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Mid-Season Recovery from Nitrogen Stress in Winter Wheat*

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ABSTRACT

Although spring-applied nitrogen (N) has been shown to be most efficient, the technique of delaying all N applications until mid-season, and the resultant effect on maximum yields, has not been thoroughly evaluated. This experiment was conducted to determine if potential yield reductions from early-season N stress can be corrected using in-season N applications. Data from three experimental sites and two growing seasons (six site-year combinations) were used to evaluate three preplant N rates (0, 45, and 90 kg ha^{-1}) and a range of in-season topdress N rates. Topdress N amounts were determined using a GreenSeeker hand-held sensor and an algorithm developed at Oklahoma State University. Even when early-season N stress was present (0-N preplant), N-applied topdress at Feekes 5 resulted in maximum or near-maximum yields in four of six site-year combinations when compared with other treatments receiving both preplant and topdress N.

Keywords: N stress, mid-season N, N recovery

INTRODUCTION

As environmental and economic issues become a concern, it is important for action to be taken to address them. Fertilizer is one of the most controversial environmental issues in today's world. Vidal et al. (1999) stated that the application of nitrogen (N) at rates exceeding those needed for plant utilization

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represents an unnecessary input cost for wheat producers and can also harm aquatic and terrestrial environments.

The current method for determining N-fertilization rates in cereal-production systems is to subtract soil-test N from a specified yield goal-based N requirement. The yield goal represents the best achievable yield in the last four to five years (Raun et al., 1999, 2001). There are, however, more precise and efficient ways of obtaining fertilizer recommendations to maximize yield and minimize cost. Following extensive soil sampling, optical-sensor measurements of plants, and geostatistical analysis, several authors have reported that the spatial scale of N availability was at 1 m^2 and that each square meter needed to be treated independently (Raun et al., 1998; Solie et al., 1999; Raun et al., 2002). When N-management decisions are made on areas of 1 m^2, the variability that is present at that resolution can be detected using optical sensors (measuring the normalized difference vegetative index, NDVI) and treated accordingly with foliar application of N (Solie et al., 1996; Stone et al., 1996; Raun and Johnson, 1999), which increases nitrogen-use efficiency (NUE) (Stone et al., 1996). Recently, methods for estimating winter wheat N requirements based on early-season estimates of N uptake and potential yield were developed (Raun et al., 2002; Lukina et al., 2001). Remote sensing collected by a modified daytime-lighting reflectance sensor was used to estimate early-season plant N uptake. The estimate was based on a relationship between NDVI and plant N uptake between Feekes physiological growth stage 4 (when leaf sheaths lengthen) and 6 (when the first node of stem is visible) (Solie et al., 1996; Stone et al., 1996; Large, 1954). The NDVI was calculated using the following equation:

$$\mathrm{NDVI} = (\rho_{\mathrm{NIR}} - \rho_{\mathrm{Red}})/(\rho_{\mathrm{NIR}} + \rho_{\mathrm{Red}})$$

where ρ_{NIR} = fraction of emitted near infrared (NIR) radiation returned from the sensed area (reflectance) and ρ_{Red} = fraction of emitted red radiation returned from the sensed area (reflectance).

Increasing NUE by just 20% would result in savings exceeding $4.7 billion per year (Raun and Johnson, 1999). Improving NUE will also decrease the risk of NO_3-N contamination of inland surface and ground water (Stone et al., 1996; Raun and Johnson, 1999), as well as hypoxia in specific oceanic zones, which is believed to be caused by excess N fertilizer (Raun and Johnson, 1999; Malakoff, 1998).

Raun et al. (2002) stated that it is possible to measure the quantitative response to fertilizer N for a given area, which is why the N fertilization-optimization algorithm (NFOA) was developed. It determines the prescribed N rate needed for each square meter based on predicted yield potential without added N fertilizer (YP_0) and the specific response index (RI) for each field. Johnson and Raun (2003) defined RI as the amount of yield response to expect from an application of fertilizer N versus the yield with no additional N, and stated that RI may range from 1 to as high as 4. Raun et al. (2002) explained that the NFOA accounts for spatially variable potential yield, early-season N uptake, and responsiveness of the crop to N input. The algorithm calculations are performed as follows:

1) Predict YP_0 from the equation for grain yield and in-season estimate of yield (INSEY), where: INSEY = NDVI (Feekes 4–6)/days from planting, where growing degree days (GDD) > 0 [GDD = $(T_{min} + T_{max})/2$–4.4°C, where T_{min} and T_{max} represent daily ambient high and low temperatures]. Lukina et al. (2001) showed that a single equation could be used to predict grain yield over a wide production range (0.5–6.0 Mg ha^{-1}), diverse sites, and with differing planting and harvest dates. Dividing NDVI at Feekes 5 (an excellent predictor of early-season plant N uptake) by the days from planting to the NDVI sensing date resulted in an index that would approximate N uptake per day.
2) Predict the magnitude of response to N fertilization, in-season RI (RI_{NDVI}), computed as: NDVI collected from growing winter wheat anytime from Feekes 4 to Feekes 6 in non-limiting fertilized plots divided by NDVI in a parallel strip receiving the farmer preplant N rate. The RI_{NDVI} has been found to be highly correlated with the RI at harvest ($RI_{Harvest}$), which is similarly computed by dividing the highest mean grain yield of the N-rich treatment by the mean grain yield of 0-N treatment (check plot) (Mullen et al., 2001). The farmer preplant N rate could range anywhere from zero to a rate for non-N limiting conditions (Raun et al., 2002).
3) Determine the predicted yield with additional N (YP_N) based on both RI_{NDVI} and the YP_0, as follows: $YP_N = YP_0 \times RI_{NDVI}$. The RI_{NDVI} was limited so as not to exceed 3.0 and YP_N was similarly limited not to exceed the maximum obtainable yield (YP_{max}). The YP_{max} was determined by the farmer, or by measuring the maximum NDVI in the N-rich strip (N applied at adequate but not excessive rates preplant) (Oklahoma State University, 2004) and using that value to calculate the YP_{max} using the yield-potential equation. The YP_{max} can also be defined as a biological maximum for a specific cereal crop grown within a specific region and under defined management practices (e.g., YP_{max} for dry land winter wheat produced in central Oklahoma would be 7.0 Mg ha^{-1}). The RI_{NDVI} was capped at 3.0, as in-season applications of N would be unlikely to lead to YP_N being more than three times greater than baseline YP_0.
4) Calculate predicted grain N uptake (PNG) at $YP_N(GNUP_{YPN})$, average percent N in the grain multiplied by YP_N: $GNUP_{YPN} = YP_N \times PNG$.
5) Calculate PNG at YP_0, average percent N in the grain multiplied by YP_0: $GNUP_{YP0} = YP_0 \times PNG$.
6) Determine in-season fertilizer N requirement (FNR): $FNR = (GNUP_{YPN} - GNUP_{YP_0})/0.60$ A divisor of 0.60 in the above equation is used because the theoretical maximum NUE of an in-season N application is approximately 60%.

The use of active growing days from planting and NDVI (estimate of total N uptake and or biomass) in computing INSEY allows integration of the effects of both winter and spring growing conditions and date of planting. The INSEY index is essentially the rate of N uptake (kilograms of forage N assimilated per day) by the plant. This approach is consistent with work showing the relationship between above-ground plant dry weight and cumulative GDD (Rickman et al., 1996). Further analyses have shown that a reliable INSEY could be obtained by dividing NDVI by the days from planting to sensing date (where $GDD > 0$) (Raun et al., 2002; Mullen et al., 2003). Mullen et al. (2003) also stated that the INSEY was used to estimate N uptake in the grain based on a predicted yield level. Finally, topdress fertilizer N rates have been determined using predicted wheat N uptake (measured by NDVI) at Feekes 5 (an excellent predictor of early-season plant N uptake) and projected grain N uptake from INSEY (grain N uptake minus early-season plant N uptake) (Lukina et al., 2001).

Johnson et al. (2000) defined the harvest response index ($RI_{Harvest}$) as follows: $RI_{Harvest}$ = (highest mean yield N treatment)/(mean yield check treatment).

The use of $RI_{Harvest}$ does not allow for in-season adjustment of N. In-season sensor measurements of NDVI as an indicator of wheat N uptake between plots receiving N and those not receiving N can be used in the same way, using the following equation:

$$RI_{NDVI} = (\text{highestmean NDVI N treatment})/(\text{mean NDVI check treatment})$$

Mullen et al. (2003) concluded that basing fertilizer N rates on INSEY and RI_{NDVI} may help optimize in-season fertilizer application, which in turn could increase NUE and yield. Thus the first objective of this work was to determine if RI_{NDVI} could accurately predict $RI_{Harvest}$ at Feekes growth stages 5, 9, 10.5, and 11.2. They also found that RI_{NDVI} measured at Feekes 5 was highly correlated to $RI_{Harvest}$. Mullen et al. (2003) recognized that after remote sensing data is collected, yield enhancing and limiting factors may occur that result in underestimation or overestimation of $RI_{Harvest}$ by RI_{NDVI}. For example, in 1999, early spring rains after a dry fall planting period improved post-sensing growing conditions. Timely rainfall may have increased the N response, resulting in a larger $RI_{Harvest}$ than predicted by RI_{NDVI}. The additional objectives of this work were to determine if potential yield reductions from early stress can be corrected by using in-season fertilizer applications, and to evaluate the relationship between RI_{NDVI} and $RI_{Harvest}$ over years and locations.

MATERIALS AND METHODS

Three experimental sites were selected for this study. The Covington site was located at a cooperating farmer's field. The soil at this site was a Kirkland-Renfrow silt loam, fine, mixed, superactive, thermic Udertic Paleustoll. The

Stillwater Research Station at Lake Carl Blackwell, Oklahoma, had Port Oscar silt loam, fine-silty, mixed, super active, thermic Cumulic Haplustoll soil. The Tipton site had Tillman-Hollister silt loam, fine-loamy, mixed, thermic, Pachic Urgiusoll soil.

