}$ (15.7 kg N ha^{-1}) treatments. It was interesting to observe that all the treatments had higher soil NH_4-N than the NO_3-N. Compared to 2021, 2022 had 23 times and two times higher soil NO_3-N and NH_4-N, respectively. When summed across the soil depth, cumulative NO_3-N and NH_4-N was 1.1 kg NO_3-N ha^{-1} and 28 kg NH_4-N ha^{-1} in 2021 and 24 kg NO_3-N ha^{-1} and 55 kg NH_4-N ha^{-1} in 2022, respectively.

Discussion

NO_3-N Leaching

Split N application is considered as an effective strategy to reduce NO_3-N leaching in sandy soils (Mueller et al., 2017; Preza-Fontes et al., 2021; C. A. Shapiro et al., 2019; Sitthaphanit et al., 2009). The University of Nebraska-Lincoln recommends using at least 60% of total N inputs during the growing season for sandy soils (Iqbal et al., 2023). Given the increasing NO_3-N concentration in the groundwater of Nebraska, Natural Resource Districts of Nebraska are increasingly looking to find additional strategies to minimize the NO_3-N leaching in the wellhead protection areas. Meanwhile, there is increasing evidence that the use of EEFs, including the urease and nitrification inhibitors, can significantly reduce N losses without impacting corn yield and economic returns at suboptimal (Rose et al., 2018; Allende-Montalbán et al., 2021), or optimal N rates (Abalos et al., 2014; Díez-López et al., 2008; Diez et al., 2010; Nelson et al., 2008; Sanz-Cobena et al., 2012; M D Serna et al., 1994; María D Serna et al., 2000; Wilson et al., 2010). However, no study has reported the use of EEFs at suboptimal N rates to reduce NO_3-N leaching, especially in comparison with conventional split N application. Moreover, very few studies have evaluated the effect of urease inhibitors on NO_3-N leaching under field conditions (Dawar et al., 2011a, 2011b; Sanz-Cobena et al., 2012; Zaman et al., 2009).

In this study, 40-78% lower pore-water NO_3-N concentration and 60-67% NO_3-N leaching with $(U+UI)_{PP}$ and $(U+UI+NI)_{PP}$ compared to conventional U_{split} indicate that the use of EEFs can be very effective in reducing NO_3-N leaching in the vulnerable sandy soils of BGMA and elsewhere. These results were similar to Deiz et al. (2010), who found that a single pre-plant application of DCD and DMPP (3,4-dimethylpyrazole phosphate) nitrification inhibitors at the recommended N rate significantly decreased NO_3-N leaching by 29% without impacting corn yield when compared to split N application. They attributed the reduction in NO_3-N leaching to 30% lower soil NO_3-N production in the nitrification inhibitor plots than with no nitrification inhibitor. The lower NO_3-N leaching from $(U+UI)_{PP}$ + $(U+UI+NI)_{PP}$ in our study could be due to delay in urea hydrolysis and ammonium oxidation as the previous studies have shown that urease and nitrification inhibitors can slow the release of NH_4-N and NO_3-N for 16-95 days under favorable conditions and thus, reduce the risk of NO_3-N leaching compared to conventional N sources with single pre-plant or split N application (Allende-Montalbán et al., 2021; Chaves et al., 2006; Irigoyen et al., 2003; Serna et al., 2000). Additionally, the dry years in our study might have delayed the conversion of urea to NH_4-N, resulting in lower NO_3-N concentrations and, subsequently, NO_3-N leaching.

In contrast, Mateo-Marín et al. (2020) observed no differences in NO_3-N leaching and grain yield between EEFs when used as pre-plant vs. split application in the sandy soil of a maize-wheat rotation in Spain. However, the insignificant effect in their study could be due to non-limiting N availability at an optimum N rate than a suboptimum N rate, as Rose et al. (2018) in a meta-analysis suggested that beneficial effects of EEFs on improving nitrogen use efficiency and reducing N losses are more likely at suboptimal N rates. Furthermore, it is worth mentioning that grain yield across both years from suboptimal rates of $(U+UI)_{PP}$ and $(U+UI+NI)_{PP}$ in this study (16.4 and 15.2 Mg ha^{-1} at 180 kg N ha^{-1}) was similar to grain yield at optimum N rates with $(U+UI)_{split}$ application (15.6 Mg ha^{-1} at 230 kg N ha^{-1}) in our companion study (Singh et al., under review). At the same time, $(U+UI)_{PP}$ and $(U+UI+NI)_{PP}$ at suboptimal N rate in this study had 53-62%

lower NO_3-N leaching (10.8 and 13.6 kg NO_3-N ha^{-1} at 180 kg N ha^{-1}) than $(U+UI)_{split}$ application at optimal N rate (28.7 kg NO_3-N ha^{-1} at 230 kg N ha^{-1}) in the companion study. This clearly provides evidence that using EEFs at suboptimal N rates could substantially mitigate NO_3-N leaching without impacting corn yield. Furthermore, as expected, $(U+UI)_{PP}$ + $(U+UI+NI)_{PP}$ had 71% lower NO_3-N leaching than U_{PP}, confirming the significant advantage of using urease and nitrification inhibitors in slowing the release of nitrogen and decreasing NO_3-N leaching losses than the conventional urea nitrogen source, as reported in previous studies (Prakash et al., 1999; Zaman et al., 2009; Zvomuya et al., 2003).

Though urease inhibitor, when used in the split application (i.e., $(U+UI)_{split}$), showed a trend of lower NO_3-N leaching than the conventional U_{split} and U_{PP}, the NO_3-N leaching from $(U+UI)_{split}$ + $(U+UI+NI)_{split}$ was generally higher than $(U+UI)_{PP}$ + $(U+UI+NI)_{PP}$, indicating significant benefits of using EEFs in a single application than split nitrogen application with EFFs. These results were similar to the observation by Allende-Motalban et al. (2021) who found that a single application of urease inhibitors was more effective in delaying urease activity, slowing N availability, and reducing potential N losses than the split application of urea with urease inhibitors in sandy soil in corn. Moreover, in this study, though conventional U_{split} decreased NO_3-N leaching by 33% compared to U_{PP} (63.5 vs. 42.6 kg N ha^{-1}) in 2022, it did not provide as many benefits in decreasing NO_3-N leaching as indicated by insignificant differences between U_{PP} vs. U_{split}. This was likely due to significant NO_3-N leaching losses immediately after UAN sidedressing, as reflected by higher pore-water NO_3-N concentration during the early part of the late vegetative phase (Figure 4.1). This illustrates the significant vulnerability of UAN to NO_3-N leaching losses during the early growing season (VE to V8) when there is less crop N uptake (Liu et al., 2019; Rutan & Steinke, 2018; Shapiro et al., 2016; Woolfolk et al., 2002).

Regardless of the treatment's effect on NO_3-N leaching, we observed more considerable differences in NO_3-N leaching between the two study years. It was interesting to observe that higher NO_3-N leaching losses in 2022 than in 2021 were not due to percolation but higher NO_3-N concentration in water samples (Table 4.3.2), contradicting the common understanding that NO_3-N leaching amount is mainly driven by drainage amount (Diez et al., 1997; Pittelkow et al., 2017; Sanz-Cobena et al., 2012; Tan et al., 1996; Yagüe & Quílez, 2010). The higher NO_3-N concentration in 2022 could partly be due to disk tillage by farmer in 2022 than no-till in 2021, as rainfall intensification has been shown to increase NO_3-N leaching from tilled cropping systems compared to no-till cropping system (Hess et al., 2020; Ritter et al., 1993). Nonetheless, the dry conditions of this experimental study must be considered when interpreting the NO_3-N leaching results. However, we speculate an even greater benefit of using EEFs with normal or wet years when there could be more vulnerable conditions for NO_3-N leaching losses with higher drainage volume during the early growing season.

Crop Yield, Nitrogen Uptake, And Net Returns

Previous studies have reported either a significant improvement (Allende-Montalbán et al., 2021; Khan et al., 2014) or no effect of EEFs on crop yield (Diez et al., 2010; Woodley et al., 2020). In a meta-analysis, Rose et al. (2018) suggested that EEFs are unlikely to increase crop and biomass yields beyond conventional nitrogen fertilizers when applied at the economic optimum N rate. In this study, although using EEFs did not consistently improve corn grain yield across both years, there was a trend of higher grain yield and plant biomass with EEF treatments compared to the conventional U_{split} and U_{PP} in 2022. Moreover, there was a significantly higher grain yield with EEFs than U_{PP} in 2021. The higher grain yield with EEFs was reflected by relatively higher grain and plant N uptake, PFP, AE, and NRE in the EFF treatments (particularly $(U+UI)_{PP}$) than the conventional U_{split} and U_{PP} treatments (Tables 4 and 5). These results confirm the previous findings that the urease and nitrification inhibitors significantly improve nitrogen use efficiency and crop N uptake (Abalos et al., 2014; Shapiro et al., 2016; Zaman et al., 2009). Moreover, the higher NRE with the $(U+UI)_{PP}$ + $(U+UI+NI)_{PP}$ than the U_{split} and U_{PP} illustrates the ability of these nitrogen products to stabilize the N during the growing season, as previous studies revealed that the effect of urease and nitrification inhibitors in stabilizing N in the soil can last for 16-95 days during the favorable conditions (Allende-Montalbán et al., 2021; Chaves et al., 2006; Irigoyen et al., 2003; Serna et al., 2000). These results were consistent with the improvement in crop yield benefits with EEFs in the previous findings (Allende-Montalbán et al., 2021; Khan et al., 2014; Maharjan et al., 2014b; Shapiro et al., 2016; Woodley et al., 2020). In a meta-analysis, Rose et al. (2018) revealed that using EEFs significantly enhanced crop yield upto 11% at sub-optimal N rates. In another study, Allende-Montalban et al. (2021) reported that a single pre-plant application of N inhibitors resulted in higher corn yield and NUE than the split application of Urea with inhibitor. They attributed the improved grain yield and NUE from a single pre-plant application of N inhibitor to decreased urease activity, better synchronization of N release from EEFs and crop N uptake, and higher grain N uptake. Meanwhile, other studies found no difference between single pre-plant application of EEFs and split application with conventional N source on corn yield (Allende-Montalbán et al., 2021; B. Ren et al., 2022).

