IN-SEASON NITROGEN REQUIREMENT FOR MAIZE USING MODEL AND SENSOR-BASED RECOMMENDATION APPROACHES

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ABSTRACT

Nitrogen (N) management for corn (*Zea mays* L.) can be improved by applying a portion of the total required N in-season, allowing for adjustments which are responsive to actual field conditions. This study was conducted to evaluate two approaches for determining in-season N rates: Maize-N model and active crop canopy sensor. The effects of corn hybrid and planting population on recommendations with these two approaches were considered. In a 2-yr study, a total of twelve sites were evaluated over a 3-state region, including sites in Missouri, Nebraska, and North Dakota. Over all site-years combined, in-season N recommendations were generally lower when using the sensor-based approach than the model-based approach. This resulted in observed trends of higher partial factor productivity of N (PFP_N) and agronomic efficiency (AE) for the sensor-based treatments than the model-based treatments. Overall, yield was better protected by using the model-based approach than the sensor-based approach. For two Nebraska sites in 2012 where high levels of N mineralization were present, the sensor approach appropriately reduced N application, resulting in no decrease in yield and increased profitability when compared with the non-N-limiting reference. This indicates that specific conditions will increase the environmental and economic benefit of the sensor-based approach. The optimal N rate (ONR) was also determined using a linear-plateau model, considering hybrid and population differences ($P \leq 0.05$) for both the linear and plateau parts of the model.

Compared to the ONR, the model-based approach more closely estimated ONR than the sensor-based approach when considering all sites collectively. Overall, the model-based approach erred by over-recommending N, while the sensor-based approach erred by under-recommending N.

Keywords: Site-specific crop management, Maize-N model, soil fertility, crop canopy sensor

INTRODUCTION

Low nitrogen use efficiency (NUE) has been attributed to several factors including poor synchrony between N fertilizer and crop demand, unaccounted for spatial variability resulting in varying crop N needs, and temporal variances in crop N needs (Shanahan et al., 2008). It is estimated that 75% of N fertilizer is applied prior to planting (Cassman et al., 2002), resulting in high levels of inorganic N, such as nitrate, in the soil before the stage of rapid crop uptake occurs. Because of this, improvements in NUE can be achieved by attaining greater synchrony between the crop N need and the N which is available to the plant from all sources throughout the growing season (Cassman et al., 2002). Applying a portion of the N fertilizer alongside the growing crop allows fertilizer availability to coincide more closely with the time in which the crop needs the most N and is expected to increase NUE. Spatial variability of soil properties presents further challenges to N management. Nitrogen supplying capacity can vary throughout a field. Mamo et al. (2003), showed that N mineralization of organic matter (OM) varied spatially within a field. Additionally, the N fertilizer need by the crop can vary spatially across a field, due to varying yield potential. Mineralization of N is also dependent on soil water and temperature which vary with landscape position; therefore OM content should not be used as a sole criterion when delineating N management zones (Schmidt et al., 2002). Managing N application based on spatial variability can reduce the overall N rate applied and increase profitability compared with a uniform N application (Mamo et al., 2003). Variable rate application of N decreases the risk of overfertilization or underfertilization, compared with uniform applications. In addition to the spatial variability component of N management, temporal variations in N response and N mineralization related to environmental factors have also been observed (Mamo et al., 2003). Climate and management interactions cause tremendous year-to-year variation in both crop N requirement and yield (Cassman et al., 2002). Together, spatial and temporal variation creates uncertainty as to the optimal N fertilizer quantity for any given year (Roberts et al., 2010). Determining the amount and timing of N needed by the crop over a spatially diverse field is critical for improving NUE.

Active crop canopy sensors are available to monitor the N status of the crop, allowing growers to make management decisions that are reactive to actual growing season conditions, thereby improving NUE. Sensors can be an effective indicator of in-season crop need as they serve to integrate the conditions and stresses that have already occurred during the early growing season. Crop canopy sensors are designed to detect specific wavelengths of light reflected by crop canopies. These wavelengths are combined to create indices that are correlated with specific crop conditions of interest. For sensor information to be useful for calculating optimal N sidedress application rates, algorithms must be developed which will incorporate sensor reflectance measurements. Holland and Schepers (2010) developed a generalized N application model that was used with crop canopy sensor data in this study.

Simulation models have also been identified as a precision management technique which has potential to maximize the synchrony of crop demand for N and fertilizer N supply thereby having potential to increase NUE (Cassman et al., 2002). Models are a method of N management which account for the interactions between management and environmental conditions. The Maize-N model was developed to estimate economically optimum N fertilizer rates for maize by taking into account soil properties, indigenous soil N supply, local climatic conditions and yield potential, crop rotation, tillage and fertilizer formulation, application method and timing (Setiyono, et al., 2011). The model was validated in experiments in central Nebraska, eastern South Dakota, and western Nebraska and included both irrigated and rainfed systems. The EONR simulated by Maize-N was relatively robust across the different sites.

