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G2365

In-Season Nitrogen Management for Irrigated Corn

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Overview

With developments in sensor technologies and fertilizer application systems over the past 10 years, the University of Nebraska-Lincoln (UNL) recommends that irrigated corn growers adopt sensor-based in-season nitrogen (N) management. This approach offers clear advantages in profitability and N use efficiency (NUE) compared to traditional N management approaches. Fall N application, and significant N application prior to planting in the spring, is not recommended for irrigated corn. In-season application of the majority of fertilizer N through the irrigation system (fertigation) or with a high-clearance applicator is encouraged to maximize N use efficiency and profit. A base rate of 50–100 lb N/acre should be applied at or near planting, with the majority of fertilizer N applied during the growing season between V8 and R2 growth stages. In-season N application is an effective strategy to maximize the profitability of N fertilizer use and reduce the environmental impact of corn production in Nebraska.

Current Nitrogen Management Recommendations

Current UNL fertilizer nitrogen recommendations for corn originate from research conducted across the state over the past 50 years and longer. These recommendations have the goal of maximizing profit and minimizing environmental impacts of fertilizer application for corn production. Nitrogen fertilizer recommendations include components of fertilizer rate, timing, placement and source, and consider all sources of nitrogen available to the crop other than fertilizer before calculating a fertilizer recommendation. Nebraska's primary corn N rate algorithm resulted from research conducted over 81 site-years in Nebraska from 1976 to 1981. Grain yield from these studies typically averaged around 100 bu/acre for dryland and 150 bu/acre for irrigated corn. A detailed study to review and potentially revise the UNL corn N rate algorithm was conducted from 2002 through 2004, involving 34 irrigated site-years, mostly on producer fields. (Dobermann et al., 2011). A primary motivation for the study was that corn grain yield levels increased significantly during the 1980s and 1990s, and there was concern about the validity of the corn N rate algorithm with higher yield levels. The average corn grain yield from this study was 235 bu/acre. This study, conducted about 25 years after the previous research, confirmed that the general form of the UNL corn N rate algorithm continued to be accurate, despite higher yield levels. The study refined the corn N rate algorithm to include adjustments for application timing and economic considerations, based on the price of fertilizer and the price of corn. Current nitrogen fertilizer recommendations for corn can be found in Extension publications EC117, *Nutrient Management Suggestions for Corn*, and EC155, *Nutrient Management for Agronomic Crops in Nebraska*.

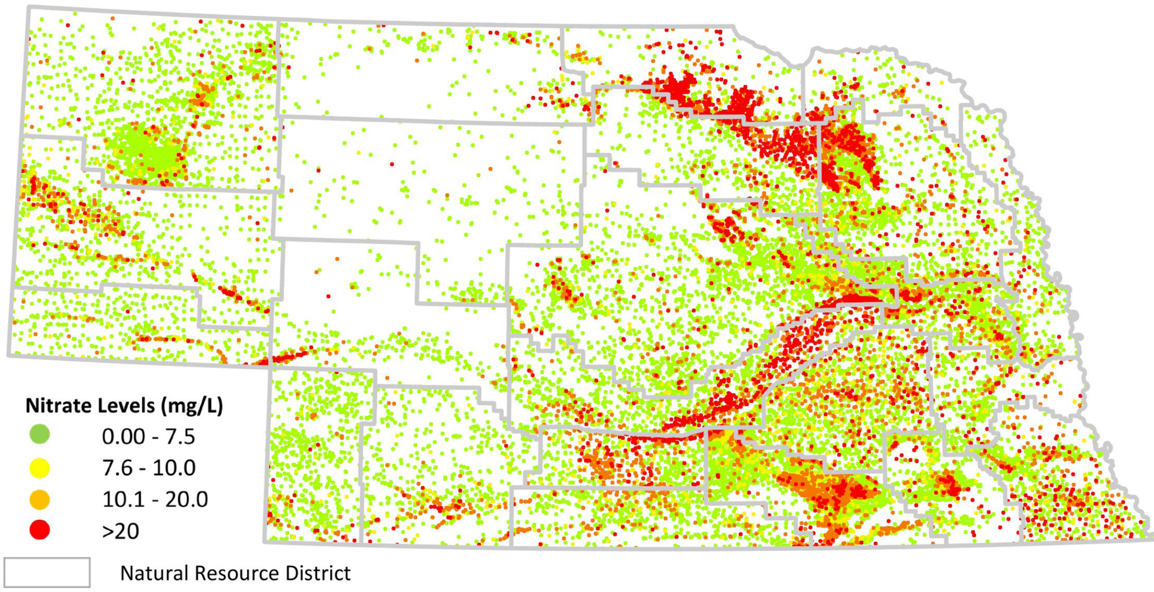

Figure 1. Groundwater nitrate-N concentration from 142,259 samples from an average of 5,786 wells of all types, 2000-2019. Nebraska Groundwater Quality Monitoring Report, 2022.

