Published online August 23, 2017

Predicting Early Season Nitrogen Rates of Corn Using Indicator Crops

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ABSTRACT

Use of optical reflectance sensors has proven to determine optimum N fertilizer requirements and direct in-season N fertilizer applications. However, corn (*Zea mays* L.) producer adoption of this technology has been slow due to limited time to determine N deficiencies and apply N fertilizer in-season. A study was established in north-central Oklahoma to investigate the N fertilizer response of winter wheat (*Triticum aestivum* L.) and spring barley (*Hordeum vulgare* L.) as indicator crops with N fertilizer applied at sufficient (168 kg N ha^{-1}) and zero N rates and to estimate optimal early season N fertilizer application rates of the subsequent corn crop. In the spring, corn was planted adjacent to the indicator crops and harvested to determine the agronomic optimum N rates at 100 and 95% of optimum yield and response of N fertilizer at harvest ($RI_{Harvest}$). In-season response of the indicator crops was determined using the normalized difference vegetative index (RI_{NDVI}) and was used to provide input values to calculate the algorithm N recommendations of the corn crop. Data analysis determined that positive relationships, though not significant, were observed between $RI_{Harvest}$ and RI_{NDVI} at Feekes 5/6 and 7 in wheat and Feekes growth stage 5 of barley. Significant relationships between optimum N rates and algorithm N recommendations were observed; however, the slopes of the relationships were negative, which was not to be expected. The potential of indicator crops to predict the early season response of corn to N fertilizer is unique and could help refine N management strategies.

Core Ideas

- Early season N deficiencies in corn are hard to recognize, or they appear later in the season, and are too late to correct the deficiency.
- Indicator crop growing over the winter and early spring cycle makes perfect sense in terms of being able to detect N deficiencies earlier in the growing season.
- Indicator crop concept could apply to other cereals and potentially cover crops.

Published in Agron. J. 109:1–8 (2017)
doi:10.2134/agronj2016.09.0519
Available freely online through the author-supported open access option

Various methods have been proposed to identify optimum N fertilizer rates for corn grain production, including yield goal (Stanford, 1973), maximum return to N (Sawyer et al., 2006), soil sampling (Magdoff et al., 1984; Bundy et al., 1993; Khan et al., 2001), chlorophyll meters (Schepers, 1994), and crop reflectance (Solari et al., 2008; Tubaña et al., 2008). Among these techniques, crop reflectance measurements collected from active optical reflectance sensors offer "on-the-go" and mid-season evaluation of the plant's nutritional status.

Crop reflectance measurements, often expressed as normalized difference vegetative index (NDVI), are used to determine the crop response to additional N fertilizer known as response index (RI) (Mullen et al., 2003; Raun et al., 2005). The RI is determined using a representative area in a field that has a non-limiting amount of N fertilizer (N-rich strip) and an unfertilized or under-fertilized area in the same field (farmer practice). It is expressed in the following equation:

$$RI_{NDVI} = NR_{NDVI}/FP_{NDVI}$$

where NR_{NDVI} is the NDVI collected from the N-rich strip and FP_{NDVI} is the NDVI measured from an adjacent area with fertilizer applied at the farmer practice rate.

Grain yield as an indicator of N uptake between plots receiving and not receiving N can be used in the same way using the following equation (Mullen et al., 2003):

$$RI_{Harvest} = \frac{\text{Highest mean yield from N treatment}}{\text{Mean yield from check treatment}}$$

Active optical reflectance sensors have been used to determine optimum N fertilizer requirements in corn and have shown the ability to improve N fertilizer use efficiency when compared to fixed-rate applications (Tubaña et al., 2008). However, the adoption of this N fertilizer application technology has been slow due

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Abbreviations: $AONR_{100}$, agronomic optimum nitrogen rate at 100% of optimum yield; $AONR_{95}$, nitrogen rate at which grain yield is at 95% of optimum grain yield; GANR, generalized algorithm nitrogen recommendation; INSEY, in-season estimate of yield potential; LCB, Lake Carl Blackwell Agricultural Experiment Station West of Stillwater, OK; NDVI, normalized difference vegetative index; NFOA, nitrogen fertilization optimization algorithm, RI, response index; $RI_{Harvest}$, response index of grain yield; RI_{NDVI}, response index of normalized difference vegetative index measured mid-season; STW, Efaw Agricultural Experiment Station near Stillwater, OK.

to agronomic, economic, and technical reasons (Schepers, 2013). The short timeframe to determine N deficiencies and apply N fertilizer mid-season is the most notable reason for corn producer's reluctance despite the substantial work directed to identifying the earliest growth stage at which N deficiencies can be detected (Teal et al., 2006; Martin et al., 2007).

In corn, early season N deficiencies are not readily evident until growth stages V7 to V9 in Oklahoma (Teal et al., 2006; Martin et al., 2007) and V11 in Nebraska (Solari et al., 2008). Beyond growth stage V7 (corn height of ~0.5 m), N fertilizer applications using traditional side-dress equipment becomes a challenge due to clearance constraints. The use of high clearance N applicators may offer a good option but many producers do not have access to this equipment nor are these applicators compatible to apply anhydrous ammonia, which is often a more cost effective N fertilizer source. Thus, it is imperative to widen the window of opportunity to identify and correct N deficiencies in corn for producers to adopt N management strategies without corn height being a limiting factor. Alternative and reliable strategies need to be investigated to identify early season N deficiencies in corn.

