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ABSTRACT

This study was conducted to determine the scale at which spatial variability should be treated using an in-season nitrogen fertilization optimization algorithm (NFOA). Treatments included variable nitrogen (N) rate applications at three resolutions (0.84, 13.4, and 26.8 m^2), two treatments of 90 kg N ha^{-1} fixed rate applied preplant or midseason, and a check plot. Treatments were arranged in a completely randomized design with three replications established at two locations for three years. On average, the NFOA-based N rates achieved a higher N use efficiency (NUE) of 41% compared with only 33% of the 90 kg N ha^{-1} fixed rate applied midseason. The highest NUE among the NFOA-based N rate treatments was 56% at 13.4 m^2 resolution. These benefits were attributed to a large reduction in NFOA-based N rate recommendations. Determining midseason N rate requirements using NFOA at 13.4 m^2 resolution resulted in increased NUE and net return to N fertilizer.

Keywords: yield potential, nitrogen fertilization optimization algorithm, resolution, spatial variability, nitrogen use efficiency

INTRODUCTION

Liberal applications of nitrogen (N) fertilizer in crop production has led to the reduction of farmers' revenues and increased human health and environmental risks. Current worldwide N use efficiency (NUE; increased grain N uptake per

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unit of N applied) in cereal grains averages only 33% and the unaccounted 67% of applied N is lost via gaseous plant emissions, soil denitrification, surface runoff, volatilization, and leaching (Raun and Johnson, 1999). Conventional N fertilization based on soil testing of representative samples from large farm areas is at fixed rates and usually applied before crop establishment. Due to spatial variability in the field, single rates may estimate N requirements far from the actual values needed to achieve a target yield goal which may result in excess or under application of N at certain locations in the field. Moreover, N in the soil changes with time as environmental conditions highly influence mineralization and immobilization, the predominance of one process over the other determines the level of available N for plant use.

To meet the demand of the projected 7.5 billion world population in 2020 (FAO, 2004), wheat (*Triticum aestivum* L.) production needs to increase beyond the current yield level of 556 million tons (FAO, 2003) by 40% (Rosegrant et al., 1997). Since the potential of the Green Revolution has been exhausted and there is a continuous decline in arable land, future gains in wheat production and revenues will have to come from increased productivity at reduced inputs.

Farmers often apply N fertilizer in excess to avoid deficiency of crop requirements. According to the FAO (2005), the present total consumption of nitrogenous fertilizer in the world is estimated to be 85.1 Mt N yr^{-1}. For the past 34 years, agricultural food production was doubled due to a 6.87-fold increase in N fertilization (Tilman, 1999). Improper N fertilizer management has resulted in greater use of energy resources, increased production costs, and increased environmental and human risks (Sharpe et al., 1988). Rabalais et al. (2001) reported that excessive N fertilizer application has exacerbated hypoxia within the Gulf of Mexico. Moreover, high N rates may result in poor N uptake and thus decreased N use efficiency (NUE) (Sowers et al., 1994). The benefits of increasing NUE includes increased profit by reducing N fertilizer inputs and reduction of environmental and human health risks associated with nitrate contamination (Huggins and Pan, 1993).

Several studies were conducted to develop management systems that would increase NUE. Proper timing of application and adequate N rates are important considerations to provide crop requirements and can therefore improve NUE. Wheat farmers in the Great Plains typically apply fertilizer N either one-time before planting, or split in small amounts before planting followed by a late-winter or early spring topdressing (Kelley, 1995). Similarly, Cassman et al. (1992) showed that preplant and in-season N fertilizer management improved both yield and protein content of wheat. Split applications maximize crop utilization of applied fertilizer N throughout the growing season (Mascagni and Sabbe, 1991; Boman et al., 1995) by supplying N when it is needed for plant growth and development. Late-season applied N allows the farmers to adjust N rates according to crop needs and may also reduce potential N losses from leaching and denitrification over the winter. Further, many researchers have found that one-time, large preplant applications of N fertilizer may lead to decreased NUE due to losses or immobilization before plant uptake (Welch et al., 1996; Olson and Swallow, 1984; Lutcher and Mahler, 1988; Fowler and Brydon, 1989; Wuest and Cassman, 1992). While multiple late-season N applications is an effective way to increase NUE, the common method of using surface soil testing for adjusting N rates before planting is not suited for detecting late-season deficiency. In addition, environmental factors such as soil temperature and moisture affect N cycling, transformation, and movement, which complicate the present N status monitoring of the crop.

Remote sensing could provide an inexpensive, non-destructive, and rapid assessment of crop N status in the field (Filella et al., 1995). Several studies used remotely sensed spectral measurements to evaluate 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; Stone et al., 1996a; Bronson et al., 2003). Some researchers used spectral data to estimate crop yields using simple regression equations (Moran et al., 1997; Raun et al., 2001). Normalized Difference Vegetation Index (NDVI; Rouse et al., 1973) is one of the spectral vegetation indices used to assess plant health and is determined by dividing the difference in the reflectance in the red (670 nm) and near infrared (NIR; 780 nm) by the sum of reflectance at these two wavebands (Tucker, 1979). The NDVI was found to be a useful index to estimate crop yield of wheat (Colwell et al., 1977; Tucker et al., 1980; Pinter et al., 1981), millet, and sorghum (Bartholome, 1988). Stone et al. (1996a) and Solie et al. (1996) reported that NDVI can reliably predict both biomass and N uptake in winter wheat when measurements were done between Feekes physiological growth stages 4 and 5. Similarly, Lukina et al. (1999) were able to show high correlations between percentage of soil coverage by wheat and NDVI at these growth stages. At Feekes growth stage 5, Reeves et al. (1993) used direct in-season measurements of total N uptake in winter wheat.