In this study, the relatively higher NRE with EEFs than the U_{split} and U_{PP} can also be explained by lower NO_3-N leaching losses and potentially higher soil N availability with high crop N uptake in EEFs treatments (Drury et al., 2017; Ren et al., 2022). Zaman et al. (2008) reported that plants take less energy to convert NH_4-N or Urea-N to amides, amino acids, and proteins from the Agrotain-coated urea. Similar trends of increased efficiency of plants in utilizing NH_4-N and Urea-N from the Agrotain-coated fertilizer than the regular urea was reported in literature (Blennerhassett et al., 2006; Quin et al., 2006). These facts suggest that in our study, $(U+UI)_{PP}$ + $(U+UI+NI)_{PP}$ might have retained the nitrogen in urea-N or NH_4-N forms for a more extended period of time, thereby increasing the crop N uptake, NRE, and resulting in less NO_3-N leaching losses. Overall, the better crop yield, NRE, and lower NO_3-N leaching from EEFs, particularly from the $(U+UI)_{PP}$ + $(U+UI+NI)_{PP}$ in our study, indicate that the use of EEFs can be a win-win strategy to largely increase the environmental and economic benefits in the groundwater contaminated areas. This was further illustrated by the significantly higher RTN and RTN_{Env} values from the EEF treatments than U_{PP} in 2021 and significantly higher RTN_{Env} from the EEF treatments than U_{split} and U_{PP} in 2022. In fact, these results provide clear evidence that the use of EEFs can not only reduce the environmental damage cost associated with NO_3-N removal from the NO_3-N contaminated water but also increase farm profits. Moreover, in addition to higher RTN and RTN_{Env} benefits, single pre-plant application of EEFs ($(U+UI)_{PP}$ and $(U+UI+NI)_{PP}$) can also provide other economic and environmental benefits (not included in our economic analysis) including less machinery use (farmer's time, gas, CO_2 emissions, oil, and soil compaction effect) (Allende-Motalban et al., 2021) and reduced in-season N_2O emissions and NH_3 volatilization associated with split N application (Ren et al., 2019; Venterea et al., 2011). Furthermore, using EEF at suboptimal rates provides a similar corn yield than the optimum N rate with regular N fertilizers (as referred to above with companion study - Singh et al., under review; Shapiro et al., 2016), thereby further increasing economic benefits with less N input and more environmental benefits. Reduced N rates can also result in other long-term benefits including reduced soil acidification, liming needs, and other associated long-term management costs (Rose et al., 2018). Therefore, we recommend that in addition to crop yield and environmental advantages, additional benefits of using EEFs at a reduced N rate be considered when evaluating their economic and environmental performance.

Residual Soil Nitrogen

Post-harvest soil N can significantly impact NO_3-N leaching losses during the winter period in the US Midwest (Bohman et al., 2020; Iqbal et al., 2018). In this study, $(U+UI)_{PP}$ had higher residual soil NH_4-N than the other treatments in 2021, which indicates some effects of urease inhibitors in retaining nitrogen in stable NH_4-N form for a prolonged time. These results were consistent with the findings of Allende-Montalbán et al. (2021) who reported lower urease activity in soil after maize harvest in the pre-plant urease inhibitor treatment than in the check treatment. However, in 2022 of this study, $(U+UI)_{PP}$ had statistically similar NH_4-N than other fertilized treatments and similar NO_3-N than U_{split} and $(U+UI+NI)_{PP}$ which suggests that different effect of urease inhibitor in 2022 than in 2021 on residual soil N could be due to specific site-year's soil, tillage management, crop phenology, and weather conditions (Corrochano-Monsalve et al., 2020; Dong et al., 2018). Nevertheless, the significantly higher residual soil NO_3-N and NH_4-N in all fertilizer treatments in 2022 suggests that despite adopting the best practice of split N application, there remains considerable potential for off-season N losses in some years. Moreover, the sum of residual soil inorganic N at 0-1.2 m depth was two times higher than the NO_3-N leaching losses each year (14 kg NO_3-N ha^{-1} in 2021, 37 kg NO_3-N ha^{-1} in 2022). These results were supported by previous studies that indicated considerable risk for off-season N losses in the US Midwest agricultural system (Bohman et al., 2020; Shapiro et al., 2016; Tan et al., 1996).

Notably, 2022 had 23 times higher soil residual NO_3-N and two times higher soil residual NH_4-N across all treatments than in 2021, which coincided with higher NO_3-N leaching losses (14-63 kg NO_3-N ha^{-1}) and lowering grain yield (13-16 Mg ha^{-1}) in 2022 than in 2021 (7-21 kg NO_3-N ha^{-1}, 15-17 Mg ha^{-1}). Though lower grain yield in 2022 could explain the higher NO_3-N leaching losses and high residual N, we believe the higher NO_3-N losses and residual in 2022 could partly be due to disk tillage practice in 2022 that could have led to higher organic matter mineralization, as indicated by higher NRE than applied N in some treatments in 2022 (Table 4.4). These results suggest that change in N dynamics (organic matter mineralization, crop N uptake, and NO_3-N leaching, etc.) resulting from inter-annual variability is the major impediment to mitigating N losses into the environment (Bohman et al., 2020). Moreover, across both years, it was interesting to observe 2.7 times higher residual soil NH_4-N than residual soil NO_3-N, likely originating from fertilizer and organic matter mineralization. This was similar to the results of companion studies (Singh et al., under review) and another of our recent study in central Nebraska, where we found significantly higher NH_4-N than NO_3-

N (Neels et al., 2024). The higher levels of NH_4-N in these studies indicate a missing N credit in UNL fertilizer recommendation where only NO_3-N credits are considered for N recommendations (Iqbal et al., 2023).

Conclusion

Using conventional N sources presents a significant challenge in reducing N losses. Meanwhile, EEFs are emerging to stabilize N and better synchronize the N availability with crop N uptake, thereby decreasing environmental N losses in soils vulnerable to NO_3-N leaching. In this study, conventional U_{split} application did not significantly decrease NO_3-N leaching, corn yield, and economic returns compared to U_{PP}. However, the use of EEFs (i.e., UI and UI+NI) in single pre-plant application not only substantially decreased NO_3-N leaching with the levels approaching check treatments in both years but had the same or even better crop yield and improved economic returns than conventional U_{split} and U_{PP}. Notably, though the split application of EEFs with UAN decreased NO_3-N leaching and increased corn yield than U_{PP}, the single application of EEFs had significantly lower NO_3-N leaching than their split application with UAN (i.e., $(U+UI)_{split}$, and $(U+UI+NI)_{split}$). Across all N treatments, the lower NO_3-N leaching from single pre-plant application of EEFs was also explained by relatively higher grain and biomass yield, crop N uptake, NRE, PFP, and AE, indicating these treatments as the most efficient N management system for improving N recovery efficiency. These findings provide clear evidence that using EEFs as pre-plant could be a very effective strategy in mitigating NO_3-N leaching losses while improving economic benefits in groundwater-contaminated areas. We propose further exploring additional environmental (potentially reduced greenhouse gas emissions) and economic benefits (reduced N rate, soil acidification, liming needs, oil use, machinery use, etc.) of using EEFs in the future.

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CHAPTER 5

IMPACT OF SPLIT NITROGEN APPLICATIONS ON NITRATE LEACHING AND CORN YIELD

Abstract

Little information is available on optimizing the number of nitrogen (N) splits based on nitrate (NO_3-N) leaching and crop yield in sandy soils. To test this, we evaluated the impact of multiple N splits (2, 3, 4 and 5-N splits) on NO_3-N leaching and corn grain yield in an irrigated loamy sand soil on a producer site in Northeast Nebraska. Porous suction cup lysimeters were installed at a depth of 120 cm to collect pore water samples from 23 leaching events in 2021, a dry year. Increasing the number of N-splits did not affect the pore-water NO_3-N concentration, however, it was 169%, 152%, 150%, and 129% higher in 2-(6.1 mg L^{-1}), 3-(5.1 mg L^{-1}), 4-(5.6 mg L^{-1}), and 5-N (5.7 mg L^{-1}) split treatments compared to a control (2.2 mg L^{-1}) i.e., without N application. Though the 2-, 3-, 4-, and 5-N-splits had 110%, 71%, 120%, and 91% higher area-based NO_3-N leaching than control, less deep percolation and more evapotranspiration in control led to no significant differences in area-based NO_3-N leaching among all treatments. All N-splits had higher crop yield, nitrogen use efficiency, plant N uptake, HI, and aboveground biomass than control; however, no significant differences of these parameters were observed among all N-splits. Across all N-split treatments, the inclusion of environmental cost reduced the return to nitrogen (RTN) by 92-143 US$ ha^{-1} but had no significant effect among the N-splits. The results indicate that increasing the number of N-splits does not provide agronomic, economic, and environmental benefits in a dry year.

