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Field-Scale Nitrogen Recommendation Tools for Improving a Canopy Reflectance Sensor Algorithm

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Abstract. Nitrogen (N) rate recommendation tools are utilized to help producers maximize grain yield production. Many of these tools provide recommendations at field scales but often fail when corn N requirements are variable across the field. This may result in excess N being lost to the environment or producers receiving decreased economic returns on yield. Canopy reflectance sensors are capable of capturing within-field variability, although the sensor algorithm recommendations may not always be as accurate at predicting corn N needs compared to other tools. Therefore, the integration of within-field canopy reflectance sensor tools with field-scale N recommendation tools may help account for yield variability from N applications, and improve N rate recommendations by utilizing the strengths of multiple tools. Research was conducted to determine which N rate recommendation tool was most effective at recommending economical optimal N rates (EONR) under varying soil and weather conditions across the Corn Belt. A second objective using a canopy reflectance algorithm was evaluated to by changing the base N rate of the algorithm which was determined by these tools. Research was conducted on N response plots across eight U.S. Midwest states in 2014 and 2015. Two sites from each state totaling 32 site years, resulting in a range of historically productive areas, were used to evaluate differences in soil and weather environments. Field-scale tools that were compared included pre-plant soil nitrate test, pre-sidedress soil nitrate test, maximum return to N

(MRTN), yield goal based calculations, and the Maize-N crop growth model. These tools were also compared to N recommendations form a canopy reflectance sensor using the Holland and Schepers algorithm. Tools were evaluated for an at-planting and/or sidedress N application. Each tool's performance was evaluated using the root mean square errors (RMSE) and the average difference of the tool's N recommendation to the measured site's EONR, and the percentage of sites where the N recommendations were within 30 kg N ha^{-1} of EONR. A second objective was to determine if the Holland and Schepers algorithm could be improved by integrating the best performing N recommendation tools that were previously evaluated. Tools were integrated by replacing the base N rate, or the farmer's historical N rate, with the N recommended from the best performing tools. Results of comparing the performance of all tools showed that for recommendations made at-planting the Wisconsin PPNT, MRTN and state-specific yield goals performed the best. For sidedress recommendations MRTN and state-specific yield goal recommendations were the best performing tools. The canopy reflectance sensor using the farmer's N rate as the base N rate for the algorithm recommendation did not perform as well as the farmer's N rate as a standalone recommendation. For the second objective of replacing the farmer's N rate as the base N rate in the algorithm with MRTN or the state-specific yield goal showed minimal improvement. The canopy reflectance sensor performed better when using the scaling factor to increase the MRTN and state-specific yield goal calculations by a factor of 1.75 and 1.65, respectively. The canopy reflectance sensor was best improved by adding 56 and 70 kg N ha^{-1} to the overall Holland and Schepers algorithm when using MRTN and the state-specific yield goal as the base N rate, respectively. Overall, using these tools as the base N rate for this algorithm is not appropriate as it caused under-recommendations of EONR and growers would be required to speculate on the scaling factor or how much extra N to apply to the recommendation in order to maximize the performance.

Keywords. *Nitrogen recommendation, Maize-N, Canopy reflectance sensors, PPNT, PSNT, Yield goal, MRTN, Maximum return to nitrogen, and Corn*

Introduction

Corn (*Zea mays* L.) growth is often restricted under conditions of limited soil nitrogen (N) concentrations. Farmers are advised to follow the 4R guidelines of nutrient stewardship (right rate, right time, right source, and right place) when deciding to apply fertilizer N. When these guidelines are not followed, fertilizer N applications can result in increased N pollution (Snyder, 2012). Nitrogen-associated pollution (e.g. hypoxia and greenhouse gases) results in added costs to society due to decreased environmental or economical services (Pretty et al., 2003). Finding a balance between over- and under-applying fertilizer N is necessary to optimize profits while also limiting N lost to the environment. This is challenging because optimal N for plant growth varies both spatially, as well as temporally, due to interactions between soil and weather conditions (Scharf et al., 2005). Understanding that corn N needs differ as a result of variability in soil and weather conditions, multiple N fertilizer recommendation tools have been developed over the past several decades to aid in determining the most accurate N rate needed to optimize profits and minimize environmental pollution.

Growers have a variety of tools they can use to determine the optimal N fertilizer rate for their fields. These tools include mass balance calculations based on a yield goal or potential, preplant soil nitrate test (PPNT), pre-sidedress soil nitrate test (PSNT), maximum return to N (MRTN) calculation, crop growth models, and in-season N applications using canopy reflectance sensors. Previous research has shown the strengths and weaknesses of these tools (Table 1).

Table 1: Strengths and weaknesses compared for each N fertilizer recommendation tool.