Raun et al. (2002) utilized NDVI-derived in-season estimated yield (INSEY), biomass produced per day, to project midseason N rate requirements in wheat. Compared with the midseason flat rate of 45 kg N ha^{-1}, NUE was increased by $>15\%$ when midseason N fertilization was based on INSEY. In 2005, Raun et al. (2005) proposed the use of an nitrogen fertilization optimization algorithm (NFOA) consisting of the following components: 1) INSEY, NDVI measured at Feekes growth stage 5 divided by the number of positive growing degree days or $\mathrm{GDD} = \left(\frac{T_{max}+T_{min}}{2}\right) - 4.4°\mathrm{C}$, 2) responsiveness of the wheat crop to N fertilizer that can be estimated by the ratio of NDVI readings in non-limiting N strips and NDVI readings in the farmer practice, and 3) spatial variability using the coefficient of variations (CV) from NDVI readings. The addition of CV in the algorithm is important especially in areas where spatial variability becomes significant enough to reduce crop yields. Arnall et al. (2006) reported that when CVs from NDVI readings were greater than 20%, plant stands were likely <100 plants m^{-2} and as such considered poor. Further, Morris et al. (2005) noted that maximum yields could be achieved, even when N fertilization was delayed until midseason when plot CVs were less than 18%.

The relationship established between NDVI measurements and biomass production was used to develop the technology that employs real-time optical sensing to predict the yield potential (YP_0) of a crop and to variably apply N fertilizer based on the predicted yield (Stone et al., 1996a, 1996b). The optical sensor-based variable rate technology developed at Oklahoma State University can sense submeter-variability on-the-go while variably apply N fertilizer based on plant needs. Various research programs have noted that spatially variable N fertilizer applications may reduce adverse environmental impacts and increase economic returns (Fiez et al., 1995). To effectively use this technology, sensing and treatment applications should be done at the finest resolution at which variation occurs, such that if management practices are employed at this resolution, a positive impact on production and profit will be achieved. Some studies reported that significant differences in soil and plant variables occur within a sampling distance as short as 0.3 m (Raun et al., 1998) and less than 1.96 m^2 (Solie et al., 1996). LaRuffa et al. (2001) demonstrated that in a high yielding environment producing >2300 kg ha^{-1} grain, treating the variation at finer resolutions tended to increase NUE. Recent work by Raun et al. (2002) has shown that the present NUE was increased by 15% when N fertilization was based on optically sensed INSEY and response index (RI), an estimate of crop response to N fertilizer. This study was conducted to determine at which scale spatial variability should be treated using the current in-season NFOA, and to determine the benefits of treating variability at different resolutions.

MATERIALS AND METHODS

Field experiments were established in Chickasha and Tipton, Oklahoma in September and October 2003, respectively. In the 2005–06 cropping season, no trial was conducted at Tipton but an additional site was established at the Lake Carl Blackwell (LCB) Irrigated Research Station. Before treatment application, composite soil samples were taken from the entire site at 0–15 cm depth, air-dried, processed and analyzed for pH, ammonium (NH_4)-N, nitrate (NO_3)-N, Mehlich-III extractable phosphorus (P), and exchangeable potassium (K). Soil classifications for all sites and results of the soil analyses are presented in Table 1.

Variable N rates were applied at three resolutions (0.84, 13.4 and 26.8 m^2), and two N application methods (preplant and midseason) at a fixed rate of 90 kg N ha^{-1}, and a check plot were laid-out in a completely randomized design (CRD) with three replications (Table 2). Field activities and cropping information from 2003 to 2006 are detailed in Table 3. Each plot, measuring 3.7×7.3 m, was divided into subplots using the different resolutions mentioned. The resolutions were made by creating subplots with dimensions of

Table 1
Classification and initial chemical properties of soils (0–15 cm) collected from resolution trials at three locations, Oklahoma

Site	Series	Classification	pH	NH_4-N	NO_3-N	P	K
				mg kg^{-1}			
Chickasha	Dale silt loam	fine-silty, mixed, superactive, thermic Pachic Haplustoll	6.3	7.2	30	46	230
Tipton	Tillman-Hollister clay loam	fine, mixed, thermic Pachic Arguistolls	7.0	7.7	1	12	21
LCB	Pulaski fine sandy loam	coarse-loamy, mixed, superactive, nonacid, thermic Typic Ustifluvent	6.4	9.6	13	15	150

pH–1:1 soil:water; K and P–Mehlich III; NH_4-N and NO_3-N–2 M KCl.

0.91 × 0.91 m, 3.7 × 3.7 m, and 3.7 × 7.3 m for 0.84, 13.4 and 26.8 m^2 whole plots, respectively.

Midseason N application for plots using the NFOA approach at different resolutions required NDVI measurements, CVs from the NDVI readings, and number of days where GDD > 0 (Table 3) collected at Feekes growth stage 5 (Pseudo-stem strongly erected) (Large, 1954). The GreenSeeker™ Hand Held Optical Sensor (NTech Industries, Inc., Ukiah, California) was used to measure canopy reflectance and to collect NDVI readings based on a unit view of 0.6

Table 2
Treatment structure and description of resolution trials at three sites in Oklahoma, 2004–2006

No.	Treatment Code	N Rate, kg ha^{-1}	Method	Resolution, m^2
1	Check	0	Check	—
2	Preplant-90	90	Preplant	—
3	Mid-90	90	Topdress	—
4	Mid-NFOA-0.84 m^2	*	Midseason NFOA	0.84
5	Mid-NFOA-13.4 m^2	*	Midseason NFOA	13.4
6	Mid-NFOA-26.8 m^2	*	Midseason NFOA	26.8

*Rates were determined based on Nitrogen Fertilization Optimization Algorithm (NFOA).

