Precision Agric
DOI 10.1007/s11119-016-9431-3

Evaluation of mid-season sensor based nitrogen fertilizer recommendations for winter wheat using different estimates of yield potential

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Abstract Optical sensors, coupled with mathematical algorithms, have proven effective at determining more accurate mid-season nitrogen (N) fertilizer recommendations in winter wheat. One parameter required in making these recommendations is in-season grain yield potential at the time of sensing. Four algorithms, with different methods for determining grain yield potential, were evaluated for effectiveness to predict final grain yield and the agronomic optimum N rate (AONR) at 34 site-years. The current N fertilizer optimization algorithm (CNFOA) outperformed the other three algorithms at predicting yield potential with no added N and yield potential with added N ($R^2 = 0.46$ and 0.25, respectively). However, no differences were observed in the amount of variability accounted for among all four algorithms in regards to predicting the AONR. Differences were observed in that the CNFOA and proposed N fertilizer optimization algorithm (PNFOA), under predicted the AONR at approximately 75 % of the site-years; whereas, the generalized algorithm (GA) and modified generalized algorithm (MGA) recommended N rates under the AONR at about 50 % of the site-years. The PNFOA was able to determine N rate recommendations within 20 kg N ha^{-1} of the AONR for half of the site-years; whereas, the other three algorithms were only able recommend within 20 kg N ha^{-1} of the AONR for about 40 % of the site-years. Lastly, all four algorithms reported more accurate N rate recommendations compared to non-sensor based methodologies and can more precisely account for the year to year variability in grain yields due to environment.

Keywords Nitrogen recommendations · Optical sensors · Yield potential · Winter wheat

Abbreviations

AONR	Agronomic optimum N rate
CNFOA	Current N fertilizer optimization algorithm

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Published online: 14 January 2016

DPG	Days of potential growth
GA	Generalized algorithm
GDD	Growing degree day
INSEY	In-season estimate of yield
MGA	Modified generalized algorithm
PPNT	Preplant nitrate test
PNFOA	Proposed N fertilizer optimization algorithm
NDVI	Normalized difference vegetation index
RI	Response index
SI	Stress index

Introduction

Average nitrogen (N) fertilizer use efficiency for cereal grain production in the developed world is estimated to be about 42 % (Raun and Johnson 1999). For winter wheat (*Triticum aestivum* L.), these can typically range from 27 to as high as 50 % depending on the growing season and production practices (Olson and Swallow 1984; Lees et al. 2000; Raun et al. 2002). Current soil testing based N fertilizer recommendation for winter wheat in Oklahoma recommends that 33 kg N ha^{-1} be applied for each Mg ha^{-1} a producer hopes to produce minus the amount of N available in a soil nitrate test (Zhang and Raun 2006). This methodology has proven to deliver more profitable N fertilizer recommendations (Makowski and Wallach 2001); however, when grain yield goals are employed, the risk of predicting environmental conditions is placed on the producer, especially if all N fertilizer is to be applied prior to planting (Raun et al. 2005).

Mid-season N fertilizer applications in winter wheat have reportedly increased N fertilizer use efficiency and at times grain yields (Olson and Swallow 1984; Alcoz et al. 1993; Boman et al. 1995). The advent of ground based active optical sensors that estimate plant biomass and calculate the normalized difference vegetative index (NDVI) of the growing winter wheat plant has achieved for more accurate N fertilizer recommendations along with variable fertilizer rate application (Solie et al. 2012) as long as N is the main growth-limiting factor (Zillmann et al. 2006). The use of these optical sensors coupled with algorithms to produce N fertilizer recommendations have proven to increase N fertilizer use efficiency as well as increase economic return for producers (Raun et al. 2002; Ortiz-Monasterio and Raun 2007).

Numerous parameters have been evaluated to aid in making sensor based N fertilizer recommendations. Raun et al. (2011) reported that yearly data from three long-term soil fertility experiments revealed maize (*Zea mays* L.) and winter wheat grain yields were consistently independent of the crop's level of response to N fertilization. Because of their independent responses and influence of both on demand for N fertilizer, it was concluded both should be utilized to determine in-season N fertilizer recommendations. These conclusions were further confirmed in the work of Arnall et al. (2013) who reported the same independence between grain yield and N fertilizer response from seven long-term soil fertility experiments in Oklahoma, Nebraska, Iowa, and Wisconsin.

The concept of a grain harvest index, calculated as the maximum yield of fertilized plots divided by yield of unfertilized plots, was first proposed by Johnson and Raun (2003) to predict adjustments to N fertilizer requirements. Raun et al. (2011) and Arnall et al. (2013)

also reported the index to be extremely variable and unpredictable from year to year. In an effort predict the grain harvest index in-season, Mullen et al. (2003) utilized the concept of Biggs et al. (2002), which compares crop reflectance of an unfertilized field or typical farmer practice to a high N reference strip. Mullen et al. (2003) reported the ratio of NDVI of the high N reference area divided by the NDVI of the farmer practice or unfertilized area correlated well with the grain yield harvest index when NDVI values were measured at Feekes (Large 1954) growth stages 5, 9, and 10.5. The equations from the linear relationships between the two response indices (RI) could then be employed to predict the harvest response index value.

Using the sum of two post-dormancy NDVI readings, measured at Feekes growth stages 4 and 5, divided by the difference in growing degree-days (GDD) between the two readings, Raun et al. (2001) was able to accurately predict wheat grain yield potential without additional N (YP_0). Building on this work, Lukina et al. (2001) observed that NDVI sensor measurements between Feekes growth stages 4 and 6 divided by the number of days from planting to sensing was highly correlated with final wheat grain yield and their in-season estimation of yield was then subsequently used to calculate the potential N removed in the grain. With the ability to accurately predict grain yield and the harvest index, Raun et al. (2002) incorporated these two parameters into an algorithm and later adjusted the algorithms (Raun et al. 2005) to determine N fertilizer recommendations for winter wheat. Early work did show that these algorithms coupled with the use of variable rate technology was reported to increase N fertilizer use efficiency by more than 15 % in winter wheat (Raun et al. 2002).