	Pros	Cons	Citation
Yield Goal	Mass balance approach that is easily calculated and based on research indicating ratio of total N to biomass is relatively constant under adequate N fertilization. Nitrogen recommendations can be adjusted for previous management using credits.	Often poor relationships between calculation and EONR exist due to inaccurate use of crediting previous management and crop N inputs, incorrect estimation of yield levels, inability to account for soil N supply, does not account for current N or corn prices, and overestimates in dry years and underestimates in wet years, and does not account for within field variability due to soil and water properties.	Lory and Scharf, 2003; Sawyer et al., 2006; Stanford, 1973
PPNT	Soil NO_3 levels can be assessed for residual N and N supplied by manure that could be available for plant use. Can be used as an adjustment to other N recommendations. Fertility samples are often taken and could be used for this test resulting in minimal extra labor. Sampling can be taken during a lull in seasonal work.	Not a useful tool in more humid regions due to N loss during wet springs. Inaccurate test results due to varying weather affecting N mineralization rates. Additional cost and labor required.	Bundy and Andraski, 1995; Lory and Scharf, 2003; Magdoff et al., 1984; Schmidt, 2005; Schröder et al., 2000; van Es et al., 2007
PSNT	Better accounting of N loss from leaching or denitrification and N inputs from mineralization than PPNT. Successful at identifying N-sufficient sites.	Additional in-season sampling required and limited by wet conditions and short laboratory turn around. Limited by N loss due to temperature and rainfall immediately before and after sampling. Does not account for within field spatial variability due to soil and water properties. Inaccurate test when following alfalfa or a manure application. Not recommended for use on coarse-textured soil in some states.	Andraski and Bundy, 2002; Fox et al., 1989; Laboski and Peters, 2012; Magdoff et al., 1984; Magdoff, 1991; Meisinger et al., 1992
Canopy Reflectance Sensors	Nitrogen recommendations can be adjusted for plant response to soil and water variability within fields. Provides a real time assessment of corn N status during the season. Various algorithms allows for adaptability for different conditions. Works well when high soil variability or uncertain N loss is present.	Expensive upfront costs for sensors and applicators. Sensor is not sensitive to within field changes in crop height. Amount of crop canopy closure affects readings, excessive soil exposure resulting in a diluted index value and a closed canopy results in saturated measurements.	Biggs et al., 2002; Holland and Schepers, 2010; Kitchen et al., 2010; Shanahan et al., 2008

MRTN	Data is easily updated with additional experimental plots. Calculations reflect current economic status by including price of fertilizer and corn. Provides a range of N rates that are within $1.00/acre of maximum profitability that farmers can use depending on their risk factor.	Does not address the issue of year to year temperature or rainfall variability. Can't predict site-specific N requirements and unlikely to accurately estimate EONR for each specific environment. Does not account for within field spatial variability due to soil and water properties. Must estimate what the price of corn will be at the end of the season.	Nafziger et al., 2004; Sawyer et al., 2006; van Es et al., 2007
Crop Growth Models	Estimates possible weather scenarios during a growing season to minimize N loss and predict N supplied by the soil. Non static N recommendation based on the genetic, environmental, and management conditions.	Models may need to be calibrated to specific climate and soil conditions. Many parameters are estimated or generalized.	Sawyer, 2013; Setiyono et al., 2011; van Es et al., 2007

The majority of these tools function at a field scale, with only the canopy reflectance sensors that prescribe N on a per plant or small area basis. This makes canopy reflectance sensors unique, possessing the ability of providing a variable N fertilizer recommendation on-the-go to address site-specific crop N needs. This is especially helpful in fields that exhibit high N supply variability as it does with manure, legumes, soil variability, or under conditions of high N loss from excessive precipitation (Kitchen et al., 2010). Under these conditions, canopy reflectance sensors are better able to reduce risk associated with N applications (Shanahan et al., 2008). The ability to detect variable crop N needs have also resulted in increased profits when compared to a uniform N rate (Kitchen et al., 2010; Scharf et al., 2011).

While increased profits have been reported when compared to fixed rates, the ability of canopy reflectance sensors to prescribe optimal N rates is still limited on a regional scale. For canopy reflectance sensors to accurately prescribe N close to a site’s EONR, some algorithms have been developed that require a base N rate to go along with the reflectance values in order to generate an N recommendation. Algorithms can either have a predetermined base rate, which can change for different growth stages, or the user determines what the base N rate should be. Algorithms that require the user to determine the base N rate contain the same level of uncertainty that other non-canopy reflectance sensor recommendation tools face with estimating EONR.

There needs to be a method of estimating the base N rate required by the algorithm in order to effectively use a single algorithm at a regional scale. These base rates could be determined using currently available N recommendation tools. The integration of canopy reflectance sensors and some other versatile tools should provide a farmer with greater confidence that optimal N rates are being applied throughout a field. The objective of this evaluation was to compare corn N recommendation tools across the U.S. Midwest. A secondary objective was to assess if recommendations from non-canopy sensing tools could provide a better base recommendation for the sensor algorithm than using the farmer’s historical N rate.

Methods

Experimental Setup

This project was undertaken with public-private collaborations between DuPont Pioneer and eight U.S. Midwest universities (University of Iowa, University of Illinois Urbana-Champaign, University of Minnesota, University of Missouri, North Dakota State University, Purdue University, University of Nebraska-Lincoln, and University of Wisconsin-Madison). Each state conducted research on two sites each year during 2014 to 2015. A total of 32 site-years of data ranging in soil productivity and weather conditions were collected. All states followed a similar protocol for plot research implementation including: weather data collection, soil and plant sample timing and collection methodology, N application timing, N source, and N rates. Treatments included N fertilizer rates between 0 and 315 kg N ha^{-1} applied either all at-planting or were split, where 45 kg N ha^{-1} was put on at-planting and additional fertilizer N applied at the V9 corn growth stage (Table 2). A DuPont Pioneer® hybrid that provided the best genetics for that geographic area was planted to reach a target population of 86,500 seed ha^{-1}. All other plant growth limiting factors were controlled by each university according to the representative state's guidelines.

Table 2: N treatment used on plots either applied all at-planting or split applied with a sidedress application at V9. All treatments were replicated four times at each site in a randomized complete block design.

Treatments	At-planting N	Split Applied N	Total N
	-----------------Kg N ha^{-1}	-----------------	
1	0	0	0
2	45	0	45
3	90	0	90
4	135	0	135
5	180	0	180
6	225	0	225
7	270	0	270
8	315	0	315
9	45	45	90
10	45	90	135
11	45	135	180
12	45	180	225
13	45	225	270
14	45	270	315

Meteorological data during the growing season was obtained using on-site weather stations (HOBO U30 Automatic Weather Station; Onset Computer Corporation, Bourne, MA). Temperature and precipitation data were recorded every 15 minutes. Historic weather data up to the past 30 years was obtained from nearby weather stations and interpolated using a weighted average based on distances of the weather stations to the field.