Introduction

Nitrogen (N) fertilizer is the most yield limiting nutrient for maize production with agronomic, economic, and environmental consequences (Poffenbarger et al., 2017). The nitrogen use efficiency of maize production has recently improved in Nebraska from 1988 to 2012 (49 to 67 kg grain kg N^{-1}) due to adoption of N management practices including N application timing, economy-based N recommendation strategies, improved hybrids, and N credits accounting from irrigated water, legumes, manure. (Ferguson, 2015). However, significant challenges remain for sustaining crop production while protecting environmental quality. Currently, about 40 to 50% of applied N is used by crops (Zhang et al., 2015), while the remaining N is either lost to the atmosphere through ammonia volatilization and nitrous oxide emission, or to the groundwater through nitrate (NO_3-N) leaching (Powlson, 1993). Evidence of annual N-leaching loss is reflected in groundwater NO_3-N concentration far exceeding the Environmental Protection Agency (EPA) drinking water limit of 10 mg NO_3-N L^{-1} for about one million hectares (ha) area of Nebraska (Juntakut et al., 2019; NDEQ, 2018). High NO_3-N in groundwater poses significant environmental and human health risks, as more than 90% of Nebraska residents rely on groundwater for drinking purposes (Nolan & Hitt, 2006; Ouattara et al., 2022). Therefore, it is imperative to continuously improve N management by increasing nitrogen use efficiency (NUE) and economic returns while decreasing NO_3-N leaching losses to the groundwater (Grant et al., 2012; Motasim et al., 2022).

Previous studies have identified several factors influencing N-leaching loss to groundwater, including fertilizer management, crop cultivation practices, irrigation management, precipitation surplus, soil texture, manure management, and others

(Ebrahimian et al., 2012; Wick et al., 2012). In general, higher NO_3-N leaching losses are linked to poor synchrony between the N supply and crop N uptake (Cassman et al., 2002; Robertson & Vitousek, 2009), excessive N inputs (Cassman et al., 2002; Shanahan et al., 2008), and heavy rainfall during the early growing season (Fernandez et al., 2020; Zhou et al., 2018). These N losses tend to be greater during April-June period when soil N is available due to soil organic matter mineralization and fertilizer application but have limited crop N uptake (Bowles et al., 2018). Meanwhile, narrowing the time between soil N application and crop N uptake can shorten the time for N losses (Nafziger & Rapp, 2020). Therefore, splitting the N application during the growing season is an effective strategy for matching soil N availability with crop N needs (Chen et al., 2006; Ciampitti & Vyn, 2012), improving NUE (Lü et al., 2012; Olson et al., 1986) and reducing N losses (Preza-Fontes et al., 2022; Sitthaphanit et al., 2009).

Contrasting results on the number of multiple N-splits on NUE, crop yield, and N losses exist in the literature. For example, Venterea & Coulter (2015) found that applying N in three equal splits did not affect crop yield, but increased nitrous oxide emissions more than early season N application in a silt loam soil. Similar results have been reported by Mueller et al. (2017), who found no yield response to the late split-N application at the R1 growth stage of corn in sandy loam soil. Other studies reported that delaying N application for too long until tasseling (Walsh et al., 2012) or silking (Silva et al., 2005) can have negative impacts on grain yields and NUE (Adriaanse & Human, 1993; Jung et al., 1972). However, some studies reported either a decrease (Binder et al., 2000; Sitthaphanit et al., 2009; Walsh et al., 2012) or no crop yield response (Jaynes & Colvin, 2006; Ning et al., 2017; Roberts et al., 2016; Scharf et al., 2002; Yan et al., 2014) with late split-N application. The authors of these studies attributed the yield decrease or no yield response to either irreversible yield loss with early season N stress or sufficient N availability early in the growing season, respectively. In contrast, Lü et al. (2012) and Zhou et al. (2019) found that applying N in 3-splits (V6, V10, and R1) and 4-Splits (sowing, V6, V12, and R1) increased grain yield than applying N at 2-N splits (sowing and V6). Nevertheless, optimizing the number of N-splits to improve NUE, increase crop yield, and decrease NO_3-N leaching risk, especially in sand soils, remain unresolved as an approach to minimize groundwater contamination (Azad et al., 2020; Scharf et al., 2002; Wang et al., 2016). However, none of the studies have investigated the number of N-splits based on NO_3-N leaching in the Midwest, probably because this type of research is often costly and requires intensive sampling for NO_3-N leaching measurements. Meanwhile, in other regions, studies have reported either a decrease (Sitthaphanit et al., 2009) or no effect (Wang et al., 2016) with increasing the number of split-N applications on NO_3-N leaching in sandy soils. Rubin et al. (2016) recommended split N application for irrigated sandy soils along with economic optimum N rate to minimize NO_3-N leaching risk.

Sandy soils possess greater NO_3-N leaching risk to groundwater due to high soil porosity, hydraulic conductivity, and lower water holding capacity, compared to clay soils (Silva et al., 2005). With the increasing risk of nitrate contamination in sandy soils of the Bazile Groundwater Management Area (BGMA) in Nebraska, the Natural Resource Districts (NRDs) have begun to more strongly regulate N fertilizer use. The BGMA is one of the groundwater quality management areas developed by Nebraska in 1986 and accepted by the Environmental Protection Agency (EPA) in 2016 (Figure 2.1).

The BGMA has approximately 1958 sq. km. area with >10 mg NO_3-N L^{-1} in groundwater and provides drinking water to 7,000 Nebraskans. Depending on the groundwater NO_3-N concentration levels, the groundwater management plans in the BGMA and Nebraska are divided into different areas, known as phase levels. If the groundwater has 0-5 mg NO_3-N L^{-1}, it is categorized as Phase I. If the NO_3-N in the groundwater ranges from 5.1-9.0 mg NO_3-N L^{-1}, it is considered Phase II. While Phase III constitutes the irrigation wells with >9 mg NO_3-N L^{-1}. If areas are under Phase III for five years, those areas would be considered under Phase IV. One of the many requirements in the Phase III area is not to exceed spring pre-plant N application above 112 kg N ha^{-1}. Although the current recommendations can result in higher corn yield with potentially fewer N losses; environmental stewardship has ignited the need to optimize the number of N-splits and determine a cut-off to last N application during the growing season to minimize NO_3-N leaching while maintaining crop yield and profitability. Understanding that optimizing the number of N-splits would profoundly influence the NO_3-N leaching in the area, this study aimed to optimize the number of N-splits based on NO_3-N leaching and grain yield. The objectives of this study were to (1) optimize the number of N splits based on crop yield, NO_3-N leaching losses, and profitability, and (2) assess the impact of N splits on nitrogen use efficiency, nitrogen recovery efficiency, return on nitrogen, and residual nitrogen. We hypothesized that increasing the number of N-split applications before tasseling would decrease the NO_3-N leaching and improve corn yield in irrigated sandy soils of the BGMA and similar water management areas of Nebraska and elsewhere.

Materials And Methods

Experimental Site

This on-farm study was designed as a two-year experiment in 2021 and 2022 near Creighton, NE (42°25'02.3"N, 98°02'52.3"W), however, due to an equipment calibration error, the planned N application rates did not occur in 2022, so we are presenting 2021 data only. The experimental site was in a Phase III area of the Bazile Groundwater Management Area (BGMA) in the Upper Elkhorn Natural Resource District (NRD). Soil at the experimental site is an excessively drained Thurman loamy sand soil (Soil Survey Staff, 2022) that contained 82.3% sand, 9.7% silt, and 8% clay. The groundwater table depth at the site was approximately twelve meters in Fall 2020. The site is at an altitude of 568 m and has a humid climate (Li et al., 2023; Singh et al., 2021) with an annual average precipitation of 714 mm with significant interannual variability. The long-term annual and growing season average temperature at the site is 9.6°C and 20°C, respectively (HPRCC, 2023). Before the treatment establishment, soil samples were collected at 0-20 cm soil depth to determine soil physical and chemical properties. The specific soil properties are listed in Table 2.1.

Experimental Design And Treatments

The experiment was conducted in a field with a center pivot overhead sprinkler irrigation system. The outer two spans of the pivot were equipped with a variable rate irrigation (VRI) system (Valmont Industries, Valley, NE), used to establish experimental plots in a randomized complete block design with one control and four N-split treatments (2-N splits, 3-N splits, 4-N splits, and 5-N splits). The details of N application timings and rates are given in Table 5.1. The treatments were replicated three times on 24 m long and 36 m wide plots. All the experimental plots including the non-treated control received MAP (mono ammonium phosphate) broadcast by the farmer at the rate of 140 kg ha^{-1} (equivalent to 16 kg N ha^{-1}) at pre-plant. All the treatments, except the control, received the same total seasonal N application rate at 202 kg N ha^{-1} (excluding N rate from MAP application) at different timings (Table 5.1), which was closer to the economical optimum N rate in the area.

Table 5.1 Nitrogen fertilizer treatments in 2021 at the study site.

N source	Total N applied	Urea-Agrotain	UAN†			
N timing*			V4	V8	V12	VT
N method		Preplant	Side-dress	fertigation		
	kg N ha^{-1}					
2 N-splits	202	67	135	0	0	0
3 N-splits	202	67	101	0	34	0
4 N-splits	202	67	67	34	34	0
5 N-splits	202	67	33	34	34	34

† UAN, Urea Ammonium nitrate.
*V4, 4-leaf stage; V8, 8-leaf stage; V12, 12-leaf stage; VT, tasseling.

To minimize the NH_3 volatilization losses at pre-plant, a urease inhibitor (AGROTAIN) from Koch industries was used to coat urea at the recommended rate of 2.1 L AGROTAIN per ton Urea. The AGROTAIN-coated urea was surface broadcasted at pre-plant with a 3-m wide dry fertilizer drop spreader (Barber Engineering Co.). The UAN (32%N) was side-dressed with a 6-m wide liquid applicator in the furrow at the V4 crop growth stage on June 4th, 2021. To minimize NH3 volatilization losses, 19.05 mm irrigation was applied within 24 hours following side-dressing. The treatments 3-N, 4-N, and 5-N were fertigated (UAN 28% N) through the central pivot at growth stages listed in Table 5.1. The management decisions such as crop hybrid selection, herbicide application, and irrigation scheduling were at the discretion of the farmer.

