Evaluating nitrogen management strategies for groundwater quality improvement under a changing climate across the Wisconsin Central Sands

By

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Abstract

Across the Midwest, farmers, researchers, policy makers and communities are confronting increasing groundwater contamination due to agricultural practices, particularly the use of synthetic nitrogen fertilizer, coupled with the challenge of employing these practices to continue growing profitable crops. Additionally, not only are the impacts of agricultural practices felt at the local level—often in the form of agricultural runoff, unsafe drinking water, soil erosion, and decreased stream and lake levels—but also nationally. As agricultural runoff travels downstream to the Gulf of Mexico, excess nutrients have resulted in dead zones. It is likely that ongoing and future climate change across the Midwest will exacerbate current struggles and may leave many fields more vulnerable to nitrate leaching. Moving forward, to ensure safe drinking water and restore and protect ecosystem services, nitrogen management strategies need to be improved and implemented. The Wisconsin Central Sands (WCS) faces many of the challenges felt by communities across the Midwest when managing agricultural land with growing water quality contamination. The WCS region serves as a case study in improving nitrogen management for groundwater quality. To better identify pathways to improved groundwater quality, we incorporated on-farm research related to drivers of water quality variability, observations of soil-plant-environment interactions, agroecosystem modeling, and farmer surveys.

In chapter one, we evaluated/quantified the spatiotemporal variability of nitrate concentrations in irrigation water across the WCS region. Additionally, we analyzed the influence of well depth, well casing diameter, nitrogen application rate, year and week of sampling event on nitrate concentration in irrigation water. We found that nitrate levels varied

more across space than time, that nitrogen application rate was the most significant predictor of nitrate concentration, and that on average, nitrate levels in irrigation water across the WCS are 19.0 mg/L, or nearly twice the threshold for safe drinking water set by the EPA. In chapter two, we measured leaf level photosynthesis and calculated key photosynthetic parameters for two cultivars of potato grown under four nitrogen application rates. We found that nitrogen application rate (season total N), days after emergence (DAE), and temperature were significant predictors of Vc_{max} (maximum rate of carboxylation). We also found that at the highest level of nitrogen application (403.5 kg N/ha), both N content (%) and Vcmax declined relative to a nitrogen application rate of 336.3 kg N/ha. In chapter three, we modeled the impact of nitrogen best management practices (BMPs) with varied N rates on irrigated corn yield and nitrate leaching. To better understand the effectiveness and tradeoffs of BMPs considering increased weather variability, we used cluster analysis to group similar weather years. We found that nitrate leaching could be reduced through the use of BMPs (20%) and reduced nitrogen application rates (40%), but there was little room for mitigation during years experiencing wetter than average growing seasons. Additionally, nitrate concentration in the groundwater never reached safe/healthy levels (below 10 mg/L) in our simulations. In chapter four, we surveyed farmers on their current use of nitrogen BMPs, levels of concern towards environmental and economic challenges, as well as barriers to implementing certain BMPs. Our findings highlight that growers feel the greatest level of concern for the cost of government regulation and ineffective government policies, and 100% of respondents felt at least a little concerned about groundwater quality. While the BMP of split application was widely adopted (69%), growers perceived lack of information as a substantial barrier to adopting the practice of crediting nitrate in irrigation water.

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Introduction

Across the globe, agriculture has drastically altered the landscape, in turn shaping the quality and quantity of available freshwater. With the discovery of the Haber-Bosch process and the resulting development of synthetic nitrogen fertilizer roughly one hundred years ago, fertilizer application to cropland has become common practice. While crop yield has increased drastically with the use of synthetic fertilizer, it has come at a cost to water quality. As nutrients leave the land through leaching and runoff, they enter and contaminate nearby waterways. Cyanobacteria blooms form in surface water in response to nutrient runoff from agriculture, posing a threat to both human and environmental health (Jeppesen et al., 2005). Additionally, eutrophication, or excess nutrients, contribute to dead zones, resulting in fish kills and cascading impacts on local ecosystems (Dale, Virginia H. Wright, 2010; Rabalais et al., 2002; Turner & Rabalais, 1991). Below the surface, contamination of groundwater due to nitrate leaching through the soil profile has created unsafe drinking water (Johnson & Kross, 1990; Keeney et al., 1994; Power & Schepers, 1989; Spalding & Exner, 1993; Wick et al., 2012).

High levels of nitrate in groundwater are associated with methemoglobinemia (blue baby syndrome) (McCasland et al., 1985; Shuval & Gruener, 1975) and colorectal, ovarian, thyroid, bladder, and kidney cancers (Manassaram et al., 2006; Mathewson et al., 2020). Not only are high levels of nitrate in drinking water associated with negative health and environmental impacts, but they are also economically expensive. Recent work by Mathewson et al. (2020) estimated that in Wisconsin, $23 to $80 million is spent annually treating nitrate attributable health outcomes. For those who receive their drinking water from a private well, the burden is often higher. In Wisconsin, the economic cost and health risk is often felt by the individual, who is responsible for testing their drinking water, in addition to paying for the cost of any remediation if unsafe levels of any contaminant are found. As a result, the current system favors the polluters, with little safety nets in place for the residents most impacted. Considering more than 43 million people (15% of the U.S. population) across the U.S. rely on private wells as their main source of drinking water, the problem is far reaching (T. D. Johnson et al., 2019) .

The challenge of preventing continued degradation of water quality is exacerbated by ongoing and future climate change (IPCC, 2023). An increase in frequency of extreme rainfall events increases the risk of nitrate leaching as rainfall moves nitrogen past the plant root zone, preventing it from being taken up by crops and promoting leaching to groundwater below (Hess et al., 2020; Martinez-Feria et al., 2019). Additionally, rainfall events increase the risk of runoff and erosion, allowing sediment bound nutrients to travel into nearby surface waterways. Such rainfall events are especially concerning for cropping systems already vulnerable to nitrogen loss, such as high N demanding crops, crops grown on sandy soil, and cropping systems under poor N management.

While some initiatives have begun to address groundwater quality contamination, there is often concern over potential crop yield reductions. However, by implementing best management strategies (BMPs), growers may be able to maintain crop yields while reducing groundwater contamination. Past research highlights the need to implement the 4R's: the right rate, right timing, right placement and right source when it comes to nitrogen management (Hochmuth et al., 2014; The Fertilizer Institute, n.d.). Specific recommendations include split application of fertilizer, properly crediting all sources of nitrogen, the use of slow release fertilizer, implementing crop rotations, and cover cropping. Other conservation practices include the use of no-till agriculture, buffer strips and increasing perennial grassland, wetland restoration, removing vulnerable land from agricultural management, and rotation grazing (Bowles et al., 2018; Campbell et al., 2021; Demissie et al., 2012; Dinnes et al., 2002; Shrestha et al., 2010; Waddell et al., 2000; Wepking et al., 2023; Werling et al., 2014). However, it is still unclear if these practices are sufficient to improve water quality by large magnitudes (Davidson et al., 2016; Hansen et al., 2017; McLellan et al., 2018).

In the Midwest, corn and potato cropping systems may benefit especially from the use of BMPs when it comes to promoting water quality improvements. In the U.S., corn is the largest user of nitrogen and is planted on the most acres, with roughly 90 million acres of corn planted each year (Ribaudo et al., 2011); as a result, improving nitrogen management in corn cropping systems is imperative for addressing groundwater quality challenges across the Midwest. While grown on fewer acres—about 1 million acres annually—potato cropping systems may benefit disproportionately from improved nitrogen management strategies due to their extreme vulnerability to nitrate leaching. A recent meta-analysis conducted by Shrestha et al. (2023) found that on average, fertilized potato cropping systems leached 59 kg N/ha, approximately 25 kg N/ha more than corn. Using nitrogen management strategies that reduce the inherent risk and vulnerability of potato cropping systems to nitrate leaching can aid in addressing water quality goals.

Despite the consensus on agricultural use as a leading cause of nonpoint-source pollution to rivers, streams, and groundwater (National Water Quality Assessment) paired with development of voluntary BMPs, large scale reductions in nutrient pollution have not occurred (McLellan et al., 2018; Porter et al., 2015). Lack of improvement may be partially explained by the role of legacy nutrients, or nutrients applied decades ago but still stored in the soil today, hindering water quality improvements despite the use of BMPs today (Motew et al., 2017;

Sharpley et al., 2013; Van Meter et al., 2016, 2018). Additionally, despite the development of BMPs and the supporting science illustrating their benefits, widespread adoption of BMPs has not occurred. Recent work has found that two-thirds of U.S. cropland are not managing nitrogen effectively (Ribaudo et al., 2011). Specifically, the recommended rate of nitrogen fertilizer was not applied to 53 million acres, nitrogen was applied at incorrect times on 40 million acres, and improper methods of nitrogen application were used on over 61 million acres. Similar findings were reported by the Upper Mississippi River Basin (NRCS, 2012). These findings also highlight region differences in nitrogen management, emphasizing that cropland in the corn belt and great lakes region of the county was more likely to receive excess fertilizer application. However, past research has also indicated that the implementation of BMPs alone may not be enough to meet water quality goals (McLellan et al., 2018; Porter et al., 2015). Instead, water quality improvement may be met with a combination of in-field BMPs, downstream nutrient removal practices, policy change, or landscape transformation (Bowles et al., 2018; Campbell et al., 2021; McLellan et al., 2018; Porter et al., 2015).

The Wisconsin Central Sands (WCS) exemplifies many of the current challenges facing communities across the globe when it comes to maintaining crop yields while simultaneously preventing water quality degradation and over use. Located in the center of Wisconsin, the WCS is comprised of large-scale agricultural production, forests, wetlands, trout streams and lakes. Historically, the western portion of the WCS contained numerous wetlands, which were then drained in the 1920's for agriculture use (Wisconsin Department of Natural Resources, n.d., 2015). Currently, the eastern portion of the WCS is dominated by agriculture, while the western portion consists primarily of forests and remaining wetlands. Today, agriculture in the region is possible due to the invention of the center-pivot irrigation system in the 1940's, allowing for the pumping and distribution of groundwater through high-capacity wells. Common crops grown in the area include potato, corn, soybean, and a range of vegetables (Heineman & Kucharik, 2022). Potato and corn cropping systems are two of the highest nitrogen demanding crops grown in the region (Laboski et al., 2012), but also provide large economic revenue. The potato cropping system is of particular interest, generating an estimated $522 million for the Wisconsin economy (Kashian et al., 2014), but also requiring large amounts of nitrogen and frequent irrigation.

As a result of a combination of the geology, hydrology, and land use, the eastern portion of the region is highly susceptible to groundwater contamination and nonpoint source pollution (Wisconsin Department of Natural Resources, 2015). Groundwater contamination due to N leaching has been heavily documented across the region (Groundwater Coordinating Council, 2020; Luczaj & Masarik, 2015; Masarik et al., 2018; Romano et al., 2021). A recent study conducted in Portage County, which falls within the boundaries of the WCS, found that 24% of private wells tested above 10 ppm, about 2.5 times higher than the state average (Masarik et al., 2018). Though Wisconsin is not the only state with an inability to provide its residents with safe drinking water, the drinking water contamination across the state has generated national attention.

Overuse of groundwater is also a growing concern. Since the 1950's, high-capacity wells in the WCS have become prolific, increasing from less than 100 to over 3000 today. Each well has the potential to pump 100,000 gallons of water a day, allowing for potentially large implications on groundwater withdrawal (Wisconsin Department of Natural Resources, 2021). Past research has shown that declines in water levels and streamflow cannot be attributed to climate alone, and that groundwater pumping may be responsible for decrease water levels by 4 ft. (Kraft et al., 2012; Kraft & Mechenich, 2010).

Ongoing groundwater contamination and water quantity challenges are further compounded by climate change, which is creating warmer and wetter conditions across the area. Specifically, the region is seeing an increase in overall nighttime temperatures and an increase in both total precipitation and number of extreme rainfall events (Wisconsin Initiative on Climate Change Impacts, 2021). This is likely to exacerbate water quality issues and will increase the demand for irrigation water throughout the growing season.

Managing nitrogen effectively requires many pieces of a moving puzzle. My PhD research has incorporated many aspects of this puzzle, and generally seeks to improve nitrogen management strategies across the Wisconsin Central Sands (WCS) to improve groundwater quality.

A key aspect of improving nitrogen management is increasing nitrogen use efficiency (NUE) and as a result, decreasing the amount of nitrogen available to leach into the groundwater. To improve NUE, all nitrogen sources must be accounted for when determining nitrogen fertilizer application rates; in areas such as the WCS, this includes the nitrate present in irrigation water. By quantifying the magnitude of nitrate in irrigation water, determining the spatiotemporal variability of nitrate concentrations, and identifying significant predictions of nitrate concentrations in irrigation water, growers can begin to more accurately credit nitrate in irrigation water and reduce overall fertilizer use.

An additional component of nitrogen management and improved NUE relies on determining how nitrogen application rates impact crop physiology, and how these impacts may change under increased weather variability and climate change. Understanding the impact of nitrogen application rate on leaf level photosynthesis helps us determine how much nitrogen the crop is using and provides crucial data for modeling carbon and nitrogen cycling in agroecosystems.

Another key aspect of improving nitrogen management is evaluating the effectiveness of BMPs to reduce nitrate leaching below the root zone and reduce the nitrate concentration of drinking water, while quantifying the potential tradeoffs to crop yield. As researchers, farmers, and policy makers continue to attempt to address groundwater quality challenges across Wisconsin, understanding both the opportunities and limitations of BMPs is a necessary step to addressing groundwater contamination.

Lastly, but maybe most importantly, a necessary component of improving nitrogen management strategies is using sound science to inform on the ground changes in nitrogen management practices. Agronomic and ecosystem service research is crucial for determining the current state of groundwater contamination, identifying options to mitigate nitrate loss, and reducing uncertainty when it comes to a changing climate. However, if the science isn't accompanied with changes in behavior and land management, we cannot expect our water quality goals to be met.

Together, my dissertation chapters work to improve nitrogen management strategies and NUE across the WCS through 1) improved and more accurate crediting of all nitrogen sources, specifically the nitrate found in irrigation water, 2) greater knowledge of potato ecophsyiological responses to nitrogen application rate and environmental variables, 3) quantifying the effectiveness of BMPs on reducing nitrate leaching and nitrate concentration and the potential tradeoffs to corn yield, and 4) determining what BMPs are currently implemented in the WCS, identifying the barriers to crediting N in irrigation water, and surveying top concerns and challenges for farmers in the region.

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Chapter 1: Quantifying the spatiotemporal variability of nitrate in irrigation water across the Wisconsin Central Sands

Abstract

The Wisconsin Central Sands (WCS) is home to large scale vegetable production on sandy soils and managed with frequent irrigation, fertigation, and widespread nitrogen fertilizer application, all of which make the region highly susceptible to nitrate loss to groundwater. While groundwater is used as the primary source of drinking water for many communities and rural residences across the region, it is also used for irrigation. Considering the high levels of nitrate found in the groundwater, it has been proposed that growers more accurately account for the nitrate in their irrigation water as part of nitrogen management plans. Our objectives were to 1) determine the magnitude of nitrate in irrigation water, 2) quantify the spatiotemporal variability of nitrate, and 3) determine key predictors of nitrate concentration in the region. We sampled irrigation water from 38 fields across six farms from 2018-2020. Across the three years of our study, nitrate concentration varied more across space than time. On average, our samples tested at 19.0 mg L^{-1} nitrate-nitrogen, or nearly two times the EPA threshold for safe drinking water, equivalent to 48.5 kg ha^{-1} of applied nitrate with 25.4 cm (or 10 inches) of irrigation. To better understand the spatiotemporal variability in nitrate levels, week of sampling, year, well depth, well casing, and nitrogen application rate were analyzed for their role as predictor variables. Based on our linear mixed effects model, nitrogen application rate was the greatest predictor of the nitrate concentration of irrigation water ($p<0.05$).

1.1 Introduction

Across the Midwest, large scale agricultural production and fertilizer application to cropland has increased crop yields but drastically altered biogeochemical cycling and has directly contributed to surface and groundwater contamination (Dubrovsky et al., 2010; Bouwman et al., 2013; Fowler et al., 2013). Nitrogen use efficiency of crops has historically remained low, with about 50% of applied nitrogen fertilizer lost to the environment (Cassman et al., 2002). In areas with large scale agricultural production with animals, the inadequately timed or additional challenges that come with application of manure also exacerbate losses of nitrogen to the environment (Almasri and Kaluarachchi, 2004). As nitrogen leaves the land through leaching and runoff, it enters and contaminates nearby waterways (David et al., 2010). Streams and rivers contaminated by nitrogen experience conditions of eutrophication and hypoxia, in which the supply of excess nutrients limits oxygen resulting in fish kills and loss of biodiversity (Rabalais et al., 2002; Howarth et al., 2011). Contamination of groundwater due to nitrate leaching through the soil profile has resulted in unsafe drinking water (Power and Schepers, 1989; Johnson and Kross, 1990; Kraft and Stites, 2003; Vashisht et al., 2015). Additionally, nitrogen has the ability to be stored in the soil profile and groundwater for long periods of time, creating a legacy problem (Van Meter et al., 2016, 2018; Van Meter and Basu, 2017; Chen et al., 2018). Nitrogen already present in groundwater can contribute to significant time lags in water quality improvement, in which it may take decades of management change before water quality improvements come to fruition (Van Meter et al., 2017, 2018; Campbell et al., 2021).

The Wisconsin Central Sands (WCS) exemplifies many of the current challenges facing farmers across the Midwest US when it comes to balancing agricultural production with environmental stewardship – and in particular, nitrate contamination of groundwater. Groundwater contamination in the WCS is especially concerning considering 52% of its residents access their drinking water from private wells (Wisconsin Department of Natural Resources, 2015). A study in Portage County in the WCS, found that 24% of private wells tested above 10 ppm nitrate, bout 2.5 times higher than the state average (Masarik et al., 2018). The WCS is dominated by sandy soils with low water holding capacity and rapid drainage, low cation exchange capacity, and a relatively shallow depth to the water table (Wisconsin Department of Natural Resources, 2015; Nocco et al., 2017). While these attributes may seem like significant obstacles to overcome for farming, the region is home to a thriving potato and vegetable production industry, but is also comprised of large tracts of forest, wetlands, trout streams, and lakes. Common crops grown in the area include potato, corn, soybean, and a range of vegetables. Historically, the western portion of the WCS contained numerous wetlands, which were then drained in the 1920s for agricultural use (Wisconsin Department of Natural Resources, 2015). Agriculture in the region has been made profitable by the widespread adoption of center-pivot irrigation systems since the 1950s, allowing for the pumping and distributing of groundwater through high-capacity wells that withdraw more than 100,000 gallons per day (Hindall, 1978). Growers in the WCS employ frequent irrigation due to crop water demand, high evapotranspiration (ET), low water holding capacity of the soil, and rainfall variability during the growing season (Wisconsin Department of Natural Resources, 2015; Nocco et al., 2019).

Considering the high levels of nitrate in WCS groundwater, which is reapplied to the landscape as irrigation water, it has been proposed that growers should account for the nitrate in irrigation water when determining fertilizer rates (Keeney and Follett, 1991; Karim, 1995). While past field studies on nitrogen rate application guidelines have been conducted in the WCS, they have not been updated in 30 years, during which time nitrate concentration has risen (Saffigna et al., 1977). Additionally, nitrogen rate application guidelines are based on a few sites that do not account for variability in nitrate levels in groundwater across the region. While high nitrate levels in groundwater are documented, it is unclear how nitrate levels vary spatially and temporally across the region. By more accurately accounting for the nitrate in irrigation water, growers can work within the current agricultural system to reduce further contamination to groundwater. We aimed to 1) determine the spatial variability of nitrate concentrations in irrigation water and examine variables (e.g., land use, land cover, depth-to-well, and well construction) that may explain spatial variability and 2) determine how nitrate levels in irrigation water vary within-season and year-to-year. The overarching goal of this work is to provide growers with information and data to reduce fertilizer use by accounting for the nitrate already present in irrigation water, and as result, decrease further contamination to groundwater.

1.2 Methods

1.2.1 Study Region

The WCS spans 6300 km^2 of agricultural land in central Wisconsin, irrigated with over 2,100 high-capacity wells (Nocco et al., 2017). The most common crops are field corn, soybean, sweet corn, alfalfa, potato and vegetable crops, and common two and three year crop rotations include continuous corn, alfalfa followed by alfalfa, and corn-soybean rotations (Figure 1) (Heineman and Kucharik, 2022). The region has a moist continental climate (Arguez et al., 2010) and over the last 30 years (1991-2020) the average high and low temperatures during the summer (Jun-Aug) were 26ºC and 14ºC, respectively, with 335 mm of rainfall (National Oceanic & Atmospheric Administration, 2010). Based on farm records, supplemental annual irrigation ranges from 193 to 404 mm across the region, depending on weather and crop needs (Nocco et al., 2017). Similarly, previous work using high-capacity well pumping records estimated 90 to 280 mm of irrigation was applied annually from 2008 to 2010 across corn fields (Kraft et al., 2012). Past work by Nocco et al. (2017) estimates actual evapotranspiration (ET) using a water budget approach to range from 322 to 455 mm annually for common crops grown in the region, and similar findings were reported in recent work using a remotely sensed water budget approach (Smail et al., 2021). Climate change has caused the region to experience a 15-20% increase in summer rainfall between 1950 and 2020, and a 2.5ºC increase in annual minimum and maximum temperature (Wisconsin Initiative on Climate Change Impacts, 2021). Climate change is projected to cause nighttime minimum temperatures to continue to rise, as well as an increase in the frequency of hot days (greater than 32ºC) and extreme rainfall events (Wisconsin Initiative on Climate Change Impacts, 2021).

1.2.2 Sample collection

Irrigation water samples were collected and analyzed weekly during the growing season in 2018, 2019, and 2020 to quantify spatiotemporal variability in nitrate and chloride concentration. We installed funnel systems on farms spanning a north-south spatial gradient across the WCS for repeated passive collection of irrigation water samples. Funnel systems were simple, portable, and cost-effective, consisting of a plastic funnel at canopy height, and using PVC pipe and a fence post to route water to a 3-gallon storage container (see supplemental material). Once per week the volume of water collected from each funnel was measured and a subsample collected in a 125-mL HDPE bottle which was stored at 4 degrees Celsius until analysis.

During the 2018 growing season, samples were collected from four farms, with 5 to 6 fields (each field serviced by a different high capacity well) sampled at each farm. During the 2019 field season, samples were collected from 5to 7 fields at 6 farms, and in 2020 5 farms were included. Approximately half the fields were re-sampled each year of the study and the measurement approach yielded approximately 90 water samples per week of active irrigation.

Three funnels were placed at different points along the length of each center pivot irrigation system to address in-field spatial variation. Three funnels were placed at each farm in an area free of irrigation to quantify precipitation inputs. As a result of the passive system of sampling, back calculations were performed (Table 1) for each sample to account for any dilution that may have occurred due to precipitation. Throughout the three years of the study, any field receiving regular irrigation was included. A wide array of crops were grown on the fields sampled, including soybean, potato, sweet corn, field corn, cabbage, hemp, pea, carrot, and strawberry (see Supplemental Table S1).

1.2.3 Sample analysis

Samples were analyzed for nitrate-nitrogen using a portable, hand held liquid membrane, combination ion selective electrode (ISE) approach (Hanna Instruments, Woonsocket, RI). Nitrate concentration was determined by adding 1 mL of ionic strength adjuster to each 50 mL sample, and then measuring the voltage that occurs as a result of the ion exchange between the solution and membrane (Hanna Instruments, 2017). To verify results, each year 10% of water samples were sent to the University of Wisconsin Stevens Point Water and Environmental Analysis Lab and analyzed for nitrate-nitrogen using a Lachat Instruments Flow Injected Analyzer which was considered the standard. Based on a comparison between the two methods for each year of pooled data, it was determined that there was good agreement between the two approaches. A subset of samples were also measured for Total Kjeldahl Nitrogen (TKN), which provided additional confirmation of fertigation (i.e. fertilizer plus irrigation) events. From 2018-2020, 418 measurements were included after excluding fertigation events, extreme precipitation events, and contamination of some samples due to insects and rodents.

1.2.4 Predictors of nitrate concentration in wells

We analyzed the effect of land use and land cover (LULC) (Nolan et al., 2002; Wick et al., 2012), quality of well construction (Spalding and Exner, 1993), and well depth to determine if these factors were significant predictors of nitrate concentration in irrigation water for each well (Almasri and Kaluarachchi, 2004; Wheeler et al., 2015). Well depth and well casing diameter data was obtained from public well records provided by the Wisconsin Department of Natural Resources (Wisconsin DNR,), and LULC for each well was obtained from the USDA Cropland Data Layer from 2008 to 2020 (USDA-NASS). The Cropland Data Layer was used in combination with CropScape at a 30 m pixel resolution to determine a Common Land Unit for each field (Heineman and Kucharik, 2022). To determine the mix of LULC in the vicinity of each high capacity well, a 500 m radius was applied to each well based off the work of Johnson et al. (2009), and the LULC within that area was determined for each year from 2008 to 2020. Spatial analysis was performed using ArcMap v.10.7.1, and a pixel count for each LULC type per well was determined annually. Using the University of Wisconsin nutrient recommendation guidelines, the 30m pixel count for specific crops was multiplied by the respective nitrogen rate recommendation (Laboski et al., 2012). Nitrogen application rates for common crops such as field corn, sweet corn, potato, and dry beans were assumed to be 224, 168, 247, and 45 kg ha^{-1} respectively based on nitrogen rate guidelines for sandy, irrigated soil with low organic matter (Laboski et al., 2012). The impact of crop rotations was not considered in this approach, and no crediting of legumes or other sources of nitrogen were incorporated. Using this approach, the average rate of potential nitrogen fertilizer application in the 500 m radius around each well was estimated annually and then summed for the 2008-2020 period.

1.2.5 Statistical analysis

Statistical analysis was used to determine whether well information (depth and casing diameter), total nitrogen fertilizer application, week of growing season, or year were significant predictors of well nitrate concentration. A linear mixed effects model was developed, with field nested in farm as random effects on log transformed data. This model was selected to allow for both field and farm to be tested without losing degrees of freedom, while allowing for the hierarchical structure implicit in our study design. The linear mixed effects model was developed in R Studio v. 4.0.4 using the lme4 package (R Core Team, 2022). Data was tested for normal distribution through a qqplot of residuals. Similar models were evaluated, with our chosen model selected based on AIC score. In the few instances when well depth or well casing information was unavailable, those wells were excluded from analysis.

To quantify the spatial and temporal variability in nitrate concentration, spatial and temporal coefficients of variation (CV) were calculated several ways. The CV was computed by determining the ratio between the standard deviation and sample mean. The CV was chosen as an indicator of relative variability as it is independent of mean. Nitrate concentration data was grouped and analyzed at the well level (combining all temporal data points for each well) to quantify within-season temporal variability in nitrate concentration for each growing season. Data was also grouped annually at the farm level (combining data of all wells found on a single farm) to quantify spatial variability across all farms. We compared these differing values to the annual CV at the farm level – which quantified spatial variability across all wells on the same farm. To determine variability across all years, interannual data was grouped at the well level and at the farm level to examine temporal and spatial variability, respectively. By comparing the average interannual CVs at the well level to the farm level, temporal and spatial variability across all three study years was compared.

1.3 Results

1.3.1 Nitrate concentration in irrigation water

Eighty-two percent (n=344) of irrigation water samples had a nitrate-nitrogen value exceeding 10 mg L^{-1}. Across all years and samples collected, the average nitrate-nitrogen concentration in irrigation water was 18.8 mg L^{-1}, approximately 2 times the EPA standard for safe drinking water (U.S. EPA, 2009). Nitrate-nitrogen concentration varied widely throughout the study from 1 mg/L to 45 mg L^{-1} (Figure 2 and Figure 3). Average farm level nitrate-nitrogen concentration was 15-25 mg L^{-1}, with Farm 1 experiencing the highest average concentration, and Farm 4 the lowest. The interannual variability in average nitrate-nitrogen concentration at the farm level was approximately +/- 5 mg L^{-1}. Yearly averages of nitrate-nitrogen were highest in 2020 at 19.6 mg L^{-1}, followed by 2018 at 18.7 mg L^{-1}; the lowest average values were observed in 2019 at 18.1 mg L^{-1} (see Supplemental Table S2). Approximately 53% of wells (16 out of 30) sampled for multiple years of the study had less than 3 mg L^{-1} of interannual variation in average nitrate-nitrogen concentration (Figure 2), and 90% of wells (27 out of 30) experienced less than 5 mg L^{-1} of interannual variation in average nitrate-nitrogen concentration.

1.3.2 Within season well temporal variability compared to farm level spatial variability

In 2018, the nitrate concentration CV was higher at the farm level (spatial) than the field or well level (temporal) for all fields except one (21 of 22). Therefore, greater spatial variability was present at each farm compared to within-season temporal variability for the majority of individual wells. In 2018 (Table 2), Farm 3 experienced the smallest amount of spatial variation in nitrate concentration, with a CV of 0.16, followed by Farm 1 at 0.20. Farms 2 and 4 experienced higher levels of spatial variability in nitrate concentration with CVs of 0.32 and 0.56, respectively. In 2019, Farm 1 demonstrated the lowest CV of 0.30. Wells on Farm 2 and Farm 3 had CVs of 0.41 and 0.31 respectively, followed by Farm 4 at .65 and Farm 6 at 0.70 and Farm 5 at 0.71. Across the 31 fields/wells sampled in 2019, only 5 experienced greater within-season variability than farm spatial variability. During the 2020 growing season, Farm 3 once again experienced the lowest level of variability with a coefficient of variation of 0.26, followed by Farms 1 and 2 at 0.34 and 0.36 respectively. Farms 5 and 6 once again demonstrated higher levels of spatial variability across all wells with CVs of 0.74 and 0.51, respectively. Across the 25 wells sampled in 2020, only 3 experienced greater within-season variability than spatial variability across all wells at each farm (Table 2). In total, farm level spatial variability was larger than within-season temporal variability in 89% of cases. While overall results suggest that significant spatial and within-season temporal variability were present in nitrate concentration, spatial variability between wells at individual farms was generally higher in magnitude than within-season temporal variability at each farm's individual wells.

1.3.3 Interannual temporal variability vs. farm level spatial variability

When comparing variability across years, there was greater overall variability in 2019 with a CV of 0.53, followed by 2020 at 0.47, and 2018 at 0.35 (see Supplemental Table S2). Farms 4, 5, and 6 all experienced higher levels of average spatial variability from 2018-2020, above 0.60. Farms 1, 2, and 3 all demonstrated lower levels of spatial variability in nitrate concentration from 2018-2020 – with CV < 0.40 (Table 3). When summarizing the data for all three years at the well level, interannual variability at the well level was lower than farm level spatial variability for 35 of the 38 wells sampled. The CV for individual wells in the study ranged widely from 0.09 to 1.02. Overall, based on our measurements of nitrate concentration, spatial variability across all farms was higher than interannual temporal variability in 92% of the wells sampled.

1.3.4 Impacts of land use/land cover, well depth, well casing diameter, week of sampling, and year on nitrate concentration

Well depth, well casing diameter, year and week of growing season were not statistically significant predictors of nitrate concentration at a p value of $p < .05$. Based on these results, there is no evidence of an association between week of growing season and nitrate level in our analysis and therefore no within-season trends in nitrate concentration levels (see Figure 3 and Table 4). Nitrogen application rate was significant at a p value of $p < .05$.

1.4 Discussion

1.4.1 *Unsafe levels of nitrate in groundwater in the Wisconsin Central Sands*

Our results demonstrate both the high prevalence and magnitude of nitrate contamination of groundwater in the WCS. Considering only about one in every four wells test below the EPA threshold for safe drinking water, and the average nitrate concentration per sample was approximately 2 times above the safe drinking water threshold, it is clear that considerable action must be taken if groundwater quality is to improve. Past research has highlighted the importance of considering nitrate already in the groundwater system which can take years or decades to discharge to surface waters because of long hydraulic residence times (Meals et al., 2010; Van Meter and Basu, 2017). Moving forward, it’s important for people to understand that seeing actual improvements to surface water quality will be delayed by these lag times (Meals et al., 2010; Campbell et al., 2021) adding to the communication challenge of whether adopting different management practices is making a difference in the WCS. Our results are comparable to other regions vulnerable to nitrate contamination. Previous research across vulnerable areas of Nebraska found that on average, nitrate concentration in groundwater was 18 to 19 mg L^{-1} (Exner et al., 2014). Similarly, past work conducted across prominent dairy regions of California found that shallow monitoring wells on agricultural land tested on average at 24 mg L^{-1} of nitrate, in comparison to 64 mg L^{-1} at the dairies themselves (Harter et al., 2014). In support of these findings, Ransom et al. (2018) found that when measuring groundwater nitrate concentration, those wells located in vulnerable regions (previous contamination, coarse soils and a shallow depth to groundwater, or runoff-prone region with a shallow depth to groundwater) were twice as high as those locates in less vulnerable zones.

1.4.2 Greater variability in nitrate concentration across space than time

Our findings indicate that nitrate concentration in irrigation water has greater spatial variability in comparison to temporal variability. Lower temporal variability can likely be best explained by the integration of different aged water and the sheer volume of water being pumped from high capacity wells. Considering groundwater residence times can be on the order of decades for this region (Kraft et al., 2008), little variation in groundwater nitrate concentration within season and across years may be expected. Similarly, our findings demonstrated that the year of sampling was not a statistically significant predictor of nitrate concentration. Past studies spanning multiple years are in agreement with these conclusions, indicating that the majority of nitrate levels of wells remained steady during a 16 month sampling period of private water wells across the Midwestern US (Ruckart et al., 2008), a study in the Central Sands of irrigation wells (Karim, 1995), and across multiple decades in wells deeper than 30 m based on an Iowa study (McDonald and Splinter, 1982). A study conducted on a dairy farm in Ireland reported similar conclusions as our study, finding higher spatial variability in nitrate concentration in comparison to temporal variability (Baily et al., 2011). While temporal variability was more limited than spatial variability in this study, temporal variability can still be inherent in high capacity wells. Past work has pointed to greater variability in the concentration of contaminants sampled from high capacity wells due to pumping rates (Nightingale and Bianchi, 1980; Keith et al., 1983; Gosselin et al., 1994).

Spatial variability in N concentration may be explained by a range of factors not included in our study, such as direction of groundwater flow, depth to water table, variation in soil texture, age of well, localized weather, management strategies and historical land use. Past research conducted in a similar environment in the Waikato Region of New Zealand (sandy soils, intensive cultivation) have also pointed to the role of site-specific factors in contributing to nitrate concentration variability despite relatively uniform land cover (McLay et al., 2001).

1.4.3 Challenges in predicting nitrate levels

Our statistical modeling did not find well depth to be a significant predictor of nitrate concentration. However, past research has established a relationship between well depth (Almasri and Kaluarachchi, 2004; Nolan and Hitt, 2006; Dubrovsky et al., 2010) and nitrate concentration. The deeper the well, the more likely the water sampled is to be a mix of ages and land uses. Additionally, the longer the residence time of groundwater, the more likely nitrate is to be converted to other forms through denitrification (Dubrovsky et al., 2010). While our study did not find a statistically significant relationship between well depth and nitrate concentration, it should be noted that many of these past studies were conducted in urban environments or using private wells. It is possible that considering the size of high-capacity wells, not all relationships demonstrated among residential wells would be transferable to high capacity wells. Additionally, well depth is often correlated with the type of well, and depth is relative to the region of installation. Considering all the wells in our study are high capacity within the same region of the state, our wells were relatively homogenous. For instance, most of the observed well depths in our study were 18 to 50 meters, with only one well deeper than 100 meters (see Supplemental Figure S1). The other well construction factor explored in our model was well casing diameter, which was found to have no statistically significant relationship with nitrate concentration.

Of the variables tested, nitrogen application rate was the largest driver of nitrate concentration in irrigation water, with higher levels of nitrogen application rates corresponding to higher nitrate levels in irrigation water (see Supplemental Figure S3). This finding is supported by previous research which have observed a significant relationship between land cover or agricultural intensity and nitrate concentration (Almasri and Kaluarachchi, 2004; Gardner and Vogel, 2005; Benson et al., 2006; Chaudhuri et al., 2012; Wheeler et al., 2015). Specifically, a study conducted in a similarly agriculturally dominated watershed found that high levels of nitrate were related to both high levels of recharge and high levels of on-ground nitrate loading (Almasri and Kaluarachchi, 2004). However, past studies conducted in regions with sandy soil and intensive agricultural land use have demonstrated differing findings (McLay et al., 2001) pointing to the idea that site-specific factors (management, hydrogeology, soil characteristics) may override overall land-cover impacts in some cases.

While temporal variability in our study was lower than spatial variability, it was still present. Variability in annual precipitation may be driving these results. Higher rates of rainfall are often associated with greater nitrate leaching, however, increases in precipitation also dilute nitrate concentration in groundwater (Boumans et al., 2001; Wick et al., 2012). The Hancock

Agriculture Research Weather Station, located in the center of our region of study measured 46 cm, 57 cm, and 44 cm of rainfall for the 2018, 2019, and 2020 growing season respectively. The year of highest rainfall, 2019, also correlates with the lowest year of average nitrate concentration, which is supported by past research studies (Wick et al., 2012). Additionally, 2019 also had the greatest variability in nitrate concentration as measured by CV. Considering our passive system of collecting irrigation water involved back calculating based on measured rainfall, our calculations of nitrate concentration were more sensitive to changes in rainfall than other approaches.

1.4.4 Average nitrate in irrigation water in the WCS provides approximately 20% of overall N fertilizer recommendations

The majority of the wells sampled in our study tested above the EPA threshold for safe drinking water of 10 mg L^{-1} nitrate-nitrogen. While this number clearly indicates unsafe drinking water, it has less meaning when thinking about nutrient management plans and N fertilizer applications. To determine how much plant available N is being applied through irrigation water, a simple calculation can be done (Delaune and Trostle, 2012). A grower must estimate the average amount of inches of irrigation applied during a growing season, as well as the N concentration of the specific well they are using to irrigate. Once analyzed, NO_3-N levels are typically reported in values of mg L^{-1} or ppm of nitrogen, which then can be converted to lbs. per inch of irrigation water by multiplying by 0.226. The resulting value multiplied by annual centimeters of irrigation estimates the nitrogen applied through irrigation water (expressed as kg of nitrogen per ha, N kg ha^{-1}).

$$kg\ of\ N\ per\ ha = NO3 - N\ \left(\frac{mg}{L}\ or\ ppm\right) * \ 0.226\ * \frac{cm\ of\ irrigation\ applied}{2.54} * 1.12\ kg/ha \quad (1)$$

Depending on the crop being grown and the amount of irrigation occurring in each growing season, the amount of N in irrigation water may account for a substantial portion of the required N inputs for that crop. For instance, corn grown in the WCS typically receives a recommended N fertilizer application of 224 kg N ha^{-1}. If we assume a grower is adding 25.4 cm (or 10 inches) of supplemental irrigation during a growing season, and the irrigation water has a concentration of 19 mg L^{-1} nitrate-nitrogen, the grower is then adding approximately 48.5 N kg ha^{-1} through irrigation water, or 20% of the total nitrogen inputs required by corn. Alternatively, if we assume less irrigation is applied because of crop water needs or increased rainfall, and as a result, a grower irrigates 12.7 cm (or 5 inches), substantially less N is supplied through irrigation water at 24.25 N kg ha^{-1} (or approximately 10% of the total nitrogen inputs required for corn).