Soil samples for PPNT were collected in the spring prior to planting and N fertilization, and consisted of a composite of 10 samples taken from each of the four blocks. Samples were taken at three depths (0-30.5, 30.5-61, and 61-91.5 cm). Soil samples needed for the PSNT were collected from plots that received no fertilizer (n=4 per site). Each plot had six samples taken at two depths (0-30.5 and 30.5-61 cm), which were then combined to total two samples per plot. Soil samples were kept at < 5^{o}C until they were air dried, crushed, and passed through a 2 mm sieve. Ground samples were analyzed for nitrate-nitrogen (NO_3-N).

Nitrogen Recommendation Tools to be Evaluated

Farmer's N Rate, Yield Goal, PPNT, PSNT, and MRTN

The farmer's historical N rate was recorded as the fertilizer N rate the farmer or research station intended to apply to that area. Sites where no farmer's N rates were recorded were omitted from analysis.

Nitrogen fertilizer recommendations were calculated using each state's guideline for the following decision tools: yield goal, PPNT, PSNT, and MRTN. Some states never recommended or no longer recommend using some of these N recommendation tools; in which case the last published method was used. This was the case for the majority of states participating in this research, as they have moved away from using yield goal based recommendations. Each yield goal calculation was used to determine an N recommendation for all 32 sites across the Corn Belt. Using each individual state's yield goal recommendation on a regional scale was done to evaluate if one state's method worked better on a larger geographic area. This was also done with each state's PPNT and PSNT. Additionally, the yield goal was evaluated when each state used their respective yield goal calculation (state-specific yield goal).

The MRTN was evaluated by obtaining values for Iowa, Illinois, Minnesota, and Wisconsin from the online Iowa state extension MRTN calculator using a ratio 10:1 for the price of corn to N fertilizer (http://extension.agron.iastate.edu/soilfertility/nrate.aspx). Values for Indiana and North Dakota were determined from extension publications (Camberato and Nielsen, 2015; Franzen, 2014). Both Missouri and Nebraska do not currently recommend this approach and were excluded from the MRTN evaluation (Table 3).

Table 3: Corn N recommendation approaches used by different states in the U.S. Midwest.

Tools	Approach	Reference
Indiana YG	Calculation using yield potential and previous soybean (*Glycine max*) crop credit of 34 kg N ha^{-1}. $N_{rec} = 1.12^{\dagger} [-27 + 1.36*YG - N_{credit}]$	Vitosh et al., 1996
General YG	Calculation using a yield goal and previous soybean crop credit of 45 kg N ha^{-1}. $N_{rec} = 1.12^{\dagger} [1.2*YG - N_{credit}]$	Stanford, 1973
Minnesota Central and East YG	Calculation using a yield goal, organic matter content, and previous soybean crop credit of 22 to 45 kg N ha^{-1}. *(Table 1 of publication)*	Schmitt et al., 2002
Missouri YG	Calculation using a yield goal, plant population, and N supplying power of the soil based on organic matter and cation exchange capacity. $N_{rec} = 1.12^{\dagger}[0.9*YG + 4*Pop - N_{SOM\text{-}credit}]$	Buchholz et al., 2004
Nebraska YG	Calculation using a yield goal, inorganic soil NO$_3$-N, N supplied from organic matter, and N credits from previous soybean crop of 50 kg N ha^{-1}. Nitrogen recommendation rate is adjusted for soil texture classification and time of N fertilizer application. Recommended to use preplant soil NO$_3$-N but it was excluded for this calculation. $N_{rec} = 1.12^{\dagger}[35 + 1.2*YG - 0.14*YG*SOM - N_{Credit}] *Time_{adj} * Price_{adj}$	Shapiro et al., 2008
North Dakota YG	Calculation using yield potential with N credits from previous soybean crop credit of 45 kg N ha^{-1}. $N_{rec} = 1.12^{\dagger} [1.2*YG - N_{credit}]$	Franzen, 2010
General PPNT	Calculated by subtracting soil NO$_3$-N concentration from current N recommendation methods, yield goal or MRTN from a depth of 60 cm. $N_{rec} = 1.12^{\dagger} [MRTN^{\ddagger} - NO_3\text{-}N_{(0\text{-}60\ cm)}]$	Bundy et al., 1999
Minnesota East PPNT	Calculated by MRTN values minus residual NO$_3$-N calculated credit from the top 60 cm of soil. $N_{rec} = 1.12^{\dagger} [MRTN^{\ddagger} - Ncredit\ based\ on\ NO_3\text{-}N_{(0\text{-}60\ cm)}]$	Rehm et al., 2006
Minnesota West PPNT	Calculation using MN yield goal minus the soil NO$_3$-N concentration in the top 60 cm. $N_{rec} = 1.12^{\dagger} [MN\ YG - NO_3\text{-}N_{(0\text{-}60\ cm)} - N_{credit}]$	Schmitt et al., 2002
North Dakota PPNT	Calculation using ND yield goal minus soil NO$_3$-N concentration in the top 60 cm. $N_{rec} = 1.12^{\dagger} [ND\ YG - NO_3\text{-}N_{(0\text{-}60\ cm)}]$	Franzen, 2010
Nebraska PPNT	Calculation using a NE yield goal minus NO$_3$-N content in the top 120 cm. $N_{rec} = 1.12^{\dagger} [NE\ YG - NO_3\text{-}N_{(0\text{-}120\ cm)}]$	Shapiro et al., 2008

