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

Long-Term Effects of Nitrogen Management Practices on Grain Yield, Nitrogen Uptake, and Efficiency in Irrigated Corn

K. W. Freeman [a]; Kefyalew Girma [a]; R. K. Teal [a]; D. B. Arnall [a]; B. Tubana [a]; S. Holtz [a]; J. Mosali [b]; W. R. Raun [a]
[a] Department of Plant and Soil Sciences, Oklahoma State University, Stillwater, Oklahoma, USA
[b] The Samuel Roberts Noble Foundation, Inc., Ardmore, Oklahoma, USA

Online Publication Date: 01 December 2007
To cite this Article: Freeman, K. W., Girma, Kefyalew, Teal, R. K., Arnall, D. B., Tubana, B., Holtz, S., Mosali, J. and Raun, W. R. (2007) 'Long-Term Effects of Nitrogen Management Practices on Grain Yield, Nitrogen Uptake, and Efficiency in Irrigated Corn', Journal of Plant Nutrition, 30:12, 2021 - 2036
To link to this article: DOI: 10.1080/01904160701700467
URL: http://dx.doi.org/10.1080/01904160701700467

Journal of Plant Nutrition, 30: 2021–2036, 2007

ISSN: 0190-4167 print / 1532-4087 online
DOI: 10.1080/01904160701700467

Long-Term Effects of Nitrogen Management Practices on Grain Yield, Nitrogen Uptake, and Efficiency in Irrigated Corn

K. W. Freeman,[1] Kefyalew Girma,[1] R. K. Teal,[1] D. B. Arnall,[1] B. Tubana,[1] S. Holtz,[1] J. Mosali,[2] and W. R. Raun[1]

[1]Department of Plant and Soil Sciences, Oklahoma State University, Stillwater, Oklahoma, USA
[2] The Samuel Roberts Noble Foundation, Inc., Ardmore, Oklahoma, USA

ABSTRACT

Crop management strategies that improve Nitrogen Use Efficiency (NUE) increase profits while reducing the detrimental effects on the environment associated with fertilizer nitrogen (N) loss. Effective N management should include several critical factors that are very interrelated. A study was conducted at the Panhandle Research and Extension Center, Goodwell, OK to evaluate the effects of multiple nitrogen management practices including N rate, source, time of application, methods of fertilizer and residue incorporation over a long period of time on grain yield, N uptake and NUE in irrigated corn. Fourteen treatments were evaluated in a randomized complete block design with three replicates. Results of data analyzed on the individual year and averages of all years showed that grain yield and N uptake were improved with N rates and N management practices compared to checks. Both N recovery and efficiency of use were high for the 118 kg N ha^{-1} rate.

Keywords: corn, denitrification, immobilization, leaching, mineralization, nitrogen fertilizer recovery

INTRODUCTION

Nitrogen (N) is required in large quantities for corn production and is considered the most yield limiting nutrient. Commonly, farmers apply excess N regardless

Received 31 January 2006; accepted 15 May 2007.
Address correspondence to William R. Raun, Department of Plant and Soil Sciences, Oklahoma State University, 044 North Ag Hall, Stillwater, OK 74078. E-mail: wrr@mail.pss.okstate.edu

of crop requirement and nature of crop management practices (Torbert et al., 2001). According to the Food and Agriculture Organization of the United Nations, about 85 million Mt of nitrogenous fertilizers were applied globally in 2002 (FAO, 2004). Of this about 13% was used in U.S. The report also indicated that nitrogenous fertilizer consumption continued to grow worldwide with the objective to increase production per unit area while in USA figures reflect a stagnant consumption from year to year since 1991. This indicates that US producers have unlimited N sources and typically apply excess N to their fields as proven by surface and ground water N contamination levels. Yet, improvement of N Use efficiency (NUE) has been a primary focus of soil scientists and agronomists for a long time (Raun and Johnson, 1999; Raun et al., 2002; Khosla et al., 2002). Crop management strategies that improve NUE obviously increase farm profits while reducing the detrimental effects on the environment associated with fertilizer N loss (Grant et al., 2002; Schepers et al., 1991).

Raun and Johnson (1999) estimated worldwide NUE for cereal production to be 33%. The authors also presented a complete detail of the mechanisms by which N is lost and the direct and indirect strategies to reduce this loss. Among the many causes and pathways for direct N loss, application of N in amounts that exceed crop growth requirements is the major factor. It has been clearly shown in the literature that applying the correct rate of N is considered to be the single most important factor in improving NUE (Power and Schepers, 1989; Magdoff, 1991). This can be easily achieved by simply implementing laws governing mobile nutrients and using soil test facilities when available (Bray, 1954).