Monitoring N availability throughout the winter and early spring using alternative cereals as indicator crops could be a potential option to widen the application window for N fertilizer application in corn. This approach allows the indicator crop to demonstrate distinguishable differences in response to residual fall and early spring N mineralization, which can be highly variable in dryland systems (Meisinger et al., 1992; Forrestal et al., 2012), near or at the time of corn planting. These soil N pools (residual and mineralized N) are otherwise less recognizable during the early growth stages of corn, especially when temperatures are low and crop growth is slow. The use of indicator crop reference strips will advance the detection of N deficiencies in corn.

The proposed system will provide farmers with much greater flexibility to use active optical reflectance sensors to apply N fertilizer pre-plant or early season to corn. Hence, the objective of this study was to evaluate the response of winter wheat and spring barley indicator crops to applied N over winter and early spring to potentially estimate corn N fertilizer response and optimal early season N fertilizer application rates of the subsequent corn crop.

MATERIALS AND METHODS

Field experiments were initiated under conventional tillage practices in the fall of 2012 and continued through 2014 at Efaw (STW; 36.081118°, –97.063270°, elevation 272 m above sea level) agronomy research station near Stillwater, OK, and Lake Carl Blackwell (LCB; 36.090792°, –97.172486°, elevation 293 m above sea level) agronomy research station West of Stillwater, OK (Table 1). All soil fertility parameters were managed to ensure N was the only limiting nutrient (Table 2) based on regional fertilizer recommendations described by Zhang and Raun (2006). A summary of field activities for each cropping year including N fertilizer application dates, planting dates, cultivars or hybrids, sensing dates, irrigation amounts, and harvest dates are reported in Table 3.

Winter wheat and spring barley were planted in late fall and early spring, respectively, in strips adjacent to the eventual corn trial and served as the indicator crop reference strips. Care was taken to make sure the strips would be placed in an area with the same soil properties and cropping history as the area of the subsequent corn crop. Prior to planting, each indicator crop reference area (6 m wide by 21 m long) was divided into two strips (3 m wide by 21 m long) and was either applied with a sufficient rate (168 kg N ha^{-1}; N-rich strip) or a zero rate (farmer practice) of N fertilizer as broadcast urea ammonium nitrate (UAN; 280 g N kg^{-1}). Winter wheat was planted using a Kincaid model 2010 grain drill (Kincaid Equipment and Manufacturing, Haven, KS) at 100 kg ha^{-1} spaced at 18 cm. Spring barley was planted using the same Kincaid model 2010 grain drill at 112 kg ha^{-1} spaced at 18 cm (Table 3).

Table 1. Soil map unit and taxonomic classification for each location, 2013 and 2014.

Year	Location†	Soil mapping unit	Soil Taxonomic Classification
2013	STW	Easpur loam, occasionally flooded, 0–1% slope	Easpur: fine-loamy, mixed, superactive, thermic Fluventic Haplustolls
	LCB	Port-Oscar Complex, occasionally flooded, 0–1% slope	Port: fine-silty, mixed, superactive, thermic Cumulic Haplustolls Oscar: fine-silty, mixed, superactive, thermic Typic Natrustalfs
2014	STW	Norge loam, 3–5% slope	Norge: fine-silty, mixed, active, thermic Udic Paleustolls
	LCB	Pulaski fine sandy loam, 0–1% slope, occasionally flooded	Pulaski: coarse-loamy, mixed, superactive, nonacid, thermic Udic Ustifluvents

† STW, Efaw Agronomy Research Station near Stillwater, OK. LCB, Lake Carl Blackwell, Agronomy Research Station West of Stillwater, OK.

Table 2. Pre-plant soil sample (0–15 cm) chemical properties, 2013 and 2014.

Year	Location†	Soil pH‡	NH_4–N§	NO_3–N§	P¶	K¶	Total N#	Organic C#
			mg kg^{-1}				mg g^{-1}	
2013	STW	6.0	8.4	1.7	18.4	106	1.2	10.2
	LCB	6.1	6.2	5.3	24.2	139	1.1	9.5
2014	STW	5.1	8.7	1.7	84.1	108	0.8	7.0
	LCB	5.2	7.4	6.9	34.1	142	0.8	8.1

† STW, Efaw Agronomy Research Station near Stillwater, OK. LCB, Lake Carl Blackwell Agronomy Research Station West of Stillwater, OK.
‡ 1:1 soil water.
§ 2 M KCl extract (Mulvaney, 1996).
¶ Mehlich III extract (Mehlich, 1984).
# Dry combustion (Schepers et al., 1989).

Crop canopy reflectance measurements were collected at Feekes 3, 4, 5, 7, and/or 10 growth stages (Large, 1954) of the indicator crops to estimate biomass accumulation and potential N deficiency. Spectral reflectance was measured the entire length of each respective, unreplicated strip down the center of the plot at 70 cm above the crop canopy using a GreenSeeker (Trimble Agriculture Division, Westminster, CO) active optical reflectance crop sensor. All values were expressed as plot averaged NDVI. The GreenSeeker crop sensor utilizes red (660 nm) and near infrared (NIR; 780 nm) wavelengths and calculates NDVI as:

$$NDVI = NIR_{(780)} - red_{(660)}/NIR_{(780)} + red_{(660)}$$

In the spring, corn was planted adjacent to the indicator crop reference strips at 65,000 seeds ha^{-1} using a John Deere 7300 Integral MaxEmerge planter (Deere & Company, Moline, IL). It should be noted, the corn was not planted over, but adjacent to, the indicator crop reference strips which were allowed to continue to grow and sensing data was still collected while the corn crop was still small. Nitrogen fertilizer was applied prior to planting as broadcast UAN at 45, 90, 135, 180, and 225 kg N ha^{-1}, plus a control treatment without N fertilizer application. Fertilizer was mechanically incorporated immediately after application to minimize potential N loss mechanisms. The experiment was a randomized complete block design with three replications. Plots consisted of four rows spaced at 0.76 m wide that were 6.10 m long. For the 3 site-years that were irrigated, a surface drip system was utilized and water applied to meet estimated evapotranspirational demand. Amount of water supplied through irrigation was monitored and measured (Table 3).