Table 3
Field activities for all sites and years, 2003–2006

Site	Cropping season	Variety	Seeding rate kg ha^{-1}	Date‡				Number of GDD * > 0
				Planting	Sensing	TD† Application	Harvest	
Chickasha	2003-04	OK102	90	09-30-03	03-17-04	03-17-04	06-03-04	111
	2004-05	2174	134	10-05-04	03-07-05	03-07-05	06-21-05	112
	2005-06	Endurance	90	10-05-05	03-27-06	03-27-06	06-09-06	120
Tipton	2003-04	2158	80	11-07-03	03-11-04	03-16-04	05-27-04	127
	2004-05	Cutter	80	09-30-04	02-28-05	03-03-05	06-14-05	119
LCB	2005-06	Fannin	97	10-13-05	03-13-06	03-14-06	06-15-06	106

Lake Carl Blackwell

‡Date in month-day-year.

†Topdress application date for treatments 3, 4, 5 and 6.

Sensing accomplished at Feekes growth stage 5 (Pseudo-stem strongly erected) (Large, 1954).

*Growing degree days computed as $GDD = \frac{T_{max}+T_{min}}{2} - 4.4^{\circ}C$

$\times$ 0.01 m area held at a distance of 0.6 to 1.0 m from the crop canopy. The sensor measures red (671 $\pm$ 10 nm) and NIR (780 $\pm$ 10 nm) reflectance and calculates NDVI using the equation:

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

where:

ρ_{NIR} = fraction of emitted NIR radiation returned from the sensed area
ρRed = fraction of emitted red radiation returned from the sensed area.

The optical sensor was also used to obtain non-destructive CV measurements from the NDVI readings for each subplot sensed.

The index INSEY was calculated by dividing NDVI by the number of days from planting to sensing where GDD > 0. The NDVI-derived-INSEY is an index that predicts biomass produced on a daily basis and can be used to predict $\mathrm{YP_0}$ using the current algorithm for wheat (Raun et al., 2002). Yield potential when N is applied ($\mathrm{YP_N}$) was determined by multiplying $\mathrm{YP_0}$ with the response index ($\mathrm{RI_{NDVI}}$). The $\mathrm{RI_{NDVI}}$ was determined by dividing the average NDVI from plots with the highest N applied by the NDVI average of check plots (0 N rate). The collected CV was used to adjust N rate recommendations. The N rate required to achieve $\mathrm{YP_N}$ for each subplot of the resolutions tested was computed using the equation (Raun et al., 2005):

$$\mathrm{R_n} = \frac{\mathrm{YP_o N_g}}{\epsilon_{\mathrm{n}}}(\mathrm{RI} - 1)\left(\frac{(\mathrm{CV_{Cap}} - \mathrm{CV_{Plot}})}{(\mathrm{CV_{Cap}} - \mathrm{CV_{Critical}})}\right)$$

where:

$\mathrm{R_n}$ = N application rate, kg N ha^{-1}
$\mathrm{N_g}$ = N content in grain, 0.0239 kg N kg^{-1}
ϵ_{n} = Expected NUE
RI = Adjusted RI,

$$\left(\frac{\mathrm{NDVI_{N-Rich}}}{\mathrm{NDVI_{Farmer}}} \times 1.69\right) - 0.7$$

$\mathrm{CV_{Cap}}$ = Maximum coefficient of variation
$\mathrm{CV_{Critical}}$ = Critical coefficient of variation value
$\mathrm{CV_{Plot}}$ = Coefficient of variation from the NFOA-treated plot's NDVI readings.

The $\mathrm{YP_0}$ equations and values of CV incorporated in the functional algorithm for midseason N rates, and the prices of N fertilizer and grain were updated for each cropping year (Table 4). Nitrogen fertilizer was applied as urea ammonium nitrate solution (UAN, 28–0-0) on designated subplots of 0.84 m^2 resolution using a pulse modulated sprayer. For areas of lower resolutions (13.4 and 26.8 m^2), a backpack sprayer was used to apply midseason N.

The entire plot area was harvested with a self-propelled Massey Ferguson 8XP combine. Grain yield and percent moisture content were recorded using a Harvest Master yield-monitoring computer. Moisture content of the final grain yield data was adjusted to 12%. Grain subsamples were collected, oven dried at 70°C for 72 hours and processed to pass through a 106 μm 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 percent grain N by grain yield. Nitrogen use efficiency was calculated by dividing the increase in grain N uptake due to N fertilization (N $\text{Uptake}_{\text{FERILIZED}}$ − N $\text{Uptake}_{\text{CHECK}}$) by the amount of N applied. Net return to N fertilizer was computed by subtracting the cost of total N applied from gross income (price of grain kg^{-1} multiplied by grain yield increase due to N fertilization). Sensor and field data were collected from 2004 to 2006 (Table 5). Statistical analysis was performed using the SAS for Windows (SAS, 2002). Analysis of variance (ANOVA), a procedure use to partition sources of variation, was conducted using SAS General Linear Model (GLM) Procedure to determine if there were differences in mean grain yield, grain N uptake, NUE and net return to N fertilizer due to treatment.

RESULTS

Total Nitrogen Applied

The midseason NFOA-based N fertilizer rates were consistently lower than the 90 kg N ha^{-1} fixed rate which ranged only from 35 to 84 kg N ha^{-1} across site years (Table 6). The N requirements projected by the algorithm tended to be higher when average NDVI readings were higher as exemplified at Chickasha in 2005 (Table 5). At this site, the NFOA-projected N rates averaged 84 kg N ha^{-1}, the highest projected rate across site years. The Tipton site in 2004 had similar average NDVI readings of 0.702, but the algorithm prescribed an average of only 35 kg N ha^{-1}. This was attributed to a higher average CV (16.7%), wider CV range (29%) and lower response to N fertilizer (1.39) in this particular site and year (Table 5). While Tipton in 2005 had a lower NDVI, the NFOA prescribed higher midseason N rates due to higher response to N fertilizer ($RI_{NDVI} = 2.11$).

