Corn Production as Affected by Nitrogen Application Timing and Tillage

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ABSTRACT

Utilizing conservation tillage practices and increasing fertilizer N use efficiency for corn (*Zea mays* L.) are necessary for optimizing growers' profits and for minimizing loss of sediment and nutrients to the environment. A 3-yr study was conducted on a Nicollet clay loam (fine loamy, mixed, mesic, Aquic Hapludoll)–Webster clay loam (fine loamy, mixed, super active, Typic Endoquoll) soil complex in southern Minnesota to determine the effects of four tillage systems (no tillage, strip tillage, one-pass field cultivate, and chisel plow) and two N application times on corn production following soybean [*Glycine max* (L.) Merr.]. Anhydrous ammonia was applied at 123 kg N ha^{-1} either in late October when soil temperatures at 15 cm were generally below 10°C or in April before planting. Tillage system had a statistically significant effect on corn production but showed no interaction with the N timing treatments. Maximum differences among tillage systems were 4.3% for grain yield, 5.1% for silage yield, and 8.6% for total N uptake. In 1 yr, when April and May were wet and warm, grain yield and total N uptake were reduced 20 and 27%, respectively, with fall N. Apparent N recovery was reduced from 87% for spring N to 45% for fall N. Corn production was not affected by time of N application in the other 2 yr. Relative leaf chlorophyll, measured by a SPAD meter at the V10, R1, and R3 growth stages, was highly correlated to relative corn grain yield, and could be used as a diagnostic tool at the V10 stage to determine sidedress N needs under non-irrigated conditions. Because the risk of N loss is greater with fall N application, N should be applied in the spring on these soils to minimize risk and optimize profitability regardless of tillage system.

Tillage system and N application timing are important management decisions that farmers make for corn production on the highly productive but poorly drained soils of the northern Corn Belt. Dominance of the corn–soybean rotation in this region is raising concern about sediment and nutrient contributions to surface waters (Randall, 2002). Conservation tillage practices like no tillage (NT) are effective at managing crop residue to reduce erosion. However, widespread adoption of NT for corn on glacial till soils in Minnesota (USA) has not occurred. Researchers have responded to grower concerns of reduced yield potential and lack of adoption of NT by studying modified NT systems that conserve residue and are agronomically competitive with more conventional tillage practices. Randall et al. (2001) showed that fall strip tillage (ST) for corn following soybean produced greater yields than NT on a clay loam soil in one of two studies and ST yields were equal to conventional tillage (CP) in both studies. On a silt loam soil Vetsch and Randall (2002) concluded that surface residue and corn yield following soybean could be optimized using modified NT systems (including ST) and starter fertilizer. In Iowa Mallarino et al. (1999) found that ST frequently increased early growth but seldom increased corn grain yields compared with NT.

Best Management Practices (BMPs) for N are complicated by residue management and tillage. Spring, preplant application of fertilizer N to medium and fine-textured soils of the northern Corn Belt is considered to be a BMP with conventional tillage systems. However, spring preplant application of anhydrous ammonia to NT and ST is often considered undesirable by growers because of delayed planting and compaction concerns on wetter soils. Moreover, preplant broadcast application of urea and urea–ammonium nitrate (UAN) without a urease inhibitor is not an option with NT and ST systems because when left unincorporated these N sources are susceptible to volatilization losses (Keller and Mengel, 1986; Mengel et al., 1982). With a urease inhibitor surface applications of urea containing fertilizers can still result in yield reductions due to immobilization (Vetsch and Randall, 2000).

Time of N application studies have been reported extensively in the literature. The general conclusion among researches has been that N should be applied nearest to the time it is needed by the crop, i.e., sidedressed several weeks after corn emergence (Aldrich, 1984; Fox et al., 1986; Olson and Kurtz, 1982; Russelle et al., 1981; Stanley and Rhoades, 1977; Welch et al., 1971). There is less time for leaching or denitrification losses when N is applied after plant emergence. However, recent trends in agriculture which include increased farm size, more farmers with off-farm jobs (USDA-NASS, 1997, 1992), and greater use of postemerge herbicides, have left less time for farmers to sidedress N.

Application of N in the fall has advantages for both growers and the fertilizer industry. These economic and logistical advantages include better distribution of labor and equipment demands, time savings during the busy spring planting season, lower N costs in some years, and frequently more favorable soil conditions for field work (Bundy, 1986; Randall and Schmitt, 1998). Comparisons of corn yield with fall or preplant N application have been variable. Fall application (mid-November) produced lower corn grain yields than spring preplant application regardless of N rate in Ontario (Stevenson and Baldwin, 1969). The yield reduction associated with fall application was greater on clay soils than on loam soils. Three-year yield averages showed fall application on medium-to-fine textured soils in central and northern Illinois to be 90% as effective as spring application at 134 kg N ha^{-1} with equal yields for fall and spring appli-

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Abbreviations: CP, chisel plow tillage; NT, no tillage; OP, one-pass tillage (spring field cultivation); RLC, relative leaf chlorophyll; ST, fall strip tillage.

