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□ *Midseason fertilizer nitrogen (N) rates based on predicted yields can be projected if the quantity of N accumulated in winter wheat (*Triticum aestivum *L.) and corn (*Zea mays *L.) is known especially early in the growing season. This study was conducted in 2006 and 2007 to establish the amount of N accumulated in corn and winter wheat over the entire growing season. Plots representing three N fertilization rates 0, 45, and 90 kg ha^{-1} at Stillwater and 0, 67, and 112 kg ha^{-1} at Lahoma were selected from two long-term wheat experiments located at research stations in Stillwater and Lahoma, Oklahoma. For corn, three N fertilization rates 0, 112 and 224 kg ha^{-1} at Lake Carl Blackwell and 0, 56 and 112 kg ha^{-1} at Perkins were selected from N studies, located at research stations near Lake Carl Blackwell and Perkins, Oklahoma. Sequential aboveground biomass samples were collected from 1 m^2 area of wheat and 1.5 m long row (0.76 cm spacing) for corn throughout their respective growing seasons. In general, this work showed that more than 45% of the maximum total N accumulated could be found in corn plants by growth stage V8 (8th leaf collar fully unfolded). For winter wheat, more than 61% of the maximum total N accumulated at later stages of growth could be accounted for by Feekes growth stage 5 (F5, leaf strongly erected). Our findings are consistent with those of others showing that yield potential can be predicted at mid-season since such a large percentage of the total N accumulated was accounted for early on in the growing cycle of either wheat or corn.*

Keywords: nitrogen, biomass, corn

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INTRODUCTION

After water, nitrogen (N) is generally the most limiting factor in cereal crop production (Szumigalski and Van Acker, 2006). Continuous crop production depletes soil N; therefore, the addition of N fertilizer is necessary to maintain yields. Since N is required in such large amounts, it is a major economic factor in crop production. Raun and Johnson (1999) estimated N use efficiency (NUE) for world cereal grain production systems, encompassing all application schemes, to be close to 33%. A 20% increase in NUE for cereal production around the world would be worth $10 billion annually (Raun, 2005). This low efficiency is due to loss of plant available N through several mechanisms that are attributed to the lack of synchronization of plant demand and soil or fertilizer supply of N. There is lack of information concerning the peak growth stage of a crop when N accumulation can be optimized. Attempts have been made by researchers to understand peak growth stages of N accumulation by crops, optimum time of application, and movement and translocation of N within the plant (Hanway, 1962; Shanahan et al., 2004; Austin et al., 1977).

Dry matter and N accumulation are associated closely (Justes et al., 1994, 1997) with critical N concentration. Previous research on wheat has shown that N accumulation by the grain is assumed to occur mainly before anthesis. Thus, by maturity, the plant already contains greater than 80% of its final N content (Austin et al., 1977). Hanway (1962) observed that early season N accumulation was relatively rapid; it decreased later in the season and continued at a decreased rate until maturity, whereas Roy and Wright (1974) observed an almost linear increase in the accumulation of N until maturity.

According to Shanahan et al. (2004), with corn, a steady increase in dry matter and N accumulation was observed between the V4 (4th leaf collar fully unfolded) and V8 corn growth stages, after which a fast increase was measured between V8 and R2 (blister) where corn N requirements were anticipated to be high. From R2, another steady state increase was observed until R4 (dough), after which no increase in dry matter or N accumulation was measured. These authors recommended the window between V8 and R2 as the best time to apply side-dress N. Walsh (2006) recommends following pre-plant N applications with midseason side-dress N at or before the V10 (10th leaf collar fully unfolded) growth stage to supply the growing corn with adequate N when it is required in the greatest quantities. Ma et al. (1999) reported that only 20% of the total plant N was accumulated by V6 (6th leaf collar fully unfolded), whereas N accumulation increased considerably until two weeks after R1 (silking), accumulating 50–60% of the total plant N, then N accumulation slowed and ultimately stopped. A by-plant corn N fertilization study showed that forage N accumulation can be predicted from growth stages V8 to V10 (Raun, 2005). A study by Licht and Al-Kaisi (2005) reported that greater than half of the total N accumulated by VT (tasseling) was present by the V12 (12th leaf collar fully unfolded). Another study at Oklahoma State University (Freeman et al., 2007) confirmed these results, reporting that over 50% of the total N was accumulated by V10.

Wuest and Cassman (1992) reported that increasing the rate of preplant N fertilizer in wheat had little effect on postanthesis accumulation of N and that grain N content could be increased by applying N fertilizer at anthesis. The preplant applied N is lost easily by leaching, volatilization, and various other routes before crop uptake. In the same line of work, Stevens et al. (2005a) reported that while the percentage decreased with increasing rate, 20 to 55% of applied fertilizer N was converted to organic or clay-fixed forms during the growing season. Dhugga and Waines (1989) found that the amount of postanthesis accumulation of N was determined by the demand for N in the grain. Mossedaq and Smith (1994) reported that wheat grain yields usually were maximized if N fertilizer was applied just before stem elongation; this effect is due to crop N demand being great at the most rapid phase of crop growth. In corn, N applied at V6 resulted in greater N recovery (Sainz Rozas et al., 2004) than if the fertilizer N was applied at planting.

Past research indicated that wheat (Garabet et al., 1998) or corn (Stevens et al., 2005b) total N accumulation increased with increasing N fertilizer (Garabet et al., 1998; Kanampiu et al., 1997; Sainz Rozas et al., 2004; Stevens et al., 2005a, 2005b). Cox et al. (1993) reported that N concentrations of corn plants at V8 and V16 (16th leaf collar fully unfolded) display linear responses to increasing N rates suggesting that forage quality improves with additional N. Devienne-Barret et al. (2000) observed that the rate of N accumulation of a crop is determined by its growth rate (without any N deficiency) and the soil N concentration.

Differences in the level of translocation of preanthesis N and rates of N accumulation, contribute to differences in grain yield and grain N content in corn (Muchow, 1988). Also, Hanway (1962) suggested that the demand of N during the grain-filling process is so great that it may not be possible for the plant to maintain the level of accumulation required to fulfill that need. Therefore, the plant compensates by translocating N to the grain from other parts of the plant.

The literature presents contradicting information as to the growth stage in which wheat or corn accumulates N and the appropriate time of N fertilizer application to optimize use efficiency. The previous research addressed specific work documenting N accumulation in wheat or corn with limited number of sampling times. It is indispensable to collect comprehensive data over critical growth stages of these two crops to define the optimum growth stage for mid-season N application. Furthermore, accumulation of N as a function of time under limiting and non-N limiting conditions within the same trial has not been documented. Therefore the objectives of this study were to quantify the aboveground dry biomass and amount of N accumulated in winter wheat or corn over the entire growing season under N-limiting or non-N-limiting conditions.