Corn grain was mechanically harvested from the two middle rows of each four row plot and was adjusted to 155 g kg^{-1} moisture content. Agronomic optimum nitrogen rate at 100% of optimum yield ($AONR_{100}$) was determined using the SAS PROC NLIN procedure (SAS Institute, 2011) at each location. The $AONR_{100}$ is the N rate that produces optimum corn grain yield and where additional N fertilizer does not increase and may decrease grain yield. Linear plus plateau and quadratic plus plateau models were evaluated on each site-year of corn N response and the $AONR_{100}$ was calculated using the best-fit model (Cerrato and Blackmer, 1990). Because the increase in grain yield may not be as great for each unit of N added as the grain yield approaches optimum, the N rate at which 95% of the agronomic optimum yield ($AONR_{95}$) was also determined using the equations from the nonlinear analysis of corn N response.

In-season measurements of NDVI from the indicator crop reference strips were utilized to calculate two different N fertilizer recommendations. One was the Oklahoma State University corn generalized algorithm nitrogen recommendation (GANR) (Solie et al., 2012). The GANR, as proposed by Solie et al. (2012), was developed for variable N rate recommendations were the maximum grain yield potential is incorporated into a continuous function that is sigmoidal in shape and bound by bare soil NDVI and the assumed maximum grain yield for the region. The

Table 3. Field activities for each location, 2013 and 2014.

Field activity	2012–2013 STW†	2012–2013 LCB	2013–2014 STW	2013–2014 LCB
Winter wheat				
Cultivar	Doublestop	Doublestop	Iba	Doublestop
N application	1 Oct.	3 Oct.	23 Oct.	10 Oct.
Planting	11 Oct.	9 Oct.	23 Oct.	24 Oct.
Sensing-Fk. 3	19 Feb.	18 Feb.	12 Mar.	25 Feb.
Sensing-Fk. 4	5 Mar.	6 Mar.	20 Mar.	11 Mar.
Sensing-Fk. 5/6	29 Mar.	21 Mar.	4 Apr.	19 Mar.
Sensing-Fk. 7/8	12 Apr.	12 Apr.	.	3 Apr.
Sensing-Fk. 9/10	29 Apr.	29 Apr.	17 Apr.	17 Apr.
Spring barley				
Cultivar	Pinnacle	Pinnacle	Pinnacle	Pinnacle
N application	5 Feb.	6 Feb.	13 Feb.	13 Feb.
Planting	5 Feb.	6 Feb.	13 Feb.	14 Feb.
Sensing-Fk. 3	29 Mar.	21 Mar.	–	28 Mar.
Sensing-Fk. 4	–	–	–	3 Apr.
Sensing-Fk. 5	12 Apr.	12 Apr.	17 Apr.	10 Apr.
Sensing-Fk. 6/7	29 Apr.	29 Apr.	–	22 Apr.
Sensing-Fk. 8/9	–	–	–	26 Apr.
Sensing-Fk. 10	22 May	–	–	2 May
Corn				
Hybrid	P1498	DK63-55	DK63-55	DK63-55
N application	18 Mar.	18 Mar.	31 Mar.	25 Mar.
Planting	20 Mar.	20 Mar.	1 Apr.	3 Apr.
Sensing-V5/6	22 May	18 May	13 May	13 May
Harvest	9 Sept.	5 Sept.	4 Sept.	27 Aug.
Irrigation, mm	50	28	0	8
Rainfall, mm	621	827	375	517

† STW, Efaw Agricultural Experiment Station near Stillwater, OK. LCB, Lake Carl Blackwell Agricultural Experiment Station West of Stillwater, OK.

Table 4. Response index from the in-season sensor measurements of normalized difference vegetative index (RI_{NDVI}) collected from wheat and barley indicator crops along with corn grain yield response ($RI_{Harvest}$) to applied N fertilizer for Stillwater (STW) and Lake Carl Blackwell (LCB), 2013.

Location	Crop	Growth stage (Feekes)	RI_{NDVI}†	$RI_{Harvest}$‡
STW	Wheat	3	1.20	1.31
		4	1.06	1.31
		5	1.19	1.31
		7	1.26	1.31
		9	1.37	1.31
	Barley	3	1.07	1.31
		5	1.08	1.31
		7	1.13	1.31
		10	1.23	1.31
LCB	Wheat	3	1.23	1.12
		4	1.54	1.12
		5	1.69	1.12
		7	1.78	1.12
		10	2.16	1.12
	Barley	3	1.20	1.12
		5	1.77	1.12
		7	1.92	1.12

† RI_{NDVI} = Nitrogen-rich strip normalized difference vegetative index (NDVI)/farmer practice NDVI.

‡ $RI_{Harvest}$ = Highest mean yield nitrogen treatment/mean yield check treatment.

Table 5. Response index from the in-season sensor measurements of normalized difference vegetative index (RI_{NDVI}) collected from wheat and barley indicator crops along with corn grain yield response ($RI_{Harvest}$) to applied N fertilizer for Stillwater (STW) and Lake Carl Blackwell (LCB), 2014.

Location	Crop	Growth stage (Feekes)	RI_{NDVI}†	$RI_{Harvest}$‡
STW	Wheat	3	1.08	2.22
		4	1.15	2.22
		6	1.66	2.22
		9	1.56	2.22
	Barley	5	1.95	2.22
LCB	Wheat	3	1.31	1.50
		4	1.44	1.50
		5	1.75	1.50
		7	2.20	1.50
		9	1.96	1.50
	Barley	3	1.02	1.50
		4	1.11	1.50
		5	1.21	1.50
		6	1.30	1.50
		8	1.40	1.50
		10	1.61	1.50

† RI_{NDVI} = Nitrogen-rich strip normalized difference vegetative index (NDVI)/farmer practice NDVI.