To improve the accuracy of the algorithms' ability to determine N fertilizer rate recommendations, researchers have attempted to improve the ability to predict the in-season estimate of YP_0. Currently estimates of YP_0 are determined from non-linear relationships with actual grain yield and the NDVI divided by the number of GDD's from planting to sensing (Raun et al. 2005). One parameter that has been evaluated is the effect of soil moisture properties on YP_0 (Walsh et al. 2013; Bushong et al. 2016). Bushong et al. (2016) reported improved ability to predict grain yield compared to current estimates by altering the GDD's to only count if soil moisture was adequate for growth and also included a crop water stress index (SI) at the time of sensing.

Concerned with some of the limitations of Lukina et al. (2001) and Raun et al. (2005), Solie et al. (2012) developed a generalized algorithm for variable rate N applications. Some of the concerns addressed by Solie et al. (2012) were that the maximum yield potential was not incorporated into a continuous function, boundary conditions were not included, and crop growth stage and differing rates of biomass accumulation at each growth stage were not fully accurate. Using sigmoidal relationships and boundary parameters determined from bare soil NDVI measurements and maximum grain yield for the region, Solie et al. (2012) was able to produce a model that could accurately recommend N fertilizer rates for changing growth stages of both maize and wheat.

The effectiveness of these algorithms to accurately recommend the proper sensor based N fertilizer rate in winter wheat, when compared to one another, has not been determined. The objective of this study was to evaluate the effectiveness of four proposed sensor-based N fertilizer rate recommendation methods to predict the winter wheat grain yield parameters that affect N rate recommendations and their ability to reliably estimate the agronomic optimum N rate (AONR).

Table 1 Site characteristics of mid-season N fertilizer response trials used to evaluate sensor based N fertilizer recommendations

Trial no.	Location (year)	Soil series	USDA taxonomic classification	Maximum yield (YP_{max}) (Mg ha^{-1})	Range of mid-season N rates (kg N ha^{-1})	Preplant N rate (kg N ha^{-1})
1	Lahoma, OK (2013)	Grant	Fine-silty, mixed, superactive, thermic Udic Argiustolls	7.5	0–134	28
2	Lahoma, OK (2012)	Grant	Fine-silty, mixed, superactive, thermic Udic Argiustolls	7.5	0–134	28
3	Lahoma, OK (2011)	Grant	Fine-silty, mixed, superactive, thermic Udic Argiustolls	7.5	0–134	28
4	Lahoma, OK (2010)	Grant	Fine-silty, mixed, superactive, thermic Udic Argiustolls	7.5	0–134	28
5	Hennessey, OK (2013)	Bethany	Fine, mixed, superactive, thermic Pachic Paleustolls	5.0	0–134	28
6	Hennessey, OK (2012)	Bethany	Fine, mixed, superactive, thermic Pachic Paleustolls	5.0	0–134	28
7	Hennessey, OK (2011)	Bethany	Fine, mixed, superactive, thermic Pachic Paleustolls	5.0	0–134	28
8	Hennessey, OK (2010)	Bethany	Fine, mixed, superactive, thermic Pachic Paleustolls	5.0	0–134	28
9	LCB, OK (2013)	Port	Fine-silty, mixed, superactive, thermic Cumulic Haplustolls	5.8	0–134	28
10	LCB, OK (2012)	Port	Fine-silty, mixed, superactive, thermic Cumulic Haplustolls	5.8	0–134	28
11	LCB, OK (2011)	Port	Fine-silty, mixed, superactive, thermic Cumulic Haplustolls	5.8	0–134	28
12	LCB, OK (2010)	Port	Fine-silty, mixed, superactive, thermic Cumulic Haplustolls	5.8	0–134	28
13	LCB, OK (2010)	Port	Fine-silty, mixed, superactive, thermic Cumulic Haplustolls	7.1	0–134	0
14	LCB, OK (2010)	Port	Fine-silty, mixed, superactive, thermic Cumulic Haplustolls	7.1	0–134	45
15	LCB, OK (2012)	Port	Fine-silty, mixed, superactive, thermic Cumulic Haplustolls	7.1	0–134	0
16	LCB, OK (2012)	Port	Fine-silty, mixed, superactive, thermic Cumulic Haplustolls	7.1	0–134	45
17	Covington, OK (2003)	Renfrow	Fine, mixed, superactive, thermic Udertic Paleustolls	6.2	0–155	0
18	Covington, OK (2003)	Renfrow	Fine, mixed, superactive, thermic Udertic Paleustolls	6.2	0–168	45
19	Covington, OK (2003)	Renfrow	Fine, mixed, superactive, thermic Udertic Paleustolls	6.2	0–184	90
20	LCB, OK (2003)	Port	Fine-silty, mixed, superactive, thermic Cumulic Haplustolls	5.4	0–184	0
21	LCB, OK (2003)	Port	Fine-silty, mixed, superactive, thermic Cumulic Haplustolls	5.4	0–184	45
22	LCB, OK (2003)	Port	Fine-silty, mixed, superactive, thermic Cumulic Haplustolls	5.4	0–184	90
23	Tipton, OK (2003)	Tipton	Fine-loamy, mixed, superactive, thermic Pachic Argiustolls	5.4	0–190	0
24	Tipton, OK (2003)	Tipton	Fine-loamy, mixed, superactive, thermic Pachic Argiustolls	5.4	0–190	45
25	Tipton, OK (2003)	Tipton	Fine-loamy, mixed, superactive, thermic Pachic Argiustolls	5.4	0–190	90