Wisconsin PPNT	Calculated by subtracting soil NO_3-N concentration in the top 120 cm from the current state's suggested N recommendation 56 kg N ha^{-1} was subtracted from the measured soil NO_3-N to account for background soil NO_3-N. $N_{rec} = 1.12^{\dagger}[MRTN^{\ddagger}-(\Sigma NO_3\text{-}N_{(0\text{-}91\ cm)}-50)]$, *no adjustments made if sum of* NO_3*-N is below 50 lbs N* ac^{-1}*.*	Laboski and Peters, 2012
MRTN	Yield response from years of N response trials. Response is averaged over different geographical locations, or soils with relative economics of grain and N prices.	Sawyer et al., 2006
Iowa PSNT	Critical concentration of 25 ppm is reduced if there is excess spring precipitation. Concentration of soil NO_3-N above the critical limit results in no additional N applied. Below the critical limit, the soil NO_3-N taken from the top 30 cm is subtracted from the critical limit. $N_{rec}= 1.12^{\dagger}[(25\ ppm\ NO_3\text{-}N) – NO_3\text{-}N\ ppm_{\ (0\text{-}30\ cm)}]*8$	Blackmer et al., 1997
Illinois PSNT	MRTN or yield goal recommendation is adjusted proportionally if soil NO_3-N concentration from the top 30 cm is below 25 ppm and above 10 ppm. Full recommended rate is applied if concentration falls below 10 ppm and no additional N is applied if above 25 ppm.	Fernández et al., 2009
Indiana PSNT	Calculation using yield goal and soil NO_3-N concentration in the top 30 cm. *(Table 2 of publication)*	Brouder and Mengel, 2003

[†] *1.12 was used to convert N recommendations from lbs N* ac^{-1} *to kg N* ha^{-1}*.*

‡ MRTN values were used except when states did not recommend MRTN, in which case that state's yield goal calculation was used.

Maize-N Crop Growth Model

The Maize-N crop model (Yang et al., University of Nebraska – Lincoln, 2008) version 2015.4.0 was used for all sites. Historical weather data for the previous 30 years and the current year's weather was used up to the date of N application. This weather information was used to predict N mineralization up to the time of fertilizer application. All parameters used to model corn growth and corn N uptake and use remained unchanged from the recommended settings. Only information required by the program's main interface was entered specifically for each site, such as management records (e.g. date of planting, plant population, average historical yield, tillage operations, and pervious crop) and soil information (e.g. bulk density, % organic matter, rooting zone depth, soil pH, and soil NO_3-N).

Canopy Sensing

Reflectance measurements were taken on each treatment prior to the sidedress application, at V8-V10 with the exception of two sites that were measured at V5-V6. The two harvest rows of each plot were sensed using a RapidSCAN CS-45 (Holland Scientific, Lincoln NE, USA) held about 60 cm above the canopy. All reflectance data were averaged together to provide a single value for each plot. The Holland and Schepers (HS; Holland and Schepers, 2010) algorithm was used to calculate an N fertilizer recommendation from the reflectance measurements. This algorithm is based on a sufficiency index:

$$SI = \frac{VI_{Sensed\ Crop}}{VI_{Reference}} \qquad [1]$$

where SI was the sufficiency index; $VI_{Sensed\ Crop}$ was the vegetative index obtained from sensing the crop where fertilizer was applied and $VI_{Reference}$ was the vegetative index obtained from sensing an N-rich crop. The vegetative index used was the normalized difference red edge (NDRE). The NDRE was calculated for each site using the red-edge (730 nm; RE) and near-infrared (780 nm; NIR) wavelengths measured from each plot:

$$NDRE = \frac{NIR - RE}{NIR + RE} \quad [2]$$

For eq. 1, NDRE calculated for the $VI_{\text{sensed crop}}$ or the corn to be fertilized was obtained from sensor readings of treatments that received 45 kg N ha^{-1} at-planting (n=28 per site). For NDRE of the reference crop ($VI_{\text{Reference}}$), readings were used from treatments that received 225 and 270 kg N ha^{-1} all at-planting (n=8 per site). Fertilizer N recommendations were then calculated using:

$$N_{Rec} = \left(MZ_i * N_{Opt} - N_{PreFert} - N_{CRD} + N_{Comp}\right) * \sqrt{\frac{(1-SI)}{\Delta SI}} \quad [3]$$

where N_{Rec} was the calculated N fertilizer recommendation; MZ_i is a scaling value ($0 \geq MZ_i \leq 2$) used to adjust the N recommendation based on areas of high or low yield performance; N_{Opt} was the base N rate, which was determined by the farmer; $N_{PreFert}$ was the amount of N already applied prior to sensing; N_{CRD} was N credits associated with the previous crop, nitrate in irrigation water, manure, or residual nitrate; N_{Comp} was N needed to compensate for growth limiting conditions; SI was the sufficiency index; ΔSI was used as a method of determining the level of SI values that would receive the full N recommendation.

N_{Rec} from eq. 3 used to evaluate the canopy reflectance sensor were calculated using MZ_i =1.0, N_{Opt} was set as the recorded historical farmer's N rate for each site, $N_{PreFert}$ = 45 kg N ha^{-1}, N_{CRD} = 0, N_{Comp} = 0, SI was previously calculated from eq. 1 and the ΔSI = 0.3.

Improvement of Canopy Reflectance Sensor

To determine if the canopy reflectance sensor could be improved by integrating N recommendations from other tools, the base N rate or N_{Opt} (eq. 3) was changed to equal those from other tools' N recommendations. A new N recommendation from HS algorithm was then calculated using the changed N_{Opt} and the performance compared to the HS algorithm where N_{Opt} was equal to the farmer's N rate.