cations at 201 kg N ha^{-1} (Welch et al., 1971). Considerable year-to-year variation among 12 location–years was observed, suggesting the impact of weather variability on loss of N. In an extensive review of N application timing, Bundy (1986) concluded that fall N application is an acceptable option on medium-to-fine-textured soils where winter temperatures retard nitrification. However, under these conditions fall-applied N is usually 10 to 15% less effective than spring-applied N. The relative effectiveness is largely determined by soil characteristics and climatic conditions, and, therefore, varies substantially among locations and years. An 8-yr study reported by Randall et al. (2003a) illustrated the large year-to-year effect of climatic conditions, but when averaged across years, nitrate losses to subsurface tile drainage from a corn–soybean rotation in Minnesota were reduced 17% by applying N in the spring compared with late in October.

Strip tillage for corn after soybean in the northern Corn Belt is preferred in the fall immediately after soybean harvest due to more favorable and drier soil conditions, greater availability of time, over-winter settling of soil in the tilled area, and a warmer and drier seedbed ideal for early planting in the spring (Randall and Hill, 2000). An attractive feature of the ST system is the opportunity to gain efficiency by placing fertilizer deep (15–20 cm) into the strip-tilled zone at the time of doing the fall tillage. However, soil temperatures are often greater than 10°C at this time, and the potential for N loss is greatly increased (Keeney, 1982). Thus, a dilemma occurs for the farmer. Should he/she (i) perform early ST combined with N application, taking a chance on N loss; (ii) perform ST combined with N application late in the fall, taking a chance on poor conditions for ST; or (iii) perform the ST early in the fall and apply fertilizer N the following spring, thus losing some labor efficiency but potentially gaining N efficiency.

The SPAD chlorophyll meter has been used as a diagnostic tool to identify N responsive sites at varying growth stages in corn by correlating chlorophyll meter readings at various N sufficiency levels (N rates) with corn grain yield and/or total N uptake (Piekielek and Fox, 1992; Bullock and Anderson, 1998; Varvel et al., 1997). Piekielek and Fox (1992) found that chlorophyll meter readings at the V6 corn growth stage were effective in identifying fields that would respond to sidedress N applications. Varvel et al. (1997) reported the chlorophyll meter could detect N deficiencies by the V8 stage. Bullock and Anderson (1998) found SPAD readings at V7 were not correlated to final grain yield. The importance of these findings is significant for dryland corn production as sidedressing N after V8 becomes more difficult, whereas late season applications of N under irrigated corn production are commonplace. The usefulness of the chlorophyll meter as a diagnostic tool for determining if supplemental N applications are needed when N has been fall-applied is worthy of research.

There is no research in the literature that examines the performance of fall vs. preplant applications of anhydrous ammonia across a range of tillage systems including ST on corn production in a corn–soybean rotation. The objectives of this study were to determine (i) the effect of time/placement of N in a wide range of tillage systems on corn production and N recovery, (ii) the interaction between time of N application and tillage system for corn production following soybean, and (iii) the influence of time of N application and tillage on the diagnosis of N sufficiency by measuring leaf chlorophyll content with the SPAD meter.

MATERIALS AND METHODS

The experimental site was located at the University of Minnesota Southern Research and Outreach Center, Waseca, MN (44.06° N, 93.52° W) on a tile drained Nicollet–Webster clay loam soil complex (Aquic Hapludoll and Typic Endoquoll, respectively). Subsurface tile drainage lines were spaced 23 m apart, and plots were planted perpendicular to the tile lines. The 0.8-ha site consisted of two 0.4-ha experimental units, which were rotated between corn and soybean starting in 1996. Soil samples taken to a 15-cm depth in September of 1996 averaged 6.8 pH, 22 mg kg^{-1} Bray P_1 (very high), and 135 mg kg^{-1} exchangeable K (high), respectively (Rehm et al., 1994). Fertilizer P and K were broadcast applied at 50 and 140 kg ha^{-1}, respectively, in November of 1996.

Twelve treatments were arranged in a randomized, complete-block design (split-plot arrangement) with four replicates (blocks). Four tillage systems for corn (NT, ST, OP, and CP) were the main plots. Each main plot was 13.7 m wide (18, 76-cm rows) by 15.2 m long. Subplots were 4.6 m wide (six, 76-cm rows) and consisted of N timing-placement (fall, in-row; spring, mid-row; and a zero-N check) treatments.

Strip tillage (Randall and Hill, 2000) was performed to a 20-cm depth on 28 Oct. 1996, 21 Oct. 1997, and 26 Oct. 1998 with a DMI (CASE DMI, Goodfield, IL) strip-till unit with fertilizer injection knives. Corn was planted directly into the ST zone without preplant tillage. Chisel tillage to a 20-cm depth was performed with a DMI Model 2500 on 2 Nov. 1996, 10 Nov. 1997, and 6 Nov. 1998. The CP and OP systems were field cultivated to a 10-cm depth before planting corn on 24 Apr. 1997 and 1998 and 29 Apr. 1999.