In one sense, it is not surprising that the general equation for fertilizer nitrogen recommendation for corn based on late 1970s research was still valid 25 years later, since the equation uses a mass balance approach. This approach is based on research by George Stanford (Journal of Environmental Quality, 1973), which showed a relatively constant relationship between corn grain yield and nitrogen uptake from all sources of N of 1.2 lb N/bu corn. (Stanford's paper included data from research in Nebraska). Thus, a nitrogen fertilizer rate recommendation that accounts for yield potential will naturally increase as yield level increases, all other factors being equal. It is also important to note that Stanford considered other sources of N, especially residual mineral N present in soil and that mineralized from soil organic matter, as credits to be considered before determining a fertilizer N rate.

The value of 1.2 lb N uptake/bu of corn is often mistakenly viewed as a fertilizer N requirement, which is inaccurate. The current UNL N rate algorithm for corn starts with corn uptake of 1.2 lb N/bu, then credits N from various sources. These N credits include N mineralized from soil organic matter, soil residual inorganic N, N contributed from irrigation water, N from manure, and N credit from previous legume crops. Once N credits from these various sources are accounted for, the remaining N requirement is filled with inorganic fertilizer.

The current UNL N rate algorithm for corn grain is:

$$[35 + (1.2 \times EY) - (8 \times NO_3\text{-}N\ ppm) - (0.14 \times EY \times OM) - \text{other N credits}] \times Price_{adj} \times Timing_{adj}$$

EY = Expected yield, bu/acre

NO_3-N ppm = nitrate-N concentration in soil, in parts per million

OM = Soil organic matter, %

$Price_{adj}$ - adjustment factor for N fertilizer and corn prices

$Timing_{adj}$ = adjustment factor for N application timing

and is available as an online corn N rate calculator at https://agritools.unl.edu/tools/nitrogen, and in the Extension Circular, EC117, *Nutrient Management Suggestions for Corn*. The online calculator allows the inclusion of credits from soil organic matter, soil residual N, irrigation water nitrate, manure and the previous crop, and includes factors of expected yield, fertilizer price, corn price, and application timing to calculate the recommended fertilizer rate.

It should be noted that this is an empirical equation, not a mechanistic model. The numbers in front of the factors for NO_3-N ppm and EY*OM are regression coefficients based on data from the 1976–1981 and 2002–2004 research studies. These coefficients provide the best fit for the equation under conditions in which the studies were conducted—namely Nebraska soils and weather. Consequently, the application of this equation outside Nebraska conditions may produce recommendations with uncertain accuracy.

Water Quality and Nitrogen Use Efficiency Trends

There has been concern about elevated nitrate-N levels in Nebraska groundwater since the early 1960s, following the rapid adoption by Nebraska farmers of inorganic nitrogen fertilizers starting in the early 1950s. Figure 1 illustrates areas of Nebraska with groundwater nitrate-N levels that are of concern. Since the early 1980s there have been a variety of regulations and educational efforts to influence farmer fertilizer management practices, mostly through Nebraska Natural Resources Districts (NRDs). These educational and regulatory efforts, based