1.4.5 Limitations

Our study aims to quantify the spatiotemporal variability of nitrate levels in irrigation water across the Wisconsin Central Sands. We chose to collect water samples passively using deployed water collection systems across fields in the region. This technique was easily replicable, cost-effective, and required little time investment from growers. This allowed for sample collection from roughly ~36 fields weekly during the growing season, a quantity and spatial scale that otherwise would not have been possible. However, our passive system of collection allows for more errors than sampling from a well directly. Most notably, the passive system of collection collects any form of precipitation falling in the field – including rainwater, irrigation water, and liquid fertilizer. Though rainfall was measured separately at each farm to allow for accounting of any rainfall, localized rainfall events were an additional challenge.

In our mixed effects model, the variables analyzed included well depth, well casing, land cover, week of sample collection, and year of sampling. We recognize this is not a complete list of factors that would explain variability in nitrate concentration. Specifically, incorporating a groundwater flow model would be useful, though outside the scope of our study.

1.5 Conclusions

This study provides growers with added knowledge to develop more efficient nitrogen management plans. If growers were to begin accounting for the nitrate credits that can be attributed to irrigation water for each field, they could reduce fertilizer use and cost, and limit further groundwater contamination from excess nitrogen application. Crediting, or accounting for nitrate, can be quickly implemented without changes in agricultural infrastructure and offers an option to mitigate groundwater contamination within the current system of agriculture. Furthermore, as policy makers begin considering how to address groundwater contamination, farmers may face increasing pressure to tackle groundwater quality challenges, and every potential tool to reduce nitrate loss from agroecosystems should be considered. Our research demonstrates that across the WCS, nitrate levels in irrigation water are substantial and need to be considered in nitrogen management plans. Additionally, as climate change continues to increase the frequency of extreme rainfall events, improved nitrogen management will become more challenging. Considering the wide spatial variability present in our data, we advise against any broad quantitative blanket recommendations for crediting of N in irrigation water. Instead, we suggest growers test the nitrate concentration of each well used for irrigation and base their crediting on individual well samples. Considering the low temporal variability in nitrate concentration, our data suggests that wells may only need to be tested annually or biannually.

1.6 Acknowledgements

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1.8 Tables and Figures

Table 1. Approach and equations used to calculate nitrate-nitrogen [mg L^{-1}] present in irrigation water samples containing rainwater.

Variable	*Metric of Measurement or Calculation*
Total Volume [ml]	Total volume of liquid measured from each in-field collection container
Sample NO_3-N [mg L^{-1}]	Measured concentration of NO_3-N taken from a X ml subset of total volume
Sample NO_3-N [kg ha^{-1}]	$\frac{Total\ Volume\ [ml] \times Sample\ NO_3N\ \left[\frac{mg}{L}\right] \times (1 \times 10^8)}{(1 \times 10^9) \times 78.5 \times 2.54 \times 2.54}$
Rainfall Volume [ml]	Volume of rainfall measured in off-field precipitation container
Irrigation Volume [ml]	$Total\ Volume\ [ml] - Rainfall\ Volume\ [ml]$
Irrigation NO_3-N [kg ha^{-1}]	$Sample\ NO_3N\ \left[\frac{kg}{ha}\right] - Rainfall\ NO_3N\ [\frac{kg}{ha}]$
Irrigation NO_3-N [mg L^{-1}]	$\frac{Irrigation\ NO_3N\ \left[\frac{kg}{ha}\right] \times\ 5.0645\ surface\ area\ constant}{Irrigation\ Volume\ \times 1000}$

Table 2. Annual farm level spatial variability vs. well level within season temporal variability during the 2018, 2019 and 2020 growing season. Bolded numbers indicate farm level spatial variability for each year. Individual well data at each farm are denoted by capital letters A-F.

		2018				2019				2020			
Farm	**Well**	**Mean**	**CV**	**Min**	**Max**	**Mean**	**CV**	**Min**	**Max**	**Mean**	**CV**	**Min**	**Max**
Farm 1		**24.06**	**0.20**	**16.60**	**36.50**	**26.50**	**0.30**	**7.85**	**40.08**	**25.00**	**0.34**	**8.66**	**39.96**
Farm 1	A	19.60	0.07	18.30	20.90	22.11	0.40	7.85	37.11	18.55	0.06	16.96	20.04
Farm 1	B	23.58	0.11	20.80	26.70	27.07	0.20	17.28	31.41	27.36	0.29	14.71	36.58
Farm 1	C					21.28	0.65	9.82	36.50	14.18	0.24	8.66	17.14
Farm 1	D	31.48	0.12	28.40	36.50								
Farm 1	E	20.90	0.29	16.60	25.20	24.73	0.18	18.05	31.05	24.14	0.16	20.09	30.40
Farm 1	F	21.85	0.13	18.60	24.90	32.85	0.17	24.60	38.31	28.33	0.26	23.19	33.47
Farm 1	G	24.33	0.10	21.90	26.60								
Farm 1	H					31.61	0.29	22.09	40.08	36.68	0.06	33.45	39.96
Farm 2		**15.07**	**0.32**	**7.60**	**25.90**	**17.55**	**0.41**	**6.68**	**31.16**	**20.07**	**0.36**	**6.94**	**32.79**

Farm 2	A	9.02	0.14	7.60	10.50	8.49	0.19	6.68	10.89	9.44	0.17	7.65	10.84
Farm 2	B	15.38	0.14	13.10	17.90	13.64	0.15	10.21	17.10	15.02	0.23	10.24	22.44
Farm 2	C	10.80	0.04	10.40	11.30	12.32	0.19	8.48	13.96	11.27	0.54	6.94	15.60
Farm 2	D	21.80	0.18	16.30	25.90	27.07	0.12	23.29	31.16	25.71	0.23	12.82	32.56
Farm 2	E	17.68	0.04	17.10	18.50	24.15	0.09	22.01	27.45	24.41	0.22	15.41	32.79
Farm 2	F	16.20	0.11	13.90	18.00	18.89	0.17	14.79	24.42	20.17	0.15	15.29	24.21
Farm 3		**19.94**	**0.16**	**14.00**	**25.10**	**19.93**	**0.31**	**9.27**	**29.78**	**17.98**	**0.26**	**7.73**	**27.10**
Farm 3	A	22.87	0.10	20.60	25.10	18.01	0.32	12.45	23.86				
Farm 3	B	16.63	0.09	14.00	19.00	17.50	0.34	9.27	29.51	15.39	0.27	7.73	21.60
Farm 3	C	20.43	0.08	18.80	23.20	23.76	0.12	19.95	27.13	19.60	0.20	11.20	27.10
Farm 3	D	22.24	0.13	18.20	24.30	29.78	NA	29.78	29.78	22.99	0.14	17.70	26.40
Farm 4		**15.93**	**0.56**	**4.70**	**30.00**	**14.26**	**0.65**	**2.09**	**33.23**				
Farm 4	A	29.61	0.13	23.05	33.23								
Farm 4	B	15.60	0.26	10.60	20.60	15.59	0.17	12.34	20.73				
Farm 4	C	28.35	0.08	26.70	30.00								
Farm 4	D	12.25	0.13	11.10	13.40								
Farm 4	E	26.37	0.09	24.00	28.60								
Farm 4	F	6.42	0.26	4.70	8.70	6.30	0.38	2.70	9.11				
Farm 4	G					8.72	0.37	6.08	14.89				
Farm 4	H					7.41	1.02	2.09	12.73				
Farm 5						**15.18**	**0.71**	**2.23**	**38.34**	**18.39**	**0.74**	**2.12**	**44.79**
Farm 5	A					5.00	0.67	2.23	8.71	7.13	0.15	5.96	8.64
Farm 5	B					9.53	0.16	7.63	11.28	14.39	0.29	10.91	20.47
Farm 5	C					4.73	0.42	2.65	6.60	3.51	0.21	2.12	4.22
Farm 5	D					32.40	0.10	27.67	34.86	30.25	0.35	12.39	41.96
Farm 5	E					15.12	0.19	10.47	19.20	13.34	0.46	7.15	25.71
Farm 5	F					31.67	0.30	25.01	38.34	37.23	0.16	29.71	44.79
Farm 6						**14.44**	**0.70**	**0.92**	**33.00**	**14.67**	**0.51**	**2.63**	**27.50**
Farm 6	A					24.62	0.53	9.50	33.00	20.15	0.52	12.80	27.50
Farm 6	B					19.15	0.30	14.02	27.11	25.79	NA	25.79	25.79
Farm 6	C					5.29	0.34	3.21	6.39	10.67	0.47	2.88	15.55
Farm 6	D					8.40	0.50	1.25	12.95	16.49	0.03	15.92	17.07
Farm 6	E					24.96	0.13	21.65	27.95	20.16	0.42	10.69	27.09
Farm 6	F					1.08	0.21	0.92	1.24	6.05	0.51	2.63	8.55

Table 3. Interannual temporal well level variability (denoted by capital letters A-F) vs. farm level spatial variability. Bolded numbers indicate farm level spatial variability calculated over the combined 3 years of the study.

Farm	Well	Mean	CV	Min	Max
		25.33	**0.30**	**7.85**	**40.08**
Farm 1	A	20.42	0.30	7.85	37.11

Farm 1	B	26.37	0.23	14.71	36.58
Farm 1	C	16.84	0.51	8.66	36.50
Farm 1	D	31.48	0.12	28.40	36.50
Farm 1	E	23.96	0.17	16.60	31.05
Farm 1	F	28.43	0.24	18.60	38.31
Farm 1	G	24.33	0.10	21.90	26.60
Farm 1	H	34.99	0.16	22.09	40.08
		18.04	**0.38**	**6.68**	**32.79**
Farm 2	A	8.89	0.16	6.68	10.89
Farm 2	B	14.58	0.19	10.21	22.44
Farm 2	C	11.65	0.23	6.94	15.60
Farm 2	D	25.43	0.20	12.82	32.56
Farm 2	E	23.10	0.21	15.41	32.79
Farm 2	F	18.78	0.17	13.90	24.42
		18.93	**0.25**	**7.73**	**29.78**
Farm 3	A	20.44	0.23	12.45	25.10
Farm 3	B	16.14	0.27	7.73	29.51
Farm 3	C	20.46	0.18	11.20	27.13
Farm 3	D	23.27	0.15	17.70	29.78
		14.85	**0.61**	**2.09**	**33.23**
Farm 4	A	29.61	0.13	23.05	33.23
Farm 4	B	15.59	0.19	10.60	20.73
Farm 4	C	28.35	0.08	26.70	30.00
Farm 4	D	12.25	0.13	11.10	13.40
Farm 4	E	26.37	0.09	24.00	28.60
Farm 4	F	6.35	0.32	2.70	9.11
Farm 4	G	8.72	0.37	6.08	14.89
Farm 4	H	7.41	1.02	2.09	12.73
		17.10	**0.73**	**2.12**	**44.79**
Farm 5	A	6.33	0.36	2.23	8.71
Farm 5	B	11.55	0.32	7.63	20.47
Farm 5	C	3.92	0.33	2.12	6.60
Farm 5	D	30.91	0.28	12.39	41.96
Farm 5	E	14.17	0.34	7.15	25.71
Farm 5	F	35.64	0.19	25.01	44.79
		14.54	**0.61**	**0.92**	**33.00**
Farm 6	A	22.83	0.48	9.50	33.00
Farm 6	B	20.10	0.29	14.02	27.11
Farm 6	C	8.65	0.55	2.88	15.55

Farm 6	D	11.64	0.45	1.25	17.07
Farm 6	E	22.56	0.28	10.69	27.95
Farm 6	F	4.06	0.86	0.92	8.55

Table 4. ANOVA table of linear mixed effects model

	Sum sq	Mean sq	Num DF	Den DF	F value	Pr(>F)
Well Depth	0.13	0.13	1	24.17	1.15	0.29
Well Casing	0.27	0.13	2	25.07	1.21	0.32
Nitrogen Application	0.51	0.51	1	25.29	4.58	0.04*
Year	0.35	0.18	2	337.02	1.57	0.21
Week	0.30	0.30	1	332.53	2.69	0.10

*Significant at the .05 probability level. **Significant at the .01 probability level. ***Significant at the .001 probability level.

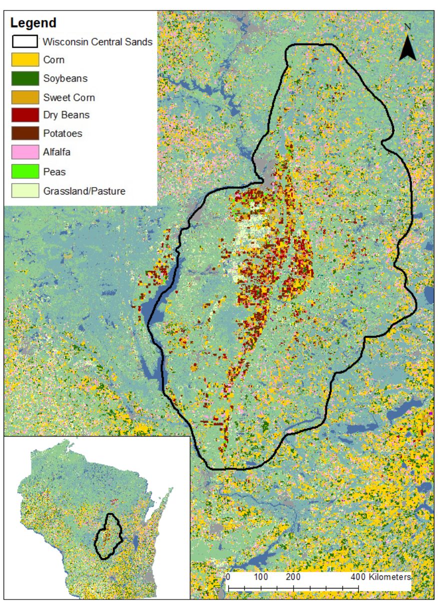

Figure 1. Common cropping systems of the Wisconsin Central Sands.

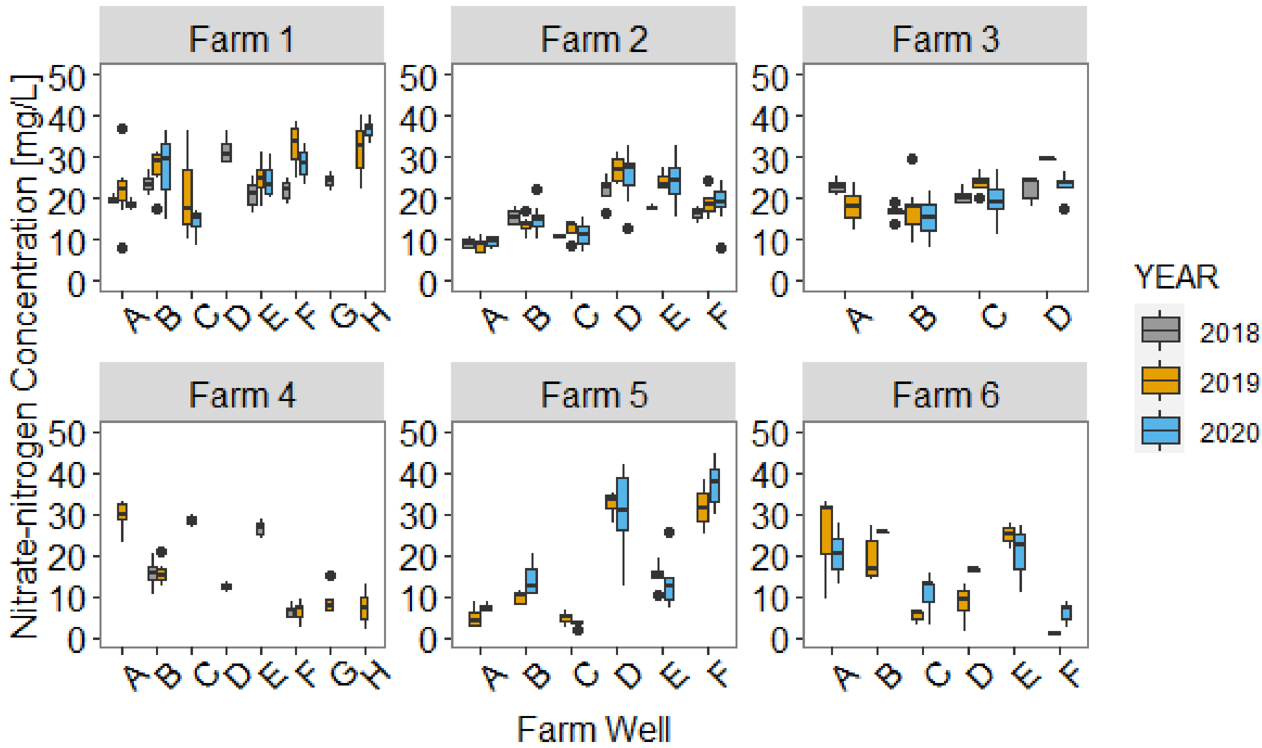

Figure 2. Nitrate-nitrogen concentration [mg L^{-1}] for each well measured in the 2018, 2019, and 2020 growing season. Year is indicated by color, and farm is indicated by panel.

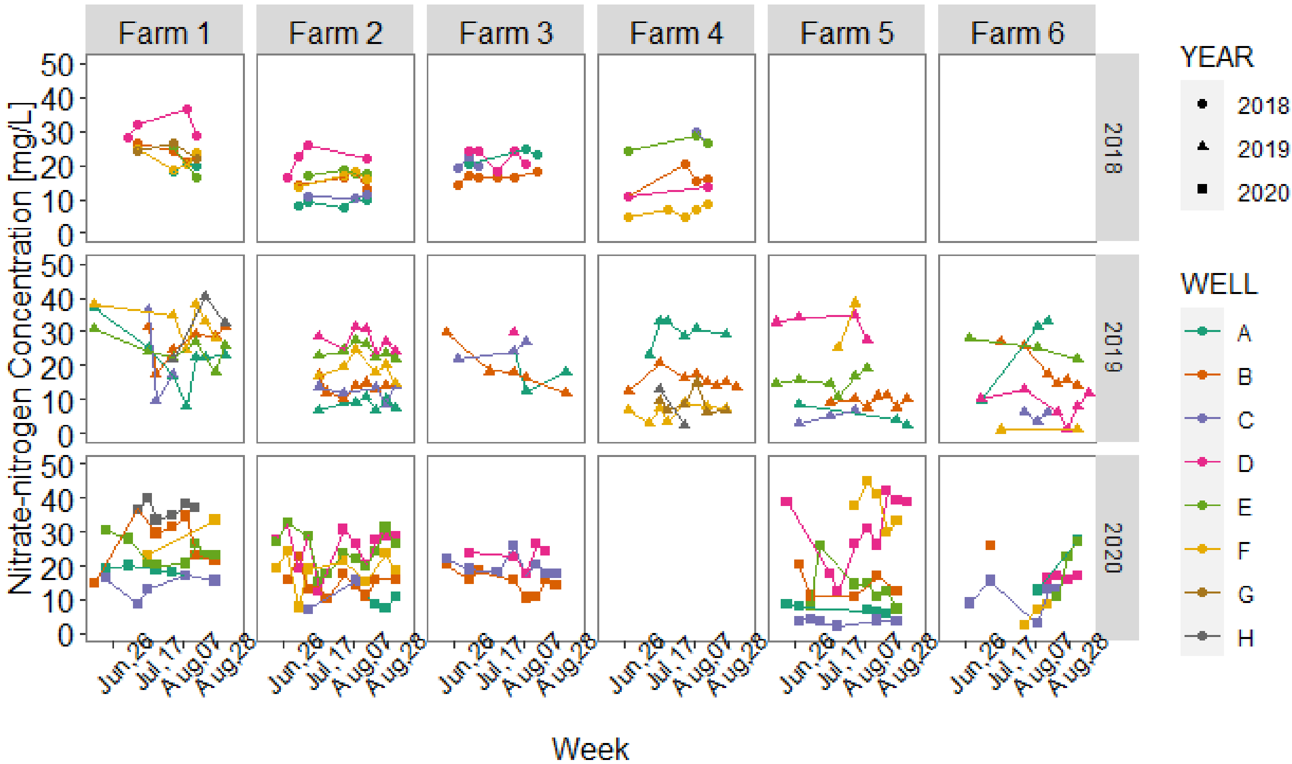

Figure 3. Nitrate-nitrogen concentration [mg L^{-1}] throughout each growing season. Shape of point indicates year, and color of line indicates field.

1.9 Supplemental Material

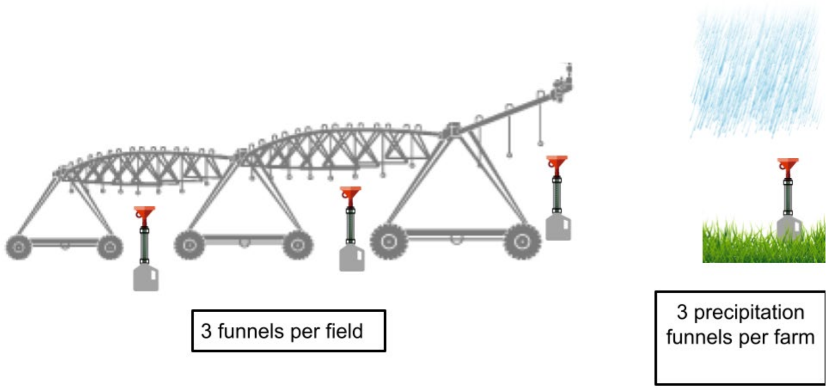

Figure S1. Passive funnel system used to collect irrigation water from a center pivot irrigation system in conjunction with rainfall measurements.

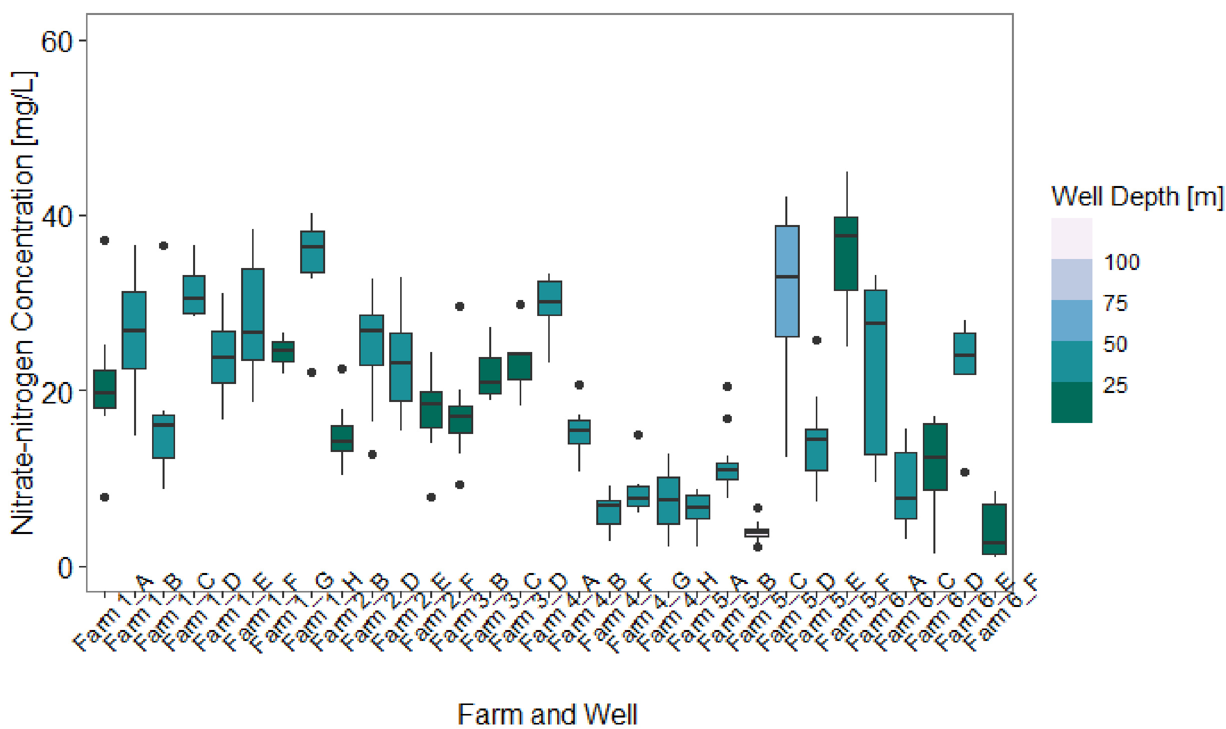

Figure S2. Boxplot of well depth [m] and nitrate-nitrogen concentration [mg L^{-1}] for wells in the study.

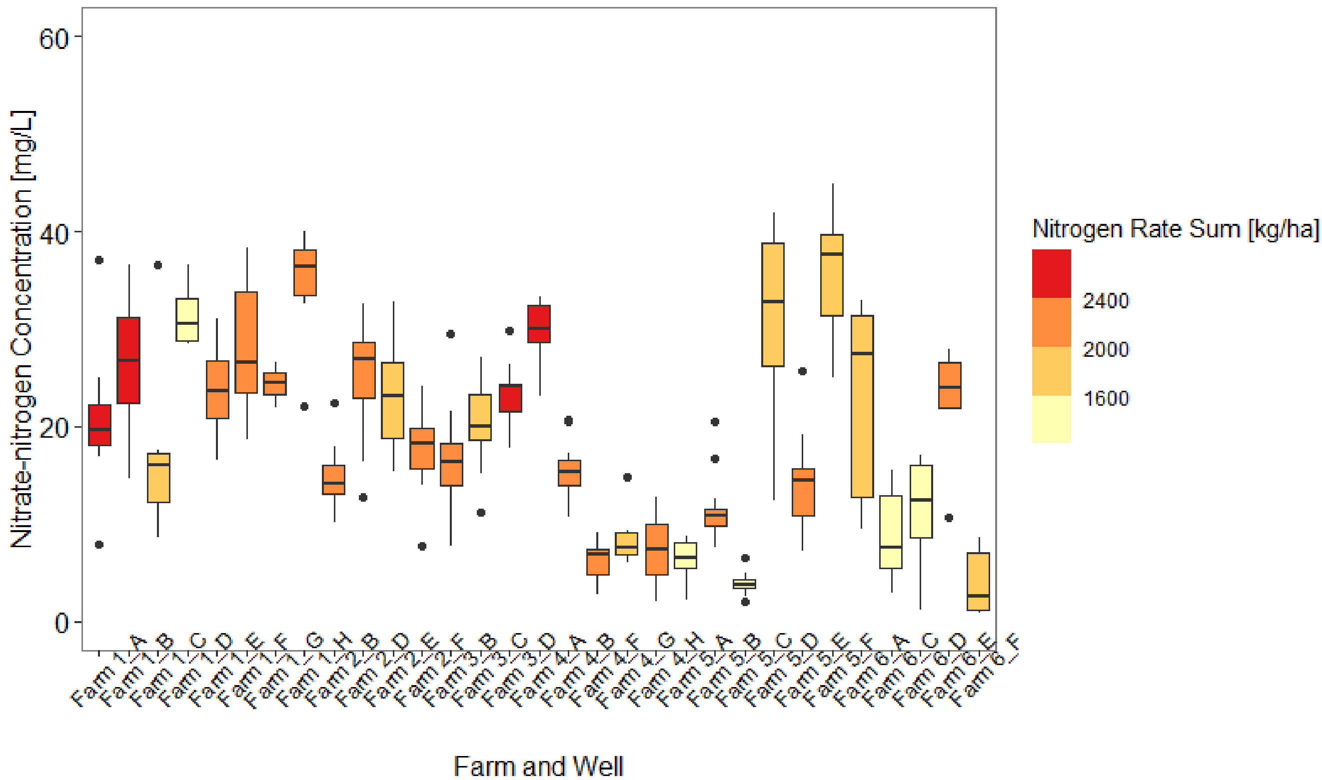

Figure S3. Nitrate-nitrogen concentration [mg L^{-1}] and the sum of nitrogen applied [kg ha^{-1}] to each well area from 2008-2020.

Table S1. Crop(s) grown on each field sampled during the 2018, 2019, and 2020 growing season.

		2018		2019		2020	
Farm	**Well**	**Crop(s)**	**Samples (#)**	**Crop(s)**	**Samples (#)**	**Crop(s)**	**Samples (#)**
Farm 1	A	Field Corn	3	Soybean	7	Potato	8
Farm 1	B	Field Corn	4	Soybean	6	Potato	6
Farm 1	C			Potato	4	Green Bean, Alfalfa	6
Farm 1	D	Soybean	4				
Farm 1	E	Field Corn	2	Field Corn	7	Potato	7
Farm 1	F	Soybean	5	Potato	8	Green Bean, Alfalfa	3
Farm 1	G	Field Corn	3				
Farm 1	H				4	Soybean	4
Farm 2	A	Corn	5	Soybean	8	Soybean	9

Farm 2	B	Corn	4	Soybean	8	Soybean	11
Farm 2	C	Corn	4	Soybean	6	Soybean	9
Farm 2	D	Corn	3	Soybean	7	Soybean	12
Farm 2	E	Corn	4	Soybean	7	Soybean	9
Farm 2	F	Corn	4	Soybean	6	Soybean	10
Farm 3	A	Potato	3	Field Corn	4		
Farm 3	B	Corn	7	Peas	9		20
Farm 3	C	Peas	6	Potato	4		15
Farm 3	D	Sweet Corn	4	Potato	1		5
Farm 4	A			Soybean	7		
Farm 4	B	Forage Corn	4	Soybean	8		
Farm 4	C	Forage Corn	2				
Farm 4	D	Forage Corn	2				
Farm 4	E	Forage Corn	3				
Farm 4	F	Forage Corn	5	Soybean	7		
Farm 4	G			Soybean	6		
Farm 4	H			Edible Bean	2		
Farm 5	A			Peas, Edible Bean	3	Potato	8
Farm 5	B			Seed Corn	7	Peas, Green Bean	5
Farm 5	C			Potato	4	Cabbage	7
Farm 5	D			Potato	5	Help, Strawberry, Soybean	9
Farm 5	E			Peas, Cabbage	5	Alfalfa	4
Farm 5	F			Potato	5	Corn	6
Farm 6	A			Beets	2	Sweet Corn	2
Farm 6	B			Soybean	7	Peas	2
Farm 6	C			Edible Been	5	Sweet Corn	5
Farm 6	D			Field Corn	6	Gren Bean	4
Farm 6	E			Carrots	6	Sweet Corn	3
Farm 6	F			Field Corn	3	Sweet Corn	3

Table S2. Variability at the year level for the 2018, 2019, and 2020 growing seasons.

Year	Mean	CV	Min	Max
2018	18.72	0.35	4.70	36.50
2019	18.09	0.53	0.92	40.08
2020	19.62	0.47	2.12	44.79

Chapter 2: Effect of nitrogen rate and environmental variables on the ecophysiological response of field grown potatoes

Abstract

Understanding the ecophysiological responses of potato (*Solanum tuberosum* L.) to a range of environmental conditions will aid in more efficient management strategies that address both water quantity and water quality challenges. While end of season biomass is a useful measurement, it overlooks the plant physiological changes that occur in response to dynamic environmental conditions. Furthermore, climate change will increase weather variability, highlighting the need to measure potato physiology at multiple points throughout a growing season to evaluate the impact of increased variability. To determine how photosynthetic rate in potato cropping systems varies across different nitrogen rate treatments (44.8, 269, 336.3, 403.5 kg N/ha), leaf level gas exchange measurements were collected throughout the 2020 growing season, including light response curves, CO_2 response curves (e.g., assimilation (A) vs. internal CO_2 (Ci)), and diurnal measurements. A-Ci curves were fit to determine Vcmax (the maximum rate of carboxylation) and Jmax (the maximum rate of electron transport). We found that Vcmax increased with increasing nitrogen application rates up to ~403.5 kg N/ha, but then both leaf N concentration and leaf photosynthetic rate declined. Additionally, we found that nitrogen application rate, leaf temperature, and days after emergence (DAE) were significant predictors of Vcmax. Our findings illustrate potential drivers of photosynthetic rate in potato plants, while also indicating that high nitrogen application rates may not increase photosynthesis; this information can help inform improved nitrogen management strategies for potato cropping systems.

2.1 Introduction

Maintaining efficient potato (*Solanum tuberosum* L.) production systems are regionally and globally important for both economic revenue and for providing energy dense food for human consumption. Global potato production is widespread, with 100 countries producing potatoes and a total of 368 million tons of potatoes produced globally in 2018 (FAO 2020). Compared to other major crops, potato production contributes to more food calories per unit of land area (FAO, 2008). Additionally, potato production contributed ~$101 billion to the US economy in 2021 (Miller and Knudson, 2023). While providing economic revenue and food for consumption, potato production is resource intensive. Potatoes are grown in well-drained soil to reduce disease (Fiers et al., 2012) and reduce compaction (Stark et al., 2020) and are characterized by their shallow rooting system (Stark and Westermann, 2003). In combination with their shallow rooting system (Corey and Blake, 1953; Durrant et al., 1973; Shock et al., 2007) and often coarse textured soil and sensitivity to soil moisture (Stark et al., 2020), potato cropping systems are more susceptible to water stress, and as result, require frequent irrigation (Tanner et al., 1982; Stark and Love, 2003; Shock et al., 2007). In part due to their soil and rooting properties, potatoes also have high nitrogen requirements to support high yield potential (Lesczynski and Tanner, 1976; Saffigna et al., 1976). Adding to the challenge, potatoes typically have low nitrogen use efficiency, with 50 to 60% of the nitrogen applied never taken up by the plant (Stark and Westermann, 2003), leading to nitrogen losses to the environment. High nitrogen requirements combined with the low water holding capacity of the soil, shallow rooting system, frequent irrigation, and extreme rainfall have resulted in N contamination of the groundwater.

Managing nitrogen effectively in potato production is not only critical for water quality concerns, but also due to impacts on vine and tuber biomass production, tuber size grade, specific gravity, and internal and external tuber quality (Millard and MaCkerron, 1986; Dwelle, 2003; Stark and Westermann, 2003). Following the plant establishment growth stage, aboveground vines and belowground tubers often are forced to compete for limited nutrient resources. Nitrogen availability can alter the timing of growth stages by influencing the ratio of the vine growth promoter, gibberellic acid (GA), and vine growth inhibitor, abscisic acid (ABA) (Stark and Westermann, 2003). There is uncertainty surrounding the ecophysiological response of potato to changes in nitrogen fertilizer application rates under dynamic environmental conditions. While past research has determined that nitrogen application rate influences both nitrogen uptake and potato yield (Extension,; Vos, 1997; Stark and Westermann, 2003), less is known about the impact of nitrogen rate on leaf-level potato ecophysiology that controls N and water use (Raymundo et al., 2014).

For photosynthesis to occur, plants require CO2, water, and light to transform energy from the sun into chemical energy. In addition, nitrogen is an essential nutrient required for plant growth. Nitrogen is a key component of the proteins and enzymes required for photosynthesis, such as Rubisco (Lu et al. 2022), and influences leaf structure and nitrogen allocation. However, previous research has demonstrated little relationship between leaf level photosynthetic rate and applied N (Firman and Allen, 1988) and N concentration (Marshall and Vos, 1991; Vos and Van Der Putten, 1998). Rather, Vos proposed that potatoes may maintain constant productivity per unit leaf area by adjusting leaf size and branching (Vos, 2009) while Olesinski et al. (1989) demonstrated that increasing N fertilizer boosted photosynthesis. Generally, past research on the relationship between photosynthetic rate and N fertilizer application amount have been conducted under full sun and saturated light, not considering how physiological response may change under a range of future CO_2 concentrations and varying light intensities. However, research on potato's physiological response to climate change has increased, including studies of elevated CO_2 (Miglietta et al., 1998; Schapendonk et al., 2000; Fleisher et al., 2008a; b, 2014; Kaminski et al., 2013); however, these studies have often not included varied N fertilizer treatments or multiple cultivars.

Measurements of photosynthesis and the drivers of photosynthesis can support improved nitrogen management strategies, plan for ongoing and future climate change, and provide a crucial addition to crop yield focused approaches. Vcmax (the maximum rate of carboxylation) and Jmax (the maximum rate of electron transport), serve as the key parameters defining photosynthetic capacity (Walker et al., 2014). Understanding how these key parameters change in response to environmental conditions, nitrogen application rate, and growth stage is imperative for understanding leaf level photosynthesis. One way to limit the amount of nitrogen lost to the environment is to increase the amount of nitrogen being taken up by the plant or increase the nitrogen use efficiency (NUE). To do so, measurements of leaf level N concentrations help indicate whether the nitrogen applied as fertilizer is being used efficiently by the plant. Additionally, one way to determine the influence of nitrogen application rate on plant productivity is through measures of leaf-level photosynthesis, which indicates the rate that CO_2 is assimilating in the plant, and Vcmax and Jmax which constrain the maximum rates of photosynthesis. Not only can information at the leaf level scale up to understand photosynthesis, carbon fluxes, and corresponding crop yield at a larger level, understanding the response of Vcmax to environmental drivers and nutrient management can help increase potato production and improve NUE.

Moving forward, it is essential for potato management to consider both water quantity and water quality challenges, while adapting to a changing climate. To do so, it is necessary to understand the ecophysiological response of potatoes to both management and environmental changes. As the climate continues to change, understanding the ecophysiological response of potatoes under a range of conditions, such as extreme heat and an increase in nighttime temperatures, will be imperative for mitigating and responding to potential yield declines and increased risk for nitrate leaching losses and groundwater quality contamination. By understanding leaf-level changes in photosynthesis and its key parameters, land managers can fine tune nitrogen management strategies to reduce the amount of nitrogen lost to the environment.

The overarching goal of this research was to examine the ecophysiological response of field grown potatoes to varied N fertilizer applications under varied environmental conditions. As the temperature continues to rise and rainfall becomes more extreme, potatoes will likely experience increased heat and water stress, resulting in changes in potato ecophysiology. Additionally, as growing season changes occur in response to environmental drivers and plant growth stage, these ecophysiological changes are likely to vary across the growing season.

2.2 Methods

2.2.1 Study Site

We conducted field research in the Wisconsin Central Sands (WCS), an important US potato production region characterized by sandy soils, thousands of high capacity wells and center pivot irrigation systems, and a shallow water table. Specifically, we quantified how leaf level photosynthetic rate and Vcmax responded to a range of nitrogen fertilizer application treatments for two market classes/varieties of potato. Field trials to study potato variety response to N and water management (led by Prof. Yi Wang, UW-Madison) were carried out in outdoor experimental plots at the University of Wisconsin's Hancock Agricultural Research Station, located near Hancock, Wisconsin (44.120ºN, -89.540ºW; elevation, 328 m). We collected data during the 2020 field season as part of the N rate portion of the ongoing experiment, where varied amounts of N fertilizer (Table 1) were added at different phenological stages to span a range of total N that potato received during the entire growing season. Nitrogen was applied at planting, emergence (hilling), tuber initiation, early bulking and during mid bulking stages. Aside from the nitrogen applied as starter and at hilling, N was applied through side-dressing use dry fertilizer on each side of the potato hills (Wang et al., 2022). The experiment took place on loamy sand, with 85% sand, 8% silt, 7% clay, and 0.8% organic matter. The region is classified moist continental climate (Arguez et al., 2010; Nocco et al., 2018). Over the past three decades (1991-2020), the average high and low temperatures during summer (Jun-Aug) were 26ºC and 14ºC respectively, accompanied by 335 mm of rainfall as reported by the National Oceanic & Atmospheric Administration (2010) and 94 to 376 mm of supplemental irrigation is typically applied (Nocco et al., 2019). Over the last seventy years, climate change has contributed to a 15-20% increase in summer rainfall and a 2.5ºC rise in annual minimum and maximum temperature, (WICCI, 2021). Projections indicate that climate change will lead to further increased nighttime minimum temperatures, more frequent hot days (above 32ºC), and an increased frequency of extreme rainfall events (Wisconsin Initiative on Climate Change Impacts, 2021).

