This article was downloaded by:[Oklahoma State University]
On: 10 July 2008
Access Details: [subscription number 791983175]
Publisher: Taylor & Francis
Informa Ltd Registered in England and Wales Registered Number: 1072954
Registered office: Mortimer House, 37-41 Mortimer Street, London W1T 3JH, UK

Journal of Plant Nutrition

Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713597277

Adjusting Midseason Nitrogen Rate Using a Sensor-Based Optimization Algorithm to Increase Use Efficiency in Corn

B. S. Tubaña [a]; D. B. Arnall [a]; O. Walsh [a]; B. Chung [a]; J. B. Solie [a]; K. Girma [a]; W. R. Raun [a]
[a] Department of Plant and Soil Sciences, Oklahoma State University, Stillwater, Oklahoma, USA

Online Publication Date: 01 August 2008

To cite this Article: Tubaña, B. S., Arnall, D. B., Walsh, O., Chung, B., Solie, J. B., Girma, K. and Raun, W. R. (2008) 'Adjusting Midseason Nitrogen Rate Using a Sensor-Based Optimization Algorithm to Increase Use Efficiency in Corn', Journal of Plant Nutrition, 31:8, 1393 — 1419

To link to this article: DOI: 10.1080/01904160802208261
URL: http://dx.doi.org/10.1080/01904160802208261

PLEASE SCROLL DOWN FOR ARTICLE

Full terms and conditions of use: http://www.informaworld.com/terms-and-conditions-of-access.pdf

This article maybe used for research, teaching and private study purposes. Any substantial or systematic reproduction, re-distribution, re-selling, loan or sub-licensing, systematic supply or distribution in any form to anyone is expressly forbidden.

The publisher does not give any warranty express or implied or make any representation that the contents will be complete or accurate or up to date. The accuracy of any instructions, formulae and drug doses should be independently verified with primary sources. The publisher shall not be liable for any loss, actions, claims, proceedings, demand or costs or damages whatsoever or howsoever caused arising directly or indirectly in connection with or arising out of the use of this material.

Journal of Plant Nutrition, 31: 1393–1419, 2008
Copyright © Taylor & Francis Group, LLC
ISSN: 0190-4167 print / 1532-4087 online
DOI: 10.1080/01904160802208261

Adjusting Midseason Nitrogen Rate Using a Sensor-Based Optimization Algorithm to Increase Use Efficiency in Corn

B. S. Tubaña, D. B. Arnall, O. Walsh, B. Chung, J. B. Solie, K. Girma, and W. R. Raun

Department of Plant and Soil Sciences, Oklahoma State University, Stillwater, Oklahoma, USA

ABSTRACT

This study was conducted to formulate an in-season nitrogen (N) fertilization optimization algorithm (NFOA) to estimate midseason N rates that maximize corn (*Zea mays* L.) growth and minimize fertilizer inputs. Treatments included: a zero kg N ha^{-1}; three treatments of 134 kg N ha^{-1} fixed rate applied in split, preplant, or sidedress; two treatments of 67 kg N ha^{-1} fixed rate preplant or sidedress applied; three NFOA-based midseason N rates (RI-NFOA, RICV-NFOA, flat-RICV-NFOA) with (67 kg N ha^{-1}) and without preplant N; and two resolutions (0.34 and 2.32 m^2) tested for RICV-NFOA only. With the 67 kg N ha^{-1} preplant application, midseason RI-NFOA-based N rates resulted in an N use efficiency (NUE) of 65% while the 134 kg N ha^{-1} fixed rate split applied had 56% NUE. Using the RICV-NFOA, NUE and net returns to N fertilizer were higher when spatial variability was treated at 2.32 m^2 resolution.

Keywords: Corn, yield potential, nitrogen fertilization optimization algorithm, response index, coefficient of variation, normalized difference vegetation index

INTRODUCTION

Corn is grown throughout the world and is one of the most important cereal crops for human consumption. In 2003, the United States produced 38% or 257 million metric tons of the world's corn production (US Grain Council, 2003). Traditionally, farmers treat each field uniformly and base their nitrogen (N)

Received 25 May 2007; accepted 8 August 2007.

Address correspondence to William R. Raun, 044 North Ag Hall, Department of Plant and Soil Sciences, Oklahoma State University, OK 74078. E-mail: bill.raun@okstate.edu

management decisions on yield goals which can be determined from a recent 5-year crop yield average plus an increase of 10–30% to assure non-limiting supply of N (Johnson, 1991; Dahnke et al., 1988). Johnson et al. (1997) used both yield goal and soil nitrate (NO_3-N) levels as basis for N rate recommendations and developed a recommendation guideline for wheat (*Triticum aestivum* L.): 33 kg N ha^{-1} should be applied for every 1 Mg of yield goal. For corn, Schmitt et al. (1998) reported that 20 kg N ha^{-1} is required for every 1 Mg of yield goal. The soil NO_3-N level present in the soil should be subtracted when using these recommendation guidelines. Since N fertilizer requirement is temporally dependent (Baethgen and Alley, 1989) and may vary among and within fields (Ferguson et al., 2002), uniform application of N fertilizer is not an efficient practice (Mulla and Bhatti, 1997; Khosla and Alley, 1999; Khosla et al., 2002; Hornung et al., 2003; Koch et al., 2004).

Traditional N management systems may result in reduced economic returns, poor NUE, and increased environmental and health risks (Huggins and Pan, 1993; Raun et al., 2002). The presence of excess N fertilizer in the soil-plant system has been reported to be the main source of NO_3-N accumulation in the soil (Vyn et al., 1999). Spruill et al. (1996) reported that N fertilization in agricultural areas has been cited as the cause of high NO_3-N concentration in perched groundwater. Within the Midwest Corn Belt, NO_3-N concentrations in surface waters are often > 10 mg L^{-1}, the U.S. Environmental Protection Agency's maximum contaminant level for drinking water (Jaynes et al., 1999; Mitchell et al., 2000). As a result, cost of water treatment in some cities has increased due to installation of denitrification systems to remove NO_3-N from drinking water (Dinnes et al., 2002). The Mississippi River watershed serves as the drainage of NO_3-N-contaminated surface water that was leached and/or washed from corn-soybean production areas in the Midwest (David et al., 1997; Goolsby et al., 1999; Jaynes et al., 1999). This in turn was identified as the primary source of NO_3-N in the Gulf (Goolsby et al., 1999) and as the leading cause of hypoxia in the northern Gulf of Mexico (Rabalais et al., 1996).

Practices employed to improve nitrogen use efficiency (NUE) include proper timing of N applications, avoiding excess application of N fertilizer (Kanampiu et al., 1997) and multiple inputs of N in small amounts (Sowers et al., 1994), all of these reduce the potential loss of unused N in the soil system. Fageria and Baligar (2005) reported that besides using appropriate N forms, placement, and timing, the use of diagnostic tools and models that can estimate plant N requirement on a need basis can improve N management decision. Split N fertilizer applications are important to maximize crop utilization of applied N throughout the growing season (Boman et al., 1995). Cassman et al. (1992) showed that both yield and protein content of wheat were improved when multiple applications of N before planting and during the growing season was adopted. Late-season N deficiency detection could allow farmers the option of adjusting N rates according to crop growth which could reduce potential N losses due to leaching and denitrification (Johnson and Raun, 1995). However, the environmental factors influencing N cycling complicate the present N status monitoring of crops (Westerman et al., 1994). Below et al. (1992) noted that the lack of a relationship between responsiveness to fertilizer N and late-spring soil NO_3-N tests was partly due to a variable proportion of the soil N as ammonium (NH_4)-N. Traditionally, corn N requirements have been based on soil testing (Magdoff, 1991), tissue N concentration (Tyner and Webb, 1946), and chlorophyll concentration or leaf greenness (Varvel et al., 1997). Blackmer and Schepers (1996) reported that these methods can be expensive, time consuming, require multiple samples and may produce inaccurate crop N requirement estimates.