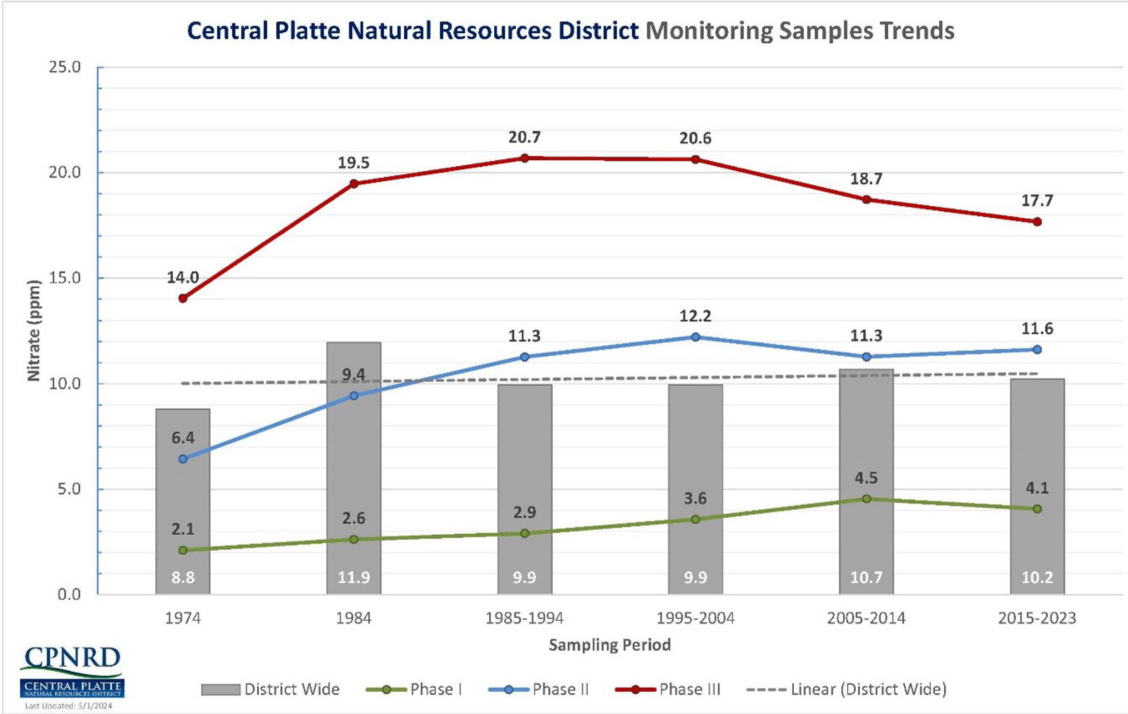

Figure 2. Groundwater nitrate-N trends, Central Platte Natural Resources District. Data is from CPNRD monitoring wells. Phases I, II and III are areas within the NRD with increasing average groundwater nitrate-N concentrations, and thus increasing restrictions on when N is applied.

on University of Nebraska-Lincoln research and Extension publications, have resulted in significant gains in how efficiently Nebraska farmers use nitrogen fertilizer. Figure 2 illustrates data from the Central Platte Natural Resources District (CPNRD), showing declines in groundwater nitrate-N levels since 2004 in the most contaminated areas (Phase III). The CPNRD was the first to implement a Groundwater Management Area (GWMA) due to elevated nitrate levels, which required farmers in the area to attend training sessions on nitrogen and irrigation management, and restricted when fertilizer could be applied. The CPNRD has been able to slow or reverse the trend of increasing nitrate concentrations in the most impacted areas, but on average there is a gradual trend for increasing nitrate concentrations, and the most contaminated areas remain above the EPA drinking water standard of 10 ppm NO_3-N. In much of Nebraska this trend for continuing increase in groundwater nitrate-N levels is partially due to the transit time of nitrate through the vadose zone (the unsaturated zone between the root zone and the aquifer). Due to the depth of the aquifer, nitrate entering the aquifer may have leached from the root zone several years to several decades ago and does not reflect current crop management practices. However, areas of the state with shallow aquifers also continue to see increasing groundwater nitrate concentrations (Juntakut et al., 2019), suggesting that more should be done to reduce nitrate loss from commercial fertilizers. Research at UNL in collaboration with NRDs calculated the partial N balance (difference between N inputs and grain N removal) across corn producers over several years as a proxy of N losses to the environment (Tenorio et al., 2021). About 70% of corn producers had a surplus N balance, indicating that N inputs were higher than N removal with grain. Corn producers with a large surplus of N were consistently over-applying N over the years.