Crop Yield, Nitrogen Use Efficiencies, And Economic Return

At physiological maturity, the middle 12 rows were harvested with a commercial combine by the farmer. To determine corn N uptake, we hand harvested two 3 m rows per plot and separated them into corn grain and stover (stalk, leaves, cobs). The stover was shredded using a portable woodchipper. Ears and subsamples of chopped corn stover were weighed and dried at 71°C to determine moisture content. Ears were shelled to separate grain and cobs. Grain and stover were milled and analyzed for total N using the dry combustion method at a commercial laboratory (Ward Laboratories Inc., Kearney, NE). Hand harvest grain yield was adjusted to 15.5% moisture content. The N concentration in grain and stover, and plant population were used to calculate total aboveground biomass, harvest index (HI), N uptake by grain, plant, and N harvest index. We also calculated different nitrogen use efficiency indicators (Congreves et al., 2021) including partial factor productivity (PFP, Eq. 5.1), corn nitrogen use efficiency (NUE_{corn}, Eq. 5.2), agronomic efficiency (AE, Eq. 5.3), nitrogen recovery efficiency (NRE, Eq. 5.4), nitrogen utilization efficiency (NutE, Eq. 5.5), and the economic indicators including the net return to nitrogen (RTN; Eq. 5.6) and net return to nitrogen considering environmental costs (RTN_{Env} ; Eq. 5.7) as follows:

$$\text{PFP (kg kg}^{-1}) = \frac{\text{Grain yield}}{\text{Fertilizer N}} \quad \text{(Eq. 5.1)}$$

$$\text{NUE}_{\text{corn}}(\text{kg kg}^{-1}) = \frac{\text{Grain N uptake}}{\text{Fertilizer N}} \quad \text{(Eq. 5.2)}$$

$$\text{AE (kg kg}^{-1}) = \frac{\text{Yield}_{\text{trt}} - \text{Yield}_{\text{control}}}{\text{Fertilizer N}} \quad \text{(Eq. 5.3)}$$

$$\text{NRE (\%)} = \frac{\text{Plant N uptake}_{\text{trt}} - \text{Plant N uptake}_{\text{control}}}{\text{Fertilizer N}} \text{ x } 100 \text{ (Eq. 5.4)}$$

$$\text{NUtE (kg kg}^{-1}) = \frac{\text{Grain Yield}}{\text{Plant N uptake}} \quad \text{(Eq. 5.5)}$$

$\mathrm{RTN} = (\mathrm{Yield_{Corn}} \text{ x } \mathrm{Price_{Corn}}) - (\mathrm{Input_N} \text{ x } \mathrm{Price_N})$ (Eq. 5.6)

$\mathrm{RTN_{Env}} = \mathrm{RTN} - (\mathrm{NO_3{-}N_{leached}} \text{ x } 18.54^{*})$ (Eq. 5.7)

*18.54 US$ kg^{-1} NO_3-N was the environmental cost associated with NO_3-N leaching (Preza-Fontes et al., 2023; Sobota et al., 2015).

Lysimeter Installation And Water Sampling

To monitor the pore water NO_3-N and NH_4-N concentration below the crop rootzone, two suction-cup lysimeters were installed approximately 30 m apart at 1.2 m soil depth in each experimental plot following the method described by Venterea et al. (2011) and Maharjan et al. (2014). The suction cup lysimeters were purchased from Irrometer Company Inc. (Model SSAT - Soil Solution Access Tube) and contained 100-kPa high flow ceramic cup attached to rubber tubing designed to apply the pressure and collect water samples at the soil surface. The suction cup lysimeters were installed using silica powder slurry to cover the ceramic cup at the bottom of the vertical hole bored with a 1.2 m long and ~19 mm wide soil probe. The soil from the hole was used to re-fill the hole around the lysimeter tube, followed by the placement of a finely powdered bentonite layer at the soil surface to prevent the preferential flow of water. Pore-water samples from the lysimeters were collected one to three times a week following rain or irrigation events from 20 May to 15 October, 2021. To pull the pore water from the ceramic cup, a pressure of ~80 kpa was applied to the suction cup through the rubber tubes. After about 4 hours, the rubber tube line was opened to collect the pore-water sample with a 20 mL syringe and samples were acidified with 0.1N hydrochloric acid before transferring to the lab in a cooler. In total, there were 690 water samples collected during the 23 leaching events.

Water Balance And NO_3-N Leaching Calculations

A soil water balance equation (Eq. 5.8) was used to estimate the draining water *via* deep percolation below the root zone using the following approach (Djaman & Irmak, 2013):

$$DP_i = P_i + I_i - R_i - ET_i \pm \Delta S_i \text{ (Eq. 5.8)}$$

where DP is deep percolation, P is precipitation, I is irrigation, ET is evapotranspiration, ΔS is soil water storage in the root zone, and i is current day. Units are mm day^{-1}. The value of P was determined using High Plains Regional Climate Center (HPRCC) data collected at a weather station near the site, while I is the amount of irrigation applied in the field by the farmer (249 mm throughout the growing season). The ET values were calculated as a product of an alfalfa reference (Djaman & Irmak, 2013) mean crop coefficient (K_{cr}) based on the stage of growing degree days (Lo et al., 2019) and the reference ET estimates incorporated with the daily weather data using the Penman-Monteith equation (Allen et al.,1998, Allen et al., 2000). The model output ET values for 2-, 3-, 4-, 5- N splits and control were 591, 587, 588, 590, and 579 mm, respectively. The K_{cr} values for the curve was derived from the NDVI data collected during the R_1 corn growth stage using the relationship [K_{cr} = 1.308*(NDVI) + 0.027] given by Singh & Irmak (2009) for irrigated corn in Nebraska. The water in the soil profile at the start of the growing season was assumed to be at field capacity. We estimated runoff for our experiment using the United States Department of Agriculture–Natural Resources Conservation Service (USDA NRCS) curve number method (USDA-NRCS, 1985). The model output for daily percolation for 2-, 3-, 4, 5-N split and control treatments were 83.6, 84.4, 84.3, 83.8, and 86.1 mm, respectively. Daily leaching mass of NO_3-N and NH_4-N were determined as the product of daily deep percolation and daily NO_3-N and NH_4-N concentration. The daily NO_3-N (Eq.

5.9) and NH_4-N mass from suction-cup lysimeters water sample were the product of (a) daily estimation(s) of deep percolation and (b) average of previous days pore water NO_3-N and NH_4-N concentrations after last deep percolation event occurred, and (c) 0.01 (kg ha^{-1}) unit conversion factor (Pawlick et al., 2019).

$$[\mathrm{NO_3} - \mathrm{N}]_{\mathrm{leached}} = \frac{1}{n}\sum_{i=1}^{n}[NO_3 - N]_{120cm} \text{ x } DP_i \text{ x } 0.01 \text{ (Eq. 9)(Eq. 5.9)}$$

Where i is the day when deep percolation happens, and n refers to the days since last deep percolation occurred. To calculate seasonal average pore water NO_3-N concentrations, the daily pore water NO_3 concentrations were averaged across days in the corn growth stage. Sub-seasonal pore water NO_3-N concentrations were calculated based on the corn growth stages and the sampling dates between (i) planting and 8-leaf stage (early vegetative phase), (ii) 8-leaf to tasseling (late vegetative phase), and (iii) tasseling to physiological maturity (reproductive phase), derived and validated from field observations to compute the effect of treatments over time (Rudnick et al., 2017; Singh et al., 2021). For seasonal pore water concentrations, the average was performed across all dates while the daily NO_3-N amounts were summed up for area-scaled based seasonal NO_3-N leaching losses. Our data showed that >70% of ammonium values were below detection limit, therefore, ammonium data analysis was not performed.

Residual Soil Nitrate And Ammonium Analysis

In fall 2021, six undisturbed deep core (0-120 cm) soil samples were collected after corn harvest from each experimental plot within non-trafficked rows. The truck mounted Giddings hydraulic probe (Giddings Machine Co., Fort Collins, CO) was used for sampling soil cores with a diameter of 44 mm. The intact cores were sliced at the following depth increments: 0-30, 30-60, 60-90, and 90-120 cm. The six soil cores per plot were composited by depth before being transported to the lab in a cooler. The soil samples were extracted with 2M KCL solution (5:1 solution to soil ratio) after shaking for 1 hr, followed by filtration through Whatman #1 filter paper. Soil extracts from deep core soil samples and lysimeter water samples were analyzed for NO_3-N and NH_4-N concentration using VCl_3/Griess method (Miranda et al., 2001) and the Berthelot reaction (Kandeler & Gerber, 1988), respectively.

Statistical Analysis

Two-way repeated measures analysis of variance (ANOVA) was performed using PROC GLIMMIX with replication as a random factor, treatment as a fixed factor, and crop growth stage and/or date as a repeated fixed factor using the autoregressive (1) structure for the residuals (Singh et al., 2023), for analyzing the differences between (i) sub-seasonal, and (ii) daily pore water NO_3-N concentrations. Similarly, two-way repeated measures ANOVA was performed using PROC GLIMMIX with replication as random factor, treatment as a fixed factor, and depth as a repeated fixed factor for residual soil N (both NO_3-N and NH_4-N). One way ANOVA was performed with replication as a random factor and treatment as a fixed factor to analyze the differences among treatments for grain yield, biomass yield, grain N uptake, plant N uptake, harvest index, N harvest index, NO_3-N leaching, partial factor productivity, N use efficiency, agronomic efficiency, N recovery efficiency, N utilization efficiency, return to N, and return to N considering environmental costs. The least square means estimates were used to analyze the differences among treatments. The significance was calculated at the 0.05 probability level.