Potatoes were planted on May 1st, 2020, in a split-plot design and nitrogen rates were randomized for each plot. Emergence occurred approximately four weeks after planting on May

21st, 2020. All subplots contained eight 6-m long x 0.9-m wide rows. Guard rows were planted to prevent possible contamination between plots. For more details on the experimental design and field layout see Wang. et al (2022).

According to the University of Wisconsin Extension recommendations, potatoes produced in the WCS should receive 246 to 280 kg N/ha for yields ranging between 451 hundredweight (cwt) and 650 cwt (Laboski et al., 2012). As a result, nitrogen rate treatments reflect low, recommended, and high application rates. For each nitrogen rate trial, two varieties of potato, Hodag and W9433 (recently named Lakeview Russet), were studied. Hodag is commonly used for chip production in the processing market, while W9433 is a recently developed Russet variety that can be used for fresh market. Irrigation, pesticide and vine desiccant application were based on the University of Wisconsin Extension recommendations (Bradford et al., 2023). Based on University of Wisconsin Extension guidelines, it is recommended that potatoes are irrigated when 35-40% of the total available water has been depleted, using an effective rooting depth of 18 inches (Curwen and Massie, 1984, ?; Sanford and Panuska, 2015). Using these recommendations, potatoes are typically irrigated every other day during the middle of the growing season during tuber bulking.

2.2.2 Gas exchange measurements

Leaf level gas exchange measurements were taken using a LI-COR 6400xt portable gas exchange analyzer (LICOR Inc., Lincoln, Nebraska, USA). Two instruments were used to take gas exchange measurements, with both operating simultaneously, to increase the number of measurements taken. The portable system consists of an infrared gas analyzer, leaf chamber, and computer console, allowing for the control of light intensity, temperature, flow rate, relative humidity, and CO_2 concentration. To measure photosynthesis and transpiration, an open system approach was taken, calculating photosynthesis and transpiration based on the differences in CO_2 and H_2O concentrations in in-chamber and pre-chamber air streams. Conceptually, the rate of photosynthesis is measured as the difference between photosynthetic carbon assimilation and the CO_2 that is lost during mitochondrial respiration, and the following equations were used in measurement calculations. See LI-COR 6400 user manual for more information (LI-COR Biosiences,).

Plant physiological and accompanying soil moisture data were collected during the 2020 growing season across the four N experimental trials (Table 2). Data collection focused on three ecophysiological components: light response curves, CO_2 response curves (A-Ci), and survey measurements. Ecophysiological measurements began 28 days after emergence, during tuber initiation. Light response curves were taken in stepwise increments from 0 to 2000 micromoles quanta m^{-2} s^{-1} photosynthetic active radiation (PAR) and CO_2 response curves ranged from 0 to 1200 ppm CO_2, also in stepwise increments. Response curves were taken between 10 am and 4 pm local time, and for each leaf sampled, both a light and CO_2 response curve were performed. Leaves served as replicates, and for each nitrogen application rate, at least 7 leaves were sampled (see Table 4). All gas exchange measurements were performed at the top of the canopy, using the second fully expanded leaflet. During the 2020 growing season, the majority of response curves were taken near an air temperature of 25°C; but leaf temperature was dictated by the ambient environmental conditions and curves were ultimately captured at leaf temperatures ranging from 22 to 35°C. During measurements, relative humidity was maintained between 40-70%. Three concurrent soil moisture measurements (volumetric water content) to a depth of 60mm were taken at the time of gas exchange measurements for each plant using a Delta-T soil moisture sensor (Delta-T Devices Ltd., Cambridge U.K.).

On two clear days during the growing season (July 27th and August 11th, 2020), survey photosynthesis measurements were taken to provide an instantaneous measurement of the current rate of photosynthesis under ambient environmental conditions. Survey measurements were collected from sunrise (~5:45 am) to sunset (~8:45 pm). All diurnal survey measurements occurred after all nitrogen fertilizer had been applied for each respective treatment. As a result, three nitrogen treatments were measured hourly: 44.8, 269, and 403.5 kg N/ha, and five leaves in each treatment were measured at each hour, with leaves, rather than blocks, serving as replicates due to time constraints. In total, 430 photosynthesis measurements were taken for each day of survey measurements. Photosynthesis measurements were taken on the second fully expanded leaf at the top of the canopy.

2.2.3 Leaf C and N concentration

Following photosynthetic rate measurements of response curves, each leaf was collected for nitrogen content analysis and dried at 80ºC for 24h. After drying, samples of at least 8-10 mg of leaf dry matter were ground and analyzed for total C and N via combustion at 900 degrees Celsius using a Flash EA 1112 CN Automatic Elemental Analyzer (Thermo Finnigan, Milan, Italy). Due to possible contamination during analysis, in which a portion of sample lids were not securely fastened during grinding, approximately 50% of leaves analyzed for leaf N concentration had to be excluded.

2.2.4 Data Analysis

Analysis was performed using RStudio version 4.0.4, Rstudio Team (2020). Vcmax and Jmax were calculated from A-Ci curves using the plantecophys package (Duursma 2015) based on Farquhar-Berry-von Caemmerer model of leaf photosynthesis (Farquhar 1980). After data cleaning, 80 A-Ci curves were used in analysis. A multiple linear regression model was used to determine predictors of Vcmax. Variables considered were N rate application, potato cultivar, DAE (Days after Emergence), potato growth stage, leaf N content (%), leaf temperature (°C), volumetric soil moisture content (%), and the instrument used for gas exchange measurements. Initial analysis found no significant differences between instruments used in gas exchange measurements, and further analysis excluded instrument as a variable. Considering that both N fertilizer applications and leaf N content are directly related, and only a subset of the data was associated with a leaf N concentration, leaf N concentration was excluded from the model to avoid multicollinearity. Post hoc analysis was completed using the emmeans package (Length, 2023).

2.3 Results

2.3.1 Standardized Vcmax– calculated at 25°C

Our results found the average Vcmax and Jmax for each nitrogen rate trial at a standardized temperature of 25°C to be 71.0, 79.9, 113.6 and 89.2 µmol m^{-2} s^{-1} for the 44.8, 269, 336.3, 403.5 kg N/ha trials, respectively. However, for each N rate trial, Vcmax was highly variable with standard deviations (SD) from 19 to 27 µmol m^{-2} s^{-1}. Subsequent results and analysis presented here will report values of Vcmax at the actual leaf temperature, rather than corrected Vcmax values at 25°C.

2.3.2 Significant predictors of Vcmax

When determining the influence of nitrogen application rate, DAE, cultivar, soil moisture, and temperature on Vcmax, our model had an adjusted R^2 of 0.546, which is consistent with similar studies (Smith 2018). Analysis of Variances (ANOVA) of the multiple linear regression model found N fertilizer application rate, leaf temperature, and DAE to be statistically significant predictors of Vcmax in field grown potatoes (Table 3). Neither cultivar nor soil moisture were found to be statistically significant predictors of Vcmax. While insignificant, surface 0-60mm volumetric moisture content of soil ranged from .05 -16.2%, a range that is mostly realistic for sandy, coarse textured soil and supported by previous studies (Nocco 2017). However, a few measurements fall outside of the expected or reasonable measurement for soil moisture at less than 1% and may indicate less accuracy in soil moisture measurements at low levels.

2.3.3 Impact of Nitrogen

Based on A-Ci curves, calculated Vcmax was 97, 128, 150, and 120 µmol m^{-2} s^{-1} for the 44.8, 269, 336.3, and 403.5 kg N/ha nitrogen rate trials, respectively (Table 4). Our findings demonstrate that Vcmax increases with increasing nitrogen rate application, up until a threshold. Specifically, our results indicate that Vcmax was highest at a nitrogen rate application of 336.3 kg N/ha, before declining at 403.5 kg N/ha (Fig. 1). ANOVA output suggests that when using 40 kg N/ha as a reference or baseline, both 336.3 kg N/ha and 403.5 kg N/ha were significant drivers of Vcmax, and 269 kg N/ha was significant at $p < 0.1$ (Table 3). Nitrogen rate treatments have both a substantial, and statistically significant impact on Vcmax. Specifically, adding 336.3 kg N/ha was associated with a 42 µmol m^{-2} s^{-1} increase in the maximum rate of carboxylation in comparison to a rate of 44.8 kg N/ha. Based on Tukey post hoc analysis, significant differences in average Vcmax existed between the 44.8 kg N/ha and 336.3 kg N/ha nitrogen application treatments (Fig. 1).

While leaf N content was excluded from our multiple linear regression model to avoid multicollinearity, we found leaf N content to be strongly correlated with nitrogen application rate (0.73) based on Pearson's correlation test. For each of the nitrogen rate treatments, the average nitrogen content of sampled leaves was 3.67, 4.98, 5.88, and 5.09 % for the 44.8, 269, 336.3, and 403.5 kg N/ha nitrogen application rates respectively (Table 4; Fig. 2). Similar to nitrogen rate application, the maximum nitrogen concentration in sampled leaves was observed under a nitrogen rate of 336.3 kg N/ha. Leaf N content rose with increasing nitrogen rate applications up to a rate of 336.3 kg N/ha, before declining at 403.5 kg N/ha (Table 4).

2.3.4 Impact of leaf temperature

Leaf temperature was found to have a positive, statistically significant relationship ($p < .001$) with Vcmax (Table 3; Fig. 3), where Vcmax increased by approximately 9 µmol m^{-2} s^{-1} per ºC increase in leaf temperature (Fig. 3). Though initially we sought to measure photosynthetic rates near a consistent leaf temperature of 25°C, ambient environmental conditions and limitations of the Li-Cor 6400 resulted in a wide range of leaf temperatures from 22 °C to 35 °C recorded during gas exchange measurements. While Vcmax measurements taken at 25°C ranged from 32 to 137 µmol m^{-2} s^{-1}, they were also taken across a wide time frame (49 to 91 DAE), and at all nitrogen application rates, which likely explain the large variability (Fig. 3). Our results indicate that Vcmax was strongly influenced by temperature, with 9 out of 10 of the highest Vcmax calculations occurring at a leaf temperature above 30ºC. In the only instance when a temperature above 34 °C did not result in a Vcmax above 200 µmol m^{-2} s^{-1}, soil moisture content was less than 1% and the plant had received a deficient amount of nitrogen. Therefore, our findings may indicate that higher temperatures lead to an increase in Vcmax when water and nitrogen are not limiting.

2.3.5 Impact of DAE/Growth Stage

Based on model interpretation, we found DAE to be a strong predictor of Vcmax, with Vcmax decreasing with continued DAE (Table 3). Gas exchange measurements, and resulting Vcmax calculations, were taken starting 28 days after emergence and continuing to 98 days after emergence. To better visualize the relationship between DAE and growth stage of potato, growth stages were defined as follows: Tuber initiation (15 DAE - 41 DAE), Early Bulking (42 DAE - 57 DAE), Mid Bulking (58 DAE - 88 DAE) and Maturation (89 DAE - 100 DAE). Based on these classifications, the average Vcmax calculated during tuber initiation, early bulking, mid bulking, and maturation was 115, 136, 112, and 60 µmol m^{-2} s^{-1} respectively. These findings highlight the occurrence of a peak in Vcmax during the middle of the growing season (Fig. 3), when the plant is in the tuber bulking stage of growth. During the end of tuber initiation and beginning of early tuber bulking (41 to 43 DAE), a spike in Vcmax occurred. The initiation of early tuber bulking also corresponded with the occurrence of the highest daily average leaf temperatures, which were recorded on 42 DAE and 43 DAE at 34 and 32°C respectively.

2.4.6 Diurnal changes in photosynthesis

Survey measurements were used as a tool to evaluate changes in photosynthesis throughout the length of the day under ambient environmental conditions and three of the nitrogen rate trials (44.8, 269, and 403.5 kg N/ha). Our results demonstrate that the highest rate of photosynthesis occurred around 11AM local time, with lower rates associated with the early morning and late afternoon hours (Fig. 4). Differences between nitrogen rate trials were most apparent after 8 AM and prior to 3 PM. During this period, hourly measurements of photosynthesis were similar between the 269 and 403.5 kg N/ha treatments, with the 44.8 kg N/ha treatment experiencing reduced levels of photosynthesis. Specifically, when comparing photosynthetic rate at solar noon, the average rate of photosynthesis was 19, 27, and 25 μmol CO_2 m^{-2} s^{-1} for the 44.8, 269, and 403.5 kg N/ha treatments respectively. However, when comparing measurements taken at 4 PM local time (1600 hours), the treatments experienced little variability in photosynthetic rate, measuring a rate of 11, 8, and 10 μmol CO_2 m^{-2} s^{-1} across the respective 44.8, 269, and 403.5 kg N/ha treatments (Fig. 4). Our results demonstrate that during peak hours of daylight, plants managed with lower nitrogen inputs (44.8 kg N/ha) had reduced levels of photosynthesis in comparison to the recommended (269 kg N/ha), and high (403.5 kg N/ha) nitrogen rate treatments. Furthermore, there were minimal differences in photosynthetic rate between the recommended and high nitrogen rate treatments throughout the day. During the hottest portion of the day (3-5 PM local time), as well as during light limiting periods (6-8 AM local time), plants experienced similar rates of photosynthesis across all three nitrogen rate treatments.

2.4 Discussion

2.4.1 Limited increases in Vcmax and N content at the highest N application rate

At the recommended nitrogen application rate (269 kg N/ha) our Vcmax calculations are in strong agreement with past studies, which have observed a Vcmax of 77 μmol m^{-2} s^{-1} (Vaccari et al., 2001) and 72 μmol m^{-2} s^{-1} for potatoes grown under similar conditions (Bowden et al., 1990; Wullschleger, 1993). Our findings indicate that nitrogen application rate and leaf level N concentration are highly correlated, and both Vcmax and N concentration peaked at a nitrogen rate application of 336.3 kg N/ha, declining with a nitrogen rate application of 403.5 kg N/ha. These findings are partially supported in the literature, as past studies across a wide range of plants have established that a positive relationship exists between Vcmax and nitrogen leaf content (Evans, 1983; Sage and Sharkey, 1987; Lu et al., 2022). However, the relationship between Vcmax and nitrogen content in potato cropping systems remains less clear. Previous studies focused on the relationship between photosynthesis and leaf nitrogen content in potato cropping systems have returned inconsistent findings. Rather, they suggest that potato plants may respond to nitrogen limitations by limiting leaf size, thereby helping to maintain a consistent leaf N content across leaves (Vos, 1997; Vos and Van Der Putten, 1998). Similar to our findings, recent work by Li (2016) demonstrated a relationship between nitrogen levels and net photosynthetic rate, with the highest photosynthetic rate associated with sufficient nitrogen and with lower photosynthetic rates associated with nitrogen-deficient and excess nitrogen conditions. This may be explained by changes in source sink relationships, in which excess nitrogen decreases the source capacity of potato (Li et al., 2016; Croft et al., 2017). Our findings also demonstrate that Vcmax increases with increasing nitrogen application rate only up until a threshold, at which excessive nitrogen application rates no longer increase leaf level photosynthesis. In terms of on the ground management decisions, our findings emphasize the risk to potato yield that may result from over application of nitrogen, as evident by a decrease in the maximum rate of carboxylation (Vcmax) at the leaf level.

Our findings may also be explained by the confounding factor of DAE, as the last N application did not occur until July 23rd (58 DAE), lower levels of photosynthesis and leaf N content may be partially due to the DAE or growth stage of measurements, which all occurred after mid-tuber bulking and have been associated with lower rates of photosynthesis (Dwelle et al., 1981; Ghosh et al., 2000). Additionally, as the last N rate application was not applied until mid-bulking, it is likely that source-sink relationships also could have factored in, as the leaf is translocating nutrients to the tuber (Xu et al., 2012; Li et al., 2016). Alternatively, our results may indicate that high levels of N, especially applied late in the growing season, may not result in increased N concentrations in the leaf, and as a result, have little impact on leaf level photosynthesis, which may limit overall plant productivity. Future research evaluating the impact of higher N application rates earlier in the season may help explain our findings. In addition, measurements of tuber N concentration at time of leaf measurements would shed light on the translocation of nutrients (from the source to the sink) that is occurring during later growth stages in potato and would also help to parse out our results.

2.4.2 Vcmax increased with increasing temperature under irrigated conditions

We found a positive relationship between Vcmax and leaf temperature. Past work has established a physiological (Badger and Andrews, 1974; Badger and James Collatz, 1977; Jordan and Ogren, 1984; Brooks and Farquhar, 1985; Bernacchi et al., 2001) and empirical link between Vcmax and temperature, determining that the Michaelis-Menten coefficients of Rubisco and the CO_2 compensation point are temperature dependent (Medlyn et al., 2002), and thus influence calculations of Vcmax. However, there is less understanding of species-specific relationships between Vcmax, Jmax and temperature (Leuning, 2002; Medlyn et al., 2002), with limited studies evaluating the relationship within potato cropping systems. Studies that have chosen to evaluate the response of Vcmax to temperature in potato plants have not supported a consensus. For example, past work has found that potatoes grow optimally at 24 °C (Dwelle et al., 1981; Timlin et al., 2006), at a range between 16 to 25 °C (Ku et al., 1977), a range of 24 to 30 °C Burton (1981), and shifting from 24 °C to 20 °C as the growing season progresses (Fleisher et al., 2006; Timlin et al., 2006). Alternatively, past work conducted in an irrigated greenhouse found no reduction in photosynthesis for potatoes grown at temperatures of up to 38ºC (Wolf et al., 1990), highlighting the potential for potato cropping systems to adapt with little impact on photosynthesis at relatively high temperatures, if enough irrigation or rainfall occur.

Our results align with past research which has demonstrated a positive relationship between photosynthetic rates of potatoes grown at moderately high temperatures, up to 28 to 30°C (Dwelle et al., 1981; Hancock et al., 2014), which may highlight little impairment in CO_2 assimilation. Past research has suggested that decreases in tuber yield observed at high temperatures are not a result of a decrease in photosynthesis, but instead indicate a change in C partitioning (Hancock et al., 2014). Additionally, our temperature range was dictated by ambient conditions and ranged from 22 °C to 35 °C and may not have exceeded potato's optimum temperature range for growth and photosynthesis. Additionally, as the plots in our study were well irrigated, it is likely that irrigation reduced the impacts of extreme temperatures by reducing or preventing water stress in addition to maintaining cooler temperatures. Irrigation has been linked to an increase in transpiration, which contributes to an evaporative cooling effect (Mueller et al., 2015; Nocco et al., 2019), which may have allowed the leaves to remain at cooler temperatures (Notes: Statistical analysis found no significant interaction between N rate and temperature, indicating that nitrogen rate was likely not altering the plants response to higher temperatures). Recent work by Obiero (2020) may also help explain our findings, noting that high temperatures (30°C) had little impact on the photosynthetic rates of young leaves, the leaves primarily measured in our study. Together, our results illustrate the possibility for potato production to be sustained, or even increase, with rising temperatures and the use of irrigation, as evident by an increase in the photosynthetic capacity at the leaf level. However, our study was conducted under well irrigated conditions, under which irrigation amount and frequency increased in response to increases in plant water demand and ET and may not measure the full impact of increasing temperatures.

2.4.3 Soil moisture had little impact on Vcmax under irrigated conditions

Soil moisture did not affect Vcmax, contrasting with previous work demonstrating that a combination of recent, high temperatures and low soil moisture reduced Vcmax across 98 species of plants (Smith and Dukes, 2018). Similarly, in a study focused on leaf gas exchange properties of potato, Ghosh (2000) found that soils with lower moisture were associated with a lower net photosynthesis rate across all growth stages. Studies incorporating drought or irrigation deficits came to similar conclusions, indicating that potatoes grown under water stress experienced reduced maximum canopy photosynthesis (Vos and Oyarzún, 1987; Fleisher et al., 2008a). As the plots in our study were irrigated regularly, the potato crop did not experience prolonged drought or water stress, which may explain why soil moisture content was not found to be a significant driver of photosynthesis. Additionally, past research highlights that impacts of drought on photosynthesis are more likely to be expressed at the canopy level, in comparison to the leaf level (Jefferies, 1995) and are more likely to felt during tuber initiation than at other growth stages (Daryanto et al., 2017), which may help explain why our leaf level measurements taken across all growth stages did not identify soil moisture as a statically significant driver of photosynthesis. Our soil measurements were taken in the top 6 cm of the soil, which also does not reflect the full experience of the root zone. Past research conducted in the WCS region has observed spatiotemporal variability in soil moisture depending on the depth and timing of measurements (Nocco et al., 2018), which could help to further explain the relationship between Vcmax and soil moisture. Our results may also point to the influence of sufficient soil moisture in mitigating heat stress felt by the plant during high temperatures, or conversely, the influence of insufficient soil moisture in hindering photosynthetic capacity given otherwise optimal conditions.

2.4.4 Vcmax decreases as the growing season progresses

Our results highlight that DAE/Growth Stage are significant predictors of photosynthetic capacity, or more specifically, Vcmax. This finding is supported by past research on a variety of plant species. Past research has demonstrated seasonal variation in leaf biochemistry and photosynthetic processes for temperate deciduous forests – specifically, maximum leaf photosynthesis, stomatal conductance, and Vcmax (Croft et al., 2017). Similar results were found for potato when measuring photosynthesis throughout the growing season, with gross photosynthetic rate being lower at the beginning and end of the growing season (Dwelle et al., 1981; Ghosh et al., 2000; Fleisher et al., 2008a). Our findings may in part be driven by leaf age, despite selecting for leaves at the top of canopy, new growth was limited as maturation was reached, and older leaves are expected to experience reduced photosynthetic capacity (Obiero et al., 2020). Our findings are also likely driven by changes in the source sink relationship (Humphries, 1967; Sale, 1974; Li et al., 2016). In a potato source-sink relationship, the source generally refers to a mature leaf where assimilates are synthesized, while the tuber is a sink, and represents the area where assimilates accumulate (Venkateswarlj and Visperas, 1987; Li et al., 2016). Crop yield is determined both by the amount of assimilation at the source, as well as the amount of accumulation at the sink. As a result, potato yield is controlled by both the ability of the source to produce assimilates and the ability of the sink to store assimilates, which are both influenced by environmental conditions (Wang et al., 1997). Changes in the source sink relationship would help explain the increase in photosynthesis following tuber establishment found in our study and previous work (Moorby, 1968), as leaf nitrogen is dynamically partitioned between photosynthetic and nonphotosynthetic pools in response to growth, demand, and environmental drivers (Xu et al., 2012; Croft et al., 2017). Our findings emphasize the dynamic response of Vcmax during the growing season and may point to avenues for improved simulation of Vcmax in process-based ecosystem and crop models.

2.4.5 Little difference in Vcmax between potato cultivars

We found no significant difference between photosynthetic response, as measured by Vcmax, between the two potato cultivars included in the study (Table 3). However, past research has demonstrated cultivar differences in net photosynthesis rate when comparing early to late maturing cultivars (Schapendonk et al., 2000; Barnaby et al., 2019) Additionally, Tekalign and Hammes (2005) found a difference in net photosynthesis rates when comparing cultivars with differences in floral and berry development, as did Vos and Groanworld (1989) when measuring cultivars with known differences in water-use-efficiency. However, both cultivars used in our study are mid/late season cultivars with similar properties. W9433, a recently developed cultivar, is used most for fresh market, while Hodag was developed for processing. As a result, there may be some expected variation in starch and sugar concentration, as cultivars grown for processing require higher starch and lower sugar concentrations. A recent study conducted at the same site as our study on similar cultivars of potato, found inconsistent interactions between cultivar and nitrogen rate on plant nitrogen content (Wang et al., 2022), but photosynthetic rate was not evaluated. As neither Hodag nor W9433 are known to differ in water or nitrogen use efficiency or exhibit other key differences (Wisconsin Seed Potato Improvement Association, 2019), our findings may highlight the physiological similarities between fresh market and processing market potato varieties and their response to changing nitrogen availability. Our findings should not be extrapolated to other cultivars, as large variability in genotype is likely to exist, which may impact physiological responses.

2.4.6 Photosynthesis varied in response to diurnal environmental changes

Our measurements of diurnal changes in photosynthesis demonstrated a peak in photosynthetic rate before noon, and a decline throughout the afternoon. Dwelle (1983) demonstrated similar findings, with all diurnal leaf level measurements of potato clones reaching a peak rate of photosynthesis by noon and declining throughout the afternoon. Timlin et al. (2006) also found similar trends when measuring diurnal changes in canopy level photosynthesis for potato. These findings are likely driven by a combination of decreased radiation and light intensity and cooler temperatures during the early morning and evening hours which would limit photosynthetic capacity, in addition to the availability of water (Reich et al., 2007; Smith and Dukes, 2013, 2018; Ali et al., 2015). Past research has found that in irrigated potatoes, a mid-afternoon depletion in photosynthesis is most likely driven by water stress (Manhas and Sukumaran, 1988), which has been observed by increased stomatal resistance (Manhas and Sukumaran, 1988) and may also be associated with low leaf water potentials and lower crop yields for irrigated crops (Ezekiel, 1987), which may help explain our findings.

2.4.7 Limitations and next steps

While our study attempted to capture the photosynthetic response of potatoes to a range of N treatments and environmental conditions across an entire growing season – it was a non-exhaustive approach and measurements on leaf age, specific leaf area, and LAI may have provided additional insight. Additionally, there is great variability in Vcmax between and within plant species. For instance, the Vcmax of plants within the same plant functional time can vary by a factor of 2 to 3 (Croft et al., 2017). As a result, assessing relationships between treatments and environmental conditions can be challenging to parse out. While grown under ambient environmental conditions, the potatoes in this study were grown in research plots, which may experience different growing conditions than potatoes grown in commercial fields. Additionally, aside from the nitrogen rate treatments, management decisions pertaining to irrigation and pesticide application followed the University of Wisconsin Extension recommendations, which may not accurately represent the decisions of growers.

We may also expect our findings to vary in response to the timing and number of nitrogen split applications. In this study, fertilizer was applied in one to three events, depending on the nitrogen rate treatment. However, a common practice in the WCS is fertigation, in which fertilizer is applied with irrigation water, often in small quantities and more frequently. As a result, nitrogen concentration and Vcmax may vary under fertigation practices, if more nitrogen is being taken up by the plant and allocated to the leaves. Our results highlight that an increase in nitrogen rate is associated with a steady increase in Vcmax up until a rate of 336.3 kg N/ha before declining by a rate of 403.5 kg N/ha. While our findings demonstrate that the relationship between Vcmax and nitrogen availability is not exponentially positive, and is in fact, constrained, our results also indicate likely improvements in photosynthesis and yield at N application rates of 336.3 kg N/ha – a rate well above recommended guidelines.

Compared to other widely grown crops, potato crop models have received less attention in their advancement (White et al., 2011; Raymundo et al., 2014). To improve and develop more accurate potato crop models, essential for understanding regional implications and evaluating climate change impacts, comprehensive field studies and observations are needed to assess potato growth and physiological response under diverse environmental conditions and treatments across entire growing seasons (Leach et al., 1982).

While end of season biomass is a useful measurement, it overlooks the plant physiological changes that occur in response to dynamic environmental conditions and management practices. Considering large scale crop production is conducted in a field setting, we can expect both management and environmental factors to vary throughout a growing season. By collecting ecophysiology data, we can shed light on drivers of productivity and stress that would not be immediately evident in crop yield data alone. Furthermore, climate change will increase weather variability, highlighting the need to measure potato physiology across time and space to better parse out the physiological impacts as they occur. Moving forward, continued ecophysiological research can further improve nitrogen management in potato cropping systems, while helping on the ground managers better plan for the future.

2.5 Conclusions

Understanding how the photosynthetic capacity of field grown potatoes respond to various environmental conditions and nitrogen availability at the leaf level is crucial for accurately simulating global carbon fluxes and managing nitrogen most efficiently. As climate change continues, understanding how potato physiological responses, such as Vcmax, change throughout the growing season and in response to dynamic conditions will be crucial for managing potato production. Measurements of Vcmax can inform optimum nitrogen management by indicating how the photosynthetic capacity of crops change in response to nitrogen application rates as well as any interactions between management practices and environmental conditions. Through more fine-tuned nitrogen management, we can increase NUE while minimizing environmental impacts relative to current management practices. These findings can aid in improving decision support tools and models that better represent potato production and environmental tradeoffs under a changing climate.

Our findings indicate that Vcmax varied in response to nitrogen availability, growth stage (DAE), and temperature. In contrast, Vcmax was not different across the two potato cultivars included in our study. Our findings have important implications for improving the representation of potato in process-based ecosystem and crop models, with specific implications for more accurate modeling of the relationship between Vcmax and nitrogen availability throughout the growing seasons. findings also point to the ability for potato to withstand moderate increases in air temperature, with the presence of well monitored irrigation. Additionally, our findings have on the ground implications, highlighting the possibility for excess nitrogen to result in lower leaf level photosynthesis and possibly reduce corresponding crop yield.

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2.8 Tables and Figures

Table 1. Timing and quantity of nitrogen applied for the four nitrogen rate trials (44.8, 269, 336.3, and 403.5 kg N/ha).

Experimental Potato N trial	**Planting N**	**Emergence N**	**Tuber Initiation N**	**Early Bulking N**	**Mid-Bulking N**	**Season Total N**
Date	**5/1**	**5/21**	**6/12**	**7/8**	**7/23**	
Trial 1	44.8	0	0	0	0	44.8
Trial 2	44.8	78.5	145.7	0	0	269
Trial 3	44.8	78.5	145.7	67.2	0	336.3
Trial 4	44.8	78.5	145.7	67.2	67.2	403.5

Table 2. Summary of the nitrogen rate trials included in the study and the ecophysiological data collected.

Treatments	Cultivars	Sampling Period	Data Collected
Trial 1. 44.8 kg N/ha Trial 2. 269 kg N/ha Trial 3. 336.3 kg N/ha Trial 4. 403.5 kg N/ha	W9433 Hodag	28 to 98 days after emergence (DAE)	Light response curves CO_2 response curves Leaf N content Soil moisture (0-60mm) Survey measurements of photosynthesis

Table 3. Analysis of variance (ANOVA) table of multiple linear regression model output. Level of significance denoted by: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1.

	Estimate	Std. Error	t value	Pr(>|t|)	
(Intercept)	-130.939	47.591	-2.751	0.008	**
Cultivar W9433	5.397	7.972	0.677	0.501	
RunningN269	17.121	9.406	1.820	0.074	.

RunningN336.3	42.801	14.737	2.904	0.005	**
RunningN403.5	25.678	11.043	2.325	0.023	*
Soil Moisture Content (%)	2.167	1.341	1.617	0.111	
Temp (°C)	9.120	1.408	6.478	0.000	***
DAE	-0.667	0.275	-2.429	0.018	*

Table 4. Average and standard deviation (SD) of Vcmax [μmol m^{-2} s^{-1}], Jmax [μmol m^{-2} s^{-1}], and leaf N [%] concentration across nitrogen rate treatments [kg N/ha].

Nitrogen rate trial	Average Vcmax	SD Vcmax	Average Jmax	SD Jmax	Average N con.	SD N con.	Sample Size
44.8	96.40	35.35	165.87	49.20	3.67	0.71	29
269	127.93	54.63	212.30	63.96	4.98	0.81	29
336.3	150.47	31.23	233.19	21.16	5.88	0.59	7
403.5	120.44	41.36	214.47	53.64	5.09	0.75	15

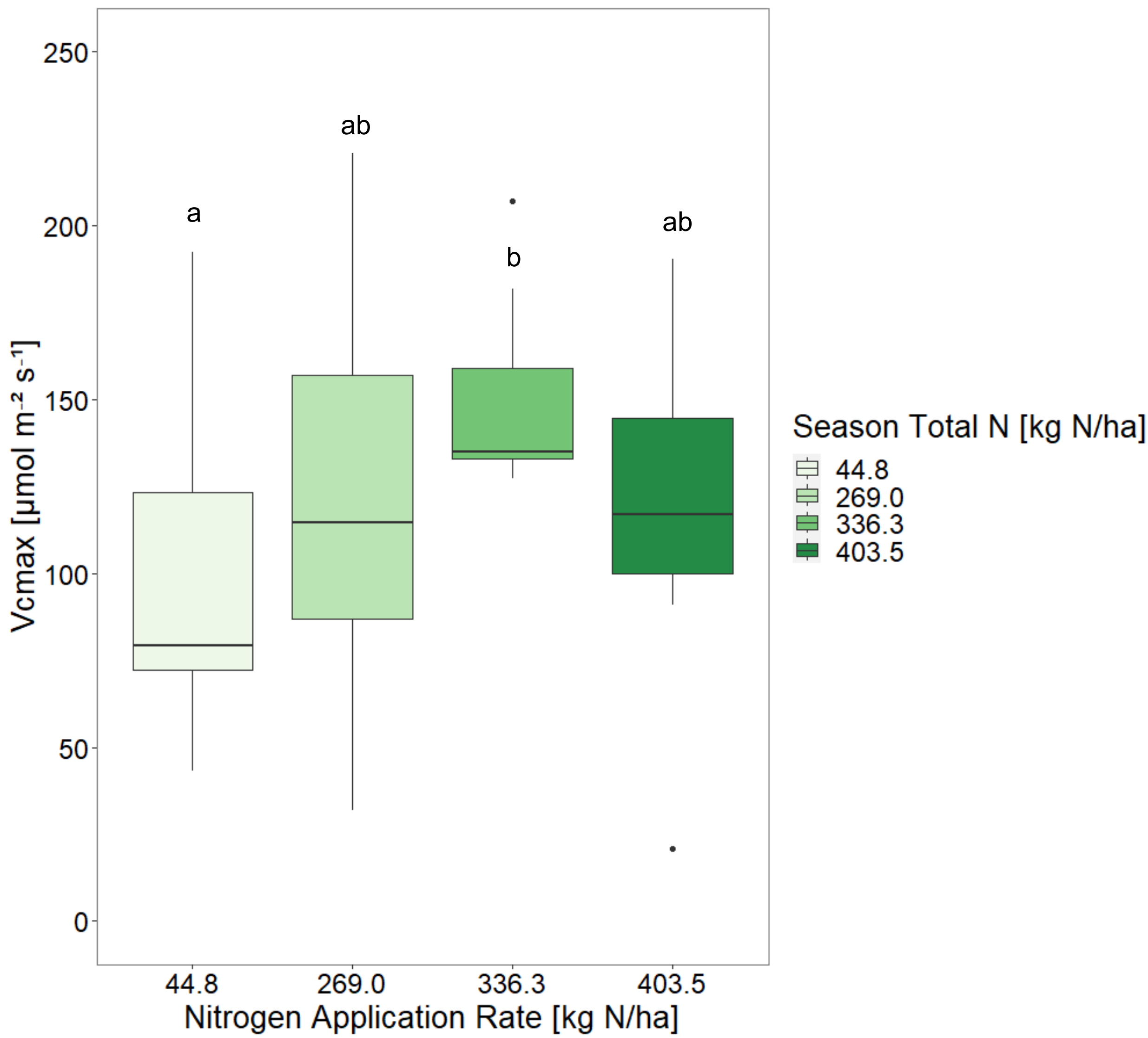

Figure 1) The distribution of calculated Vcmax [µmol m^{-2} s^{-1}] in relation to seasonal total nitrogen application [kg N/ha] across four nitrogen application rates: 44.8, 269.0, 336.3, 403.5. Letters indicate statistically significant groups based on Tukey HSD post-hoc analysis. Color darkens with increasing season total nitrogen application.

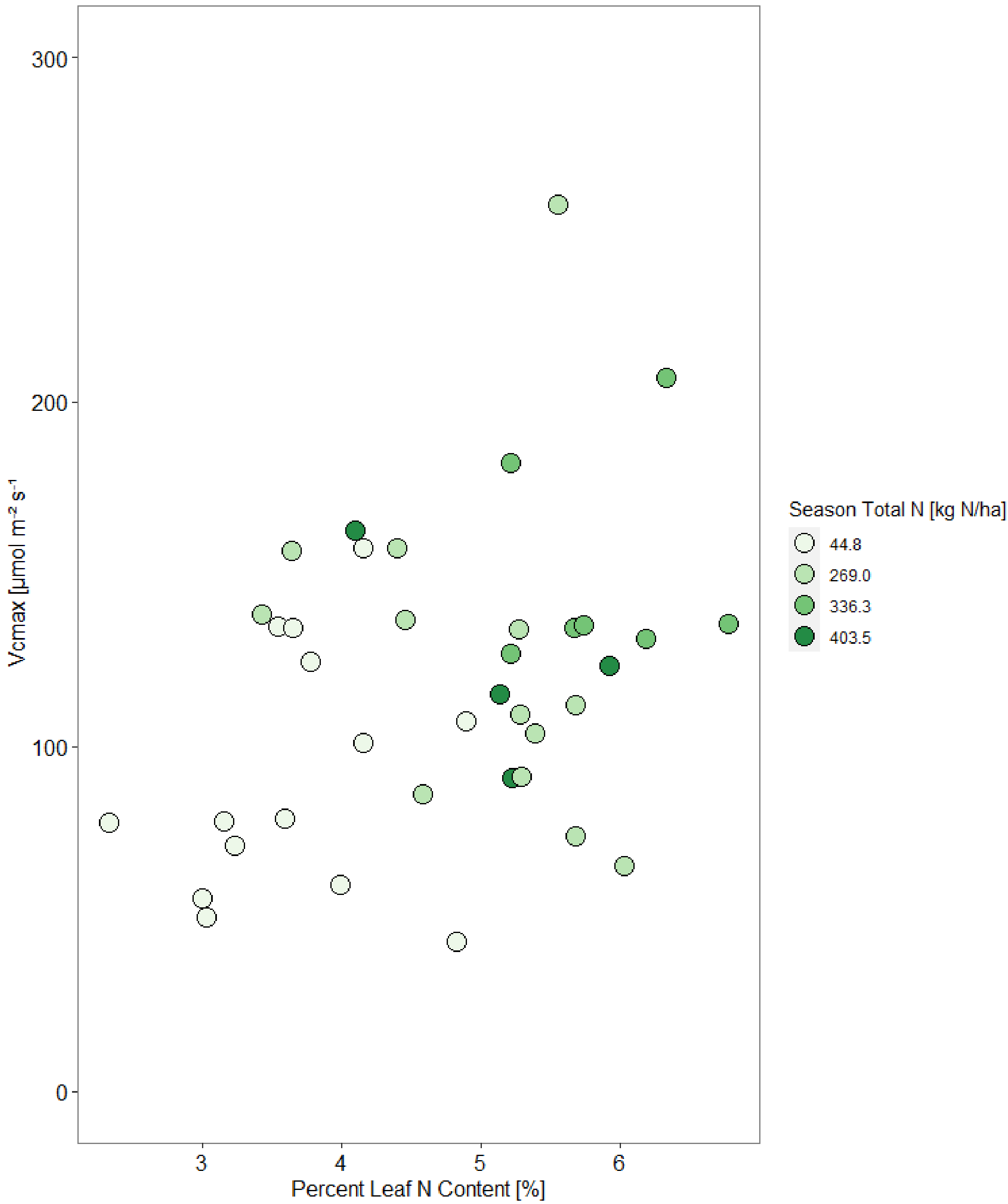

Figure 2) The distribution of Vcmax [µmol m^{-2} s^{-1}] in relation to percent of leaf N content [%] across four nitrogen application rates: 44.8, 269.0, 336.3, 403.5. Color darkens with increasing season total nitrogen application.