Another factor that has a considerable effect on NUE is the type (source) of fertilizer N used which determines the rate of loss and availability of the nutrient. It has been generally agreed that despite the mobile nature of N, a source that releases N slowly when the crop is not in need, and that makes it available when the crop is growing fast and assimilation is at its peak would improve uptake and efficiency. Tsai et al. (1992) suggested the use of ammonium-N (NH_4-N) fertilizers can reduce leaching and denitrification losses and allow extended availability for late season uptake. Several researchers demonstrated this by quantifying the benefit of NH_4 based N sources (Wang and Below, 1992). Wang and Below (1992) reported a 35% increase in uptake when N was supplied as NH_4. Some researchers associated the use efficiency of NH_4-N based N fertilization to its advantage for the fast growing corn crop in terms of reduced energy cost for assimilation compared with NO_3-N (Pan et al., 1984; Salsac et al., 1987; Huffman, 1989; Randall and Mulla, 2001). In irrigated corn, Freney (1997) also recommended slow-release N to control loss of fertilizer N.

In the literature it has been extensively documented that little can be achieved by adjusting only rates and sources of N. Time of application is another crucial factor in improving NUE. Several studies presented data where time of application improved N uptake and protected the environment (Randall et al., 1997; Power et al., 1998; Karlen et al., 1998). The most common N-application in most of the Midwest corn growing states is a single preplant rate applied in the fall (Randall et al., 1997) which is driven more by socio-economic factors such as labor availability, cost of fertilizers which are relatively cheaper, and soil conditions such as workability (Randall and Schmitt, 1998). Preplant application of fertilizer especially several months before planting does not seem rational in relation to fertilizer dynamics in the soil. According to Sanchez and Blackmer (1988), 50 to 60% of fall applied N fertilizer is lost from the surface soil through several of the pathways that lead to N loss from the soil. Ironically, the quantity lost in monetary terms will be huge while its consequence on the environment is even more alarming. Repeated research in southern Minnesota confirmed that N fertilizer application immediately before planting improved NUE by more than 20% when compared to fall application (Randall, 1997).

The process of residue decomposition is essentially a function of the carbon (C):N ratio. This ratio is dependent on available N for microbial growth to carry on decomposition (Green and Blackmer, 1995; Green et al., 1995). Thus supplementing the soil with fertilizer N would be important to hasten the process of decomposition as initial phase of the process usually results in rapid immobilization of available inorganic N in the soil (Sinha et al., 1977; Doran, 1987; Somda et al., 1991). It has been well documented that residue incorporation naturally allows N to be plant available for longer periods of time since the process involves initial immobilization followed by slow mineralization (Aulakh et al., 1991; Maskina et al., 1993). This shows that this factor has direct implication for improving NUE.

Effective N management strategies should include several critical factors that are interrelated (Oberle and Keeney, 1990). Nitrogen management in irrigated systems although not very different from dryland corn production, needs special care due to the fact that irrigation water supply can make N loss mechanisms more complex (Bundy, 1986; Meisinger et al., 1985). No research has addressed the combined effects of different fertilizer management practices in the irrigated corn production area of Oklahoma, especially with due emphasis to NUE. This study was conducted to evaluate the long term effects of multiple N management practices including N rate, source, time of application, methods of fertilizer and residue incorporation on grain yield, N uptake and N use efficiency in irrigated corn in Oklahoma. Due to the nature of this kind of trial and because treatment response was erratic from 1995 to 2000, only the last four years were used.

MATERIALS AND METHODS

Four years data (2001–2004) were obtained from an experiment established in the spring of 1995 at Panhandle Research and Extension Center, Goodwell, OK. The growing season at this location is characterized by warm and dry summers. The experimental site is 250 m from the weather station of the research center where hourly air and soil temperature and precipitation were monitored. The soil of the experimental site is a Richfield loam (fine, montmorillonitic, mesic Aridic Argiustoll). Initial soil test results showed that both phosphorus and potassium were 100% sufficient for corn. Inorganic N level was 63 mg kg^{-1} [37 kg NH_4-N ha^{-1} and 26 kg nitrate (NO_3)-N ha^{-1}] while total N and organic carbon were about 1.2 and 11 g kg^{-1}, respectively.

Fourteen treatments consisting of: four rates of N (0, 118, 236, and 354 kg N ha^{-1}), two N fertilizer sources [anhydrous ammonia (82% N) and urea (46% N)], two times of N application, N incorporation and straw incorporation (after harvest and preplant) were evaluated (Table 1). The experimental design was a randomized complete block with three replications. The plot size was 3.05 m by 12.19 m. Each treatment was applied to a fixed plot over the experimental

Table 1
Treatment structure of the irrigated corn experiment at the Panhandle Research and Extension Center at Goodwell, OK, 1995–2004