A randomized complete block design was employed with 15 treatments and 4 replications. Plot size was 3.05 m $\times$ 6.1 m with 3.05 m alleys. Three preplant N rates (0, 45, and 90 kg ha^{-1}) were applied to plots as ammonium nitrate (34-0-0). Topdress N application rates were determined utilizing the NFOA (Raun et al., 2002) with four different RI values. The RI values evaluated were 1.0, 1.3, 1.6, and 2.0. Algorithms differed for 2003 and 2004 whereby the coefficient of variation (CV) was used in 2004 to alter yield potential achievable with N fertilization (Oklahoma State University, 2004). Response index was calculated as reported by Johnson and Raun (2003). Spectral reflectance was measured using a GreenSeeker Hand Held Optical Sensor (N-tech Industries, Ukiah, CA) that collected NDVI measurements. This device uses a patented technique to measure crop reflectance and calculate NDVI. The unit senses a 0.6 $\times$ 0.01 m spot when held at a distance of approximately 0.6–1.0 m from the illuminated surface. The sensed dimensions remain approximately constant over the height range of the sensor. The sensor unit has self-contained illumination in both the red (650 $\pm$ 10 nm FWHM) and NIR (770 $\pm$ 15 nm FWHM) bands. (FWHM = full width at half maximum.) The device measures the fraction of the emitted light in the sensed area that is returned to the sensor; the fractions are used within the sensor to compute NDVI.

The sensor unit is designed to be hand held and measurements are taken as the sensor is passed over the crop surface. The sensor samples at a very high rate (approximately 1000 measurements per second), and averages measurements between outputs. The sensor outputs NDVI at a rate of 10 readings per second. Reflectance readings were collected throughout the growing season. The NDVI readings taken for the topdress N-fertilization application from all experiments were collected post-dormancy. The date when readings were collected generally corresponded to Feekes growth stage 5 (when the pseudo-stem, formed by sheaths of leaves, is strongly erect) (Large, 1954). Topdress N was foliar applied to the whole plot using urea ammonium nitrate (UAN, 28-0-0) with a Solo backpack sprayer (amounts were calculated and then measured with a graduated cylinder). For the smaller rates, a pulse-modulated sprayer designed by Oklahoma State University (OSU) was used.

Winter wheat grain was harvested using a self-propelled Massey-Ferguson 8XP combine. An area of 2.0 $\times$ 6.1 m was harvested from the middle of each plot, and a Harvest Master yield-monitoring computer installed on the combine recorded yield data. A sub-sample of grain was taken and dried in a forced-air oven at 66°C, ground to pass a 100 μm screen, and analyzed for total N content using a Carlo-Erba NA-1500 Dry Combustion analyzer (Schepers et al., 1989). Statistical analysis was performed using SAS (SAS Institute, 2001). Treatment structure for 2002–2004 is reported in Table 1. Initial soil samples, chemical

Table 1
Treatment structure for all three experimental sites (Covington, Lake Carl Blackwell, and Tipton, Oklahoma, 2002–2004)

Treatment	Pre-Plant N Rate (kg ha)$^{-1}$	Topdress N*RI†	
1	0	YP_0	0
2	0	YP_N	RI
3	0	YP_N	RI * 1.3
4	0	YP_N	RI * 1.6
5	0	YP_N	RI * 2.0
6	45	YP_0	0
7	45	YP_N	RI
8	45	YP_N	RI * 1.3
9	45	YP_N	RI * 1.6
10	45	YP_N	RI * 2.0
11	90	YP_0	0
12	90	YP_N	RI
13	90	YP_N	RI * 1.3
14	90	YP_N	RI * 1.6
15	90	YP_N	RI * 2.0

*RI is the actual response index determined for that field.
†Response index was adjusted as a function of CV in 2003–2004.

characteristics, and classification of soils are reported in Table 2. Field activities and dates are listed in Table 3.

RESULTS

Covington, 2003

At Covington in 2003 where no topdress N was applied, there was a linear increase in wheat grain yield with increasing preplant N (treatment 1 = 3170 kg ha^{-1}, treatment 6 = 4527 kg ha^{-1}, treatment 11 = 5234 kg ha^{-1}; Table 4). At this site, there was also an increase in wheat grain yield for topdress N rates whether or not preplant N had been applied. However, the yield increases from topdress N diminished with increasing preplant N. Maximum yields were not achieved at this site from mid-season topdress N applications in plots receiving no preplant N when compared with the plot that achieved maximum yield, which was not the N-rich plot (treatment 11). The plot that achieved maximum yield was treatment 10. It should be noted that even with early N stress, topdress N rates (treatment 5 = 5271 kg ha^{-1}) did produce a yield that was equal to that on the preplant non-N-limiting plot (treatment 11 = 5234 kg ha^{-1}), but that was still less than the maximum yield (treatment 10 = 5875 kg ha^{-1}). The "catch