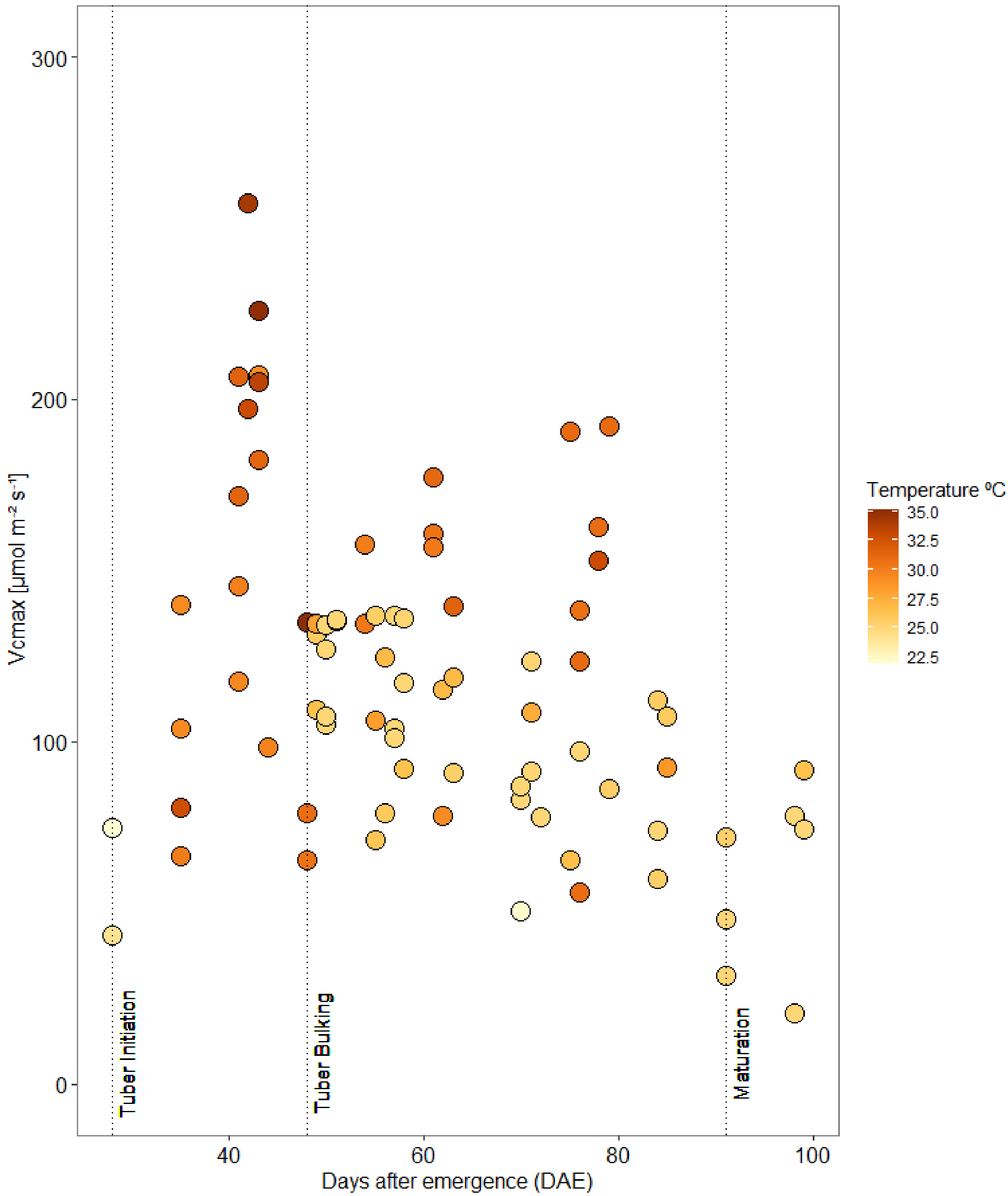

Figure 3) The distribution of Vcmax [µmol m^{-2} s^{-1}] in relation to temperature [°C] across the growing season. Vertical lines indicate potato growth stage, with Tuber Initiation (DAE = 28), Tuber Bulking (DAE = 48), and Maturation (DAE = 89) specified. Color darkens with increasing temperature.

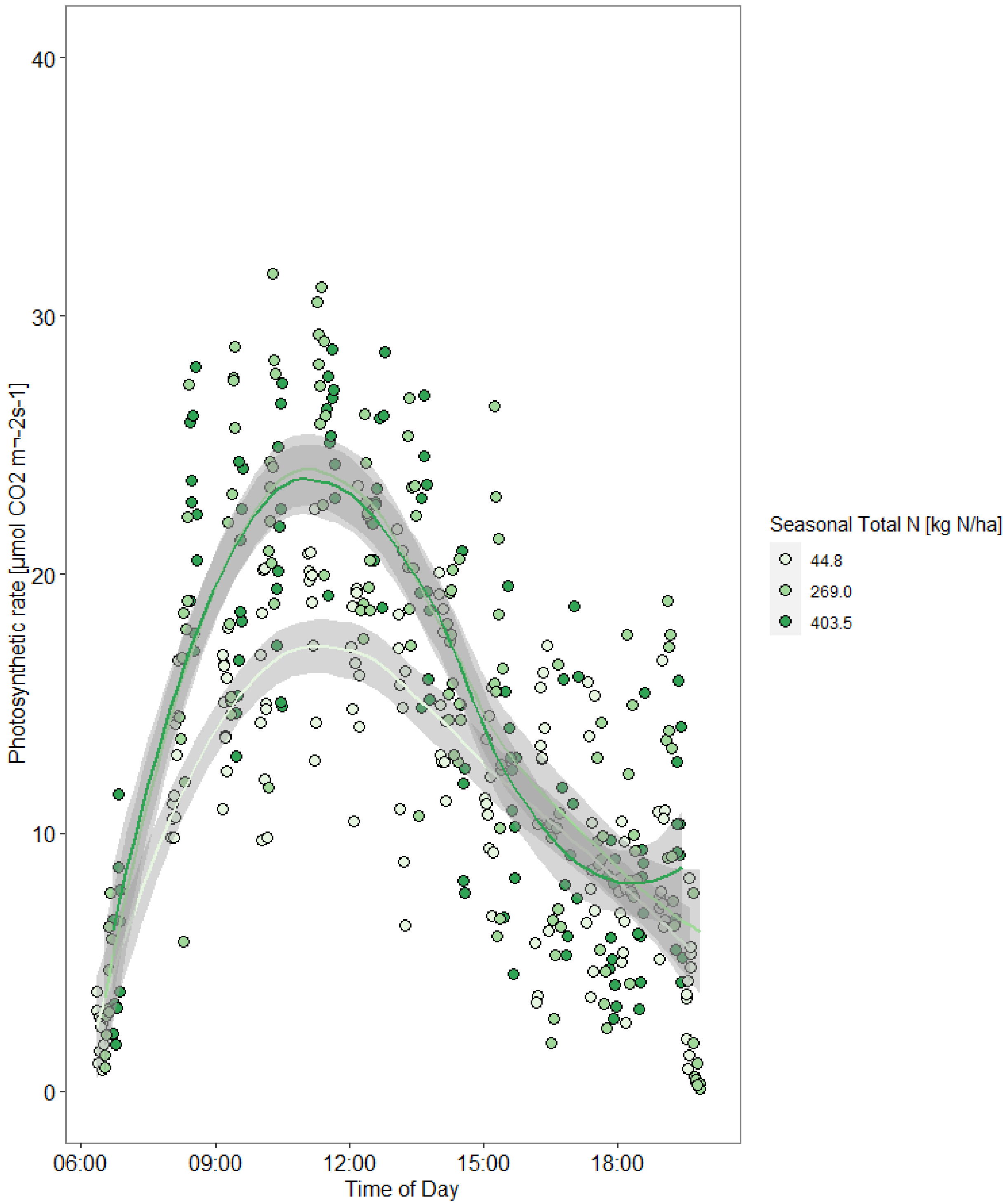

Figure 4) Diurnal measurements of the rate of photosynthesis from sunrise to sunset, taken on August 11th, 2020, across three different nitrogen application rates. Measurements were taken every hour, with 5 replicates for each treatment (N application rate and cultivar). Color indicates season total N [kg N/ha], darker colors correspond with increasing nitrogen amounts. LOESS trend line depicted with the grey region surrounding each line indicating a 95% confidence interval.

Chapter 3: Realistic expectations and limitations of BMPs to meet water quality goals in Wisconsin's Central Sands

Abstract

Maintaining agricultural production while preventing further groundwater contamination is a challenge communities across the Midwest are striving to address. The Wisconsin Central Sands (WCS) is all too familiar with this challenge, as the sandy soil, high water table, and production of high nitrogen demanding crops have left the region extremely vulnerable to nitrate leaching. Considering documented high levels of nitrate in groundwater across the region, best management practices (BMPs) have been proposed to reduce nitrate loss to the environment while maintaining crop yields. Using the Agro-IBIS agroecosystem model, we examined 42 nitrogen management scenarios across the WCS for the years 1979 to 2021. We evaluated the impact of BMPs on corn yield and nitrate leaching, as well as their effectiveness under a changing climate. We found that by implementing either fertigation or split application management practices, nitrate leaching could be reduced by more than 20% with little reduction in corn yield. However, greater reductions in nitrate leaching to approach federal water quality goals, were only achieved when nitrogen application rates were reduced by 100 kg-N/ha. Furthermore, increased precipitation, which is likely to be more common as climate change continues, hindered the effectiveness of BMPs. Despite reducing nitrogen application rates and implementing BMPs, nitrate concentration in groundwater never fell below 10 mg/L, the standard for safe drinking water. Our findings illustrate limited potential for BMPs to reduce nitrate leaching in the WCS to meet safe drinking water standards.

3.1 Introduction

To address current groundwater contamination, the impact of best management practices on corn yield and nitrate leaching needs to be evaluated, with a specific emphasis on the influence of ongoing climate change and increased weather variability. Across the central US, sandy soils are found in some agricultural regions where supplemental irrigation and nitrogen fertilizer allow for cultivation of potato, corn, soybean and other vegetable crops to thrive. Without the use of center pivot irrigation systems, low crop productivity would result due to the low water and nutrient holding capacity inherent with sandy soils.

For crops receiving supplemental N inputs, manure or fertilizer is used to support attaining profitable yields. However, losses of nitrate (N) from agricultural systems are a key driver of water quality degradation and the associated human and animal health risks and contribute to economic losses for farmers (Johnson & Kross, 1990; Lewandowski et al., 2008; Power & Schepers, 1989). Overapplication of N, poorly timed applications, plant stress, soil with low water holding capacity, soil with low cation exchange capacity, and heavy rainfall can contribute to NO_3-N leaching below the root zone. As a result, coarse textured, sandy soils are extremely vulnerable to NO_3-N loss. Once nitrate has left the plant root zone, it can move to the groundwater below, creating unsafe drinking water (Gillon et al., 2015). High levels of nitrate in drinking water have been associated with methemoglobinemia, thyroid disease, and colorectal cancer (D. Keeney et al., 1994; D. R. Keeney & Follett, 1991; McElroy et al., 2008) and environmental degradation in the form of fish kills and loss of biodiversity (Goolsby, 2000; Howarth et al., 2011; Rabalais et al., 2002). While the impacts of nitrate pollution are often felt locally, they have regional and national implications as well, as demonstrated by the hypoxic or “dead” zone in the Gulf of Mexico, in which excess nutrients applied upstream travel down the Mississippi River contributing to eutrophic conditions and a depletion in oxygen levels, resulting in fish kills (Goolsby, 2000; Rabalais et al., 2002; Turner & Rabalais, 1991; Van Meter et al., 2018). Specifically, corn has a low nitrogen use efficiency (NUE) and 60% of the nitrogen applied is often lost to the environment through volatilization, and denitrification (Basso et al., 2018; Cassman et al., 2002; Davies et al., 2020; Wortmann et al., 2011). These processes contribute to greenhouse gas emissions as well as both surface water and groundwater pollution (Cassman et al., 2002; Keeney & Follett, 1991; Rabalais et al., 2002).

Considering the challenges associated with nitrogen management – particularly on irrigated sandy soils – the use of best management practices (BMPs) is recommended for corn to optimize crop yield, profit, and nitrogen use efficiency (NUE) while limiting loss to the environment (Lamb & Barber, n.d.-a). BMPs have generally been used to refer to voluntary practices that are economically sound and limit the amount of N lost to the environment, while still promoting/allowing the use of N fertilizer (Lamb & Barber, n.d.-b; Rehm et al., 2008). Past research for corn grown on sandy soil in the Upper Midwest have cited using the correct N rate (Lamb & Barber, n.d.-a), split applications (Lamb & Barber, n.d.-a; Rubin et al., 2016; C. a Shapiro et al., 2008) nitrogen crediting of legumes, and the use of nitrogen stabilizers as BMPs (Lamb & Barber, n.d.-a). Other work has pointed to fertigation (Lamm & Schlegal, 2013; Rubin et al., 2016; C. a Shapiro et al., 2008), crediting of N in irrigation water (Cahn et al., 2017) and cover cropping (Struffert et al., 2016) as other possible BMPs to implement.

Recent work has demonstrated the effectiveness of BMPs towards reducing nitrate leaching while maintaining desired or expected crop yields. Specifically, Maharjan et al. (2014) found that split applications of urea increased corn yield and decreased nitrate leaching in comparison to a one-time application of a slow release fertilizer. Similarly, recent research in Minnesota for sandy soils found that by applying fertilizer across three events throughout the growing season, agronomic efficiency and recovery efficiency increased by 30% relative to corn receiving 100% of fertilizer at pre-planting (Davies et al., 2020). A meta-analysis by Quemada et al. (2013) found that crop yield could be maintained, and nitrate leaching could be reduced by up to 80% with improved irrigation management. Similarly, Spalding et al. (2001) demonstrated a decrease in NO3-N leaching due to a combination of more efficient irrigation practices (furrow to sprinkler) and use of fertigation, with only minor reductions in crop yield (6%). However, various levels of success, or lack thereof, have also been documented. A meta-analysis comparing strategies to reduce nitrate leaching found that fertigation did not significantly alter nitrate leaching, yield, or NUE (Quemada et al., 2013). Similarly, Struffert et al. (2016) found little change in nitrate leaching despite the use of enhanced-efficiency fertilizers and split fertilizer applications, and Bundy and Andraski (2005)found that cover crops grown on sandy soil in Wisconsin did little to utilize nitrogen left over from the previous cropping system.

Due to the large-scale agricultural production, sandy soil, shallow depth to groundwater, and frequent irrigation and fertilizer application, the Wisconsin Central Sands (WCS) region exemplifies many of the challenges associated with N and irrigation management on sandy soils. Success or failure of BMP implementation in this region could help farmers adapt management in other regions with similar soils and crop production goals. The coarse textured soil lends itself to a high hydraulic conductivity, a low water holding capacity and a low cation exchange capacity (CEC). As a result, the soil does not retain water or nutrients easily, making frequent irrigation and fertilizer application necessary for profitable crop yields.

As a result of the historical land use, current land use, and hydrologic and geologic features of the region, the WCS is faced with water quantity and quality challenges. Specifically, groundwater contamination due to nitrate leaching from agricultural fields has been heavily documented (Kraft, 1998; Kraft et al., 2014; Luczaj & Masarik, 2015; Masarik et al., 2018; Romano et al., 2021) with wells testing on average 2x the EPA threshold for safe drinking water (Campbell et al. n.d.). In response to the vulnerability of the WCS to nitrate leaching, efforts have been made to identify implement BMPs, including split application of fertilizer (Laboski et al., 2012) and implementing fertigation, which directly injects N fertilizer into irrigation systems allowing for irrigation and fertilizer to be applied simultaneously (Elasbah et al., 2019; Kafkafi & Tarchitzky, n.d.; Power & Schepers, 1989). The future effectiveness of BMPs will also be challenged by a changing climate, as will the leakiness of the N cycle in general. Projections for Wisconsin suggest warming during the growing season, an extended growing season, and increased precipitation with a higher frequency of extreme rainfall events (Wisconsin Initiative on Climate Change Impacts, 2021). Timing of rainfall will likely impact NO_3-N leaching pulses, or heavy losses of N (Moreno et al., 1996; Olsen et al., 1970). Rising temperatures alter plant N demand and timing of uptake (Kucharik, 2006) and may increase water stress (Lobell & Gourdji, 2012) which may reduce uptake of nutrients and increase NO_3-N leaching potential (Bennett et al., 1989; Bowles et al., .2018). Moving forward, it is imperative that when addressing the effectiveness of BMPs not only are today's conditions considered, but future climate and weather variability as well.

To address the uncertainty of BMPs and their effectiveness in a changing climate to reduce nitrate leaching in the WCS, we used a regionally-calibrated agroecosystem model (Agro-IBIS) to investigate the impacts of varied N management and irrigation on corn yield and nitrate leaching. We were interested in targeting the following overarching question: can water quality and corn production goals be simultaneously supported in the WCS in a changing climate? Our specific objectives were to: 1) examine the impact of the magnitude of total N fertilizer applied to support production, 2) quantify the impact of split fertilizer application events in combination with/without the use of fertigation, and 3) investigate the impact of "background" N in irrigation water. Model simulated nitrate leaching tradeoffs with corn productivity across a series of 42 scenarios were analyzed to address our objectives.

3.2 Methods

Four grid cells were used to represent a typical farm in the WCS with the geographic coordinates (44.098, -89.55538) approximating the location of the University of Wisconsin - Hancock Agricultural Research Station located in Waushara County, Wisconsin. The region is classified as a moist continental climate (Arguez et al., 2010; Nocco et al., 2018) and on average receives 335 mm of rainfall (National Oceanic & Atmospheric Administration, 2010) and 94 to 376 mm of supplemental irrigation (Nocco et al., 2019). The soil is classified as loamy sand, with 85% sand, 8% silt, 7% clay, and 0.8% organic matter (Wang et al., 2022). Nitrogen and irrigation management in the region typically includes the use of inorganic fertilizer and center pivot irrigation systems.

3.2.1 Agroecosystem modeling

The Agro-IBIS agroecosystem model was used to run scenarios of N and irrigation management in corn for typical farm in the WCS that is representative of the regional agroclimatic (e.g. soil type, agricultural management, and climate) conditions. Agro-IBIS simulates the coupled C, water, N, phosphorus, and energy exchange in the soil-plant-atmosphere system of corn, soybean, wheat, miscanthus, switchgrass, and natural vegetation (grasses and trees) (Kucharik et al., 2000; Kucharik & Brye, 2003; Motew et al., 2017; Vanloocke et al., 2010). The HYDRUS-1D soil physics model is implemented to simulate variably saturated soil water flow and nutrient transport in the soil profile (Soylu et al., 2014), allowing for simulations of potential nitrate leaching below the plant root zone. The model requires inputs of soil textural data, land cover/land use, nutrient management (N and P from manure and inorganic fertilizer), and daily weather (temperature, precipitation, specific humidity, solar radiation, and wind speed). By incorporating biophysical processes and accounting for varied crop and nutrient management, Agro-IBIS can simulate many of the challenges felt by growers in the region in relation to temperature, water, and nutrient stress, the presence of legacy nutrients, and the shifting growing season in response to ongoing climate change.

Prior to running scenarios of N and irrigation management, we ran a long-term model spin-up from 1650 to 1961 to achieve a steady-state equilibrium in soil biogeochemical cycling, reflecting changes in land use and the build-up of soil organic C and N pools. Model simulations were executed using a 60-min time-step on a 1 x 1-km regularly spaced grid and paired with the POLARIS dataset which provides a probabilistic remapping of the USDA Soil Survey Geographic database (SSURGO) soil textural data to delineate dominant soil texture and soil physical properties for each grid cell and soil layer (Lark et al., 2022). The model simulates a total of 100 soil layers, covering a depth of 10m. These layers have varying thickness, gradually increasing from the surface to the bottom of the soil profile. Soil properties are assigned to different soil textural categories based on the work of Rawls et al. (1982). These assigned properties reflect values suitable for loamy sands, which are representative of the soils found in the modeled cells and the wider WCS region. For exact values of soil properties used, refer to the supplemental information. Daily gridded weather data (air temperature, precipitation, relative humidity, solar radiation, and wind speed) from the gridMET (Abatzoglou, 2013) database that was interpolated from 4-km to 1-km spatial resolution. Agro-IBIS uses statistical models to interpolate daily weather variables to the hourly time-step (Kucharik et al., 2000). For simulated years spanning 1650 through 1978 a random draw of weather years was used from the actual data time-series of 1979 through 2021; simulation years from 1979 through 2021 represent the actual weather time-series from gridMET and were used in subsequent analysis.

3.2.2 Model parameterization, calibration, and evaluation

Agro-IBIS has been been previously calibrated and evaluated extensively across the central US (Kucharik et al., 2006; Kucharik & Brye, 2003; Kucharik & Twine, 2007; Motew et al., 2017, 2018; Soylu et al., 2014; Vanloocke et al., 2010; VanLoocke et al., 2012; Zipper et al., 2015). However, it has not been specifically evaluated for irrigated corn on sandy soils receiving varied amounts of N fertilizer. Model evaluation of simulated corn yield response across a range of N fertilizer application rates and applied irrigation water was performed using N rate trial data conducted at the Hancock Agricultural Research Station for field corn during the 2015 and 2016 growing seasons (Ruark, unpublished data). Trials were conducted using nitrogen application rates ranging from 0 kg-N/ha to 336 kg-N/ha of N. The field trials received N fertilizer through side-dress applications at two or three points during the growing season, depending on the total rate of fertilizer applied. Side-dress applications occurred on or near June 3, June 24, and July 15 for each field season. For the 2015 and 2016 field studies, the following nitrogen rates were used: 0, 67, 135, 202, 269, and 336 kg-N/ha. USDA county level corn yield data for irrigated and rainfed corn combined for Waushara County was also used for model evaluation (USDA National Agricultural Statistics Service, 2017). Published (and unpublished) data for nitrate leaching for corn grown on sandy soils in the Midwest US were consulted to evaluate the magnitude of simulated values produced by Agro-IBIS.

Based on observed irrigated yield response and maximum yield values, original Agro-IBIS values for Vcmax (plant maximum rate of carboxylation at 15ºC) and specific leaf area (m^2 leaf area per kg of C) were slightly modified (see Supplemental Information for specific values used). The model was parameterized to define the fraction of plant available water that would trigger an irrigation event, and the average rooting depth that is used to calculate the total plant available water. The timing of irrigation events are based on the amount of actual plant available water content (AWC) in relation to the maximum available water content for the soil based on the average rooting depth. Maximum plant AWC is defined as water content between permanent wilting point and field capacity. Corn rooting depth was set to a static value of 46 cm (18 inches). While corn rooting depth does not remain constant throughout developmental stages, the effective rooting depth at growth stage v8 (8 leaf stage) and earlier has been documented around 12-18 inches (Kranz et al. 2008). Additionally, while the effective full rooting depth for field corn has been measured as 91 cm (36 inches) (Kranz et al., 2008; Sanford & Panuska, 2015), a large fraction of total root biomass is located closer to the soil surface. As a result, irrigation management is generally evaluated using a shallower depth (Irmak & Rudnick, 2014; Sharma, 2019) Considering WCS farmers are more likely to irrigate based on the driest conditions in fields, and most of our irrigation scenarios took place before the silking stage of reproductive growth, we chose to use an effective rooting depth of 46 cm for all simulations.

The irrigation threshold was set at 0.70 of the maximum plant AWC, meaning irrigation occurs when the actual AWC is 70% or less of the maximum AWC. This threshold was determined based on the literature (Irmak et al., 2014; Liang et al., 2016), as well as a model sensitivity analysis. The sensitivity analysis revealed that using a irrigation threshold that approximates 70-80% of maximum AWC (based on root depth of 46cm) produced the highest crop yield and irrigation applied had that best agreed observed irrigation data for field corn in the WCS (see Supplemental Information). The amount of supplemental irrigation applied during each irrigation event was kept constant at 10 mm (0.4 inches) per event and occurred over a 6-hour period, which is representative of rates applied through center-pivot irrigation systems in the WCS. Irrigation was only triggered to occur after corn was planted. As part of N fertilizer application events, 5 mm (0.2 inches) of irrigation water was applied within 24 hours of fertilizer application.

3.2.3 Nitrogen management scenarios

Multiple scenarios were developed to simulate differences in the method and magnitude of N fertilizer applied to irrigated field corn in the WCS. More specifically, scenarios modified the timing of N fertilizer application and number of nitrogen fertilizer events, the type of BMP used, the overall rate of N fertilizer application, and whether background nitrate was present in the irrigation water or not. In total, 42 unique scenarios were simulated by Agro-IBIS (Table 1).

The two BMPs modeled were 1) *fertigation*, the addition of nitrate to irrigation water, and 2) *split application* of N fertilizer, where it is applied in multiple events throughout the growing season. While both BMPs involve applying N fertilizer at multiple points throughout the growing season, there are key differences. Modeled fertigation scenarios match plant water and N needs simultaneously, and these scenarios were designed to apply N only on days when irrigation was already occurring. However, if a required N application through fertigation didn't occur during the desired growth stage or range of growth stages due to a limited need for irrigation, then fertigation was forced to occur. In contrast, the split application BMP was modeled to apply N fertilizer and incorporate that with irrigation at a specific growth stage, regardless of plant water needs.

The following four scenarios were developed to simulate differences in the timing and number of split N fertilizer application events: 1) 100% of fertilizer applied at planting; 2) 33% of fertilizer applied at planting, and growth stages v6 and v12 (three splits); 2) 25% of fertilizer applied at planting, and growth stages v4, v6 and v8 (four splits); and 4) 12.5% of fertilizer applied at planting, v4, v6, v8, v10, v12, v14, and R1 (eight splits). For scenarios modeling fertigation, a range in growth stages was used rather than one defined stage. Corn phenological stages were used to determine the timing of nitrogen application. To account for the differences across years due to weather and climate, each growth stage was associated with its corresponding growing degree days (GDDs) based on a 1500 GDD (physiological maturity) generic corn hybrid and adapted from (Lauer, 1997; Neild & Newman, n.d.). For corn, Agro-IBIS uses a base temperature of 10ºC to calculate GDDs.

Three different rates of baseline N fertilizer applied were used for each split application/timing scenario outlined above: 140 , 240, and 340 kg-N/ha of N. Nitrogen fertilizer rates were chosen to represent low, optimal, and high N application scenarios that likely contribute to varied water quality outcomes (Emily Marrs Heineman, 2023), with 240 kg-N/ha regarded as a recommended N rate provided by University of Wisconsin Extension report A2809 for growing continuous corn on irrigated, sandy soil in Wisconsin (Laboski 2012). Because recommended N rates are not required by regulation, a range of N rate application values were chosen to reflect actual farm management decisions, in which higher N rates are often more likely to represent actual application rates. In contrast, substantially lower N fertilizer rates may reflect a conservation minded approach to N management and could help meet current and future water quality goals.

To evaluate the impact of the "background nitrate" already present in irrigation water supplied through high capacity wells and groundwater pumping in the WCS, all N fertilizer management strategies and N rate combination scenarios had two additional options added: 1) no additional nitrate present in the irrigation water, and 2) additional nitrate present in the irrigation water at a concentration of 20 mg/L. A concentration of 20 mg/L was used to reflect an average concentration of nitrate in irrigation water for farms growing corn in rotation for the WCS based on a recent observational study (Campbell et al. in prep). To calculate the amount of nitrate present in each mm of irrigation water, conversions based on Cahn et al. (2017) and Delaune and Trostle (2012) were used.

3.2.4 Data Analysis and Visualization

All analysis and visualization were completed using Rstudio v.4.2.0. For analysis purposes, annual growing season precipitation and average maximum daily temperature were calculated based on daily values from April 1st - October 1st for each respective year of our study (1979 - 2021).

3.2.5 Climate classifications

To analyze the influence of historical weather variability on crop yields and nitrate leaching and allow for a connection to be made to future climate change, k-means clustering, as defined by Hartigan et al. (1979), was used to determine groups of years with distinct climatic differences, in the maximum daily temperature and precipitation during the growing season (April-October). Analysis was completed in Rstudio v.4.2.0, using the kmeans function of the factoextra package (Alboukadel et al., 2020). Similar approaches have been taken by Carvalho et al. (2016) and Fovell and Fovell (1993). Using an unsupervised machine learning algorithmic approach, K-means clustering separates data into distinct clusters so that objects (or years) within the same cluster are as similar as possible, and objects (or years) from other clusters are as dissimilar as possible. Prior to cluster analysis, the maximum daily temperature and precipitation values during the April-October period were standardized, or scaled, to allow for comparisons between variables. To determine the optimal number of clusters, the gap statistic method was used (Tibshirani et al., 2001), which pointed to nine clusters as the optimal number of groups. From these nine optimal clusters, four were chosen to represent contrasting and broad categories of growing season climatic conditions: warm-wet, warm-dry, cool-wet, and cool-dry, which provide a spectrum of conditions likely to be experienced in the future as climate change continues. The subset of clusters was chosen based on their calculated and assigned center values (centroid), which indicated greatest deviation from the mean for both average maximum daily temperature and average growing season precipitation. Clusters ranged in size from two to four years. Moving forward, our analysis focuses on using these defined clusters of years in order to represent warm-wet, warm-dry, cool-wet, and cool-dry conditions and the resulting implications for agronomic and environmental services (corn yield and nitrate leaching). For more details on this approach, see supplemental information.

3.2.6 Percent change calculations

Percent change from baseline conditions was calculated for both corn yield and nitrate leaching using the following standard equations:

$$\frac{Crop\ Yield\ -\ Baseline\ Crop\ Yield}{Baseline\ Crop\ Yield} \times 100 \quad (2)$$

$$\frac{Nitrate\ Leaching\ -\ Baseline\ Nitrate\ Leaching}{Baseline\ Nitrate\ Leaching} \times 100 \quad (3)$$

To compare the combined effects of varied nitrogen application rate and N management practices (split fertilizer and fertigation) on corn yield and nitrate leaching, a single baseline scenario was defined as 100% of fertilizer applied at planting at a rate of 240 kg-N/ha, with no additional N present in irrigation water. To evaluate the impact of weather variability on corn yield and nitrate leaching for different N management scenarios, model output from similar weather years (warm/wet, warm/dry, cool/wet, and cool/dry) were grouped together.

To quantify the impact of N management practices alone on both corn yield and nitrate leaching, a baseline scenario was defined as 100% of fertilizer applied at planting, for each respective nitrogen application rate: 140, 240, and 340 kg-N/ha, analysis using this approach can be found in the supplemental information. Results for both corn yield and nitrate leaching were averaged across all years of simulations (1979-2021). As a result, three separate baseline scenarios were used in determining the impact of management practices without any confounding impact due to nitrogen rate or weather variability.

3.3 Results

3.3.1 Model evaluation

In comparison to USDA county level averages, the model overpredicted corn yield (see Supplemental Information). However, county level data includes both irrigated and rainfed fields, and as a result, we would expect model results that only represent irrigated corn to overpredict yield. When comparing modeled vs county level corn yield for 2010-2021, our R^2 value was 0.16 (see Supplemental Information). In comparison to N rate trials occurring at the Hancock Agricultural Research Station, our simulated yield data followed a similar response curve, but slightly underpredicted corn yields at rates above 0N applied and reached a yield plateau at a lower N rate than observed data suggested. Overall, our modeled corn yield approximated the field data extremely well, with an R^2 value of 0.99 (see Supplemental Information). When evaluating all three methods, corn yield averages were 161, 189, and 219 bu/ac for county level data (2010-2021), modeled data (all 42 scenarios), and observed field data (N application rates above 134 kg-N/ha), respectively. The greatest variability was evident in the field data, with a standard deviation (SD) of 25.3, followed by county level data (SD=18.5), and modeled data (SD=18.1). See supplemental information for more details.

Simulated irrigation quantities were evaluated using annual data specific to the WCS for 2010-2021 (Heineman, 2023) that was determined from high capacity well pumping records, tax parcel information, and crop type at the individual field scale. Good agreement was found between observed and simulated average annual irrigation for corn, with the observed average for the WCS being 160.0mm yr^{-1} (6.3 in yr^{-1}) (Heineman, 2023) compared to a simulated value of 149.9mm yr^{-1} (5.9 in yr^{-1}). Heineman (2023) also used a simple N budget model for the WCS to quantify the NO3-N leaching potential given current agricultural land management and reported an average annual potential NO3-N leaching rate of 86.1 kg-N/ha (range of 25-160 kg-

N/ha) for continuous corn receiving 240 kg-N/ha for the 2010-2021 time period (corn yields were 150-220 bu/ac). This average value is a bit lower than the average of the Agro-IBIS simulated scenarios for 240 kg-N/ha, but the range of potential NO3-N leaching agreed well between the Heineman (2023) study and our simulations. Model simulated nitrate concentrations of drainage beneath the root zone also showed excellent agreement with previously collected data on the concentration of nitrate in groundwater across a transect of the WCS during the 2018-2020 growing seasons (Campbell et al. under review). The overall average nitrate concentration for model scenarios was 20.2 mg/L, and the average field data collected across 6 farms and more than 40 individual wells was 19.0 mg/L.

3.3.2 Impact of nitrogen application rate on corn yield and nitrate leaching

When averaged across all N management scenarios, corn yield increased 16 bu/ac (or 11%) when N fertilizer application rates increased from 140 kg-N/ha to 240 kg-N/ha, but only increased by 1 bu/ac when the N application rate changed from 240 kg-N/ha to 340 kg-N/ha (Fig. 1). Overall, N fertilizer application rates of 140, 240, and 340 kg-N/ha were associated with average corn yields of 178, 194, and 195 bu/ac. Considering all N management scenarios, nitrate leaching increased with increasing nitrogen application rate (Fig. 2). Base N fertilization rates of 140, 240 and 340 kg-N/ha were associated with 77, 115, and 153 kg-N/ha of nitrate (NO_3-N) leaching, respectively, on average. Results indicate that NO_3-N leaching increased approximately 38 kg-N/ha (or 33%) when increasing from a N fertilizer application rate of 240 kg-N/ha to a N rate of 340 kg-N/ha (Fig. 2).

3.3.3 Impact of timing and number of N fertilizer application events

Corn yield increased minimally with an increasing number of split fertilizer application events and use of fertigation across all N fertilization rates. On average, corn yield was 185.6, 189.9, 189.7, and 190.2 bu/ac for one, three, four, and eight split fertilizer application events, respectively. Simulations suggested that scenarios with a base N rate of 140 kg/ha experienced the greatest benefit by implementing a greater number of fertilizer application events, with corn yields 7 to 12% higher than those with fertilizer applied entirely at planting (Fig. 3). At higher nitrogen application rates (240 and 340 kg/ha), the impact of timing and number of N fertilizer application events was negligible, causing corn yield to change +/- 1% relative to baseline conditions.

Across all N application rates and both BMP types (fertigation and split), an increase in the number of fertilizer application events led to a reduction in nitrate leaching. On average, one, three, four, and eight application events resulted in 136, 113, 115, and 107 kg/ha of nitrate leaching below the plant root zone. However, nitrate leaching was slightly higher when applied in four application events compared to three. The greatest simulated reduction (22%) in NO3-N leaching compared to the baseline occurred when N fertilizer was applied in eight equal events throughout the growing season (Fig. 4).

3.3.4 Impact of type of BMP on corn yield and nitrate leaching

Fertigation and split application BMP scenarios resulted in similar average corn yields of 190.1 and 189.7 bu/ac, respectively, compared to baseline scenarios (185.5 bu/ac). Our findings illustrate that by incorporating either BMP, fertigation or split applications, there was limited risk to crop yield given a 2.5% increase on average across those scenarios compared to the baseline simulations (Fig. 3). Overall, regardless of the timing and number of fertilizer application events, fertigation and split application BMP strategies resulted in corn yields within 4 bu/ac of each other (Fig. 1).

While comparable corn yields and nitrate leaching were achieved through either fertigation or split application BMP approaches, on average, nitrate leaching was reduced by 3% more using fertigation compared to the split N application approach. Scenarios applying N fertilizer through fertigation or split application approaches resulted in annual average nitrate leaching values of 110.7 and 113.4 kg/ha, respectively, compared to 136 kg/ha for the baseline scenarios. Therefore, implementing either fertigation or split application BMP resulted in a 16 to 19% decrease in nitrate leaching. However, the two BMP approaches did not produce consistent results when considering the timing and number of nitrogen fertilizer events. For all scenarios modeling the BMP of fertigation, NO3-N leaching decreased with increasing number of fertigation events, but there was less consistency in NO3-N leaching reduction for split application scenarios. The greatest difference in BMP approach was evident when fertilizer was applied in four applications; fertigation was more effective at reducing nitrate leaching (-18%) below the baseline scenarios than the split BMP approach (-12%) (Fig. 4).

3.3.5 Impact of accounting for background nitrate in irrigation water

Additional nitrate provided by irrigation water has significant interannual variability given the linkage to the amount of water applied which is controlled by both precipitation and temperature variability during the growing season. Across the 1979-2021 study period, the amount of growing season precipitation ranged from 413 mm (1989) to 855 mm (2010). As a result, the amount of irrigation applied varied from 42 mm (1993) to 287 mm (2012) and the amount of background nitrate applied through irrigation water ranged from 1.6 kg/ha (1993) to 26.1 kg/ha (2012). See supplemental information for annual average weather conditions.

Averaging across all nitrogen rates and management practices, accounting for additional background nitrate in irrigation water led to an average corn yield of 191.4 bu/ac, in comparison to a baseline average of 187.1 bu/ac, or a 2.3% increase. For baseline N rate scenarios with 100% of fertilizer applied at planting, the additional irrigation background nitrate increased crop yields by 10%, 0.5% and 0.05% at N rates of 140, 240, and 340 kg/ha, respectively (Fig. 3) in comparison to scenarios with no background N present. The impact of background levels of irrigation nitrate on corn yield was consistent across BMP type and all number of fertilizer application events.

By including the background nitrate in irrigation, NO3-N leaching was 5 to 10% higher in comparison to scenarios without background nitrate present (Fig. 4). Averaging across all nitrogen rates and management practices, scenarios with additional nitrate present in irrigation water lost 120 kg N/ha to leaching, in comparison to 111 kg N/ha for those without. Applying fertilizer in multiple events throughout the growing season reduced the impact of the background nitrate in irrigation water on nitrate leaching. When fertilizer was applied in multiple events throughout the growing season, scenarios with background concentrations of N in the irrigation water still experienced an overall reduction in NO3-N leaching, ranging from 2-17% (Fig. 4). However, the magnitude of reduction was muted under scenarios with nitrate present in irrigation water in comparison to those without. The impact of type of BMP, fertigation or split, on nitrate leaching was similar across scenarios with “background” N found in irrigation water and those without.