Statistics

Grain yield was determined based the two middle rows of each plot and adjusted to 155 g kg^{-1} moisture content. Data were analyzed by site using SAS version 9.2 (SAS Institute Inc., Cary, NC). The EONR was calculated using a quadratic-plateau function (Scharf et al., 2005; Cerrato and Blackmer, 1990). Proc NLIN in SAS 9.2 was used to fit the data to the quadratic-plateau function. The EONR (kg N ha^{-1}) was calculated for all 32 site years using treatments 1 to 8 for tools evaluated at-planting and 1, 2, and 9 to 14 for tools evaluated for a sidedress N application (Table 2) as shown:

$$EONR = \frac{(-b - (ratio)}{(2c)} \quad [5]$$

where *b* and *c* = linear and quadratic response coefficients from the optimized quadratic function, and ratio = \$0.88 kg^{-1} N/\$0.03 kg^{-1} grain (i.e., N price/corn price). The EONR was set to not exceed the maximum N rate (315 kg N ha $^{-1}$).

Performance for all tools was evaluated based on accuracy, or how close each tool's N recommendation came to EONR for all 32 sites. One method used to measured accuracy was using the root mean square error (RMSE) where the RMSE was calculated by:

$$RMSE = \sqrt{average((Tool's\ N\ Recommendation - EONR)^2)} \quad [4]$$

Accuracy was also determined as the average difference between the tool's N recommendation and EONR. Additionally, the percentage of sites where the N recommendation was within 30 kg N ha^{-1} of EONR was calculated. Tools that performed well had a low RMSE, an average difference between the N recommendation and EONR close to zero, and a higher percentage of sites where the N recommendation was within 30 kg N ha^{-1} of EONR.

Initial results showed one site had an abnormally low EONR due to previous soybean crops being damaged and supplying an unaccounted amount of residual N. This site was omitted resulting in a potential total of 31 sites used to evaluate the N recommendation tools.

Results and Discussion

N Recommendation Tools Compared

At-Planting vs Sidedress

Tools used to make a sidedress N recommendation performed better than tools used to make an at-planting recommendation. The average RMSE of all the tools evaluated at sidedress was 14.7 kg N ha^{-1} less than the average of RMSE for the at-planting tools (Table 4). Additionally, there was an 8.4% increase of sites where the tool's N recommendations were within 30 kg N ha^{-1} of EONR compared to the tools used to make an at-planting recommendation (Fig. 1).

Table 4: RMSE and average difference (N recommendation tool – EONR) for each N recommendation tool compared across 31 sites in the 2014 and 2015 growing season. Tools with the lower RMSE values and average values closest to zero indicate a greater accuracy. The number of sites (n) included in the evaluation differed for each tool based on the availability of information required to fully run each test.

		At-Planting		Sidedress	
N Recommendation Tool	n	RMSE	Average	RMSE	Average
		---------------------- kg N ha^{-1}			----------------------
Farmer NR	31	74.2	11.4	67.9	26.5
General Yield Goal	27	99.4	15.7	88.6	32.2
MN Yield Goal (East)	27	95.0	-35.1	75.6	-18.7
IN Yield Goal	27	103.9	27.7	95.3	44.1
MO Yield Goal	27	132.9	97.7	136.7	114.1
ND Yield Goal	27	99.3	-28.0	81.9	-11.6
NE Yield Goal	27	85.2	-1.0	74.9	15.4
State-Specific Yield Goal†	23	65.7	5.8	46.1	15.3
MRTN	24	60.7	-0.6	49.8	9.8
Maize-N	31	106.7	30.2	108.8	-0.9
General PPNT	31	96.7	-59.1	-	-
MN PPNT (East)	31	110.0	-76.9	-	-
MN PPNT (West)	27	96.0	-18.4	-	-
ND PPNT	27	99.3	-28.0	-	-
NE PPNT	27	91.9	-40.8		
WI PPNT	29	60.1	-3.3	-	-
IA PSNT	31	-	-	68.4	-21.1
IL PSNT	31	-	-	54.7	8.1
IN PSNT	27	-	-	80.4	30.0
Canopy Reflectance Sensor	31	-	-	83.5	-53.0

† indicates that each state used their respective state yield goal recommendation