Table 2
Initial surface (0–15 cm) soil chemical characteristics and classification at Covington, Lake Carl Blackwell, and Tipton, Oklahoma

		mg kg^{-1}				g kg^{-1}	
Location	pH	NH_4-N	NO_3-N	P	K	Total N	Organic C
Covington	5.4	10.87	5.17	57	255	1.09	13.3
Classification: Kirkland-Renfrow silt loam (fine, mixed, superactive, thermic Udertic Paleustoll)							
Lake Carl Blackwell	5.3	3	11	12	122	0.68	8.18
Classification: Port Oscar silt loam (fine-silty, mixed, super active, thermic Cumulic Haplustoll)							
Tipton	7.0	4	6	46	284	0.65	6.26
Classification: Tillman-Hollister silt loam (fine-loamy, mixed, thermic, Typic Paleustoll)							

*pH—1:1 soil:water; K and P—Mehlich III; NH_4-N and NO_3-N—2M KCL; Total N and Organic Carbon—dry combustion.

up" effect being evaluated in this work provokes the following question: Can maximum yields be produced when no N is applied preplant and N applications are delayed until February or March? At this site, it was not possible to catch up where no N was applied preplant but topdress N was applied mid-season (treatment 10 = 5875 kg ha^{-1}; Table 4).

Recent work has shown that when CVs are <18, catch-up is possible (catch-up: waiting to apply all N topdress and still achieving maximum yields) (Oklahoma State University, 2004). Consistent with this work, all CVs were >18 at this site, indicating that catch-up was not going to be possible, which was confirmed.

Nitrogen-use efficiency was the greatest for the 0 N preplant treatments plus mid-season applied N (treatments, 1–5), but it should be noted that NUEs were generally quite high at this site (Table 4).

The RI estimated using in-season NDVI readings was underestimated at this site ($RI_{NDVI} = 1.27$ and $RI_{Harvest} = 1.7$, Table 4). It is possible that the N-rich treatment (Large, 1954) may not have received enough preplant N to estimate RI_{NDVI} accurately. The RI_{NDVI} over time for 2003 did not change much from Feekes 3 to Feekes 5 (RI_{NDVI} = 1.18, 1.24, and 1.27; Table 3). The $RI_{Harvest}$ was much higher than the RI_{NDVI} values ($RI_{Harvest} = 1.7$; Table 4).

Lake Carl Blackwell, 2003

At Lake Carl Blackwell in 2003, there was a linear increase in grain yield for N applied preplant (treatment 1 = 3207 kg ha^{-1}, treatment 6 = 3579 kg ha^{-1},

Table 3
Field activities and dates, Covington, Lake Carl Blackwell, and Tipton, Oklahoma, 2002–2004

	Covington	Lake Carl Blackwell	Tipton
2002–2003			
Cultivar	Jagger	Jagger	Custer
Planting date	10-07-02	10-01-02	09-26-02
Seeding rate (kg ha^{-1})	67	90	80
Preplant N date	09-23-02	09-05-02	09-17-02
Topdress N date	02-22-03	02-21&22-03	03-06-03
Rainfall (mm)	443	434	365
Sensing 1 (F 3–4)	01-27-03	01-24-03	01-28-03
GDD	78	84	98
RI_{NDVI}	1.18	1.15	1.45
Sensing 2 (F 4–5)	02-12-03	02-12-03	02-18-03
GDD	85	92	112
RI_{NDVI}	1.24	1.13	1.5
Sensing 3 (F 5–6)	02-22-03	02-20-03	03-06-03
GDD	91	96	119
RI_{NDVI}	1.27	1.14	1.49
Grain harvest date	06-09-03	06-19-03	05-29-03
$RI_{Harvest}$	1.7	1.3	1.5
2003–2004			
Cultivar	2174	Jagger	2158
Planting date	09-29-03	10-07-03	09-23-03
		10-24-03(re-plant)	(dry planted)
Seeding rate (kg ha^{-1})	78	90	80
Preplant N date	09-17-03	09-10-03	09-09-03
Topdress N date	02-19-04	03-10-04	03-17-04
Effective date			11-07-03
Rainfall (mm)	569	545	331
Sensing 1 (F 2–3)	12-08-03	01-05-04	12-16-03
GDD	60	54	74
RI_{NDVI}	1.47	1.10	0.92
Sensing 2 (F 3–4)	01-15-04	02-19-04	02-18-04
GDD	77	68	106
RI_{NDVI}	2.19	1.10	1.09
Sensing 3 (F 4–5)	02-12-04	02-25-04	03-11-04
GDD	82	72	127
RI_{NDVI}	2.18	1.11	1.49
Sensing 4 (F 5–6)	02-18-04	03-09-04	NA
GDD	83	84	NA
RI_{NDVI}	2.02	1.24	NA
Sensing 5 (F 9)	03-09-04	03-18-04	NA
GDD	100	93	NA

(Continued on next page)

Table 3
Field activities and dates, Covington, Lake Carl Blackwell, and Tipton, Oklahoma, 2002–2004 (*Continued*)