The NFOA at the highest resolution (0.84 m^2) consistently prescribed the lowest N rates except at Chickasha in 2005 where the average CV reading was only 5.2%, the lowest value collected. The differences among the NFOA-based N rates of the three resolutions across site years were more pronounced

Table 4

Yield potential equations, and data used to compute midseason nitrogen rates and net returns to N fertilizer at three locations in Oklahoma, 2004–2006

		Coefficient of Variation,%		Grain Price	Price of N Fertilizer
Year	YP_0 Equation	Critical	Maximum	US \$ kg^{-1}	US \$ kg N^{-1}
2004	$YP_0 = 359^*EXP(INSEY^*324.4)$	25	100	0.12	0.59
2005	$YP_0 = 522^*EXP(INSEY^*274.7)$	20	60	0.12	0.71
2006	$YP_0 = 532^*EXP(INSEY^*270.1)$	20	60	0.18	0.75

YP_0 = yield potential equation.

‡Number of days from planting to sensing where GDD>0.

†Lake Carl Blackwell.

All winter wheat grain, Source: USDA, NASS.

Average estimated U.S. farm level N fertilizer prices (urea, UAN 32, ammonia); United States Department of Energy, 2005).

INSEY = in-season estimated yield computed by dividing NDVI readings at Feekes growth stage 5 by the number of positive growing degree days (GDD $= \frac{T_{max}+T_{min}}{2} - 4.4°C$) from planting to sensing.

Table 5
Sensor and field data collected at three locations in Oklahoma, 2004–2006

	Chickasha		Tipton		LCB	
Variables	2004	2005	2006	2004	2005	2006
Average NDVI	0.283	0.705	0.458	0.702	0.373	0.539
Average CV, %	12.9	5.2	13.0	16.7	23.6	13.1
Maximum CV, %	20.9	14.9	28.4	37.9	37.9	26.8
Minimum CV, %	7.1	2.0	4.2	8.9	11.0	3.7
Adj. RI_{NDVI}†	1.95	1.42	1.36	1.24	2.11	1.38
$RI_{HARVEST}$‡	1.46	1.40	1.48	1.39	2.06	1.00
YP_0, kg ha^{-1}	818	2676	1501	1994	1316	2130
Check Yield, kg ha^{-1}	1216	2999	2583	3393	1250	2435

Average NDVI of midseason NFOA-based N treated plots.

†Adjusted in-season response index, determined by dividing average Normalized Difference Vegetation Index (NDVI) at Feekes

growth stage 5 of Preplant-90 by the Check. Adjustment made using the equation $(RI_{NDVI} \times 1.69) - 0.7$.

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

YP_0 = predicted yield potential of the check plot.

CV = Coefficient of variation from the NDVI readings of midseason NFOA-based N treated plots.

Table 6
Total nitrogen fertilizer applied at fixed and midseason NFOA-based rates at different resolutions at three locations in Oklahoma, 2004–2006

	Chickasha			Tipton			LCB	
Treatment Code	2004	2005	2006	Avg.	2004	2005	Avg.	2006
	Total N Applied, kg N ha^{-1}							
Check	0	0	0	0	0	0	0	0
Preplant-90	90	90	90	90	90	90	90	90
Mid-90	90	90	90	90	90	90	90	90
Mid-NFOA-0.84 m^2	41	90	36	56	34	39	36	53
Mid-NFOA-13.4 m^2	50	80	43	58	37	62	50	62
Mid-NFOA-26.8 m^2	47	82	45	58	35	61	48	66
Average	46	84	41	57	35	54	45	60

Refer to Table 2 for treatments' full description.

Average of midseason NFOA-based N rates.

Table 7
Wheat grain yield response to applied nitrogen at fixed and midseason NFOA-based rates at three locations in Oklahoma, 2004–2006

	Chickasha				Tipton			LCB
Treatment Code	2004	2005	2006	Avg.	2004	2005	Avg.	2006
	Grain Yield, kg ha^{-1}							
Check	1216	2999	2583	2266	3393	1250	2322	2435
Preplant-90	1697	3628	3705	3010	4689	2081	3385	2308
Mid-90	1781	4186	3834	3267	4726	2578	3652	2308
Mid-NFOA-0.84 m^2	1628	4179	3330	3046	4253	1945	3099	2637
Mid-NFOA-13.4 m^2	1708	4169	3453	3110	4267	2130	3198	2676
Mid-NFOA-26.8 m^2	1746	3813	3886	3148	4092	2194	3143	2692
Pr>F	0.04	0.01	0.47	—	0.01	0.01	—	0.01
Yield Avg.‡	1629	3829	3465	—	4237	2030	—	2509
SED	133	144	184	—	135	77	—	173

Refer to Table 2 for treatments' full description.
‡Average yield of all treatments by site year in kg ha^{-1}.
SED = Standard error of the difference between two equally replicated means.

in cropping seasons where the average CV was high. This observation was exemplified at Tipton in 2005 where the spatial variability treated at 0.84 m^2 using the NFOA had the lowest N applied at only 39 kg N ha^{-1} compared with the lower resolutions' (13.4 and 26.8 m^2) of 62, and 61 kg N ha^{-1}.

Grain Yield

There were significant differences ($Pr < 0.05$) in mean grain yield at all sites and years except Chickasha in 2006 (Table 7). On average by site, the highest yield was 4237 kg ha^{-1} obtained at Tipton in 2004, the same site year where a high average NDVI reading of 0.702 was reported (Table 5).