Treatment#	N-rate kg ha^{-1}	N-Source	N-time of application	N-method of incorporation	Residue incorporation
1	0	—	—	—	After harvest
2	0	—	—	—	Preplant
3	118	Urea	Broadcast after harvest	After harvest	After harvest
4	236	Urea	Broadcast after harvest	After harvest	After harvest
5	354	Urea	Broadcast after harvest	After harvest	After harvest
6	118	Urea	Broadcast after harvest	Preplant	Preplant
7	236	Urea	Broadcast after harvest	Preplant	Preplant
8	354	Urea	Broadcast after harvest	Preplant	Preplant
9	118	Anhydrous ammonia	Preplant	Knife-inject	Preplant
10	236	Anhydrous ammonia	Preplant	Knife-inject	Preplant
11	354	Anhydrous ammonia	Preplant	Knife-inject	Preplant
12	118	Urea	Broadcast preplant	Preplant	Preplant
13	236	Urea	Broadcast preplant	Preplant	Preplant
14	354	Urea	Broadcast preplant	Preplant	Preplant

period. Corn was planted each year in mid to late April at a seeding rate of 74, 000 seeds ha^{-1}. A roundup ready corn hybrid was used in all years. Tillage practices included using disc plow in the fall for all plots receiving after harvest residue incorporation treatment and a disc plow was also used in the spring before planting for those plots assigned to preplant incorporation of residue. In the spring after residue incorporation, a field cultivator with rolling baskets was used to prepare the seedbed. Urea was applied using a calibrated broadcast applicator. Anhydrous ammonia was injected with a piston pump DMI rolling coulter applicator. Corn was under center-pivot irrigation that was used to ensure adequate moisture conditions when soil moisture fell below a level that could support healthy corn growth. Weed control was performed using a glyphosate herbicide to control all weeds.

At physiological maturity, corn ears were picked and shelled using a Massey 8XP mechanical harvester from the two center rows. Grain weight of the shelled corn was recorded and sub-samples were taken for moisture and total N determination in the grain. These sub-samples were dried in a forced air oven at 66°C for one week and ground to pass a 140 μm mesh screen. Total N in corn grain was quantified using a Carlo Erba 1500 dry combustion analyzer using the procedure described in Schepers et al. (1989). Grain yield (Mg ha^{-1}) was calculated from the plot grain weight adjusted for standard moisture of 15.5%. From the grain yield and the percent N in grain, N uptake (kg ha^{-1}) was calculated. Nitrogen Fertilizer Recovery was calculated using the yield and N uptake data as the ratio of the difference of corn grain N uptake of N fertilized plots minus that of the check plot divided by the corresponding N rate (Moll et al., 1982; Boman et al., 1995; Raun et al., 1998). The N fertilizer recovery was calculated separately for the two residue incorporation times using the respective check plots.

The grain yield, N uptake and NUE data were then subject to statistical analysis using combinations of SAS procedures (SAS, 2001). A preliminary homogenous variance test was conducted for all variables using both Levene and Bartlett tests (Levene, 1960; Snedecor and Cochran, 1989). The results of the test showed that the N fertilizer recovery data was not in agreement with the assumption of homogenous variance and thus was scaled down using a natural log variance stabilization method before analysis and then means were scaled back to the original for the purpose of reporting. Several single degree of freedom contrasts of interest were developed and tested to answer several hypotheses within in the study (Table 2).

Soil samples were collected in August 2005 after corn harvest using mechanical auger. From each plot 12 cores were randomly collected and composited for each of two depths (0–15 and 15–30 cm). Soil was then left to air-dry at room temperature for two weeks. Following this, soil was mechanically crushed to pass approximately an 8 mm screen and subsequently a portion of the sample was ground to $<$2 mm by placing the sample in a mechanical grinder before total C and N determinations. Soil was analyzed for total C and N concentration

Table 2
Analysis of Variance (ANOVA) for treatment main effect and planned contrasts used to detect differences in group of treatments in irrigated corn experiment at the Panhandle Research and Extension Center, Goodwell, OK, 2001–2004

Effect/contrast description	Grain yield				N uptake				N use efficiency			
(reference Trt#)	2001	2002	2003	2004	2001	2002	2003	2004	2001	2002	2003	2004
Treatment	ns	ns	$p < 0.1$	***	ns	$p < 0.1$	$p < 0.1$	***	ns	*	$p < 0.1$	*
Linear, urea broadcasted after harvest and incorporated after harvest (1, 3–5)	ns	$p < 0.1$	*	***	ns	**	**	***	ns	***	ns	*
Quadratic, urea broadcasted after harvest and incorporated after harvest (1,3–5)	ns	ns	ns	**	$p < 0.1$	ns	ns	$p < 0.1$	ns	*	ns	ns
Linear,urea broadcasted after harvest and incorporated preplant (2, 6–8)	ns	ns	$p < 0.1$	***	ns	ns	**	***	ns	ns	ns	ns
Quadratic, urea broadcasted after harvest and incorporated preplant (2, 6–8)	ns	*	ns	*	ns	$p < 0.1$	$p < 0.1$	ns	ns	ns	ns	ns
Linear, anhydrous ammonia preplant injected (2, 9–11)	ns	ns	ns	***	ns	$p < 0.1$	***	***	ns	ns	*	ns
Quadratic, anhydrous ammonia preplant injected (2, 9–11)	ns	ns	ns	*	ns	ns	ns	$p < 0.1$	ns	ns	$p < 0.1$	ns