	Covington	Lake Carl Blackwell	Tipton
RI_{NDVI}	1.9	1.22	NA
Grain harvest date	06-13-04	6-14-04	05-27-04
$RI_{Harvest}$	1.89	1.24	1.68

Covington had 18-46-0 @ 56 kg ha^{-1} banded with seed (2002), and had 11-52-0 @ 50 kg ha^{-1} banded with seed (2003).
Lake Carl Blackwell had 0-46-0 @ 45 kg ha^{-1} preplant incorporated (2003 and 2004).
F = Feekes growth stages, determined by (Large, 1954).
GDD = Growing Degree Days: $T_{max} + T_{min}/2–4.4°C$.

treatment 11 = 4276 kg ha^{-1}; Table 5). There was an increase in grain yield for topdress N rates for the 45 kg ha^{-1} preplant rates, but no increase from topdress N where 90 kg ha^{-1} was applied preplant. Maximum yields were achieved at this site from mid-season topdress N applications in plots receiving 0 preplant N

Table 4
Treatment, preplant nitrogen, topdress nitrogen RI factor, topdress nitrogen applied, total nitrogen applied, yield, grain nitrogen uptake, and % NUE for Covington, Oklahoma, 2003

Treatment	Preplant N	Topdress N RI	Topdress N applied	Total N applied	Grain yield	Grain N uptake	% NUE
			kg ha^{-1}				
1	0	0	0	0	3170	61	—
2	0	RI	19	19	4295	85	126
3	0	RI * 1.3	48	48	4630	93	67
4	0	RI * 1.6	74	74	5122	114	72
5	0	RI * 2.0	122	122	5271	130	57
6	45	0	0	45	4527	94	73
7	45	RI	22	67	4936	104	64
8	45	RI * 1.3	54	99	5419	113	53
9	45	RI * 1.6	86	121	5215	122	50
10	45	RI * 2.0	134	179	5875	146	47
11	90	0	0	90	5234	125	71
12	90	RI	23	113	5225	117	49
13	90	RI * 1.3	60	150	5708	140	53
14	90	RI * 1.6	94	184	5569	136	41
15	90	RI * 2.0	138	228	5522	146	37
RI_{NDVI}					1.27		
$RI_{Harvest}$					1.7		
SED					219	9	10

Table 5
Treatment, preplant nitrogen, topdress nitrogen RI factor, topdress nitrogen applied, total nitrogen applied, yield, grain nitrogen uptake, and % NUE for Lake Carl Blackwell, Oklahoma, 2003

Treatment	Preplant N	Topdress N RI	Topdress N applied	Total N applied	Grain yield	Grain N uptake	% NUE
			kg ha^{-1}				
1	0	0	0	0	3207	58	—
2	0	RI	19	19	3570	68	53
3	0	RI * 1.3	58	58	3802	84	45
4	0	RI * 1.6	104	104	4453	102	42
5	0	RI * 2.0	141	141	4453	119	43
6	45	0	0	45	3579	70	27
7	45	RI	23	68	4527	90	47
8	45	RI * 1.3	75	120	4360	100	35
9	45	RI * 1.6	120	165	4472	108	30
10	45	RI * 2.0	139	184	4546	127	38
11	90	0	0	90	4276	105	52
12	90	RI	23	113	4230	94	32
13	90	RI * 1.3	80	170	4341	114	33
14	90	RI * 1.6	117	207	4406	119	30
15	90	RI * 2.0	120	210	4537	117	28
RI_{NDVI}					1.14		
$RI_{Harvest}$					1.3		
SED					313	10	14

in comparison with the maximum yielding plots (treatment 4 = 4453 kg ha^{-1}, and treatment 5 = 4453 kg ha^{-1}; Table 5). At this site, maximum yields were achievable with no preplant N plus a topdress rate for the maximum yielding plot (treatment 10 = 4546 kg ha^{-1}) and also for the N-rich plot (treatment 11 = 4276 kg ha^{-1}).

The CVs (9, 9, and 7) from sensor readings in treatments 1, 6, and 11 at the time topdress N was applied tended to decline as preplant N increased. Consistent with previous work (Oklahoma State University, 2004), CVs were <18, and it was expected that catch-up would be possible, which was confirmed (4453 kg ha^{-1} under treatments 4 and 5 versus 4537 kg ha^{-1} under treatment 15, Table 5).

The NUE at this site varied across all treatments. In general, the 0 preplant-plus-topdress treatments had the highest NUE with the exception of treatment 11 (Table 5).

The RI estimated using in-season NDVI readings slightly underestimated $RI_{Harvest}$ at this site (RI_{NDVI} = 1.14 and $RI_{Harvest}$ = 1.3; Table 5). RI_{NDVI} over time for 2003 did not change much from Feekes 3 to Feekes 4 (RI_{NDVI} = 1.15, 1.13, and 1.14; Table 3). The $RI_{Harvest}$ was higher than the RI_{NDVI} ($RI_{Harvest}$ = 1.3, Table 5).