‡ $RI_{Harvest}$ = Highest mean yield nitrogen treatment/mean yield check treatment.

Table 6. Generalized algorithm nitrogen recommendation (GANR) and the agronomic optimum N rates at Stillwater (STW) and Lake Carl Blackwell (LCB) in 2013.

Location	Crop	Growth stage (Feekes)	GANR†	NFOA‡	$AONR_{100}$§	$AONR_{95}$¶
			kg N ha^{-1}			
STW	Wheat	3	9	40	185	140
		4	8	12	185	140
		5	83	38	185	140
		7	119	52	185	140
		9	150	74	185	140
	Barley	3	2	14	185	140
		5	28	16	185	140
		7	70	26	185	140
		10	102	46	185	140
LCB	Wheat	3	27	41	52	0
		4	175	96	52	0
		5	227	123	52	0
		7	239	139	52	0
		10	269	206	52	0
	Barley	3	1	36	52	0
		5	243	137	52	0
		7	275	163	52	0

† GANR, Generalized algorithm nitrogen recommendations.

‡ NFOA, Nitrogen fertilization optimization algorithm.

§ $AONR_{100}$, Agronomic optimum nitrogen rate at 100% of optimum yield; determined using either a linear plus plateau model or a quadratic plus plateau model.

¶ $AONR_{95}$, Nitrogen rate at which grain yield is at 95% of optimum grain yield.

most recent version of this algorithm was accessed via the online interface at the end of the 2014 growing season (Oklahoma State University, 2014). The other was a modification of the nitrogen fertilizer optimization algorithm (NFOA) as described by Tubaña et al. (2008). This algorithm utilizes the difference in N removed in the grain determined from a RI_{NDVI} value multiplied times an in-season estimate of yield (INSEY) potential determined by the methods of Teal et al. (2006). The INSEY was determined by sensing the unfertilized corn plots at the corn growth stage V6. The modification for this method is that the RI_{NDVI} value would be from the selected indicator crop and not the corn crop. For both methods, farmer practice NDVI and N-rich strip NDVI from the winter wheat and spring barley indicator crops were used as RI inputs using the following assumptions: bare soil NDVI = 0.18, maximum yield for the region = 13.4 Mg ha^{-1}, mass per volume of grain = 725 kg m^{-3}, grain N = 1.2%, and N use efficiency = 50% (Oklahoma State University, 2014).

To address the objective of determining an optimal early season N fertilizer rate for corn, the relationships between the RI_{NDVI} and $RI_{Harvest}$, as well as the optimum N rates, GANR, and NFOA were evaluated using the SAS PROC REG procedure (SAS Institute, 2011). The relationships were evaluated with values from specific growth stages and were aggregated together by indicator crop species for the regression analysis.

RESULTS AND DISCUSSION

Indicator Crop Normalized Difference Vegetative Index

Farmer practice and N-rich strip NDVI values collected from the wheat and barley indicator crops resulted in RI_{NDVI} values ranging from 1.06 to 2.20 and 1.02 to 1.95, respectively, for all four locations (Tables 4 and 5). Mullen et al. (2003) explains that if RI_{NDVI} of winter wheat is <1.1 at any growth stage, the probability of obtaining a response to additional N fertilizer will be low. For all the growth stages evaluated across all locations, 85% of the RI_{NDVI} values of the two respective indicator crops were >1.1 suggesting that the subsequent corn crop would be responsive to additions of N fertilizer, which was confirmed by the greater corn $RI_{Harvest}$ values (1.12–2.22) measured in the current study.

The respective calculated corn GANR and NFOA ranged from 0 to 270 kg N ha^{-1} and 6 to 206 kg N ha^{-1} using wheat and 0 to 275 kg N ha^{-1} and 2 to 163 kg N ha^{-1} using barley as indicator crops (Tables 6 and 7). Most of the low N fertilizer recommendations (<20 kg N ha^{-1}) occurred at the early vegetative growth stages (Feekes 3 and 4) of both indicator crops. Sensor data collected at Feekes growth stages 3 and 4 of the wheat indicator crop did occur prior to corn planting while the sensor data collected for all other wheat growth stages and all of the barley growth stages occurred after corn planting, but prior to corn growth stage V6 (Abendroth et al., 2011). In 2014 at STW, sensor data was recorded for only one growth stage (Feekes 5) of the barley. This was due to developing differences in maturity between the N-rich strip and farmer practice strip. The lack of rainfall (<60 mm) after planting, and the added N stress to the check plot rapidly advanced the maturity in the farmer practice strip. Nitrogen fertilizer applications made to corn at growth stage V6 or before could be accomplished using traditional sidedress equipment. The sigmoidal model utilized in the generalized algorithm predicts a low potential grain yield in response to a low NDVI at early stages of the indicator crop due to a transition region between bare soil and the central region of the model (Solie et al., 2012). Solie et al. (2012) explained that in this region, crop stands are poor or growth is retarded due to other agronomic factors resulting in low biomass accumulation and consequently limited increase in grain yield which then leads to low calculated N fertilizer recommendation. High N fertilizer recommendations (>150 kg N ha^{-1}) occurred when RI_{NDVI} of the indicator crop was also high (>1.5) as a result of a larger denominator in grain yield potential equation

Table 7. Generalized algorithm nitrogen recommendation (GANR) and the agronomic optimum N rates at Stillwater (STW) and Lake Carl Blackwell (LCB) in 2014.