RESULTS

Climate

Figure 5.1 (a-c) shows the total water input received by the experimental site during the 2021 growing season. During the entire season, the total water input by precipitation and irrigation was 376 mm and 249 mm, respectively. The total precipitation during the growing season (376 mm) was 11% lower than the last ten year's average growing season precipitation (424 mm) at the site. Within the growing season, the precipitation during the early vegetative, late vegetative, and reproductive phases was consistently lower than the average last ten years of precipitation during the same period. The precipitation accounted for 50% (57 mm), 76% (185 mm), and 50% (133 mm) of total water received during the early vegetative (116 mm; Figure 5.1a), late vegetative (243 mm; Figure 5.1b) and reproductive (266 mm: Figure 5.1c) stages, respectively. The irrigation accounted for 50% (59 mm), 24% (58 mm), and 50% (133 mm) of total water received during the early vegetative (116 mm; Figure 5.1a), late vegetative (243 mm; Figure 5.1b) and reproductive (266 mm: Figure 5.1c) stages, respectively. Overall, the higher total water input occurred in the reproductive phase (43%), followed by the late (39%) and early (19%) vegetative phase, respectively.

NO_3-N Leaching

The pore water NO_3-N concentrations from the daily water samples from the lysimeter are shown in Figure 5.1 (d-f). During the 2021 growing season, 23 leaching events occurred following the precipitation or irrigation events (Figure 5.1d-f). The daily pore water NO_3-N concentration significantly varied during the entire season, ranging from 0.002 to 12.95 mg NO_3-N L^{-1} across all treatments. A higher pore water NO_3-N concentration was observed at the start of the season, which decreased as the season progressed. The decreasing pore water NO_3-N concentration trend over the growing season was stronger than the N treatments themselves (Figure 5.1d-f).

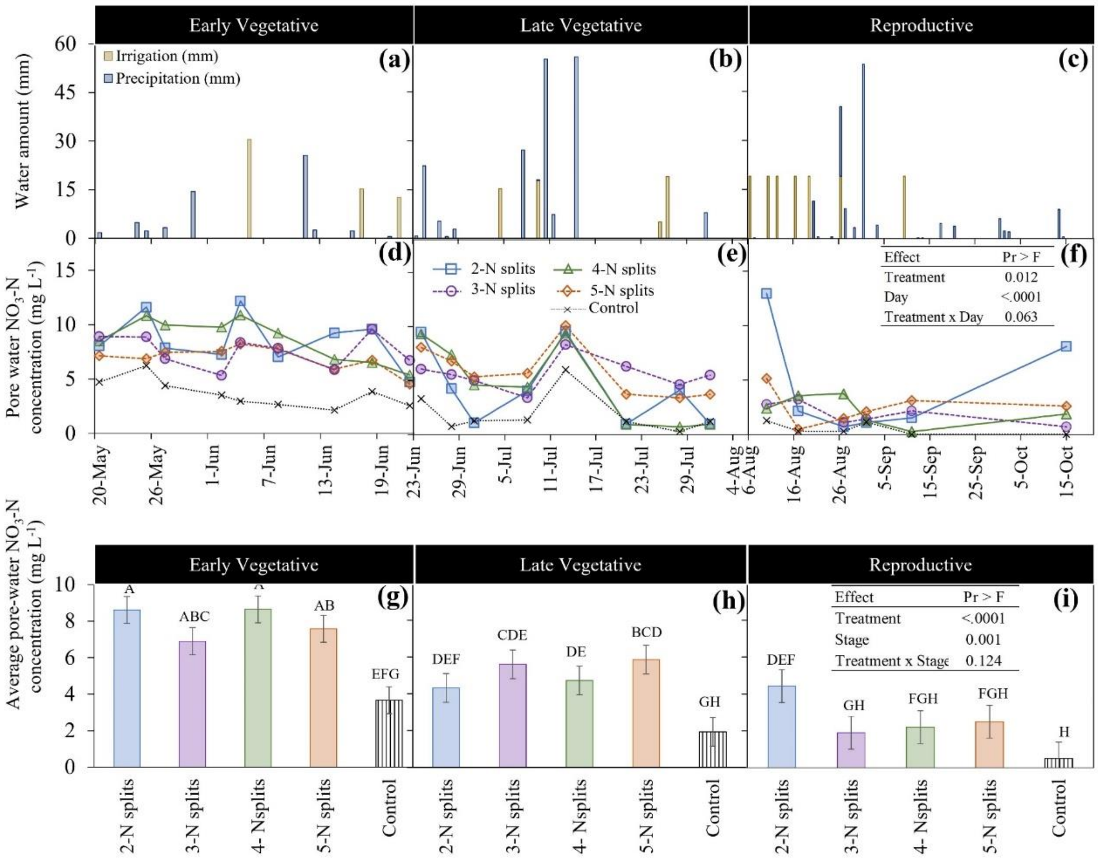

Figure 5.1 The upper panels (a-c) show water inputs (mm) for three maize growth phases – early vegetative (planting to V8), late vegetative (V8-VT) and reproductive phases (R1-R6), while daily and subseasonal pore water NO_3-N concentrations (mg L^{-1}) are shown in the middle panels (d-f) and lower panels (g-i), respectively.

There were significant main as well as interaction effects of treatment and sampling date on pore water NO_3-N concentrations (Figure 5.1d-f). The pore water NO_3-N concentrations were significantly higher in the split-N treatments than the control throughout the growing season. However, no differences among the 2-, 3-, 4-, and 5-N split treatments were observed on daily pore water NO_3-N concentrations. When averaged across the season, the daily pore water NO_3-N concentrations were 6.06, 5.14, 5.59, and 5.65 mg NO_3-N L^{-1} which were 169%, 128%, 148%, and 151% higher in 2-, 3-, 4-, and 5-N split treatments compared to control (2.25 mg NO_3-N L^{-1}), respectively. To evaluate the treatment impact on the pore water NO_3-N concentrations within the season, we segregated the data into three crop growth stages i.e. Early Vegetative phase (VT-V8), Late Vegetative phase (V8-VT), and Reproductive phase (R1-R6). There were no significant interaction effects between treatment and crop growth phases ($p = 0.12$). However, treatment ($p < 0.001$) and crop growth stages main effects ($p = 0.001$) on pore water NO_3-N concentrations were significant (Figure 5.1g-i). The pore water NO_3-N concentrations in the early vegetative (7.08) stage were 58% and 207% higher than the late vegetative (4.48; $p = 0.0065$) and reproductive phases (2.30; $p = 0.0001$), respectively. Similarly, the pore water NO_3-N concentration in the late vegetative phase was 94% higher than in the reproductive phase ($p = 0.0033$; Figure 5.1 g-i). Furthermore, there were significant treatment effects within the three crop growth stages. No significant differences in pore water NO_3-N concentration among the four N splits (2-N, 3-N, 4-N, 5-N) occurred in the early vegetative phases. However, the control treatment (2.03 mg NO_3-N L^{-1}) had significantly lower pore water NO_3-N concentrations than the four N-split treatments (4.79 – 5.78 mg NO_3-N L^{-1}). A similar trend with significantly lower pore water NO_3-N concentration in control than four N splits was observed during the late vegetative phases. Unlike vegetative growth stages, a different treatment effect on pore water NO_3-N concentration was observed during the reproductive phases, where the 2-N split had significantly higher pore water NO_3-N concentration than other three N splits (3-, 4- and 5-N) and control.

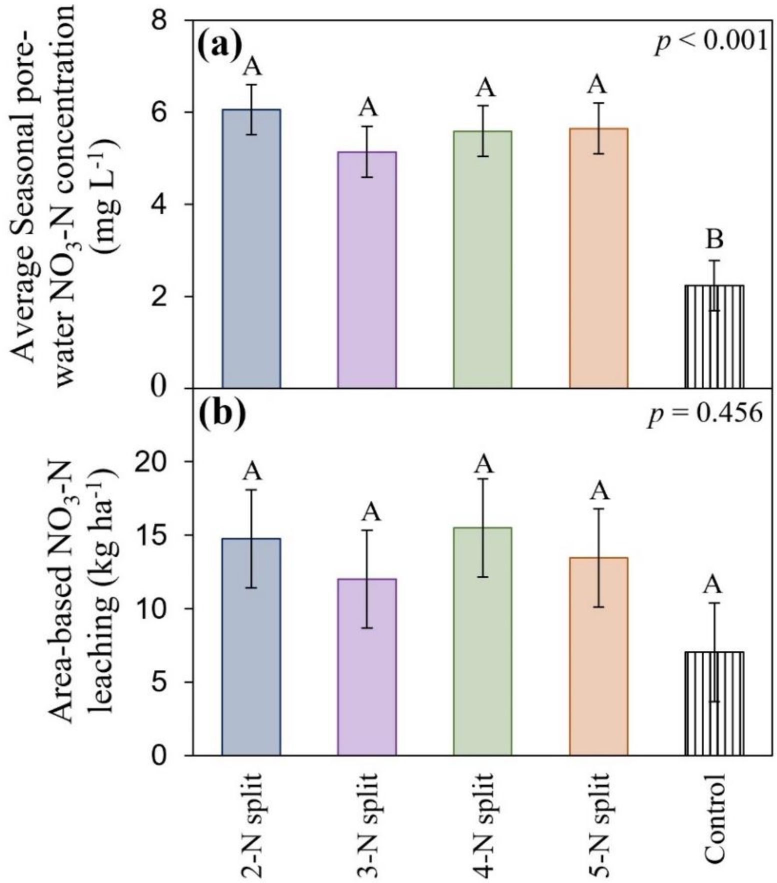

Figure 5.2 Treatment means and significance (error bars) of (a) seasonal average pore-water NO_3-N concentration (mg L^{-1}) and (b) area-based NO_3-N leaching (kg ha^{-1}) as affected by N-splits.