Linear, urea broadcast and incorporated preplant (2, 12–14)	ns	ns	*	***	ns	ns	***	***	*	*	*	***
Quadratic, urea broadcast and incorporated preplant (2, 12–14)	ns	ns	ns	*	ns	$p < 0.1$	ns	*	ns	ns	ns	ns
Within preplant residue incorporation, urea vs anhydrous ammonia (6–8, 12–14 vs 9–11)	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Urea broadcasted after harvest vs preplant (6–8 vs 12–14)	*	ns	ns	ns	ns	ns	$p < 0.1$	*	ns	ns	$p < 0.1$	*
Urea incorporated after harvest vs preplant (3–5 vs 12–14)	ns	ns	ns	*	ns	ns	ns	ns	ns	ns	ns	ns
Anhydrous ammonia knifed vs urea broadcasted and incorporated preplant (9–11 vs 12–14)	ns	ns	*	***	ns	*	***	***	—	—	—	—
Residue incorporation after harvest vs preplant (1, 3–5 vs 2, 6–14)	ns	ns	**	***	$p < 0.1$	***	***	***	—	—	—	—

*Significant at the 0.05 probability level. ** Significant at the 0.01 probability level. *** Significant at the 0.001 probability level.
† NS, nonsignificant at 0.05 probability level.

with dry combustion at 1350°C (Leco CNS-2000, St. Joseph, MI). Soil standards were used for calibration.

RESULTS AND DISCUSSION

Results of Analysis of Variance (ANOVA) showed that treatment effect was significant in two of four years for grain yield (Table 2). Treatment effect was also significant for grain N uptake and nitrogen fertilizer recovery in three of four years. Some single degree of freedom contrasts and trend analyses were also significant. Mean grain yields, N uptake and NUE are reported in Tables 3 and 4

Grain Yield

Averaged over four years, mean corn grain yield for the different fertilizer N treatments ranged from 6.87 to 7.59 Mg ha^{-1}while grain yield inj the control

Table 3

Grain yield (Mg ha^{-1}) and N uptake (Kg ha^{-1}) of irrigated corn experiment at Panhandle Research and Extesnion Center at Goodwell, OK, 2001–2004

	Grain yield (Mg ha^{-1})					N uptake (kg ha^{-1})				
Treatment	2001	2002	2003	2004	Mean	2001	2002	2003	2004	Mean
1	2.80	5.81	5.82	8.67	5.77	40.4	81.7	75.8	88.7	71.6
2	3.21	6.24	5.76	7.67	5.72	44.1	86.3	71.1	73.5	68.8
3	2.76	6.98	7.73	13.11	7.64	41.2	116.7	112.0	132.9	99.7
4	3.10	5.93	7.79	13.48	7.58	48.2	92.4	114.6	146.2	99.1
5	3.80	6.81	8.39	13.68	8.17	60.3	108.8	131.3	156.1	114.1
6	3.55	6.83	6.49	10.21	6.77	55.4	102.5	89.5	98.2	86.4
7	4.12	6.88	8.56	12.99	8.14	58.9	106.0	128.1	145.0	109.5
8	4.57	5.59	6.88	12.00	7.26	73.4	97.1	108.0	139.4	104.5
9	2.45	6.53	8.00	11.05	7.01	42.0	99.8	116.0	109.5	91.8
10	2.96	6.59	6.00	12.55	7.03	51.2	106.3	99.1	143.4	100.0
11	3.13	6.21	7.65	12.67	7.42	55.2	103.6	123.5	144.4	106.7
12	4.17	6.62	7.93	12.94	7.91	67.9	108.8	120.0	136.3	108.2
13	4.11	6.25	7.37	12.04	7.44	71.6	103.6	117.7	141.1	108.5
14	3.96	6.40	8.48	13.26	8.03	65.3	101.0	135.2	156.0	114.4
SED†	0.97	0.50	1.00	1.04		15.1	9.6	15.7	13.1	

†Standard error of difference of two means calculated using the equation: SQRT(MSE/r_1+ MSE/r_2). Where MSE is the mean square obtained from Analysis of Variance (ANOVA) for the error term in the model; r_1 and r_2 are number of observations per respective mean.