Location	Crop	Growth stage (Feekes)	GANR	NFOA†	$AONR_{100}$‡	$AONR_{95}$§
			kg N ha^{-1}			
STW	Wheat	3	0	6	224	220
		4	1	12	224	220
		6	72	52	224	220
		9	57	44	224	220
	Barley	5	165	75	224	220
LCB	Wheat	3	14	29	95	49
		4	52	41	95	49
		5	174	70	95	49
		7	270	112	95	49
		9	210	90	95	49
	Barley	3	0	2	95	49
		4	0	10	95	49
		5	1	20	95	49
		6	7	28	95	49
		8	24	37	95	49
		10	98	57	95	49

† NFOA, Nitrogen fertilization optimization algorithm.

‡$AONR_{100}$, Agronomic optimum nitrogen rate at 100% of optimum yield; determined using either a linear plus plateau model or a quadratic plus plateau model.

§ $AONR_{95}$, Nitrogen rate at which grain yield is at 95% of optimum grain yield.

(Solie et al., 2012). When compared to the GANR, the NFOA recommendations had a tendency to produce similar or slightly higher N recommendations at early growth stages, but displayed lower N fertilizer recommendations at later growth stages of the indicator crop. This is likely due to the fact that the GANR yield with added N is capped with an arbitrarily selected max yield for the region, whereas, the NFOA yield with added N is limited to the potential response of added N to the current yield potential of the corn that was sensed at V6.

Because of the use of multiple wheat cultivars and corn hybrids in this experiment, potential concerns for inconsistency in crop reflectance of wheat/barley cultivar and corn hybrid that could confound the results do have merit. However, previous research has shown that wheat genotype was independent of N uptake and vegetation index (Reusch, 2005) and that genotypic differences are typically observed more with chlorophyll meter readings (Samborski et al., 2009). For corn, NDVI differences among hybrids at different N rates have been observed (Solari et al., 2008), but when N fertilizer response among dark and light tinted corn hybrids was utilized to make N fertilizer recommendations, no significant differences in applied N and final grain yield were observed (Shanahan, 2013).

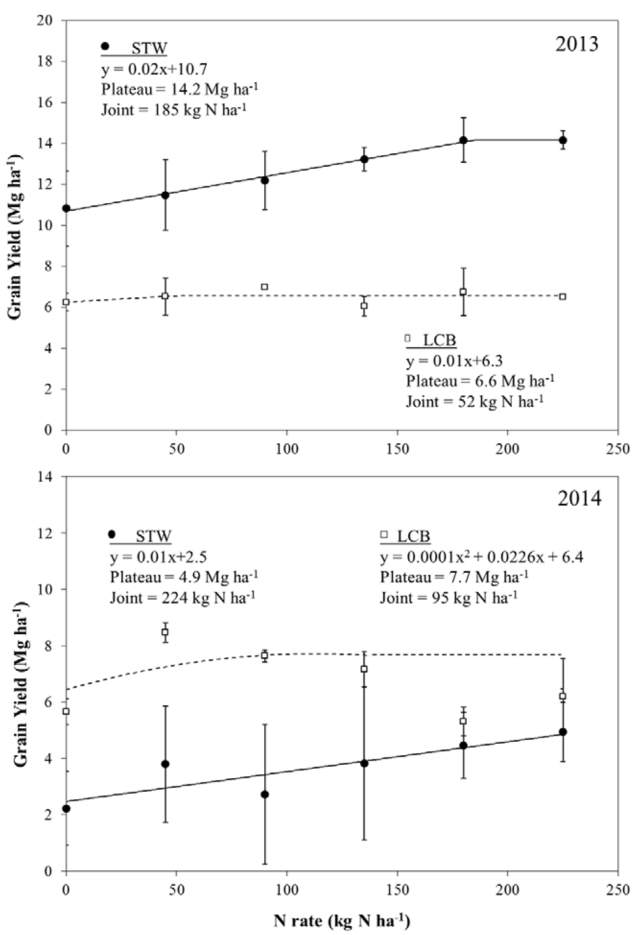

Fig. 1. Influence of pre-plant N fertilizer on corn grain yield (Mg ha^{-1}) for Stillwater (STW) and Lake Carl Blackwell (LCB), 2013 and 2014. Error bars represent ± 1 SE.

Corn Grain Yield

Corn grain yields at all locations were responsive to the addition of pre-plant N fertilizer (Fig. 1). Corn grain yields collected in this experiment were similar to grain yields observed from previous Oklahoma corn experiments using pre-plant N fertilizer (Tubaña et al., 2008; Walsh et al., 2012, Bushong et al., 2014). In 2013, a linear plus plateau response model was used to fit the different N rates with corn grain yield at both locations. The $AONR_{100}$ for STW and LCB locations based on the linear plateau model were 185 and 52 kg N ha^{-1}, respectively. In 2014, quadratic and linear models were used to determine the influence of pre-plant N fertilizer on corn grain yield at LCB and STW, respectively (Fig. 1). At LCB, the $AONR_{100}$ was calculated at 95 kg N ha^{-1} and at STW was 224 kg N ha^{-1}. The large range in AONR could be expected due to the variable environmental conditions experienced and the impact on N demand. For example, seasonal rainfall ranged from 375 to 827 mm for the four sites (Table 3). When the equations that best described the N fertilizer response for each site were employed to determine $AONR_{95}$, the values were obviously lower than the $AONR_{100}$ (Tables 6 and 7). The $AONR_{95}$ at STW in 2013 and LCB in 2014 were approximately 45 kg N ha^{-1} lower (Tables 6 and 7). There was not much difference between the optimum N rates at STW in 2014; the site with the highest optimum N rates of the four sites evaluated (Table 7). The LCB 2013 site reported the lowest $AONR_{100}$ and that 95% of the optimum yield could have been achieved with no N added (Table 6).