Winter wheat planted at Tipton in 2005 was the most responsive to N fertilizer applications. This was reflected in the RI_{NDVI} (2.11) and $RI_{HARVEST}$ (2.06) values recorded. In 2004 at Chickasha, a high RI_{NDVI} of 1.95 was obtained but the corresponding $RI_{HARVEST}$ was only 1.46. These were the two lowest yielding site years which obtained only 1629 and 2030 kg of grain ha^{-1} (Table 7). While these site years were responsive to N fertilizer, the average NDVI readings presented in Table 5 were recorded to be the lowest. The average NDVI reading at Chickasha was only 0.283 while at Tipton in 2005 it was 0.373.

The highest grain yields were obtained from plots with a fixed N rate of 90 kg N ha^{-1}, excluding LCB in 2006, where even the check plot produced higher grain yields. When fixed rates were preplant applied, increases in yields were lower compared to when N was applied midseason. Furthermore, in some site years, plots that were applied with NFOA-based N rates produced higher grain yields. On average at Chickasha, NFOA-based N rate treatments obtained 100 kg ha^{-1} more grain yield than 90 kg N ha^{-1} preplant, and >300 kg ha^{-1} at LCB. These yield differences were small but plots employing NFOA-based N rate treatments received 40% less N when compared to the 90 kg N ha^{-1} fixed rate. One-time, large preplant N fertilizer applications are not beneficial to crops since at the early growth stages the demand for N is very low. Doerge et al. (1991) documented that the N flux (kg N ha^{-1} day^{-1}) increases to a maximum during the jointing stage. The start of stem elongation, Feekes growth stage 6 (Large, 1954) or Zadoks 31 (Zadoks et al., 1974), is identified to be the start of the rapid N uptake by the wheat crop. The amount of N that is taken up by the crop during the early stages of growth can potentially be lost even before the crop reaches the maximum vegetation production, where the demand for N peaks. However, modest amounts of N applied preplant or at planting are important for early crop establishment.

The increase in grain yields of plots with NFOA-based N rates at different resolutions varied. There were site years where the NFOA-based N rates exceeded the grain produced by plots that received the 90 kg N ha^{-1} fixed N rate. In 2006 at Chickasha, grain yield of the NFOA-based N rate of 45 kg N ha^{-1} was higher than the 90 kg N ha^{-1} fixed rate (both preplant and midseason applied). However, this yield difference (3886 versus 3834 kg ha^{-1}) was not significant (SED = 184). In 2006 at LCB, grain yield differences between fixed and NFOA-based N rate treated plots (13.4 and 26.8 m^2) was significant (SED = 173). While there were site years that the NFOA-based N rates did not obtain grain yields as high as the fixed rate treated plots, it is important to take note that these variable rates never exceeded the 90 kg N ha^{-1} fixed rate. Moreover, on average, the NFOA-based N rates prescribed almost half (40% less) of the fixed rate.

Grain Nitrogen Uptake

There were significant differences ($Pr < 0.05$) in mean grain N uptake across sites and years excluding 2006 at Chickasha (Table 8). For the check plot's grain N uptake, the lowest value of 19 kg ha^{-1} was obtained in 2005 at Tipton followed by 26 kg N ha^{-1} at Chickasha in 2004. These two lowest grain N uptake values represented the same site years where the two highest RI_{NDVI} values were obtained (Table 5) implying that winter wheat was very responsive to N fertilizer application. However, on average, these two site years were also reported to have the lowest grain yield. The highest grain N uptake among treatments was obtained in plots where N was applied midseason at a 90 kg N ha^{-1} fixed rate across sites and years excluding 2006 at Chickasha. The difference in N uptake between NFOA and fixed rate treatments was not

Table 8
Grain nitrogen uptake response to applied nitrogen at fixed and midseason NFOA-based rates at different resolutions at three locations in Oklahoma, 2004–2006

	Chickasha				Tipton			LCB
Treatment Code	2004	2005	2006	Avg.	2004	2005	Avg.	2006
	Grain N Uptake†, kg ha^{-1}							
Check	26	58	55	46	51	19	35	54
Preplant-90	45	83	64	64	84	35	59	86
Mid-90	50	99	70	73	87	48	68	94
Mid-NFOA-0.84 m^2	36	94	67	66	65	33	49	76
Mid-NFOA-13.4 m^2	41	95	72	69	70	39	54	82
Mid-NFOA-26.8 m^2	40	88	72	67	68	40	54	91
Pr>F	0.01	0.01	0.06	—	0.01	0.01	—	0.01
Grain N Uptake Avg.‡	40	86	67	—	71	36	—	80
SED	2.6	3.9	3.9	—	3.8	1.6	—	6.0

Refer to Table 2 for treatments' full description.
†Grain yield multiplied by the percent N in grain.
‡Average grain N uptake of all treatments by site year in kg N ha^{-1}.
SED = Standard error of the difference between two equally replicated means

proportionate to the difference in the N rates applied. While the NFOA-based N rate recommendations were 40% less than the 90 kg N ha^{-1} fixed rate, grain N uptake differences at Chickasha, Tipton and LCB were only 8, 23 and 12%, respectively, and less than the fixed rates'.

The average of the midseason NFOA-based N rate treatments across sites and years obtained only 87% of the grain N uptake of the 90 kg N ha^{-1} fixed rate treatment applied midseason. No pronounced trend was observed when the NFOA-based N rate treatments at different resolutions were compared. On average, grain N uptake values were very similar at Chickasha. At 0.84, 13.4 and 26.8 m^2 resolutions, average grain N uptake values were 66, 69 and 67 kg N ha^{-1}, respectively. The 26.8 m^2 resolution obtained the highest grain N uptake of 91 kg N ha^{-1} at LCB, while the 13.4 and 26.8 m^2 resolutions had the same grain N uptake of 54 kg N ha^{-1} at Tipton.