Table 1 continued

Trial no.	Location (year)	Soil series	USDA taxonomic classification	Maximum yield (YP_{max}) (Mg ha^{-1})	Range of mid-season N rates (kg N ha^{-1})	Preplant N rate (kg N ha^{-1})
26	Covington, OK (2003)	Renfrow	Fine, mixed, superactive, thermic Udertic Paleustolls	6.2	0–224	0
27	Covington, OK (2003)	Renfrow	Fine, mixed, superactive, thermic Udertic Paleustolls	6.2	0–224	45
28	Covington, OK (2003)	Renfrow	Fine, mixed, superactive, thermic Udertic Paleustolls	6.2	0–224	90
29	LCB, OK (2004)	Port	Fine-silty, mixed, superactive, thermic Cumulic Haplustolls	5.4	0–184	0
30	LCB, OK (2004)	Port	Fine-silty, mixed, superactive, thermic Cumulic Haplustolls	5.4	0–184	45
31	LCB, OK (2004)	Port	Fine-silty, mixed, superactive, thermic Cumulic Haplustolls	5.4	0–184	90
32	Tipton, OK (2004)	Tipton	Fine-loamy, mixed, superactive, thermic Pachic Argiustolls	5.4	0–215	0
33	Tipton, OK (2004)	Tipton	Fine-loamy, mixed, superactive, thermic Pachic Argiustolls	5.4	0–215	45
34	Tipton, OK (2004)	Tipton	Fine-loamy, mixed, superactive, thermic Pachic Argiustolls	5.4	0–215	90

LCB Lake Carl Blackwell

Materials and methods

Site information

To evaluate the effectiveness of different sensor based N fertilizer recommendations data were collected from 34 mid-season N fertilizer response trials. Each of these sites received a range of N fertilizer rates from 0 to as high as 224 kg N ha^{-1}. Fertilizer was applied as either urea (460 g N kg^{-1}) or urea-ammonium-nitrate (280 g N kg^{-1}) at the Feekes 5 (Large 1954) growth stage. Normalized difference vegetative index data were recorded either the day before or the day of mid-season N fertilizer application with a handheld Greenseeker (Trimble, Sunnyvale, CA, USA) active optical sensor. Site soil characteristics along with ranges in N fertilizer application rates are described in Table 1.

Agronomic optimum N rate (AONR) was calculated post-harvest by plotting actual grain yield versus the range of mid-season N fertilizer rates (Table 2). Linear plateau modeling was used to quantify the maximum maintained grain yield that was achieved across N fertilizer treatments for each site-year.

Sensor based recommendations

Current nitrogen fertilization optimization algorithm (CNFOA)

As previously reported by Raun et al. (2011) and Arnall et al. (2013), the use of both the crop's YP_0 and the predicted harvest RI should be employed to make accurate mid-season sensor based N fertilizer recommendations. The theory for the CNFOA is described by Raun et al. (2005). The YP_0 was determined by dividing the NDVI by the cumulative number of days between planting and sensing where growing degree-days (GDD) were greater than zero with a growth threshold value of 4.4 °C. This gives an empirical value known as the in-season estimate of yield (INSEY). The equation below describes an exponential relationship between final grain yield and INSEY.

$$YP_0 = 590 * \exp(\mathrm{INSEY} * 258.2) \quad (1)$$

The parameters listed in Eq. 1 do not have the same values as those published in Raun et al. (2005). These values have been updated with more recent field data and are maintained and published by Oklahoma State University (2014).

The predicted harvest RI was determined using the relationship established by Mullen et al. (2003). The harvest RI was predicted from the in-season RI derived by dividing the NDVI of an N rich area ($NDVI_{NR}$) by the NDVI of the farmer practice ($NDVI_{FP}$). The equation below describes the relationship and was used to predict the harvest RI.

$$\text{Harvest RI} = 1.69 * (NDVI_{NR}/\ NDVI_{FP}) - 0.70 \quad (2)$$

The parameters listed in Eq. 2 are not the same values as published in Raun et al. (2005). These values have been updated with more recent field data and are maintained and published by Oklahoma State University (2014).

The N fertilizer rate recommendation (N_{rec}) was calculated using Eq. 3 as described by Raun et al. (2005).

$$N_{rec} = [(YP_N - YP_0) * (GN\%) * (GW)]/\eta \quad (3)$$

The parameters YP_N (yield potential with additional mid-season N fertilizer) are defined using the following equation.

$$YP_N = YP_0 * \text{ Harvest RI, but cannot exceed the } YP_{max} \tag{4}$$

The YP_{max} is the maximum yield for the region and η is N fertilizer use efficiency assumed to be 0.50. The GN % is grain N % and the GW is grain weight.

Proposed nitrogen fertilization optimization algorithm (PNFOA)

The process for determining N fertilizer recommendation from the PNFOA was conducted using the same theories and principals of the CNFOA. The proposed method utilizes a multiple linear regression model for determining YP_0 that incorporates NDVI measurements as well as soil moisture data, collected from adjacent climate monitoring sites, to estimate grain yield (Bushong et al. 2016). Three parameters are included: NDVI, days of potential growth (DPG), and stress index (SI). This NDVI value was collected in the unfertilized or farmer practice area with a Greenseeker handheld sensor. The DPG is the cumulative number of days where temperature and soil moisture exceed thresholds for substantial growth between planting and sensing. The SI is the ratio of soil profile water at the time of sensing compared to the estimated evapotranspiration from sensing to harvest. Model parameters computed for each site are listed in Tables 2 and 3. A complete description of how each parameter is calculated and the model intercept and parameter estimates are described by Bushong et al. (2016).