Remotely sensed crop spectral properties have been used to assess multiple crop parameters such as photosynthetic capacity, productivity and potential yield (Penuelas et al., 1994; Aparicio et al., 2000; Thenkabail et al., 2000; Ma et al., 2001; Raun et al., 2001; Baez-Gonzales et al., 2002; Teal et al., 2006a). These crop biophysical traits have been utilized in various ways to determine optimum crop N requirements. Stone et al. (1996) correlated plant N spectral index with total N uptake to determine N requirements in winter wheat. Other studies correlated spectral measurements to plant biomass (Wallburg et al., 1982; Kleman and Fagerlund, 1987; Wanjura and Hatfield, 1987; Casanova et al., 1998; Felton et al., 2002; Bronson et al., 2003) and plant N content (Blackmer et al., 1994; Bronson et al., 2003) which can be used as parameters to estimate crop N requirements. Spectral measurements have also been utilized by many researchers to determine yield potential (YP_0) using simple regression equations (Moran et al., 1997; Raun et al., 2001; Teal et al., 2006a). Yield potential is simply a function of all conditions of the growing environment (Johnson, 1991), and is an integral component of the fertilizer N management decision. Raun et al. (2001) reported that YP_0 can be predicted in-season using optical sensors. They used Normalized Difference Vegetation Index (NDVI; Rouse et al., 1973), the most widely used spectral vegetation index, to determine in-season estimated yield (INSEY). The index INSEY, a measure of biomass produced per day, is the NDVI reading (Feekes growth stages 4 to 6; Large, 1954) divided by the number of growing degree days ($GDD = ((T_{max} + T_{min})/2) - 4.4°C$). The model that best fit the relationship between INSEY and actual grain yield was used to estimate YP_0. Raun et al. (2002) developed a functional algorithm (NFOA) that can precisely estimate midseason N requirements of winter wheat. The projected midseason N requirement is based on N demand of the predicted YP_0 while taking into account seasonally dependent crop responsiveness to applied N. Their work has shown that NUE of winter wheat was improved by more than 15% when this approach was employed compared with conventional N rate recommendations. Arnall et al. (2006) used the coefficient of variation (CV) from NDVI readings to evaluate plant-stand densities in winter wheat. Using a linear-plateau model, they reported that a <100 plants m^{-2} population having a CV value of 20% was considered a poor stand. Raun et al. (2005) used this information to further refine the algorithm. The mathematical adjustment in the algorithm using CV is important in areas with pronounced spatial variability. In the algorithm, when the CVs of the sensed area become higher than the 20% critical CV, the N rate recommendation decreases. The successful use of sensor-based N rate recommendations in winter wheat prompted the development of a functional algorithm for equally important crops like corn. The objectives of this study were to determine the NFOA that could be used to estimate midseason N rates for optimum corn growth and to determine the optimum resolution to treat spatial variability in corn.

MATERIALS AND METHODS

Field trials were established on three soil types: an Easpur loam soil (fine-loamy, mixed, superactive, thermic Fluventic Haplustolls) located at Stillwater (EFAW) Research Station, a Pulaski fine sandy loam soil (coarse-loamy, mixed, superactive, nonacid, thermic Udic Ustifluvents) at Lake Carl Blackwell (LCB) Irrigated Research Station, and a Teller sandy loam soil (fine-loamy, mixed, active, thermic Udic Argiustolls) at Perkins Research Station, Oklahoma. Prior to crop establishment, comprehensive soil samples at 0–15 cm were collected, air-dried and processed to pass 2 mm sieve for Mehlich III-extractable phosphorus (P), exchangeable potassium (K), NH_4-N, and NO_3-N determination (Table 1). The experiments consisted of 13 treatments arranged in randomized complete block design (RCBD) (Table 2). Treatments included: a zero kg N ha^{-1}; three treatments of 134 kg N ha^{-1} fixed rate applied in split, preplant or sidedress; two treatments of 67 kg N ha^{-1} fixed rate applied either preplant or sidedress; three NFOA-based midseason N rates (RI-NFOA, RICV-NFOA, flat-RICV-NFOA) with (67 kg N ha^{-1}) and without preplant N; and two resolutions (0.34 and 2.32 m^2) tested for RICV-NFOA only. The flat-RICV-NFOA-based midseason N rates were determined from the average of the variable rates determined by the RICV-NFOA.

Table 1

Soil chemical properties determined from initial soil samples (0–15 cm) at three locations, Oklahoma

Site	pH	Total N	Organic C	NH_4-N	NO_3-N	P	K
		g kg^{-1}			mg kg^{-1}		
EFAW	5.9	0.65	10.24	13.9	3.7	20	90
LCB	5.6	0.76	9.87	28.4	4.4	45	144
Perkins	6.2	0.44	6.40	9.2	8.1	14	118

pH – 1:1 soil:water; K and P–Mehlich III; NH_4-N and NO_3-N–2 M KCl, Total N and Organic C–dry combustion.

Table 2
Treatment structure and description of the trials conducted at Efaw, Lake Carl Blackwell, and Perkins, 2004–2006

Treatment	Preplant N kg ha^{-1}	Midseason N kg ha^{-1}	Resolution m^2
1	0	0	—
2	0	67	—
3	0	134	—
4	67	67	—
5	67	0	—
6	134	0	—
7	0	RICV-NFOA	0.34
8	67	RICV-NFOA	0.34
9	0	Flat-RICV-NFOA	—
10	67	Flat-RICV-NFOA	—
11	67	RICV-NFOA	2.32
12	0	RI-NFOA	0.34
13	67	RI-NFOA	0.34

NFOA = Nitrogen Fertilization Optimization Algorithm.

RICV-NFOA = Algorithm for adjusting midseason N rate recommendation for the predicted YP_0 using response index and coefficient of variation as the components.

Flat-RICV-NFOA = Utilized the average of N rates determined by RICV-NFOA.

RI-NFOA = Algorithm for adjusting midseason N rate recommendation for the predicted YP_0 using response index.

Table 3 provides information on field activities, corn varieties, and planting rates for all sites from the 2004–2006 cropping years. Plots with preplant N were fertilized either before or at planting. The NDVI readings and CVs were collected between V7–V9 leaf growth stages for sidedress application of the NFOA treatments. A GreenSeeker^{TM} Hand Held Optical Sensor (NTech Industries, Inc.) was used to measure NDVI at a distance of 0.6 to 1.0 m from the corn canopy. The GreenSeeker$^{\text{TM}}$ sensor calculates NDVI using the equation:

$$NDVI = \frac{\rho_{NIR} - \rho_{Red}}{\rho_{NIR} + \rho_{Red}}$$

where:

ρ_{NIR} = fraction of emitted near-infrared (NIR) radiation (780 ± 10 nm) from the sensed area

ρ_{RED} = fraction of emitted red (671 ± 10 nm) radiation from the sensed area.

The NDVI readings when divided by the number of days from planting to sensing will give INSEY, which is an index of biomass produced per day and can be used to predict YP_0 using the algorithm for corn (Teal et al., 2006a).

Table 3
Field trial information for all sites, 2004–2006

Site	Year	Variety	Planting rate plants ha^{-1}	Date[±]			
				Planting	Sensing[¶]	Sidedress application	Harvest
EFAW	2004	113 BT	66,000	04-07-04	06-01-04	06-02-04	09-03-04
	2005	38B51	59,000	03-30-05	05-25-05	05-25-05	08-27-05
	2006	38B51	54,000	03-30-06	05-24-06	05-24-06	09-01-06
LCB[§]	2004	108 BT	66,000	04-03-04	06-11-04	06-12-04	08-27-04
	2005	38B51	74,000	04-12-05	05-31-05	05-31-05	09-07-05
	2006	38B51	79,000	03-31-06	05-22-06	05-23-06	08-18-06
Perkins	2004	108 BT	59,000	04-02-04	06-03-04	06-07-04	09-01-04
	2005	8454Y61	49,000	03-28-05	06-06-05	06-06-05	08-31-05
	2006	OKC5020	49,000	03-30-06	05-30-06	05-30-06	08-14-06

[±] Date in month-day-year.

[§] Lake Carl Blackwell.

[¶] Sensing dates done between V8-V9 leaf growth stages.

Yield potential when N is applied (YP_N) was determined by multiplying YP_0 by the response index (RI_{NDVI}: the NDVI of the 134 kg N ha^{-1} preplant treated plot divided by the NDVI of the check plot). The N rate required to achieve the YP_N for each plot was computed using the equation:

$$R_n = \frac{YP_0 N_g}{\varepsilon_n}(RI - 1)\left(\frac{(CV_{Cap} - CV_{Plot})}{(CV_{Cap} - CV_{Critical})}\right)$$

where:

R_n = N application rate, kg N ha^{-1}
N_g = N content in grain, 0.0125 kg N kg^{-1}
ε_n = Expected NUE
RI = Adjusted RI, $\left(\frac{NDVI_{N\ Rich}}{NDVI_{Farmer}} \times 1.64\right) - 0.528$
CV_{Cap} = Maximum coefficient of variation
$CV_{Critical}$ = Critical coefficient of variation value
CV_{Plot} = Coefficient of variation from the plot's NDVI readings.

Table 4 presents the YP_0 equations, critical CVs and maximum CVs used for each site year. In 2005, the critical CV was determined based on plant population using the linear equation: $y = (-0.0003 \times \text{plant population}) + 36.315$ (www.nue.okstate.edu). Flat and varied amounts of N were applied as urea ammonium nitrate (UAN, 28-0-0) at the base of the plants of designated subplots using syringes (± 0.1 mL).