Tipton, 2003

At Tipton in 2003 where 0 topdress N was applied, there was a linear response to N (treatment 1 = 1357 kg ha^{-1}, treatment 6 = 1264 kg ha^{-1}, treatment 11 = 2082 kg ha^{-1}). Also, there was an increase in wheat grain yield whether or not preplant N was applied (Table 6). Maximum yields were not achieved at this site from mid-season topdress N applications in plots receiving 0 preplant N in comparison with the maximum yielding plot (treatment 14). At this site, it was not possible to catch up with no N preplant plus a topdress N application, even though CVs were relatively low (Table 6). However, it should be noted that catch-up was possible if treatment 5 was compared with treatment 11 (treatment 5 = 2278 kg ha^{-1} and treatment 11 = 2082 kg ha^{-1}).

Table 6
Treatment, preplant nitrogen, topdress nitrogen RI factor, topdress nitrogen applied, total nitrogen applied, yield, grain nitrogen uptake, and % NUE for Tipton, Oklahoma, 2003

Treatment	Preplant N	Topdress N RI	Topdress N applied	Total N applied	Grain yield	Grain N uptake	% NUE
			kg ha^{-1}				
1	0	0	0	0	1357	29	—
2	0	RI	22	22	1311	27	—
3	0	RI * 1.3	45	45	1673	35	13
4	0	RI * 1.6	66	66	1859	43	21
5	0	RI * 2.0	98	98	2278	60	31
6	45	0	0	45	1264	27	—
7	45	RI	30	75	1673	38	12
8	45	RI * 1.3	66	111	2240	56	24
9	45	RI * 1.6	86	131	2092	54	19
10	45	RI * 2.0	129	174	2612	72	25
11	90	0	0	90	2082	50	23
12	90	RI	41	131	2612	67	29
13	90	RI * 1.3	74	164	2808	75	28
14	90	RI * 1.6	123	213	3086	87	27
15	90	RI * 2.0	160	250	3031	90	24
RI_{NDVI}					1.49		
$RI_{Harvest}$					1.5		
SED					190	5	7

Response index estimated using in-season NDVI readings was the same as $RI_{Harvest}$ ($RI_{NDVI} = 1.49$ and $RI_{Harvest} = 1.5$) (Table 6).

Covington, 2004

At Covington in 2004, there was a linear increase in wheat grain yield with increased N where no topdress was applied (treatment 1 = 1985 kg ha^{-1}, treatment 6 = 2846 kg ha^{-1}, and treatment 11 = 3751 kg ha^{-1}, Table 7). At this site, there was a significant increase in wheat grain yield, and N rates required to maximize yields diminished as preplant N rates increased. It should be noted that the highest yielding plot had a 0 preplant rate (treatment 5; Table 7), thus suggesting that catch-up was possible with respect to maximum yield and also with the N-rich plot.

The CVs for treatments 1, 6, and 11 were 18, 21, and 15, respectively. Some of the CVs were $\leq$18, indicating that maximum yields could be achieved even when early-season N stress was present.

Table 7
Treatment, preplant nitrogen, topdress nitrogen RI factor, topdress nitrogen applied, total nitrogen applied, yield, grain nitrogen uptake, and % NUE for Covington, Oklahoma, 2004

Treatment	Preplant N	Topdress N RI	Topdress N applied	Total N applied	Grain yield	Grain N uptake	% NUE
			kg ha^{-1}				
1	0	0	0	0	1985	38	—
2	0	RI_cv	86	86	3736	71	38
3	0	RI * 1.3_cv	129	129	4000	78	31
4	0	RI * 1.6_cv	167	167	4454	92	32
5	0	RI * 2.0_cv	186	186	4831	104	35
6	45	0	0	45	2846	54	36
7	45	RI_cv	108	153	4391	90	34
8	45	RI * 1.3_cv	163	208	4494	96	28
9	45	RI * 1.6_cv	150	195	4598	102	33
10	45	RI * 2.0_cv	163	208	4699	109	34
11	90	0	0	90	3751	81	48
12	90	RI_cv	138	228	4765	112	33
13	90	RI * 1.3_cv	127	217	4601	108	32
14	90	RI * 1.6_cv	130	220	4760	111	33
15	90	RI * 2.0_cv	98	188	4551	98	32
RI_{NDVI}					2.02		
$RI_{Harvest}$					1.89		
SED					254	7	3

The NUEs were generally higher for the 90 kg ha^{-1} preplant treatments (Table 7), most likely because this site was N responsive.

The RI_{NDVI} was slightly overestimated at this site (RI_{NDVI} = 2.02 and $RI_{Harvest}$ = 1.894) (Table 7). The RI_{NDVI} over time for 2004 did not change from Feekes 3 to Feekes 4 (RI_{NDVI} = 1.47, 2.19, 2.18, 2.02, 1.9, and 1.9; Table 3). The $RI_{Harvest}$ differed slightly from the RI_{NDVI} (RI_{NDVI} = 2.02 and $RI_{Harvest}$ = 1.89, Table 3).