Generalized algorithm (GA)

A generalized N fertilizer recommendation was determined by Eq. 3 described above. However, the GA uses parameterized, symmetric, sigmoidal models to determine the YP_0 and $YP_{N,}$ which are calculated using a similar sigmoidal relationship to the YP_0 that accounts for the $NDVI_{RI}$. The use of sigmoidal models is thought to better reflect the actual growth pattern of a developing crop. The YP_{max} is used as the plateau for both sigmoidal models. The equations for determining YP_0 and YP_N are described below in Eqs. 5 and 6, respectively.

$$YP_0 = YP_{max}/(1 + \exp[-(NDVI_{FP} - \text{Inf})/K]) \tag{5}$$

$$YP_N = YP_{max}/(1 + \exp[-(NDVI_{RI} * NDVI_{FP} - \text{Inf})/K]) \tag{6}$$

The inflection point (Inf) and curvature (K) parameters were a function of the $NDVI_{FP}$. For a complete description of the model and model parameters for predicting these parameters for wheat only, reference Solie et al. (2012).

Modified generalized algorithm (MGA)

This algorithm follows the same principals and utilizes the same sigmoidal models for estimating YP_0 and YP_N as described by Solie et al. (2012). Modifications were made in the estimations of the inflection point and curvature values based upon bare soil NDVI readings and would allow for a greater maximum yield potential (Oklahoma State University 2014).

Table 2 Preplant NO_3 test (PPNT) values, NDVI measurements, computed response index (RI) values, and agronomic optimum N rates (AONR) for mid-season N response trials used to evaluate sensor based N fertilizer recommendations

Trial no.	PPNT (kg N ha^{-1})	$NDVI_{FP}$	$NDVI_{NR}$	$NDVI_{RI}$	Predicted harvest RI[a]	AONR (kg N ha^{-1})
1	15	0.206	0.213	1.03	1.05	46
2	10	0.562	0.639	1.14	1.22	113
3	–	0.456	0.503	1.10	1.16	132
4	16	0.440	0.554	1.26	1.43	56
5	12	0.369	0.520	1.41	1.68	66
6	21	0.558	0.708	1.27	1.44	112
7	–	0.649	0.752	1.16	1.26	140
8	25	0.669	0.777	1.16	1.26	97
9	20	0.246	0.335	1.36	1.60	56
10	11	0.544	0.646	1.19	1.31	68
11	–	0.753	0.794	1.05	1.08	56
12	12	0.708	0.786	1.11	1.18	0
13	–	0.419	0.441	1.05	1.08	0
14	–	0.408	0.441	1.08	1.13	0
15	–	0.695	0.764	1.10	1.16	101
16	–	0.753	0.764	1.01	1.01	0
17	11	0.461	0.554	1.20	1.33	77
18	11	0.508	0.554	1.09	1.14	73
19	11	0.537	0.554	1.03	1.04	0
20	25	0.636	0.746	1.17	1.28	108
21	25	0.709	0.746	1.05	1.08	21
22	25	0.734	0.746	1.02	1.02	0
23	13	0.376	0.641	1.70	2.18	108
24	13	0.503	0.641	1.27	1.45	75
25	13	0.609	0.641	1.05	1.08	93
26	–	0.411	0.631	1.54	1.89	128
27	–	0.509	0.631	1.24	1.40	56
28	–	0.592	0.631	1.07	1.10	26
29	–	0.509	0.613	1.20	1.34	45
30	–	0.535	0.613	1.15	1.24	21
31	–	0.574	0.613	1.07	1.10	0
32	–	0.625	0.889	1.42	1.70	108
33	–	0.805	0.889	1.10	1.17	46
34	–	0.866	0.889	1.03	1.03	16

$NDVI_{FP}$ NDVI farmer practice, *$NDVI_{NR}$* NDVI N-rich strip, *$NDVI_{RI}$* NDVI response index, *AONR* agronomic optimum N rate

[a] Computed using the linear equation of Harvest RI $= 1.69(NDVI_{RI}) - 0.70$

Table 3 Nitrogen fertilization optimization algorithm parameters utilized in estimating yield potential according to the methods of Bushong et al. (2016)

Trial no.	GDD[a]	DPG	SI
1	92	6	0.98
2	93	69	0.99
3	93	93	1.00
4	79	79	1.00
5	93	67	0.72
6	117	106	0.86
7	89	46	0.70
8	90	90	0.78
9	102	17	1.00
10	111	99	0.97
11	98	55	1.00
12	81	81	1.00
13	81	81	1.00
14	81	81	1.00
15	111	99	0.97
16	111	99	0.97
17	77	77	0.80
18	77	77	0.80
19	77	77	0.80
20	94	94	0.81
21	94	94	0.81
22	94	94	0.81
23	108	108	0.78
24	108	108	0.78
25	108	108	0.78
26	83	78	0.78
27	83	78	0.78
28	83	78	0.78
29	82	82	0.94
30	82	82	0.94
31	82	82	0.94
32	122	28	0.91
33	122	28	0.91
34	122	28	0.91

DPG days of potential growth, *SI* stress index

[a] Cumulative number growing degree days (GDD) with a temperature threshold of 4.4 °C

Assumptions

For all four algorithms described above, assumptions were made concerning some of the inputs. To evaluate the effectiveness of each model to predict the AONR these assumptions were consistent across all algorithms. The assumed values were derived from numerous site-years of observed sensor data in winter wheat, and are typically recommended for producers using sensor-based technology. Below is a list of the assumptions used.

YP_{max} = Maximum recorded yield for the trial location.

Fertilizer use efficiency (η) = 0.50

Wheat grain nitrogen % $= 23.9$ g kg^{-1}
Grain weight $= 774$ kg m^{-3}
Bare soil NDVI $= 0.150$

Weather data

Weather data were downloaded from adjacent climate-monitoring sites that are part of the Oklahoma Mesonet (2014) and imported into Microsoft Access databases. Structured query language was developed to retrieve and summarize weather data to create desired model parameter variables. Weather data that was downloaded included average daily temperature and soil moisture data content expressed as the calibrated change in soil temperature over time. The volumetric water content was then derived from the soil moisture measurement and the model parameters of DPG and SI were determined.