The objective of this study was to evaluate these two approaches for determining in-season N rates: Maize-N model and sensor reflectance data with the Holland and Schepers algorithm. Utility in predicting N need is evaluated for both approaches over a 3-state region, including sites in Missouri, Nebraska, and North Dakota. Additionally, the study investigated effects of maize hybrid and population on the efficacy of the two N recommendation strategies. Estimated ONR for each site was compared to in-season N rates generated by these two technologies.

MATERIALS AND METHODS

Twelve sites were chosen in Nebraska, Missouri, and North Dakota for the 2012 and 2013 growing seasons (Table 1). For each state, a site that with high and moderate yield potential was chosen. Each experimental site contained four replications of 16 treatments arranged in a randomized complete block design. Two hybrids were selected for each site. Hybrids used in Missouri and Nebraska were characterized by having a high or low drought score. Each hybrid was planted at a high and low seeding rate. Seeding rates for Missouri sites were 76,600 and 101,300 seeds ha^{-1}, and rates for Nebraska and North Dakota sites were 79,000 and 103,800 seeds ha^{-1}. Four N treatments were implemented: unfertilized check, N-rich reference, sensor-based, and model-based. The unfertilized check received no N during the study. The N-rich reference received N in a quantity that was considered to be non-limiting to yield for the individual site. The N-rich rate was 280 kg ha^{-1} for Missouri sites, 224 kg ha^{-1} for North Dakota sites, and ranged from 268 to 280 kg ha^{-1} for Nebraska sites. The sensor-based and model-based treatments received an initial N rate and an in-season N rate. The initial N rate for sensor-based and model-based treatments was 56 kg ha^{-1} for Missouri sites, 0 kg ha^{-1} for North Dakota sites, and 84 kg ha^{-1} for

Table 1. Characteristics of research sites and cropping information including site yield potential classification, predominant soil subgroup, site organic matter, and previous crop for sites in Missouri (MO), Nebraska (NE), and North Dakota (ND) in 2012 and 2013.

Site ID	Site yield potential	Predominant soil subgroup	Organic matter	Previous crop
			--%--	
MORO12	High	Fluventic Eutrudepts	1.5	Soybeans
MOLT12	Moderate	Vertic Epiaqualfs	2.6	Soybeans
NECC12	High	Pachic Udertic Argiustolls	3.9	Corn
NEMC12	Moderate	Cumulic Haplustolls	1.7	Corn
NDDN12	High	Typic Epiaquerts	5.3	Corn
NDVC12	Moderate	Calcic Hapludolls	3.6	Wheat
MOTR13	High	Fluventic Hapludolls	1.9	Soybeans
MOBA13	Moderate	Vertic Epiaqualfs	1.9	Soybeans
NECC13	High	Udic Argiustolls	2.8	Soybeans
NEMC13	Moderate	Oxyaquic Haplustolls	2.1	Corn
NDAR13	High	Typic Epiaquerts	3.4	Soybeans
NDVC13	Moderate	Calcic and Pachic Hapludolls	3.6	Wheat

Nebraska sites. In-season N applications were applied to both model-based and sensor-based treatments at the time of crop canopy sensing. In-season N applications were applied to sensor-based and model-based treatments using recommendations from the Holland and Schepers sensor algorithm (Holland and Schepers, 2010) and Maize-N: Nitrogen Recommendation for Maize model (Yang et al., University of Nebraska – Lincoln, 2008) respectively.

For the Maize-N model treatments, Version 2008.1.0 was used for the 2012 growing season, and did not take into account weather that had occurred in that growing season to determine mineralized N. For 2013, Version 2013.2.0 was used which contains updates to allow the model to utilize current weather data in order to estimate the amount of mineralization of N that had occurred since the last crop. The long-term weather data was then used to predict mineralization of N for the remainder of the season, based on historical trends. A separate iteration of the model was run for each unique hybrid and population treatment combination. For site MOTR13, due to an error in N credits applied for the model input values, the economically optimum N rate and in-season N recommendation was incorrectly reduced by 18 kg N ha^{-1}.

Crop canopy reflectance data was collected from all treatment plots prior to the in-season N fertilizer application of sensor-based and model-based treatments. Data was collected using a RapidSCAN CS-45 Handheld Crop Sensor (Holland Scientific, Lincoln, NE) oriented in the nadir position and at least 0.6 meters above the crop canopy. The sensor is equipped with a modulated light source and three photodetector measurement channels: 670 nm, 730 nm, and 780 nm. Travel speed through the field resulted in collection of approximately one sensor reading every 25 cm. Two rows per plot were scanned, producing one average value from each measurement channel per row. The values generated for each row were then averaged together to create one value for each wavelength per plot. This study used the NDRE index (Equation 1) as it includes wavelengths that have been previously found to be more sensitive to chlorophyll content of the plant (Scharf and Lory, 2009).

$$\mathrm{NDRE} = \frac{\mathrm{R_{NIR}} - \mathrm{R_{RED\ EDGE}}}{\mathrm{R_{NIR}} + R_{\mathrm{RED\ EDGE}}} \tag{1}$$

where:

$\mathrm{R_{NIR}}$ = near-infrared reflectance (780 nm)