For soybean following corn, the CP system was stalk chopped, fall chisel plowed, and field cultivated; the OP tillage system was spring disked; while the NT and ST systems received no tillage before planting soybean in 20-cm rows with a no-till coulter cart drill.

Nitrogen treatments were applied as anhydrous ammonia without a nitrification inhibitor at a rate of 123 kg N ha^{-1}; the recommended rate for an expected corn yield of 9 to 11 Mg ha^{-1} (Rehm et al., 1994). Fall N was applied on the same dates as the fall ST. Soil temperature at the 15-cm depth averaged 8.3, 9.0, and 13.0°C on the date of application in 1996, 1997, and 1998, respectively. In the following 10-d period, soil temperature at this depth averaged 4.5, 6.2, and 9.8°C for these years, respectively. These application dates and temperatures closely follow the general recommendation to delay fall application of N until soil temperatures are <10°C (Keeney, 1982). The soils remained frozen from late-November or early December through late-March each winter. Spring N was applied mid-row on 24 Apr. 1997, 14 Apr. 1998, and 28 Apr. 1999. Fall N was applied in or near the next year's crop row for all tillage systems except NT, where it was applied at a 2° angle to next year's rows to delineate it from ST. A control (0 kg) N treatment was also included in each main (tillage) plot to serve as a reference for calculation of N recovery, determining nitrification of the anhydrous ammonia, and determining the relationship between leaf chlorophyll content and grain yield.

Table 1. Spring and growing season air temperature and precipitation departures from normal for 1997–1999 at Waseca, MN.

Month	30-yr normal†	Year 1997	1998	1999
		temp., °C		
Apr.	6.2	−0.4	3.4	2.5
May	14.3	−3.2	4.3	1.4
June	19.5	1.9	−0.9	0.3
Apr.–June	13.3	−0.6	2.3	1.4
Apr.–Sept.	16.3	−0.1	2.1	0.8
		precip., mm		
Apr.	75	−38	8	84
May	93	7	14	48
June	104	−26	7	−3
Apr.–June	272	−57	29	129
Apr.–Sept.	576	40	−58	30

† 1961–1990 normal period.

Corn (Pioneer brand 3730) was planted at 79 000 plants ha^{-1} on 28 Apr. 1997, 30 Apr. 1998, 1 May 1999 with a John Deere (Moline, IL) Model 7100 planter equipped with Yetter (Colchester, IL) Combination Residue Managers (row cleaners and a 25-wave, 36-cm diam. coulter). Excellent weed control was obtained with a combination of pre- and postemergence applications of herbicides and row cultivation on 26 June 1997.

Soil samples were taken biweekly from mid May through mid to late June to a 30-cm depth from all three N treatments in the CP and ST systems. Four 2-cm diameter cores were taken from three row positions: 0 (in-row), 19, and 38 cm (mid-row) from the row for a total of 12 cores per plot. Samples were dried in forced-air ovens at 38°C, ground to pass a 2-mm sieve, extracted with 2 *M* KCl, and analyzed for NO_3–N and NH_4–N using a Lachat system.

Leaf chlorophyll content was measured with a Minolta SPAD meter at the V6, V10, R1, and R3 corn growth stages (Ritchie et al., 1986). Thirty SPAD meter readings were taken from each plot and the average recorded. Average meter readings were converted to relative values by dividing the average meter reading for each plot by the average meter reading from the plot with the highest average (a non-N-limiting condition) within each replication and multiplying by 100, similar to the procedure described by Peterson et al. (1993).

Corn grain yield and moisture content were measured by harvesting two, 14-m rows in each six-row plot with a plot combine. Grain yields are expressed on a 15.5% moisture basis. Corn silage yield was measured by harvesting 4.5 m of row at physiological maturity; data are expressed on a dry matter basis. Corn grain and silage samples were dried at 65°C, ground to pass a 1-mm sieve, and analyzed for total N (Technicon Industrial Method, no. 325-74W Sept. 1974; Ammoniacal Nitrogen/BD Acid Digests; Technicon Industrial Systems, Tarrytown, NY).

Daily air temperature and precipitation data were recorded during the growing season at a site located 1.5 km from the experimental location. Analysis of variance statistics were performed using the GLM procedure of SAS (SAS Inst., 1999). All LSDs are calculated at $P \leq 0.10$.

RESULTS AND DISCUSSION

Spring (April–June) and growing season (April–September) average air temperatures and precipitation ranged from slightly below to above normal, providing a good range of weather conditions during the 3-yr study (Table 1). Monthly precipitation varied greatly, ranging from 51% less-than-normal in April 1997 to 112% greater than normal in April 1999. The wetter and somewhat warmer-than-normal conditions in April and May of 1999 were a clear deviation from normal and significantly affected the results of this experiment.

Corn Production

High corn yields, ranging from 10.2 Mg ha^{-1} (162 bu acre^{-1}) in 1999 to 11.9 Mg ha^{-1} (189 bu acre^{-1}) in 1998 when averaged across tillage systems and N timing/placement treatments, reflect the excellent growing conditions for corn during each of the years of this study (Table 2). Grain yields from the 0 kg N control plots

Table 2. Corn grain yield, silage yield, total N uptake, and apparent N recovery as affected by tillage system and N timing/placement for 1997–1999.