Non-sensor based recommendation

The current non-sensor based N fertilizer recommendation is to utilize a preplant soil NO_3 test (PPNT) along with a yield goal or YP_{max} (Zhang and Raun 2006). Of the 34 research sites, 18 research sites had recorded a PPNT value (Table 2). Subtracting out the NO_3 concentrations and the preplant N fertilizer applied from the required N rate that was based upon YP_{max}, delivered a mid-season N fertilizer rate recommendation that could then be compared to the AONR.

Statistical analysis

Linear regression analysis was conducted to determine if the algorithms' measurements of YP_0 and YP_N accurately predicted the actual grain yield with no added N fertilizer and the optimum grain yield achieved at the AONR, respectively. After the linear-plateau regression models derived the mid-season AONR, these values were then compared to the N fertilizer rate recommendation for each research site. Coefficient of determination (R^2) values, root mean square error (RMSE), and number of sites within $\pm$ 20 kg N ha^{-1} were employed to determine the effectiveness of each N rate recommendation method.

Results

The difference between grain yield potential with and without added N fertilizer ultimately determines sensor based N fertilizer recommendation (Lukina et al. 2001; Raun et al. 2002). How these variables are determined differentiates the four N fertilizer recommendation algorithms. Calculated YP_0 and YP_N values were observed to be different based on the algorithm used. Both the CNFOA and PNFOA displayed a wide range of values between 1 and 6 Mg ha^{-1} (Table 4). The GA and MGA displayed a slightly narrower range, 1–5 Mg ha^{-1} of yield potential values. In comparing the GA and MGA, the MGA yield potential values were drastically lower with actual yield potential values <3 Mg ha^{-1} (Table 4).

Values of potential grain yield were compared to the optimum grain yield at the AONR to determine if they were reliable estimates of actual grain yield. Linear regression analysis revealed that there were significant relationships between optimum grain yield and YP_N for

Table 4 Estimates of grain yield potential without N fertilizer (YP_0) and with N fertilizer (YP_N) for different sensor based N fertilizer recommendation algorithms

Trial no.	CNFOA		PNFOA		GA		MGA	
	YP_0	YP_N	YP_0	YP_N	YP_0	YP_N	YP_0	YP_N
1	1.1	1.1	1.2	1.2	3.5	3.6	0.4	0.4
2	2.8	3.4	3.7	4.2	3.7	5.0	0.3	2.0
3	2.1	2.4	2.9	3.2	3.8	4.8	0.4	1.2
4	2.5	3.6	2.9	3.7	2.7	4.9	0.1	1.5
5	1.6	2.8	2.8	3.9	1.2	3.2	0.1	0.9
6	2.0	2.9	3.4	4.3	1.9	3.3	0.1	1.6
7	3.9	4.9	3.8	4.4	2.4	3.4	0.2	1.8
8	4.0	5.1	4.0	4.7	2.4	3.4	0.2	1.9
9	1.1	1.8	1.6	2.1	1.7	3.2	0.1	0.5
10	2.1	2.7	3.3	3.9	2.6	3.8	0.1	1.6
11	4.3	4.6	5.2	5.5	3.5	3.9	1.1	2.3
12	5.6	6.6	4.3	4.8	3.2	3.9	0.5	2.3
13	2.2	2.4	2.8	2.9	3.8	4.3	0.5	0.9
14	2.2	2.4	2.7	3.0	3.6	4.3	0.4	0.9
15	3.0	3.4	3.9	4.3	3.9	4.8	0.7	2.6
16	3.4	3.5	4.1	4.2	4.6	4.8	2.2	2.6
17	2.8	3.7	3.1	3.7	2.5	4.0	0.1	1.2
18	3.2	3.7	3.3	3.6	3.3	4.0	0.4	1.2
19	3.6	3.7	3.5	3.6	3.8	4.0	0.8	1.2
20	3.4	4.3	3.8	4.5	2.5	3.6	0.2	1.9
21	4.1	4.5	4.2	4.4	3.3	3.6	1.0	1.9
22	4.4	4.5	4.3	4.3	3.5	3.6	1.6	1.9
23	1.5	3.2	2.6	4.4	0.8	3.6	0.1	1.4
24	2.0	2.9	3.2	4.1	2.0	3.6	0.1	1.4
25	2.5	2.7	3.7	3.9	3.2	3.6	0.7	1.4
26	2.1	4.0	2.9	4.4	1.3	4.1	0.1	1.6
27	2.9	4.0	3.3	4.1	2.4	4.1	0.1	1.6
28	3.7	4.1	3.7	3.9	3.6	4.1	0.7	1.6
29	2.9	3.9	3.3	3.9	2.3	3.5	0.1	1.3
30	3.2	3.9	3.4	3.9	2.6	3.5	0.2	1.3
31	3.6	4.0	3.6	3.8	3.1	3.5	0.5	1.3
32	2.2	3.8	4.5	6.4	1.6	3.7	0.1	2.6
33	3.2	3.8	5.7	6.3	3.0	3.7	0.6	2.6
34	3.7	3.8	6.1	6.3	3.5	3.7	1.9	2.6