Lake Carl Blackwell, 2004

At Lake Carl Blackwell in 2004, there was a linear increase in wheat grain yield where 0 topdress N was applied (treatment 1 = 3047 kg ha^{-1}, treatment 6 = 3502 kg ha^{-1}, and treatment 11 = 3766 kg ha^{-1}, Table 8). Wheat grain yield increased as topdress N rates increased. Maximum yields were achieved at this site from mid-season topdress N applications in plots receiving 0 preplant N (treatment 3 = 3675 kg ha^{-1} versus treatment 11 = 3766 kg ha^{-1}), thus

Table 8

Treatment, preplant nitrogen, topdress nitrogen RI factor, topdress nitrogen applied, total nitrogen applied, yield, grain nitrogen uptake, and % NUE for Lake Carl Blackwell, Oklahoma, 2004

Treatment	Preplant N	Topdress N RI	Topdress N applied	Total N applied	Grain yield	Grain N uptake	% NUE
			kg ha^{-1}				
1	0	0	0	0	3047	46	—
2	0	RI_cv	37	37	3507	61	41
3	0	RI * 1.3_cv	78	78	3675	75	37
4	0	RI * 1.6_cv	104	104	3552	79	32
5	0	RI * 2.0_cv	145	145	3533	82	25
6	45	0	0	45	3502	68	49
7	45	RI_cv	39	84	3760	71	30
8	45	RI * 1.3_cv	88	133	3556	89	32
9	45	RI * 1.6_cv	116	161	3505	90	27
10	45	RI * 2.0_cv	127	172	3355	92	27
11	90	0	0	90	3766	78	36
12	90	RI_cv	47	137	3649	89	31
13	90	RI * 1.3_cv	89	179	3339	82	20
14	90	RI * 1.6_cv	113	203	3471	93	23
15	90	RI * 2.0_cv	122	212	3542	92	22
RI_{NDVI}					1.24		
$RI_{Harvest}$					1.24		
SED					137	6	8

catch-up was possible for this site with 0 preplant plus topdress application in accorance with the highest yielding plot (Table 8).

The CVs at this site varied once again for treatments 1, 6, and 11 (18, 19, and 16, respectively). Consistent with CVs of less than 18, catch-up was possible at this site.

The NUEs were generally higher for the 0 and 45 preplant kg ha^{-1} treatments (Table 8).

Response index estimated using in-season NDVI readings was the same as $RI_{Harvest}$ ($RI_{NDVI} = 1.24$ and $RI_{Harvest} = 1.24$; Table 8). The RI_{NDVI} over time for 2004 varied from Feekes 3 to Feekes 8 (RI_{NDVI} = 1.10, 1.10, 1.11, 1.24, and 1.22). The $RI_{Harvest}$ was the same as the RI_{NDVI} at fertilization (Table 3).

Tipton, 2004

At Tipton in 2004, there was a linear increase in wheat grain yield where 0 topdress N was applied. There was a significant increase in grain yield with applied topdress-N rates for the 0 and 45 kg ha^{-1} preplant rates, with no increase from topdress N for the 90 kg ha^{-1} preplant rates. Maximum yields were achieved at this site from mid-season topdress N applications in plots receiving 0 preplant N with respect to the maximum yielding plot (treatment 8 = 4845 kg ha^{-1}). Catch-up was also possible with respect to the N-rich plot (treatment 11), as treatment 5 out-yielded the N-rich plot. At this site, catch-up was possible with 0 preplant N plus topdress N applications in accordance with the highest yielding plots (Table 9).

The NUEs were generally higher for the plots receiving 0-N preplant plus topdress N (Table 9).

Response index estimated using in-season NDVI readings was underestimated for this site ($RI_{NDVI} = 1.49$ and $RI_{Harvest} = 1.68$, Table 9). RI_{NDVI} over time for 2004 changed from Feekes 3 to Feekes 5 (RI_{NDVI} = .92, 1.09, and 1.49; Table 3). The $RI_{Harvest}$ was different from the RI_{NDVI} at fertilization (Table 9).

DISCUSSION

In this study, six locations had a linear increase in wheat grain yield from topdress N applied to plots receiving 0-N preplant (Tables 4–9). Also, four of the six sites had an increase in wheat grain yield for the topdress N rates whether or not preplant N had been applied (Tables 4–9). Melaj et al. (2003) stated that N uptake increased around the time of maximum crop growth, so application of fertilizer at tillering would increase N fertilizer recovery by the crop. Early-season plant N uptake can lead to increased plant N volatilization (Lees et al., 2000). Boman et al. (1995) stated that a management strategy to reduce N loss would be to apply enough fertilizer N in the fall to establish the crop and apply

Table 9
Treatment, preplant nitrogen, topdress nitrogen RI factor, topdress nitrogen applied, total nitrogen applied, yield, grain nitrogen uptake, and % NUE, for Tipton, Oklahoma, 2004