Source of variation	Grain yield	Silage yield	Total N uptake	Apparent N recovery†
	Mg ha^{-1}		kg ha^{-1}	%
Year (Yr)				
1997	11.7	17.9	187	66
1998	11.9	18.9	215	90
1999	10.2	14.8	171	66
$P > F$	<0.001	<0.001	<0.001	<0.001
LSD (0.10)	0.2	0.3	7	6
Tillage system				
No tillage	11.1	16.8	181	75
Strip tillage	11.3	17.6	193	76
One pass‡	11.2	17.1	192	75
Chisel plow	11.6	17.7	198	70
$P > F$	0.014	<0.001	0.011	0.409
LSD (0.10)	0.3	0.3	8	
N timing/placement (N)				
Fall/in-row	10.9	16.8	184	68
Spring/mid-row	11.7	17.6	199	80
$P > F$	<0.001	<0.001	<0.001	<0.001
			Interactions, $P > F$	
Yr × Tillage	0.220	0.644	0.908	0.952
Yr × N	<0.001	<0.001	<0.001	<0.001
Tillage × N	0.240	0.330	0.392	0.394
Yr × Tillage × N	0.108	0.181	0.431	0.431
CV, %	4.3	4.0	5.9	12.4

† Based on total N uptake in control plots for each tillage system and each year.
‡ Spring field cultivate.

averaged across tillage systems for 1997, 1998, and 1999 were 7.5, 6.4, and 5.5 Mg ha^{-1}, respectively (data not shown). Apparent N recovery, defined as total N uptake in the N fertilized plots minus the control plots expressed as a percent of N applied, was significantly greater in 1998 (90%) compared with 66% in 1997 and 1999. This was due primarily to a 5.5 Mg ha^{-1} yield response to fertilizer N in 1998 compared with yield responses of 4.2 and 4.7 Mg ha^{-1} in 1997 and 1999, respectively.

Tillage system had a slight but significant ($P < 0.10$) effect on grain and silage yield and total N uptake in the aboveground dry matter when averaged across years and N timing/placement treatments (Table 2), but there were no interactions between tillage system and year or N timing/placement. Grain yields were significantly greater for the CP system compared with the NT and OP systems with yields from ST being intermediate. Silage (grain plus stover) yields were also slightly greater for the CP and ST systems compared with the NT and OP systems. Total N uptake was significantly less for NT (181 kg ha^{-1}) compared with the OP, ST, and CP systems, where uptake totaled 192, 193, and 198 kg ha^{-1}, respectively. Apparent N recovery, was not affected by tillage system.

A highly significant year × N timing/placement interaction was found for all four production parameters (Table 2). Grain and silage yields, total N uptake, and apparent N recovery were not different between fall/in-row and spring/mid-row placement of N in 1997 and 1998 (Fig. 1). But in 1999, spring application of N was consistently superior to fall application for all production parameters. Spring application increased grain yield by 2.2 Mg ha^{-1} (36 bu acre^{-1}), silage yield by 2.9 Mg ha^{-1} (1.3 ton acre^{-1}), total N uptake by 52 kg ha^{-1} (47 lb acre^{-1}), and N recovery by 42% compared with fall application. Unusually wet conditions in April and May 1999 (84 and 48 mm above normal, respectively), compared with normal to less-than-normal precipitation during these months in 1997 and 1998, likely caused substantial leaching and/or denitrification of the fall-applied N, resulting in low corn yields, reduced N uptake, and poorer N recovery. These results were similar to those reported by Welch et al. (1971) and Randall et al. (2003b), who noted the impact of spring weather on the performance of fall-applied N in Illinois and Minnesota, respectively.