Estimates are reported in Mg ha^{-1}

[a] *CNFOA* current N fertilizer optimization algorithm, *PNFOA* proposed N fertilizer optimization algorithm, *GA* generalized algorithm, *MGA* modified generalized algorithm

the CNFOA and PNFOA (Fig. 1). The CNFOA predicted optimum yield best with a coefficient of determination of 0.25. Relationships between the estimated YP_N and the optimum grain yield for both the GA and the MGA were insignificant (Fig. 2). The narrow range in YP_N values indicated that these algorithms had limited utility, especially with the data set used that had a range in optimum grain yields of approximately 1–6 Mg ha^{-1}. All algorithms had significant relationships between the YP_0 and the yield of the plots that did not receive any mid-season N fertilizer (Figs. 3, 4). The CNFOA grain yield potential prediction values performed the best ($R^2 = 0.46$) at estimating the actual grain yield of no

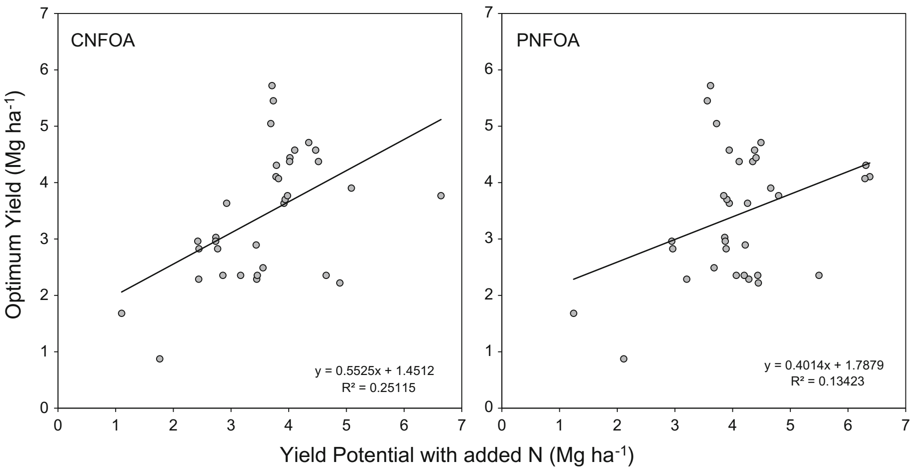

Fig. 1 Linear regression of measured optimum grain yield with estimates of yield potential with added N derived from the current N fertilizer optimization algorithm (*Left*) and the proposed N fertilizer optimization algorithm (*Right*)

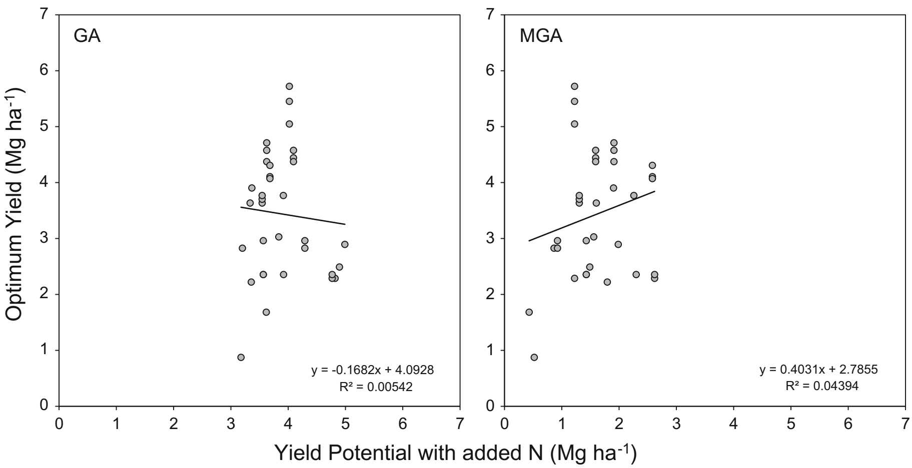

Fig. 2 Linear regression of measured optimum grain yield with estimates of yield potential with added N derived from the generalized algorithm (*Left*) and the modified generalized algorithm (*Right*)

added mid-season N fertilizer of the four algorithms evaluated. Little difference was observed between the performance of the GA and the MGA to estimate YP_0; however, the range in YP_0 values for the GA was more similar to the actual range in grain yields compared to the MGA (Fig. 4).

The algorithm that provided an N fertilizer recommendation closest to the AONR was based upon 34 yield responses to mid-season N fertilizer application. The range in AONR for this evaluation was 0–140 kg N ha^{-1} (Table 2). When the sensor based N fertilizer recommendations for each research site were regressed against the AONR for each research site, negligible differences were observed in the coefficient of determination and

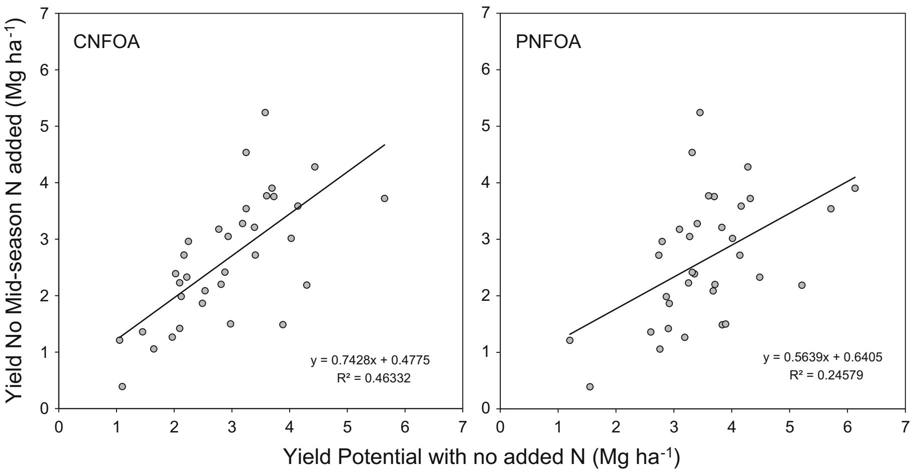

Fig. 3 Linear regression of measured grain yield of plots with no mid-season N fertilizer with estimates of yield potential without added N derived from the current N fertilizer optimization algorithm (*Left*) and the proposed N fertilizer optimization algorithm (*Right*)