Nitrogen Use Efficiency

The ANOVA showed that the differences in NUE among treatments were not significant ($Pr < 0.05$) (Table 9). This outcome was consistent across sites and years. It is noteworthy that one-time preplant application of 90 kg N ha^{-1} resulted in the lowest NUE among treatments which also occurred consistently

Table 9
Nitrogen use efficiency response to applied nitrogen at fixed and midseason NFOA-based rates at different resolutions at three locations in Oklahoma, 2004–2006

	Chickasha				Tipton			LCB
Treatment Code	2004	2005	2006	Avg.	2004	2005	Avg.	2006
	Nitrogen Use Efficiency†,%							
Check	—	—	—	—	—	—	—	—
Preplant-90	21	28	14	21	37	17	27	35
Mid-90	27	45	17	30	41	32	36	44
Mid-NFOA-0.84 m^2	26	40	32	32	43	36	39	40
Mid-NFOA-13.4 m^2	30	47	39	39	56	31	44	44
Mid-NFOA-26.8 m^2	31	37	38	35	49	34	41	54
Pr>F	0.58	0.48	0.26	—	0.87	0.07	—	0.48
NUE Avg.‡	27	39	28	—	45	30	—	43
SED	4.5	7.9	9.2	—	13.6	4.0	—	6.6

Refer to Table 2 for treatments' full description.
†Estimated by subtracting the grain N uptake of the check plot from the fertilized plot, divided by the N rate applied.
‡Average nitrogen use efficiency of all the treatments by site year.
SED = Standard error of the difference between two equally replicated means

across sites and years. Note that this is similar to the observation in grain yield response that was reported earlier. The lowest NUE was 14% at Chickasha in 2006 from the plots that received 90 kg N ha^{-1} preplant. The highest was 56% obtained in 2004 at Tipton from plots treated with variable N rates prescribed by the NFOA at a 13.4 m^2 resolution.

On average by site, the midseason NFOA-based N rate recommendations resulted in a higher NUE when compared with the fixed N rate preplant application, except at LCB for the NFOA treatment at 0.84 m^2 resolutions. At Chickasha, the fixed rate treatments were only 21 and 30% while the NFOA-based plots ranged from 32 to 39%. At Tipton, the fixed N plot recorded only 27 and 36% compared to 39, 44, and 41% of NFOA-based treatments. The 90 kg N ha^{-1} fixed rate treatment obtained 35 and 44% NUE while the NFOA-based treatments were 40, 44, and 54% at LCB. On average across sites and years, the NFOA approach resulted in 41% NUE compared with 33% of the 90 kg N ha^{-1} fixed rate applied midseason. The highest NUE values achieved among the midseason NFOA-based plots were 39 and 44% for Chickasha and Tipton sites, respectively, both treated at 13.4 m^2 resolutions. At LCB, treatments at the 26.8 m^2 resolution obtained the highest NUE value of 54%.

Net Return to Nitrogen Fertilizer

Analysis of variance showed that mean net returns to N fertilizer were significantly different ($Pr < 0.05$) at Chickasha in 2005, at Tipton for both years (2004 and 2005), and at LCB (Table 10). At Chickasha, the highest net return among treatments was consistently achieved by at least one of the NFOA-based N rate treatments. The highest net return was 460 $ ha^{-1} from plots with midseason NFOA-based N rates treated at the 13.4 m^2 resolution. Similarly, at LCB, 642 $ ha^{-1} net return was achieved from the midseason NFOA-based N rate recommendation at the 26.8 m^2 resolution. However, at Tipton, there was no economic benefit obtained when midseason NFOA-based rate recommendations were used. On average at Tipton, midseason NFOA-based N rate recommendations' net return were comparable with the 90 kg N ha^{-1} fixed rate's applied preplant. However, this was not the case when compared with the fixed rates applied midseason. The midseason application of 90 kg N ha^{-1} resulted in significantly higher net returns of 524 and 256 $ ha^{-1} in 2004 and 2005, respectively.

Savings from reduced fertilizer use when using the NFOA-based approach was determined by subtracting the net return of 90 kg N ha^{-1} fixed rate treatment applied midseason from the net return of the NFOA-based N rate treatments (Table 10). The highest savings from reduced N fertilizer use was 101 $ ha^{-1} when compared with the 90 kg N ha^{-1} rate applied midseason. This can be attributed to the large reduction in the amounts of N applied (Table 6).

When comparing net returns of the NFOA-based N rate treatments at different resolutions, treating spatial variability at 13.4 m^2 resolution had the highest net return. Using the NFOA to prescribe N rates at the finest resolution of 0.84 m^2 did not exhibit any additional economic benefit (Table 10). At 0.08 $ kg^{-1} of wheat grain, the lowest wheat grain price reported in the past 10 years (USDA NASS, 2007), treating spatial variability at 0.84 m^2 exceeded net returns of the lower resolutions (13.4 and 26.8 m^2) only when the price of N fertilizer was at least 0.60 $ kg N $^{-1}$ (Figure 1). However, when wheat grain price was 0.18 $ kg^{-1}, the highest reported in the past 10 years (USDA NASS, 2007), there was a consistent decreasing trend of net returns with increasing resolution for the three prices (0.40, 0.60, and 0.80 $ kg N^{-1}) of N fertilizer evaluated (Figure 2).