The cumulative area-based NO_3-N leaching losses were determined for the treatments using soil water NO_3-N concentrations and deep percolation measured from the soil water balance equation. This area-based NO_3-N leaching ranged from 7.0 – 15.5 kg NO_3-N ha^{-1} across all treatments. The treatments neither significantly affected NO_3-N leaching across the entire season ($p = 0.46$; Figure 5.2), nor within each growth stage. Though not significantly different, the 2-, 3-, 4-, and 5-N splits had 110%, 71%, 120%, and 91% higher NO_3-N leaching than the control across the entire season. Total NO_3-N leaching losses across the split N treatments were equivalent to 5.5-7.1% of the applied nitrogen. Crop growth stages had a significant effect on NO_3-N leaching. Early, late, and reproductive crop stages had NO_3-N leaching of 5.4, 4.9, and 2.3 NO_3-N ha^{-1}, respectively. On the other hand, early and late vegetative growth stages had 33 and 16% higher NO_3-N leaching than the reproductive phases. When averaged across treatments, early vegetative, late vegetative, and reproductive phases accounted for 51, 32 and 17% of the entire season NO_3-N leaching, respectively.

Agronomic Response, Residual Soil Nitrogen, And Economical Analysis

The NDRE, the crop tissue N concentration, grain yield, total biomass, and plant N uptake across treatments are shown in Table 5.2 and Figure 5.3. There were significant differences among the treatments for the NDRE, crop tissue N concentration, corn grain yield, total biomass, HI, and grain and plant N uptake. Across all the treatments, the NDRE values for all the treatments were low at V6 and gradually increased at V12 and VT. Compared to the control treatment, NDRE values were significantly higher in all split-N treatments; however, there were no differences among the four N splits. Furthermore, the crop tissue N concentration, grain yield, total biomass, HI, and grain and plant N uptake were significantly higher in the 2-5N splits than in the control (Figure 5.3 & Table 5.2). On the other hand, an N-addition of 202 kg N ha^{-1} in split-N treatments resulted in a yield increase of 57-70%, depicting yield benefits with N addition. However, increasing the number of split applications did not result in yield benefits as there were no significant differences among all N-split treatments on corn yield (Figure 5.3a). Likewise, the number of N-splits did not affect crop total biomass and HI, although these were 53-64% and 2.7-3.9% higher for N-splits than the control treatment, respectively. Furthermore, there were no differences in the NHI ($p = 0.17$) among the treatments.

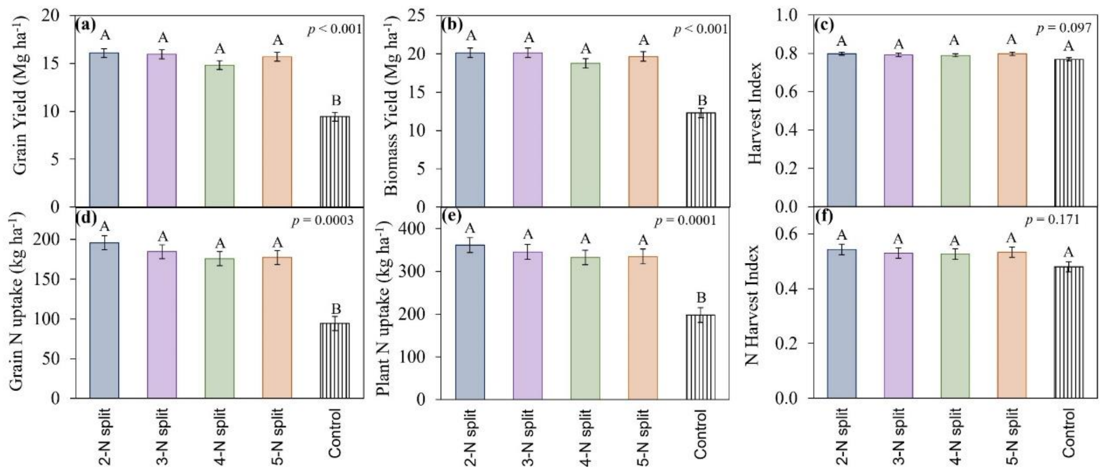

Figure 5.3 Treatment means and significance (error bars) of grain yield (a), biomass yield (b), harvest index (c), grain-N uptake (d), plant-N uptake (e), and N harvest index (f) as affected by N-splits.

Compared to the control treatment, all split N treatments significantly increased grain ($p = 0.0003$) and plant N-uptake ($p = 0.0001$). However, there were no grain and plant N uptake differences among the four N-split treatments (Figure 5.3d-e). No significant differences were observed among the treatments for PFP ($p = 0.39$: Table 5.2), NUE_{crop} ($p = 0.51$), AE ($p = 0.41$), NUtE ($p = 0.18$), and NRE ($p=0.51$) (Table 5.2). Across all treatments, PFP, NUE_{crop}, AE, NUtE, and NRE ranged from 73 to 80 kg kg^{-1}, 0.87 to 0.96 kg kg^{-1}, 31 to 33 kg kg^{-1}, 45 to 48 kg kg^{-1}, and 67 to 81%, respectively.

Increasing the number of N-splits did not affect the RTN or RTN_{Env} (Table 5.2). Adding N in split-N treatments increased the RTN by 954-1203 US$ ha-1. However, when environmental costs were considered in the analysis, there was a decrease in net returns of 13-17% (92-143 US$ ha-1), resulting in RTN_{Env} of 798-1082 US$ ha-1 across all N-split treatments. Though not statistically significant, 2-N splits had modestly higher

RTN and RTN_{Env} than three or more N-splits, indicating no economic benefit of increasing the number of split-N applications during the dry growing conditions observed in this study.

There were no significant main or interaction effects of treatments and depth on residual soil NO_3-N and NH_4-N (Figure 5.4a, b). However, it was interesting to note higher values of residual soil NH_4-N than NO_3-N across all treatments and depths. Residual soil NH_4-N ranged from 70 to 101 kg ha^{-1}, while residual soil NO_3-N ranged from 0 to 12 kg ha^{-1} across all treatments and depths.

Table 5.2 Treatment means and significance of partial factor productivity (PFP), corn nitrogen use efficiency (NUE_{corn}), agronomic efficiency (AE), nitrogen utilization efficiency (NUtE), nitrogen recovery efficiency (NRE), return to N (RTN), and RTN considering environmental costs (RTN_{Env}) as affected by nitrogen splits at Creighton, NE

Treatment	PFP	NUE_{corn}	AE	NUtE	NRE (%)	RTN	RTN_{Env}	NDRE			ELNC †
	kg grain kg^{-1} N					$ ha^{-1}		V6	V12	R1	(%)
2 N-splits	80	0.96	33	45	81	1203a§	1060 a	0.3 a	0.5 a	0.68 a	3.1 a
3 N-splits	79	0.91	32	46	73	1175a	1083 a	0.3 a	0.6 a	0.66 a	3.0 a
4 N-splits	73	0.87	27	45	67	954 a	798 a	0.3 a	0.5 a	0.65 a	2.9 a
5 N-splits	78	0.88	31	47	68	1125a	1006 a	0.3 a	0.6 a	0.65 a	2.9 a
Control	-	-	-	48	-	-	-	0.2 b	0.4 b	0.53 b	2.1 b
SE¶	2.6	0.5	2.6	2	7	104	162	0	0	0.01	0.2
Significance (P_r > F)	0.4	0.51	0.4	0.2	0.5	0.4	0.62	**0.01**	**0.01**	**0.01**	**0.01**

§ Least significant difference at the 95% confidence level by PROC GLIMMIX-SAS treatment means followed by the same letter are not significantly different. Columns that do not contain letters indicate no significant difference between treatments.

† ELNC, Ear leaf N concentration at R1 stage.
¶ SE, standard error of the mean.

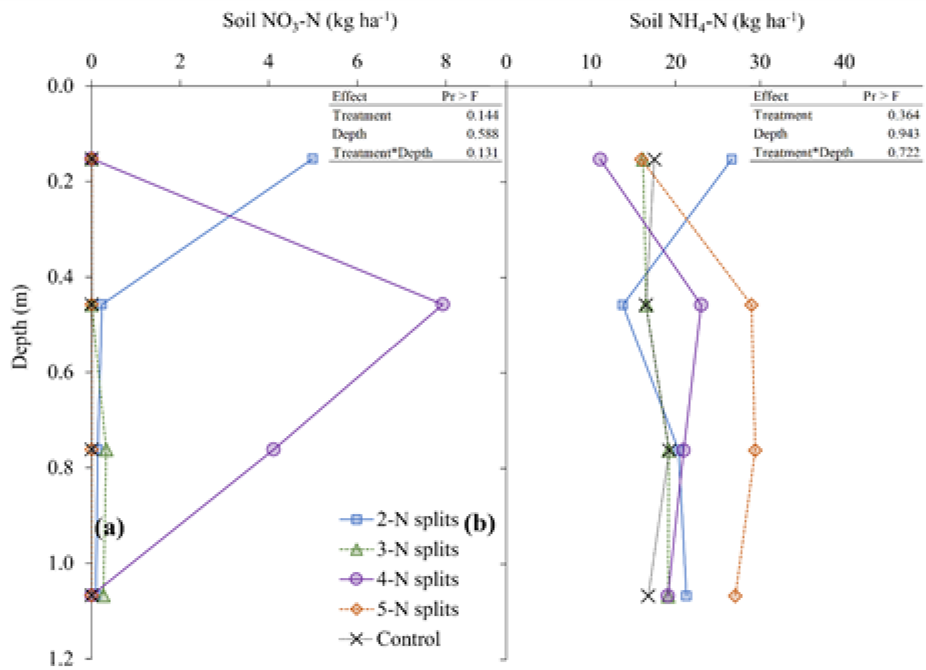

Figure 5.4 The residual soil N in the soil profile (0 – 120 cm) at the end of the growing season.