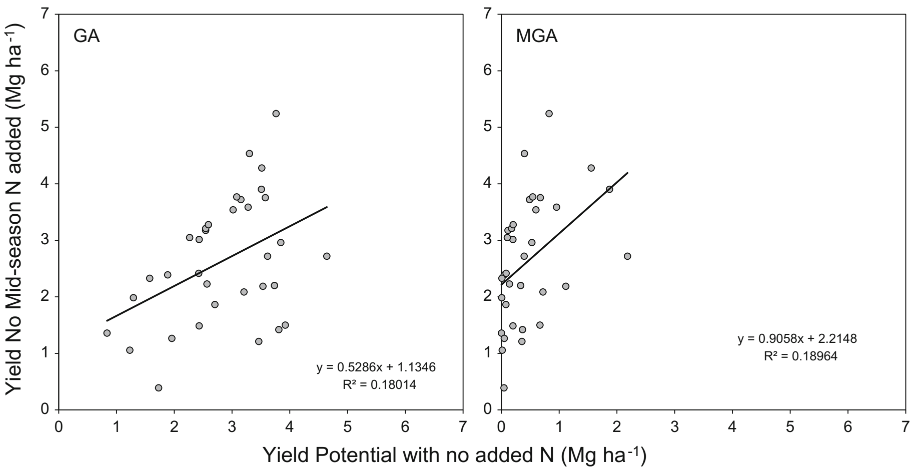

Fig. 4 Linear regression of measured grain yield of plots with no mid-season N fertilizer with estimates of yield potential without added N derived from the generalized algorithm (*Left*) and the modified generalized algorithm (*Right*)

RMSE values for each algorithm (Table 5). However, differences were observed in the percent of sites under and over predicted as well the number of sites within 20 kg N ha^{-1} (Table 5). For approximately 75 % of the sites, both the CNFOA and PNFOA had N recommendations less than the AONR. Linear regression equations support this with slopes greater than one and intercepts greater than zero (Fig. 5). The GA and MGA nearly split half-and-half the number of sites in which they recommended less N and the sites where they recommended more than the AONR (Table 5). A more evenly distributed spread in

Table 5 Coefficient of determination (R^2), root mean square error (RMSE), and percent of sites that predicted N fertilizer recommendations under, over, and within 20 kg N ha^{-1} of agronomic optimum N rate (AONR)

Method	R^2	RMSE	Percent under AONR	Percent above AONR	Percent within 20 kg N ha^{-1}
CNFOA	0.33	37.1	74	26	44
PNFOA	0.32	37.0	76	24	50
GA	0.34	36.8	53	47	41
MGA	0.33	37.1	50	50	41
PPNT	0.11	39.8	50	50	22

CNFOA current N fertilizer optimization algorithm, *PNFOA* proposed N fertilizer optimization algorithm, *GA* generalized algorithm, *MGA* modified generalized algorithm, *PPNT* pre-plant NO_3 soil test

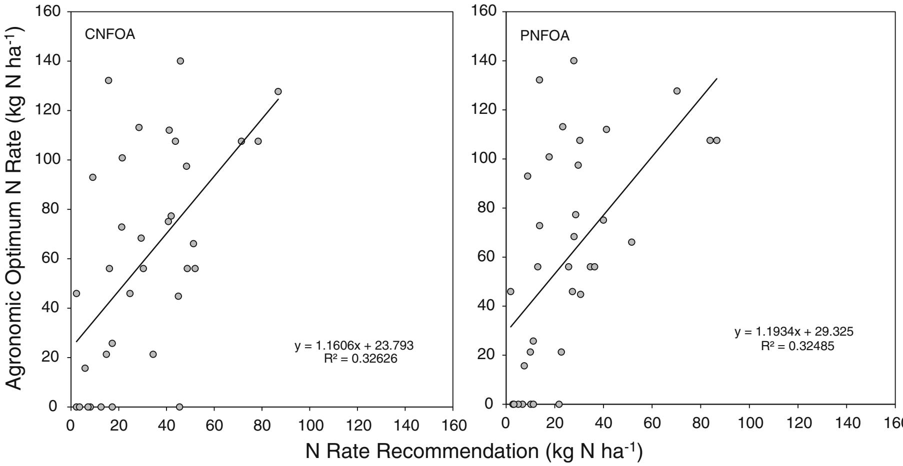

Fig. 5 Linear regression of agronomic optimum N rates with N fertilizer rate recommendations derived from the current N fertilizer optimization algorithm (*Left*) and the proposed N fertilizer optimization algorithm (*Right*)

recommended N rates was observed for both the GA and MGA compared to the CNFOA and PNFOA (Fig. 6). The recommended values for GA and MGA ranged between zero and 140 kg N ha^{-1}, much higher than the CNFOA and PNFOA, which were <85 kg N ha^{-1}. The sensor based N fertilizer recommendations outperformed the non-sensor based PPNT (Table 5). The PPNT accounted for 11 % of the variability in AONR and only delivered N recommendations to within 20 kg N ha^{-1} in one of five site-years.

Discussion

The lack of correlation between YP_N and optimum grain yield at the AONR for both the GA and MGA did not hinder either algorithm's ability to predict an AONR compared to the other algorithms. If improvements could be made in the estimation of YP_N, the overall ability of the algorithms to determine a more accurate N fertilizer rate would increase. The use of YP_{max} as the numerator in the sigmoidal models of the GA proposed by Solie et al.