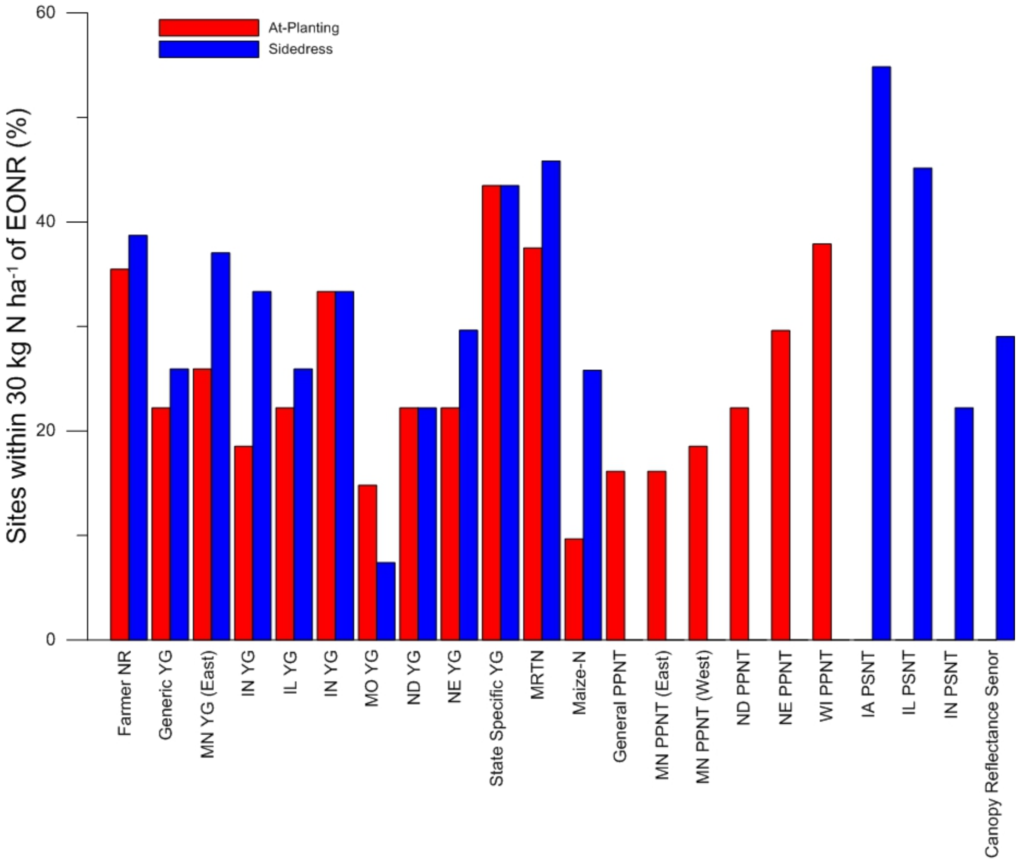


Fig. 1: The percentage of sites within 30 kg N ha^{-1} of EONR for each N recommendation tool used either for at-planting or for a sidedress application. Tools that had a higher calculated percentage or taller bar had a greater number of sites where the tool's N recommendation came close to the measured site-specific EONR value.

Yield Goal Calculations

The majority of the yield goal based recommendations had a lower RMSE when used to make a sidedress N recommendation. However, yield goal recommendations decreased in accuracy as the average difference between the tool's N recommendation and EONR increased by 13.2 kg N ha^{-1} (Table 4). These yield goal calculations resulted in N recommendations that were overestimating EONR at-planting and to a greater extent at sidedress. Of all the state yield goal calculations that were used for all sites (not including the state-specific yield goal), the Nebraska yield goal had the lowest RMSE and average difference between the N recommendations and EONR for at-planting and sidedress N recommendations (Table 4). The Nebraska yield goal was the most complex N recommendation tool out of the yield goal based tools evaluated. Unlike the other yield goal based tools, it allows for adjustments to be made on the timing of fertilizer applications and soil classifications as either sandy or medium to fine textured.

The poorest performing yield goal tool, which had the highest RMSE, greatest average value away from zero, and the lowest percentage of sites where the N recommendation was within 30 kg N ha^{-1} was the Missouri yield goal (Fig. 1, Table 4). This yield goal calculation was unique from the other methods as it used plant population, soil cation exchange capacity, and organic matter to determine an N recommendation (Table 3). The majority of sites overestimated EONR except for five sites, three of which came from Missouri and Illinois all of which had a similar argillic horizon or claypan, and two sites from Nebraska that were the only sites that were mainly coarse-textured soils (sites classified as a loamy sand or sand with >83% sand).

Conversely, the performance improved when each state used their respective yield goal calculation (state-specific yield goal). The state-specific yield goal was not only the best among the yield goal calculations but it was also one of the best performing of all the tools evaluated at-planting and at sidedress. This suggests that no individual method may be considered optimal for the entire U.S. Midwest region, but instead, the performance of a particular yield goal calculation may be more accurate at a state or smaller regional scale. This was the case with the Missouri yield goal, which was accurate in identifying EONR for claypan soils but overestimated EONR on river bottom soils within 30 km of each other (data not shown). This further justifies the reasoning many states used to develop their own yield goal calculations based on their own soil and climatic conditions.

MRTN

The MRTN N recommendations had the second lowest RMSE value at-planting and the second lowest RMSE value for sidedress N applications. Additionally, it was one of the most accurate tools for at-planting and sidedress N recommendations with the percentage of sites within 30 kg N ha^{-1} of EONR being 37.5 and 45.8%, respectively (Fig.1, Table 4). Other comparison studies have found similar results with MRTN performing better than other N recommendation tools. Febrer et al. (2014) found higher revenues using MRTN based calculations than yield goal calculations based on seven sites in Illinois from 1999-2008. Additionally, research over 79 sites in the U.S. Midwest compared MRTN performance to a crop growth model (Adapt-N; http://adapt-n.cals.cornell.edu/) and showed that MRTN recommendations were more likely to be within 28 kg N ha^{-1} of EONR than Adapt-N (Laboski et al., 2015).

Preplant Nitrate Test and Pre-sidedress Soil Nitrate Test

Nitrogen recommendations based on preplant soil NO_3-N, or PPNT, did not perform any better than the yield goal or MRTN recommendations without adjusting for soil NO_3-N. Many of the PPNT tests simply subtracted the concentration of measured NO_3-N from the N recommendation being used (Table 3). This often results in N recommendations, such as the MN (east), ND, and NE yield goal calculations which already underestimate EONR to further underestimate EONR (Table 4). Poor performances in PPNT N recommendations may be attributed to residual effects from the previous crop types, like soybean (*Glycine max*) that were planted the prior year. Research has indicated that the PPNT may not be a useful tool when corn follow soybean, especially when no manure was applied (Rehm et al., 2006; Shapiro et al., 2008).

An exception to the poor performing PPNT tools was the WI PPNT. This tool had the lowest RMSE of all tools evaluated and on average underestimated EONR by 3.3 kg N ha^{-1} (Table 4) with 29.6 % of sites that were within 30 kg N ha^{-1} of EONR. The reason for the improved performance was that the PPNT used MRTN or the state-specific yield goal when no MRTN was available. These N recommendations were then adjusted by subtracting the sum of all measured soil NO_3-N concentration down to 91 cm and subtracting 50 ppm from that total. However no changes to the base N recommendations were called for if the sum of the soil NO_3-N was less than 50 ppm. For the majority of these sites this was the case which resulted in using the MRTN or state-specific yield goal calculation unadjusted. Both of these recommendations performed well without any adjustments. What little improvement that was observed may not be worth justifying the use of this tool due to the extra cost and effort required to soil sample. Under a different rotation or when manure has been applied, the use WI PPNT would be more favorable.