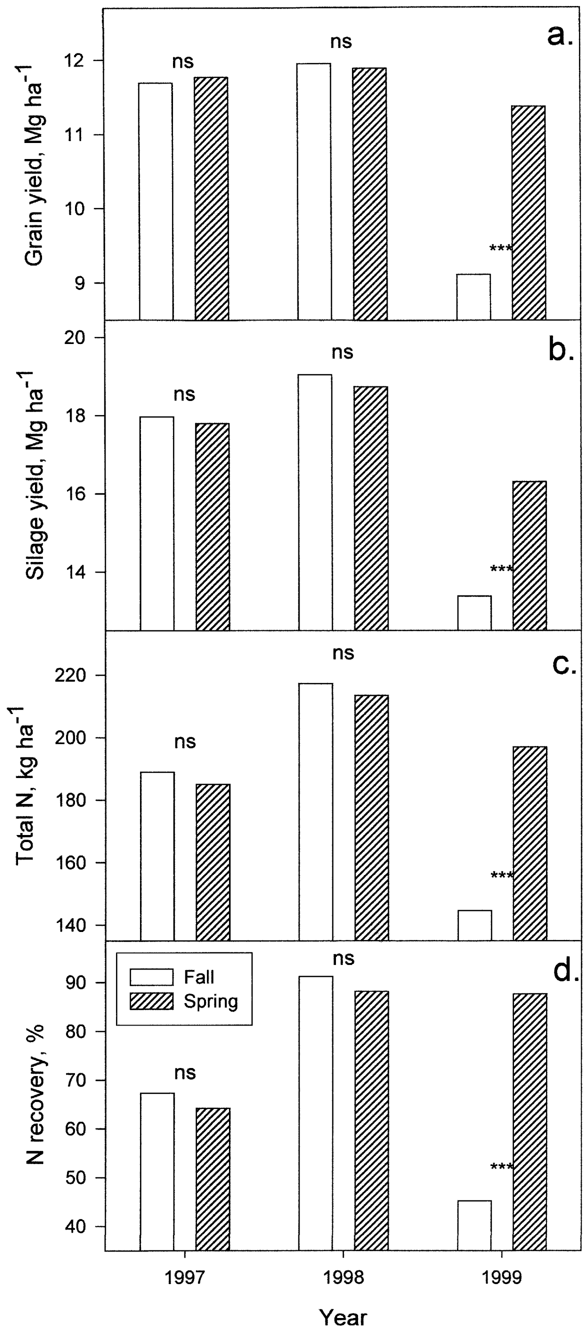

Fig. 1. Interaction between year and time/placement of N for grain yield, silage yield, total N uptake, and apparent N recovery.

Soil Ammonium and Nitrate

Soil NH_4–N and NO_3–N concentrations in the 0- to 30-cm layer for the two N timing/placement treatments and the control plots were determined on a biweekly basis in the CP and ST treatments each spring. Because differences between the two tillage systems were not found, the NH_4–N and NO_3–N data for the two systems were combined. In addition, the NH_4–N and NO_3–N concentrations from the control (0 kg N rate) treatment were subtracted from the NH_4–N and NO_3–N concentrations for the fall and spring N treatments. Thus, the soil NH_4–N and NO_3–N data found in Fig. 2 represent the net effect of the N timing/placement treatments averaged across the two tillage systems.

In mid-May 1997 and 1998, NO_3–N concentrations for fall-applied N were greater than for spring-applied N, indicating substantial nitrification of the fall-applied N by the VE growth stage. By the V4 to V6 growth stage in mid-to-late June, significant nitrification of spring-applied N had occurred and NO_3–N concentrations were significantly greater than for fall-applied N. Nitrate-N concentrations for the fall N treatment decreased from 17 in mid-May to 7 mg kg^{-1} in late June 1997 and from 13 in mid-May to 5 mg kg^{-1} in mid-June 1998, suggesting leaching out of the top 30-cm zone during this 4 to 6-wk