$\mathrm{R_{RED\ EDGE}}$ = red edge reflectance (730 nm)

The sufficiency index (SI) was generated by dividing the NDRE from the sensor-based treatment by the NDRE from the corresponding N-rich reference treatment for each replication. Sensor-based treatments were paired to N-rich reference treatments with the same hybrid and plant population. The SI was then used in the modified algorithm by Holland and Schepers (2010, modified 2012) to determine an N application rate. In addition to the user providing the SI, this algorithm requires the user to input three other variables: crop growth stage, amount of N fertilizer applied prior to crop sensing and in-season fertilization, and user-predicted ONR. For this study, the user-predicted ONR was calculated using algorithms developed by the University of Nebraska-Lincoln and North Dakota State University for producers applying a uniform rate of N.

In-season N was applied to model and sensor treatments using different N sources and methods for each site. Nitrogen for Missouri sites was hand applied using Super-U (46% N). Nebraska sites N was hand applied using UAN (32%). At North Dakota sites, UAN (28%) was applied using a walk behind applicator with streaming drop nozzles that the operator pushed through the field. Upon physiological maturity, corn from all plots was harvested. Due to uneven irrigation following the in-season N application, MORO12 yield data was considered to be unreliable and was discarded. Partial factor productivity for N ($\mathrm{PFP_N}$) was calculated by dividing grain yield by total fertilizer N rate. Agronomic efficiency (AE) was calculated by taking the difference in yield between the fertilized treatment and the check and dividing by total N application. The data was analyzed using the GLIMMIX procedure in SAS 9.2 (SAS Institute Inc., Cary, NC). Mean separation test was done using Fisher's LSD.

In order to make an estimation of the agronomic ONR, a linear-plateau response curve representing yield as a function of N rate was derived using the N rates and corresponding yields from this study. Unique linear-plateau relationships were created for each site. The high N reference was assumed non-limiting for N and thus used to generate the plateau portion of the response relationship. Tests of statistical differences ($\alpha = 0.05$) due to plant population and hybrid for the high N reference treatments were determined using the GLM procedure in Statistical Analysis System (SAS). If a significant difference in plateau yield occurred for plant population or hybrid, then individual means for these treatments were used to create separate plateaus, to reflect different mean values. If no statistically significant differences were found for plant population or hybrid for the high N reference, the overall mean of the high N reference was used to determine the plateau value. For the linear part of the linear-plateau relationship, the N check (no N), and the sensor-based and model-based treatment results were used. The yield of the N check, established the linear model intercept. The model-based and sensor-based N rate and yields were utilized to determine the slope of the function. Stepwise linear regression ($\alpha = 0.05$) was used to test for significant intercept and slope differences, as impacted by plant population and/or hybrid treatments. The procedure allowed for unique linear models to be generated when significant differences occurred with no N and/or with N additions. Optimum N rate for all unique combinations of the linear-plateau models was determined by solving for the joint of the linear-plateau model, as follows:

$$ONR = (plateau - a)/b \tag{2}$$

where:

a = the linear regression intercept
b = the linear regression slope

Using this approach ONR was determined for 8 of the 12 sites. For the remaining four sites, a reliable estimate of ONR could not be determined. The ONR was then compared graphically to actual N applied for both the model-based and sensor-based treatments, to examine which treatment was best at predicting ONR. For both the model and sensor N recommendation approaches, a linear regression analysis was performed using the REG procedure in SAS. The intercept was suppressed from the model statement so that it would be set to 0. R^2 values shown are the adjusted R^2.

RESULTS AND DISCUSSION

Plant population and hybrid differences were not found to influence sensor or model utility. Nitrogen application is summarized for the sensor and model treatments for each site, averaged across hybrid and population treatments at that location (Figure 1). For the majority of sites, in-season N rates for the model-based treatments were higher than in-season N rates for the sensor-based treatments. For one site, NECC12, no in-season N application was recommended using the sensor-based approach. There were two sites in which a higher in-season N application was recommended by the sensor approach than the model approach. MOBA13 had a higher N recommendation with the sensor approach than with the model approach and NDVC13 had a higher N recommendation using the sensor approach as the model did not recommend any N application at this site. The model approach did not recommend any N application at NDVC13 largely due to high levels of nitrate already present in the soil. At MOTR13 the in-season N rate for the model approach was erroneously reduced by 18 kg ha^{-1}. This resulted in the total N rate for the model treatments being 25 kg ha^{-1} lower than the N rate for the reference rather than only 7 kg ha^{-1} lower than the reference N rate.