MATERIALS AND METHODS

Two years of data (2006 and 2007) were collected to assess aboveground dry biomass and N accumulation in winter wheat or corn throughout their growing seasons. Total rainfall by month for each site and year is reported in Table 1.

Corn

Two experiments were superimposed on previously established long-term experiments. In the spring of 2006, the first corn experiment was superimposed on the Lake Carl Blackwell (LCB), Oklahoma N study at the Robert L. Westerman Irrigated Research Facility. This site is located on a Paluski fine sandy loam (coarse-loamy, mixed, superactive, nonacid, thermic Udic Ustifluvent). In the Spring of 2007, an additional N Study experiment was initiated to further evaluate cereal N accumulation. This site is located on a Teller fine sandy loam (fine-loamy, mixed, active, thermic Udic Argiustoll) at the Cimarron Valley Research Station in Perkins, Oklahoma. The experimental design of both long-term corn experiments

TABLE 1 Total monthly rainfall at Lahoma (Experiment 502), Stillwater (Experiment 222), Lake Carl Blackwell, and Perkins, for the 2005–06, and 2006–07 growing seasons

	Experiment 502		Experiment 222		Lake Carl Blackwell		Perkins
	2005–06	2006–07	2005–06	2006–07	2006	2007	2007
Month†			Rainfall, cm‡				
September	2.9	0.9	9.0	3.4			
October	6.4	1.5	4.8	4.0			
November	0.2	1.8	0.0	3.2			
December	1.0	4.3	0.2	7.1			
January	0.3	1.9	1.8	3.4			
February	0.0	0.7	0.2	1.1			
March	7.0	12.4	4.7	13.9	4.7	13.9	13.4
April	5.1	6.7	13.1	10.5	13.1	10.5	7.1
May	1.9	13.1	8.5	26.5	8.5	26.5	25.8
June					6.1	42.5	35.2
July					8.0	17.8	17.6
August					4.5	0.0	5.8
September					—	—	6.2
Total (cm)	24.7	43.2	42.1	73.0	44.8	111.2	111.1

†For wheat, growing season begins in the fall and ends in the summer of the following year.
‡Data obtained from the Oklahoma Mesonet (Oklahoma Mesonet, 2007).

consisted of 13 treatments arranged in a randomized complete block design with three replications. Three treatments were used from both experiments representing 0, 112, and 224 kg N ha^{-1} from LCB and 0, 56, and 112 kg N ha^{-1} from Perkins; all N was applied preplant. At both sites, the individual plots measured 3-m wide by 6-m long with 4 rows, of which 1.5-m of row were harvested at each growth stage from the border rows. Nitrogen was applied as urea ammonium nitrate (28% N), and phosphorus (P), and potassium (K) were applied as triple superphosphate fertilizer (20% P) and potassium chloride (50% K) to sufficiency level. The variety 'DKC 66-23' was planted on 31 March 2006, and 6 April 2007 on 76-cm wide rows at a seeding rate of 78,300 seeds ha^{-1} at LCB, and the variety 'DKC 50-20′ was planted on May 16, 2007, on 76-cm wide rows at a seeding rate of 60,000 seeds ha^{-1} at Perkins. For weed control, 4.7 L ha^{-1} and 3.5 L ha^{-1} of 'Brawl II ATZ' {033.0% Atrazine (2-chloro-4-ethylamino-6-isopropylamino-s-triazine) and 26.1% s-Metolachlor [Acetamide, 2-chloro-N-(2-ethyl-6-methylphenyl)-N-(2-methoxy-1-methylethyl)-, (S)]; Tenkoz, Inc., Alpharetta, GA, USA}, were applied at planting at LCB and Perkins, respectively, for all site years. Corn aboveground dry biomass samples were collected from 1.5-m of row, at various growth stages throughout the growing seasons. Samples were collected at corn developmental stages (Ritchie et al., 1997) V6, V8, V10, V12, VT, R1, R3 (milk), R5 (dent) and R6. Harvesting, growth stages, and number of days from planting to destructive aboveground biomass sampling where growing degree days were greater than zero (GDD $>$ 0) are presented in Table 2 for corn.

Winter Wheat

Two winter wheat experiments also were superimposed on previously established long-term trials. The first experiment was superimposed on Experiment 222 located at the Stillwater Agronomy Research Station. Experiment 222 was established in 1969 on a Kirkland silt loam (fine, mixed, superactive, thermic Udertic Paleustoll). The second experiment was superimposed on long-term Experiment 502 initiated in 1970 at the North Central Experiment Station in Lahoma, OK. Experiment 502 is located on a Grant silt loam (fine-silty, mixed, superactive, thermic Udic Argiustoll). The experimental design for Experiment 222 was a randomized complete block with a total of 13 treatments and four replications. The experimental design for Experiment 502 was also a randomized complete block with 14 treatments and four replications. For the objective at hand, only those treatments that received only preplant N were used from these long-term fertility experiments. Three treatments were used from Experiment 222, representing application rates of 0, 45, and 90 kg N ha^{-1}, likewise three treatments were used from Experiment 502, representing N application rates of 0, 67, and 112 kg N ha^{-1}. Both experiments were established under conventional tillage. Individual plots of

TABLE 2 Harvest date, growth stage, and number of days from planting to destructive aboveground biomass sampling where growing degree days were greater than 0 (GDD > 0) in corn experiments, 2006–2007

2006			2007		
Harvest date	Growth stage†	GDD‡ > 0	Harvest date	Growth stage	GDD > 0
		Corn, Lake Carl Blackwell			
5-16-06	V6	46	6-5-07	V10	61
2-22-06	V8	52	6-19-07	R1	75
6-2-06	V12	63	7-2707	R5	113
6-13-06	VT	74	8-17-07	R6	134
		Corn, Perkins			
—	—	—	6-18-07	V6	34
—	—	—	7-3-07	V8	49
—	—	—	7-13-07	VT	59
—	—	—	7-27-07	R2	73
—	—	—	9-12-07	R6	120

†Corn growth stages as defined by Ritchie et al. (1997) are as follows: V6, 8, 10 and 12- 6th, 8th, 10th and 12th leaf collar fully expanded, respectively; VT- Tassel fully emerged; R1,2, 5 and 6- silking, blister, dent and maturity, respectively.

‡Number of days from planting to destructive aboveground biomass sampling where GDD [(Tmin + Tmax in °C)/2–4.4°C] was more than 0.

both experiments measured 18-m long however, they differed in widths, with plots at Experiment 222 measuring 6-m wide and those at 502 measuring 5-m wide.