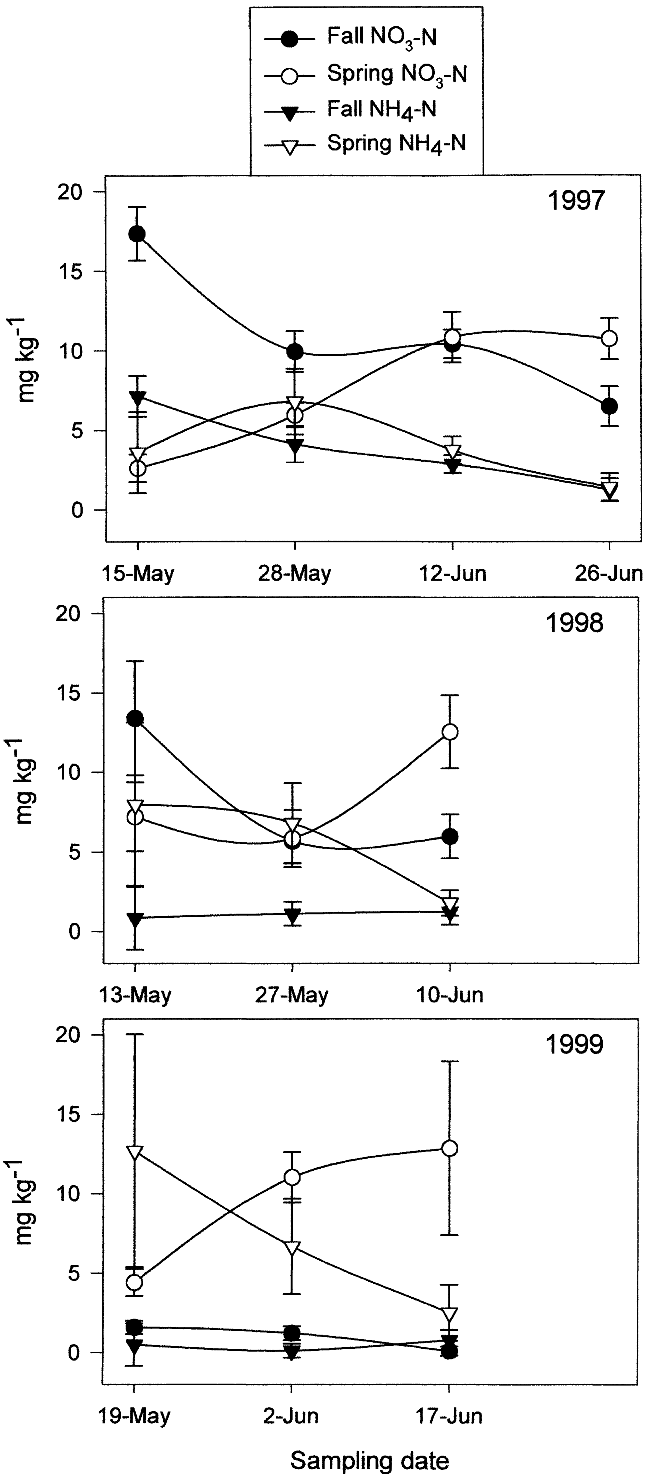

Fig. 2. Ammonium- and nitrate-N concentrations in the 0- to 30-cm soil layer in May and June as affected by time of N application in 1997, 1998, and 1999. Standard error of the mean expressed as error bars.

period. Ammonium-N concentrations ranged between 2 and 7 mg kg^{-1} in 1997 and were not different between N timing/placement treatments. In 1998, NH_4–N was <2 mg kg^{-1} throughout the spring for fall-applied N, but ranged from 8 mg kg^{-1} in mid-May to 2 mg kg^{-1} in mid-June for spring-applied N.

In 1999, the soil NH_4–N and NO_3–N picture changed considerably compared with 1997 and 1998. Ammonium-N and NO_3–N concentrations were both <2 mg kg^{-1} from mid-May to mid-June for fall-applied N, whereas NO_3–N concentrations for spring-applied N increased from 5 mg kg^{-1} in mid-May to 12 mg kg^{-1} in mid-June. Ammonium-N showed a corresponding decrease from 13 mg kg^{-1} in mid-May to 3 mg kg^{-1} in mid-June. These results document substantial loss of fall-applied N from the sampling zone (and perhaps from the rooting zone) by mid-May under wetter and warmer-than-normal April and May conditions, and clearly suggest this to be the primary reason in 1999 for severely reduced corn yields, N uptake, and N recovery from fall-applied N. Anhydrous ammonia applied on 28 April showed a relatively high concentration of NO_3–N (12 mg kg^{-1}) in mid-June and was not affected by wet spring conditions conducive to leaching and denitrification.

Leaf Chlorophyll

Relative leaf chlorophyll (RLC) content determined by a SPAD meter is shown in Table 3 for the V6, V10, R1, and R3 stages for each year. A combined ANOVA across years (not shown) found all interactions with year to be significant at $\alpha = 0.10$ except year $\times$ tillage $\times$ N timing/placement for V6 and R3; thus, RLC data are presented for each individual year.

Across the 12 diagnostic scenarios (3 yr $\times$ 4 growth stages yr^{-1}), RLC was influenced by tillage system in 7 instances and by N treatment in all 12 instances. Averaged across N treatments, lowest RLC values always occurred with NT, whereas RLC was always highest for CP tillage except in 1999 at the V10 stage when RLC was highest for the OP system. Averaged across tillage systems, RLC was always markedly lower for the control (0 kg N rate) plots, even at the V6 growth stage. Relative leaf chlorophyll was not statistically different between fall and spring application except for the V10, R1, and R3 growth stages in 1999. The significantly lower RLC for fall-applied N compared with spring-applied N in 1999 corresponds well with the soil mineral N data in Fig. 2 and the N uptake and recovery data in Table 2 and Fig. 1. Tillage $\times$ N treatment interactions were significant in 8 of 12 scenarios (Table 3), primarily due to consistently lower RLC for the 0-N control plots in the NT system compared with the other three tillage systems, especially CP. Analyses of RLC data averaged across tillage systems indicates very little temporal change in RLC from growth stage V6 to R3 when sufficient N is applied for optimum production (except for fall-applied N in 1999). When N was not applied, RLC values at V6 averaged 90% across the 3 yr but declined to <70% at the R3 stage.

The relationship between RLC at the four growth stages and relative grain yield for each year is shown in Table 4 and Fig. 3. Each relationship is based on the data from all four tillage systems and all three N treatments. Two pools of data are evident in the relationships for 1997 and 1998. One pool located >80% relative

Table 3. Relative leaf chlorophyll as affected by tillage and N management at various growth stages in 1997–1999.