Figure 2 depicts the differences in yield based on N strategy for the 2012 sites. No yield is available for MORO12 due to uneven irrigation resulting in confounding results and loss of data. For the remaining five sites, there was a

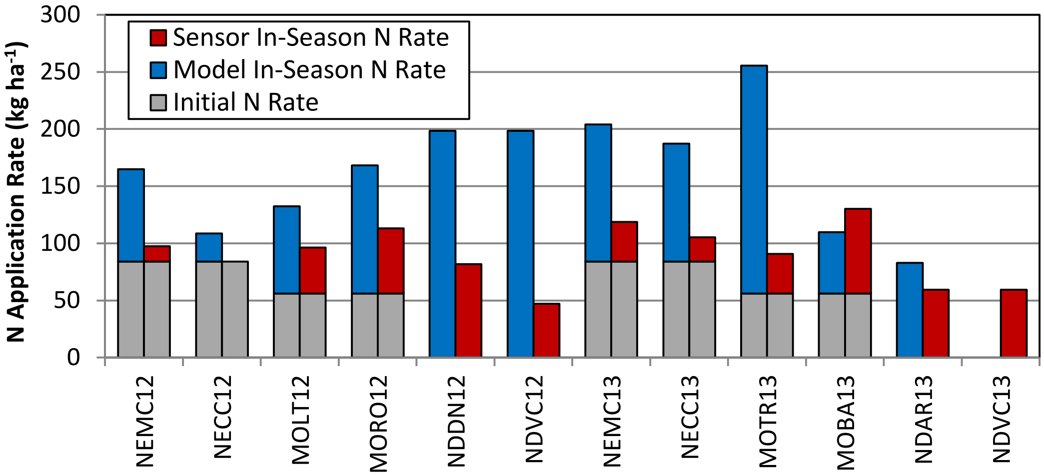

Figure 1. N rate applied to sites in Nebraska (NE), Missouri (MO), and North Dakota (ND) in 2012 and 2013. Initial and in-season rates are indicated for model-based and sensor-based treatments. In-season N was conducted at V8 to V10 and applications were made at the same time for model and sensor treatments at a given site.

significant difference in yield due to N strategy at four sites. The model-based and sensor-based treatments were not significantly different in yield at any site. The yield for the model-based approach was not significantly lower than the yield for the reference treatment at any site; however the sensor-based approach was significantly lower in yield than the reference treatment at two of the five sites (NDDN12 and NDVC12). This indicates that at these two North Dakota sites, the model-based approach did a better job of protecting yield compared to the sensor-based approach. Lower than expected yields for MOLT12 were due to drought conditions. High yields for the check treatment at the Nebraska sites are explained by unusually high rates of mineralization of N early in the growing season which reduced response to fertilizer N applied. At these two sites, the sensor-based approach had a lower N rate than the model-based approach, however yield was not significantly different. Grain yield for N strategy main effect of each site in 2013 is shown in Figure 3. Lower N rates for model-based and sensor-based treatments contributed to significantly lower yield than reference treatments in four cases (two due to model-based approach and two due to sensor-based approach). MOTR13 had exceptionally high yields, such that both the model and sensor N rates limited yield. However, at this site the in-season N rate for the model approach was erroneously reduced by 18 kg ha^{-1}. This resulted in the total N rate for the model treatments being 25 kg ha^{-1} lower than the N rate for the reference rather than only 7 kg ha^{-1} lower than the reference. This difference would likely have resulted in yields for the model treatments being closer to that of the reference. At the North Dakota sites, no significant response to fertilizer N was seen. Factors other than N limited crop production there, therefore reducing the N response. Sensor-based treatments had a significantly lower yield than model-based treatments at two of the six sites, while model-based treatments had a significantly lower yield than sensor-based treatments at one of the six sites. Overall, yield results indicate that the model-based approach better protects yield

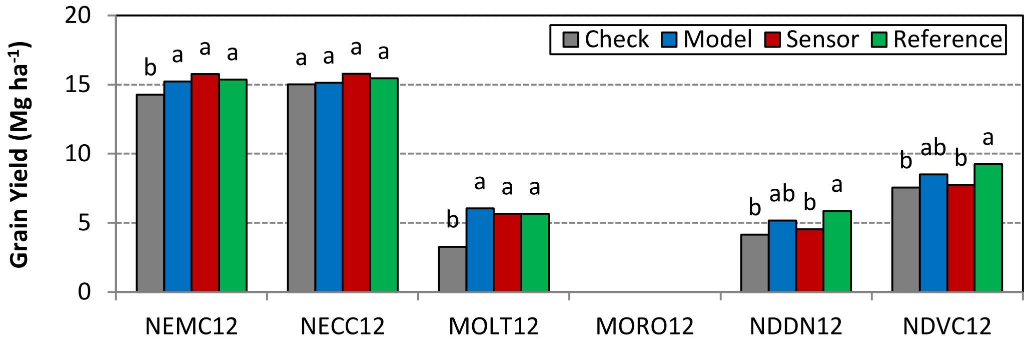

Figure 2. Grain yield for sites in Nebraska (NE), Missouri (MO), and North Dakota (ND) in 2012 arranged by N strategy. Bars with the same letters are not significantly different at P≤0.05. Significance letters apply within site.