Table 4
Nitrogen fertilizer recovery (Natural log de-transformed) in irrigated corn experiment at the Panhandle Research and Extension Center at Goodwell, OK, 2001–2004

	N recovery				
Treatment	2001	2002	2003	2004	Mean
1	—	—	—	—	—
2	—	—	—	—	—
3	4.6	29.7	33.9	37.5	25.7
4	3.9	5.7	14.7	24.4	11.9
5	6.1	7.7	15.7	19.0	12.1
6	9.5	13.7	15.6	23.5	15.6
7	7.6	8.3	24.2	30.3	17.6
8	8.3	3.7	10.4	18.6	10.3
9	3.8	11.5	38.0	30.6	21.0
10	5.0	8.5	11.8	29.6	13.7
11	4.0	4.9	14.8	20.0	10.9
12	20.1	19.0	41.4	53.3	33.5
13	14.1	7.3	19.8	28.7	17.5
14	7.5	4.2	18.1	23.3	13.3
SED†	5.9	6.8	9.9	8.0	4.3

†Standard error of difference of two means calculated using the equation: SQRT($MSE/r_1 + MSE/r_2$). Where MSE is the mean square obtained from Analysis of Variance (ANOVA) for the error term in the model; r_1 and r_2 are number of observations per respective mean.

treatments ranged from 6.2 to 6.6 Mg ha^{-1}. Averaged over all treatments that received N, Treatments 3 to 14, 1.81 and 4.33 Mg ha^{-1} more corn grain yield was obtained compared with the average of the two check plots (Treatments 1 and 2) in 2003 and 2004, respectively. Within residue incorporation after harvest, plots that received N (Treatments 3–5) resulted in 2.15 and 4.76 Mg ha^{-1} higher grain yield than the check plot (Treatments 1), respectively, in 2003 and 2004. Similarly, when residue was incorporated preplant, the N treated plots (Treatments 6–14) resulted in 1.72 and 4.52 Mg ha^{-1} higher corn grain yield compared with the corresponding check plot in 2003 and 2004, in that order.

Except in 2004, no significant linear or quadratic trends in grain yield were obtained with increasing N rates within different N sources, time of N applications and residue incorporation. A contrast made between the two N sources for preplant incorporated residue revealed that grain yield was increased when the source was urea by 1.23 Mg ha^{-1} in 2001. This could be due to the fact that when urea is broadcast and incorporated it would be distributed well in the soil covering large surface area unlike anhydrous ammonia and would be available for microbial immobilization. This would enhance fast decomposition and eventual release of N from organic pools through mineralization for extended times over the crop season. Continuous application of large quantities of anhydrous ammonia would cause significant decline in soil pH in the root zone of corn which might also contribute to lower yield. This could be due to the difference in placement of the two fertilizers than the fertilizers themselves. Clear difference in N sources were documented between acid forming N fertilizers such as diammonium phosphate and base forming fertilizers such as urea (Norman et al., 1987).

A mean comparison made between the residue incorporation times revealed that grain yield was higher by 1.24 Mg ha^{-1} when residue was incorporated after harvest than when it was incorporated preplant in 2004. Despite continuous application of fertilizer to the fixed plots from year to year, it seems that magnitude of difference in yield was apparent. This suggests that the irrigation water used to supplement the corn crop is removing N from the root zone and hence continuous application of inorganic fertilizer is required. In fact Wienhold et al. (1995) reported that although supplemental irrigation appears to be a viable technology for growing corn, great care must be taken and the system must be optimized to prevent N leaching from the root zone.

Nitrogen Uptake

Within after harvest residue incorporation (Treatments 3–5) an extra 24.3, 43.5, 56.1 and 14.8 kg N ha^{-1} was taken up by corn compared with the check (Treatment 1) in 2002, 2003, 2004 and the average of the four years, respectively. Alternatively, within preplant residue incorporation, N treatments (Treatments 6-14) resulted in an extra 16.0, 16.8, 44.1 61.3 and 23.3 kg ha^{-1} N uptake in 2001, 2002, 2003, and 2004 and averaged over four years, respectively compared with the corresponding check (Treatment 2).

Within after harvest application and incorporation of urea and residue, a linear trend for 2001, 2003, 2004 and for the average of the four years was observed for grain N uptake. Similarly, within preplant application and incorporation of urea and residue, grain N uptake showed a linear trend in response to N rates in 2001 through 2004 and for the average of the four years. N rates also showed a linear trend when the source was anhydrous ammonia in 2003, 2004 and averaged over four years (Table 1 and 3).

For the years 2001 through 2004 and the average of the 4 years, N treated plots resulted in higher N uptake ranging from 14 to 56 kg ha^{-1}. Comparison made between the two sources revealed that there was not a significant difference in N uptake between the two sources except in 2001 where urea was greater by 15.9 kg ha^{-1}compared to anhydrous ammonia. This was consistent with the grain yield increase shown above. Similarly residue incorporation time did not have any effect on N uptake. Preplant broadcasted Urea generally resulted in superior N uptake than that broadcasted after harvest. Urea applied and incorporated preplant improved N uptake by a magnitude of 6.7 to 18.8 kg ha^{-1} in four years and averaged over all years compared with anhydrous ammonia injected at the same time.