Predictive Nitrogen Management

The accuracy of the UNL corn N rate algorithm for corn has been generally validated through many demonstration projects, on-farm research, and detailed research studies in Nebraska from 2004 through 2023. On average the algorithm produces a nitrogen fertilizer recommendation approaching the economic optimum fertilizer N rate (EONR), though the accuracy will vary with location and year. For most fields in Nebraska, the UNL corn N rate algorithm will be within ± 30 lb N/acre of EONR. Over the past twenty years there have been many regional and national studies investigating approaches to developing

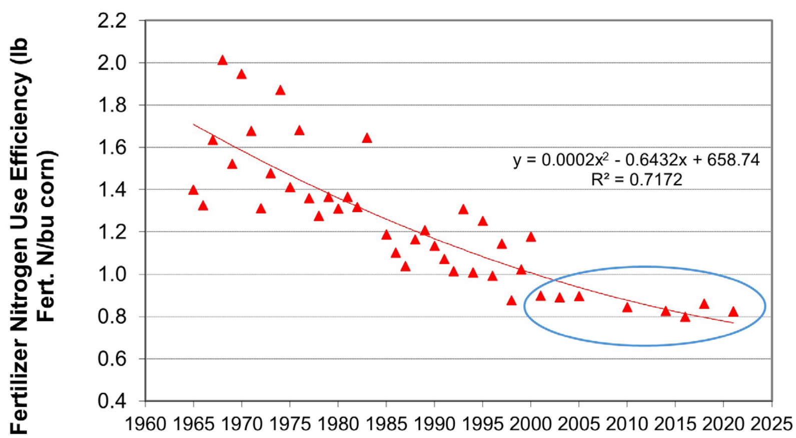

Figure 3. Fertilizer nitrogen application for corn in Nebraska, 1965–2021. Summary produced from data reported by producers in USDA National Agricultural Statistics Service (NASS) surveys, and the Nebraska Department of Agriculture.

EONR recommendations for corn. A significant review paper by Morris, et al. (2018) documented these efforts. Authors of this review in 2018 stated that "*Nitrogen recommendations for the foreseeable future in humid regions will poorly predict the amount of N needed for corn at individual fields*". A major research project conducted over eight states across the Corn Belt, including Nebraska, at 49 sites from 2014 through 2016 evaluated N recommendations tools for corn (Kitchen, et al., 2017). A recent publication from this study (Ransom, et al., 2023) found that individual N recommendation tools across all 49 sites poorly estimated EONR ($R^2 \leq 0.24$), while combining three at-planting N rate recommendation tools improved the ability to predict EONR with an R^2 of 0.46. (R^2 is a statistical measure of the ability of the model to fit the data; an R^2 of 1 means the model perfectly fits the data). While combining EONR prediction tools increased the accuracy of EONR prediction over the use of a single tool, an R^2 of 0.46 still reflects a relatively poor ability to accurately predict the correct N rate.

Figure 3 illustrates that fertilizer N application by corn producers in Nebraska has gradually reduced over the past 50 years from around 1.7 lb fertilizer N/bu corn grain in 1965 to around 0.8 lb fertilizer N/bu corn grain in 2021. This is a tremendous improvement in fertilizer use efficiency, resulting in increased profit for Nebraska farmers and reduced environmental impact. Unfortunately, there continue to be significant areas of Nebraska with groundwater nitrate-N in excess of the EPA drinking water standard of 10 ppm. There has also been little change in the amount of fertilizer N applied per bushel of corn over the past 20 years, as shown in Figure 3 (blue outline), with average grower fertilizer N application of around 0.8–0.9 lb fertilizer N/bu corn grain from 2000–2021. This lack of further reduction in N application per bushel raises the question of whether we've reached a limit to improving NUE, or if broad adoption of different practices is needed to further improve NUE. A recent survey in Nebraska found that 45% of farmers apply all N in early spring (33% pre-plant and 12% at planting), 14% in the fall, 12% during the growing season, and 29% use split application (Balboa et al., 2023). The survey also found corn producers applying an average of 169 lb N/acre, with 80% using soil lab recommendations and 67% relying on personal experience/intuition. More advanced N recommendation tools generally had low adoption (crop models 23%, sensor-based algorithms 11%, and other digital tools 11%), indicating there is potential for growth in use of these tools.

Our overall inability to accurately predict EONR for corn can be explained by the complexity of N interactions with soil and the environment. Nitrogen exists in many organic and inorganic forms in soil, which are highly influenced by weather—particularly rainfall and temperature. Nitrogen is subject to loss from the soil via leaching and gaseous emissions (N_2O and NH_3). Consequently, our ability to predict N dynamics in soil, and availability of N from soil and fertilizer to the crop, is dependent on our ability to predict weather. Until we can perfectly predict weather, we cannot perfectly predict N availability to a crop. We are comfortable using the Nebraska N rate algorithm for corn as a good predictive model available for Nebraska. However, our research shows that reactive management strategies, applying most of the N fertilizer during the growing season, and basing the application rate on crop N status, can increase profit and NUE for most growers, particularly for irrigated fields capable of fertigation.