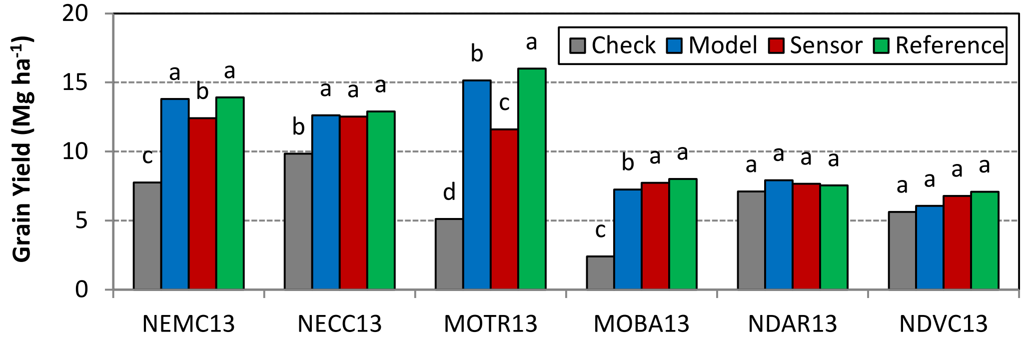

Figure 3. Grain yield for sites in Nebraska (NE), Missouri (MO), and North Dakota (ND) in 2013 arranged by N strategy. Bars with the same letters are not significantly different at P≤0.05. Significance letters apply within site.

potential than the sensor-based approach.

There was a significant difference in PFP_N among N strategies at all sites. These differences are represented graphically in Figures 4 and 5 for 2012 and 2013 respectively. In 2012 where sensor-based treatments had lower in-season N rates, the sensor-based approach had a significantly higher NUE than the model-based approach for all sites, as seen by PFP_N. For Nebraska sites this difference was attributed to high levels of N mineralization resulting in high yields, even for the check treatment which received no N application. The sensor approach appropriately reduced the in-season N recommendation at these sites, while the model did not. It should be noted that the model Version 2008.1.0 was used in 2012, which lacked the capability of estimating anticipated additions of available N due to mineralization by using in-season weather. For site NEMC12, the sensor-based in-season N rate was 14 kg N ha^{-1} while the model-based in-season N rate was 81 kg N ha^{-1}. However, if Maize-N Version 2013.2.0 which uses current season weather for estimation of N mineralization of soil organic matter would have been used, the in-season N rate would have been reduced to 62 kg N ha^{-1}. The use of Version 2013.2.0 would in this case improve the in-season N recommendation by appropriately lowering the N rate; however, the rate was still higher than the sensor-based rate. For site NECC12, the sensor-based in-season N

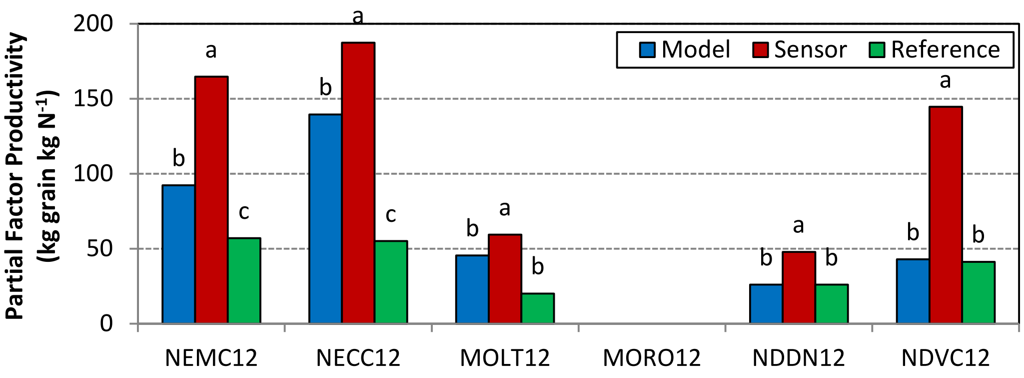

Figure 4. Partial factor productivity of N arranged by N strategy for sites in Nebraska (NE), Missouri (MO), and North Dakota (ND) in 2012. Bars with the same letters are not significantly different at P≤0.05. Significance letters apply within site.

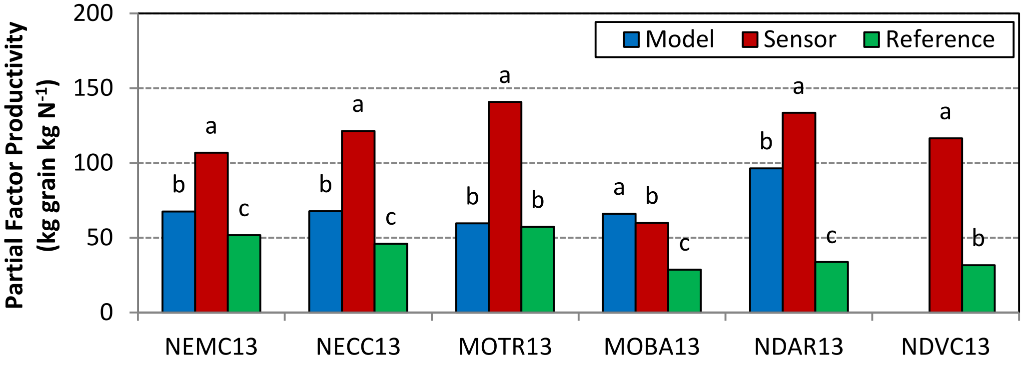

Figure 5. Partial factor productivity of N arranged by N strategy for sites in Nebraska (NE), Missouri (MO), and North Dakota (ND) in 2013. Bars with the same letters are not significantly different at P≤0.05. Significance letters apply within site.