The variety ‘Endurance’ was planted on 7 October 2005 and 3 October 2006, on 15-cm wide rows at seeding rates of 95 kg ha^{-1} at Experiment 222. The variety ‘Overley’ was planted on 15 October 2005 and 2 October 2006 in 19-cm rows at a seeding rate of 83 kg ha^{-1} at Experiment 502 in both years. At Experiment 222, N was applied one day before planting using urea (46% N) with, 30 and 37 kg ha^{-1} P and K, respectively. At Experiment 502, P was applied one day before planting at 20 kg P ha^{-1}. At this site K was applied preplant to all treatments at rate of 56 kg K ha^{-1}. For both sites, the P source was triple superhosphate (20% P), and the K source was potassium chloride (50% K). For the control of weeds, 2.34 L ha^{-1} of diclofop-methyl (34.7% methyl-2-[4-(2,4-dichlorophenoxy) phenoxy] propanoate; Bayer Crop Science, Raleigh, NC, USA) were applied in January for all site years. In addition, 22 mL ha^{-1} of ‘Finesse herbicide’ {62.5% of chlorsulfuron (2-chloro-N-[(4-methoxy-6-methyl -1,3,5-triazin-2-yl)aminocarbonyl] benzenesulfonamide) and 12.5% of Metsulfuron (methyl (methyl 2-[[[[(4-methoxy-6-methyl-1,3,5-triazin-2-yl)amino]carbonyl] amino]sulfonyl]benzoate); DuPont, Wilmington, DE, USA} was applied to Experiment 222 in January 2006 and both years to Experiment 502. Furthermore, ‘Olympus Flex’ (6.75% propoxycarbazone-sodium and 4.50% mesosulfuron-methyl, Bayer CropScience) was applied at 55 mL ha^{-1} to Experiment 222 in November 2006.

Winter wheat aboveground dry biomass samples were collected from 1-m^2 areas at various growth stages throughout the growing seasons. Samples were collected at Feekes growth stages (Large, 1954) F3 (tillers formed), F4 (leaf sheaths lengthen, F4.5 (leaf sheaths erect), F5, F6 (first node visible, F7 (second node visible), F10 (boot stage), F10.4 (heading 3/4 complete), F10.5 (heading complete), F10.5.3 (flowering complete to base of spike), F10.5.4 (kernels watery ripe), F11.1 (milky ripe), F11.2 (nearly ripe) and F11.4 (harvest ready). Harvesting, growth stages, and number of days from planting to destructive aboveground biomass sampling where growing degree days were greater than zero are presented in Table 3 for winter wheat.

Sampling and Analysis

Aboveground biomass was harvested at the crown of the wheat plant at each growth stage with hand clippers and hand chopped at the crown

TABLE 3 Harvest date, growth stage, and number of days from planting to destructive aboveground biomass sampling where growing degree days were greater than 0 (GDD > 0) in winter wheat experiments, 2006–2007

2006			2007		
Harvest date	Growth stage†	GDD‡ > 0	Harvest date	Growth stage	GDD > 0
Winter wheat, Experiment 502					
1-19-06	F4	70	2-20-07	F4	82
3-7-06	F5	97	3-6-07	F5	95
3-13-06	F6	103	3-15-07	F6	104
3-29-06	F7	114	4-24-07	F10.5.3	142
4-14-06	F10.4	130	5-5-07	F11.1	152
5-5-06	F11.1	151	5-17-07	F11.2	164
6-5-06	F11.4	182	6-11-07	F11.4	189
Wheat, Experiment 222					
1-4-06	F3	67	2-8-07	F4	79
1-12-06	F5	72	2-22-07	F4.5	84
3-9-06	F6	114	3-8-07	F5	96
3-27-06	F7	124	3-19-07	F6	107
4-4-06	F10.5	143	4-3-07	F10.0	122
5-3-06	F11.2	162	4-16-07	F10.5	132
5-26-06	F11.4	185	4-30-07	F10.5.4	146
—	—	—	5-14-07	F11.1	160
—	—	—	6-6-07	F11.4	183

†Feekes (F) wheat growth stages as defined by Large (1954) are as follows: F3- tillers formed, F4- leaf sheaths lengthen, F4.5- leaf sheaths lengthen, F5- leaf sheaths strongly erect, F6- first node visible, F7- second node visible, F10- boot stage, F10.4- heading $\frac{3}{4}$ complete, F10.5- heading complete, F10.5.3- flowering complete to base of spike, F10.5.4- kernels watery ripe, F11.1- milky ripe, F11.2- nearly ripe and F11.4- harvest ready.

‡Number of days from planting to from planting to destructive aboveground biomass sampling where GDD [(Tmin + Tmax in °C)/2–4.4°C] was more than 0.

of the corn plant with a machete. Wet above ground biomass samples were weighed and dried in a forced air oven at 60°C for 10 days and weighed again before grinding. Samples were ground to pass a 0.125-mm (120-mesh) sieve. The aboveground dry biomass N content was determined with a Carlo-Erba (Milan, Italy) NA-1500 dry combustion analyzer using the procedure outlined by Schepers et al. (1989) for both crops. At the later growth stages, the straw and grain of wheat and stover and grain of corn were separated for analysis. Aboveground dry biomass and N accumulation were then determined and recorded. However, the sum of the separated components was used to obtain the aboveground dry biomass produced per plot. Total N accumulation was computed by summing the total of the parts times percent N in aboveground dry biomass when morphological separation was required (grain and straw for wheat, stover and grain for corn).

All data were subjected to analysis of variance (ANOVA) using procedures in SAS (SAS, Cary, NC, USA) mainly Mixed Procedure (PROC MIXED). After preliminary statistical analysis showed a significant site and year effect, data were analyzed for each site-year. Additionally, main effects of growth stage and N rates and their interactions were significant for all site-years at $P \leq 0.05$ for both crops. Therefore, simple effects (Winer, 1971) of growth stage and N rate were tested for each site-year. Unequally spaced orthogonal polynomial contrasts were fitted to aboveground dry biomass and N accumulation data for growth stages (using corresponding GDD > 0 for each growth stage) for each site-year. Polynomial (or trend) contrasts are appropriate when there are increasing levels of a factor (such as dosage) or when the levels are defined by time intervals (Keppel, 1991). The coefficients for this analysis were developed using SAS/IML procedure (SAS). Likewise, equally spaced orthogonal polynomial contrasts were fitted to aboveground dry biomass and N accumulation data for N rates for each site-year. Least-square means (LS means), significance of simple effects of N rate and growth stage (using GDD > 0), and corresponding polynomial orthogonal contrasts for each site-year are presented in Tables 4 (corn) and 5 (wheat).