Reactive In-Season Management

Significant crop uptake of N for corn begins around the V6 growth stage (Figure 4). From that point until around the R2 growth stage, N uptake is rapid and at a fairly linear rate. Less than 50 lb N/acre is needed to reach the V8 growth stage, but around 150 lb N/acre is needed by the R2 growth stage. (These N amounts are from all sources, not just fertilizer). An ideal N fertilization approach would

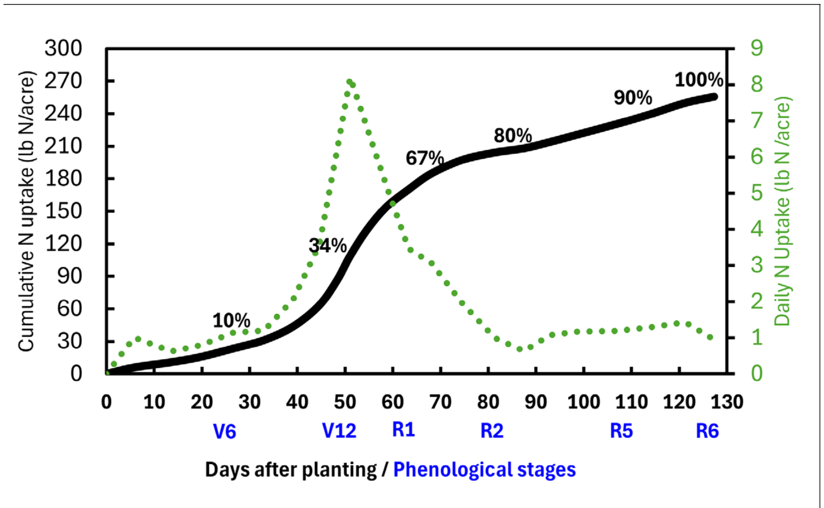

Figure 4. Typical cumulative nitrogen uptake for corn (black line) and daily N uptake (green line) (from all sources). Based on Bender et al., 2013, with a yield of 220–230 bu/acre.

steadily provide the N needed by the crop during the period of rapid N uptake between V8 and R2 growth stages and would leave little excess N available for environmental loss. Instead of attempting to predict EONR for corn *before* the growing season, reactive methods seek to prevent or minimize crop N deficiency *during* the growing season, using sensors measuring light reflected from the crop canopy. Crop canopy sensing approaches use light reflected from the crop in both visible and near-infrared wavebands to detect developing N deficiency in the crop before it becomes visible to the human eye. Sensing approaches can be either passive (using the sun as a light source) or active (using an integral, pulsed light source unaffected by sunlight). Sensing systems can be ground-based (handheld or vehicle-mounted) or aerial (UAV, airplane or satellite). Substantial research over the last 25 years has documented the ability of optical sensing techniques to detect developing N deficiency in crops and to improve NUE with sensor-informed in-season fertilization (Raun, et al., 2002; Solari, et al., 2008; Solari, et al., 2010).

Active Crop Canopy Sensor Management with High-Clearance Applicator

Project SENSE (Sensors for Efficient N Use and Stewardship of the Environment) was a research and extension project conducted in Nebraska from 2015-2021. The project conducted trials of sensor-based in-season N application for corn with over 80 site-years on farmer-cooperator fields. The project compared standard grower N management practices to in-season N application using a high-clearance applicator, with N rate controlled by an active (light-emitting) crop canopy sensor. Sensor-based application occurred once during the growing season, between V8 and V12 growth stages. This approach is not purely reactive, in that an algorithm is used to predict the remaining N requirement for the crop based on canopy reflectance at these growth stages. Averaged over all site-years, sensor-based in-season management reduced N application by 33 lb N/acre compared to grower practices (NOFRN Results 2020). Although yield on average was slightly less (1.2 bu/acre) with sensor management compared to grower management, it still averaged 221 bu/acre and partial profit increased significantly with sensor management compared to grower management—from $10–24/acre, depending on the price of N fertilizer and corn. Nitrogen fertilizer applied per bushel with sensor-based management improved to 0.72 lb fertilizer N/bu of corn, compared to the average grower application of 0.86 lb fertilizer N/bu of corn.