		Year (corn growth stage)											
		1997				1998				1999			
Tillage	N Timing/placement	V6	V10	R1	R3	V6	V10	R1	R3	V6	V10	R1	R3
		relative leaf chlorophyll content, %											
No tillage	Control	89	87	80	72	86	88	71	57	88	72	68	59
No tillage	Fall/in-row	97	98	97	98	93	98	97	95	93	80	83	79
No tillage	Spring/mid-row	95	98	98	97	90	96	95	93	94	99	98	96
Strip-till	Control	92	89	82	76	91	88	73	60	90	74	70	61
Strip-till	Fall/in-row	99	98	98	97	95	97	96	92	93	86	89	85
Strip-till	Spring/mid-row	98	97	97	97	95	97	96	95	98	99	97	99
One-pass	Control	90	88	81	74	91	87	77	64	85	75	73	61
One-pass	Fall/in-row	96	97	98	97	98	97	98	96	95	92	91	86
One-pass	Spring/mid-row	97	99	99	97	97	97	97	96	97	100	100	99
Chisel plow	Control	93	91	85	81	94	91	82	73	92	75	75	66
Chisel plow	Fall/in-row	100	98	98	97	98	98	99	98	96	85	92	87
Chisel plow	Spring/mid-row	98	99	97	96	98	98	99	99	97	99	99	99
Tillage system													
No tillage		94	95	92	89	90	94	88	82	92	83	83	78
Strip-till		96	95	92	90	94	94	88	82	94	86	85	82
One-pass		95	95	92	89	96	94	90	85	92	89	88	82
Chisel plow		97	96	93	91	97	95	93	90	95	86	89	84
$P > F$		0.008	0.392	0.449	0.120	<0.001	0.270	0.009	<0.001	0.239	<0.001	0.005	0.066
LSD (0.10)		1				2		3	2		1	2	4
N timing/placement													
Control		91	89	82	76	90	89	76	63	89	74	71	62
Fall/in-row		98	98	98	97	96	97	97	95	94	86	89	85
Spring/mid-row		97	98	98	97	95	97	97	96	96	99	98	98
$P > F$		<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
LSD (0.10)		1	1	1	1	1	1	1	2	2	1	1	2
		Interactions, $P > F$											
Tillage × N		0.665	0.049	0.017	0.008	0.470	0.390	0.031	0.040	0.041	<0.001	0.004	0.608
CV, %		1.5	1.3	1.8	2.8	2.4	1.7	2.6	4.2	2.7	1.8	2.9	4.2

grain yield represents the fall and spring N treatments while those <70% relative grain yield were from the 0-N control plots. In 1999, with significant loss of fall-applied N, the data were distributed more uniformly between 50 and 100% RLC. Relationships were greatest but equal when RLC was taken at the R1 and R3 stages as indicated by r^2 values ≥0.90 in all years. However, delaying RLC diagnosis until these late growth stages probably would be too late under nonirrigated conditions to provide a consistent response to supplemental N if deficiencies began to occur. Our data indicates very satisfactory correlations in all years ($r^2 = 0.84$ to 0.88) when RLC was determined at the V10 stage. However, the slope of the regression lines at the V10 stage was considerably more steep (less sensitive from an interpretation and calibration perspective) than the regression lines at the R1 and R3 stages. Slopes ranged from 1.3 to 2.0 for the R1 and R3 stages across all years, whereas slope ranged from 1.9 to 4.4 at the V10 stage (Table 4). Under nonirrigated and N yield-limiting conditions, growers still would be able to sidedress-apply N and expect a yield response to supplemental N applied at the V10 stage in most years. Attempting to diagnose potential N deficiency at the V6 stage was problematic in all years, with r^2 ranging between 0.50 and 0.77. Moreover, regression line slope ranged from 3.4 to 3.8 at the V6 stage. In 1999, when some of the fall-applied N was lost and N deficiency developed, RLC determined at the V6 stage (94%) did not predict the potential for a yield-limiting N deficiency nearly as well as RLC at the V10 stage (86%) (Table 3). These results were similar to those reported by Bullock and Anderson (1998) where SPAD readings at V7 were not correlated to final grain yield but were strongly correlated when taken at the R1 stage. Piekielek and Fox (1992) proposed other factors such as high rates of N from row-applied fertilizer could raise chlorophyll levels and affect the accuracy of RLC as a diagnostic technique. Because the fall-applied N was applied near or beneath the row (ST), this may have affected RLC at the V6 stage in our study.

CONCLUSIONS

The conclusions drawn from this study should be of assistance to corn producers seeking to improve N use efficiency across a wide range of tillage systems. Time of application had a substantial effect on corn production and N use efficiency in 1 of 3 yr. When wet and

Table 4. Regression equation parameters, r^2, n, and model probability of significance for each of the 12 diagnostic summaries shown in Fig. 3.

		Regression equation parameters†				
Year	Growth stage	Slope	Intercept	r^2	n	Model $P > F$
1997	V6	3.8	−280	0.77	48	<0.001
1997	V10	3.2	−220	0.84	48	<0.001
1997	R1	2.0	−110	0.90	48	<0.001
1997	R3	1.5	−55	0.90	48	<0.001
1998	V6	3.4	−240	0.50	45	<0.001
1998	V10	4.4	−340	0.85	45	<0.001
1998	R1	1.9	−94	0.95	45	<0.001
1998	R3	1.3	−28	0.94	45	<0.001
1999	V6	3.4	−240	0.53	48	<0.001
1999	V10	1.9	−87	0.88	48	<0.001
1999	R1	1.7	−75	0.91	48	<0.001
1999	R3	1.3	−35	0.94	48	<0.001

† Relative grain yield = Intercept + slope × relative leaf chlorophyll content.