RESULTS

Aboveground Dry Biomass Accumulation in Corn

In 2006, at LCB, above ground dry biomass accumulation showed a linear relationship with corn growth stage for the 0 kg ha^{-1} N rate and a quadratic relationship for 112 and 224 kg ha^{-1} N rates (Table 4). For all N rates, aboveground dry biomass slowly increased from growth stages V6 to V8, after which the amount accumulated increased to V12 (Table 4). Accumulation continued to increase until VT for the 0 and 224 kg ha^{-1} N rates, whereas the 112 kg ha^{-1} N rate showed a slight decrease in the amount of aboveground dry biomass after V12.

TABLE 4 Means, significance of simple effect of N rates and growth stage (GDD > 0), and corresponding polynomial orthogonal contrasts for corn experiments conducted at Lake Carl Blackwell (LCB) in 2006 and 2007, and Perkins, 2006–2007

Growth stages/ GDD > 0	Biomass, kg ha^{-1} N rate, kg ha^{-1}						N accumulation, kg ha^{-1} N rate, kg ha^{-1}					
	0	112	224	Effect	L[£]	Q	0	112	224	effect	L	Q
	Corn experiment LCB, 2006											
V6/46	695	1264	1174	*[†]	*	*	11.6	39.1	42.1	**	**	ns
V8/52	966	2350	1761	*	ns	*	14.8	59.1	56.8	*	*	*
V12/63	2712	6037	5760	*	*	*	32.3	115.2	130.6	*	*	ns
VT/74	3789	5484	6331	*	*	ns	42.3	67.8	104.3	**	**	ns
Effect	***	***	***				***	*	**			
L	***	***	***				**	**	**			
Q	ns	*	**				ns	*	*			
	Corn experiment LCB, 2007											
V10/61	1249	2186	2236	*	*	ns	19.7	50.3	54.9	**	**	*
R1/75	4318	6366	5981	*	*	*	41.2	84.1	119.6	**	**	ns
R5/113	11606	18777	24166	ns	*	ns	70.8	162.0	155.9	***	***	*
R6/134	7416	12938	15962	ns	*	ns	46.9	103.5	125.3	***	***	ns
Effect	**	***	***				*	*	*			
L	***	***	***				*	ns	*			
Q	ns	*	***				*	**	*			
	Corn experiment Perkins, 2007											
	0	56	112	Effect	L	Q	0	56	112	Effect	L	Q
V6/34	167	277	356	ns	*	ns	4.2	8.5	12.1	*	*	ns
V8/49	891	1547	1460	***	***	**	10.1	18.9	25.5	**	***	ns
VT/59	1887	2950	4004	**	***	ns	—[‡]	—	—	—	—	—
R2/73	3870	4378	6141	*	**	ns	29.2	31.8	56.3	*	**	ns
R6/120	6220	7440	8502	ns	*	ns	—	—	—	—	—	—
Effect	***	***	***				***	**	***			
L	*	***	***				***	***	***			
Q	ns	ns	ns				ns	ns	ns			

[£]L and Q denote linear and quadratic trends. [†] *, **significant at the 0.05, 0.01 and 0.001 probability levels, respectively. [‡]data missing; corn growth stages are as defined in Table 2.

GDD > 0—number of days from planting to destructive aboveground biomass sampling where GDD [(Tmin + Tmax)/2–4.4°C] was more than 0.

Means and probabilities down a column represent growth stage effects, whereas, means and probabilities across a row represent N rate effects.

At this location in 2006, biomass accumulation was significantly affected by N rate at each corn growth stage. Accordingly, it had quadratic trends for all stages except VT, where only linear trend was observed (Table 4). There were differences between the 0 kg ha^{-1} treatment and those that received fertilizer throughout the entire growing season; however, they were greatest at V12. So, the 112 kg ha^{-1} N rate accumulated 3325 kg ha^{-1} more aboveground dry biomass than the 0 kg ha^{-1} N rate. Similarly, the 224 kg

ha^{-1} N rate accumulated 3048 kg ha^{-1} more aboveground dry biomass than the 0 kg ha^{-1} N rate.

Similar relationships as LCB in 2006 were observed between corn aboveground dry biomass and stage at LCB in 2007 (Table 4). In 2007 at LCB, for all N rates, aboveground dry biomass accumulation increased slowly from growth stage V10 to R1, followed by a rapid accumulation reaching a maximum at R5 (Table 4). A linear N rate trend was observed at V10, R5 and R6 stages although N rate simple effect was not significant for the latter two growth stages. At R1, biomass accumulation had a quadratic relationship with N rate. At R5, the largest differences in aboveground dry biomass occurred with the 0 kg ha^{-1} N rate having 7171 and 12,560 kg ha^{-1} less aboveground dry biomass than the 112 and 224 kg ha^{-1} N rates in the order given (Table 4).

At Perkins in 2007 aboveground biomass accumulation increased linearly with stage for 0 and 56 kg ha^{-1} N rates. The relationship was quadratic for 112 kg ha^{-1} N rate (Table 4). At this site, for all N rates, aboveground dry biomass accumulation increased throughout the entire growing season reaching a maximum accumulation at R6 (Table 4). Except at V8, N accumulation in corn was linearly related to N rate. The 0 kg ha^{-1} N rate accumulated only slightly less aboveground dry biomass until V8 (Table 4), afterwards aboveground dry biomass differences due to N rate became more pronounced. The 112 kg ha^{-1} N rate had the highest aboveground dry biomass at all growth stages after V8 (Table 4). By R6 it had 2282 kg ha^{-1} more aboveground dry biomass than the 0 kg N ha^{-1} rate and 1062 kg ha^{-1} more aboveground dry biomass than the 56 kg N ha^{-1} rate.

Nitrogen Accumulation in Corn

At LCB in 2006, N accumulation had a linear relationship with growth stage for 0 kg N ha^{-1} and a quadratic relationship for 112 and 224 kg N ha^{-1} rates (Table 4). For both 112 and 224 kg ha^{-1} N rates, N accumulation increased slowly from V6 to V8 (13 kg N ha^{-1}), followed by a rapid increase until reaching its maximum of 115 and 131 kg N ha^{-1} at V12 for the 112 and 224 kg ha^{-1} N rates, respectively (Table 4). By the V8 growth stage, 35, 51 and 44% of the total N was accumulated for the 0, 112 and 224 kg N ha^{-1} rates in the order given (Table 4).

Except at V8, which showed quadratic relationship, N accumulation was linearly related to N rate (Table 4). Corn growth stage VT had the highest rate of N accumulation throughout the season. In contrast, the other growth stages had fast accumulation from 0 to 112 kg N ha^{-1} rate and a subsequent slow accumulation as the crop progressed to maturity. Looking at the data differently, at V12, the 0 kg ha^{-1} N rate had 83 kg ha^{-1} less N accumulated than the 112 kg N ha^{-1} rate. As well, this same no N' treatment had 98 kg ha^{-1} less N than the highest N rate (224 kg N ha^{-1} rate).