DISCUSSION

The components of the NFOA which include the predicted YP_0, RI, and CV, can be determined in-season. This approach makes N rate recommendations tailored for the current crop, and thus are not based on historical information. Each of these components provides an important function so that the algorithm can precisely estimate N application based on N demand at the predicted YP_0 while

Table 10
Net return to nitrogen fertilizer for resolution trials at three locations in Oklahoma, 2004–2006

	Chickasha			Tipton			LCB	
Treatment Code	2004	2005	2006	Avg.	2004	2005	Avg.	2006
	Net return to N Fertilizer, \$ ha^{-1}							
Preplant-90	154	386	344	295	519	194	357	592
Mid-90	164	455	344	321	524	256	390	615
Mid-NFOA-0.84 m^2	175 (11)	454 (0)	443 (99)	357 (37)	499 (0)	213 (0)	356 (0)	553 (0)
Mid-NFOA-13.4 m^2	179 (15)	460 (5)	444 (100)	361 (40)	499 (0)	220 (0)	359 (0)	568 (0)
Mid-NFOA-26.8 m^2	186 (22)	415 (0)	445 (101)	348 (41)	479 (0)	229 (0)	354 (0)	642 (27)
Pr>F	0.41	0.01	0.10	—	0.01	0.01	—	0.01
Net Return Avg. ‡	168	424	408	—	489	422	—	572
SED	14	18	33	—	16	10	—	28

Refer to Table 2 for treatments' full description.

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

Grain price kg^{-1} multiplied by yield and then subtracted by cost of total N applied. Prices of fertilizer and wheat grain are reported in Table 4.

‡Average net returns to N fertilizer of all the treatments by site year in \$ ha^{-1}.

Values in parentheses are savings on cost of N fertilizer applied using NFOA approach; computed by subtracting net returns of Mid-90 from NFOA treatments.

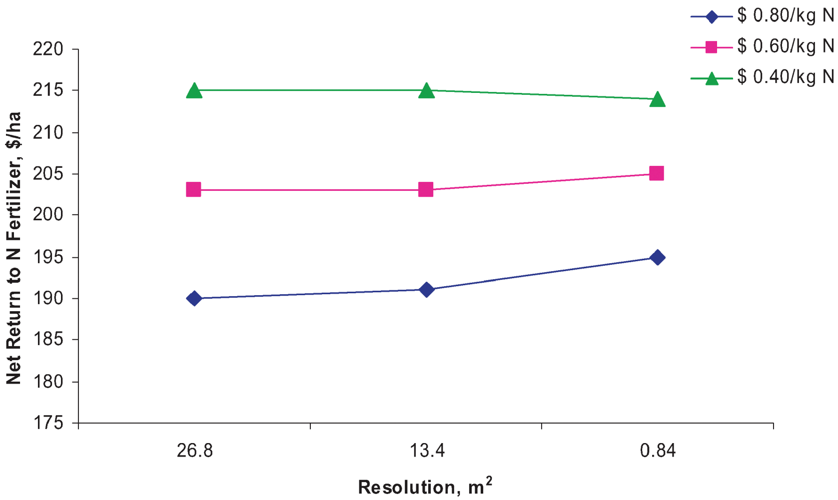

Figure 1. Net returns to nitrogen fertilizer for different resolutions and prices of N fertilizer at a fixed wheat grain price of 0.08 \$ kg^{-1}.

taking into account field spatial variability and the seasonally dependent crop responsiveness to applied N. The NDVI normalized by GDD is used to predict the YP_0 using the equation presented in Table 4, which is annually updated. The

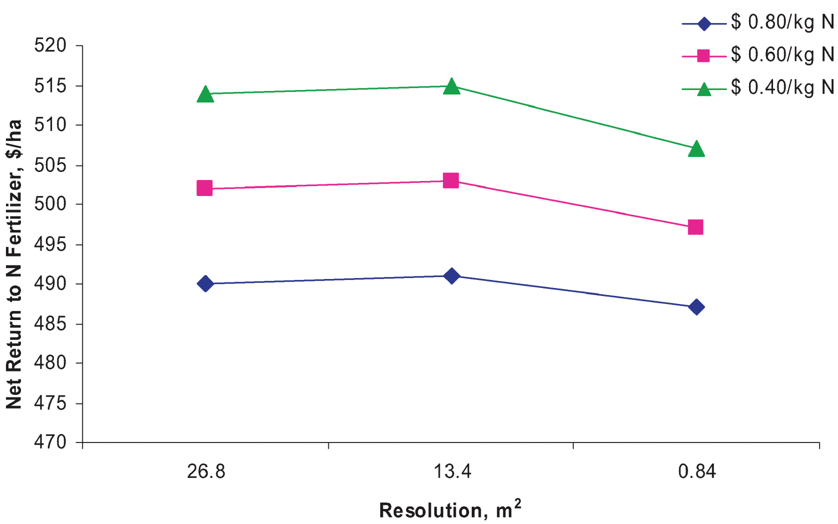

Figure 2. Net returns to nitrogen fertilizer for different resolutions and prices of N fertilizer at a fixed wheat grain price of 0.18 \$ kg^{-1}.

coefficient values from recent years' YP_0 equations have been relatively stable. The recent YP_0 equation for 2007 is $YP_0 = 590^*EXP(INSEY^*258.2)$ (http://www.nue.okstate.edu/Yield_Potential.htm). The strength of this YP_0 equation is limited by significant changes in growth conditions that occur after sensing which can either adversely or favorably influence crop YP_0. Otherwise, the YP_0 equation can be used to obtain reasonable estimates of actual grain yield. The closest projection was at Tipton in 2005 where the predicted YP_0 was 1616 kg $ha^{-1}$and the actual yield obtained at harvest was 1250 kg ha^{-1} (Table 7). However at Chickasha in 2006, the predicted YP_0 was 1501 kg ha^{-1}, which was only 58% of the actual yield.