3.3.6 Weather variability effects on corn yield and nitrate leaching

Growing season weather variability had significant impacts on simulated crop yield across all N management scenarios, with the highest levels of productivity (200.3 bu/ac) supported by wetter and cooler conditions and the lowest yields (179.6 bu/ac) occurred in the driest and warmest years (Table 2). However, weather effects on corn yield were not consistent across N application rates. At a N fertilizer rate of 140 kg/ha, warmer and drier growing seasons were associated with the highest corn yield (169 bu/ac), and cooler and wetter conditions had the lowest (147 bu/ac) (Fig. 1). In sharp contrast, at higher nitrogen application rates (240, 340 kg/ha), the highest and lowest yields occurred under cool/wet and warm/dry conditions, respectively (Fig. 1)

Wetter conditions under both warmer and cooler temperature regimes resulted in the greatest nitrate leaching across all N management practices (Figs. 2, 7); the lowest (99.7 kg/ha) and highest (159.9 kg/ha) average annual nitrate leaching rates were associated with warm-dry and warm-wet weather years, respectively (Table 2). Compared to the long-term average, nitrate leaching was 7.2 and 13.8% lower for cool-dry and warm-dry conditions, respectively. In contrast, nitrate leaching was 38.5 and 32.8% higher than the average for cool-wet and warm-wet years, respectively (Table 2). The nitrate concentration in drainage water increased slightly by 2-3% (Table 2) during the driest years but decreased 1-7% in the wettest years (Table 2, Fig. 5).

3.3.7 Crop yield and water quality tradeoffs across all management scenarios

To determine the impact of unique management changes (type of BMP, number of fertilizer application events, and rate of nitrogen application) on nitrate leaching and corn yield averaged over all study years, the practice of applying 100% of 240 kg/ha of fertilizer at planting was defined as the baseline. Reducing the rate of fertilizer had the greatest impact on reducing nitrate leaching in comparison to the other modeled management strategies (Fig. 4). At the fertilizer rate of 240 kg/ha, the use of BMPs reduced nitrate leaching by 3-22%, with the greatest reduction occurring when fertilizer was applied across eight events. Reducing the nitrogen rate application to 140 kg/ha at planting resulted in a 28% reduction in nitrate leaching relative to the baseline, whereas applying 340 kg N/ha at planting increased nitrate leaching by 7% relative to the baseline (Fig. 4).

The greatest reductions in nitrate leaching (42-47%) occurred when both 1) the nitrogen application rate was reduced to 140 kg/ha, and 2) nitrogen fertilizer was applied across 3, 4, or 8 events (Figs. 4, 7). Comparable nitrate leaching reductions occurred for both fertigation and split BMP approaches. Reductions in N fertilizer rate did contribute to crop yield declines. At a base nitrogen rate of 140 kg/ha and no additional N in irrigation water, crop yield declined by 9 to 12% compared to the baseline (Fig. 3). However, the combination of receiving background N through the irrigation water and having the 140 kg-N/ha base fertilizer rate applied across three events or more, still supported a 36 to 41% decrease in nitrate leaching but led to a minimal 4% decrease in crop yield (Fig. 4). However, even when nitrate leaching was reduced by 47%, the nitrate concentration in drainage water was 11 to 13 mg/L, which is above the EPA threshold for safe drinking water of 10 mg/L (Fig. 5). Of the 42 scenarios simulated, there was no combination of BMP and reduced N fertilizer rates that led to drainage nitrate concentrations falling below 10 mg/L.

3.3.8 Weather variability and climate change challenge the beneficial impacts of BMPs

The effectiveness of BMPs should be evaluated for both the current and future climate. For years experiencing above average rainfall, the use of BMPs limited NO3-N leaching increases relative to applying 100% of N fertilizer at planting. In the absence of BMPs, wetter than average conditions resulted in a 32-38% increase in nitrate leaching at a rate of 240 kg-N/ha, but nitrate leaching still increased by 2-15% under wetter than average conditions when using BMPs (Fig. 7). In contrast, for drier than average conditions with a rate of 240 kg-N/ha applied at planting, NO3-N leaching was 7-13% lower with no BMPs, and NO3-N leaching was reduced by 12-33% with the use of BMPs (Fig. 7).

At the highest N rate of 340 kg-N/ha and no BMPs, nitrate leaching increased 16-85%, with the greatest increases occurring during the wettest conditions (Fig. 7), and leaching increased by 35-52% when BMPs were implemented (Fig. 7). For these N management scenarios under drier than average conditions, nitrate leaching increased by up to 17%, but BMPs helped support a 10% decline in nitrate leaching compared to the baseline averages at a N rate of 340 kg-N/ha.

The greatest and most consistent reductions in nitrate leaching (10-56%) occurred by reducing the fertilizer application rate from 240 kg/ha to 140 kg/ha (Fig. 7). When fertilizer was reduced to a rate of 140 kg/ha, nitrate leaching reductions of greater than 45% were possible when BMPs were implemented under drier than normal conditions. However, under wetter than average conditions, nitrate leaching reductions were substantially smaller, reducing by 26 to 28% (Fig. 7). At nitrogen application rates of 240 and 340 kg/ha, corn yield variations were influenced the most by weather variability rather than N management strategies. As a result, at N applications rates of 240 kg/ha and above, limited trade-offs existed when evaluating management strategies and their impact on corn yield versus nitrate leaching.

Though nitrate leaching and nitrate concentration values followed similar trends in response to the use of BMPs, differences emerged. In contrast to nitrate leaching values, where the greatest reductions occurred under drier than average conditions, the greatest reductions in nitrate concentration occurred under wetter than average conditions (Table 2, Fig. 5). In general, nitrate concentration increased by a smaller magnitude than nitrate leaching relative to baseline conditions, with the percent change in nitrate concentration ranging from + 38 to -55% (see supplemental information); in comparison, nitrate leaching values ranged +85 to -55% relative to baseline conditions (Fig. 7). Additionally, when nitrogen fertilizer was applied at the extension recommended rate of 240 kg/ha, the use of BMPs reduced nitrate concentration across all weather conditions. No combination of N management strategies or weather conditions reduced nitrate concentration to a value below 10 mg/L (Fig. 5).

3.4 Discussion

3.4.1 Increasing N application rates disproportionately influence nitrate leaching, not corn yield

Corn yield increased with an increasing N fertilizer rate from 140 kg-N/ha to 240 kg-N/ha but did not increase at a N rate of 340 kg-N/ha, indicating a plateau in corn yield response to nitrogen fertilizer. These findings are similar to observed field data (Halvorson & Bartolo, 2014) and a meta-analysis (Shrestha et al., 2023), in which minimal increases in corn yield occurred after a nitrogen application rate of 254 and 250 kg-N/ha, respectively. Considering field data was used in our model calibration, it is expected that our modeled results followed similar trends to those observed in the field. Our study demonstrated increased levels of nitrate leaching with corresponding increases in the rate of nitrogen application. Field studies conducted on sandy soils elsewhere report comparable nitrate leaching values, with Struffert et al. (2016) reporting nitrate leaching values of 86 kg-N/ha at a nitrogen application rate of 250 kg-N/ha, and an average NO3-N leaching rate of 57.9 kg-N/ha for corn and corn-soybean rotations grown on sandy soil with corn receiving 120 kg-N/ha (Shrestha et al., 2023). Similarly, Sexton et al. (1998) observed 72 kg-N/ha of nitrate leached for corn grown on sandy, irrigated soil with a nitrogen application rate of 202 kg-N/ha. Model findings are consistent with field studies that highlight a disproportionate increase in NO3-N leaching in comparison to corn yield gains above 150 kg-N/ha of applied fertilizer (Shrestha et al., 2023).

3.4.2 NO3-N leaching decreases with increasing number of fertilizer application events, with little impact to corn yield

At extension recommended N fertilizer rate of 240 kg-N/ha, corn yields were not significantly impacted by the timing and number of N application events. This result is supported by other field studies. For example, Ventera and Coutley (2015) found no significant change in corn yield between fields receiving 100% of fertilizer at planting, or in equal three-way splits at planting, v6, and v14 growth stages, and similar findings were reported by Fernandez et al. (2016) and Jaynes (2013). However, others found that by applying fertilizer in split applications, corn yield was significantly higher than when 100% was applied at planting (Davies et al., 2020; Struffert et al., 2016), even when N rates exceeded university recommendations (Davies et al., 2020). Model scenarios highlighted that corn yield increased with increasing number of application events at a lower nitrogen rate of 140 kg-N/ha. This is also supported by previous field studies that suggested high corn yields could still be achieved with lower nitrogen rates when N was applied during multiple application events throughout the growing season (Gehl et al., 2005; Rasse et al., 1999). The difference in corn yield response to timing and number of fertilizer application events at different nitrogen application rates is likely driven by the corn yield nitrogen response. Considering corn yield often reaches a maximum around a rate of 250 kg-N/ha (Halvorson & Bartolo, 2014; Shrestha et al., 2023), we would expect little change in corn yield for scenarios receiving 240 and 340 kg-N/ha of N regardless of management practice.

Our results demonstrated that nitrate leaching decreased when fertilizer was applied multiple times throughout the growing season. These findings are also supported by previous field studies that have found that by applying fertilizer in three applications throughout the growing season, agronomic efficiency and recovery efficiency increased by over 30% compared to preplant applications of fertilizer (Davies et al., 2020). Similarly, Martin et al. (1994) found that by applying fertilizer during 4 events throughout the growing season, leaching was reduced by 50% in comparison to the conventional preplant approach that applies all fertilizer at once. Previous research on sandy soil also supports model findings, demonstrating that in sandy loam soil increasing fertigation frequency to weekly, in comparison to 3 events, reduced leaching by approximately 25% (Azad et al., 2020). These findings are likely driven by the improved timing of nitrogen applications with plant nitrogen needs. By applying nitrogen fertilizer between growth stage v4 and R1, N is made available during peak nitrogen uptake by crops, while limiting the amount of nitrate available for leaching during spring rain-events before the plant has an increased N demand (C. a Shapiro et al., 2008).

3.4.3 Fertigation is most effective at reducing NO3-N leaching in comparison to basic split applications

Our findings demonstrated little difference in corn yield in response to the type of BMP implemented, fertigation or split application approach. A past meta-analysis conducted by Quemada et al. (2013) found similar findings, indicating no significant difference in corn yield or nitrate leaching between the practice of fertigation or two to four split applications of fertilizer applied conventionally. Similarly, research on sandy soil found that an intensive fertigation approach, in which nitrate was applied weekly or biweekly, had no impact on corn yield relative to the conventional sidedress applications (Gascho & Hook, 1991). Gascho et al. (1984) had similar results, finding that side-dressing produced crop yields greater to or equal to a fertigation approach. Considering BMPs serve to reduce nitrate loss to the environment while maintaining crop yield, similar corn yields across BMPs can be expected. Additionally, the modeling of our fertigation and split application approach were very similar in that both approaches received the same amount of fertilizer applied in the same number of events, at generally the same points in the growing season. Additionally, as mentioned previously, our model results indicate little room for gains in corn yield when nitrogen application rates of 240 kg-N/ha and above were used.

While both fertigation and split application BMP approaches performed similarly in their ability to reduce nitrate leaching, fertigation scenarios were slightly more effective. This is likely driven by improved timing of fertilizer events and increased nitrogen use efficiency under fertigation scenarios, as well as our scenario design. While split application scenarios were modeled to apply fertilizer when reaching a GDD threshold that corresponded with growth stage, fertigation scenarios experienced more flexibility – applying fertilizer over a wider range of GDDs, based on irrigation management. As a result, split application scenarios received fertilizer over smaller periods of time and with no consideration of plant water needs. As fertigation scenarios were developed to prioritize the application of nitrogen fertilizer to correspond with irrigation, which reflected air temperature, soil water content and plant water use, fertigation likely resulted in increased N uptake due to increased plant water uptake (Kafkafi & Tarchitzky, n.d.) in comparison to the more basic split application approach. As a result, our findings point to increased nitrogen use efficiency when nitrogen management/application is paired with optimally timed irrigation. Our results indicate that the greatest differences in nitrate leaching between the two BMPs approaches occurred when fertilizer was applied in four application events throughout the growing season. In terms of timing, scenarios involving four application events received nitrogen at planting and growth stages v4, v6 and v8, while scenarios involving three application events received nitrogen at planting, growth stage v6, and growth stage v12. Our findings may indicate that when using the split application BMP approach, for greater reductions in nitrate leaching, application events need to be further spread out – rather than applying 75% of the total nitrogen between growth stages v4 to v8. Alternatively, our findings may also point to reduced nitrogen need, and resulting nitrogen uptake, during earlier growth stages (v4), in comparison to later growth stages (v12) (Cornell University Cooperative Extension, 2017). However, considering scenarios implementing the fertigation approach experienced greater declines in nitrate leaching when applied in four applications vs. three applications, this is less likely.

3.4.4 "Background" N levels in irrigation water increase NO3-N leaching with little benefit to corn yield

Based on our findings, by choosing not to apply credit for N in irrigation water in the WCS, growers are potentially over-applying nitrogen with no added benefit to boosting corn yield, but instead are increasing the risk for even more nitrate leaching to groundwater and degraded water quality. Our findings indicate that when applying the UW extension recommended N rate of 240 kg-N/ha, failing to factor in the background N in irrigation water resulted in no change in crop yield but increased nitrate leaching below the plant root zone. However, when a lower amount of N is applied, 140 kg-N/ha, the extra background N in irrigation can provide a boost in crop yield across all N BMPs. These findings can best be explained by the relationship between corn yield and nitrogen availability. Past research has indicated that as higher N application rates are reached, corn yield plateaus, or does not increase with increasing amounts of nitrogen (Halvorson & Bartolo, 2014; Shrestha et al., 2023).

Considering the use of recommended nitrogen rates is not enforced and the overapplication of nitrogen is often perceived to be worth additional cost to reduce the risk lower crop yield (Mitchell, 2004; Mitchell et al., 2021), on farm management decisions are most likely to reflect a nitrogen application rate of 240 kg-N/ha and above, rather than a lower, conservative rate of 140 kg-N/ha. Previous research supports this behavior, finding that growers tended to apply the same quantity of fertilizer regardless of recommended rates (Ferguson, 2014). When irrigation and nitrogen application are properly managed and timed, model results indicate that the lack of crediting for N in irrigation water further contributes to the risk of continued groundwater contamination. Previous recommendations from the University of Wisconsin Extension have not advised crediting N in irrigation water, citing challenges associated with timing, variability, and the idea that these "background levels" of nitrate in irrigation water were included in nitrogen response research and subsequently represented in current nitrogen rate recommendations (Wolkowski et al., 1995). Our findings support new recommendations from neighboring states advising farmers and growers to begin crediting for N in irrigation water, especially when irrigation water tests above 10 mg/L N-NO3 (Lamb & Barber, n.d.-a; C. A. Shapiro et al., 2019), which is further supported by recent research indicating nitrate in irrigation water is used as effectively by crops as nitrogen fertilizer (Cahn et al., 2017).

3.4.5 Increased growing season precipitation limits groundwater quality improvements

Our findings highlight how ongoing climate change and increased weather variabil*ity* influence both corn yield and nitrate leaching, and the effectiveness of BMPs. In relation to corn yield, our results demonstrate that when conditions are warmer and drier than usual, we can expect crop yield declines in the WCS. Our findings can be explained by biophysical and plant physiological processes, in which under warm-dry conditions the plant may be experiencing increased water and heat stress. Past research has demonstrated reduced NUE for corn under severe water stress (Bennett et al., 1989). Similarly, past modeling work has demonstrated that combined heat and drought stress will amplify negative impacts to crop yield, in comparison to the impact of the respective individual stresses (Jin et al., 2017), exacerbating the potential for nitrate leaching (Bowles et al., 2018). Additionally, both empirical (Schlenker & Roberts, 2009) and modeling (Lobell et al., 2013) studies have found that extreme heat has a strong relationship with water stress by lowering both water demand and future water supply, further limiting crop yield.

Model output indicated that with sufficient N fertilizer, the highest corn yields occurred under cooler and wetter than average conditions, followed by wetter and warmer than average conditions. These findings highlight the importance of adequate water availability in alleviating plant water stress and promoting crop growth. Previous studies evaluating the impact of climate change on corn yield in Wisconsin came to similar conclusions, finding a trend of increasing corn yield under wetter and cooler conditions, with yields rising 5 to 10% (Kucharik & Serbin, 2008). The smaller simulated yield increase under warmer and wetter conditions (in comparison to cooler and drier), may indicate that corn grown during these years may have experienced heat stress that was not ameliorated by ample soil moisture, resulting in lower crop yields due to decreased NUE (Bennett et al., 1989). However, the overall increase in corn yield under warmer and wetter than average conditions can possibly be explained by an extended growing season accompanying warmer temperatures (Kucharik, 2008), resulting in a greater accumulation of carbon and resulting in a boost to corn yield. However, in contrast to our findings for recommended nitrogen rate applications and above, our model results indicated that under nitrogen application rates of 140 kg-N/ha, drier than average conditions produced the highest corn yield. This is likely driven by the reduced nitrate leaching experienced under drier conditions (Bowles et al., 2018; Randall & Mulla, 2001; Shrestha et al., 2023) resulting in increased nitrogen uptake, which is critical for corn that may be experiencing increased nitrogen stress.

In relation to nitrate leaching, our findings indicate that climate change and weather variability have the potential to mitigate or exacerbate nitrate leaching relative to the average climate of the region, depending on the timing and amount of rainfall. The highest levels of nitrate leaching were found for years experiencing greater than average rainfall, and either warmer or cooler than average daily temperatures. These findings point to the stronger influence of precipitation over temperature in terms of driving NO3-N leaching loss. Considering N movement in sandy soil is largely driven by the movement of water, these results are expected and supported by past research in which the nitrate leaching amount closely mirrors the amount of drainage (Martin et al., 1994; Randall & Mulla, 2001; Struffert et al., 2016). Additionally, while all clusters of years experiencing greater than average precipitation experienced increased levels of nitrate leaching, leaching levels and crop yield were highest under cooler than average conditions in comparison to warmer than average conditions. These findings indicate that despite more N being taken up by the crop during cool-wet years, N loss to the environment remained higher during these periods in comparison to warm-wet years. This can be explained by the drivers of water and nitrate movement in the soil-plant system: precipitation and evapotranspiration (Lamb & Barber, n.d.-a). With higher temperatures, evapotranspiration increases, reducing the amount of water available for leaching. Additionally, these findings may be explained by possible extreme rainfall events and rainfall events mismatched with plant water demand during the growing season, which would result in more NO3-N leaching below the soil profile (Hess et al., 2020; Martinez-Feria et al., 2019; Randall & Mulla, 2001).

In contrast to nitrate leaching, our results found nitrate concentration to decrease with wetter than average conditions. As nitrate concentration considers the amount of nitrate leached in relation to the amount of drainage water, these findings can best be explained by the ability of rainfall and increased drainage to dilute the concentration of nitrate leached below the root zone. Our findings are supported by a recent field study conducted in the Upper Midwest on irrigated sandy soils, which found that reduction in nitrate concentration was driven by a dilution effect (Struffert et al., 2016).

3.4.6 Lower fertilizer application rates and the use of BMPs needed to meet water quality goals

Working within our current system of agriculture, our study suggests pathways to reduce nitrate leaching, while considering crop yield tradeoffs. Consistent with field studies and current extension recommendations, our results demonstrate that for corn grown on irrigated, sandy soil in the Upper Midwest – nitrogen fertilizer should be applied in incremental applications throughout the growing season. Findings demonstrate that with accurately timed fertilizer applications, there is little risk to corn yield, and rather a slight increase in yield is possible when implementing split applications or fertigation.

Similarly, our findings highlight the substantial contribution of “background” nitrate in irrigation water to nitrate leaching with limited benefits to crop yield when fertilizer is applied at recommended rates. By reducing the amount of total fertilizer applied in response to the amount of nitrate present in irrigation water, overall nitrate leaching could be reduced by 5 to 10%. However, our findings also point to the need to reconsider fertilizer rate recommendations if reductions in nitrate leaching greater than 22% are desired. Considering currently established federal water quality goals, including a 45% reduction in nitrate loading to the Gulf of Mexico (Environmental Protection Agency (EPA), 2007, 2014), our findings emphasize the limitations of using BMPs alone in reaching water quality goals.

However, our results demonstrated substantial reductions in nitrate leaching, aligning with Water Task Force goals, were possible when N fertilizer application rates were reduced and BMPs were implemented simultaneously. Specifically, we found nitrate leaching reductions of (40-50%) when fertilizer was applied at a rate of 140 kg-N/ha across a series of three or more events. Though these management changes led to some yield reduction, the boost provided by additional nitrate present in irrigation water helped ameliorate the impact, resulting in a 41% decrease in nitrate leaching and a 4% decrease in corn yield in a best base scenario. These findings highlight that nitrogen application rates of 160 to 170 kg-N/ha may reflect a compromise when it comes to considering both agronomic yield and environmental quality goals.

Moving forward, the WCS region is likely to experience warmer and wetter than average conditions during the growing season (Wisconsin Initiative on Climate Change Impacts, 2021). Based on our findings, while these conditions are likely to result in a small boost to crop yield (1%), wetter conditions are likely to exacerbate current N management challenges and increase nitrate leaching (32 to 37%). As the climate continues to shift to warmer and wetter conditions across the WCS regions, the use of BMPs will be needed to maintain nitrate leaching near current levels (2 to 15%), offering little to no room for overall improvement in current water quality.

3.4.7 Despite BMPs, groundwater remains unsafe to drink

Across the 42 scenarios modeled in our study, nitrate concentration remained about 10 mg/L across all combinations of management practices, nitrogen application rates, and climate and weather conditions. While the nitrate concentration below the root zone may be higher than that of groundwater below, these findings emphasize the barriers to achieving safe drinking water while still operating annual corn cropping-systems on sandy soil.

Rather, our findings highlight the barriers present in our current system of agriculture that hinder groundwater quality improvement. If safe drinking water is the goal, more transformative approaches to agricultural land management will need to be considered. Past research has pointed to the ability of perennial systems to improve water quality (Campbell et al., 2021; Schulte et al., 2006, 2017; Zhou et al., 2014), which could aid in transitioning away from annual cropping systems and integrating perennial cover with livestock grazing to decrease the need for corn production for animal feed (Campbell et al. 2021). Additionally, returning portions of the land to its natural habitat, such as wetland restoration, may prove more effective (Bowles et al. 2018) or keeping land out of agricultural production through conservation programs may serve as another option.

3.4.8 Modeling limitations

When attempting to represent dynamic, complex environments with numerous interactions and biophysical feedbacks, assumptions are required and often create a degree of limitation. Specifically, we assumed 100% irrigation efficiency, uniform irrigation through the center pivot system, no loss of N to volatilization during fertigation applications, and no biotic stresses (insect, pest, disease) to crop yield. Past research has pointed to irrigation efficiency of

80% for center pivot irrigation systems (Howell, 2003) and inefficiencies in fertigation due to volatilization (Fan et al., 2023).

Additionally, we chose to represent some dynamic processes as static. Rooting depth was treated as a static variable, when it's dynamic. Early in the growing season, the rooting depth may only be ½ to ⅔ of its potential depth. Past research has indicated that corn rooting depth can grow on average by 1 inch per day (Abendroth et al., 2011), highlighting the limitations with a static representation of root depth. Similarly, the irrigation trigger was assumed to remain constant throughout the growing season when a dynamic variable in response to the growth stage of the crop may result in greater water use efficiency (Kranz et al., 2008). Additionally, while Vcmax was modeled to respond to changes in both water and nitrogen stress felt by the plant, it was not modeled to vary in response to growth stage. Past work has highlighted that modeling may be improved by a dynamic representation of Vcmax (Xu et al., 2012), which was not reflected in our study.

Soil properties and parameters used in Agro-IBIS are based on a look-up table from Rawls et al. (1982). However, more recent work has highlighted the possibility that the approaches used in Rawls et al. (1982) are outdated, and new techniques are needed to more accurately estimate soil water conditions (Nemes et al., 2009). Our analysis of the impact of climate change was limited by the variables used in our clustering approach. By clustering similar weather years through k-means clustering, we were able to evaluate the impact of changes on temperature and precipitation, with years classified as warmer and wetter than average likely to increase in frequency as the climate change intensifies in the WCS.

3.5 Summary and Conclusion

For agricultural areas vulnerable to nitrate leaching, such as those on irrigated, sandy soil, our findings demonstrate that on the ground management changes, such as changes in nitrogen application rate and timing, are needed to limit further groundwater contamination. When working within our current system of agriculture, our findings highlight possible avenues towards improving groundwater quality. Specifically, our findings demonstrate that by implementing BMPs, nitrate leaching can be reduced by 22% with negligible impacts to corn yield. Our findings also emphasize the need to account for the nitrate present in irrigation water, as nitrate leaching increased by 5 to 10% when the nitrogen present in irrigation water was ignored. These approaches do not require drastic shifts in current practices, and rather focus on improved timing and crediting, and could serve as possible better management strategies with limited barriers to adoption. While greater reductions (35 to 45%) in nitrate leaching were possible if the recommended nitrate rate application was reduced by 100 kg-N/ha, they resulted in reductions to corn yield. The use of BMPs as well as the additional nitrate in irrigation water helped to mitigate yield losses, resulting in smaller magnitudes of decline (4 to 12%). Our findings may point to the need to reevaluate nitrogen rate recommendations and their calculations so that they better reflect the impact of nitrogen on water quality. Though more impactful for water quality improvements, the adoption of these strategies will require a shift in risk management practices.

As climate change continues to increase weather variability and total growing season precipitation, ongoing water quality challenges are likely to be exacerbated. Our findings indicate that as weather conditions shift towards wetter than average, the use of BMPs will be necessary in order to maintain current levels of nitrate leaching, and as a result, BMPs are unlikely to result in reductions in nitrate leaching relative to current values. To further highlight the limitations associated with managing nitrogen in inherently leaky systems, our results indicate that nitrate concentrations below the root zone never fell below 10 mg/L, despite both reducing nitrogen application rates and implementing BMPs. These findings point to the critical need to reevaluate our current agricultural production system if healthy drinking water is prioritized.

While our study highlights possible avenues towards decreasing nitrate leaching under our current system of agriculture, our findings point to the need for more transformative approaches if groundwater quality improvements are prioritized. Such changes will require a shift in our current system of agriculture, involving changes in attitude and behavior, and may take many forms. Moving forward, if water quality goals are to be met, agroecological principles and a food-systems perspective will be needed.

3.6 References

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3.7 Tables and Figures

Table 1) Nitrogen Management Scenarios. Scenarios consist of three nitrogen management practices (Planting, fertigation BMP and split application BMP), three nitrogen application rates (140, 240, and 340 kg-N/ha), and incorporate the presence or absence of "background" nitrate in irrigation water. For scenarios incorporating a BMP (fertigation or split), nitrogen was applied in 3, 4, or 8 application events throughout the growing season. In total, 42 unique scenarios were created based on the combination of management practice, nitrogen application rate, timing and number of application events, as well as the presence or absence of background nitrate.

Scen	BaseN	Yield [bu/ac	Leaching [kg/ha]	N conc	Irrigation [mm]	Fertilizer [avg]	MP	# Apps	Background N
planting_credit	140	175.5	94.0	16.6	130.6	165.9	plant	1	yes
planting_credit	240	194.8	140.5	24.9	135.6	266.9	plant	1	yes
planting_credit	340	195.5	186.7	33.1	135.9	367.0	plant	1	yes
3FERT_credit	140	186.9	80.3	14.1	133.3	165.2	FERT	3	yes
3FERT_credit	240	194.7	116.4	20.5	136.2	265.8	FERT	3	yes
3FERT_credit	340	195.2	155.3	27.4	136.5	365.9	FERT	3	yes
3splits_credit	140	185.9	81.3	14.2	135.0	165.0	split	3	yes
3splits_credit	240	194.6	118.1	20.8	137.8	265.6	split	3	yes
3splits_credit	340	195.3	156.9	27.6	138.4	365.7	split	3	yes
4FERT_credit	140	187.1	80.5	14.1	136.9	165.4	FERT	4	yes
4FERT_credit	240	194.6	115.8	20.3	138.6	265.8	FERT	4	yes
4FERT_credit	340	195.3	153.8	27.1	138.8	365.9	FERT	4	yes
4splits_credit	140	184.7	84.0	14.6	140.3	164.9	split	4	yes
4splits_credit	240	194.6	123.6	21.5	143.7	265.6	split	4	yes
4splits_credit	340	195.0	165.1	28.8	143.1	365.4	split	4	yes
8FERT_credit	140	186.8	77.1	13.2	144.1	162.0	FERT	8	yes
8FERT_credit	240	194.3	110.4	19.1	146.2	264.4	FERT	8	yes
8FERT_credit	340	194.6	147.4	25.5	146.4	364.2	FERT	8	yes
8splits_credit	140	186.9	77.0	13.2	145.8	161.0	split	8	yes
8splits_credit	240	194.0	110.5	19.0	147.4	263.1	split	8	yes

8splits_credit	340	194.6	146.8	25.3	148.1	363.2	split	8	yes
planting	140	158.4	86.1	15.1	128.1	140.0	plant	1	no
planting	240	193.9	131.8	23.4	134.5	240.0	plant	1	no
planting	340	195.4	177.2	31.5	134.9	340.0	plant	1	no
3FERT	140	174.1	71.6	12.5	131.7	140.0	FERT	3	no
3FERT	240	194.5	108.3	19.1	135.7	240.0	FERT	3	no
3FERT	340	194.8	146.2	25.8	135.8	340.0	FERT	3	no
3splits	140	173.0	72.5	12.6	133.9	140.0	split	3	no
3splits	240	194.5	109.9	19.3	137.2	240.0	split	3	no
3splits	340	195.1	147.2	25.9	138.6	340.0	split	3	no
4FERT	140	174.7	71.2	12.4	134.4	140.0	FERT	4	no
4FERT	240	194.6	107.4	18.8	138.8	240.0	FERT	4	no
4FERT	340	195.2	143.7	25.3	139.4	340.0	FERT	4	no
4splits	140	170.9	75.3	13.0	138.3	140.0	split	4	no
4splits	240	194.6	115.2	20.1	144.0	240.0	split	4	no
4splits	340	195.0	155.2	27.1	143.8	340.0	split	4	no
8FERT	140	176.2	68.9	11.8	141.6	139.8	FERT	8	no
8FERT	240	193.9	102.1	17.7	143.2	240.0	FERT	8	no
8FERT	340	194.7	137.3	23.8	146.0	339.5	FERT	8	no
8splits	140	177.0	69.0	11.8	144.1	140.0	split	8	no
8splits	240	193.9	102.0	17.7	143.4	240.0	split	8	no
8splits	340	194.9	137.1	23.6	148.8	340.0	split	8	no

Table 2) Climate and Weather Variability. Years were classified using a k-means clustering approach using the average maximum daily temperature and growing season precipitation. Classifications include baseline (average of 1979-2021), cool and dry, cool and wet, warm and dry, and warm and wet.

Condition	Yield [bu/ac]	Leaching [kg/ha]	N conc [mg/L]	Yield % Change	Leaching % Change	N concentration % Change	Irrigation [mm]	Average Fertilizer [kg/ha]	Average T Max [°C]	Precip [mm]
baseline	189.3	115.6	20.2	0.0	0.0	0.0	139.4	252.5	22.9	591.8
cool_dry	189.0	107.4	20.9	-0.2	-7.2	3.1	134.4	252.0	21.3	504.5
cool_wet	200.4	159.9	18.7	5.6	38.5	-7.2	68.0	244.9	21.2	832.1
warm_dry	179.7	99.7	20.7	-4.9	-13.8	2.5	243.7	262.0	26.4	426.5
warm_wet	189.1	153.0	20.0	-0.1	32.8	-0.8	106.4	249.3	23.0	829.3

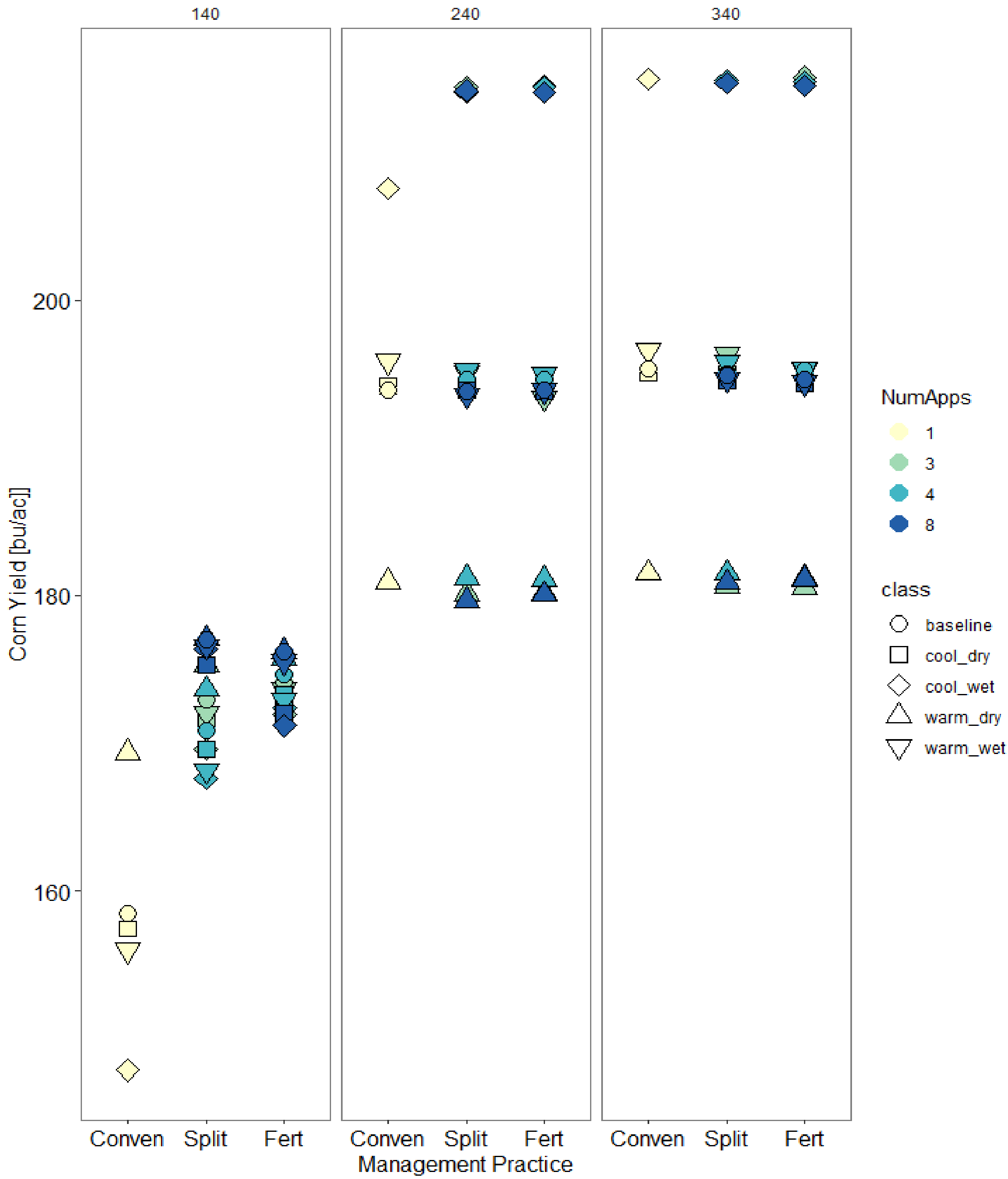

Figure 1) Average corn yield across a range of nitrogen management practices, nitrogen application rates, and climate conditions. Colors indicate the timing and number of fertilizer applications events. Panels indicate the base fertilizer rate, which does not include any background nitrogen supplied through irrigation water. Symbol shape indicates the climate category and classification.

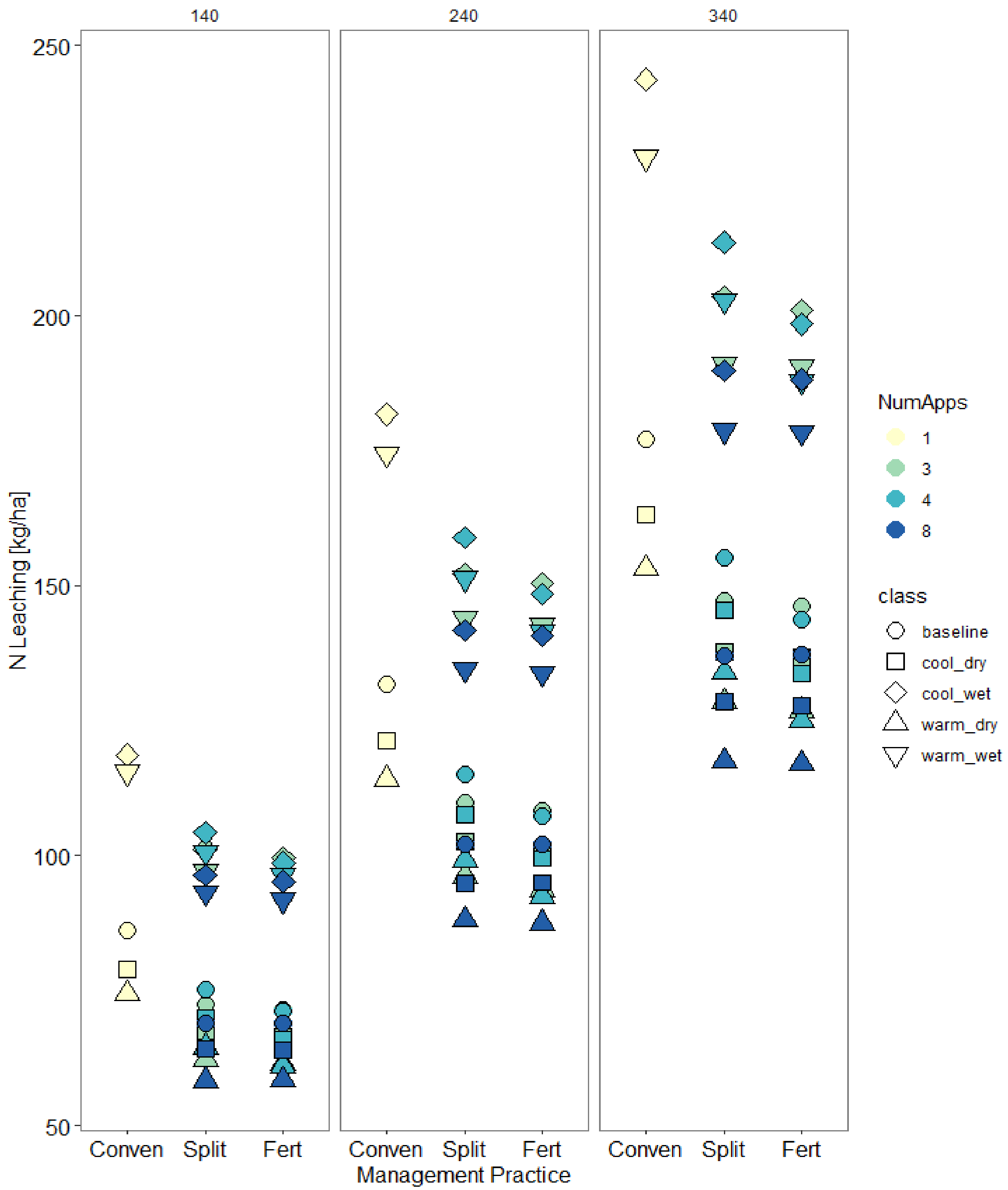

Figure 2) Average annual NO_3-N leaching [kg N ha^{-1} yr^{-1}] across a range of nitrogen management practices, nitrogen application rates, and climate conditions. Colors indicate the timing and number of fertilizer applications events. Panels indicate the base N fertilizer rate, which does not include background N supplied through irrigation water. Symbol shape indicates the climate category and classification.