The two middle rows of each plot were harvested with a Massey Ferguson 8XP combine. Grain yield and percent moisture content were recorded using a

Table 4
Yield potential equations, coefficients of variation, and days from planting to sensing that were used to compute midseason nitrogen rate requirements, 2004–2006

Year	YP_0 Equations	Coefficient of Variation, % Critical	 Cap
		CV, %	
2004	$YP_0 = 1333*EXP(INSEY*122.5)$	20	100
2005	$YP_0 = 1565*EXP(INSEY*154.7)$	20	100
2006	$YP_0 = 1202*EXP(INSEY*169.6)$	§	65

CV = Coefficient of variation.

YP_0 = Yield potential.

INSEY = In-season estimated yield computed by dividing NDVI readings at the V8 leaf growth stage by the number of days from planting to sensing.

§Determination of critical CV was based from plant population.

Cap = Maximum CV value.

Harvest Master yield monitoring computer (Harvest Master, Carson City, NV). Moisture content of the final grain yield was adjusted to 15.5%. Grain subsamples were collected, oven-dried at 70°C for 72 hours, and processed to pass 106 um screen (140 mesh screen) for total N analysis using a Carlo Erba Na 1500 dry combustion analyzer (Schepers et al., 1989). Total N uptake was determined by multiplying the percent N in grain with grain yield and NUE was computed by dividing the difference in grain N uptake of the fertilized and check plots by the N rate applied. Net return to N fertilizer was computed by subtracting the cost of total N applied from the gross income (price of grain per kg multiplied by grain yield increase due to N fertilizer application). Grain prices used were 0.10, 0.10, and 0.13 \$ kg^{-1} for 2004, 2005, and 2006, respectively (USDA NASS, 2007). The estimated average U.S. farm level N fertilizers (anhydrous ammonia, urea, and UAN 32) prices were 0.59, 0.71, and 0.75 \$ kg N^{-1} for 2004, 2005, and 2006, respectively (United States Department of Energy, 2007). Statistical analysis was performed using SAS for Windows (SAS, 2002). Analysis of variance (ANOVA) was conducted to determine if there were significant differences among treatment means of the variables measured: yield, grain N uptake, NUE, and net return to N fertilizer. A SAS Mixed Model Procedure was used to partition sources of variation.

RESULTS

Components of the Nitrogen Fertilization Optimization Algorithm

Estimates of Yield Potential

The actual grain yields increased with increasing NDVI readings (Table 5). The highest NDVI reading (0.83) collected at LCB in 2005 obtained an actual yield

Table 5
Sensor and field data collected from all experimental sites, 2004–2006

	Efaw			Lake Carl Blackwell			Perkins		
Variables	2004	2005	2006	2004	2005	2006	2004	2005	2006
Avg. $\text{NDVI}_{\text{Check}}$	0.77	0.64	0.67	0.70	0.83	0.47	0.68	0.41	0.49
YP_0, Mg ha^{-1}	8.9	9.0	9.2	5.0	21.8	5.3	5.3	4.0	4.6
Check Yield, Mg ha^{-1}	9.5	6.2	7.1	4.2	10.0	4.7	5.3	1.9	1.9
DFP	50	56	56	65	49	53	61	68	62
Avg. $\text{NDVI}_{\text{NFOA}}$‡	0.78	0.71	0.63	0.65	0.82	0.57	0.71	0.49	0.54
Adj. RI_{NDVI}†	1.10	1.26	1.34	1.40	1.42	1.94	1.26	1.62	1.52
$\text{RI}_{\text{HARVEST}}$§	1.39	1.81	2.08	1.88	1.44	1.92	1.50	2.30	1.28
Critical CV¥, %	20	20	18	20	20	9	20	19	19
Critical CV¶, %	13	16	18	13	10	9	16	19	19
Avg. CV, %	8	14	14	12	10	17	15	26	16
Maximum CV, %	31	54	52	98	44	57	66	55	54
Minimum CV, %	1	2	1	0	1	2	2	4	1
CV Range, %	30	52	51	98	43	55	64	51	53

NDVI = Normalized Difference Vegetation Index.

YP_0 = Predicted yield potential of the check.

DFP = Number of days from planting to sensing, approximately at V8 leaf growth stage.

CV = Coefficient of variation collected from midseason NFOA-based N rate treatments.

‡Average NDVI of NFOA treatments.

†Adjusted in-season response index, determined by dividing average Normalized Difference Vegetation Index (NDVI) between V8-V9 leaf growth stage of Treatment 6 (134 kg ha^{-1} preplant) by the Check plot. Adjustment was made using the equation ($\text{RI}_{\text{NDVI}} \times$ 1.64) - 0.528.

§Response index at harvest, determined by dividing the grain yield of the highest preplant N fertilized plots by the Check plot.

¥Critical CV used in the algorithm.

¶Determined from the equation: critical CV = $(-0.0003^{*}\text{plant population}) + 36.315$.

of 10.0 Mg ha^{-1}, the highest check yield recorded. In this trial, the equation derived from the relationship between the NDVI normalized by the number of days from planting to sensing (DFP INSEY) and actual yield was used to estimate the corn grain YP_0. In general, estimated YP_0 was close to the measured grain yield (Table 5). At Perkins, the estimated YP_0 (5.3 Mg ha^{-1}) was equal to the actual grain yield (5.3 Mg ha^{-1}). However, as has been reported, YP_0 can be overestimated using this approach (Raun et al., 2005). Obtaining accurate estimates of YP_0 relies on fitting a model not adversely affected by changes in growing conditions otherwise, YP_0 can be over- or underestimated. This was exemplified at LCB in 2005 and at Perkins in 2006. The discrepancy obtained at Perkins was attributed to moisture stress that occurred between sensing and harvest that adversely affected the YP_0. As a result, the estimated YP_0 of 4.6 Mg ha^{-1} was higher than the actual yield of 1.9 Mg ha^{-1}. At LCB, canopy closure at V8 leaf growth stage resulted in very high NDVI readings averaging 0.83 (Table 5) in which the sensor was exclusively measuring plant material. Since the DFP INSEY was used, the NDVI readings were normalized by DFP which were reported to be the lowest number (49 days) obtained in all site years (Table 5). The projected biomass produced per day was large due to the high NDVI reading and relatively low DFP. The equation projected what would be the final YP_0 with the biomass produced per day. Thus, YP_0 was large for this specific site year, and the amount of N in the check plot could have become limiting as plant growth continued. As a result, crop growth rate slowed in the period from sensing towards harvest which caused a reduction in the final grain yield and resulted in a large discrepancy of YP_0 (21.8 Mg ha^{-1}) and actual grain yield (10.0 Mg ha^{-1}) of the check plot. The LCB Research Station has been under irrigation since the spring of 2005. The non-limiting moisture at this site resulted in a lower number of days to reach the V8 leaf growth stage (faster growth rate) compared with the rainfed system at Efaw and Perkins (Table 5). Perkins has a sandy loam soil known to have poor water holding capacity. As a result of less favorable growing conditions at this site, average grain yields were lower than at Efaw and LCB.

Response Index

Response index at harvest ($RI_{HARVEST}$) was determined by computing the ratio of the grain yield of plot that received the highest N rate and the grain yield of the check plot (Table 5). The RI_{NDVI} was adjusted by using a previously established relationship between the vegetative response (RI_{NDVI}) and the grain yield response ($RI_{HARVEST}$) to N fertilization. The adjusted RI_{NDVI} values $[(RI_{NDVI} \times 1.64) - 0.528]$ generally provided good estimates of actual crop response to fertilizer N (Table 5). It is noteworthy that corn N response varied across sites and years as indicated by $RI_{HARVEST,}$ suggesting the importance of having in-season estimates of crop response to N fertilizer. In some site years, the response of corn to N fertilization was underestimated as shown in 2006 at Efaw, where a difference of 0.74 existed between predicted ($RI_{NDVI} = 1.34$) and observed response ($RI_{HARVEST} = 2.08$) to N fertilization. Mullen et al. (2003) explained that after sensing, enhancing or limiting factors affecting crop yield potential may occur that lead to underestimation or overestimation of $RI_{HARVEST}$ by RI_{NDVI}. Further, they explained that favorable conditions that occurred (such as timely rainfall) after sensing can increase crop N response resulting in a higher $RI_{HARVEST}$ value than RI_{NDVI}. Perkins in 2006 was the only site year where $RI_{HARVEST}$ (1.28) was underestimated by RI_{NDVI} (1.52) which exemplifies growth conditions that adversely affect crop N response between sensing to harvest. In 2005, a state-of-the-art irrigation system was installed at LCB. With this system, moisture stress can be avoided and thus, crop growth conditions were near ideal. Since 2005, the RI_{NDVI} have provided accurate estimates of crop response to N. The RI_{NDVI} and $RI_{HARVEST}$ for 2005 at LCB were 1.42 and 1.44, respectively. Similarly, close RI values are reported between estimated ($RI_{NDVI} = 1.94$) and observed ($RI_{HARVEST} = 1.92$) in 2006 at LCB (Table 5). The absence of drastic changes in growth conditions resulted in little or no change in crop response to N from sensing to harvest at this particular site.