Passive Crop Canopy Sensor (Satellite) with Fertigation

A development from Project SENSE has been the use of satellite imagery instead of high clearance vehicle-mounted active sensors to manage N in-season. This approach uses similar multispectral crop canopy reflectance to detect developing N stress in the crop. Instead of simultaneously sensing stress and applying N fertilizer, a satellite-based approach requires that imagery be obtained by the satellite, followed by data processing to determine if additional N is needed, followed by fertilizer application. The advent of satellite systems with short revisit times (as often as daily) combined with sufficient spatial resolution (≤ 30 ft) of multispectral sensors has made satellite sensing practical for in-season N management, with a short interval between detection of developing crop N stress and fertilizer application. One company using approaches developed at the University of Nebraska-Lincoln for satellite-based in-season N management is Sentinel Fertigation (https://www.sentinelfertigation.com). The Nebraska On-Farm Research Network partnered with Sentinel Fertigation, Nebraska Natural Resources Districts (NRDs), and several farmer-cooperators from 2021-2023 to evaluate in-season N application based on satellite information. Over this three-year period at 24 sites, satellite-based in-season N application decreased average N rate by 56 lb N/acre compared to standard grower practices, while reducing grain yield by only 3 bu/acre (average sensor-based yield was 249 bu/acre). Despite the slight reduction in yield, average partial profit increased by $24/acre with sensor-based in-season management. Fertilizer N application reduced to 0.60 lb fertilizer N/bu corn, compared to 0.84 lb fertilizer N/bu corn with grower management (OFRN Results 2022; OFRN Results 2023).

There are several differences between high clearance applicator—active sensor and satellite sensor—fertigation approaches to in-season N application. High clearance—active sensor in-season application normally occurs only once during the season, between V8 and V12 growth stages. This is because most applicators cannot clear the canopy height once it exceeds V12, and due to the cost of additional trips over the field by an applicator. Consequently, an algorithm is used to estimate the remaining N needed for the crop to reach maturity based on canopy reflectance. This approach can be more accurate than pre-season prediction algorithms in estimating EONR due to use of crop information during the growing season, and the much-reduced risk of environmental N loss. In contrast, satellite-based fertigation management can be purely reactive. If developing N stress is detected, N application is recommended (typically around 30–60 lb N/acre). After fertigation is triggered, crop canopy reflectance continues to be monitored, and if pending N stress develops again, fertigation is again recommended. An interval of at least a week between fertigation events is recommended to allow time for the crop to respond to fertilization. This approach of monitoring and fertilization can occur through the season between V8 and R2 growth stages. Growers typically fertigate 1–3 times during the growing season using this approach.

Components of High Clearance Applicator—Sensor-Based N Fertilization

1. Availability of a high clearance applicator.

2. Canopy sensors and control system mounted on the high clearance applicator.

3. Application of N fertilizer to the field ahead of sensing at a rate below the expected optimum N rate. Most often the base fertilizer N application should be at or near planting, at a rate around 25% of the expected total N application (usually 50–100 lb N/acre). Use of nitrification and/or urease inhibitors to reduce potential N loss is encouraged, depending on fertilizer source and application method. Some active sensor approaches require calibration blocks with N rates below and above the expected total N application applied at planting.

4. At the time of in-season N application (between V8-V12 growth stages), calibration of canopy reflectance is required. The process of calibration may vary with the type of active sensor used. This can be done by measuring crop canopy reflectance from pre-installed N rate calibration blocks, or by creating a virtual reference by measuring reflectance over a portion of the field, according to directions from the sensor manufacturer.

5. A single in-season N application. Based on canopy sensor information, an algorithm in the control system calculates a Sufficiency Index (SI) from reference and bulk field sensor readings, then determines the remaining fertilizer N needed for the crop to reach maturity (Holland and Schepers, 2010). The system then applies the needed fertilizer on the go.

Components of Sensor-Based N Fertilization

1. A fertilizer injection pump and fertilizer storage tank for the irrigation system.

2. Base N rate below the expected optimum N rate. Most often the base fertilizer N application should be at or near planting, at a rate around 25% of the expected total N application (50–100 lb N/acre). Use of nitrification and/or urease inhibitors to reduce potential N loss is encouraged, depending on fertilizer source and application method.