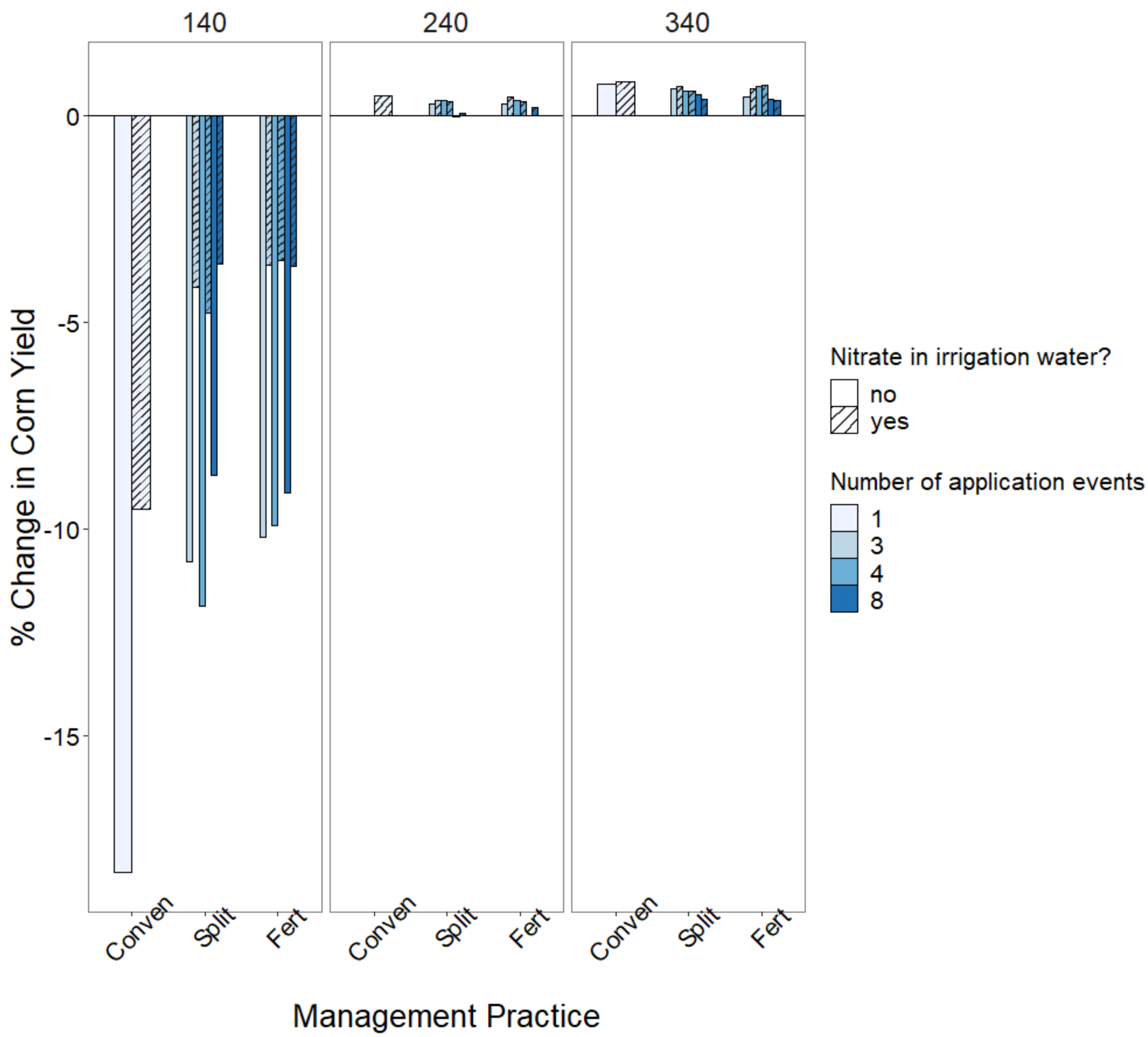

Figure 3) The percent change (%) in corn yield as a result of changes in nitrogen management practice and nitrogen application rate. Baseline was defined as 100% nitrogen fertilizer applied at planting for a rate of 240 kg/ha. Colors indicate the timing and number of fertilizer applications events. Panels indicate the base fertilizer rate, which does not include any background nitrogen supplied through irrigation water. Diagonal lines indicate whether nitrate was present in irrigation water.

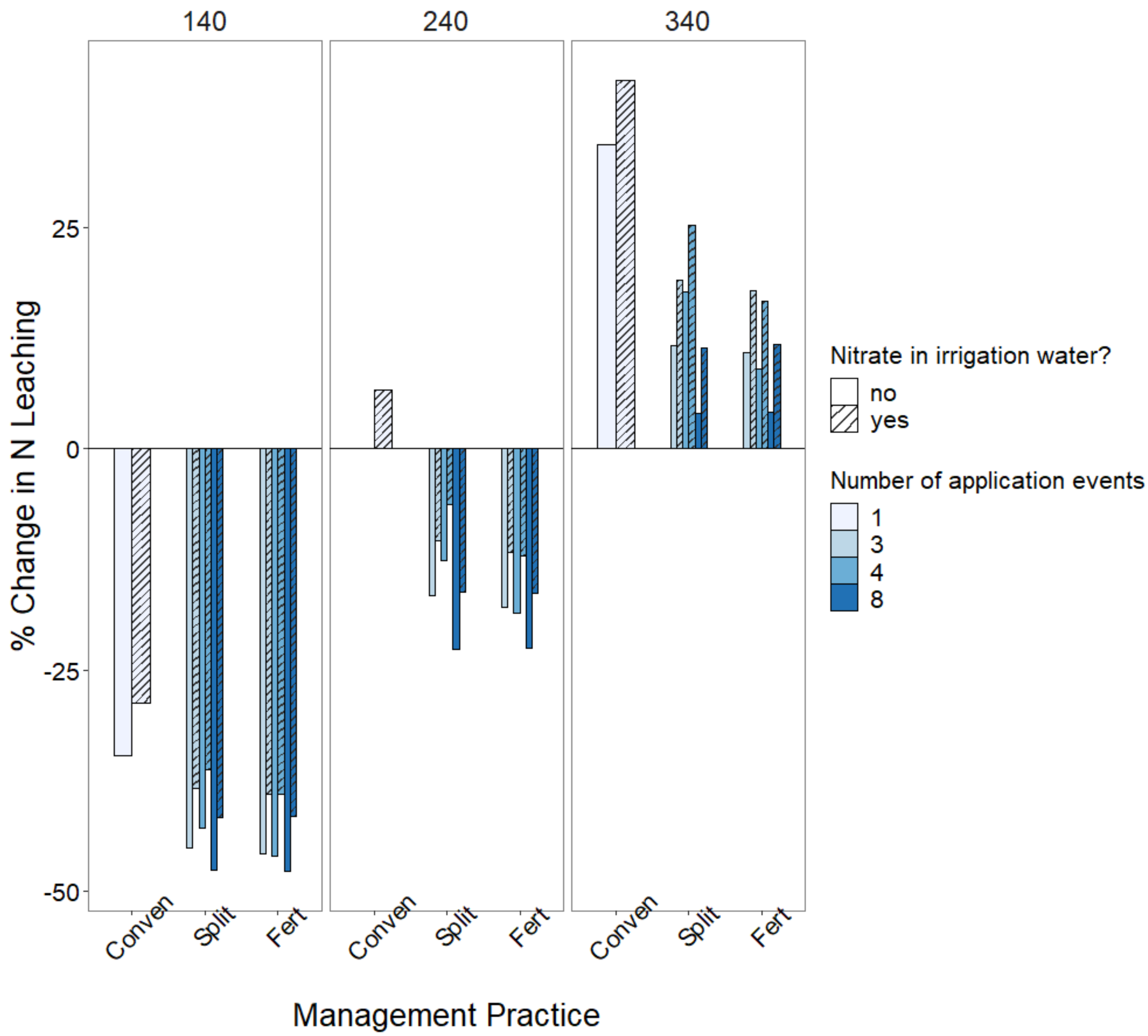

Figure 4) The percent change (%) in nitrate leaching as a result of changes in nitrogen management practice and nitrogen application rate. Baseline was defined as 100% nitrogen fertilizer applied at planting for 240 kg/ha. Colors indicate the timing and number of fertilizer applications events. Panels indicate the base fertilizer rate, which does not include any background nitrogen supplied through irrigation water. Diagonal lines indicate whether nitrate was present in irrigation water.

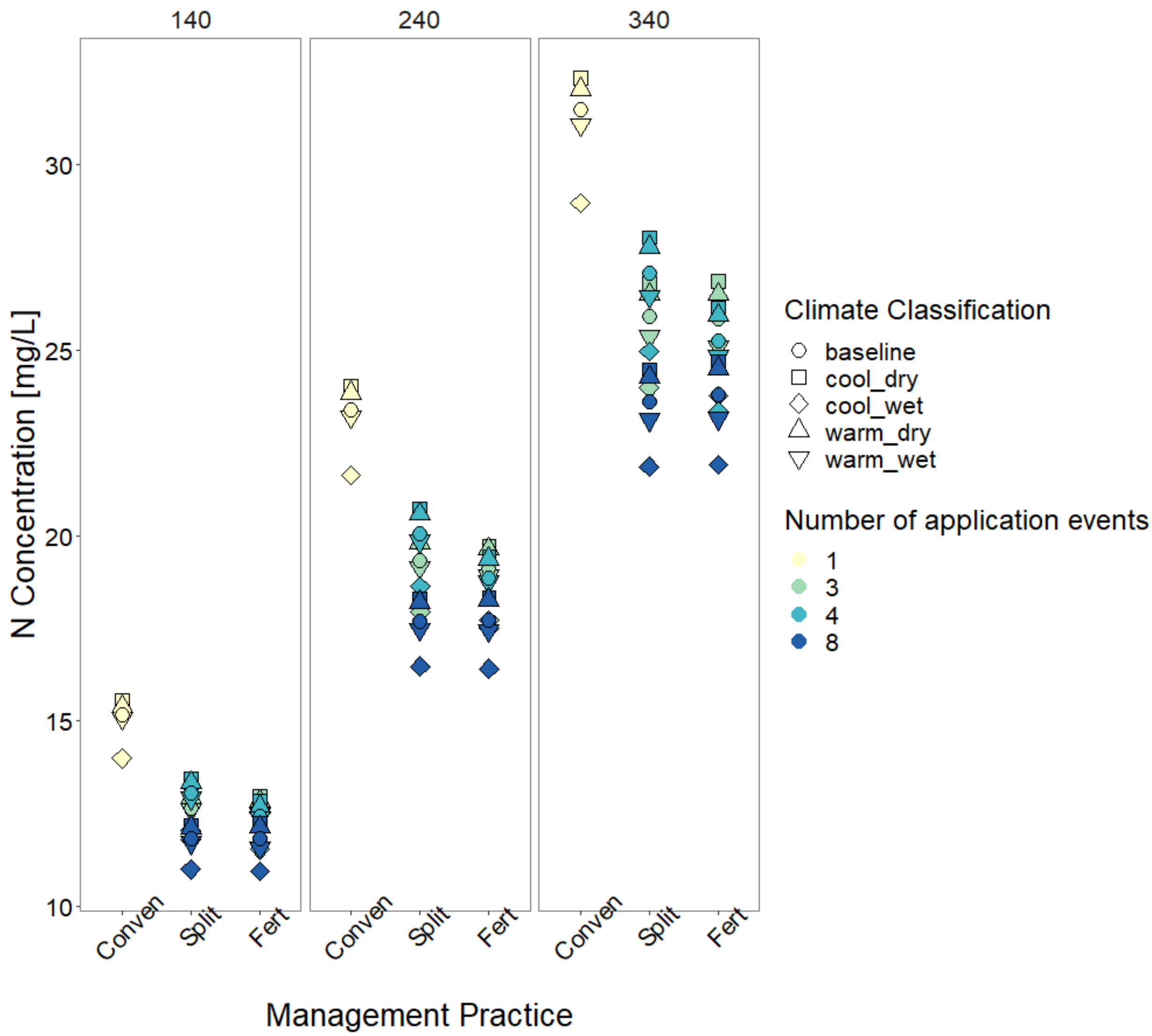

Figure 5) Average nitrate concentration [mg/L] across a range of nitrogen management practices, nitrogen application rates, and climate and weather conditions. Colors indicate the timing and number of fertilizer applications events. Panels indicate the base fertilizer rate, which does not include any background nitrogen supplied through irrigation water. Symbol shape indicates the climate category and classification.

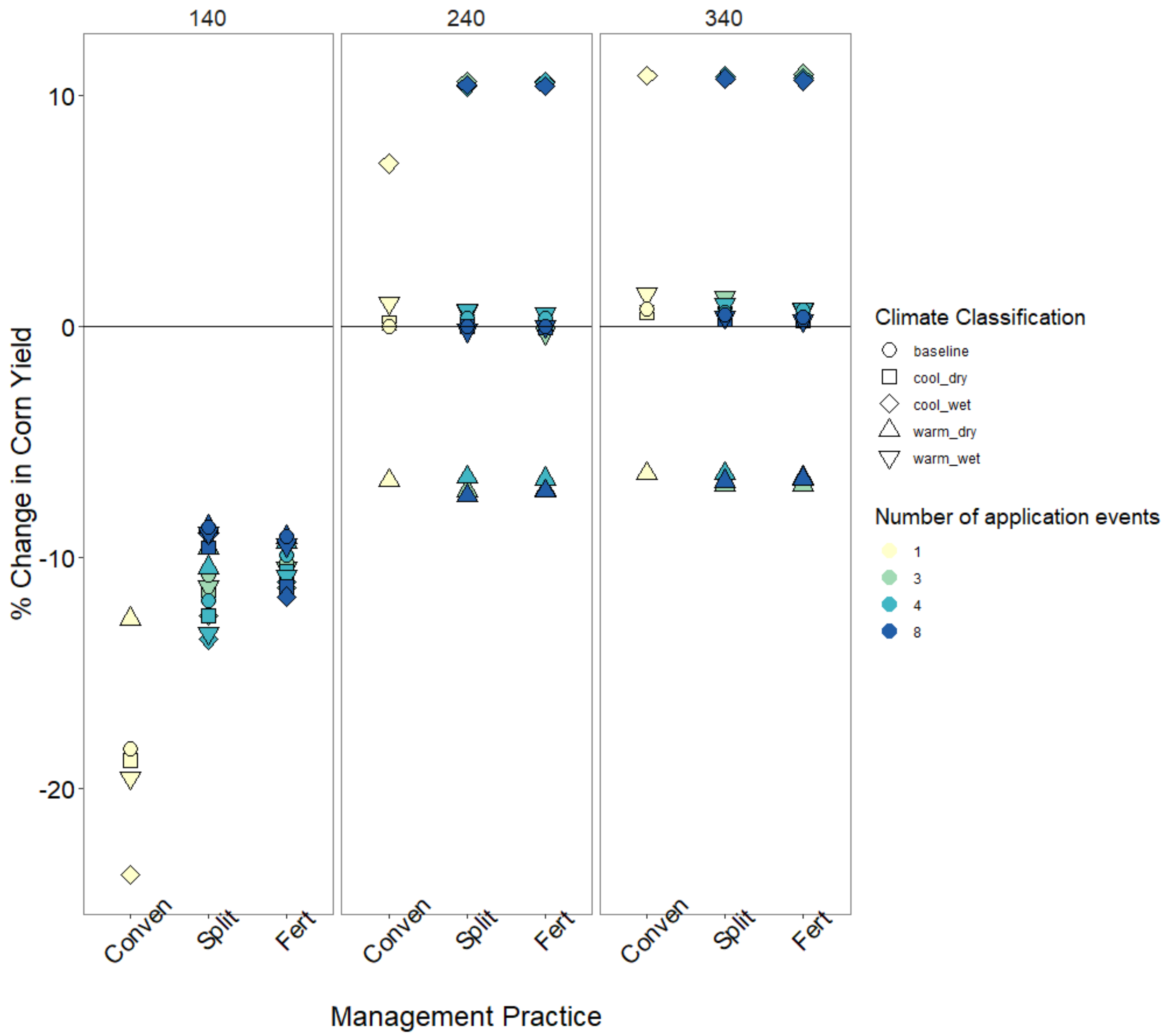

Figure 6) The percent change (%) in corn yield as a result of changes in nitrogen management practice, nitrogen application rate, and climate and weather conditions. Baseline was defined at 100% of nitrogen fertilizer applied at planting for 240 kg/ha under baseline climate conditions defined as the average of 1979 - 2021. Colors indicate the timing and number of fertilizer applications events. Panels indicate the base fertilizer rate, which does not include any background nitrogen supplied through irrigation water. Symbol shape indicates the climate category and classification.

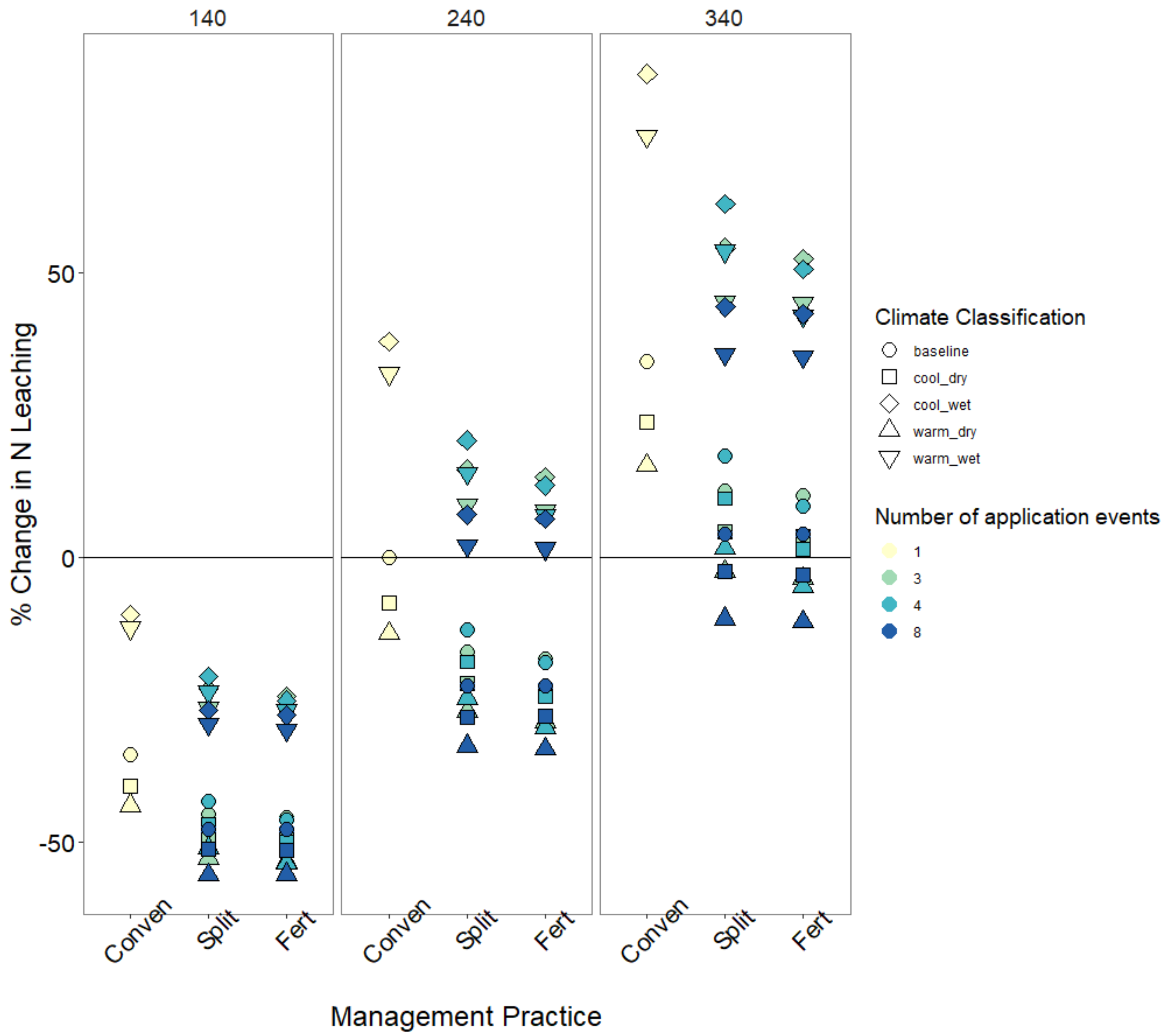

Figure 7) The percent change (%) in nitrate leaching as a result of changes in nitrogen management practice, nitrogen application rate, and climate and weather conditions. Baseline was defined at 100% of nitrogen fertilizer applied at planting for 240 kg/ha under baseline climate conditions defined as the average of 1979 - 2021. Colors indicate the timing and number of fertilizer applications events. Panels indicate the base fertilizer rate, which does not include any background nitrogen supplied through irrigation water. Symbol shape indicates the climate category and classification.

3.8 Supplemental information

Model Parameterization:

During model parameterization, the following leaf physiology parameters were adjusted: Vcmax changed from a maximum Vcmax of 34 to 40 μmol m^{-2} s^{-1} and specific leaf area changed from 47.5 to 52 (m^2 leaf area per kg of C). Compared to previous versions of Agro-IBIS, the following soil properties were adjusted: soil porosity, wilting point, and field capacity. Prior to model calibration, values of .437, .055, and .125 were used to represent porosity, wilting point, and field capacity respectively. After model calibration, soil parameters were adjusted to .368, .050, and .130 for porosity, wilting point, and field capacity respectively.

Table S1) Growing season (April 1 to October 1) maximum and minimum daily temperature (°C) and precipitation (mm) for all years of our modeling study, 1979 to 2021.

Year	Yield (bu/ac)	Precip (mm)	Tmax (°C)	Tmin (°C)
1979	194.54	799.56	22.55	9.03
1980	177.90	840.40	23.70	10.11
1981	187.43	670.89	23.03	9.45
1982	188.81	832.27	22.37	9.15
1983	157.13	851.89	23.05	10.07
1984	167.53	926.73	22.90	9.63
1985	189.37	849.75	23.56	9.90
1986	195.52	866.70	23.30	10.35
1987	166.67	738.43	24.77	10.79
1988	172.57	659.19	26.00	10.53
1989	190.18	620.94	23.09	9.11
1990	178.00	940.60	23.08	10.23
1991	195.76	863.15	24.01	10.63
1992	193.68	839.26	21.16	8.50
1993	188.14	992.19	20.84	9.34
1994	178.11	763.04	22.81	10.19
1995	141.75	802.35	22.91	10.63
1996	183.69	742.81	21.63	9.21
1997	185.37	670.26	20.82	9.09
1998	188.12	807.21	23.72	11.16
1999	199.61	886.00	22.45	10.51
2000	196.06	863.14	21.62	9.99
2001	177.69	869.56	22.87	10.71
2002	193.42	827.75	22.55	10.67
2003	202.03	694.51	22.50	9.63
2004	205.41	906.04	21.65	9.54
2005	186.35	730.09	23.83	11.06
2006	194.22	714.64	23.12	10.76
2007	190.91	827.53	23.42	10.68
2008	207.74	858.33	22.07	9.73
2009	193.11	760.25	21.62	9.08

2010	170.44	1014.52	23.43	11.62
2011	179.20	814.91	24.03	10.24
2012	186.74	731.50	26.80	10.28
2013	194.04	783.40	24.17	9.74
2014	204.41	830.48	22.01	9.70
2015	195.06	840.27	23.20	10.65
2016	195.06	1113.79	22.90	11.01
2017	220.20	989.42	22.52	9.93
2018	201.87	1139.49	22.53	10.44
2019	212.63	1174.18	21.53	10.09
2020	208.52	806.36	22.36	9.93
2021	204.39	812.03	23.43	10.49

Table S2) Model evaluation comparing the average, standard deviation (SD), standard error, and coefficient of variation (CV), minimum, and maximum values for modeled corn yield (across 42 nitrogen management scenarios), county average corn yield (2010-2021), and observed field data (applied a nitrogen application rate of 134 to 336 kg N/ha).

Type	**Corn Yield (bu/ac)**	**SD**	**Error**	**CV**	**Min**	**Max**
County	161.65	18.59	5.16	11.50	118.10	187.80
Modeled	189.29	18.17	0.43	9.60	132.81	234.81
Observed	219.83	25.34	4.48	11.53	152.09	255.87

Methods : Climate Classifications

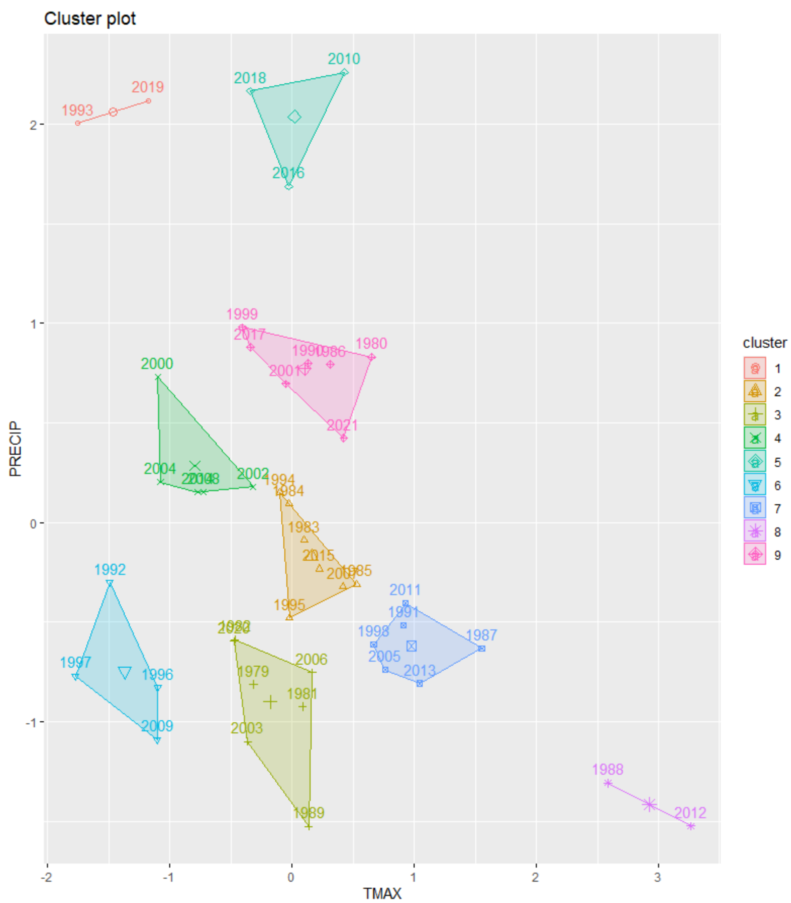

Figure S1) K-means cluster analysis based on the annual growing season precipitation (mm) and the average annual maximum daily temperature (°C).

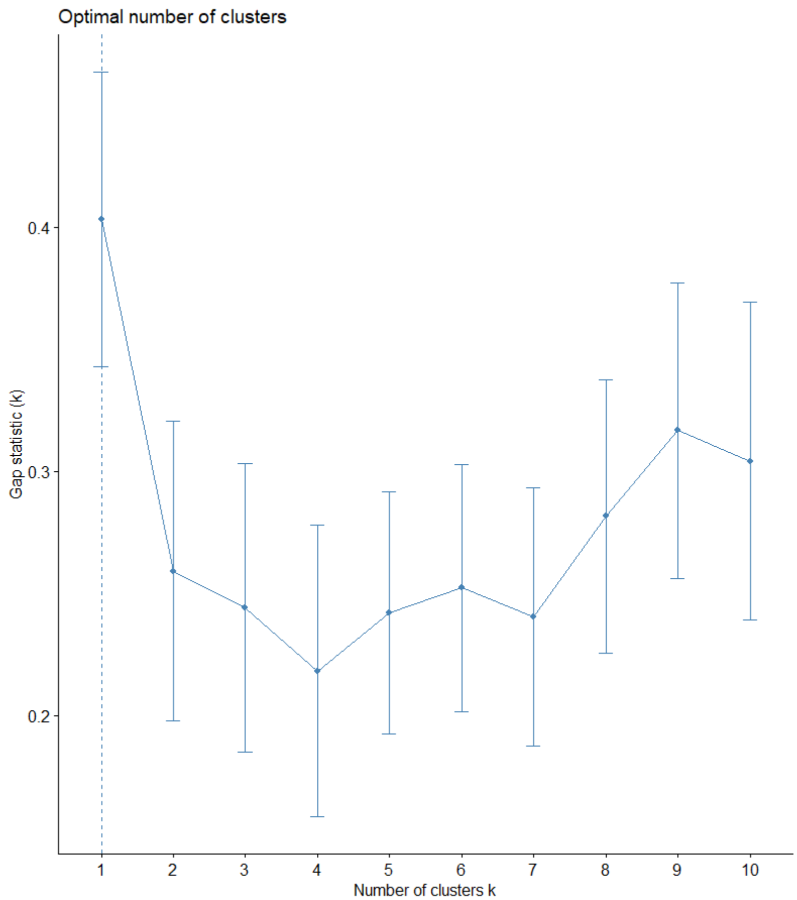

Figure S2) Gap statistics approach indicating that the ideal number of clusters based on the peak value of the y-axis.

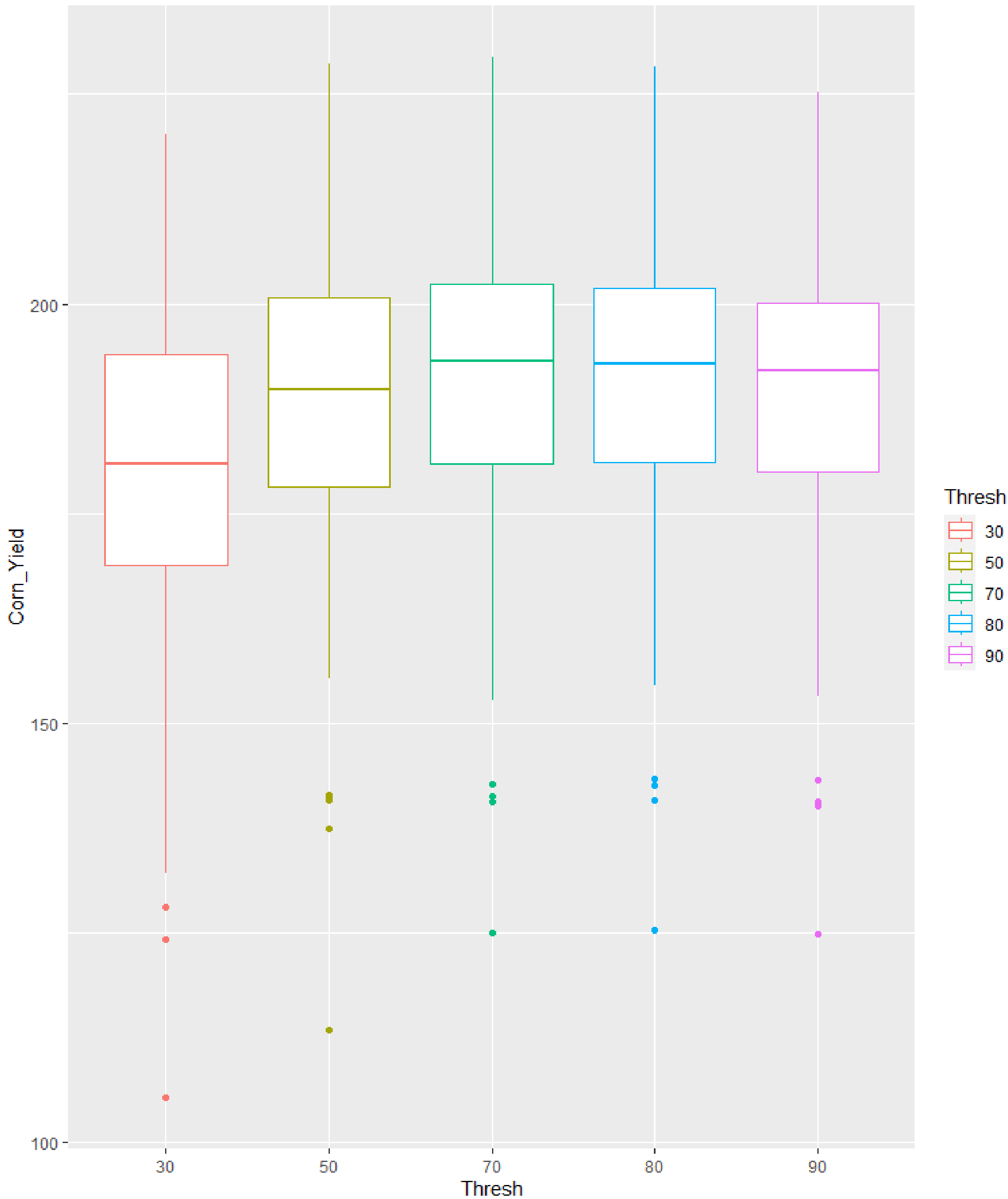

Figure S3) Box plot of modeled corn yield in response to different thresholds for triggering irrigation, 30, 50, 70, 80, and 90% of actual plant available water content (AWC). Box plots signify the range of values (vertical lines), the median (solid line), outliers (dots), and the 25th and 75th percentile range. Color signifies the irrigation threshold used for model simulations.

Results

Model Evaluation:

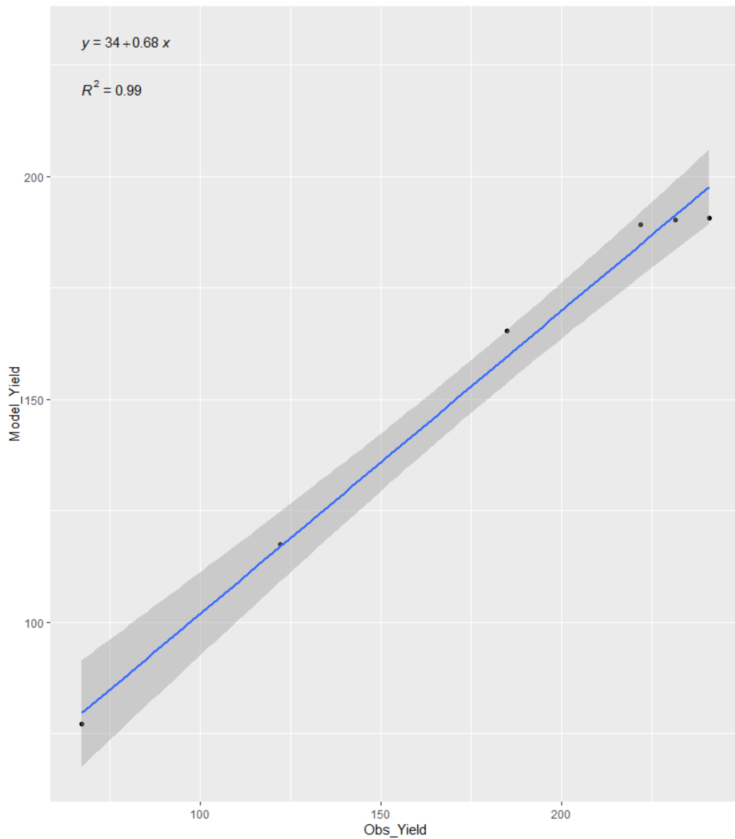

Figure S4) Relationship between modeled corn yield and observed corn yield in response to six nitrogen application rates (0, 67, 134, 201, 269, 336 kg/ha of N). The R^2 is .99, showing good agreement between our model's ability to predict corn yield in response to varying rates of nitrogen fertilizer and field data.

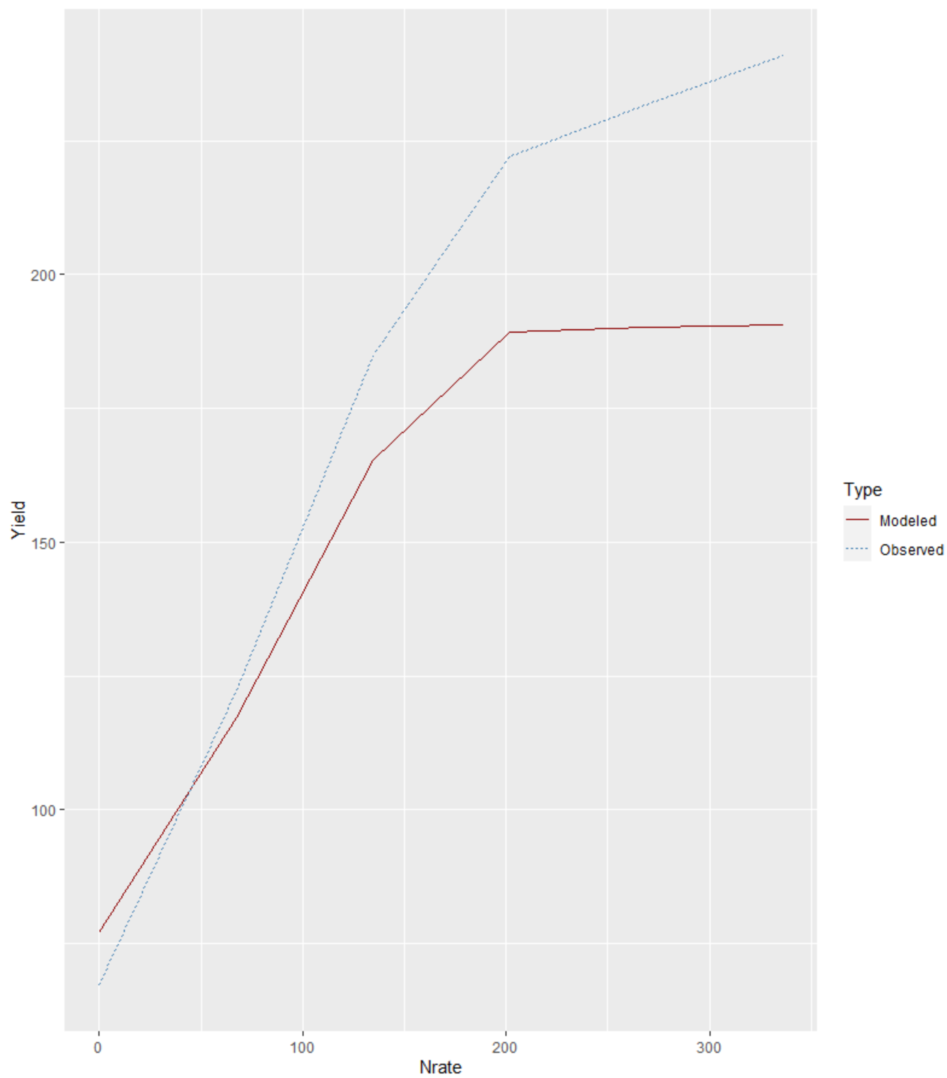

Figure S5) Relationship between nitrogen fertilizer application rate [kg/ha] and corn yield [bu/ac]. Line type and color indicate the type of data, with red soil line indicating modeled corn yield and a gray dashed line representing observed field corn yields.