rate was 0 kg N ha^{-1} while the model-based in-season N rate calculated with Maize-N Version 2008.1.0 was 25 kg N ha^{-1}. Using Version 2013.2.0 for NECC12 results in the in-season N rate being reduced to 0 kg N ha^{-1}. In this case, the updated version of Maize-N would result in an appropriately reduced in-season N rate that is equal to the N rate prescribed by the sensor-based approach and the PFP_N would be the same as the sensor-based approach in Figure 4. In 2013, lower N application resulted in a higher PFP_N for the sensor-based treatment than the model-based treatment at four of five sites and a higher PFP_N for the model-based treatment than the sensor-based treatment for 1 of 5 sites as shown in Figure 5 (no comparison can be made for site NDVC13 as the model-based approach recommended no N application). The treatments receiving the highest N rates generally have the lowest PFP_N, while treatments receiving the lowest N rates generally have the highest PFP_N. Because the treatment with the highest PFP_N likely has the lowest N rate, in many cases this resulted in reduced yield compared to treatments with a higher N rate. For this reason, PFP_N should not be solely considered as an evaluation of the effectiveness of an N strategy. It is important to realize that increasing PFP_N while simultaneously reducing yield is an undesirable scenario. Higher PFP_N is desirable within a context where yield is not negatively impacted.

In 2012 for all sites, AE of the sensor-based approach tended to be higher than the model-based approach; however, it was only significantly higher at one of the five sites (NEMC12). In 2013, the sensor-based approach had a significantly greater agronomic efficiency than the model-based approach at three sites (NEMC13, NECC13, and MOTR13), and was not significantly different at two sites (MOBA13 and NDAR13 (with PFP_N no comparison can be made for NDVC13 as there was no N application for the model-based approach) (data not shown).

Overall, when examining these measures of NUE, the sensor approach is consistently higher in NUE than the model approach. This is likely due to the frequently lower N rates recommended by the sensor N strategy than the model N strategy. Sites where NUE was increased and yield was not significantly decreased from that of the reference crop are of particular interest as this is a favorable situation. There were seven sites where the sensor treatment was not significantly lower yielding than the reference and of these seven sites, six had the highest PFP_N of all N strategies (NEMC12, NECC12, MOLT12, NECC13, NDAR13, and NDVC13). In general, this situation occurred where the site was not highly responsive to N applications. This may be due to unpredictable conditions resulting in reduced yield, such as drought, or conditions resulting in N being available from other sources such as through N mineralization. In the case of NEMC12 and NECC12, high N mineralization and lack of conditions contributing to mechanisms of N loss is suspected, resulting in these sites being less responsive to fertilizer N. Similarly, dry conditions resulted in lower yields for MOLT12, NDAR13, and NDVC13, therefore introducing another more limiting factor (water) and reducing N requirements for this site. In these cases, the sensor approach appropriately reduced in-season N application, resulting in increased N fertilizer savings and higher NUE with no significant reduction in potential yield.

There were nine sites where the model treatment was not significantly lower yielding than the reference. Of these, none had the highest PFP_N; however, for five of these sites the model treatment is significantly higher in PFP_N than the reference (NEMC12, NECC12, NEMC13, NECC13, and NDAR13). Therefore, it is possible that NUE can be improved to some degree while better protecting yield using the model approach. At sites NEMC13 and MOTR13, the model clearly better estimated N needs than the sensor. Here the sensor treatments have significantly lower yields than the model treatments. At these site yields were high and the sensor approach did not provide enough N to maximize yields. The effect of this is further seen when examining profitability.

A comparison of profitability across the N strategies was made by assuming corn could be sold for $0.20 kg^{-1} and that N fertilizer cost $1.10 kg^{-1} (data not shown). The yield for each plot was then multiplied by the price it could be sold for and the amount of fertilizer applied to each plot was multiplied by the cost of fertilizer per unit. Fertilizer cost was subtracted from grain price to determine the profit in \$ ha^{-1}. In 2012, for three of the sites there was no difference in profitability between the model-based and sensor-based treatments (MOLT12, NDDN12, and NDVC12). For the two Nebraska sites, the sensor approach was significantly more profitable than the model. This was due to lower in-season N recommendations for the sensor-based N strategy and comparable yields. In 2013, model-based treatments had a significantly higher profitability than sensor-based treatments at two of six sites (NEMC13 and MOTR13). The remaining four sites had no significant differences in profitability between model and sensor treatments. When comparing the sensor-based treatment to the reference, the sensor-based approach had a significantly higher profitability in three of six sites, and a significantly lower profitability in two of six sites. The model-based treatment had a significantly higher profitability compared to the reference in one of six sites, while the reference had a significantly higher profitability than the model-based treatment in one of six sites. A large difference in profitability was seen for MOTR13 due to reduced yields caused by insufficient N availability for both the model and, more substantially for the sensor treatments. Over all site-years combined, there was not a clear trend for profitability of these varying approaches. However, it should be noted that when considering profitability, the amount that is significant to trigger management changes for a producer is not necessarily the same as what would be considered statistically different.