Nitrogen Fertilizer Recovery

In general N recovery was higher for the 118 kg ha^{-1} N rate (Table 4). This shows that N concentration in the grain peaked at the lower rate considered in the study. Consequently, the higher rates were unnecessary and N was lost to the environment through one or more routes despite the improvement in grain N uptake with increase in rates observed in this study. Nitrogen rates showed a significant quadratic trend in 2002 and a decreasing linear trend in 2004 for N broadcast and incorporated after harvest. Similarly N rates showed a significant quadratic trend in 2003 for anhydrous ammonia injected preplant. When urea was broadcast and incorporated preplant, N rates showed a significant decreasing linear trend in recovery for all the four years and the average. Urea broadcast preplant increased recovery by 9.7 and 10.9% in 2003 and 2004, respectively compared with that broadcast after harvest. Vetsch and Randall (2004) found that when anhydrous ammonia was applied in fall, apparent N recovery wasj reduced to 45% from 87% for spring applied N.

Soil Total C and N

Both total C and N concentration were different between the two depths. Both were more abundant in the surface (0–15 cm) soil than the subsurface (15–30 cm) soil. Total C was 18.7 g kg^{-1} higher in the surface soil than the subsurface soil while total N was higher by 2.6 g kg^{-1} in the same profile. Following this, treatments were evaluated for each depth separately (Figures 1 and 2). Generally there was no significant overall treatment effect on both total C and N in both depths. However, some of the single degree of freedom contrasts reported in Table 2 were significant for total N. Total C in the surface soil was highest for Treatment 3 (118 kg N ha^{-1} as urea applied after harvest and incorporated pre-plant with preplant residue incorporation, Figure 1). In the surface soil the highest total N was observed when 118 kg N ha^{-1} urea was applied and incorporated preplant with preplant residue incorporation (Treatment 12; Figure 2). Total N was lowest at this depth for 0 N and after harvest residue incorporation (Treatment 1). It is important to note that 0 N with preplant residue incorporation (Treatment 2) resulted in higher total N than Treatment 1 but was not different from the rest of the treatments. This suggests the importance of leaving residue on the surface until bed preparation in the spring. In the subsurface soil, total

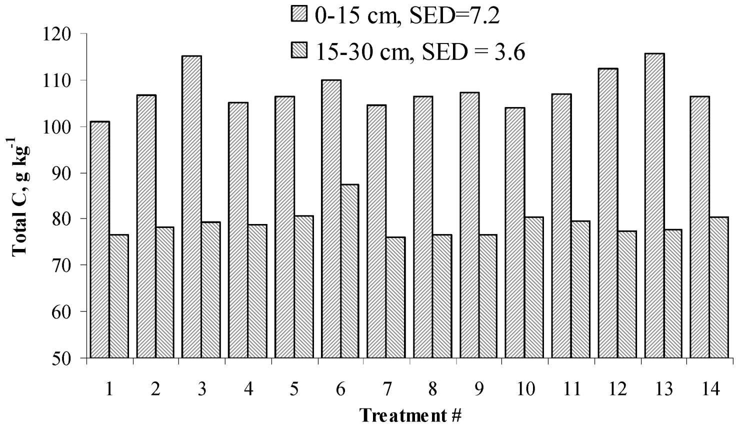

Figure 1. Total C in 0–15 and 15–30 cm depth from soil sampled at Goodwell, OK in August 2005. SED denotes Standard error of difference of two means calculated using the equation: SQRT($MSE/r_1 + MSE/r_2$). Where MSE is the mean square obtained from Analysis of Variance (ANOVA) for the error term in the model; r_1 and r_2 are number of observations per respective mean.

N was highest for Treatment 6 (which is similar to Treatment 12 except for the after harvest N application instead of preplant) while it was lowest for Treatment 11 (354 kg N ha^{-1} applied as anhydrous ammonia preplant and residue incorporated preplant).