3. Inclusion of blocks in the field with N applied at rates slightly above and slightly below the base N rate, which serve as crop reflectance calibration points to calculate a Sufficiency Index. Alternatively, a virtual reference approach may be used, based on non-stressed areas of the field.

4. Sensor information processed by a commercial advisory service, such as Sentinel Fertigation, to monitor crop N status and generate a fertilizer N rate recommendation as needed between V8 and R2 growth stages. Growers may need 1–3 fertigation events for a field, applying 30–60 lb N/acre at each fertigation event.

5. Alternatively, in-season application with a high-clearance applicator can be used, with application timing and rate informed by satellite sensors, if the applicator will clear the crop canopy.

Fertigation allows growers to use their irrigation system as the fertilizer application device, with the addition of a fertilizer injection pump and storage tank. This method enables multiple applications of fertilizer N periodically

Figure 5. Fertigation system with programmable injection pump.

during the season as needed, based on seasonal N uptake by corn (Figure 4). Satellite-based fertigation most often uses a uniform N rate applied across the field for each fertigation event. However, if the irrigation system is capable, fertilizer N rate can vary within pie-shaped sections of the field, based on satellite reflectance information. Figure 5 illustrates a programmable fertilizer injection pump, capable of varying fertigation rate in pie sections, enabling precise N management tailored to specific field conditions detected by satellite imagery.

Keep in mind that appropriate check valves must be in place and inspected by Natural Resources District staff, and the operator must be certified to conduct chemigation, before fertigation can occur. One aspect of relying on fertigation to apply the majority of N needed for the growing season is that the need for N may occur earlier in the season than the need for water. Growers should anticipate this potential and be prepared to irrigate earlier in the season and be able to fertigate with a small amount of water—perhaps 0.25 -0.5 in/acre—to apply fertilizer.

Fertigation Without Sensor Information

University of Nebraska N recommendations have always encouraged split application, with a significant amount of the total N fertilizer applied after the growing season starts. Soil is a poor place to store nitrogen fertilizer. As soon as nitrogen fertilizer is applied to soil it is subject to various loss processes in the soil. While fertilizer source selection, timing, and use of inhibitors (both urease and nitrification inhibitors, or stabilizers) can help reduce risk of N loss, the risk is still there. The longer fertilizer N remains in the soil, the greater the risk of loss. Application of fertilizer N after the wettest months of the year (May and June) decreases the risk of N loss due to leaching or denitrification.

Components of In-Season Fertilization without Sensors

1. Use the UNL corn N rate calculator (https://agritools.unl.edu/tools/nitrogen) to calculate a total fertilizer N rate, then apply a base rate of about 25% of the recommended total N rate (around 50–100 lb N/acre) at or near planting. Use of nitrification and/or urease inhibitors is encouraged, depending on fertilizer source and application method.

2. If fertigation is an option, split the remaining N needed into 2–3 applications, with timing evenly spaced between V8 and R2 growth stages. Figure 4 illustrates cumulative N uptake, daily N uptake and an illustration of N required between growth stages for 250 bu/acre corn. Application may include ground-based application if equipment will clear the crop canopy. The amount of nitrogen applied during a single fertigation event should not exceed 75 lb N/acre, to reduce risk of runoff loss or potential leaf burn. Any observed evidence in the crop of N deficiency should result in adjustment of in-season timing and rate.

Summary

- The closer N fertilizer is applied to crop use, the more efficiently it will be used by the crop.
- Irrigated corn growers should target application of 60% or more of total fertilizer N during the growing season. Fall and significant spring pre-plant applications are not recommended.
- Typically apply 50–100 lb N/acre as a base rate around planting time. Use of enhanced efficiency fertilizer (nitrification inhibitor, urease inhibitor, or controlled release formulation) is encouraged.
- Nitrogen application using a high clearance applicator and active crop canopy sensors should occur between V8 and V12 growth stages.
- Fertigation using satellite imagery to determine rate and timing should occur between V8 and R2 growth stages.
- Fertigation without use of sensor information should occur between V8 and R2 growth stages, with overall rate based on the UNL corn N calculator.
- For growers unable to use sensor-based management or to fertigate, sidedress remaining fertilizer N needed (based on UNL corn N calculator) between crop emergence and V8 growth stage.

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DOI: 10.1021/acs.est.0c05655

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