The in-season PSNT recommendations were better able to estimate EONR than PPNT. The average RMSE for PSNT was lower than PPNT by 30.4 kg N ha^{-1} and the percentage of sites that were within 30 kg N ha^{-1} increased by 10.6% (Fig. 1, Table 4). The increased performance of the PSNT over the PPNT was attributed to the PSNT being able to capture N mineralized from soil organic matter (Bundy et al., 1999; Gelderman and Beegle, 1998; Schmidt et al., 2009). Whereas the PPNT samples are taken prior to the soil being able to accumulate N mineralized from soil organic matter. Of the three PSNT tools evaluated, the Illinois PSNT had the lowest RMSE and had the closest average to zero. This method differs from the Iowa and Indiana PSNT in that it still uses other N recommendations but it is adjusted in proportion to the concentration of measured soil NO_3-N (Table 3). The soil NO_3-N was < 10 ppm, and according to the PSNT guidelines, this would indicate that a full rate of N should be applied for all but three sites. The full N rate for the Illinois PSNT would be the same N recommendation as MRTN or the state-specific yield goal. The three sites that had a NO_3-N concentration > 10 ppm resulted in N recommendations that underestimated EONR when, in fact, they should not have been unadjusted, which resulted in the overall test to become less accurate.

The accuracy of the Iowa PSNT was less than the Illinois PSNT (greater RMSE) however it was the most accurate tool evaluated as the percentage of sites that were within 30 kg N ha^{-1} was 55%. The accuracy of the Iowa PSNT could be attributed to the N recommendation being based completely on soil NO_3-N content and not a yield goal value. Furthermore, it was also adjusted for several sites where spring precipitation exceeded the historical average.

Maize-N

The Maize-N model was not well adapted to the range of soil and climatic conditions gathered in this study. The high RMSE for recommendations made at-planting showed that recommendations ranged from underestimating EONR by 196 kg N ha^{-1} to overestimating by 259 kg N ha^{-1}. While sidedress N recommendations ranged from underestimating EONR by 206 kg N ha^{-1} to overestimating by 308 kg N ha^{-1}. The accuracy of Maize-N improved for sidedress applications as the percentage of sites that fell within 30 kg N ha^{-1} went from 10% at-planting to 26% at sidedress (Fig. 1). The result of increased accuracy of using Maize-N at sidedress compared to at-planting could be a function of the model being able to better compensate for in-season N losses that would occur due to weather and management practices; however, there were still sites where this model did not work well for N-recommendations at sidedress (Setiyono et al., 2011).

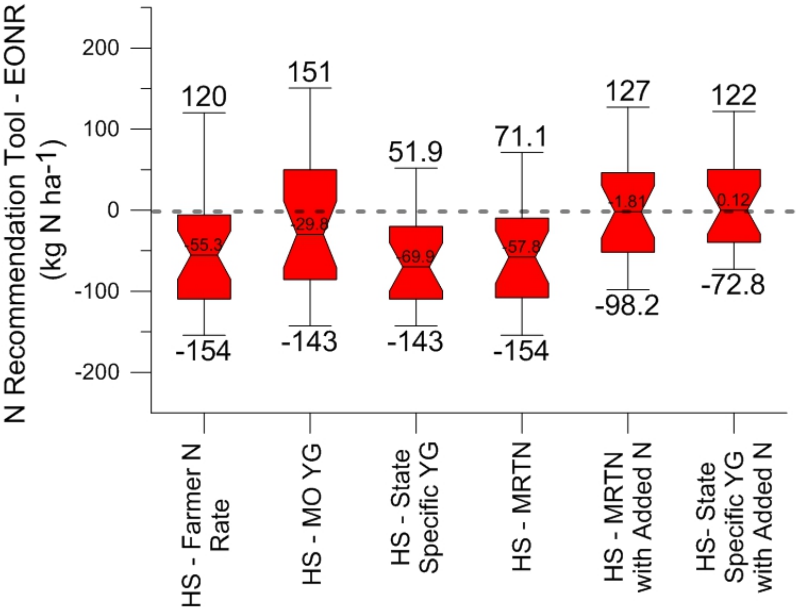
Maize-N was one of the poorest performing tools, after the Missouri yield goal, in comparison to all the other N recommendation tools. Previous research conducted in Nebraska and South Dakota showed that Maize-N had a lower RMSE than all yield goal N recommendations which included the Nebraska yield goal (Setiyono et al., 2011). This is contrary to the present study which found the Nebraska yield goal performed remarkable better than the Maize-N model.

Canopy Reflectance Sensor

The canopy reflectance sensor using the HS algorithm, on average, underestimated the amount of N required at each site by 53 kg N ha^{-1} at sidedress (Table 4). While this tool was more likely to underestimate EONR than other tools, it estimated 29% of sites that had an N recommendation within 30 kg N ha^{-1} which was comparable to the Maize-N model and the majority of yield goal recommendations used at sidedress (Fig. 1). The poor performance of the canopy reflectance sensor over all sites was a result of high SI values (average of 0.96). This indicated that the majority of corn that received 45 kg N ha^{-1} at-planting produced reflectance readings very similar to a non N-limited crop. Under high SI values, the N recommendation was decreased to minimize over application, which often results in underestimating EONR. The underestimation has also been noted in other studies where the HS algorithm, on average, prescribed 58% less N than Maize-N (Thompson et al., 2015). In some situations this did not have a significant impact on yield but for a few sites there was a decrease in net return as a result of underestimating EONR (Thompson et al., 2015).