Table 2 provides a summary of the differences in measures previously discussed between the model and sensor approaches for years 2012 and 2013. From this comparison it is clear the sensor performed better at NEMC12 and NECC12 as it recommended lower N rates, had higher yield, greater profit, and greater NUE. At all other sites, greater N application resulted in greater yield, but lower PFP_N. It is therefore less straightforward which method performed better at

Table 2. Mean differences between model and sensor treatments for N input, yield, profit, AE, and PFP_N for sites in Nebraska (NE), Missouri (MO), and North Dakota (ND) in 2012.

Model-Sensor					
site	N-input	yield	profit	AE	PFP_N
	----kg ha^{-1}----		\$ ha^{-1}	kg grain increase kg N^{-1}	kg grain kg N^{-1}
NEMC12	67	-545	-181*	-10*	-72.4*
NECC12	25	-657	-157*	-8	-47.9*
MOLT12	36	377	21	-7	-13.9*
MORO12	55	--	--	--	--
NDDN12	117	629	-8	-8	-21.9*
NDVC12	151	755	-15	-3	-101.7*
NEMC13	85	1377*	177*	-9*	-39.3*
NECC13	82	81	-74	-11*	-53.7*
MOTR13	165	3528*	510*	-39*	-81.2*
MOBA13	-20	-485*	-73	3	6.0*
NDAR13	24	270	28	2	-37.1*
NDVC13	-59	-735	-79	--	--

*Indicates significant difference at $P \leq 0.05$.

the remaining sites. In 2013, the model performed better at sites NEMC13 and MOTR13 where the model approach had significantly higher yields and profitability than the sensor approach.

The ONR values derived using the linear-plateau model are provided for each site in Table 3. Where significant differences due to plant population and/or hybrid occurred, ONR was adjusted accordingly. No estimation was made for MORO12 as yield data from this site was eliminated. For three sites (NDDN12, NDVC12, and NDVC13) for some or all treatment combinations there was no N fertilizer response due to factors such as drought, therefore these sites were eliminated from the analysis. Site NECC12 and NEMC12 were also non-responsive to fertilizer for some or all treatment combinations, however, this was believed to be due to high levels of N mineralization in the growing season, therefore these sites are included in the subsequent analysis.

Using the linear-plateau estimated ONR, the total N applied by both the model-based and sensor-based treatment approaches can be compared. Figure 6 illustrates the relationship between the estimated ONR and the total N actually applied. The diagonal line represents the location on the graph where total N applied matches the linear-plateau estimated ONR. Points falling below this line are sites where the total N applied was in excess of the optimum, and points falling above this line are sites where the total N applied was less than the optimum. Points at a greater distance from the line indicate further variation from the estimated ONR. A linear regression of the data points with an intercept of 0 was fit and is depicted with a dashed line on each graph along with the coefficient of determination.

Table 3. ONR values derived using the linear-plateau model for sites in Missouri (MO), North Dakota (ND), and Nebraska (NE) in 2012 and 2013. Where significant differences in hybrid and plant population treatments occurred, unique linear-plateau models were derived resulting in unique ONR values as shown.

ONR				
	hybrid A, low population	hybrid A, high population	hybrid B, low population	hybrid B, high population
	-------------------------kg ha^{-1}-------------------------			
MOLT12	141	73	141	73
MOTR13	245	279	245	279
MOBA13	162	124	162	124
NDAR13	45	45	45	45
NECC12	0	0	0	0
NEMC12	0	0	132	132
NECC13	184	234	138	176
NEMC13	172	172	215	215