The corn crop displayed a positive response to the addition of pre-plant N fertilizer at harvest as shown by $RI_{Harvest}$ ranging from 1.12 to 2.22 (Tables 4 and 5). All four locations had a $RI_{Harvest} > 1.0$, indicating that increased grain yields were due to added N fertilizer rather than non-fertilizer N contributions, such as mineralization or rainfall. Non-fertilizer N contributions to the corn production system are likely reasons for low $RI_{Harvest}$ values (Mullen et al., 2003).

$RI_{Harvest}$ vs. RI_{NDVI}

When the linear relationships between RI_{NDVI} and $RI_{Harvest}$ were evaluated by individual Feekes growth stage of each respective indicator crop, no significant relationships were observed for either crop (Table 8). The only growth stages with a positive relationship were observed at the Feekes 5/6 and 7 growth stages for the wheat and the Feekes 5 growth stage for the barley (Table 8). It would seem practical, that the indicator crop growth stages that could potentially display the greatest N response would occur around the Feekes 5 or 6 growth stages, as these are the growth stages with the greatest N uptake and demand. It is also encouraging that these growth stages occurred prior to the subsequent corn crop reaching the V6 growth stage. However, more data collection is needed to prove or disprove this hypothesis. Other work in Oklahoma has determined that RI_{NDVI} can provide good prediction for $RI_{Harvest}$ (R^2 = 0.56–0.75) in winter wheat (Mullen et al., 2003; Hodgen et al., 2005). Hodgen et al. (2005) also observed that slope for the relationship between RI_{NDVI} and $RI_{Harvest}$ is greater than one due to large amounts of N taken up by the wheat plant early in the season.

Table 8. Summary of relationships between normalized difference vegetative index (NDVI) and harvest response index (RI) values and generalized algorithm nitrogen recommendations (GANR) and the agronomic optimum N rates at different Feekes growth stages (Large, 1954).

Growth stage	RI_{NDVI} vs. $RI_{Harvest}$			GANR vs. $AONR_{100}$†			GANR vs. $AONR_{95}$‡		
	$P > F$	R^2	Equation	$P > F$	R^2	Equation	$P > F$	R^2	Equation
Wheat									
3 (n = 4)	0.28	0.51	$y = -3.6x + 5.9$	0.05	0.91	$y = -6.7x + 223$	0.04	0.92	$y = -8.3x + 206$
4 (n = 4)	0.54	0.22	$y = -1.0x + 2.8$	0.02	0.79	$y = -0.9x + 191$	0.14	0.74	$y = -1.0x + 164$
5/6 (n = 4)	0.75	0.06	$y = 0.5x + 0.8$	0.01	0.98	$y = -1.1x + 285$	0.04	0.92	$y = -1.3x + 277$
7 (n = 3)	0.71	0.20	$y = 0.2x + 1.0$	0.33	0.75	$y = -0.7x + 265$	0.35	0.73	$y = -0.8x + 222$
9/10 (n = 4)	0.57	0.18	$y = -0.6x + 2.6$	0.03	0.94	$y = -0.9x + 285$	0.01	0.99	$y = -1.1x + 286$
Barley§									
3 (n = 3)	0.16	0.94	$y = -2.0x + 3.5$	0.54	0.44	$y = 45.0x + 66$	0.56	0.41	$y = 45.5x + 18$
5 (n = 4)	0.51	0.24	$y = 0.6x + 0.7$	0.78	0.05	$y = -0.1x + 155$	0.87	0.02	$y = -0.1x + 115$
7/8 (n = 3)	0.55	0.42	$y = -0.3x + 1.8$	0.57	0.39	$y = -0.3x + 150$	0.55	0.42	$y = -0.3x + 105$

† $AONR_{100}$, agronomic optimum nitrogen rate at 100% of optimum yield; determined using either a linear plus plateau model or a quadratic plus plateau model.

‡ $AONR_{95}$, Nitrogen rate at which grain yield is at 95% of optimum grain yield.

§ Only 1 site-year of sensor data collected at Feekes 4, 6, 9, 10 growth stages.

Agronomic Optimum Nitrogen Rates vs. Algorithm Nitrogen Recommendations

The ability of the GANR and NFOA to predict the optimum N rate appeared to work better for the wheat than the barley. The wheat displayed significant trend for several growth stages, while the barley had no significant trends (Tables 8 and 9). However, the slopes for all the linear regression equations comparing the optimum N rates and algorithm N recommendations for the wheat were negative and the only positive slope for the barley was observed at Feekes 3 with the GANR (Tables 8 and 9). Ideally, to accept these significant results as something promising, the slopes should have a positive correlation, thus more research is needed to validate the results of this study. No major differences were observed between each respective algorithm and their ability to predict either the $AONR_{100}$ or $AONR_{95}$ (Tables 8 and 9) and with only 4 site-years of data, conclusively stating one algorithm performed better than the other would be irresponsible.

Raun et al. (2011) and Arnall et al. (2013) have reported that the level of N fertilizer response is highly variable from year to year for cereal grains, which these results confirm, and should be considered a factor when making N fertilizer recommendations. Because of the positive relationships observed at certain growth stages between $RI_{Harvest}$ of corn and RI_{NDVI} of the indicator crop, modifying algorithm N recommendations or creating different algorithms altogether could potentially be accomplished for predicting an agronomic N rate; however, more data than what is presented in this trial is definitely needed to achieve this task.