Treatment	Preplant N	Topdress N RI	Topdress N applied	Total N applied	Grain yield	Grain N uptake	% NUE
			kg ha^{-1}				
1	0	0	0	0	2329	32	—
2	0	RI_cv	48	48	3605	54	46
3	0	RI * 1.3_cv	75	75	3739	63	41
4	0	RI * 1.6_cv	140	140	4394	92	43
5	0	RI * 2.0_cv	173	173	4657	106	43
6	45	0	0	45	3533	50	40
7	45	RI_cv	97	142	4625	94	44
8	45	RI * 1.3_cv	148	193	4845	108	39
9	45	RI * 1.6_cv	151	196	4189	91	30
10	45	RI * 2.0_cv	142	187	4100	94	33
11	90	0	0	90	3909	66	38
12	90	RI_cv	120	210	4196	97	31
13	90	RI * 1.3_cv	140	230	4275	98	29
14	90	RI * 1.6_cv	134	224	4228	90	26
15	90	RI * 2.0_cv	129	219	4154	95	29
RI_{NDVI}					1.49		
$RI_{Harvest}$					1.68		
SED					260	5	4

the remaining N requirement in the late winter or early spring before rapid growth begins. Warm soil temperatures after this time would coincide with rapid wheat growth and also increase nutrient demand.

If N application is made prior to the period of rapid uptake and growth, there is a potential for increased N uptake and NUE (Sowers et al., 1994; Johnston and Fowler, 1991). At all three locations in 2003, the highest NUEs were found where preplant N was applied. In 2004, 0-N preplant plus topdress N treatment generally improved NUE. At two sites where early N stress was severe, preplant N applications were superior to 0-N preplant plus topdress N. Woolfolk et al. (2002) and Gauer et al. (1992) agree that increasing grain protein by applying higher fertilizer N rates is relatively inefficient (NUE decreases with increasing N level), especially under dry soil conditions. In our work, there was one exception at Lake Carl Blackwell in 2003, namely treatment 11 (Table 5). Treatment 11's NUE was almost the same as the highest NUE for the site (treatment 2 = 53 and treatment 11 = 52). Wuest and Cassman (1992a; 1992b) indicated that a late-season N application has greater uptake efficiency and is more effective in increasing grain N levels than N applied at planting.

Alternatively, they noted that preplant N was more effective in increasing grain yields.

This work addresses an interesting question. Can N applications be delayed until mid-season in winter wheat without decreasing wheat grain yields? The majority of farmers in this region of the wheat belt (Oklahoma) apply all of their fertilizer N at planting. Although topdress N applications have become more popular, it is still a common practice to apply anhydrous ammonia(UAN) in the fall at rates exceeding 110 kg N ha^{-1}. The ease of applying liquid UAN topdress and the advent of larger, 20–30 m wide applicators has assisted the extension of delaying fertilizer N until late February.

Because maximum yields were achieved at four of six sites where all N applied was delayed until Feekes 5, this work has useful implications for both efficiency and environmental concerns. Also, all six sites were able to catch up with respect to the N-rich plots; however, it should be noted that five of the six N-rich plots were not the maximum-yielding plots. The RI over time showed little to no change for 2003 across all three sites. However, in 2004, two of the three sites had a change in RI over time. By delaying fertilizer N applications until post dormancy, there is decreased risk of NO_3-N leaching and/or surface fertilizer N runoff when preplant applications are made to the surface without incorporation. Also, by applying fertilizer N to the foliage in late February, increased use efficiency can be realized (foliar N uptake) when compared with preplant soil-applied N (N subject to NO_3-N leaching, immobilization, denitrification, surface volatilization, and early season plant N loss).

These results are not yet definitive concerning whether or not all N should be delayed until mid-season. The reason is that exceptional growing conditions occurred, whereby timely rainfall was received immediately following topdress fertilizer N application, especially during 2004. Although not explicitly evaluated in other work conducted in Oklahoma, there have been dry springs during which delayed topdress fertilizer N was not beneficial and maximum yields were not produced. This fact was evident in many of the GreenSeeker sensor experiments conducted by OSU in 1999, 2000, and 2001, whereby the topdress N plots never achieved the same yields as those found in the N-rich strip (N applied at adequate but not excessive rates preplant) (Oklahoma State University, 2004).

CONCLUSIONS

During 2002–2004, obtaining maximum wheat grain yields from topdress N applications in 0-N preplant plots was possible at four of the six locations. At three of the six sites, the RI projection using in-season NDVI readings was underestimated. Even when early-season N stress was present (0-N preplant), N-applied topdress at Feekes 5 resulted in maximum or near maximum yields at four of six sites when compared with other treatments receiving both preplant and topdress N. Furthermore, when compared with the conventional 90 kg ha^{-1} preplant N, mid-season N applied (0-N preplant) resulted in maximum yields at all six sites. When plot CVs (estimate of plant stand) were >18, maximum yields could not be achieved when N fertilization was delayed until mid-season. Alternatively, when plot CVs were <18, delaying all N fertilization until mid-season resulted in maximum yields and increased NUE.

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