DISCUSSION

NO_3-N Leaching

NO_3-N leaching losses in the sandy soils of Nebraska have caused much concern due to environmental contamination and risks to human health (Ferguson, 2015; Power & Schepers, 1989). So, continuous efforts have been made to introduce best management practices to reduce NO_3-N leaching to groundwater. The pore water NO_3-N concentrations in this study were within the range of 6-35 mg NO_3-N L^{-1} concentration in the lysimeter water reported by Spalding et al. (2001) in the Central Platte Valley of

Nebraska during 1993-1996. However, the NO_3-N leaching losses of this study, ranging from 7.0 to 15.5 kg NO_3-N ha^{-1}, were lower than the NO_3-N leaching of 52 kg NO_3-N ha^{-1} for continuous corn observed at the West Central Research and Extension Center (WCREC) of Nebraska (Klocke et al., 1999). Although the N rates used in this study (202 kg N ha^{-1}) were comparable to the N rate used by Klocke et al. (1999), the lower NO_3-N leaching in our study could be attributed to timing and source of N application as the WCREC study applied all the N in ammonium nitrate form at fourth to sixth leaf stage of corn which could be prone to NO_3-N leaching. In contrast, N application in this study was spread from pre-plant to R1, which might have better synchronized soil N availability with crop N uptake. Furthermore, the total water inputs from precipitation and irrigation in this study (376 mm) were lower than in the WCREC study (523-858 mm/season), reflecting less NO_3-N leaching in the soil. Splitting N application and use of N stabilizer in this study demonstrate that a combination of best management practices could reduce NO_3-N leaching in soils vulnerable to NO_3-N leaching in the area.

In this study, the decreasing trend for NO_3-N leaching over the growing season appeared stronger than the treatments themselves. The higher NO_3-N leaching in the early vegetative phase indicated higher potential N losses when the crop N requirement is low at early vegetative phases compared to late vegetative phases (Herrmann & Taube, 2004; Hirel et al., 2007; Jokela & Randall, 1997; Ma et al., 2021). These results support the previous findings that applying some N during the late vegetative phase can better synchronize N availability with crop N uptake and reduce the NO_3-N leaching losses (Kabir, 2020; Pawlick et al., 2019; Sitthaphanit et al., 2009). However, optimizing the number of N-splits to increase N uptake and reduce NO_3-N leaching remains uncertain. To our knowledge, no previous study has reported the effect of the number of N splits on NO_3-N leaching in the Midwest arable cropping system. However, in other regions, studies have reported either a decrease (Sitthaphanit et al., 2009) or no effect (Wang et al., 2016) with increasing the number of split-N applications on NO_3-N leaching in sandy soils. Though we tested multiple N applications to optimize N splits in this study, we did not find a significant effect of early vs. late season N splits on NO_3-N leaching across the entire season, except with some trend of higher NO_3-N concentration with 2 splits than 3, 4, and 5 splits during the reproductive phases.

The insignificant effect of the number of N-splits on area-based NO_3-N leaching across the entire season in our study could be due to several reasons. First, using an AGROTAIN urease inhibitor across all treatments at pre-plant might have diminished the treatment effect on NO_3-N leaching during the early vegetative phase. This was confirmed in a companion study at the same farm and year, where AGROTAIN slowed the release of N after pre-plant application (data not yet published). Second, the variability of NO_3-N leaching could have led to insignificant treatment effects as the NO_3-N concentration variability of samples collected from the lysimeters is often higher when compared to NO_3-N concentration in shallow groundwater (Spalding et al., 2001). Although this variability can be due to site-specific conditions or spatial variation (Gärdenäs et al., 2005), the higher variation (i.e. standard errors) in this study failed to detect the differences among the treatments. Third, the site observed 26% less rainfall in the early vegetative phase (May until mid-June; 79 mm) compared to an average of the last ten years precipitation (108 mm) which might have reduced the NO_3-N leaching potential during the early season, especially in high N inputs in 2N-splits at V4, as timing of precipitation significantly affects NO_3-N leaching in sandy soils (Petrovic, 2003; Yahdjian & Sala, 2010). Overall, the lack of significant effect due to the number of N-splits on NO_3-N leaching indicates that multiple N-splits may not consistently decrease NO_3-N leaching, but this in part depends on when the period of high deep percolation happens relative to the time of N application (Preza-Fontes et al., 2021). Had we conducted this study without the use of AGROTAIN urease inhibitor at pre-plant or had heavy precipitation during the vegetative phases, then early season application with less N-splits might have increased NO_3-N leaching compared to a greater number of N-splits during late vegetative or early reproductive phases. Although these results were for one year, they highlight the need to test N-spits to minimize NO_3-N leaching across more years.

Although we found significantly higher NO_3-N concentration in all four split-N treatments than control, these effects were not significant when NO_3-N leaching was calculated based on the area scale NO_3-N leaching. However, it is important to note that the insignificant differences of area-based NO_3-N leaching between N-splits and control were more likely due to lower evapotranspiration leading to higher deep percolation and area-based NO_3-N leaching in control than all the fertilized treatments, especially during the later vegetative and reproductive phases (Table 5.2) (Bowles et al., 2018). This kind of effect where NO_3-N leaching increases with high deep percolation, has been observed in previous studies (e.g. Bowles et al., 2018). Similar to the findings of this study, Maharjan et al. (2014) reported no differences in NO_3-N leaching between split N application and control in sandy loam soil in Minnesota. Despite having no significant differences in NO_3-N leaching between split-N and control treatments, NO_3-N leaching from split-N treatments was almost two times greater than the NO_3-N leaching losses from the control, demonstrating the environmental impact of using N fertilizers in the cropping system. These results indicate that further optimization of N splits would be necessary to control NO_3-N leaching, as groundwater contamination is a concern for public health. Meanwhile, it is important to note that NO_3-N leaching cannot be minimized to zero even when no nitrogen is applied. Relatively higher NO_3-N leaching in control might be due to continuous mineralization of soil organic matter or irrigation of water with high NO_3-N concentration. Previous studies have reported similar or higher levels of NO_3-N leaching from control than observed from control in this study (Helmers et al., 2012; Lawlor et al., 2008; Preza-Fontes et al., 2021; Ruffatti et al., 2019).

Crop Yield and Nitrogen Use Efficiency

In-season N application have been shown to improve NUE and decrease N losses (Walsh et al., 2012). In this study, although all split-N applications significantly increased crop yield compared to control, no differences in crop yield among the split-N treatments indicate that N availability was not limited at any crop growth stage in the fertilized treatments. These insignificant differences in crop yield were reflected by no differences in NDRE values from V6 to R1, NUE, crop tissue N concentration at R1, and crop N uptake at harvest among these treatments (Tables 4). On the other hand, there was an adequate N supply with N recovery reaching 68-81% of the applied N across all split-N treatments. Similar results have been reported by Mueller et al. (2017) who found no yield response to the late split-N application at the R1 growth stage of corn in sandy loam soil. They attributed this to sufficient soil N availability by late N application at the R1 growth stage. A positive yield response to late-season N application may be more likely when most of the N is applied early in the season (Mueller et al., 2017). On the other hand, late season application response could be observed when the initial N application is insufficient or lost through leaching or other denitrification process (Jaynes and Colvin, 2006). Other studies (Ning et al., 2017; Jaynes and Colvin, 2006; Roberts et al., 2016; Yan et al., 2014) also found no crop yield response to late season N application when N was already present in sufficient amounts in soil. In contrast, Lu et al. (2012) and Zhou et al. (2019) found that applying N in 3-splits (V6, V10, and R1) and 4-splits (sowing, V6, V12, R1) increased grain yield than applying nitrogen at 2-N splits (sowing and V6). The difference in crop yield response between the studies could be attributed to differences in N management and growing conditions between the sites. In our study, using a urease inhibitor at pre-plant might have delayed the N release and reduced NO_3-N leaching losses (observed in a companion study), and hence, N application with all-N splits might have satisfied the crop N requirements. Had we conducted this trial without the AGROTAIN urease inhibitor or with heavy precipitation in the early season, increasing the number of N-splits during late vegetative or early reproductive phases might have increased crop yield in this study.

Despite the lack of corn yield response to the number of split-N applications, 2-N splits had slightly higher values for corn yield, crop tissue N concentration, and NRE than 3, 4, and 5-N splits, indicating better source-sink performance of the 2-N splits in a dry year. This was similar to previous studies where 2-N splits were sufficient to meet crop N demand (Deng et al., 2023; Mueller & Vyn, 2018; Rutan & Steinke, 2018; Wang et al., 2016) while late-split N application negatively impacted the crop yield (Scharf et al., 2002; Adriaanse and Human, 1993; Walsh et al., 2012; Mueller and Vyn, 2018; Jaynes and Colvin, 2006), as late N application can ignore the N demand for early crop growth and cause some irreparable damage to the crop by affecting absorption of N during later crop growth stages (Deng et al., 2023). In a similar study, Deng et al., 2023 found that 4-N spits had slightly lower grain yield than 2-N and 3-N splits, supporting the results of this study. These results also highlight the importance of adequate early season N nutrition on the corn yield (Schepers et al., 1995).