CONCLUSIONS

The ability to predict the response of corn to N fertilizer at harvest, at earlier growth stages (prior to V6) using a fall or early spring planted indicator crop is unprecedented. Modifications to current corn N fertilizer recommendations that could better exploit the relationship of $RI_{Harvest}$ and RI_{NDVI} of an indicator crop would modernize N management strategies for corn producers across the United States. Encouraging results from the data analysis of 4 site-years found that positive relationships, though not statistically significant, were present between $RI_{Harvest}$ and

Table 9. Summary of relationships nitrogen fertilizer optimization algorithm N recommendations (NFOA) and the agronomic optimum nitrogen rates (AONR) at different Feekes growth stages (Large, 1954).

Growth stage	NFOA vs. $AONR_{100}$†			NFOA vs. $AONR_{95}$‡		
	$P > F$	R^2	Equation	$P > F$	R^2	Equation
Wheat						
3 (n = 4)	0.36	0.42	$y = -3.1x + 230$	0.26	0.55	$y = -4.4x + 231$
4 (n = 4)	0.02	0.83	$y = -1.8x + 212$	0.13	0.76	$y = -2.2x + 189$
5/6 (n = 4)	0.05	0.74	$y = -1.8x + 269$	0.20	0.64	$y = -2.1x + 251$
7 (n = 3)	0.01	0.99	$y = -1.5x + 265$	0.03	0.99	$y = -1.6x + 224$
9/10 (n = 4)	0.13	0.76	$y = -1.0x + 240$	0.14	0.74	$y = -1.2x + 225$
Barley§						
3 (n = 3)	0.69	0.22	$y = -1.9x + 143$	0.67	0.25	$y = -2.0x + 99$
5 (n = 4)	0.58	0.18	$y = -0.6x + 175$	0.66	0.11	$y = -0.6x + 138$
7/8 (n = 3)	0.42	0.63	$y = -0.7x + 164$	0.40	0.66	$y = -0.8x + 120$

† $AONR_{100}$, Agronomic optimum nitrogen rate at 100% of optimum yield; determined using either a linear plus plateau model or a quadratic plus plateau model.

‡ $AONR_{95}$, Nitrogen rate at which grain yield is at 95% of optimum grain yield.

§ Only 1 site-year of sensor data collected at Feekes 4, 6, 9, 10 growth stages.

RI_{NDVI} at Feekes 5/6 and 7 in wheat and Feekes growth stage 5 of barley. Significant relationships between optimum N rates and algorithm N recommendations were observed; however, the slopes of the linear relationships were negative, which was not to be expected. Further work must be conducted to identity the proper time of sensing of the indicator crop, and N algorithm recommendations need to be modified or new ones created. Findings from this study will be incorporated into future studies of other indicator crops such as cover crops to enable more reliable N fertilizer recommendations. Producers may be tentative to use indicator crop N-rich strips, nonetheless, they provide an alternative approach to corn N fertilizer recommendations and that could modernize current N management strategies.

ACKNOWLEDGMENTS

The authors would like to thank the Oklahoma Soil Fertility Research and Education Advisory Board for funding of this research project and their continued financial support of soil fertility and sensor-based nutrient management research at Oklahoma State University.

REFERENCES

Abendroth, L.J., R.W. Elmore, M.J. Boyer, and S.K. Marlay. 2011. Corn growth and development. PMR1009. Iowa State Univ. Ext., Ames.

Arnall, D.B., A.P. Mallarino, M.D. Ruark, G.E. Varvel, J.B. Solie, M.L. Stone et al. 2013. Relationship between grain crop yield potential and nitrogen response. Agron. J. 105:1335–1344. doi:10.2134/agronj2013.0034

Bundy, L.G., S.J. Sturgul, and R.W. Schmidt. 1993. Wisconsin's pre-plant soil nitrate test. A3512. Univ. of Wisconsin-Ext., Madison.

Bushong, J.T., E.C. Miller, J.L. Mullock, D.B. Arnall, and W.R. Raun. 2014. Effect of irrigation and preplant nitrogen fertilizer source on maize in the Southern Great Plains. Int. J. Agron. doi:10.1155/2014/247835

Cerrato, M.E., and A.M. Blackmer. 1990. Comparison of models for describing corn yield response to nitrogen fertilizer. Agron. J. 82:138–143. doi:10.2134/agronj1990.00021962008200010030x

Forrestal, P.J., R.J. Kratochvil, and J.J. Meisinger. 2012. Late-season corn measurements to assess soil residual nitrate and nitrogen management. Agron. J. 104:148–157. doi:10.2134/agronj2011.0172

Hodgen, P.J., W.R. Raun, G.V. Johnson, R.K. Teal, K.W. Freeman, K.B. Brixey et al. 2005. Relationship between response indices measured in-season and at harvest in winter wheat. J. Plant Nutr. 28:221–235. doi:10.1081/PLN-200047605

Khan, S.A., R.L. Mulvaney, and R.G. Hoeft. 2001. A simple soil test for detecting sites that are nonresponsive to nitrogen fertilization. Soil Sci. Soc. Am. J. 65:1751–1760. doi:10.2136/sssaj2001.1751

Large, E.C. 1954. Growth stages in cereals. Plant Pathol. 3:128–129. doi:10.1111/j.1365-3059.1954.tb00716.x

Magdoff, F.R., D. Ross, and J. Amadon. 1984. A soil test for nitrogen availability to corn. Soil Sci. Soc. Am. J. 48:1301–1304. doi:10.2136/sssaj1984.03615995004800060020x

Martin, K.L., K. Girma, K.W. Freeman, R.K. Teal, B. Tubaña, D.B. Arnall et al. 2007. Expression of variability in corn as influenced by growth stage using optical sensor measurements. Agron. J. 99:384–389. doi:10.2134/agronj2005.0268