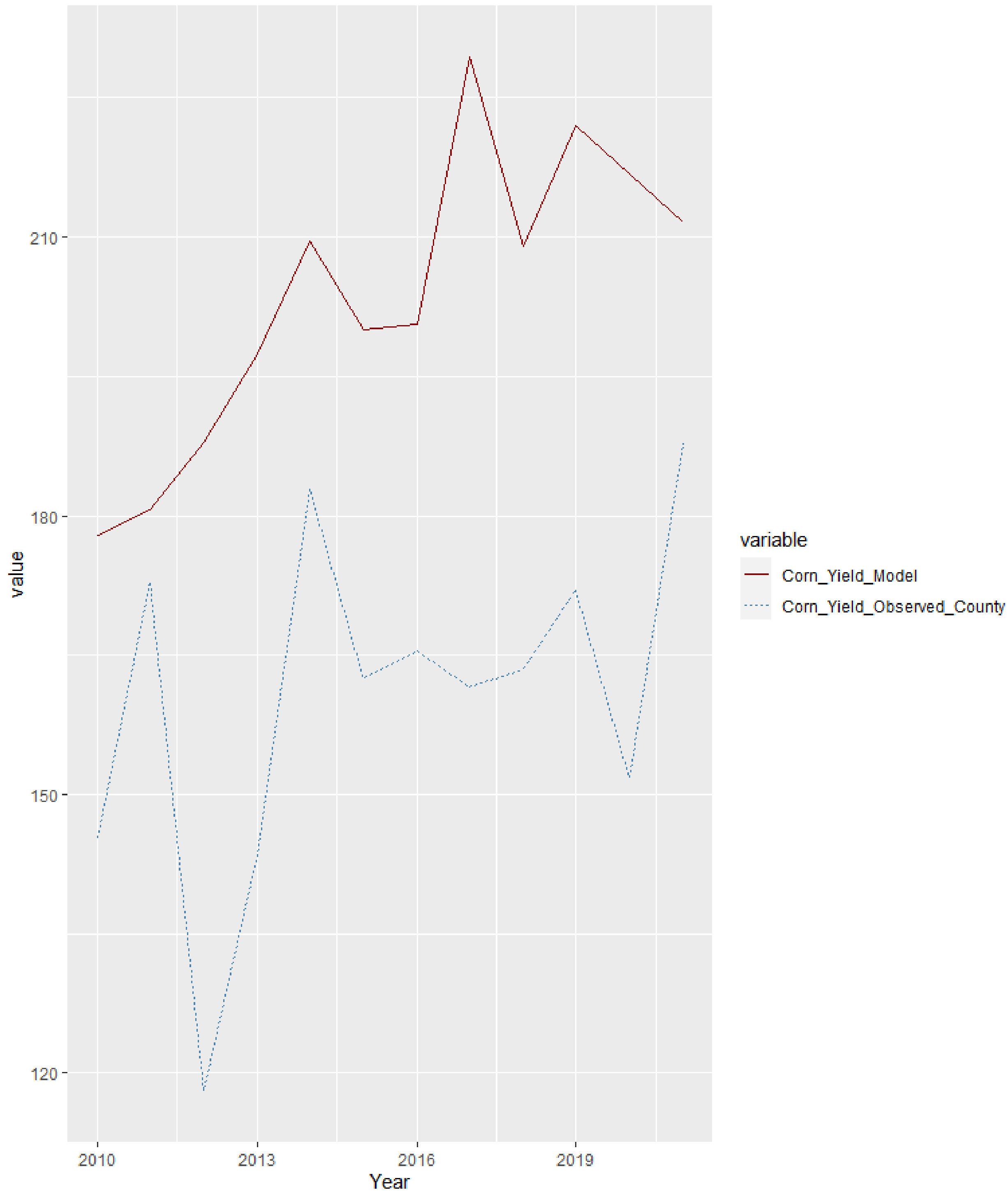

Figure S6) Annual observed county level crop yield versus simulated corn yield with a nitrogen application rate of 240 kg/ha applied 100% at planting, spanning from 2010 to 2021. Line type and color indicate the type of data, with red soil line indicating modeled corn yield and a gray dashed line representing observed county average corn yields.

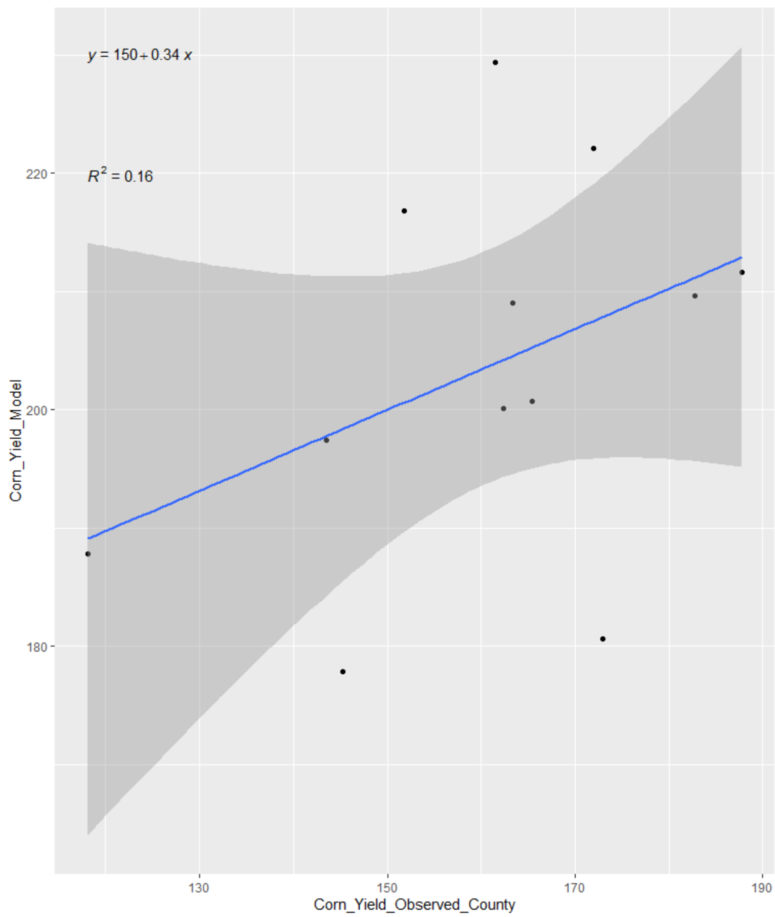

Figure S7) Relationship between modeled corn yield and observed county level average corn yield for Waushara County for 1979 to 2021. The R^2 value is .16.

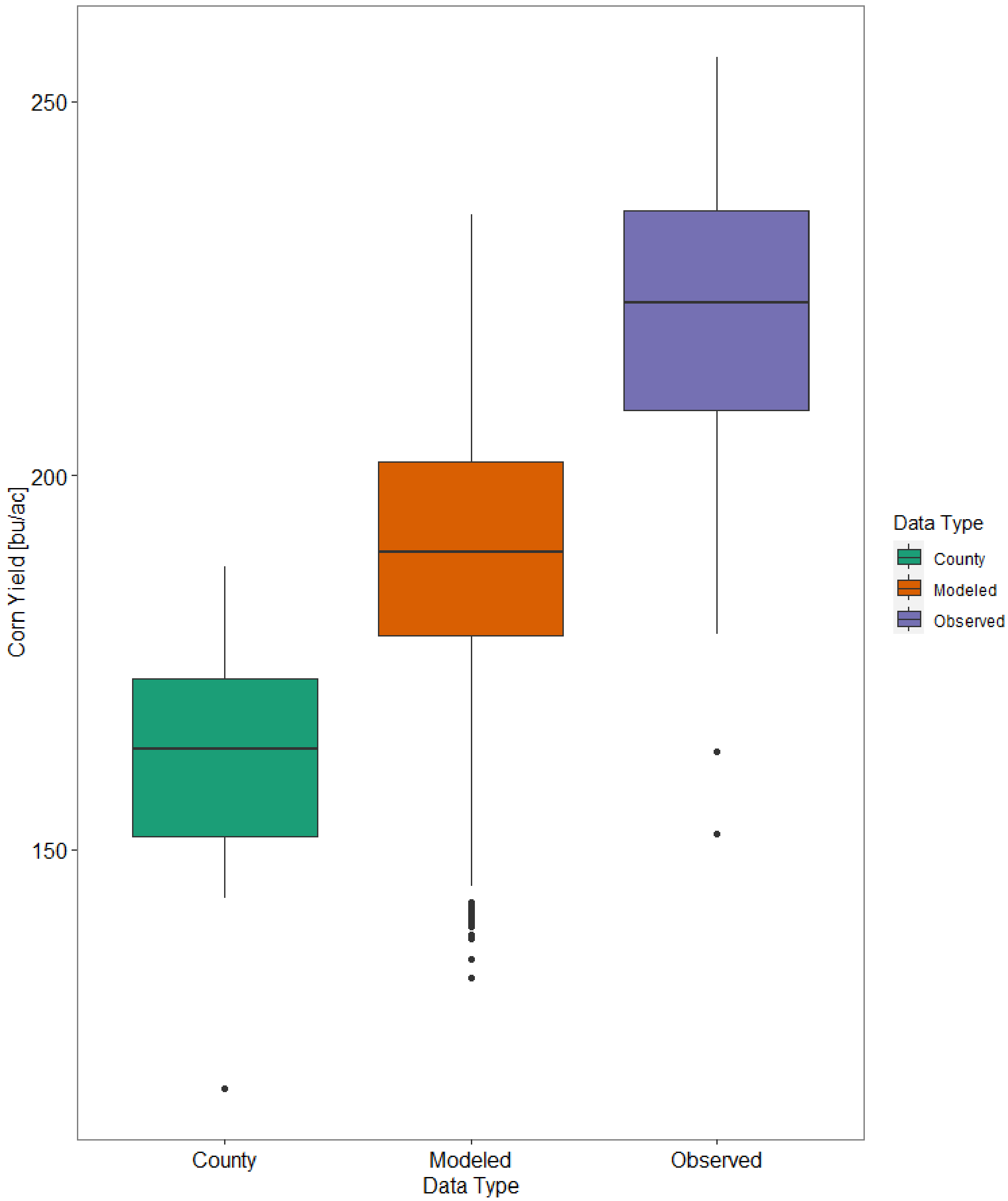

Figure S8) Model evaluation comparing modeled corn yield (across 42 nitrogen management scenarios), county average corn yield (2010-2021), and observed field data (applied a nitrogen application rate of 134 to 336 kg N/ha). Box plots signify the range of values (vertical lines), the median (solid line), outliers (dots), and the 25th and 75th percentile range.

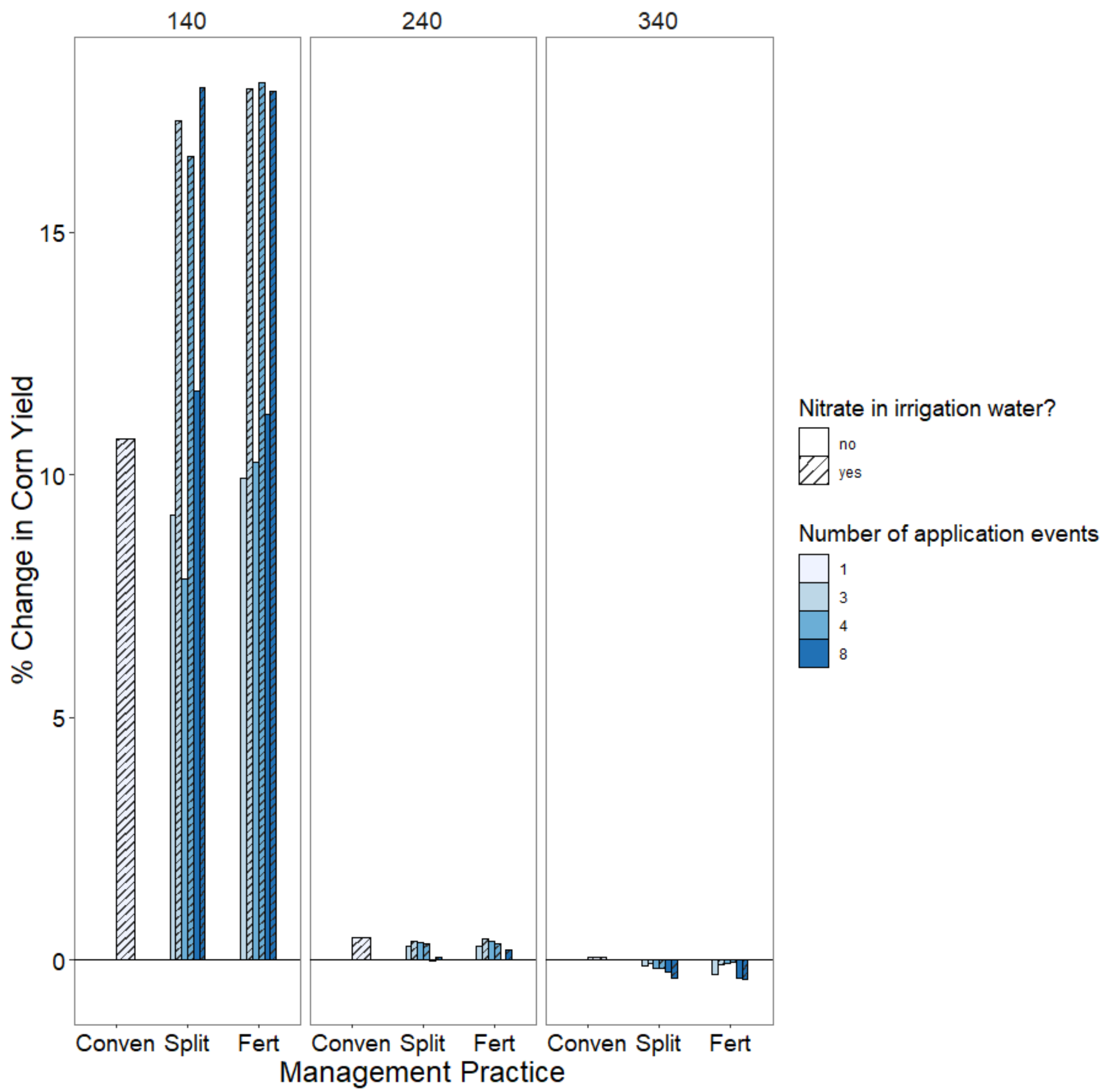

Figure S9) The percent change (%) in corn yield as a result of changes in nitrogen management practice. Baseline was defined at 100% of nitrogen fertilizer applied at planting for each respective fertilizer rate: 140, 240, and 340 kg/ha. Colors indicate the timing and number of fertilizer applications events. Panels indicate the base fertilizer rate, which does not include any background nitrogen supplied through irrigation water. Diagonal lines indicate whether nitrate was present in irrigation water.

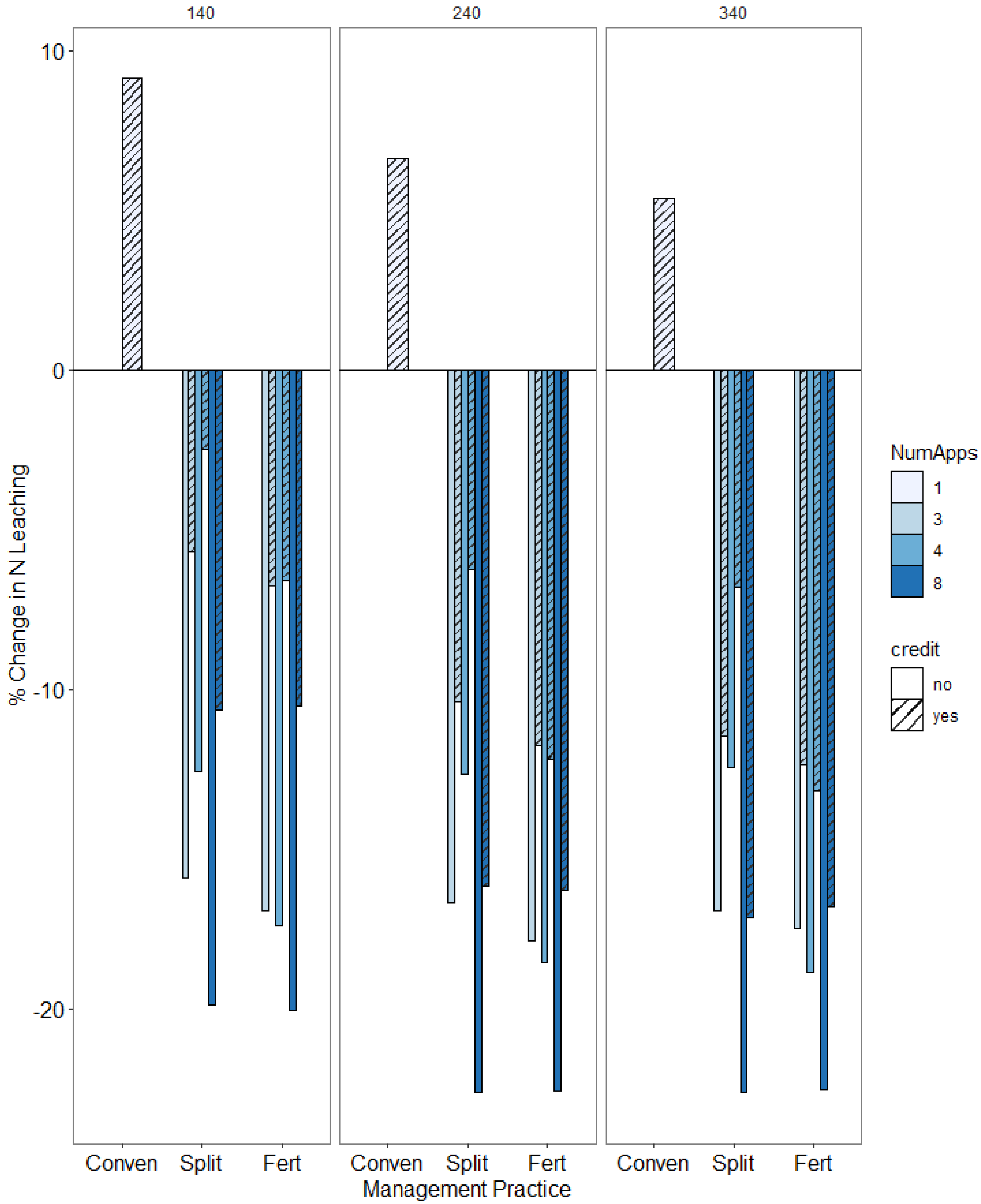

Figure S10) The percent change (%) in nitrate leaching as a result of changes in nitrogen management practice. Baseline was defined at 100% of nitrogen fertilizer applied at planting for each respective fertilizer rate: 140, 240, and 340 kg/ha. Colors indicate the timing and number of fertilizer applications events. Panels indicate the base fertilizer rate, which does not include any background nitrogen supplied through irrigation water. Diagonal lines indicate whether nitrate was present in irrigation water.

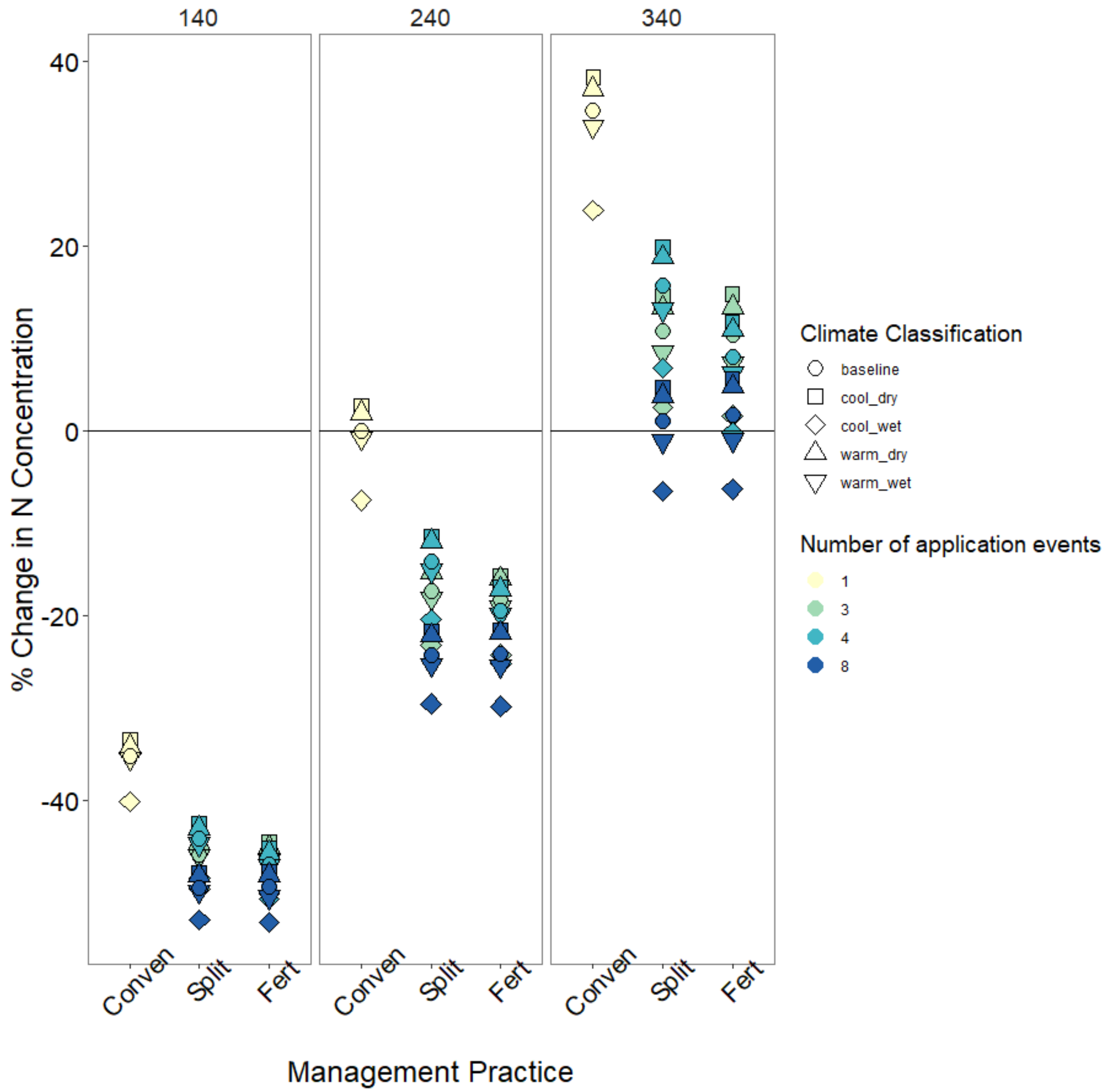

Figure S11) The percent change (%) in nitrate concentration [mg/L] as a result of changes in nitrogen management practice, nitrogen application rate, and climate conditions. Baseline was defined at 100% of nitrogen fertilizer applied at planting at 240 kg/ha under baseline climate conditions defined as the average of 1979 - 2021. Colors indicate the timing and number of fertilizer applications events. Panels indicate the base fertilizer rate, which does not include any background nitrogen supplied through irrigation water. Symbol shape indicates the climate category and classification.

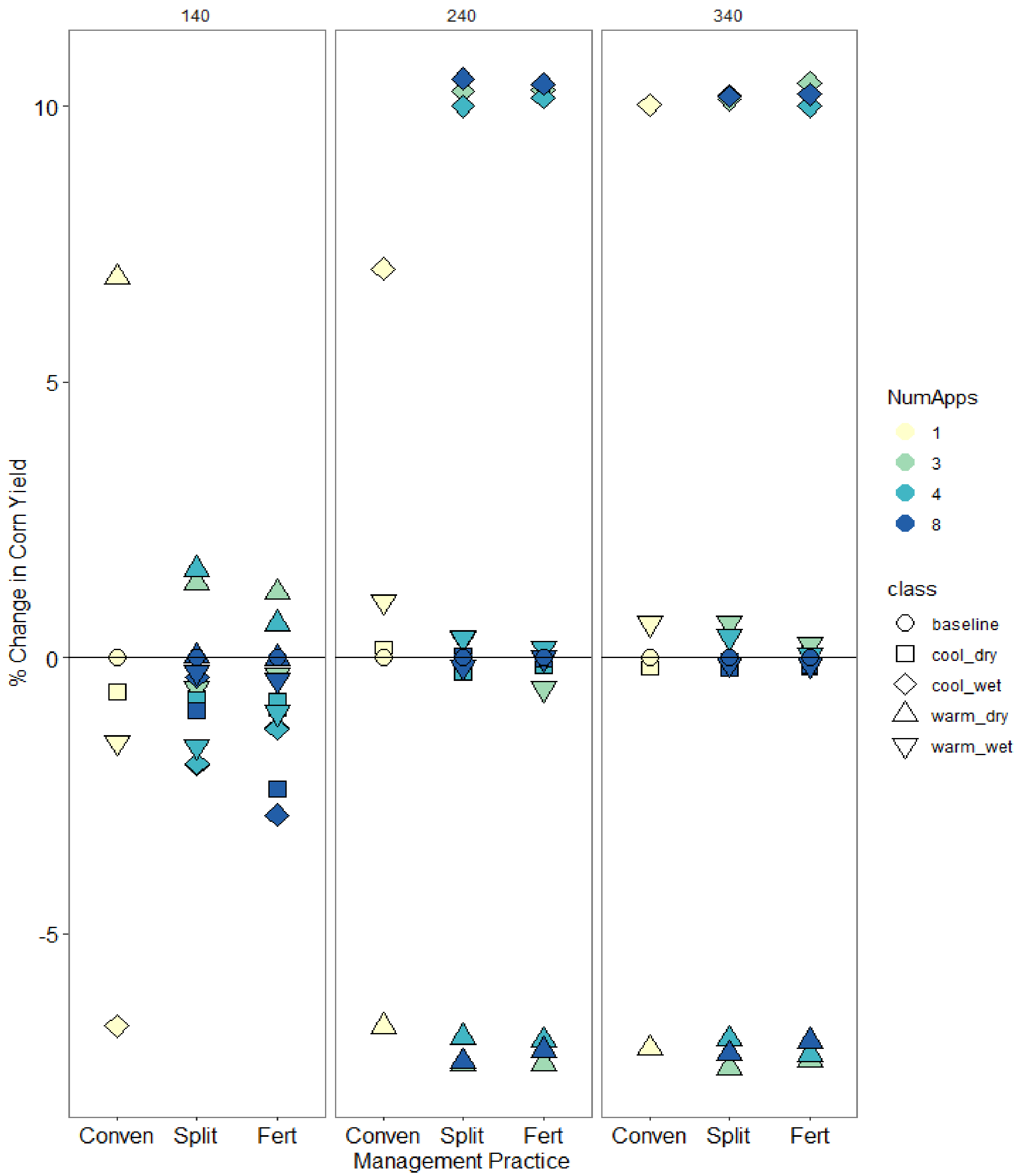

Figure S12) The percent change (%) in corn yield as a result of changes in climate and weather variability alone. Baseline was defined as the climate of 1979-2021 averaged, for each respective nitrogen application rate, management practice, and combination thereof. In total, 42 baselines were used to isolate the impact of climate alone. Colors indicate the timing and number of fertilizer applications events, becoming darker with increasing number of application events. Panels indicate the base fertilizer rate, which does not include any excess nitrogen supplied through irrigation water. Shape indicates the climate classification.

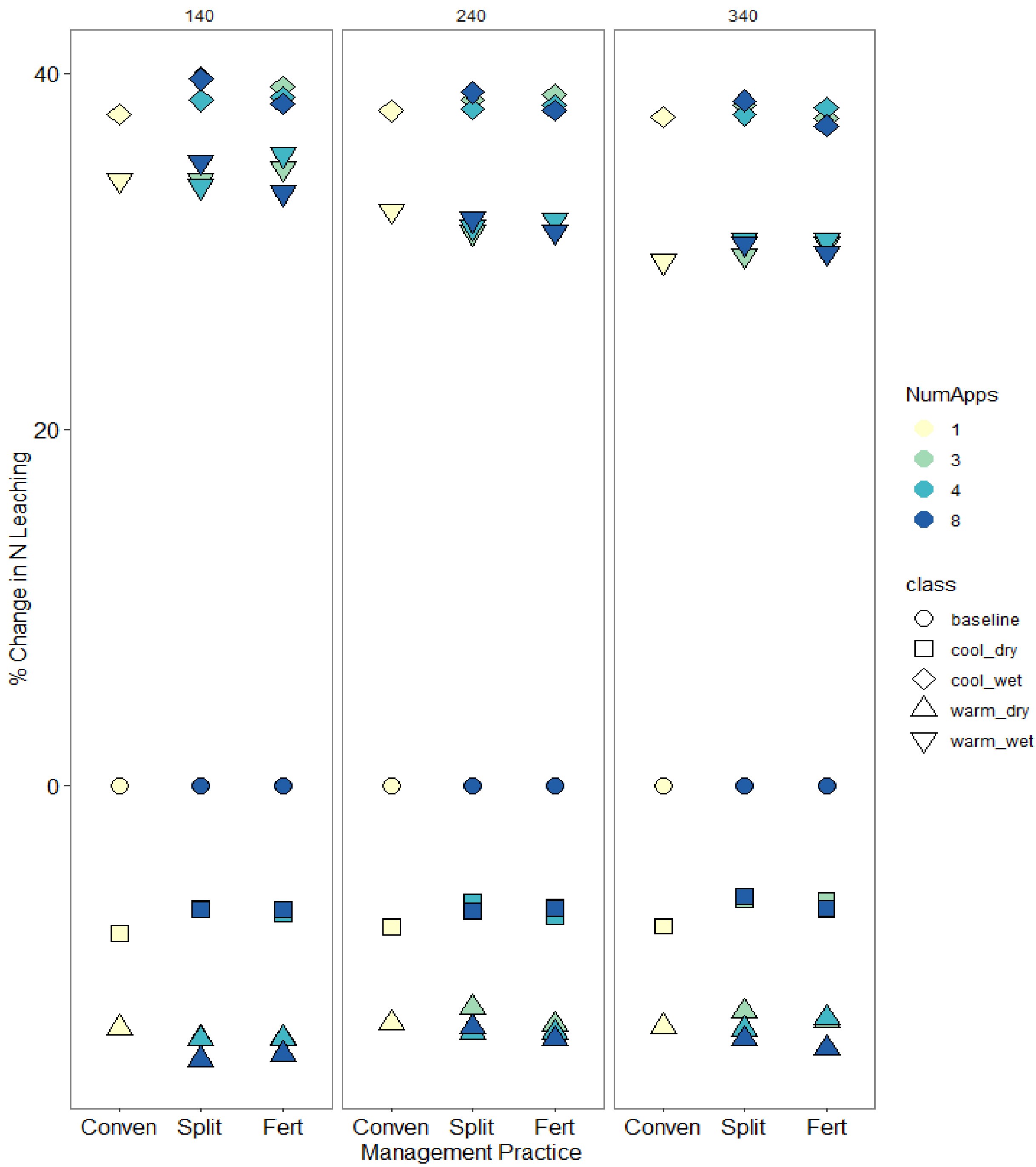

Figure S13) The percent change (%) in nitrate leaching as a result of changes in climate and weather variability alone. Baseline was defined as the climate of 1979-2021 averaged, for each respective nitrogen application rate, management practice, and combination thereof. In total, 42 baselines were used to isolate the impact of climate alone. Colors indicate the timing and number of fertilizer applications events, becoming darker with increasing number of application events. Panels indicate the base fertilizer rate, which does not include any excess nitrogen supplied through irrigation water. Shape indicates the climate classification.

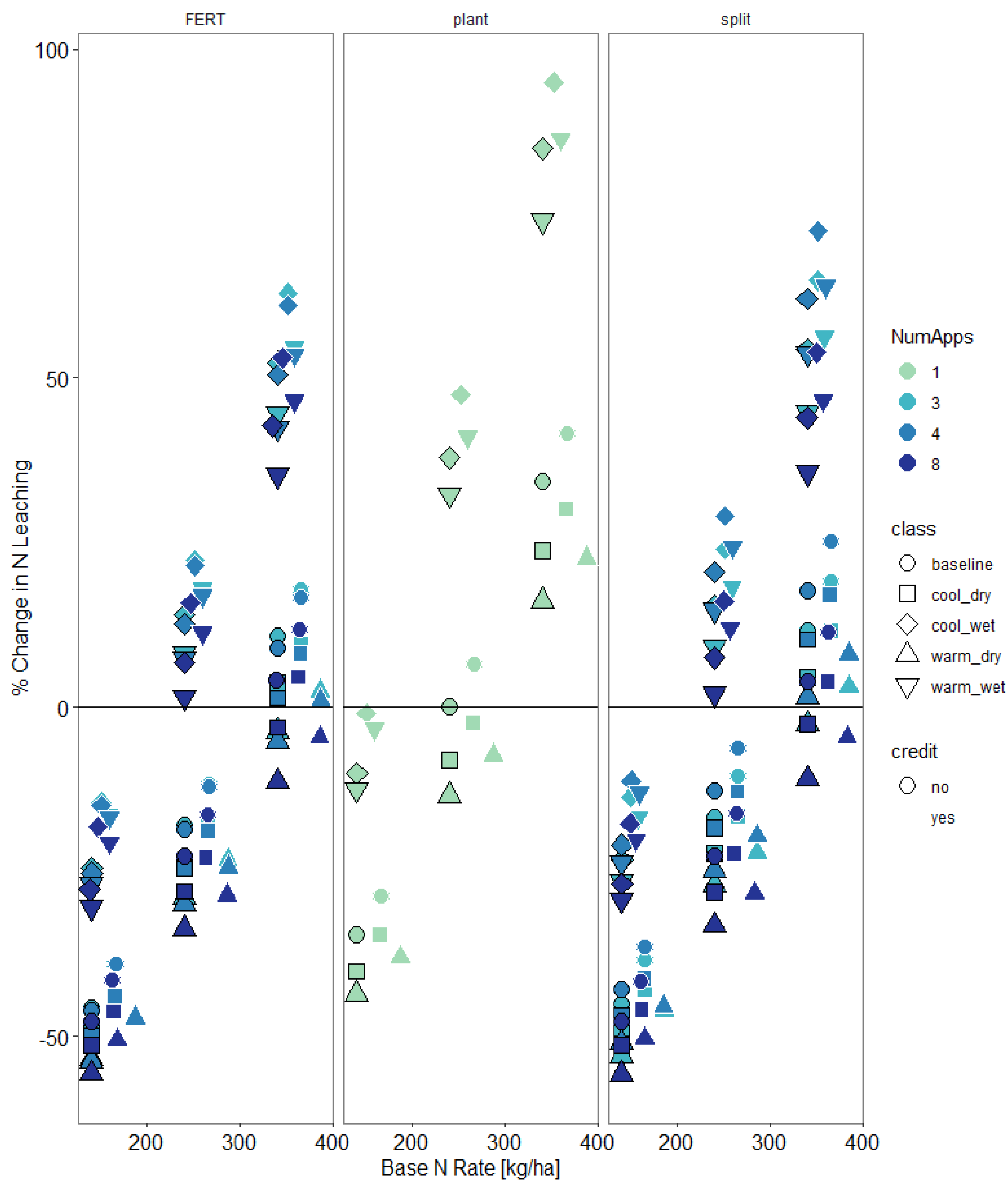

Figure S14) The percent change (%) in nitrate leaching as a result of changes in nitrogen management practice, nitrogen application rate, presence or absence of nitrate in irrigation water, and climate and weather conditions. Baseline was defined at 100% of nitrogen fertilizer applied at 240 kg/ha under baseline climate conditions defined as the average of 1979 - 2021. Colors indicate the timing and number of fertilizer applications events, becoming darker with increasing number of application events. Panels indicate the base fertilizer rate, which does not include any excess nitrogen supplied through irrigation water. Shape indicates the climate classification. Shape outline indicates presence (no outline) or absence (outline) of nitrate in irrigation water.

Chapter 4: Assessing growers' current nitrogen management practices, concerns, and barriers across the Wisconsin Central Sands

Abstract

Growers across the Wisconsin Central Sands (WCS) are faced with responding to increasing environmental contamination while continuing to maintain crop production and profit. As a result, a range of best management practices (BMPs) have been developed to reduce environmental impacts while maintaining crop yield. While there has been considerable research on impacts and tradeoffs of BMPs on agronomic and environmental variables, it is uncertain how often these practices are adopted, how they relate to growers' concerns, and the barriers to adopting them. To address these uncertainties, we surveyed farmers in the WCS on their current nitrogen management practices, levels on concern about environmental and economic agricultural challenges, as well as barriers to implementing new nitrogen management practices. We found that the majority (69%) of growers are implementing the BMP of split application, but fewer (20%) credit the nitrate found in irrigation water. Farmers reported lack of information, risk to crop yield, and unclear benefits of crediting as the largest barriers to crediting the nitrate found in irrigation water. Growers reported the highest level of concern for the economic costs of government regulation and inefficient government policies. Moving forward, future research and communication should work to address uncertainties and risk, as well as to reflect the diverse range in farmer motivations in order to increase BMP adoption.

4.1 Introduction

Wisconsin's Central Sands region faces a vexing challenge of simultaneously maintaining crop yields and economic revenue, while responding to the growing concern over groundwater contamination. Farming in the Wisconsin Central Sands (WCS) is especially challenging due to the sandy, coarse textured soil and shallow depth to water table which make the region extremely vulnerable to nitrate leaching. While the addition of nitrogen fertilizer is needed to support high yielding crops, such as corn and potato, nitrate is also readily leached through the sandy soil to the groundwater below. As concerns rise over the human and environmental impacts of increased levels of nitrate in surface and groundwater, the call for improved nitrogen management strategies is also rising.

Improved nitrogen management practices, often referred to as best management practices (BMPs) rely on voluntary practices that reduce environmental degradation while maintaining crop yield (Lamb & Barber, n.d.) . In general, these practices strive to incorporate the 4 R's of nutrient management: the right rate, the right source, the right time, and the right place (Hochmuth et al., 2014; The Fertilizer Institute, n.d.). Considering the sandy, course textured soil that characterizes much of the WCS, a large emphasis has been placed on the timing of nitrogen fertilizer applications. To enhance synchronization between available nitrogen in the soil and plant nitrogen requirements, the University of Wisconsin Extension recommends applying nitrogen fertilizer in split applications throughout the growing season (Bundy, n.d.; Laboski et al., 2012; Wolkowski et al., 1995). When determining the right rate of nitrogen fertilizer, UW Extension recommendations vary by crop, but generally consider estimated end of season crop yield, soil organic matter content, last season's crop, use of irrigation, and soil texture (Laboski et al., 2012). For any crop, an important part of determining the right rate is accurately crediting or accounting for all nitrogen sources. Aside from fertilizer, nitrogen sources may include leguminous past crops, inorganic nitrogen in the root zone, soil organic content, irrigation water, and atmospheric deposition (Cassman et al., 2002; Meisinger & Randall, 2015; Ribaudo et al., 2011). Recent work in the WCS has found nitrate levels in irrigation water to be on average 20 mg/L (Campbell et al. under review), which may provide a substantial amount of required nitrogen. However, there is still uncertainty on how to best implement nitrate crediting of irrigation water (Wolkowski et al., 1995) and it is unclear how often this practice is used and how to best increase adoption.