Residual Soil Nitrogen

Split-N application during the growing season is often implied to synchronize better the soil N availability with the crop N uptake and reduce N losses (Pawlick et al., 2019: Perza-Fontes et al., 2021; Zhou et al., 2019). However, any N left in the soil at harvest can be prone to NO_3-N leaching during the non-growing season (Tan et al., 2002; Jayasundara et al., 2007). Previous research has shown that mid-late season N application in case of less crop N uptake can leave a significant amount of residual N at harvest, which becomes available for leaching during the non-growing season (Jaynes and Colvin, 2006; Wang et al., 2016: Randall et al., 1997). In this study, no differences in residual soil NO_3-N and NH_4-N among split N-treatments corresponded to no differences in NO_3-N leaching and crop yield, indicating that most of the applied N in irrigated sandy soil was either taken up by the crop or lost during the growing season. Furthermore, the cumulative residual soil NO_3-N at 0-1.2 m depth in this study was lower (0 – 12 kg NO_3-

N ha^{-1}) than the generally reported residual soil NO_3-N value of 50 kg NO_3-N in soils of Nebraska (Shapiro et al., 2008). One reason for the less residual NO_3-N could be the soil characteristics of this study (loamy sand soil), that with sufficient water inputs via rainfall and irrigation, might have resulted in either crop N uptake or downward movement of nitrogen in soil profile, thus leaving less residual NO_3-N for the next year crop. However, compared to residual NO_3-N, it was interesting to note higher cumulative residual NH_4-N (70-101 kg NH_4-N ha^{-1}) across all treatments, either originating from fertilizer or soil organic matter mineralization.

Despite the lack of significant differences in soil NH_4-N among the treatments, 5-N split had relatively higher NH_4-N at the lower depths of 0.4-1.2m (Figure 5.4). This higher NH_4-N movement into the lower depths might have resulted from the last fertigation at R1, as NH_4-N from UAN might have moved into the soil profile without going through the nitrification process or interception by the plant roots. This NH_4-N in the soil profile at harvest could cause a significant risk of contaminating the groundwater during the non-growing season as NH_4-N would eventually convert to NO_3-N due to microbial activity (Subarao et al., 2021). Moreover, when averaged across all the treatments, cumulative residual N at 0-1.2m soil depth at harvest (70-101 kg N ha^{-1}) was 7-10 times higher than NO_3-N leaching load during the growing season, clearly indicating more risk for NO_3-N leaching during the non-growing season. This was supported by previous studies that reported that a significant portion of NO_3-N leaching occurred during the non-growing season of November – April in the region (Tan et al., 2002; Drury et al., 1996; Jayasundara et al., 2007).

Conclusion

Corn production with early season precipitation in sandy soils at the BGMA and other groundwater management areas poses a high risk of NO_3-N leaching even when high N rates are not used. So, optimizing the number of N splits with a cut-off date for N application during the late growing season is critical for protecting groundwater quality. Our one-year study occurred in a dry year where we did not observe any benefit of increasing the number of split-N applications on protecting groundwater quality or improving corn yield. The lack of significant effect of the number of N-splits on NO_3-N leaching indicates that multiple N-splits may not consistently decrease NO_3-N leaching across all years. Had we conducted this study in a normal to wet year, we may have seen the effect of increasing the number of split-N on agronomic, economic, and environmental benefits. Nevertheless, in this study, the general trend for higher NO_3-N leaching early in the season with a decreasing trend over the growing season appeared stronger than the treatments themselves, emphasizing the need for controlling the NO_3-N leaching during the early season. Furthermore, the significant treatment effect on seasonal NO_3-N concentration with insignificant treatment effect on seasonal NO_3-N leaching from this study indicates that higher pore water NO_3-N concentrations may not always translate into higher NO_3-N leaching losses, but rather deep percolation counts towards an accurate accounting of NO_3-N leaching losses. Nevertheless, this study highlights the limitation of increasing the number of split-N during a dry year and emphasizes the need to collect more data to optimize the number of split-N across multiple years with a range of dry, normal, and wet seasons.

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CHAPTER 6

SUMMARY AND GENERAL CONCLUSIONS

Higher groundwater nitrate contamination in the sandy soils of the BGMA poses a high risk to the environment and human health. Identifying and evaluating the best nitrogen management practices are critical to sustaining crop production with minimal impact on water quality in this area. A series of studies were conducted to understand the effects of N recommendation tools on agronomic, economic, and environmental performance and explore the possibility of integrating sub-optimum N rate with deficit irrigation, enhanced efficiency fertilizers, and N-splits to improve nitrogen use efficiency, and water quality in the groundwater management areas of Nebraska.

The first study showed that the static NE YG tool was more effective in predicting EONR and grain yield than the dynamic N tools. The dynamic N tools predicted nitrogen rates below EONR, resulting in yield penalties more than half of the time. However, three dynamic N tools (Canopy Reflectance Sensing, Granular, and Adapt-N) reduced nitrate leaching by 18% more than half of the time, suggesting the potential for environmental benefits using these tools. Economically, all N tools were equally effective in determining economic returns when environmental costs of NO_3-N leaching (RTN_{Env}) were included. These results highlight challenges in adopting dynamic N tools as these provide some environmental benefits but with yield penalties and no economic benefits. On the other hand, the static NE YG can provide agronomic and economic benefits but no environmental benefits. Policymakers and farmers need to prioritize environmental or economic benefits while preferring any of these N recommendation tools.

The second study demonstrated that using multiple N-splits at sub-optimum or reduced N rates can substantially reduce NO_3-N leaching in vulnerable sandy soils. Though 25% and 50% reductions in N fertilizer decreased maize yield by 8% and 11%, this reduction in N rates substantially reduced NO_3-N leaching by 24 and 51% and RTN_{Env} by \$87 ha^{-1} and \$25 ha^{-1}, respectively. These results highlight a tradeoff between reduced grain yield, reduced NO_3-N leaching, and societal economic returns in the groundwater NO_3-N contaminated areas. Furthermore, higher maize grain yield, RTN, and relatively lower NO_3-N leaching from 80% FIT indicate that reducing irrigation can minimize NO_3-N leaching without impacting maize yield and economic returns. Compared to N and irrigation management within the growing season, it was interesting to observe that yearly variation in irrigation and grain yield had a higher impact on determining NO_3-N leaching and economic returns i.e. despite having lower irrigation and total water inputs, 2021 had higher grain yield, lower NO_3-N leaching, lower residual NO_3-N and NH_4-N, and higher RTN than 2022. These results demonstrate that adjusting irrigation and N rates could substantially reduce NO_3-N leaching without impacting RTN_{Env} in the groundwater NO_3-N contaminated areas. Future research should explore irrigation scheduling and N rate models to optimize irrigation and N inputs to reduce NO_3-N leaching.

In the third study, conventional U_{split} application did not significantly decrease NO_3-N leaching, corn yield, and economic returns compared to U_{PP}. However, the use of EEFs (i.e., Agrotain and SuperU) in single pre-plant application not only substantially decreased NO_3-N leaching with the levels approaching control treatments in both years, but had the same or even better crop yield, and improved economic returns than conventional U_{split} and U_{PP}. Notably, though the split application of EEFs with UAN decreased NO_3-N leaching and increased corn yield than U_{PP}, but the single application of these EEFs had significantly lower NO_3-N leaching than their split application with UAN (i.e., $(U+UI)_{split}$, $(U+UI+NI)_{split}$). Across all nitrogen treatments, the lower NO_3-N leaching from single pre-plant application of EEFs were also explained by relatively higher grain and biomass yield, crop N uptake, NRE, PFP, and AE, indicating these treatments as the most efficient N management system for improving N recovery efficiency. These findings provide clear evidence that EEF_{PP} could be a very effective strategy in mitigating NO_3-N leaching losses while improving economic benefits in the groundwater contaminated areas.

The fourth study aimed to optimize the number of N splits with a cut-off date for N application during the late growing season to maximize the agronomic and economic benefits while protecting groundwater quality. Our one-year study occurred in a dry year where we did not observe any benefit of increasing the number of split-N applications on protecting groundwater quality or improving corn yield. The lack of significant effect of the number of N-splits on NO_3-N leaching indicates that multiple N-splits may not consistently decrease NO_3-N leaching across all years. Had we conducted this study in a normal to wet year, we may have seen the effect of increasing the number of split-N on agronomic, economic, and environmental benefits. Nevertheless, in this study, the general trend for higher NO_3-N leaching early in the season with a decreasing trend over the growing season appeared stronger than the treatments themselves, emphasizing the need for controlling the NO_3-N leaching during the early season. Furthermore, the significant treatment effect on seasonal NO_3-N concentration with insignificant treatment effect on seasonal NO_3-N leaching from this study indicates that higher pore water NO_3-N concentrations may not always translate into higher NO_3-N leaching losses, but rather deep percolation counts towards an accurate accounting of NO_3-N leaching losses. Nevertheless, this study highlights the limitation of increasing the number of split-N during a dry year and emphasizes the need to collect more data to optimize the number of split-N across multiple years with a range of dry, normal, and wet seasons.

Overall, these studies' findings will help producers and policymakers in decision-making for the right nitrogen recommendation tools, nitrogen source, and irrigation rates for improving agronomic, economic, and environmental performance in groundwater management areas of Nebraska. However, more research trials across multiple sites with variable environmental conditions could help to validate the observed results. Furthermore, future research should integrate irrigation scheduling, N rate models, and the number of N-splits to optimize the irrigation and N inputs to improve agronomic, economic, and environmental performance in the area.