At LCB in 2007, N accumulation had a quadratic relationship with growth stage attaining a maximum at R5 for all N rates (Table 4). The 0 kg N ha^{-1} rate had a relatively small accumulation rate compared to 112 and 224 kg N ha^{-1} rates, which had a similar accumulation rate. (Table 4). Nitrogen accumulation in corn had a quadratic relation with N rate at V10 and R5, and a linear relationship at R1 and R6. At R5, the 112 and 224 kg N ha^{-1} rates accumulated more than 88 kg ha^{-1} N than that of the 0 kg ha^{-1} N rate.

At Perkins in 2007, N accumulation increased linearly with growth stage (Table 4). Averaged over N rates, it accumulated an average of 10 kg N ha^{-1} from V6 to V8, followed by a further increase of 12 kg N ha^{-1} from R2 stages (Table 4). Unlike what was observed at LCB in 2007, N accumulation continued to increase until late in the growing season (Table 4). However, at this site, total amounts accumulated were much lower than that of LCB, consistent with the low yield potential on this sandy soil as the result of its being drought prone. Differences among N rates were significant at all growth stages. Nitrogen accumulation was linearly related to N rate at all stages except V8, where trend was quadratic (Table 4). The 112 kg N ha^{-1} rate accumulated the highest amount of N at all growth stages and had taken up an additional 39 and 50 kg N ha^{-1} than the 0 and 56 kg ha^{-1} N rates, respectively. At V8, the N accumulated was 20% (0 kg ha^{-1} rate), 31% (56 kg N ha^{-1} rate) and 25% (112 kg N ha^{-1} rate) of the total accumulation

Aboveground Dry Biomass Accumulation in Winter Wheat

In 2006 at Experiment 502, aboveground dry biomass had a linear relationship with stage for 0 kg ha^{-1} N rate and a quadratic relationship for 67 and 112 kg ha^{-1}. The accumulation of aboveground dry biomass increased until reaching a maximum at F11 for N rates of 67 and 112 kg ha^{-1}, after which aboveground dry biomass accumulation decreased (Table 5). By F11, the treatment effects became more pronounced having aboveground dry biomass accumulation of 4570 (at the 0 kg ha^{-1}), 6239 (at the 67 kg N ha^{-1} rate), and 7446 kg ha^{-1} (at the 112 kg N ha^{-1} rate). Looking at that same growth stage, 3.55, 3.37 and 3.75 times as much aboveground dry biomass had been accumulated since growth stage F4 in the 0, 67 and 112 kg N ha^{-1} rates, respectively. Likewise, biomass accumulation had shown a linear trend for N rate for all growth stages at Experiment 502 in 2006. In 2007 at Experiment 502, above ground biomass accumulation had an overall linear relationship with stage for all N rates (Table 5). Averaged over all N rates, the accumulation of aboveground dry biomass increased slowly until F6, after which the rate of accumulation increased to its most rapid rate until F10.5.3, gaining an additional 4444 kg ha^{-1} in that period (Table 5). Then, aboveground dry biomass decreased until F11.1 where a drop of 806 kg ha^{-1} was observed on average. Aboveground dry biomass increased again, reaching its maximum accumulation with an average of 9267 kg ha^{-1} at F11.2.

TABLE 5 Means, significance of simple effect of N rate and growth stage (GDD > 0) and corresponding polynomial orthogonal contrasts for winter wheat experiment 502 in Lahoma, Oklahoma, 2006–2007

Growth stages/	Biomass, kg ha^{-1} N rate, kg ha^{-1}						N accumulation, kg ha^{-1} N rate, kg ha^{-1}					
GDD > 0	0	67	112	Effect	L[£]	Q	0	67	112	Effect	L	Q
				Winter wheat Experiment 502, 2006								
F4/70	1287	1849	1988	**[†]	**	ns	33	60.7	73.5	***	***	ns
F5/97	1740	3060	3360	ns	*	ns	30.1	67.2	84.4	ns	*	ns
F6/103	2124	3043	3415	*	**	ns	44.5	70	89.8	*	**	ns
F7/114	2294	3745	4095	*	**	ns	31.1	60.2	82.9	**	**	ns
F10.4/130	2847	4825	5455	**	**	ns	48.8	107	141	**	**	ns
F11/151	4570	6239	7446	*	*	ns	-[‡]	—	—	—	—	—
F11.4/182	3814	3893	6294	*	*	ns	25.2	30.2	60.6	*	**	ns
Effect	***	***	***				ns	***	***			
L	***	***	***				ns	**	ns			
Q	ns	**	*				ns	***	***			
				Winter wheat Experiment 502, 2007								
F4/82	1815	1706	1531	ns	ns	ns	59.9	72.5	70.4	ns	ns	ns
F5/95	1597	1837	1990	ns	ns	ns	44.9	66.9	77.2	*	**	ns
F6/104	2187	2734	3171	**	**	ns	44.1	93	138.9	***	***	ns
F10/128	3631	5162	7217	*	**	ns	60.9	105.3	245.1	ns	*	ns
F10.5.3/142	5593	7907	7925	ns	ns	ns	81.9	115.2	134.4	ns	ns	ns
F11.1/152	4768	6518	7721	*	*	ns	48.3	80.7	124.8	*	**	ns
F11.2/164	8195	10608	11045	ns	ns	ns	70.9	107.3	137.2	ns	ns	ns
F11.4/189	4418	8465	8836	***	***	ns	76	—	203	—	—	—
Effect	***	***	***				ns	***	***			
L	***	***	***				*	***	***			
Q	ns	ns	*				ns	**	ns			

[£]L and Q denote linear and quadratic trends; [†] *, **, *** significant at the 0.05, 0.01 and 0.001probability levels, respectively; [‡] data missing; wheat growth stages are as defined in Table 3.

GDD > 0—number of days from planting to destructive aboveground biomass sampling where GDD [(Tmin + Tmax)/2–4.4°C] was more than 0.

Means and probabilities down a column represent growth stage effects, whereas, means and probabilities across a row represent N rate effects.

At Experiment 502 in 2007, N rate effect on biomass accumulation was significant at F6, F10, F11.1 and F11.4, with a positive linear relationship (Table 5). The largest difference between the 0 kg N ha^{-1} rate and the other N rates at this site occurred at F11.4, with the 0 kg N ha^{-1} treatment having 4047 and 4418 kg ha^{-1} less aboveground dry biomass than the 67 and 112 kg ha^{-1} N rates, respectively.