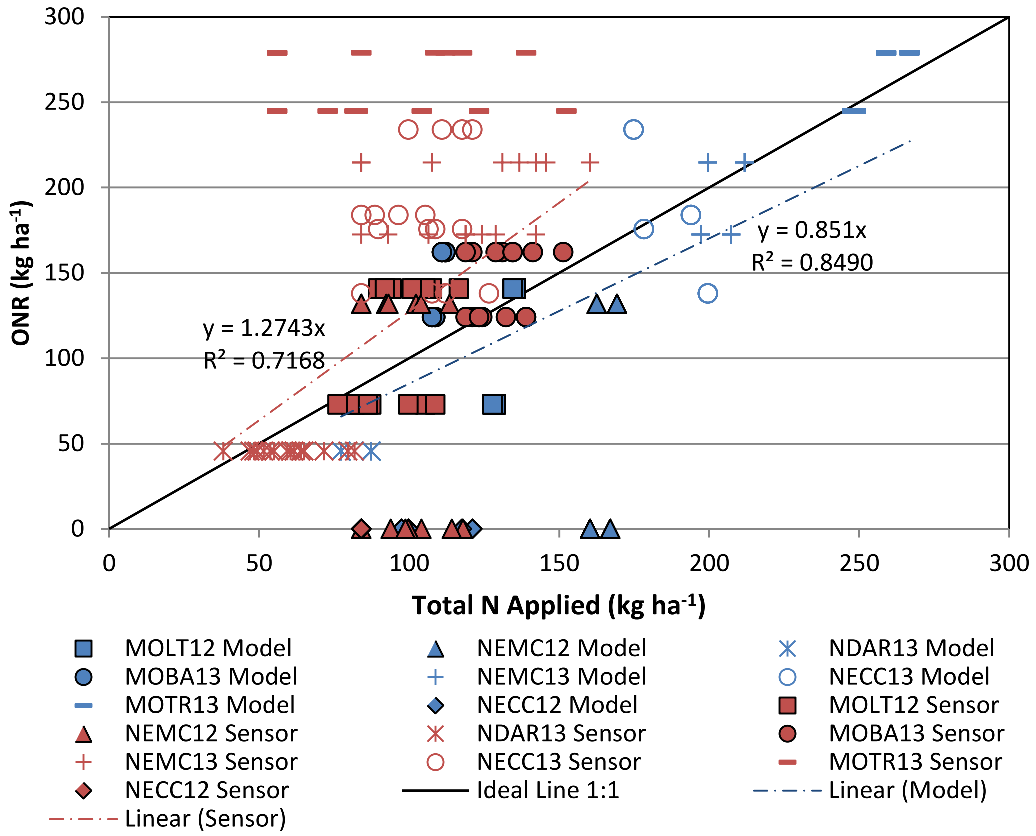

Figure 6. ONR derived from linear-plateau model compared to total N applied using model-based approach (blue symbols) and sensor-based approach (red symbols) for sites in Missouri (MO), Nebraska (NE), and North Dakota (ND).

The Maize-N model most closely approximates the linear-plateau estimated ONR (y=0.851x) and erred on the side of over-recommendation of N (Figure 6). Additionally, the Maize-N model has a higher coefficient of determination, indicating there is less deviation from ONR than for the sensor-based approach. For many locations, the sensor-based approach recommended N applications that were much lower than the linear-plateau estimated ONR, resulting in an under application of N and consequential yield loss.

CONCLUSIONS

Over all site years combined, yield was better protected by using the model-based approach than by using the sensor-based approach with the Holland and Schepers algorithm. In part, this is due to the version of the Holland and Schepers algorithm used, which allowed the N recommendations to be 0 kg ha^{-1}. More recent versions of the Holland and Schepers algorithms maintain a base recommendation even when crop stress is not detected. However, due to lower in-season N recommendations, the sensor-based approach was generally higher in NUE than the model-based approach. No clear trends in profitability were seen. In an ideal situation, N applications would be reduced without sacrificing yield. This clearly was the case for two Nebraska sites in 2012 where the sensor approach appropriately reduced N application. This demonstrates how the sensor approach is unique in its ability to be responsive to in-season growing conditions. The latest version of the model approach has some ability to do this, as N recommendations account for expected mineralization of N that has occurred in that growing season based on in-season weather up to that point. However, the Maize-N model at current does not have the ability to account for N losses through leaching, denitrification, or volatilization.

The model-based approach more closely estimated the linear-plateau derived ONR than the sensor-based approach across all sites. Additionally, the model-approach recommended N rates that erred on the side of over-application of N, resulting in fewer sites where yield was negatively impacted. For this reason, the model-based approach may be preferable to producers as yield is better protected. However, there are negative environmental implications of over-application that cannot be ignored.

It is important to keep in mind the restrictions of both approaches. While both approaches have promise, they are similarly limited in that they cannot predict the effects of weather on crop health and N availability from the time of in-season N application until harvest. For the crop canopy sensor approach, at the time of sensing, N may appear to be adequate in plants; however, this does not indicate if enough N is present in the soil to complete the growing season. Changes such as N losses through leaching, volatilization, or denitrification or additions of N through mineralization that may occur in the remainder of the growing season are not accounted for, as they are not yet expressed in the crop. Nitrogen supply, in some cases, may not be adequate to persist beyond the time of sensing. Both the model and sensor approaches have merit and may best be utilized when combined. The model has the ability to provide estimates of attainable yield and a starting point for ONR. This is valuable for the sensor approach as most algorithms for sensor-based N recommendations require either an estimate of expected yield or of ONR.

User convenience of these approaches is also necessary to consider. It should be noted that Maize N requires more up-front information, such as soil residual N supplied by the operator. Another significant difference between the two approaches is the ease of making spatially variable recommendations. The sensor approach rapidly incorporates spatial variability into its recommendation, while making spatially variable recommendations with the model is cumbersome and involves manually inputting different variables such as OM, residual N, and soil texture. Both approaches are constrained by the user applying in-season N in a narrow window of time, a condition that may limit adoption where rainfall in the early growing season might prevent in-season N applications from occurring.

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