Coefficient of Variation

Initially, the critical CV used in the algorithm was 20% (Arnall et al., 2006) and a maximum CV value of 100% to cap mathematical adjustment by the CV component. Recent studies led to an adjustment of critical and maximum CVs for the corn algorithm. Teal et al. (2006b) obtained a maximum CV of 55 % from the NDVI readings when the plant population was approximately 20,000 plant ha^{-1}. The highest CV from NDVI readings obtained by Martin et al. (2006) was 65% and thus, the maximum CV used in the algorithms was adjusted from 100% to 65% in 2006. Further, Martin et al. (2006) reported that a strong correlation existed between corn plant density and CVs from NDVI readings measured between the V7–V9 leaf growth stages. This implied that the critical CV may change depending on the plant population and thus, an equation was established that allowed the adjustment of critical CV based on plant population. The critical CV and CV based from plant population used in the NFOA treatments are reported in Table 5.

Nitrogen Fertilizer Recommendations

Amounts of N fertilizer applied in treatments 7 to 13 had a wide variation across site years (Table 6). The lowest sidedress N rate recorded was only 1 kg N ha^{-1} at LCB and the highest (132 kg N ha^{-1}) was at Efaw, both in 2005. These varying levels of N demonstrated the ability of the algorithms to adjust N recommendations based on YP_0, crop responsiveness to N fertilization and plant-stand densities, all derived from NDVI readings of the current crop.

To determine the midseason NFOA-based N rate requirements, YP_N first needs to be determined. In 2004 and 2005 for all sites, the RI_{NDVI} was determined by dividing the NDVI readings of treatment 6 (134 kg N ha^{-1} fixed rate applied preplant) by the check plot. This RI_{NDVI} was used regardless of whether the NFOA treated plots received preplant N. Generally, the resulting recommendations for the NFOA-treatments with 67 kg N ha^{-1} preplant tended to be higher than the NFOA-treatments without preplant (Table 6). The 67 kg N ha^{-1} fixed

Table 6
Sidedress nitrogen fertilizer applied at fixed and midseason-NFOA-based rates at Efaw, Lake Carl Blackwell, and Perkins, 2004–2006

	N applied		Efaw				Lake Carl Blackwell				Perkins			
TRT	Preplant	Midseason[¥]	2004	2005	2006	Avg.	2004	2005	2006	Avg.	2004	2005	2006	Avg.
		kg ha^{-1}					Sidedress N Rate, kg ha^{-1}							
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	67	67	67	67	67	67	67	67	67	67	67	67	67
3	0	134	134	134	134	134	134	134	134	134	134	134	134	134
4	67	67	67	67	67	67	67	67	67	67	67	67	67	67
5	67	0	0	0	0	0	0	0	0	0	0	0	0	0
6	134	0	0	0	0	0	0	0	0	0	0	0	0	0
7	0	RICV-NFOA	108	100	58	89	80	38	58	59	80	43	77	67
8	67	RICV-NFOA	101	127	52	93	85	23	36	48	101	80	47	76
9	0	Flat-RICV-NFOA	108	100	58	89	80	38	58	59	80	43	77	67
10	67	Flat-RICV-NFOA	101	127	52	93	85	23	36	48	101	80	47	76
11	67	RICV-NFOA	99	132	58	96	87	1	19	36	109	35	31	58
12	0	RI-NFOA	31	66	48	48	48	98	87	78	66	64	56	62
13	67	RI-NFOA	32	66	24	41	50	107	43	67	83	85	23	64

[¥] Full description is presented in Table 2.
TRT = Treatment number.

rate applied preplant provided modest amounts of N for early corn establishment which resulted in healthier corn plants and higher NDVI readings than corn plants without preplant N, more important in site years where the demand for N was large. To account for the amount of N that was applied preplant, in 2006, the RI_{NDVI} for NFOA-treatments with preplant N was determined by dividing the NDVI readings of treatment 6 by treatment 5 (67 kg N ha^{-1} fixed rate applied preplant). This is logical since for corn with preplant N, higher NDVI readings obtained at the V8 leaf growth stage would not only mean higher YP_0, but also more vigor enhanced by extra N from the preplant applied N available of the early stages of growth until V8 (sensing time). With this alteration, in 2006 across sites, midseason N rate requirements prescribed by NFOA with preplant N were lower than the NFOA without preplant, which should be expected because a portion of the total N requirement was already applied early in the season.

When plot CVs exceeded the critical CV in the algorithm, the final midseason N rate recommendations were reduced. Based on the results reported by Arnall et al. (2006), the critical CV in previous years was set at 20%. As reported in Table 5, the critical CVs used in 2004 and 2005 were higher than the critical CVs based on plant population. At Efaw in 2004 and 2005 for example, midseason RICV-NFOA recommended N rates that ranged from 100 to 127 kg N ha^{-1} while the RI-NFOA ranged only from 31 to 66 kg N ha^{-1} (Table 6). The RICV-NFOA resulted in higher recommendations for these site years because CVs from NDVI readings were lower than the critical CV set at 20%. The predicted YP_N starts to decline only when CV from NDVI readings exceeds the critical CV.

The algorithm that utilized CVs had a wider range of midseason N rate recommendations. The highest range of midseason N rates was observed at Perkins in 2005 (Table 7). We recorded a minimum of 0 and a maximum of 201 kg N ha^{-1} taking note that this site year also obtained the highest average CV of 26% (Table 5). In 2006, it is important to note that while there were large differences in minimum and maximum midseason N rates of the RI- and RICV-NFOA, the average midseason N rates of the two algorithms did not deviate as much. Excluding Efaw in 2006, RICV-NFOA projection at 2.32 m^2 resolution had smaller disparity in the minimum and maximum midseason N rates applied (Table 7). Further, the average midseason N rates at this resolution were also lower than what the RICV-NFOA projected at the 0.34 m^2 application resolution.

Responses of Measured Variables to Fixed and NFOA-Based N Rates

Grain Yield

Grain yield means were significantly different ($Pr > 0.05$) among treatments for all site years excluding Perkins in 2006 (Table 8). Soil moisture at this site

Table 7
Average, minimum, and maximum midseason nitrogen rates for five treatments employing the nitrogen fertilization optimization algorithms at three locations, 2004–2006

				Efaw			Lake Carl Blackwell			Perkins		
TRT	Preplant kg ha^{-1}	NFOA	Resolution m^2	Min	Max	Avg.	Min	Max	Avg.	Min	Max	Avg.
				Sidedress N Rate, kg ha^{-1}								
2004												
7	0	RICV	0.34	30	119	86	0	116	71	0	157	81
8	67	RICV	0.34	0	115	76	2	127	76	0	165	101
11	67	RICV	2.32	40	108	93	60	102	78	57	150	110
12	0	RI	0.34	17	46	32	22	56	43	39	88	66
13	67	RI	0.34	28	42	35	20	55	44	40	92	80
2005												
7	0	RICV	0.34	0	157	90	0	125	34	0	93	38
8	67	RICV	0.34	0	163	113	0	110	20	0	201	71
11	67	RICV	2.32	21	151	118	0	4	0	0	76	31
12	0	RI	0.34	20	80	58	0	108	88	39	89	58
13	67	RI	0.34	23	78	59	67	110	95	44	105	76
2006												
7	0	RICV	0.34	0	136	52	0	177	52	0	189	69
8	67	RICV	0.34	0	45	46	0	99	32	0	126	42
11	67	RICV	2.32	0	104	52	0	11	40	6	62	28
12	0	RI	0.34	20	70	43	33	127	78	23	102	50
13	67	RI	0.34	10	31	21	11	58	38	8	40	20

TRT = Treatment number.
NFOA = Nitrogen fertilization optimization algorithm.
RICV = NFOA refined by response index and coefficient of variation.
RI = NFOA refined by response index.

year became limiting, compounded by poor water holding capacity of the soil that masked the effect of different N rates on grain yield. On the other hand, on average by site, Efaw's and LCB's treatment 13 (RI-NFOA with 67 kg N ha^{-1} preplant) obtained the highest grain yields at 12.8 and 10.8 Mg ha^{-1}, respectively. At Efaw, this treatment received only a total of 108 kg N ha^{-1} compared with the fixed rate at 134 kg N ha^{-1} split applied (treatment 4) (Table 6). At LCB, the total N applied to this treatment equaled treatment 4. At Perkins, treatment 4 produced the highest average grain yield of 5.8 Mg ha^{-1} (Table 8). Whether fixed or NFOA-based, plots consistently produced higher grain yields when modest amounts of preplant N were applied (67 kg ha^{-1}) when compared with plots that did not receive preplant N.