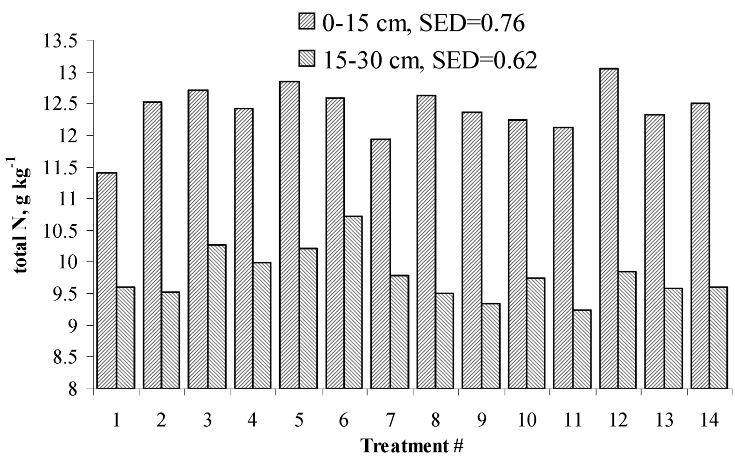

Figure 2. Total N in 0–15 and 15–30 cm depth from soil sampled at Goodwell, OK in August 2005. SED denotes Standard error of difference of two means calculated using the equation: SQRT($MSE/r_1 + MSE/r_2$). Where MSE is the mean square obtained from Analysis of Variance (ANOVA) for the error term in the model; r_1 and r_2 are number of observations per respective mean.

In summary both grain yield and N uptake were improved when the fertilizer source was urea. A long term N source study initiated in 1971 at Lahoma Research Station in Oklahoma on winter wheat also confirmed this finding (Girma et al., 2005). However urea must be applied and incorporated preplant or after harvest when residue incorporation is practiced. Corn responded to the addition of N from both sources in the two residue management systems. In irrigated corn the chance of N leaching is high as documented in the literature (Dinnes et al., 2002; Olson, 1980). Applying N after harvest was not generally efficient as several soil processes including denitrification and weather changes occur between harvest and planting.

REFERENCES

Aulakh, M. S., J. W. Doran, D. T. Walters, A. R. Moiser, and D. D. Francis. 1991. Crop residue type and placement effects on denitrification and mineralization. *Soil Sci. Soc. Am. J.* 55: 1020–1025.

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

Bray, R. H. 1954. A nutrient mobility concept of soil-plant relationships. *Soil Sci.* 104: 9–22.

Bundy, L. G. 1986. Review: Timing nitrogen applications to maximize fertilizer efficiency and crop response in conventional corn production. *J. Fert. Issues* 3: 99–106.

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

Doran, J. W. 1987. Microbial biomass and mineralizable nitrogen distributions in no-tillage and plowed soils. *Biol. Fertil. Soils* 5: 68–75.

Food and Agriculture Organization of the United Nations (FAO). 2004. FAOSTATA database Agriculture data base: Fertilizer (http://www.fao.org), FAO, Rome, Italy [Accessed January 19, 2006].

Freney, J. R. 1997. Strategies to reduce gaseous emissions of nitrogen from irrigated agriculture. *Nutr. Cycl. Agroecosys.* 48: 155–160.

Girma, K., H. Zhang and W. Raun. 2005. *Do nitrogen fertilizer sources and the timing of application affect winter wheat yields and net benefit?* Production Technology (PT) 2005–15. Oklahoma Cooperative Extension Service, Oklahoma State University, Stillwater OK.

Grant, C. A., G. A. Peterson, and C. A. Campbell. 2002. Nutrient considerations for diversified cropping systems in the Northern Great Plains. *Agron. J.* 94: 186–198.

Green, C. J., A. M. Blackmer, and R. Horton. 1995. Nitrogen effects on conservation of carbon during corn residue decomposition in soil. *Soil Sci. Soc. Am. J.* 59: 453–459.

Green, C. J., and A. M. Blackmer. 1995. Residue decomposition effects on nitrogen availability to corn following corn or soybean. *Soil Sci. Soc. Am. J.* 59: 1065–1070.

Huffman, J. R. 1989. Effects of enhanced ammonium nitrogen availability for corn. *J. Agron. Educ.* 18: 93–97.

Karlen, D. L., L. A. Kramer, and S. D. Logsdon. 1998. Field-scale nitrogen balances associated with long-term continuous corn production. *Agron. J.* 90: 644–650.

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

Levene, H. 1960. Robust tests for the equality of variance. Pp. 278–292. In I. Olkin (ed.) *Contributions to Probability and Statistics*. Stanford University Press, Palo Alto, CA.

Magdoff, F. R. 1991. Managing nitrogen for sustainable corn systems: Problems and possibilities. *Am. J. Altern. Agric.* 6: 3–8.

Maskina, M. S., J. F. Power, J. W. Doran, and W. W. Wilhelm. 1993. Residual effects of no-till crop residues on corn yield and nitrogen uptake. *Soil Sci. Soc. Am. J.* 57: 1555–1560.

Meisinger, J. J., V. A. Bandel, G. Stanford, and J. O. Legg. 1985. Nitrogen utilization of corn under minimal tillage and moldboard plow tillage: I. Four year results using labeled fertilizer on an Atlantic Coastal Plain soil. *Agron. J.* 77: 602–611.

Moll, R. H., E. J. Kamprath, and W. A. Jackson. 1982. Analysis and interpretation of factors which contribute to efficiency to nitrogen utilization. *Agron. J.* 74: 562–564.