Improvement of Canopy Reflectance Sensor

Efforts to integrate other N recommendation tools in the HS algorithm by replacing the historical farmer's N rate, or N_{Opt} in eq. 3, with the N recommendations from other tools showed minimal improvement. The replacement of N_{Opt} with some of the more accurate tools like MRTN or the state-specific yield goal resulted in a small decrease in RMSE of 3.2, and 0 kg N ha^{-1}, respectively. For both of these tools, the overall average difference between N recommendations and EONR decreased, resulting in a greater underestimation of EONR. For MRTN, there was no change in the percentage of sites where the N recommendation from the modified HS was within 30 kg N ha^{-1}. On the contrary, using the state-specific yield goal resulted in a 7.3% decrease in the percentage of sites within 30 kg N ha^{-1} (Fig. 2).



	HS - Farmer N Rate	HS - MO YG	HS - State Specific YG	HS - MRTN	HS - MRTN with Added N	HS- State Specific YG with Added N
Sites (n)	31	27	23	24	24	23
RMSE (kg N ha^{-1})	83.5	78.3	83.5	80.3	56.0	49.8
Average (Kg N ha^{-1})	-53.0	-15.7	-67.0	-57.5	-1.5	3.0
Sites within 30 kg N ha^{-1} of EONR (%)	29	19	22	29	33	44

Fig. 2: Box and whisker plots evaluating the performance of canopy reflectance sensor when the farmer's N rate (N_{opt}) in the Holland and Schepers (HS) algorithm was replaced with the N recommendations of other tools. The upper and lower whisker shows the range of values (N recommendation from tool – EONR), with the median indicated in the center of each box plot. The number of sites that were included in each evaluation (n), RMSE, average difference (N recommendation tool – EONR), and the percentage of sites that were within 30 kg N ha^{-1} were all used to measure the performance of integrating N recommendations tools with the HS algorithm.

The tool that best improved the HS when replacing the farmer's N rate was the Missouri yield goal. The Missouri yield goal alone overestimated EONR and had a large RMSE. When integrated into the HS algorithm, the new N recommendation resulted in the lowest RMSE with the most accurate N recommendation using the HS algorithm (Fig. 2). However, there was a decrease in the number of sites that were within 30 kg N ha^{-1} compared to using the farmer's N rate (29 to 18.5%).

Other methods used to improve the HS algorithm included adjusting the N_{Opt} by using the scale factor (MZ_i). This was put in the algorithm to allow farmers to change N recommendations based on spatial soil variability and corresponding growth potential (Holland and Schepers, 2010). By scaling up the N recommendations of MRTN and state-specific yield goals by a factor of 1.75 and 1.65, respectively, the canopy reflectance sensor using the HS algorithm slightly improved. By scaling the MRNT recommendation by 1.75 there was a decrease in RMSE by 6.9 kg N ha^{-1}, the average difference between the N recommendation and EONR was -0.4 kg N ha^{-1} a change of 57.1 kg N ha^{-1}, and there was no change in the percentage of sites within 30 kg N ha^{-1} of EONR. Scaling the state-specific yield goal by 1.6 resulted in a decrease of RMSE by 6.8 kg N ha^{-1} to a value of 76.7 kg N ha^{-1}, and the average difference between the N recommendation and EONR improved to -7.1 kg N ha^{-1}. Additionally, the number of sites that were within 30 kg N ha^{-1} of EONR increased by 6.0% to a value of 35%.

While some improvement was observed by using the scaling factor greater improvement to the HS algorithm was noted when the algorithm was adjusted. The HS algorithm (eq. 3) was adjusted by adding extra N kg N ha^{-1} to the N recommendation:

$$N_{Rec} = \left[\left(MZ_i * N_{Opt} - N_{PreFert} - N_{CRD} + N_{Comp}\right) * \sqrt{\frac{(1-SI)}{\Delta SI}}\right] + N_{extra} \qquad [6]$$

where N_{extra} is extra kg N ha^{-1} added to the HS N recommendation. The RMSE and average difference between the HS recommendation and EONR were best improved by adding 56 and 70 kg N ha^{-1} to the overall HS recommendations based on MRTN and the state-specific yield goal, respectively (Fig. 2). The improvement came as a lower RMSE, closer average of the HS N recommendation to EONR to zero, and an increase in the percentage of sites that were within 30 kg N ha^{-1} of EONR. However, even with a considerable improvement to the HS algorithm by adding additional N to the recommendation, there were still sites that under or overestimated EONR. The method of adding extra N to the final calculation (eq. 6) performed better than scaling the N recommendations used for N_{Opt} directly with MZ_i.

Conclusion

In general, N recommendation tools performed better at sidedress than at-planting, as determined by the average difference of the N recommendation tool and EONR, RMSE, and the number of sites where N was recommended within 30 kg N ha^{-1}. The tools that performed the best for at-planting were the Wisconsin PPNT, MRTN, and the state-specific yield goal, in that order. Tools that performed the best at sidedress were state-specific yield goal, MRTN, and the Illinois PSNT, in that order. The Maize-N crop growth model, IN yield goal, and the Missouri yield goal had the lowest performance overall. The canopy reflectance sensors using the HS algorithm did not perform as well as other tools, possibly due to minimal N stress at time of sensing resulting in the algorithm underestimating EONR. Under conditions where N stress would occur, such as when no fertilizer N was applied at-planting, it is hypothesized that the HS algorithm would perform better.

Methods of improving the canopy reflectance sensor recommendation by replacing the base N recommendation used in the HS algorithm with better performing tools did not show adequate enough improvement to recommend this on a regional scale. The tools that were used only resulted in the canopy reflectance sensor to further underestimate EONR. However when scaling the MRTN and the state-specific yield goal N recommendation used in the HS algorithm, a slight improvement occurred. The best improvement to the HS algorithm occurred when using MRTN and the state-specific yield goal as the base N rate and adding extra N to the final recommendation. While improvements are possible, these methods are not feasible on a regional scale because there is limited knowledge of what values to use to scale or how much additional N is required to optimize the HS algorithm.

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