The NFOA-projected N fertilizer rates did not exceed the 90 kg N ha^{-1} fixed rate used in any of the sites (Table 2). The only time that NFOA-based N rates equaled the fixed rate was in 2005 at Chickasha. This was also the site year where one of the NFOA's N rate recommendations recorded the highest yield among treatments. As shown in Table 6, this site year recorded the highest average NDVI reading (0.705), the lowest average CV (5.2%) and a narrow CV range (12.9%). The N rate recommendations prescribed at Tipton in 2004 were remarkably lower, even though the average NDVI reading (0.702) was equally high, as at Chickasha in 2005. The relatively lower RI_{NDVI} compared with Chickasha's caused a reduction of the N rate recommendations prescribed by the NFOA. Moreover, this site year recorded a relatively higher average CV of 16.7% and a number of subplots obtaining CV values as high as 37.9%. The higher CVs likely caused further reduction of the final N rate recommendations. This is the advantage of the present algorithm such that when variation in the field becomes pronounced (high CVs), N rate recommendations decline. The integration of CV, an estimate of variation in plant-stand densities, will assist in identifying areas in the field where N application should be reduced. This makes the current N-fertilization algorithm (Raun et al., 2005) vastly different to the algorithm used by Raun et al. (2002). The capability of the algorithm to project what the crop needs has resulted in increased NUE and net return to N fertilizer. The large savings in the amount of N fertilizer prescribed by the NFOA outweighed the large increases in grain yield and N uptake incurred by applying 90 kg N ha^{-1} midseason when computing NUE and net return. On average by site, at least two of the NFOA-based treatments consistently obtained higher NUE compared with the fixed rate (Table 9). Statistically, the increase in NUE was not significant ($Pr < 0.05$), however, considering economic and environmental perspectives, using this approach could make an impact. A 1% increase in NUE worldwide would save $234,658,462 in fertilizer cost and would result in 489,892 metric tons of N fertilizer saved which would not adversely contaminate our environment (Raun and Johnson, 1999).

The economic analysis of this trial was highlighted by presenting the net returns to N fertilizer and savings incurred when the NFOA approach was used to determine N rate requirements using the 90 kg N ha^{-1} fixed rate treatment applied midseason as a reference. Four out of six site years had at least one of the NFOA treatments exceed the net returns of the fixed rates. On average by site, the net returns of as much as 41 and 27 \$ ha^{-1} were saved at Chickasha and LCB sites, respectively. As presented earlier, grain yield of the NFOA-based N rate plots were relatively lower than that of the fixed rate applied midseason, which in turn resulted in a relatively lower net return. However, the significant reduction in the amount of fertilizer applied lowered the cost of N fertilizer input resulting in a higher net return. In addition to considerable reduction in the cost of N fertilizer used, grain yield of the NFOA-based approach in some site years exceeded the grain yield of the preplant 90 kg N ha^{-1} fixed rate. This demonstrates that the NFOA approach is very promising in terms of improving producer's income.

The results presented above and the previous study by Raun et al. (2002) demonstrate that higher NUE and net return can be achieved when N rate recommendations are based on N demand encumbered within predicted YP_0. However, the optimum resolution to treat spatial variability needs to be determined to maximize the benefit when using the NFOA to project crop N rate requirements. This is particularly important for variable rate technology where wheat fields are sensed on-the-go while concurrently treating the crop based on needs. When spatial variability was treated at the highest resolution, the only benefit obtained was a marginal increase in NUE, 36% compared with the 31 and 34% of the 13.4 and 26.8 m^2 resolutions, respectively. This was only true in one site year (Tipton, 2005) where the average CV of the plots exceeded the critical CV (20%) used in the algorithm. On average by site, treating spatial variability using the NFOA at 13.4 m^2 resulted in the highest NUE values among the treatments, reported at 56 and 44% for Chickasha and Tipton, respectively. Further, the net returns (Table 10) for this resolution for both sites were recorded to be the highest among the three resolutions tested. At LCB, the optimum resolution where the highest NUE and net return could be achieved was identified as being at 26.8 m^2. Net returns for different prices of N fertilizer at a fixed grain price of 0.18 \$ kg^{-1} consistently decreased with increasing resolution (Figure 2). However, when the price of grain was at the lower end (0.08 \$ kg^{-1}) and the price of N fertilizer was at the higher end (at least 0.60 \$ kg N^{-1}), treating spatial variability at 0.84 m^2 exceeded the net returns of the lower resolutions (Figure 2). These results also suggest that when crop stand has a CV value more than the 20% critical CV in the algorithm, treating the spatial variability at 0.84 m^2 (finest resolution in this trial) would result in a higher NUE. However, this requires further verification as there existed only a marginal difference (2%) when compared with the NUE achieved at 26.8 m^2 resolution. Further, this observation was only exhibited in one site year.

CONCLUSION

Based on the results reported, when an NFOA approach was used to determine midseason N rate requirements, treating spatial variability at a minimum of 13.4 m^2 resulted in increased NUE and net return. Treating spatial variability at 0.84 m^2 resulted in a positive impact on net return and NUE only when the average CV, an estimate of crop stand, was greater than 20%, or when the price of N fertilizer was at least 0.60 \$ kg N^{-1} provided that the price of wheat grain was 0.08 \$ kg^{-1}. Further research should be conducted to verify the benefit of treating spatial variability at a high resolution as there existed only a marginal difference in NUE when compared with the lower resolutions. Mathematical adjustment has to be made to refine the current algorithm in order to affect an increase in NUE and net return, and testing this approach has to be done under different crop stands that would result in a wider range of average CV values from the NDVI readings.

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