While understanding the science behind improved nitrogen management strategies is crucial, creating on the ground change is its own hurdle. Despite the development of BMPs they are often not widely adopted. A recent report by Ribaudo et al. (2011) found that two-thirds of U.S. cropland are not meeting the criteria for effective nitrogen management. Specifically, this study found that optimum nitrogen application rates were not used on 32% of U.S. cropland, and similarly, nitrogen application rates were applied at the improper time for 24% of U.S. cropland (Ribaudo et al., 2011). These findings are supported by a similar study focused on the Upper Mississippi River Basin, which found that appropriate nitrogen application rates, timing, and method were only used on about 16% of cropland acres from 2003 to 2006 (NRCS, 2012). Past research has attempted to explain adoption, or lack of adoption, of conservation practices, finding few consistently statistically significant predictors of adoption (Prokopy et al., 2019). However, findings indicate that those more motivated by conservation and stewardship are more likely to adopt conservation practices (Greiner et al., 2009; Prokopy et al., 2019), and perceived financial risk may hinder adoption for economically motivated farmers (Greiner et al., 2009).

To fully address our water quality challenges across the state, it is imperative to first understand current management practices and behaviors, as well as perceived barriers to adopting new practices. Incorporating social science perspectives and methodologies is a crucial component in changing management practices and improving groundwater quality. To better understand the challenges faced by growers in the Wisconsin Central Sands, as well as to improve science communication and inform new research projects, we surveyed growers about current nutrient management strategies, economic and environmental concerns, and barriers to adopting new management practices. Specific goals of the project were to 1) assess farmers' level of concern related to groundwater quality, in addition to other environmental and economic challenges; 2) assess farmers' current nutrient management practices; and 3) assess farmers' perceived barriers to adopting new management practices.

4.2 Methods

4.2.1 Survey questions

Survey questions were written to identify current nitrogen management strategies, levels of concern across a range of environmental and economic challenges, as well as to determine barriers to adopting new nitrogen management strategies. We specifically focused on better understanding the use of nitrogen crediting of irrigation water, in which fertilizer application rates reflect the nitrogen already present in irrigation water, and barriers to adopting this practice. To determine if any changes in behavior occurred over our two-year study period, a follow-up survey was sent one year after the first one, explicitly asking if any changes in crediting practices (in relation to irrigation water) had occurred over the prior 12 months. Questions were developed with assistance from the University of Wisconsin-Madison Survey Center. Questions regarding levels of concern, or likelihood of adopting a practice used the LIKERT scale with five categories (ex: very likely, somewhat likely, neither likely nor unlikely, somewhat unlikely, very unlikely). To determine basic information of respondents and their farms, we asked a few questions on farm characteristics (size, crops grown) and personal demographics (age, gender, education). One open-ended question was asked in both surveys in an effort to capture any missing information from our questions and allow respondents to more freely share their thoughts on the topics covered. To see a complete list of the survey questions, see Appendix X.

4.2.2 IRB approval

As this research involved human subjects, we obtained IRB approval during the Winter of 2019, prior to sending the initial survey to respondents. Our application was reapproved during the Winter of 2020, prior to the distribution of our follow-up survey. To reduce any risk to the respondents and ensure confidentiality, all personally identifying information was removed from survey responses, and all responses were stored in both physically and electronically secure locations requiring either a physical key or electronic passcode. Additionally, we attached a unique ID to each survey respondent in 2020, which allowed us to identify whether the same respondents answered the survey in 2021, and how their answers may have changed over this time without the use of personally identifiable information. To see recruit material and waivers of signed consent, see Appendix X.

4.2.3 Respondents

During the winter of 2020 and 2021, we sent our surveys both electronically and physically through the postal service to Wisconsin vegetable producers. Recipients' email addresses and personal addresses were obtained through the Wisconsin Potato and Vegetable Growers Association (WPVGA). Respondents were required to be 18 years of age or older and identify as a member of the WPVGA, no other restrictions were placed on respondents.

4.2.4 Timeline

Surveys were initially mailed in early January of 2020, and we requested all surveys were returned by February 1st, 2020. We explicitly requested responses by February 1st as our research team was presenting on Nitrate Crediting of Irrigation Water at the 2020 UW-Madison Division of Extension & WPVGA Grower Education Conference & Industry Show on February 4th. By taking this approach, we were able to guarantee that all responses were received before our findings were presented and distributed to the grower community. Considering we wanted to investigate the impact of more information on grower’s perceptions of nitrate crediting, and subsequently use of nitrate crediting in irrigation water, this was pertinent. In January of 2021, a similar survey was distributed, using the same mechanisms, to the same grower list. The follow-up survey was sent out in order to determine if any changes in nitrogen management practices occurred over the last year, and to evaluate possible reasons for this change.

4.3 Results

During the two-year study, we distributed surveys on grower's current nitrogen management practices, concerns, and perceived challenges and barriers to adopting new practices to 103 growers. In 2020, we received 52 responses, resulting in a response rate of 50.5%. To assess changes in nitrogen management over the course of the year, a similar survey was conducted in 2021, with 45 responses received, corresponding to a response rate of 43.6%.

4.3.1 Current nitrogen management practices

In response to questions regarding the timing of nitrogen application, the majority (69%) of respondents indicated that they apply fertilizer in split applications, and 22% indicated that they use field conditions to determine the timing of fertilizer application. A small minority (2%) indicated that they apply 100% of fertilizer at planting, and 6.6% of respondents indicated that they use an alternative method to determine when to apply fertilizer. The most common approach to applying fertilizer was broadcast (95.5%), placement (91%), closely followed by side dressing (88%), and fertigation (75%). Depending on the crop, a grower may use multiple approaches to fertilizer application in a growing season, so these responses were not mutually exclusive.

4.3.2 Well Water

While an overwhelming majority of respondents (97.8%) indicated that they have a private well that they use for drinking water, a majority (53%) reported that they had not tested for nitrate levels in these private wells over the previous 12 months. However, 56% of respondents did report testing their irrigation water for nitrate levels at least once over the previous year. When asked to estimate the amount of nitrate being delivered to crops through irrigation and rainwater (non-fertilizer sources), the majority of growers (57%) estimated between 1 and 25 lbs of N/ac, followed by 25 to 50 lbs of N/ac (30.9%). Few growers (7%) thought 0 lbs of N/ac was being delivered to their crops through irrigation and rainwater, and even fewer (5%) estimated contributions above 50 lbs N/ac.

When asked if nitrate found in irrigation water was incorporated into nitrogen management decisions, 70% of respondents indicated that they did not account for nitrate in irrigation water as part of their nitrogen management plans (46%) or adjust the amount of fertilizer in response to nitrate levels in irrigation water (24%) (Fig. 1). Almost 9% of respondents acknowledged not using a nutrient management plan. However, 20% of respondents reported reducing the amount of fertilizer applied, or in other words, crediting the nitrate found in irrigation water (Fig. 1).

Based on grower responses, the risk of reducing crop yield (55%), the unclear benefit of crediting (42.5%), and lack of information (41.4%) were either "a great deal" or "a lot" of a barrier to crediting the nitrate found in irrigation water (Fig. 2). Few respondents (5%) found time commitment to be a great deal of a barrier, with 25% indicating it was no barrier at all (Fig. 2). However, if presented with more detailed information on nitrate concentrations in irrigation water, 80% of farmers indicated that they were either extremely likely (19%) or somewhat likely (61%) to modify their nitrogen management plans in response.

4.3.3 Economic and Environmental Concerns

In response to questions regarding groundwater quality, surface water quality, pesticides in groundwater, inadequate water supply, loss of natural habitats, financial cost of government regulation, and ineffective government policies, growers indicated a wide range in level of concern. Respondents had the highest levels of concern ("extremely concerned") about the financial cost of government regulation (43%), ineffective government policies (38.6%), and contaminated surface water (36%) (Fig. 3). Fewer respondents felt extreme concern over the loss of natural habitats (25%) and groundwater quality (16%) (Fig. 3). Although groundwater quality had the lowest level of extreme concern, aa majority (52%) of respondents still felt either "extremely" or "very concerned" about groundwater quality, and 100% of responses reflected a level of concern above zero (Fig. 3).

4.3.4 BMP and Conservation Practices

The adoption of best management practices (BMP) such as cover cropping and the use of crop rotations was high among those surveyed, with 100% of respondents indicating that they've implemented cover cropping, and 97.7% indicating the use of crop rotations. The adoption of conservation practices was lower, with 30.9% reporting the use of filter strips, and 15.3% the use of native plantings.

4.3.5 Changes in Behavior

When asked in the winter of 2021 if their crediting of nitrate in irrigation changed during 2020 (in comparison to the 2019 growing season), a majority of respondents (87.5%) indicated no change in behavior. While 7.5% of respondents indicated that they increased their crediting of nitrate found in irrigation water, 5% reported a decrease in crediting. Of those who indicated a decrease in the crediting of irrigation water, 50% attributed their decision to increased information, and 50% said it was a result of using less irrigation (Fig. 4). Of those who indicated no change in irrigation crediting, the largest drivers were lack of information (57%), followed by recommendations by UW Extension, Crop Consultants, etc. (28.5%), and increased concern for groundwater quality (14.2%) (Fig. 4). For those who increased the crediting of nitrate in irrigation water, 33% indicated it was due to increased information, and 67% indicated it was due to a combination of increased information, recommendations by UW Extension, Crop Consultants, etc., and other (reducing input costs). An increase in information was cited as a reason for both an increase in crediting of nitrate in irrigation water and a decrease. Taken all together, the primary reason behind management changes (or lack of changes) in crediting was lack of information (33%) (Fig. 5).

4.3.6 Open ended questions

When given the opportunity to respond to an open-ended prompt on the subjects covered in the survey, respondents expressed a range of ideas and emotions regarding nitrate levels in groundwater. Broadly, responses fall into a few themes: those expressing the need for more research and information on nitrogen management and groundwater contamination, those expressing distrust with current recommendations and science, those expressing concern or criticism for the burden put on farmers, and those expressing the need for large scale changes in agricultural practices.

Emphasizing the need for more information and research, one respondent commented, “We need to better understand when we are losing N in our cropping systems”, with another expressing a similar sentiment, writing that “We have a lot to learn about all of these topics and how to remain sustainable both economically and environmentally”. These comments speak to farmers’ attitudes and desire for accurate, relevant science to aid in on farm decision making.

However, others pointed to a distrust in the current science and recommendations presented. One respondent wrote that there was “Too much belief in people like [prominent academic] who uses faulty information and is not made to prove anything he says”. More implicit skepticism was presented by another survey response, who suggested that the background levels of nitrate are already accounted for in the University of Wisconsin’s nitrogen application rates, suggesting “If current UW Extension recommendations were generated at

Hancock, it seems likely recommendations for N are too low. Assuming optimizing economic yield, then we should be applying more than recommended by UW Extension". Together, these comments point to the need for researchers and scientists to continue building trust with farmers and emphasize the need for sound management recommendations to be communicated by multiple sources.

Another grower felt that farmers in the region were being unfairly blamed for today's environmental challenges, writing, "My son will be the 6th generation on our farm and the land is in much better shape than it was 3 generations ago. We use less water, fertilizer, and chemicals and grow more crops with better yields. We live on this land and drink the water so why would we want to mess that up?". This may reflect a land ethic that is felt by some farmers, especially when the land will be farmed by future generations of their families. Additionally, it may point to the importance of acknowledging the BMPs some have already opted to implement, while also acknowledging the continued work to be done.

Still, others pointed to the need to deviate from current practices. A respondent commented, "Why are farms not audited for fertilizer and chemical use yearly to make sure they keep records and can justify use. It seems the university, coop, and chemical suppliers encourage and promote use (sales) to get optimal yields and use recommended amounts no matter what, especially for 'prevention'". In a similar vein, another grower emphasized the need to reduce groundwater pollution, writing that "Using a public resource, water, to produce crap that kills people, potato chips, and then contaminating the resource is wrong, and probably will be stopped."

Finally, some responses took a prophetic turn, with one grower predicting that “ I foresee the problems of nitrogen in ground water as the beginning of the end for commercial fertilizer based agriculture in the central sands.”

4.3.7 Farm(er) characteristics

The survey respondents had an average age of 54, with a median age of 57. The overwhelming majority of respondents (97%) identified as male. Asked if farming was their primary source of income, all respondents answering the question indicated it was. Among the surveyed farmers, 85% reported managing a combination of owned and rented land. In 2020, on average, farmers reported working on 2600 acres of land, however the size of farmed land varied across respondents, ranging from 300 acres to 12,300 acres. Common crops grown by survey respondents included potatoes (88.6%), field corn (79%), snap beans (75%), sweet corn (67%), and peas (60.5%). Our respondents matched the general demographic of farmers in Wisconsin considering age, sex and gender, and size of farming practice (NASS, 2019).

4.4 Discussion

4.4.1 Farmer adoption of BMPs varies widely

When it comes to current nitrogen management strategies, our results speak to the variability in the adoption of BMPs. Our findings observe widely reported adoption of split application approaches to fertilizer management, cover cropping, and crop rotations, with more limited adoption of crediting nitrate found in irrigation water. The use of split applications when applying fertilizer has been widely accepted as an effective management practice to limit nitrate leaching while maintaining or improving crop yield. As a result, the use of split application fertilizer management has been widely cited as a BMP for sandy soil by University of Wisconsin Extension publications.

However, less consensus has been reached on the efficacy of crediting nitrate in irrigation water. Until recently, it was unclear how much nitrate levels varied within a growing season, year to year, or even from well to well. As a result, it is likely that this uncertainty has resulted in lack of on the ground implementation of crediting of irrigation water, which is reflected by our survey responses. Moving forward, if crediting of nitrate in irrigation water is going to be more widely adopted, researchers will need to communicate how to best credit nitrate in irrigation water given levels of uncertainty, while also using recent and future research to mitigate the uncertainty.

4.4.2 More information needed for widespread adoption of nitrogen crediting of irrigation water

When asked to identify barriers to crediting nitrate in irrigation water, nearly 25% of respondents indicated that lack of information, risk of reducing crop yield, and an unclear benefit of crediting were all "a great deal" of a barrier. However, these findings should be interpreted with caution. Much of our research and interpersonal interactions incorporate the knowledge deficit model, which is founded on the assumption that with relevant new information, people will change their perspectives or behavior (Miller, 1983). However, numerous studies by science communicators have debunked this model, finding that communicating science to the public is more complex (Brossard et al., 2009; Davies, 2008; Simis et al., 2016; Yeo et al., 2015). Kahan et al. (2012) came to similar conclusions when surveying the public on climate change, establishing that most often apathy or disagreement on a topic does not stem from lack of comprehension, but rather from a conflict of interest (Kahan, 2015; Kahan et al., 2012).

While increased information or knowledge alone is unlikely to change behavior, these findings may indicate a need for greater communication and research on this topic, especially when it comes to managing risk and preventing continued groundwater contamination. Further underscoring this point, 80% of respondents indicated they would be “somewhat likely” or “extremely likely” to use new, more detailed information on nitrate concentrations in irrigation water to modify their nitrogen management practices. As we continue this work, it is imperative that testing for nitrate levels in irrigation water is accessible, and that farmers and growers have access to updated and accurate data.

4.4.3 Little change in management practices despite increased information

When evaluating changes in the adoption of nitrogen crediting of irrigation water over the study period (2020 growing season), we found little change in on the ground management decisions. This is in sharp contrast to the previous survey responses, indicating a likelihood or willingness to alter nitrogen management practices, specifically the crediting of nitrate in irrigation water, in response to detailed data on nitrate concentrations in groundwater. This may point to an overestimation of self-reported likelihood to adopt new practices. Past research has used the phrase “intention-behavior gap”, which is used to explain the fact that people do not always do what they intend to do (Sheeran & Webb, 2016). Previous work has demonstrated that changes in intentions are not proportional to changes in behavior, and that the framing of the intention can influence the probability of it being achieved. Specifically, viewing a goal or intention as a promotion rather than a prevention (ex: protecting water quality vs. preventing contamination) is more likely to lead to changes in behavior (Higgins, 1997). Locke and Latham (2013) also found that the more concrete the goal or intention was, the more likely it was to be achieved. Moving forward, improving framing and increasing clarity on crediting nitrate in irrigation water may help to reduce the gap between intention and behavior.

However, our results may also be explained due to lack of communication of new data, lack of sufficient information, continued risk to crop yield, challenges with translating data to management decisions, among other factors. Considering our small survey sample size and relatively limited range in questions—it's impossible to pinpoint an exact cause. However, our survey responses provide some guidance, as 33% of survey respondents in 2021 indicated that a lack of information best described their change, or lack of change, in nitrogen crediting over the 2020 growing season. While we presented information on nitrate levels in irrigation water at both the WPVGA annual conference and in an extension publication, we cannot guarantee that all survey respondents were aware of this information, or that its applicability was clear. Moving forward, it is clear researchers should continue to use effective science communication techniques to disseminate research findings in order to influence changes in management practices. However, more information alone will likely be insufficient in the wide adoption of practices.

4.4.4 High levels of concern regarding government regulation and ineffective government policies

When asked to evaluate levels of concern across wide ranging topics, farmers expressed the most concern (extremely concerned) about increased government regulation and ineffective government policies. Despite heavy attention on groundwater quality, only 16% of farmers reported feeling "extremely" concerned. However, most farmers indicated that they were either extremely concerned or very concerned about all topics, except for inadequate water supply. These findings may aid in improving messaging for future results and management recommendations, indicating growers in the region may be more motivated to implement practices to avoid government regulation, as opposed to messages centered solely on groundwater quality or quantity concerns. Additionally, these findings support previous research which found that that farmers' beliefs (Arbuckle et al., 2013) and willingness to adopt new practices were wide ranging (Martínez-García et al., 2015), indicating a need for tailored outreach reflecting the varying needs, constraints, and motivations of farmers (Arbuckle et al., 2013; Martínez-García et al., 2015), in addition to more research on effective messaging and communication strategies (Prokopy et al., 2019).

4.4.5 Need for reducing skepticism and building trust

Though a portion of farmers surveyed expressed support for research and the need for land management changes, this was also matched by skepticism and distrust from other respondents. When given the option to comment freely, some expressed distrust, specifically towards academic scientists. Recent research by Rusk et al. (2022) supports our results, finding that survey respondents were less trusting of traditional 'experts', especially agricultural researchers from academic institutions. Additionally, previous work conducted in Wisconsin found that farmers value the opinion of farm advisors over university extension educators (Woude & Shar, 2021). Past work surveying Midwest farmers by Stuart et al. (2018) found that private sector sources are viewed as highly influential, further supporting the idea that information on crediting nitrate in irrigation water may lead to high levels of adoption if it's coming from multiple sources, like fertilizer suppliers. However, considering the premise of nitrogen crediting in irrigation water is to reduce fertilizer use (and as a result, fertilizer sales), this may not be a realistic approach. Our results add to the growing body of literature showing the importance of building trust and may highlight the need for more farmer to farmer (or peer based) knowledge exchanges as well as farmer and academic partnerships. Additionally, as we strive to reduce skepticism, conducting transparent research while communicating uncertainty will be crucial.

4.5 Conclusions

These survey results represent a subset of vegetable and potato growers in Wisconsin, with most located in the Central Sands region of the state. This research has demonstrated that growers in WCS are most concerned about the financial cost of government regulation and ineffective government policies, but still experience concern about groundwater quality. Our findings highlight that some BMPs, such as split application, have been widely adopted, while the crediting of nitrate in irrigation water has been met with more uncertainty. Our results point to the need for a combination of increased information, improved risk management, and improved communication of the importance of protecting groundwater quality in order to increase farmer adoption of nitrogen crediting. Through the survey results and ongoing field work, we can deliver improved nitrogen management strategies and communication to farmers, directly benefiting them and the wider community.

4.6 References

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4.7 Figures

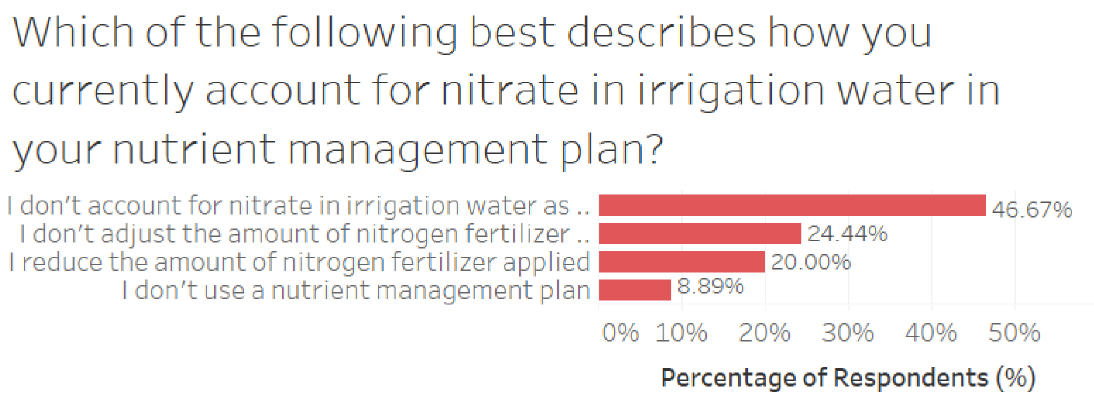

Figure 1) Growers management responses to nitrogen in irrigation water. Bar plots indicate the percentage of respondents (%) who don't account for nitrate in irrigation water, don't adjust the amount of nitrogen fertilizer used, reduce the amount of fertilizer applied, or don't use a nutrient management plan.

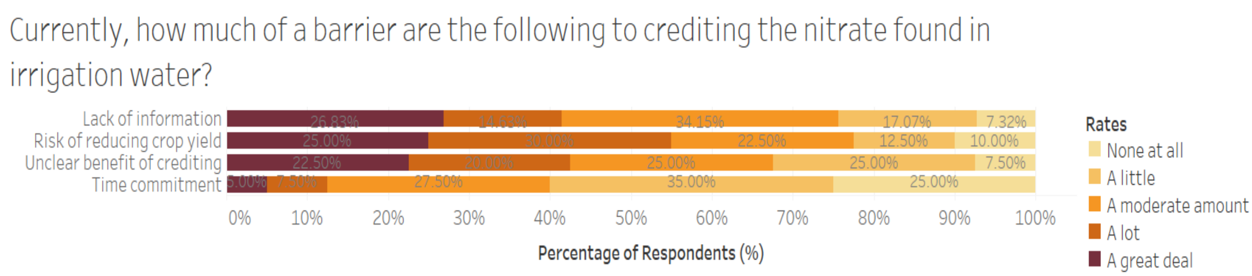

Figure 2) Growers self-reported barriers to crediting the nitrate present in irrigation water. Bar plots indicate the percentage of respondents (%) who find lack of information, risk of reducing crop yield, unclear benefit of crediting, and time commitment to be "a great deal", "a lot", "a moderate amount", "a little', or "none at all" to crediting the nitrate found in irrigation water. Color indicates level of barrier.

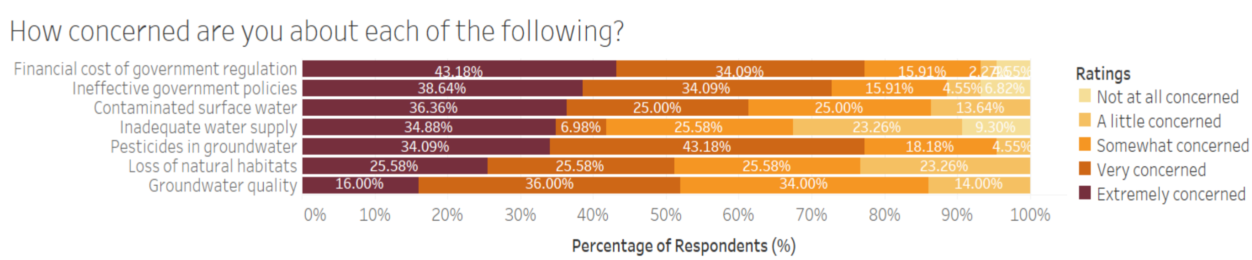

Figure 3) Growers self-reported levels of concern on a range of economic and environmental challenges. Bar plots indicate the percentage of respondents (%) who are concerned about the financial cost of government regulation, ineffective government policies, contaminations surface water, inadequate water supply, pesticides in groundwater, loss of natural habitat, and groundwater quality. Color indicates the level of concern.

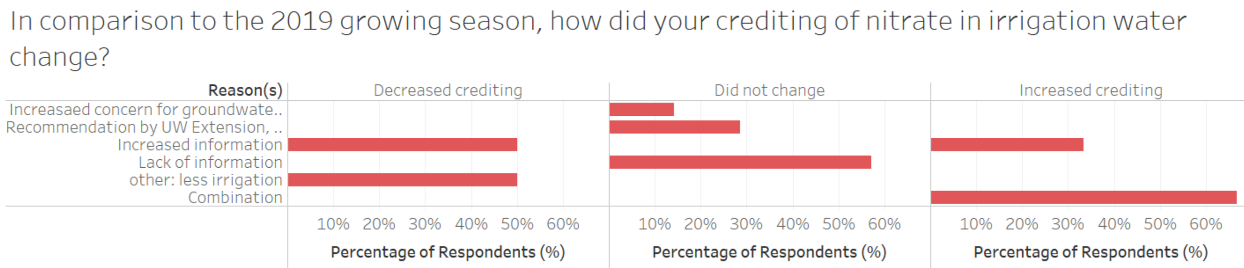

Figure 4) Growers self-reported change in nitrogen crediting of irrigation water over the 2020 growing season. Bar charts indicate the percentage of respondents (%) who reported increased concern for groundwater quality, recommendation by UW Extension, increased information, lack of information, other, or a combination of the above as their reason for change. Panels indicate the direction of change in nitrogen crediting (decreased crediting, no change, and increased crediting).

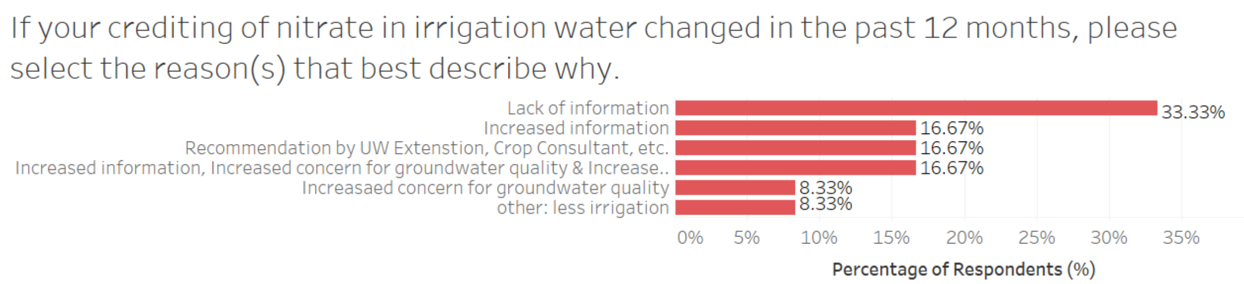

Figure 5) Growers self-reported reason for changing their nitrogen crediting of irrigation water over the 2020 growing season. Bar charts indicate the percentage of respondents (%) who reported lack of information, increased information, recommendation by UW Extension, increased concern for groundwater quality, other, and a combination of the above as the primary motivator of their decision.

Conclusions

4.8 Supplemental Information

WPVGA Grower Survey 2021 – to be completed by February 29th 2021.

We would like to ask all growers in the Wisconsin Potato and Vegetable Growers Association to complete a short survey for research. This survey is intended to assess management practices related to nitrogen management and water quality in the Central Sands region of Wisconsin. A similar survey was sent out during the winter of 2020, and we hope that by completing this additional survey, we can assess if any changes to management practices related to nitrogen management and water quality in the Central Sands region of Wisconsin have occurred in the last year. This project is conducted by the Kucharik Lab at the University of Wisconsin – Madison, and survey responses will help us better understand the usefulness of past research, as well as highlighting areas for future research. We expect this survey to take less than 15 minutes to complete, and appreciate any time you take. You have the option of taking the survey online or through a physical paper copy, please choose whichever option is most convenient. Please check your inbox for an email link to the survey. All answers will remain confidential.

The survey is intended for the primary farm operator(s), or whomever is must most familiar with the on farm management practices. Please answer the following questions, more room will be provided at the bottom for any additional feedback or comments. By completing this survey, you are consenting to participate in the research. For any questions, please contact Tracy Campbell (tacampbell@wisc.edu), graduate student in the Department of Agronomy at the University of Wisconsin-Madison.

We would appreciate all responses by February 29th 2021.

Thank you!

UNIVERSITY OF WISCONSIN-MADISON
Research Participant Information and Consent Form
Title of the Study: Assessing growers' current nutrient management practices and groundwater quality concerns.
Principal Investigator: Chris Kucharik (phone: 608-890-3021) (email: kucharik@wisc.edu)
Student Researcher: Tracy Campbell (phone: 314-398-2606) (email: tacampbell@wisc.edu)

DESCRIPTION OF THE RESEARCH

You are invited to participate in a research study about your current nitrogen management strategies, the concerns you hold regarding groundwater quality, and the challenges you face as a grower. You have been asked to participate because of your experience as a grower in the Wisconsin Central Sands. The purpose of the research is to assess current nutrient management practices, determine level of concern related to groundwater quality, and assess other challenges faced by growers in the WCS. This study is being distributed to members of the Wisconsin Potato and Vegetable Growers Association. If you choose to partake in the study, you will answer a short survey.

WHAT WILL MY PARTICIPATION INVOLVE?

If you decide to participate in this research you will be asked to complete the following survey honestly and to the best of your ability. The survey should take approximately 15 minutes to complete.

ARE THERE ANY RISKS TO ME?

There is a risk for a breach of confidentiality and for revealing personal, sensitive, or identifiable information.

ARE THERE ANY BENEFITS TO ME?

We don't expect any direct benefits to you from participation in this study.

HOW WILL MY CONFIDENTIALITY BE PROTECTED?

While there will probably be publications as a result of this study, your name will not be used. Only group characteristics will be published. De-identified research data will be held indefinitely for potential future research.

WHOM SHOULD I CONTACT IF I HAVE QUESTIONS?

You may ask any questions about the research at any time. If you have questions about the research, please contact Tracy Campbell at 314-398-2606 or tacampbell@wisc.edu.

If you are not satisfied with the response of research team, have more questions, or want to talk with someone about your rights as a research participant, you should contact the Education and Social/Behavioral Science IRB Office at 608-263-2320.

By completing the survey and submitting it back to the research team (either online or by mail), you are consenting to participate in the research. WCS Grower Survey 2021

Q1 How concerned are you about the quality of groundwater in the Central Sands?

- ◯ Not at all concerned
- ◯ A little concerned
- ◯ Somewhat concerned
- ◯ Very concerned
- ◯ Extremely concerned

Q2 Do you have a private well that you use for drinking water?

- ◯ Yes
- ◯ No

Skip To: Q4 If Do you have a private well that you use for drinking water? = No

Q3 In the past 12 months, how many times did you test nitrate levels in your private well used for drinking water?

- ◯ 0
- ◯ 1
- ◯ 2
- ◯ 3
- ◯ 4 or more

Q4 In the past 12 months, how many times did you test nitrate levels in your irrigation water?

- ◯ 0
- ◯ 1
- ◯ 2
- ◯ 3
- ◯ 4 or more

Q5 In your opinion, how much nitrogen do you think is delivered to your crops each growing season from non-fertilizer sources, like rainwater and irrigation water?

- ◯ 0
- ◯ 1-25 Ibs/ac
- ◯ 25-50 Ibs/ac
- ◯ 50-75 Ibs/ac
- ◯ 75-100 Ibs/ac
- ◯ more than 100 Ibs/ac

Q6 Which of the following best describes how you currently account for nitrates in irrigation water in your nutrient management plan?

- ◯ I don't use a nutrient management plan
- ◯ I don’t adjust the amount of nitrogen fertilizer applied
- ◯ I reduce the amount of nitrogen fertilizer applied
- ◯ I increase the amount of nitrogen fertilizer applied
- ◯ I don’t account for nitrate in irrigation water as part of my nutrient management plan

Q7 Currently, how much of a barrier are the following to crediting the nitrate found in irrigation water?

	A great deal	A lot	A moderate amount	A little	None at all
Lack of information	○	○	○	○	○
Risk of reducing crop yield	○	○	○	○	○
Time commitment	○	○	○	○	○
Unclear benefit of crediting	○	○	○	○	○

Q8 If you had more detailed information on nitrate concentrations in your irrigation water, how likely are you to use this information to modify your nitrogen fertilizer management plan?

○ Extremely likely

○ Somewhat likely

○ Neither likely nor unlikely

○ Somewhat unlikely

○ Extremely unlikely

Q9 In comparison to the 2019 growing season, how did your crediting of nitrate in irrigation water change during 2020?

○ Increased crediting

○ Decreased crediting

○ Did not change

Skip To: Q11 If In comparison to the 2019 growing season, how did your crediting of nitrate in irrigation water c... = Did not change

Q10 If your crediting of nitrate in irrigation water changed in the past 12 months, please select the reason(s) that best describe why

- ☐ Increased information
- ☐ Lack of information
- ☐ Recommendation by UW Extension, Crop Consultant, etc.
- ☐ Concern over decreased crop yields
- ☐ Increased concern for groundwater quality
- ☐ Decreased concern for groundwater quality
- ☐ Other ________________

Q11 Do you use the following method to apply fertilizer?

	Yes	No
Broadcast	○	○
Placement	○	○
Sidedressing	○	○
Fertigation	○	○

Q12 In the last 12 months, which of the following best describes your timing of fertilizer application?

- ◯ 100% at planting
- ◯ Split application
- ◯ Based on field conditions
- ◯ Other ____

Q13 Do you grow the following crops on your farm?

	Yes	No
Potato	◯	◯
Field corn	◯	◯
Sweet corn	◯	◯
Pea	◯	◯
Snap bean	◯	◯
Other	◯	◯

Q14 Do you implement any of the following practices?

	Yes	No
No-till	○	○
Cover cropping	○	○
Native plantings	○	○
Filter strips	○	○
Crop Rotations	○	○

Q15 How concerned are you about each of the following?

	Extremely concerned	Very concerned	Somewhat concerned	A little concerned	Not at all concerned
Contaminated surface water	○	○	○	○	○
Loss of natural habitats	○	○	○	○	○
Pesticides in groundwater	○	○	○	○	○
Ineffective government policies	○	○	○	○	○
Financial cost of government regulation	○	○	○	○	○
Inadequate water supply	○	○	○	○	○

Q16 How many acres is your farm?

____

Q17 Do you rent or own the land you farm?

- ○ Rent
- ○ Own
- ○ A combination

Q18 Is farming your primary source of income?

- ○ Yes
- ○ Yes, but I have additional off-farm employment
- ○ No

Q19 What is the highest grade or year of school you have completed?

- ○ Did not graduate from high school
- ○ High school graduate or GED
- ○ Some college
- ○ 4-year college graduate, with BA, BS, etc.
- ○ Some graduate work
- ○ Graduate degree, MA, MS, or higher

Q20 What is your gender?

____

Q21 What is your age?

____

Q22 Feel free to provide any additional information or thoughts regarding the topics and questions above.

____

Chapter 5: Conclusions and Future Work

The overarching goal of this work was to evaluate nitrogen management strategies across the WCS with a goal of improving groundwater quality. To do so, I paired on-farm research with leaf level measurements, process-based ecosystem modeling, and qualitative surveys. By using an integrated approach, I was able to quantify current levels of groundwater contaminations and offer avenues of improvement, while also identifying barriers to implementing new management practices.

Through on-farm research, we found that on average, nitrate levels in irrigation water and groundwater measured 19.0 mg/L, nearly twice the level for safe drinking water established by the EPA. Across the three years of our study, we determined that nitrate concentrations vary more across space (farm to farm, and field to field) than time (within the growing season and year to year). These findings can inform on the ground decision making in terms of the crediting of nitrate in irrigation water and would then reduce the total amount of nitrate applied to the landscape if implemented.

By measuring leaf-level photosynthesis throughout the growing season, we determined that temperature, nitrogen application rate, and DAE were significant predictors of Vcmax. Additionally, at the highest nitrogen application rate (403.5 kg/ha), neither leaf nitrogen content nor photosynthesis increased relative to lower nitrogen application rates (336.3 kg N/ha). Our results may point to the importance of irrigation in maintaining or improving potato yields as the temperature continues to rise. Additionally, our findings illustrate the need for continued ecophysiological measurements across dynamic conditions in order to better understand the response of potato to nitrogen application rate.

Using ecosystem modeling, we found that BMPs can reduce nitrate leaching with minimal impact to corn yield. However, in order to meet federal water quality goals, nitrogen application rates would need to be approximately 100 kg N/ha lower than currently recommended rates. Increased precipitation is likely to hinder the effectiveness of BMPs, and moving forward, more drastic or transformative land management changes are likely needed to obtain safe drinking water.

By surveying farmers, we found that use of split application BMPs were widely adopted, but that crediting of nitrate in irrigation water is implemented by only 20% of those surveyed. Growers identified lack of information, risk to crop yield, and unclear benefits as reasons for not crediting the nitrate in irrigation water. Moving forward, improved communication and further research to reduce uncertainties may help increase adoption.

Chapter 1 added the growing body of literature quantifying the groundwater quality contamination in the WCS and provides the data needed to more accurately credit the nitrate in irrigation water. Chapter 2 demonstrated avenues of improving nitrogen management in potato cropping systems, while also providing crucial data for modeling the impact of climate change on potato production in the region. Chapter 3 demonstrated that with the use of BMPs, nitrate leaching can be reduced, especially if lower levels of nitrogen fertilizer are used. Chapter 4 found that many farmers are already implementing some BMPs, such as split application of fertilizer. While this is a great step in the right direction, taken with the results in Ch.3 – these findings illustrate that considering split application and fertigation approaches are already being implemented, more drastic changes to nitrogen management practices, or more broadly, land management, will be needed to improve groundwater quality across the WCS region.

Future work

Nitrate concentrations in irrigation water and groundwater will need to continue to be measured and evaluated in the coming years and decades. This is crucial to monitor progress and determine if water quality goals are being met, in addition to further understanding the temporal trends in nitrate concentration across the region. Future work could also explore refined measurements, sampling directly from high-capacity wells to reduce the dilution effect of precipitation.

Potato nitrogen management could be improved through further research pairing ecophysiological measurements with end of season crop yield and dry matter N concentration (of petioles, stems, tubers, etc.) taken throughout the growing season. By taking this combined approach, we can better understand the source-sink relationships between tubers and leaves, and better parse out the interactions between nitrogen uptake, translocation of nutrients, and the influence of environmental variables that occur at different growth stages.

While we found limited improvements in nitrate leaching through the use of fertigation and split application BMPs, research should continue to evaluate the impact of cover cropping and crop rotations on reducing nitrate leaching. Additionally, future research should explore the impact of spatially targeted approaches (identifying hot spots, or the most vulnerable areas) in hopes of determining localized areas where the implementation of BMPs or other conservation efforts would reduce nitrate leaching the most. However, resources should also be invested in exploring more transformative approaches and thinking critically about the future of farming in the WCS. Future work may consider how to best incorporate perennial systems and avenues for implementing wetland restoration, as well as more community minded approaches to agriculture.

Finally, more research is needed on how to best translate research findings to on-the-ground management changes. Much of this work relies on collaborating with social scientists and science communicators to determine how to inform behavior and change management practices. Specific research questions might further explore farmer motivations, farmer to farmer networks, and techniques for framing and communicating uncertainty and risk.