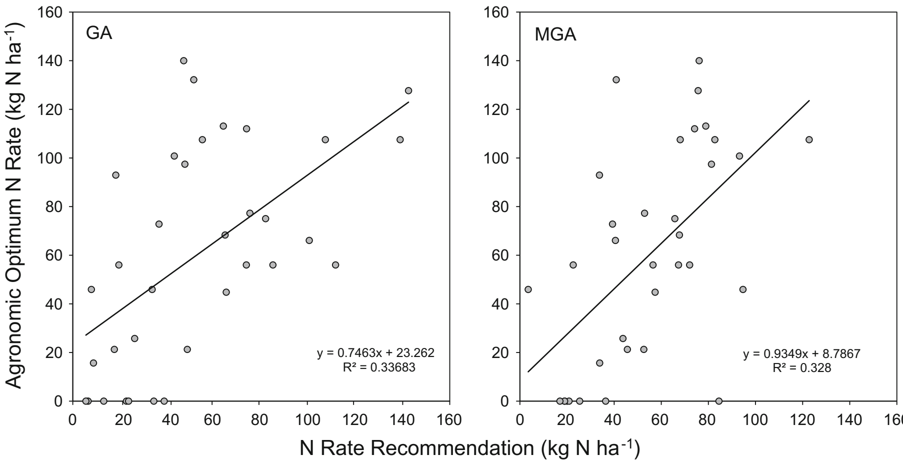

Fig. 6 Linear regression of agronomic optimum N rates with N fertilizer rate recommendations derived from the generalized algorithm (*Left*) and the modified generalized algorithm (*Right*)

(2012) could explain the lack of prediction in YP_N values. The YP_{max}, though theoretically achievable, is likely only to occur less than 10 % of the time. The estimation of YP_N from the CNFOA and PNFOA is extrapolated from the YP_0 and the $NDVI_{RI}$ which are taking into account the potential yield variability for that growing season and logically makes more sense and was supported with the range in predicted values being similar to the actual grain yield values.

As previously stated, the only difference between the CNFOA and PNFOA are the parameters used to estimate the YP_0. The results observed were contrary to results reported by Bushong et al. (2016) in that the CNFOA predicted YP_0 better than the PNFOA. The estimation of YP_0 using the PNFOA uses an algorithm developed across all growth stages and soil types. As reported by Bushong et al. (2016), when YP_0 estimates were broken down by individual growth stages, the CNFOA predicted yield better at lower growth stages (Feekes 3, 4), but there was a shift in improved performance around the Feekes 5 growth stage for the PNFOA estimate of yield. With mid-season N fertilizer being applied to the research sites just prior to first hollow-stem (Feekes 6) this could have coincided with the shift in model performance.

One of the underlying objectives of Bushong et al. (2016) was to improve grain yield prediction in order to better estimate the AONR. Without a substantial improvement in determining a better N rate recommendation, the need to include soil moisture parameters in yield prediction may be redundant and unnecessary. Perhaps the NDVI values already incorporate the soil moisture status and how it has affected crop growth as researchers have already reported that NDVI can be used in monitoring drought and scheduling irrigation (Duchemin et al. 2006).

Using the same techniques as the CNFOA, Biermacher et al. (2009) observed that algorithm N rate recommendations did not apply enough N. They also reported that because of this, the algorithms were to be modified. Based on the results observed in this study the modifications did not seem to improve the N rate recommendation. The CNFOA under predicted the appropriate N rate for agronomic optimum yield at close to three-quarters of the sites. This could be alleviated by decreasing the N fertilizer use efficiency factor (η) for determining the N rate recommendation. Raun et al. (2005) recommended using a η value more than 50 % for mid-season N applications. Research published by others, though, reported N fertilizer use efficiency values for fertilizer application practices employing sensor based methods for wheat rarely exceeded 50 % using agronomic N rates (Raun et al. 2002; Arnall and Raun 2013).

The PPNT which used yield goals or maximum yield values to set a N fertilizer rate prior to planting was not effective for improving N fertilizer use efficiency. Actual grain yields ranged from 1 to 6 Mg ha^{-1} for the sites utilized in this experiment. This range in grain yield supports the findings of Raun et al. (2011) and Arnall et al. (2013) where grain by-site yield potential can vary year to year and should be accounted for when making N fertilizer rate determinations.

Conclusions

The ability to make more accurate mid-season N fertilizer recommendations will improve N fertilizer use efficiency, winter wheat grain yield, and will have both environmental and economic benefits. Although some algorithms performed better at predicting YP_0 or YP_N, the four algorithms performed equally well in delivering N rate recommendations that correlate with the AONR. The four algorithms differed in that the CNFOA and the PNFOA under-predicted the AONR, whereas the GA and MGA predicted N rate values that were closer to a one to one relationship with the AONR. The underestimation of the CNFOA and PNFOA could be adjusted if lower NUE values are used as inputs into the algorithms. The sensor based techniques more accurately determined mid-season N fertilizer rates in winter wheat from conventional, non-sensor based approaches.

Even though the results of this study could be viewed as modest at best, they still proved sensor based techniques are an improvement on conventional, yield goal based approaches in winter wheat. Some of the less than desirable relationships between the different algorithms' N recommendation rate predictions and AONR could be due to the yield affecting climatic conditions (i.e. late freeze, hot temperature) that can occur after sensing and before harvest in the Southern Great Plains. This still leaves the door open for future work to potentially evaluate other factors that may affect predicting grain yield potential in-season.

Acknowledgments The authors would like to thank the Oklahoma Soil Fertility Research and Education Advisory Board for funding this research project and their continued financial support of soil fertility research at Oklahoma State University. The authors would also like to express their gratitude to all the current and former soil fertility graduate students who aided in the data collection and maintenance of research sites.

Compliance with ethical standards

Conflict of Interest The mention of any trademarked products or equipment utilized in this experiment was for research purposes only and does not act as an endorsement by Oklahoma State University. The authors and Oklahoma State University have no direct financial relation with any of the named manufacturers, thus the authors declare there is no conflict of interest regarding the publication of this manuscript.

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