Of the NFOA-treatments receiving preplant N, the maximum grain yield difference obtained was 1.2 Mg ha^{-1} at LCB. Grain yields ranged from 11.6 to

Table 8
Corn grain yield response to nitrogen fertilizer at Efaw, Lake Carl Blackwell, and Perkins, 2004–2006

	N Applied		Efaw				Lake Carl Blackwell				Perkins			
TRT	Preplant	Midseason[¥]	2004	2005	2006	Avg.	2004	2005	2006	Avg.	2004	2005	2006	Avg.
	kg ha^{-1}		Grain Yield, Mg ha^{-1}											
1	0	0	9.5	6.2	5.5	7.1	4.2	10.0	4.7	6.3	5.3	1.9	1.3	2.8
2	0	67	13.1	9.9	9.4	10.8	7.6	12.6	7.8	9.3	6.8	4.1	2.3	4.4
3	0	134	11.8	10.2	8.8	10.2	7.2	13.9	10.7	10.6	7.2	3.8	2.9	4.6
4	67	67	13.4	10.3	9.6	11.1	8.8	14.3	9.7	11.0	8.8	5.3	3.3	5.8
5	67	0	12.4	9.2	8.2	9.9	7.9	12.9	5.8	8.9	7.6	4.9	3.1	5.2
6	134	0	13.3	11.2	11.3	12.0	7.8	14.3	9.1	10.4	8.0	4.3	2.5	4.9
7	0	RICV-NFOA	11.2	8.6	6.9	8.9	6.2	12.0	7.6	8.6	7.1	4.1	3.2	4.8
8	67	RICV-NFOA	13.9	12.0	11.1	12.3	7.8	13.0	7.9	9.6	7.9	5.1	3.0	5.3
9	0	Flat-RICV-NFOA	13.5	9.4	9.1	10.6	6.6	11.1	7.6	8.5	7.0	3.3	2.4	4.2
10	67	Flat-RICV-NFOA	13.3	11.5	10.3	11.7	8.7	13.0	8.4	10.0	8.1	5.0	2.4	5.1
11	67	RICV-NFOA	13.3	11.4	10.1	11.6	8.6	13.5	6.8	9.6	8.5	4.9	2.5	5.3
12	0	RI-NFOA	12.9	10.1	9.2	10.7	6.8	13.9	9.5	10.0	6.7	3.4	2.2	4.1
13	67	RI-NFOA	14.0	12.4	11.9	12.8	8.4	14.6	9.4	10.8	8.4	4.9	2.6	5.3
Pr > F			0.01	0.01	0.45	—	0.01	0.01	0.01	—	0.01	0.01	0.60	—
SED			0.71	0.83	0.13	—	0.57	0.76	0.64	—	0.35	0.33	0.45	—
Avg.			12.7	10.2	9.3	10.8	7.4	13.0	8.1	9.5	7.5	4.2	2.6	4.8

[¥] Full description is presented in Table 2.

TRT = Treatment number.

SED = Standard error of the difference between two equally replicated means.

12.8 Mg ha^{-1} at Efaw, 9.6 to 10.8 Mg ha^{-1} at LCB, and 5.1 to 5.3 Mg ha^{-1} at Perkins. On average at Efaw, the RICV-NFOA at 0.34 m^2 resolution obtained 12.3 kg ha^{-1} while the 2.32 m^2 resolution, grain yield was only 11.6 Mg ha^{-1}. On the other hand, there was no pronounced benefit when plots were treated at the 0.34 m^2 resolution at both LCB and Perkins. Flat-RICV-midseason N rates were determined by using average N estimates by the RICV-NFOA. Unlike RICV-NFOA, flat-RICV-NFOA distributed N fertilizer in the entire corn row. Grain yields between RICV- and flat-RICV-NFOA had minimal differences. However, the flat-RICV's grain yield was variable dependent upon the site year (Table 8).

Grain Nitrogen Uptake

Excluding Efaw in 2004, mean grain N uptake were significantly different ($Pr > 0.05$) among treatments across site years (Table 9). On average by site, applying 134 kg N ha^{-1} either preplant or sidedress (treatment 3 and 6) at Perkins resulted in lower grain N uptake compared when N was split (treatment 4). Grain N uptake was only 76 kg N ha^{-1} for both treatment 3 and 6 compared with 93 kg N ha^{-1} for treatment 4. Perkins is a low yielding environment for corn, thus the absence of N (treatment 3) at early growth stages affected crop YP_0. Even when large amounts of N were applied at later stages the crop failed to catch up. Similarly, excess N as a result of large applications at early growth stages under dry and hot conditions at Perkins could have enhanced the process of N loss via volatilization. At LCB, marginal differences among N uptake of these treatments were obtained. Grain N uptake values were 168, 165, and 160 kg N ha^{-1} for treatment 3, 4, and 6, respectively. At Efaw, both N uptake of treatment 4 (170 kg N ha^{-1}) and 6 (176 kg N ha^{-1}) were comparable but not for treatment 3 (152 kg N ha^{-1}).

On average by site, the highest N uptake obtained was 200 kg N ha^{-1} at Efaw (treatment 13) which made a 30 kg N ha^{-1} difference when compared with treatment 4. Take note that treatment 4 received a fixed rate of 134 kg N ha^{-1} that was distributed over the entire row while treatment 13, an NFOA treatment, received only 108 kg N ha^{-1} but was applied variably. At Efaw, the NFOA-treatments with 67 kg N ha^{-1} preplant had higher N uptake compared with the treatments that received a fixed rate of 134 kg N ha^{-1} (split, preplant or sidedress). However, this was not observed at LCB and Perkins. While treatment 4 recorded the highest grain N uptake for these two sites, the difference when compared with treatment 13 was minimal. At Perkins, treatment 4 had 93 kg N ha^{-1} while treatment 13 had 86 kg N ha^{-1}. Treatment 4 at LCB obtained 165 kg N ha^{-1} while a very close value of 162 kg N ha^{-1} was obtained by treatment 13.

The use of the RI-NFOA (treatment 13) resulted in higher grain N uptake when compared with RICV-NFOA (treatment 8) at Efaw and LCB but not at Perkins. Treatment 8 had grain N uptake values of 181, 138, and 87 kg N ha^{-1}

Table 9

Total nitrogen uptake in response to fixed and midseason-NFOA-based N rates at Efaw, Lake Carl Blackwell, and Perkins, 2004–2006

	N Applied		Efaw				Lake Carl Blackwell				Perkins			
TRT	Preplant	Midseason[¥]	2004	2005	2006	Avg.	2004	2005	2006	Avg.	2004	2005	2006	Avg.
		kg ha^{-1}						Total N Uptake, kg N ha^{-1}						
1	0	0	126	88	81	98	49	131	38	73	65	22	16	34
2	0	67	173	139	137	149	106	177	98	127	90	62	36	63
3	0	134	172	147	137	152	119	202	181	168	112	68	48	76
4	67	67	190	164	157	170	135	209	150	165	135	87	57	93
5	67	0	186	131	126	148	109	175	54	113	100	70	49	73
6	134	0	165	173	190	176	126	216	138	160	116	72	41	76
7	0	RICV-NFOA	160	133	108	134	97	158	93	116	101	63	51	72
8	67	RICV-NFOA	177	187	178	181	131	184	99	138	127	83	53	87
9	0	Flat-RICV-NFOA	179	135	142	152	101	150	93	115	105	43	39	62
10	67	Flat-RICV-NFOA	185	180	169	178	140	177	113	143	131	75	41	83
11	67	RICV-NFOA	185	176	172	178	140	187	78	135	139	77	41	86
12	0	RI-NFOA	167	145	124	145	101	187	143	144	93	57	36	62
13	67	RI-NFOA	222	186	193	200	128	218	139	162	130	85	44	86
Pr > F			0.11	0.01	0.01	—	0.01	0.02	0.01	—	0.01	0.01	0.03	—
SED			16	16	24	—	8	16	15	—	6	6	7	—
Avg.			176	153	147	158	114	182	109	135	111	66	42	73

TRT = Treatment number.

SED = Standard error of the difference between two equally replicated means.

[¥] Full description is presented in Table 2.

while treatment 13 had 200, 162, and 162 kg N ha^{-1} at Efaw, LCB and Perkins, respectively. Similar N uptake values were recorded for the two resolutions evaluated. Similarly, utilizing the average of the RICV-NFOA for uniform N rate applications (flat-RICV-NFOA) resulted in minimal differences in grain N uptake (Table 9).

Nitrogen Use Efficiency

On average by site, split applications of N resulted in minimal differences in NUE when compared with preplant and sidedress applications at LCB (Table 10). At the134 kg N ha^{-1} fixed rate, NUE values were 68, 69, and 63 for sidedress, split, and preplant applications, respectively. At Perkins, when N was split applied, a higher NUE difference (13%) was obtained when compared with preplant and sidedress applications. For Efaw, preplant N applications (58%) had a minimal advantage in NUE when compared with split N applications (54%). Efaw is a high yielding site compared with Perkins thus, preplant N was required for early growth establishment to meet the demand for N. Late applications of 134 kg N ha^{-1} (treatment 3) at V8 did not help the corn plant at Efaw to catch up which resulted in lower grain yields of 10.2 Mg ha^{-1} (Table 8) and lower N uptake of 152 kg N ha^{-1} (Table 9) when compared with split applications (11.1 Mg ha^{-1} grain yield and 170 kg ha^{-1} N uptake).