Mehlich, A. 1984. Mehlich 3 soil test extractant: A modification of Mehlich 2 extractant. Commun. Soil Sci. Plant Anal. 15:1409–1416. doi:10.1080/00103628409367568

Meisinger, J.J., V.A. Bandel, J.S. Angle, B.E. O'Keefe, and C.M. Reynolds. 1992. Presidedress soil nitrate test evaluation in Maryland. Soil Sci. Soc. Am. J. 56:1527–1532. doi:10.2136/sssaj1992.03615995005600050032x

Mullen, R.W., K.W. Freeman, W.R. Raun, G.V. Johnson, M.L. Stone, and J.B. Solie. 2003. Identifying an in-season response index and the potential to increase wheat yield with nitrogen. Agron. J. 95:347–351. doi:10.2134/agronj2003.0347

Mulvaney, R.L. 1996. Nitrogen–inorganic forms. In: D.L. Sparks, editor, Methods of soil analysis. Part 3. Chemical methods. Soil Sci. Soc. Am. Book Ser. 5. SSSA, Madison, WI. p. 1123–1184.

Oklahoma State University. 2014. Library of yield prediction equations. Oklahoma State Univ., Stillwater. http://nue.okstate.edu/Yield_Potential.htm (accessed 5 Sept. 2014).

Raun, W.R., J.B. Solie, and M.L. Stone. 2011. Independence of yield potential and crop nitrogen response. Precis. Agric. 12(4):508–518. doi:10.1007/s11119-010-9196-z

Raun, W.R., J.B. Solie, M.L. Stone, K.L. Martin, K.W. Freeman, R.W. Mullen et al. 2005. Optical sensor-based algorithm for crop nitrogen fertilization. Commun. Soil Sci. Plant Anal. 36:2759–2781. doi:10.1080/00103620500303988

Reusch, S. 2005. Optimum waveband selection for determining the nitrogen uptake in winter wheat by active remote sensing. In: J.V. Staff ord, editor, Precision Agriculture 2005. Proceedings of the 5th European Conference on Precision Agriculture, Uppsala, Sweden. 9–12 June 2005. Wageningen Academic Publ., Wageningen, the Netherlands. p. 261–266.

Samborski, S.M., N. Tremblay, and E. Fallon. 2009. Strategies to make use of plant sensors-based diagnostic information for nitrogen recommendations. Agron. J. 101:800–816. doi:10.2134/agronj2008.0162Rx

SAS Institute. 2011. SAS/STAT® 9.3 User's guide. SAS Inst., Cary, NC.

Sawyer, J., E. Nafziger, G.W. Randall, L.G. Bundy, G. Rehm, and B. Joern. 2006. Concepts and rationale for regional nitrogen rate guidelines for corn. PM 2015. Iowa State Univ. Coop. Ext. Serv., Ames.

Schepers, J.S. 1994. New diagnostic tools for tissue testing. Commun. Soil Sci. Plant Anal. 25:817–826. doi:10.1080/00103629409369082

Schepers, J. 2013. Moving beyond nitrogen with field sensors. Nitrogen Use Efficiency Conference, Johnston, IA. 5–7 Aug. 2013. Oklahoma State Univ., Stillwater. http://nue.okstate.edu/Nitrogen_Conference2013/Pioneer_Iowa.htm (accessed 5 Sept. 2014).

Schepers, J.S., D.D. Francis, and M.T. Thompson. 1989. Simultaneous determination of total C, total N, and 15N on soil and plant material. Commun. Soil Sci. Plant Anal. 20:949–959. doi:10.1080/00103628909368128

Shanahan, J. 2013. Crop sensor research for corn N management at Dupont Pioneer. Nitrogen Use Efficiency Conference; Johnston, IA. 5–7 Aug. 2013. Oklahoma State Univ., Stillwater. http://nue.okstate.edu/Nitrogen_Conference2013/Pioneer_Iowa.htm (accessed 26 Apr. 2017).

Solari, F., J. Shanahan, R. Ferguson, J. Schepers, and A. Gitelson. 2008. Active sensor reflectance measurements of corn nitrogen status and yield potential. Agron. J. 100:571–579. doi:10.2134/agronj2007.0244

Solie, J.B., A.D. Monroe, W.R. Raun, and M.L. Stone. 2012. Generalized algorithm for variable-rate nitrogen application in cereal grain. Agron. J. 104:378–387. doi:10.2134/agronj2011.0249

Stanford, G. 1973. Rationale for optimum fertilization in corn production. J. Environ. Qual. 2:159–165. doi:10.2134/jeq1973.00472425000200020001x

Teal, R.K., B. Tubaña, K. Girma, K.W. Freeman, D.B. Arnall, O. Walsh, and W.R. Raun. 2006. In-season prediction of corn grain yield potential using normalized difference vegetative index. Agron. J. 98:1488–1494. doi:10.2134/agronj2006.0103

Tubaña, B.S., D.B. Arnall, O. Walsh, B. Chung, J.B. Solie, K. Girma, and W.R. Raun. 2008. Adjusting midseason nitrogen rate using a sensor-based optimization algorithm to increase use efficiency in corn. J. Plant Nutr. 31:1393–1419. doi:10.1080/01904160802208261

Walsh, O., W. Raun, A. Klatt, and J. Solie. 2012. Effect of delayed nitrogen fertilization on maize (*Zea mays* L.) grain yields and nitrogen use efficiency. J. Plant Nutr. 35:538–555. doi:10.1080/01904167.2012.644373

Zhang, H., and W.R. Raun. 2006. Oklahoma soil fertility handbook. 6th ed. Oklahoma State Univ. Press, Stillwater.