Norman, R. J., L. T. Kurtz, and F. J. Stevenson. 1987. Distribution and recovery of nitrogen-15-labeled liquid anhydrous ammonia among various soil fractions. *Soil Sci. Soc. Am. J.* 51: 235–241.

Oberle, S. L., and D. R. Keeney. 1990. Factors influencing corn fertilizer N requirements in the Northern U.S. corn belt. *J. Prod. Agric.* 3: 527–534.

Olson, R. V. 1980. Fate of tagged nitrogen fertilizer applied to irrigated corn. *Soil Sci. Soc. Am. J.* 55: 1616–1621.

Pan, W. L., E. J. Kamprath, R. H. Moll, and W. A. Jackson. 1984. Prolificacy in corn: its effects on nitrate and ammonium uptake and utilization. *Soil Sci. Soc. Am. J.* 48: 1101–1106.

Power, J. F., A. D. Flowerday, R. A. Wiese, and D. G. Watts. 1998. *Agricultural nitrogen management to protect water quality*. USDA-CREES-IDEA Bulletin No. 4, Washington, DC.

Power, J. F., and J. S. Schepers. 1989. Nitrate contamination of groundwater in North America. *Agric. Ecosyst. Environ.* 26: 165–187.

Randall, G. W., T. K. Iragavarapu, and B. R. Bock. 1997. Nitrogen application methods and timing for corn after soybean in a ridge-tillage system. *J. Prod. Agric.* 10: 300–307.

Randall, G. W., and D. J. Mulla. 2001. Nitrate-N in surface waters as influenced by climatic conditions and agricultural practices. *J. Environ. Qual.* 30: 337–344.

Randall, G. W., and M. A. Schmitt. 1998. Advisability of fall-applying nitrogen. Pp. 90–96. In *Proceedings of Wisconsin Fertilizer, Aglime, and Pest Management Conference*, Jan 20,1998, Middleton, WI. Univ. of Wisconsin, Madison, WI.

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

Raun, W. R., G. V. Johnson, and R. L. Westerman. 1998. *Soil-plant nutrient cycling and environmental quality.* Dept. Plant and Soil Sciences. Oklahoma State University, Stillwater, OK.

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

Salsac, L., S. Chaillou, J. F. Morot-Gaudry, C. Lesaint, and E. Jolivoe. 1987. Nitrate and ammonium nutrition in plants. *Plant Physiol. Biochem.* 25: 805–812.

Sanchez, C. A., and A. M. Blackmer. 1988. Recovery of anhydrous ammonia-derived nitrogen-15 during three years of corn production in Iowa. *Agron. J.* 80: 102–108.

SAS Institute. 2001. Statistical analysis software. Version 8.2 ed. SAS Inst., Cary, NC.

Schepers, J. S., M. G. Moravek, E. E. Alberts, and K. D. Frank. 1991. Maize production impacts on groundwater quality. *J. Environ. Qual.* 20: 12–16.

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

Snedecor, G. W., and W. G. Cochran. 1989. *Statistical Methods*, 8th Ed., Iowa State University Press, Ames, Iowa.

Sinha, M. K., D. P. Sinha, and H. Sinha. 1977. Organic matter transformations in soils: V. Kinetics of carbon and nitrogen mineralization in soils amended with different organic materials. *Plant and Soil* 46: 579–590.

Somda, Z. C., P. B. Ford, and W. L. Hargrove. 1991. Decomposition and nitrogen recycling of cover crops and crop residues. pp. 103–105. In W. L. Hargrove (ed.). *Proceedings of the International Conference on Cover crops for* *clean water*, April 9–11, 1991, Jackson, TN. Soil and Water Conserv. Soc., Ankeny, IA.

Torbert, H. A., K. N. Potter , and J. E. Morrison, Jr. 2001. Tillage system, fertilizer nitrogen rate and timing effect on corn yields in the Texas backland prairie. *Agron. J.* 93: 1119–1124.

Tsai, C. Y., I. Dweikat, D. M. Huber, and H. L. Warren. 1992. Interrelationship of nitrogen nutrition with maize (*Zea mays*) grain yield, nitrogen use efficiency and grain quality. *J. Sci. Food Agric.* 58: 1–8.

Vetsch, J. A., and G. W. Randall. 2004. Corn production as affected by nitrogen application timing and tillage. *Agron. J.* 96: 502–509.

Wang, X., and F. E. Below. 1992. Root growth, nitrogen uptake, and tillering of wheat induced by mixed-nitrogen source. *Crop Sci.* 32: 997–1002.

Wienhold, B. J., T. P. Trooien, and G. A. Reichman. 1995. Yield and nitrogen use efficiency of irrigated corn in the northern great plains. *Agron. J.* 87: 842–846.