On average by site, the NFOA treatments with preplant N resulted in higher NUE values compared to 134 kg N ha^{-1} split applied. The highest NUE was obtained by treatment 13 (83%) at Efaw, treatment 13 (69%) at LCB, and treatment 11 (43%) at Perkins. Without preplant N, the RI-NFOA obtained the highest NUE of 83% at LCB while the RICV-NFOA at Perkins had the highest NUE at 59%. High NUEs were achieved with 2.32 m^2 resolution in higher yielding environment (Efaw, LCB), while 0.34 m^2 resolution improved NUE in low yielding environment and when spatial variability was pronounced (Perkins). The flat-RICV's NUE values were consistently lower than the RICV-NFOA's, however minimal differences were recorded at 2, 2, and 4% at Efaw, LCB, and Perkins, respectively.

At Perkins, the RICV-NFOA with preplant N resulted in the highest NUE value due to the lowest total N input. At LCB, the high NUE value of the RI-NFOA was attributed to a large reduction in total N applied and to high grain yields produced. The use of the RI-NFOA (with preplant N) resulted in the highest NUE among the treatments at LCB. The benefit of using the RI-NFOA in improving NUE was attributed to increased grain yield and N uptake, and reduced fertilizer N input.

Net Return to Nitrogen Fertilizer

Differences in net return means were significant ($Pr > 0.05$) among treatment at LCB in 2004 and 2005, and at Perkins in 2004 and 2005 (Table 11). At

Table 10
Nitrogen use efficiency in response to fixed and midseason-NFOA-based N rates at Efaw, Lake Carl Blackwell, and Perkins, 2004–2006

	N Applied		Efaw				Lake Carl Blackwell				Perkins			
TRT	Preplant	Midseason¥	2004	2005	2006	Avg.	2004	2005	2006	Avg.	2004	2005	2006	Avg.
	kg ha^{-1}		Nitrogen Use Efficiency§, %											
1	0	0	—	—	—	—	—	—	—	—	—	—	—	—
2	0	67	71	69	67	69	86	52	88	75	38	60	30	43
3	0	134	35	44	43	41	53	53	98	68	35	34	24	31
4	67	67	48	57	57	54	65	57	84	69	52	49	30	44
5	67	0	64	52	58	58	89	65	26	60	52	71	50	58
6	134	0	30	63	81	58	57	63	70	63	38	38	18	31
7	0	RICV-NFOA	32	50	58	47	60	33	84	59	45	86	46	59
8	67	RICV-NFOA	31	52	73	52	55	58	63	59	37	42	32	37
9	0	Flat-RICV-NFOA	50	51	68	56	67	33	86	62	51	49	32	44
10	67	Flat-RICV-NFOA	35	49	66	50	60	40	69	57	39	37	22	33
11	67	RICV-NFOA	35	46	72	51	59	76	47	60	42	56	25	41
12	0	RI-NFOA	79	73	79	77	96	57	98	83	40	53	35	43
13	67	RI-NFOA	77	74	98	83	68	50	88	69	43	42	31	39
Pr > F			0.04	0.73	0.60	—	0.01	0.60	0.06	—	0.69	0.01	0.29	—
SED			12	17	20	—	6	21	16.2	—	12	8	8.6	—
Avg.			49	57	68	58	68	53	75	65	43	52	31	42

TRT = Treatment number.

§Estimated by subtracting the grain N uptake of the check plot from the fertilized plot, divided by the N rate applied.

SED = Standard error of the difference between two equally replicated means.

¥Full description is presented in Table 2.

Table 11
Net return to nitrogen fertilizer at Efaw, Lake Carl Blackwell, and Perkins, 2004–2006

	N Applied		Efaw				Lake Carl Blackwell				Perkins			
TRT	Preplant	Midseason[¥]	2004	2005	2006	Avg.	2004	2005	2006	Avg.	2004	2005	2006	Avg.
	kg ha^{-1}		Net Return to N Fertilizer[‡], \$ ha^{-1}											
1	0	0	—	—	—	—	—	—	—	—	—	—	—	—
2	0	67	321	300	110	369	324	217	178	291	461	356	82	124
3	0	134	149	220	102	261	299	299	99	397	335	671	106	102
4	67	67	310	389	262	353	313	340	245	425	436	548	159	222
5	67	0	248	331	187	268	250	246	260	223	305	91	191	213
6	134	0	298	289	186	457	409	337	145	366	663	470	58	130
7	0	RICV-NFOA	103	153	125	138	164	177	195	220	146	329	191	170
8	67	RICV-NFOA	338	274	157	472	439	245	218	283	639	331	141	172
9	0	Flat-RICV-NFOA	332	198	122	337	245	92	116	210	432	340	88	109
10	67	Flat-RICV-NFOA	283	360	175	403	390	241	206	331	535	393	56	146
11	67	RICV-NFOA	284	350	209	391	376	310	227	289	512	208	82	173
12	0	RI-NFOA	316	237	96	371	341	322	110	370	456	550	84	97
13	67	RI-NFOA	389	352	219	561	522	337	192	403	772	519	113	175
Pr > F			0.3778	0.1840	0.2031	—	0.03	0.2649	0.015	—	0.0148	0.0211	0.6499	—
SED			76	105	206	—	47	138	136	—	65	34	58	—
Avg.			281	339	474	365	288	264	401	317	163	183	113	153

[‡] Determined by subtracting the cost of fertilizer from the gross income (grain yield due to N fertilizer application × price per unit grain).

[¥] Full description is presented in Table 2.

TRT = Treatment number.

SED = Standard error of the difference between two equally replicated means.

Perkins, the response to N was masked by the more limiting effect of moisture stress and thus no significant differences ($Pr > 0.05$) in grain yields among treatments were recorded (Table 8) causing treatments to obtain comparable gross incomes. Further, the savings from lower fertilizer N rates used in some of the treatments did not compensate for the slight reduction in grain yield resulting in no significant differences in net returns to N fertilizer.

On average by site, both fixed and NFOA-based N rates with preplant obtained consistently higher net returns than treatments without preplant N. The highest net return obtained was 561 \$ ha^{-1} at EFAW, achieved when midseason N rates were based on the RI-NFOA. The RICV-NFOA net return was second highest with 472 \$ ha^{-1}. At LCB, a fixed rate of 134 kg N ha^{-1} split applied obtained the highest net return of 425 \$ ha^{-1}. The RI-NFOA's net return of 403 \$ ha^{-1} was within the upper end but not the RICV-NFOA which achieved only 283 \$ ha^{-1} without preplant and 220 \$ ha^{-1} with preplant N. At Perkins, 134 kg N ha^{-1} applied in split obtained the highest net return of 222 \$ ha^{-1} followed by the 67 kg N ha^{-1} rate preplant applied (213 \$ ha^{-1}). Both the RI- and RICV-NFOA with preplant achieved net returns that were within the upper end group amounting to 175 and 172 \$ ha^{-1}, respectively.

With preplant N, treating plots at the 0.34 m^2 resolution resulted in higher net returns at Efaw (472 versus 391 \$ ha^{-1}) than when using the 2.32 m^2 resolution. However at LCB and Perkins, the net return obtained was slightly higher at the 2.32 m^2 than 0.34 m^2 resolution. The flat-RICV's net return did not record consistent trends across site years and the highest deviation from the RICV-NFOA's net income was 53 \$ ha^{-1}.

DISCUSSION

Teal et al. (2006a) reported that NDVI and its derived indices can be used to estimate corn YP_0 when sensing is accomplished between V7–V9 leaf growth stages. They reported that NDVI measured at V8 was highly correlated with actual grain yield ($r^2 = 0.77$). Further, a strong relationship existed between the DFP INSEY and the actual grain yield ($r^2 = 0.74$). The concept of using the demand for N of the projected YP_0 to estimate crop N requirements is a better option than applying fixed N rates every cropping season. Unless drastic changes in growth conditions occurred after sensing, the YP_0 equation obtained reasonable estimates of actual grain yield. This implies that INSEY, an estimate of biomass produced per day, works but needs to be more robust i.e., should be accompanied by more risk averse prediction models. Crop response to N application as estimated by the RI was adjusted using the equation of the linear relationship between RI_{NDVI} and $RI_{HARVEST}$. The adjustment made on RI resulted in good estimates of corn response to N fertilization for most site years, especially at LCB, an irrigated site, where growth conditions were near ideal.

The RI_{NDVI} overestimated crop response to N when adverse growth condition occurred after sensing that masked the effect of N to crop growth as exemplified at Perkins.