In 2006 at Experiment 222, the 0 kg N ha^{-1} rate accumulated aboveground dry biomass slowly from Feekes growth stages 3 to 6, after which the rate of accumulation steadily increased, accumulating an additional 1201 kg ha^{-1} until F11.2 (Table 6). Overall, aboveground dry biomass accumulation showed a linear trend achieving the highest accumulation (2203 kg ha^{-1}) at F11.4, although there was a slight decrease in the amount of biomass accumulated at F10.5 for the 45 kg N ha^{-1} rate. The 90 kg N ha^{-1} rate did

TABLE 6 Means, significance of simple effect of N rate and growth stage (GDD > 0) and corresponding polynomial orthogonal contrasts for winter wheat experiment 222 in Stillwater, Oklahoma, 2006–2007

Growth stages/ GDD > 0	Biomass, kg ha^{-1} N rate, kg ha^{-1}						N accumulation, kg ha^{-1} N rate, kg ha^{-1}					
	0	45	90	Effect	L[£]	Q	0	45	90	Effect	L	Q
				Winter wheat Experiment 222, 2006								
F3/67	383.5	1250	1710	***†	***	ns	7.2	28.8	45.8	***	***	ns
F5/72	466	1388	2249	***	***	ns	—	—	—	—	—	—
F6/114	473	1619	2494	***	***	ns	9.8	31.7	46.4	***	***	ns
F7/124	753	1521	2494	***	***	ns	13.9	28.5	52.5	***	***	ns
F10.5/143	1072	1321	2072	***	***	ns	16.6	20.9	44.7	***	***	ns
F11.2/162	1673	2150	2545	**	***	ns	—‡	—	—	—	—	—
F11.4/185	1850	2203	2316	ns	ns	ns	14.2	17.8	26.9	**	**	ns
Effect	***	*	ns				***	***	***			
L	***	***	ns				*	ns	ns			
Q	ns	ns	ns				ns	*	***			
				Winter wheat Experiment 222, 2007								
F4/79	1550	2578	2409	**	*	ns	28.8	51.6	66.1	***	***	ns
F4.5/84	1212	2655	2288	***	**	**	25.4	66.1	66.1	***	***	*
F5/96	931	1810	3066	***	***	ns	19.4	52.9	109.3	***	***	ns
F6/107	2075	2887	3318	***	***	ns	42.4	77.1	106.2	***	***	ns
F10/122	1612	3349	4119	***	***	ns	26	70.2	89.7	***	***	ns
F10.5/132	1301	3866	4852	***	***	ns	17.1	56.1	81.3	***	***	ns
F10.5.4/146	2223	4496	6970	***	***	ns	26.2	48.8	97.6	***	***	ns
F11/160	2954	6520	7659	***	***	ns	—	—	—	—	—	—
F11.4/183	2753	4424	6323	***	***	ns	—	—	—	—	—	—
Effect	ns	***	***				ns	ns	***			
L	**	***	***				ns	*	ns			
Q	ns	*	*				ns	ns	**			

[£]L and Q denote linear and quadratic trends; [†] *, **, *** significant at the 0.05, 0.01 and 0.001 probability levels, respectively; [‡] data missing; wheat growth stages are as defined in Table 3.

GDD > 0—number of days from planting to destructive aboveground biomass sampling where GDD [(Tmin + Tmax)/2–4.4°C] was more than 0.

Means and probabilities down a column represent growth stage effects, whereas, means and probabilities across a row represent N rate effects.

not show a significant trend in biomass accumulation as corn continued to senescence and maturity.

In 2007 at Experiment 222, aboveground dry biomass accumulation had a quadratic relationship with growth stage for 45 and 90 kg N ha^{-1} rates, and a linear trend for 0 kg N ha^{-1} rate. Averaged overall levels of N rate, biomass increased reaching a maximum of 5034 kg ha^{-1} at Feekes growth stage 11 (Table 6).

A linear trend among N rates was observed for biomass accumulation for all growth stages but F4.5, which showed a quadratic trend (Table 6). The 90 kg ha^{-1} N rate accumulated the highest biomass at later growth stages. Prior to F5, however, the 45 kg ha^{-1} N rate had the largest amount of aboveground dry biomass, with 1235, and 268 kg ha^{-1} more aboveground dry biomass than the 0 kg N ha^{-1} rate, and 90 kg ha^{-1} N rates, respectively (Table 6). Nitrogen rate effects were most evident at F11 with differences in aboveground dry biomass that received fertilizer N averaging 7089 kg ha^{-1}, whereas the 0 kg N ha^{-1} averaged 2954 kg ha^{-1}.

It was important to note the large differences in aboveground dry biomass production between 2006 versus 2007 (Tables 5 and 6) for Experiments 222 and 502. Conditions were good for mid-season aboveground dry biomass production in 2007, whereas in 2006, prolonged drought existed through much of the season. Difference in aboveground dry biomass accumulation was 3572 kg ha^{-1} (at Stillwater) and 3182 kg ha^{-1} (at Lahoma) between 2007 and 2006. These differences may be attributed to the 2007 season achieving a higher yield potential due to large differences in rainfall between the two years (Table 1). The total rainfall for the 2006 growing season was 25 and 42 cm, whereas the total rainfall for the 2007 growing season was 43 and 73 cm, for Lahoma and Stillwater, respectively (Oklahoma Mesonet, 2007).

Nitrogen Accumulation in Winter Wheat

In 2006 at Experiment 502, N accumulation had a quadratic relationship with growth stage for 67 and 112 kg N ha^{-1} rates. For Experiment 502 in 2006, no significant changes were observed from F4 to F7, largely because very little rainfall was received during this time period. After F7, N accumulation dramatically increased reaching a maximum accumulation. For the 112 kg N ha^{-1} rate the maximum was 140 kg N ha^{-1} at F10.4 (Table 5). There was little change in N accumulation for the 0 kg N ha^{-1} treatment throughout the growing season (Table 5). Again, this result may be due to the crop having received only 25 cm of rainfall during the growing season thereby the check plot received little N from atmospheric deposition or mineralization. Ockerman and Livingston (1999) reported that total N deposition increased exponentially with increase in seasonal rainfall. By F5, 62% of the total N accumulated throughout the cycle had been taken up in the 0 and 112 kg N ha^{-1} rates, whereas 63% of the total was already accumulated in the plant in the 67 kg N ha^{-1} treatment (Table 5). Nitrogen accumulation in winter wheat increased as N rate increased for all growth stages. The smallest increase (6.4 kg N ha^{-1}) occurred at F4, whereas the largest increase occurred at F11 (Table 5). At this site in 2006, at early growth stages, the rate of N accumulation in wheat was lower with increase in N rate than latter growth stages.