Total N applied to NFOA treatments were highly varied ranging from 31 to 168 kg N ha^{-1}. It is important to take note that extremely low N rates projected by the NFOA did not result in a drastic reduction of grain yields. While in some site years NFOA treatments had lower yields than the fixed-rate treatments, decreased N rates resulted in a higher NUE. Further, the lower N rates translated in large savings outweighed the benefit of increased grain yield of plots applied with the 134 kg N ha^{-1} fixed rate. In addition to a considerable reduction in input cost due to lower N rates applied, grain yield of the NFOA-based approach with preplant N (67 kg N ha^{-1}) in some site years exceeded the grain yield of the 134 kg N ha^{-1} fixed rate split applied. This demonstrates that the NFOA approach is very promising in terms of increasing crop producers' income.

Incorporation of CV component allows the algorithm to take into account field spatial variability and helps determine if there is a need to adjust N rates depending on plant-stand densities, such that a good homogenous stand would receive more N fertilizer than a poor plant stand. While this trend was demonstrated based on the total N applied in the RICV- and RI-NFOA plots, the expected benefits in grain yield, NUE and net return were not exhibited by the RICV-NFOA at high yielding site years. Likewise, while the RI-NFOA approach excelled at high yielding site years, it was limited by adverse growth conditions occurred from sensing to harvest whereas the RICV-NFOA performed better in terms of improving NUE. These observations imply that a) the use YP_0 and adjusted RI_{NDVI} as components of the algorithm can improve NUE and net returns to N fertilizer attributed either to increased grain yield and/or large savings due to lower N rates applied provided that the crop is under near ideal growing conditions, b) CV components will play an important role in improving the algorithm especially in fields with pronounced spatial variability brought about by unfavorable growth conditions, and c) CV component requires improved mathematical adjustment to work in well established, homogenous crop stands.

There was no pronounced trend between the two resolutions tested (0.34 and 2.32 m^2) when comparing grain yields, NUE, and net returns to N fertilizer. Moreover, the flat-RICV-NFOA showed comparable grain yields, NUE and net returns with the RICV-NFOA's. These results suggest that the RICV-NFOA recommendation from a good representative area of a farmer's field thus far can be used to make uniform recommendation for an entire field. While the algorithm recommends uniform rates, this approach still encumbers the N demand based on predicted YP_0, field spatial variability, and the seasonally dependent crop responsiveness to applied N. This is very important in fields where variable rate application is not feasible.

CONCLUSIONS

This study demonstrated the benefit of applying N fertilizer on a need-basis over uniform applications of N based on historical crop information. With modest amounts of preplant N, midseason RI-NFOA-based N recommendations improved NUE to 65% compared with 56% of the 134 kg N ha^{-1} fixed rate split applied. The use of the RI-NFOA improved grain yields in four of six high yielding site years and net returns in three of six high yielding site years. At Perkins (low yielding site), the 134 kg N ha^{-1} fixed rate split applied obtained the highest grain yield and net return followed by the RI-NFOA's. The RICV-NFOA without preplant N showed an advantage over RI-NFOA in improving NUE when field variation became pronounced as a result of unfavorable growth conditions. Without preplant N in low yielding site years, the RICV-NFOA had a higher NUE (59% versus 43%) and net return (170 versus 97 \$ ha^{-1}) compared with the RI-NFOA's. With preplant N on the other hand, NUE and net returns of the RICV- and RI-NFOA were comparable. The increase in NUE can be attributed to reductions in N fertilizer input recommended by the RICV-NFOA. The use of midseason sensor-based predictions of YP_0 and RI_{NDVI} provided accurate N rate recommendations when compared with flat rates.

REFERENCES

Aparicio, N., D. Villegas, J. Casadesus, J. L. Araus, and C. Royo. 2000. Spectral vegetation indices as nondestructive tools for determining durum wheat yield. *Agronomy Journal* 92: 83–91.

Arnall, D. B., W. R. Raun, J. B. Solie, M. L. Stone, G. V. Johnson, K. Girma, K. W. Freeman, R. K. Teal, and K. L. Martin. 2006. Relationship between coefficient of variation measured by spectral reflectance and plant density at early growth stages in winter wheat. *Journal of Plant Nutrition* 29: 1983–1997.

Baethgen, W. E., and M. M. Alley. 1989. Optimizing soil and fertility nitrogen use for intensively managed winter wheat. II. Critical levels and optimum N fertilizer rates. *Agronomy Journal* 81: 120–125.

Baez-Gonzalez, A. D., P. Chen, M. Tiscareño-Lopez, and R. Srinivasan. 2002. Using satellite and field data with crop growth modeling to monitor and estimate maize yield in Mexico. *Crop Science* 42: 1943–1949.

Below, F. E., P. S. Brandau, and D. G. Bullock. 1992. Optimizing nitrogen management for corn production in Illinois. In: *Illinois Fertilizer Conference Proceedings, Urbana-Champaign, IL: University of Illinois, Urbana-Champaign, IL, 27–29 January.*

Blackmer, T. M., and J. S. Schepers. 1996. Aerial photography to detect nitrogen stress in corn. *J. Plant Physiol.* 148:440–444.

Blackmer, T. M., J. S. Schepers, and G. E. Varvel. 1994. Light reflectance compared with other nitrogen stress measurements in corn leaves. *Agronomy Journal* 86: 934–938.

Boman, R. K., R. L. Westerman, W. R. Raun, and M. E. Jojola. 1995. Spring-applied nitrogen fertilizer influence on winter wheat and residual soil nitrate. *Journal of Production Agriculture* 8: 584–589.

Bronson K. F., T. T. Chua, J. D. Booker, J. W. Keeling, and R. J. Lascano. 2003. In-season nitrogen status sensing in irrigated corn. II. Leaf nitrogen and biomass. *Soil Science Society of America Journal* 67: 1439–1448.

Casanova, D., G. F. Epema, and J. Goudriana. 1998. Monitoring rice reflectance at field level for estimating biomass and LAI. *Field Crops Research* 55: 83–92.

Cassman, K. G., D. C. Bryant, A. E. Fulton, and L. F. Jackson. 1992. Nitrogen supply effects on partitioning of dry matter and nitrogen to grain of irrigated wheat. *Crop Science* 32: 1252–1258.

Dahnke, W. C., L. J. Swenson, R. J. Goos, and A. G. Leholm. 1988. *Choosing a crop yield goal. SF-822*. Fargo, ND: N. Dakota State Ext. Serv.

David, M. B., L. E. Gentry, D. A. Kovacic, and K. M. Smith. 1997. Nitrogen balance in and export from an agricultural watershed. *Journal of Environmental Quality* 26: 1038–1048.

Dinnes, D. L., D. L. Karlen, D. B. Jaynes, T. C. Kaspar, J. L. Hatfield, T. S. Colvin, and C. A. Cambardella. 2002. Nitrogen management strategies to reduce NO_3 leaching in the tile-drained Midwestern soils. *Agronomy Journal* 94: 153–171.

Fageria, N. K., and V. C. Baligar. 2005. Enhancing nitrogen use efficiency in crop plants. *Advances in Agronomy* 88: 97–185.

Felton, W. L., C. L. Alston, B. M. Haigh, P. G. Nash, G. A. Wicks, and G. E. Hanson. 2002. Using reflectance sensors in agronomy and weed science. *Weed Technology* 16: 520–527.

Ferguson, R. B., G. W. Hergert, J. S. Schepers, C. A. Gotway, J. E. Cahoon, and T. A. Peterson. 2002. Site-specific nitrogen management of irrigated maize: Yield and soil residual nitrate effects. *Soil Science Society of America Journal* 66: 544–553.

Goolsby, D. A., W. A. Battaglin, G. B. Lawrence, R. S. Artz, B. T. Aulenbach, R. P. Hooper, D. R. Keeney, and G. J. Stensland. 1999. Flux and sources of nutrients in the Mississippi-Atchafalaya River Basin—topic 3 report for the integrated assessment on hypoxia in the Gulf of Mexico. In: *NOAA Coastal Ocean Program Decision Analysis Series No. 17*, p. 130. Silver Spring, MD: NOAA Coastal Ocean Office.

Hornung, A., R. Khosla, R. Reich, and D. G. Westfall. 2003. Evaluation of site-specific management zones: Grain yield and nitrogen use efficiency.

In: *Precision Agriculture. Proceedings of the Fourth European Conference, Berlin, 15–19 June*, eds. J. Stafford and A. Werner. The Netherlands: Waginen Academic Publishers.

Huggins D. R., and W. L. Pan. 1993. Nitrogen use efficiency component analysis: An evaluation of cropping system differences in productivity. *Agronomy Journal* 85: 898–905.

Jaynes, D. B., J. L. Hatfield, and D. W. Meek. 1999. Water quality in Walnut Creek watershed: Herbicides and nitrate in surface waters. *Journal of Environmental Quality* 28: 45–59.

Johnson, G. V. 1991. General model for predicting crop response to fertilizer. *Agronomy Journal* 83: 367–373.