In 2007 at Experiment 502, N accumulation showed a linear relationship with growth stage for 0 and 112 kg ha^{-1} N rates, and a quadratic relationship for 67 kg N ha^{-1} rate. For the 0 kg N ha^{-1} rate, N accumulation decreased from F4 to F6, followed by an increase until F10.5.3 (Table 5). Nitrogen accumulation then slightly declined to F11.1, followed by another increase to reach its highest accumulation at F11.2. The 67 kg N ha^{-1} rate began a slow increase of N accumulation during the early growing season, followed by decline at F11.1, and then rapid increase to a maximum accumulation at F11.2. With the application of 112 kg N ha^{-1}, accumulation of N in winter wheat steadily rose reaching a maximum at F11.2 and leveled off at F11.2. Fifty-five, 57 and 56% of the total N was accumulated by F5 for the 0, 67, and 112 kg N ha^{-1} rate, respectively (Table 5).

Nitrogen accumulation had a linear relationship with N rate at F5, 6, 10 and 11.1. The highest N accumulation occurred at F10. Accordingly, with the application of 112 kg N ha^{-1}, 184 and 139 kg ha^{-1} more N was accumulated compared with 0 and 67 kg ha^{-1} N rates, respectively.

For Experiment 222 in 2006, N accumulation was linearly related to growth stage for 0 kg N ha^{-1} and had a quadratic relationship for 45 and 90 kg N ha^{-1} rates. Nitrogen accumulation slowly increased reaching a maximum accumulation early in the growing season (Table 6). The 0 kg N ha^{-1} treatment slowly accumulated N reaching a maximum at F10, whereas the 45 and 90 kg ha^{-1} N rates reached a maximum accumulation at F6 and 7, respectively and declined as the season progressed.

Winter wheat N accumulation at this site in 2006 linearly increased as N rate increased except (Table 6). Although the total N accumulation was low, the N rate effects were evident throughout all growth stages. Again, this low N accumulation was attributed to the low yield potential and drought stress conditions present throughout much of the growing season. The application of pre-plant N resulted in enhanced early season growth, but as the season progressed with virtually no rainfall from November to early March (Table 1), those treatments receiving N actually lost aboveground dry biomass due to tiller abortion and sloughing off.

At Experiment 222 in 2007, N accumulation had a quadratic relationship with growth stage for the 90 kg N ha^{-1} rate (Table 6). The 45 and 90 kg N ha^{-1} rates accumulated essentially the same amount of N at the F4.5 growth stage, however, by F5, the 90 kg N ha^{-1} rate had an additional 66 kg N ha^{-1}, reaching its maximum accumulation of 127 kg N ha^{-1} (Table 6). Both 0 kg N ha^{-1} and 45 kg N ha^{-1} rates reached a maximum N accumulation at F6. For the 90 kg N ha^{-1} rate, 100% of the total N accumulation had occurred at F5 (Table 6).

DISCUSSION

This study supports previous findings on the accumulation of N in corn and wheat (Garabet et al., 1998; Kanampiu et al., 1997; Sainz Rozas et al., 2004; Stevens et al., 2005a, 2005b), and assists in quantifying total N accumulation as a function of time (Stevens et al., 2005a, 2005b). The importance of the environment on N accumulation was clearly evident over sites and years as evidenced by significant year and site differences in observed accumulated dry biomass and N accumulation values. However, this is not altogether surprising since yield levels are known to vary from year to year, thus, these types of differences should, in fact, be expected (Girma et al., 2007).

Our results also showed that total N accumulation increased with increasing levels of N fertilizer (Garabet et al., 1998; Kanampiu et al., 1997; Sainz Rozas et al., 2004; Stevens et al., 2005a) and typically had a linear response to those increasing N rates (Cox et al., 1993). However, in corn, we found that more N was accumulated by V6 (averaged 30%) than what was reported by Ma et al. (1999) who noted that only 20% of the total N was accumulated by V6. Licht and Al-Kaisi (2005) also showed increased N accumulation at vegetative corn developmental stages, with more than 55% of the total N accumulated by V12. Unlike corn, at some sites, winter wheat accumulated more than 60% of the total N accounted for at harvest early on in the growth cycle, and as early as F5. Francis et al. (1993) and Harper et al. (1987) showed that beyond anthesis (wheat) or silking (corn), both crops could lose N from plant tissue as NH_3 during the grain-filling process. Other researchers also have shown net N losses from silking to maturity in corn (Licht and Al-Kaisi 2005; Freeman et al., 2007). Net N losses from anthesis to maturity were further confirmed in winter wheat using ^{15}N by Lees et al. (2000). Although assessing N loss was not the objective of this work, winter wheat results at Experiment 502 in 2006 (Table 5) and Experiment 222 in 2006 (Table 6) and corn results at LCB in 2006 (Table 4) and LCB in 2007 (Table 4) support this finding, since a decrease in N accumulation was observed from anthesis or silking to maturity.

Work by Raun et al. (2001) showed that yield potential could be predicted early in the season from sensor readings collected from winter wheat. Similarly, Teal et al. (2007) noted that normalized difference vegetative index (NDVI) of corn could be used to predict grain yield potential from observations made at the V8 growth stage in corn. This work complements these findings showing large N accumulations at early growth stages of both crops. Averaged over sites and years where stages of growth were consistent, 61% of the total N accumulated was present by Feekes growth stage 5 in winter wheat, and 45% of the total N accumulated was present by V8 in corn.

CONCLUSIONS

The ability of wheat and corn to accumulate significant amounts of N early in the season was evident from this work. Averaged over sites and years where stages of growth were consistent, 45% of the total N accumulated was present by V8 in corn, and 61% of the total N accumulated was present by Feekes growth stage 5 in winter wheat. The large amounts of N accumulated in corn and wheat early in the season is significant considering that accurate prediction of yield potential depends heavily on our ability to quantify the size of the plant factory. Knowing that corn and wheat provide early season evidence of yield potential via the amount of total N accumulated in aerial parts will be useful for later determination of top-dress N needs.

REFERENCES

Austin, R. B., M. A. Ford, J. A. Edrich, and R. D. Blackwell. 1977. The nitrogen economy of wheat. *Journal of Agricultural Science* 88:159–167.

Cox, W. J., S. Kalonge, D. J. R. Cherney, and W. S. Reid. 1993. Growth, yield, and quality of forage maize under different nitrogen management practices. *Agronomy Journal* 85: 341–347.

Devienne-Barret, F., E. Justes, J. M. Machet, and B. Mary. 2000. Integrated control of nitrate accumulation by crop growth rate and soil nitrate availability under field conditions. *Annals of Botany* 86: 995–1005.

Dhugga, K. S., and J. G. Waines. 1989. Analysis of nitrogen accumulation and use in bread and durum wheat. *Crop Science* 29: 1232–1239.