Johnson, G. V., and W. R. Raun. 1995. Nitrate leaching in continuous winter wheat: Use of soil-plant buffering concept to account for fertilizer nitrogen. *Journal of Production Agriculture* 8: 486–491.

Johnson, G. V., W. R. Raun, H. Zhang, and J. A. Hattey. 1997. *Soil Fertility Handbook*. Stillwater, OK: Okla. Agric. Exp. Stn.

Kanampiu, F. K., W. R. Raun, and G. V. Johnson. 1997. Effect of nitrogen rate on plant nitrogen loss in winter wheat varieties. *Journal of Plant Nutrition* 20: 389–404.

Khosla, R. and M. M. Alley. 1999. Soil-specific nitrogen management on Mid-Atlantic Coastal Plain soils. *Better Crops* 83: 6–7.

Khosla, R., K. Fleming, J. A. Delgado, T. Shaver, and D. G. Westfall. 2002. Use of site specific management zones to improve nitrogen management for precision agriculture. *Journal of Soil and Water Conservation* 57: 515–518.

Kleman, J., and E. Fagerlund. 1987. Influence of different nitrogen and irrigation treatments on the spectral reflectance of barley. *Remote Sensing of Environment* 21: 1–14.

Koch, B., R. Khosla, M. Frasier, D.G. Westfall, and D. Inman. 2004. Economic feasibility of variable rate nitrogen application utilizing site-specific management zones. *Agronomy Journal* 96: 1572–1580.

Large, E. C. 1954. Growth stages in cereals: Illustration of the Feekes scale. *Plant Pathology* 3: 128–129.

Ma, B. L., L. M. Lianne, M. Dwyer, C. Costa, E. R. Cober, and M. J. Morrison. 2001. Early prediction of soybean yield from canopy reflectance measurements. *Agronomy Journal* 93: 1227–1234.

Magdoff, F. 1991. Understanding the Magdoff pre-sidedress nitrate test for corn. *Journal of Production Agriculture* 4: 297–305.

Martin, K. L., K. Girma, K. W. Freeman, R. K. Teal, B. Tubana, D. B. Arnall, B. Chung, O. Walsh, J. B. Solie, M. L. Stone, and W. R. Raun. 2006. Expression of variability in corn as influenced by growth stage using optical sensor measurements. *Agronomy Journal* 99: 384–389.

Mitchell, J. K., G. F. McIsaac, S. E. Walker, and M. C. Hirschi. 2000. Nitrate in river and subsurface drainage flows from an east-central Illinois watershed.

Transactions of the American Society of Agricultural Engineers 43: 337–342.

Moran, M. S., Y. Inoue, and E. M. Barnes. 1997. Opportunities and limitations for image-based remote sensing in precision crop management. *Remote Sensing of Environment* 61: 319–346.

Mulla, D. J., and A. U. Bhatti. 1997. An evaluation of indicator properties affecting spatial patterns in N and P requirements for winter wheat yield. In: *Precision Agriculture 1997 First European Conference Proceedings on Agriculture*, Warwick, 7–10 September 1997, ed. J. V. Stafford, pp. 145–53. Warwick, England: Warwick University.

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. *Agronomy Journal* 95: 347–351.

Peñuelas, J., J. A. Gamon, A. L. Fredeen, J. Merino, and C. B. Field. 1994. Reflectance indices associated with physiological changes in nitrogen- and water-limited sunflower leaves. *Remote Sensing of Environment* 48: 135–146.

Rabalais, N. N., R. E. Turner, D. Justić, Q. Dortch, W. J. Wiseman, Jr., and B. K. Sen Gupta. 1996. Nutrient changes in the Mississippi River and system responses on the adjacent continental shelf. *Estuaries* 19: 386–407.

Raun, W. R., J. B. Solie, G. V. Johnson, M. L. Stone, E. V. Lukina, W. E. Thomason, and J. S. Schepers. 2001. In-season prediction of potential grain yield in winter wheat using canopy reflectance. *Agronomy Journal* 93: 131–138.

Raun, W. R., J. B. Solie, G. V. Johnson, M. L. Stone, R. W. Mullen, K. W. Freeman, W. E. Thomason, and E. V. Lukina. 2002. Improving nitrogen use efficiency in cereal grain production with optical sensing and variable rate application. *Agronomy Journal* 94: 815–820.

Raun, W. R., J. B. Solie, M. L. Stone, K. L. Martin, K. W. Freeman, R. W. Mullen, H. Zhang, J. S. Schepers, and G. V. Johnson. 2005. Optical sensor-based algorithm for crop nitrogen fertilization. *Communications in Soil Science and Plant Analysis* 36: 2759–2781.

Rouse, J. W., Jr., R. H. Has, J. A. Schell, and D. W. Deering. 1973. Monitoring vegetation systems in the Great Plains with ERTS. *ERTS Symp. 3rd, Washington, DC. 10–14 December, 1972. NASA SP-351*. Vol. I: 309–317. Washington, DC: NASA.

SAS Institute. 2002. The SAS system for windows. Version 8.0. Cary, NC: SAS Institute.

Schepers, J. S., D. D. Francis, and M. T. Thompson. 1989. Simultaneous determination of total C, total N, and ^{15}N on soil and plant material. *Communications in Soil Science and Plant Analysis* 20: 949–959.

Schmitt, M. A., G. W. Randall, and G. W. Rehm. 1998. A soil nitrogen test option for N recommendations with corn. *FO-06514-GO*. St. Paul, MN: Univ. of Minnesota Ext. Serv.

Sowers, K. E., W. L. Pan, B. C. Miller, and J. L. Smith. 1994. Nitrogen use efficiency of split nitrogen applications in soft white winter wheat. *Agronomy Journal* 86: 942–948.

Spruill, T. B., J. L. Eimers, and A. E. Morey. 1996. Nitrate-nitrogen concentrations in shallow ground water of the Coastal Plain of the Albemarle–Pamlico Drainage Study Unit, North Carolina and Virginia. *U.S. Geol. Surv. Fact Sheet FS-241–96*. Reston, VA: USGS.

Stone, M. L., J. B. Solie, W. R. Raun, R. W. Whitney, S. L. Taylor, and J. D. Ringer. 1996. Use of spectral radiance for correcting in-season fertilizer nitrogen deficiencies in winter wheat. *Transactions American Society of Agricultural Engineers* 39: 1623–1631.

Teal, R. K., B. Tubana, K. Girma, K. W. Freeman, D. B. Arnall, O. Walsh, and W. R. Raun. 2006a. In-season prediction of corn grain yield potential using normalized difference vegetation index. *Agronomy Journal* 98: 1488–1494.

Teal, R. K., K. Girma, K. W. Freeman, K. L. Martin, D. B. Arnall, J. W. Lawles, and W. R. Raun. 2006b. Influence of hybrid, population, and nitrogen rate on spectral prediction of corn grain yield. In review.

Thenkabail, P. S., R. B. Smith, and E. DePauw. 2000. Hyperspectral vegetation indices and their relationships with agricultural crop characteristics. *Remote Sensing of Environment* 71: 158–182.

Tyner, E. H., and J. W. Webb. 1946. The relation of corn yields to nutrient balance as revealed by leaf analysis. *Journal of the American Society of Agronomy* 38: 173–185.

United States Department of Energy. 2005. Impact of high natural gas prices on the U.S. nitrogen industry. [Online]. Available at http://www.international.energy.gov/epact/Section_1818/The_Fertilizer_Institute_(2)_present_12-.pdf. (Retrieved April 4, 2007).

United States Department of Agriculture National Agricultural Statistic Service(USDA NASS). 2007. [Online]. Available at www.nass.usda/gov. (Retrieved: April 6, 2007).

United State Grain Council. 2003. World corn production and trade. [Online]. Available at http://www.grains.org/grains/corn.html (retrieved October 28, 2004).

Varvel, G. E., J. S. Schepers, and D. D. Francis. 1997. Ability for in-season correction of nitrogen deficiency in corn using chlorophyll meters. *Soil Science Society of America Journal* 61: 1233–1239.

Vyn T. J., K. J. Janovicek, M. H. Miller, and E. G. Beauchamp. 1999. Spring soil nitrate accumulation and corn yield response to preceding small grain N fertilization and cover crops. *Agronomy Journal* 91: 17–24.

Walburg, G., M. E. Bauer, C. S. T. Daughtry, and T. L. Housley. 1982. Effects of nitrogen nutrition on the growth, yield and reflectance characteristics of corn canopies. *Agronomy Journal* 74: 677–683.

Wanjura, D. F., and J. L. Hatfield. 1987. Sensitivity of spectral vegetative indices to crop biomass. *Transactions American Society of Agricultural Engineers* 30: 810–816.

Westerman, R. L., R. K. Boman, W. R. Raun, and G. V. Johnson. 1994. Ammonium and nitrate nitrogen in soil profiles of long-term winter wheat fertilization experiments. *Agronomy Journal* 86: 94–99.