Francis, D.D., J.S. Schepers, and M.F. Vigil. 1993. Post–anthesis loss from corn. *Agronomy Journal* 85: 659–663.

Freeman, K. W., K. Girma, D. B. Arnall, R. W. Mullen, K. L. Martin, R. K. Teal, and W. R. Raun. 2007. By-plant prediction of corn forage biomass and nitrogen accumulation at various growth stages using remote sensing and plant height measures. *Agronomy Journal* 99: 530–536.

Garabet, S., M. Wood, and J. Ryan. 1998. Nitrogen and water effects on wheat yield in a Mediterranean-type climate I. Growth, water-use, and nitrogen accumulation. *Field Crops Research* 57: 309–308.

Girma, K., S. L. Holtz, D. B. Arnall, L. M. Fultz, T. L. Hanks, K. D. Lawles, C. J. Mack, K. W. Owen, S. D. Reed, J. Santillano, O. Walsh, M. J. White, and W. R. Raun. 2007. Grain yields and response index of winter wheat as affected by weather, fertilizer and previous year yield level. *Agronomy Journal* 99: 1607–1614.

Hanway, J. J. 1962. Crop growth and composition in relation to soil fertility: II. Uptake of N, P, and K and their distribution in different plant parts during the growing season. *Agronomy Journal* 54: 217–222.

Harper, L. A., R. R. Shapre, G. W. Langdale, and J. E. Giddens. 1987. Nitrogen cycling in a wheat crop: Soil, plant, and aerial nitrogen transport. *Agronomy Journal* 79: 965–973.

Justes, E., M. H. Jeufroy, and B. Mary. 1997. The nitrogen requirement of major agricultural crops. Wheat, barley and durum wheat. In: *Diagnosis of the Nitrogen Status in Crops*, ed. G. Lemaire, pp. 73–92. Berlin: Springer-Verlag.

Justes, E., B. Mary, J. M. Meynard, J. M. Machet, and L. Thelier-Huche. 1994. Determination of a critical nitrogen dilution curve for winter wheat crops. *Annals of Botany* 74: 397–407.

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

Keppel, G. 1991. *Design and Analysis: A Researcher's Handbook*, 3rd ed. Englewood Cliffs, NJ: Prentice Hall.

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

Lees, H. L., W. R. Raun, and G. V. Johnson. 2000. Increased plant nitrogen loss with increasing nitrogen applied in winter wheat observed with 15N. *Journal of Plant Nutrition* 23: 219–230.

Licht, M. A., and M. Al-Kaisi. 2005. Corn response, nitrogen uptake, and water use in strip-tillage compared with no-tillage chisel plow. *Agronomy Journal* 97: 705–710.

Ma, B. L., L. M. Dwyer, and E. G. Gregorich. 1999. Soil nitrogen amendment effects on nitrogen uptake and grain yield of maize. *Agronomy Journal* 91: 650–656.

Mossedaq, F., and D. H. Smith. 1994. Timing nitrogen application to enhance spring wheat yields in a Mediterranean climate. *Agronomy Journal* 86: 221–226.

Muchow, R. C. 1988. Effect of nitrogen supply on the comparative productivity of maize and sorghum in a semi–arid tropical environment III. Grain yield and nitrogen accumulation. *Field Crops Research* 18: 31–43.

Ockerman, D. J., and C. W. Livingston. 1999. Nitrogen concentrations and deposition in rainfall at two sites in the Coastal Bend Area, South Texas. U.S. Geological Survey Fact Sheet FS-146-99. San Antonio, TX: U.S. Geological Survey. Available at http://pubs.usgs.gov/fs/fs-146-99/pdf/fs-146-99.pdf Accessed November 27, 2008.

Oklahoma Mesonet. Oklahoma Mesonet data. Available at http://www.mesonet.org/ Accessed December 7, 2007.

Raun, W. R. 2005. Facts and figures concerning nitrogen use efficiency: Precision sensing solutions for improved NUE in corn and wheat production systems. Available at http://nue.okstate.edu/NUE_Facts.htm Accessed December 16, 2009.

Raun, W. R., and G. V. Johnson. 1999. Improving nitrogen use efficiency for cereal production. *Agronomy Journal* 91: 357–363.

Raun, W. R., G. V. Johnson, M. L. Stone, J. B. Solie, 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.

Ritchie, S. W, J. J. Hanway, and G. O. Benson. 1997. How a corn plant develops. Special Report No. 48. Ames, IA: Iowa State University of Science and Technology Cooperative Extension Service.

Roy, R. N., and B. C. Wright. 1974. Sorghum growth and nutrient uptake in relation to soil fertility, II. N, P, and K uptake pattern by various plant parts. *Agronomy Journal* 66: 5–10.

Sainz Rozas, H. R., H. E. Echeverria, and P. A. Barbieri. 2004. Nitrogen balance as affected by application time and nitrogen fertilizer rate in irrigated no-tillage maize. *Agronomy Journal* 96: 1622–1631.

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

Shanahan, J. F., J. S. Schepers, D. D. Francis, and R. Caldwell. 2004. Use of crop canopy reflectance sensor for in-season N management of corn. *Proceedings of Great Plains Soil Fertility Conference* 10: 69–74.

Stevens, W. B., R. G. Hoeft, and R. L. Mulvaney. 2005a. Fate of nitrogen-15 in a long-term nitrogen rate study: I. interactions with soil nitrogen. *Agronomy Journal* 97: 1037–1045.

Stevens, W. B., R. G. Hoeft, and R. L. Mulvaney. 2005b. Fate of nitrogen-15 in a long-term nitrogen rate study: II. interactions with soil nitrogen. *Agronomy Journal* 97: 1046–1053.

Szumigalski, A. R., and R. C. Van Acker. 2006. Nitrogen yield and land use efficiency in annual sole crops and intercrops. *Agronomy Journal* 98: 1030–1040.

Teal, R. K., B. Tubana, K. Girma, K. W. Freeman, D. B. Arnall, O. Walsh, and W. R. Raun. 2007. In-season prediction of corn grain yield potential using normalized difference vegetation index. *Agronomy Journal* 98: 1488–1494.

Walsh, O. S. 2006. Effect of delayed nitrogen fertilization on corn grain yields. M.S. Thesis, Oklahoma State University, Stillwater, OK.

Winer, B. J. 1971. *Statistical Principles in Experimental Design*, 2nd Ed. New York: McGraw-Hill.

Wuest, S. B., and K. G. Cassman. 1992. Fertilizer-nitrogen use efficiency of irrigated wheat: I. uptake efficiency of pre-plant versus late-season application. *Agronomy Journal* 84: 682–688.