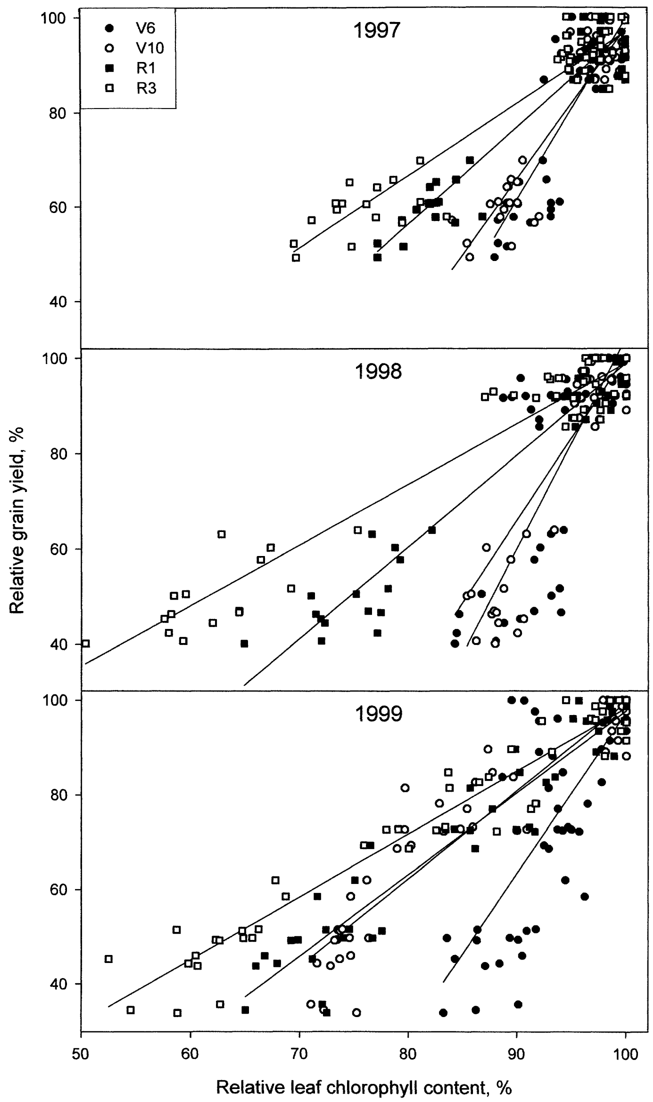

Fig. 3. Relationship between relative leaf chlorophyll content determined by SPAD meter at four corn growth stages and relative grain yield for 1997, 1998, and 1999.

warm spring conditions followed a late fall application (after 20 Oct. when soil temperatures were generally <10°C), corn grain yield and N uptake were reduced by 20 and 27%, respectively. Apparent N recovery was reduced from 87% for spring N to 45% for fall N. Under normal to drier-than-normal April and May conditions, differences between the performance of fall- and spring-applied ammonia were not observed.

Although grain yield differences among tillage systems (0.5 Mg ha^{-1}, 8 bu acre^{-1}) were statistically significant, tillage system had minimal effect on the corn production parameters measured in this study and had no effect on the performance of N timing/placement methods. Thus, based on the results from this study, late fall application of N with the ST operation when soils are <10°C would not be considered a risk-free N application strategy. Our results strongly suggest separating the two field operations by strip tilling in the fall when conditions are ideal and applying N midway between the rows the following spring. Another option for farmers using ST could be a combination of applying anhydrous ammonia containing a nitrification inhibitor with late fall ST. However, we did not evaluate this treatment.

Tillage, ranging from full-width complete disturbance for the CP system to narrow zone disturbance for the ST system, did not affect differently nitrification of either the fall- or spring-applied N. With both systems, much of the fall-applied ammonia nitrified by mid-May; whereas, little of the mid- to late April–applied ammonia had nitrified by then. By mid- to late June, NO_3–N concentrations for the spring N treatments in the top 30 cm (minus NO_3–N in the 0-N control plots) averaged about 12 mg kg^{-1} compared with 4 mg kg^{-1} for fall N across 3 yr.

Relative leaf chlorophyll at the V6, V10, R1, and R3 growth stages was influenced by both tillage and N treatment. Averaged across N treatments, RLC was always lowest for NT and usually greatest for CP tillage. Differences in RLC were not evident between the fall and spring N treatments except when N deficiencies appeared; starting by the V6 stage for fall-applied N. The correlation between RLC and relative grain yield was greatest when RLC was measured at the R1 and R3 growth stages but was also highly acceptable at the V10 stage. Diagnosis of N deficiency using a SPAD meter at the V10 stage should allow sidedress application of N in time for plant uptake and subsequent yield response under nonirrigated conditions in Minnesota. Determining RLC at the V6 stage was too early to develop a satisfactory relationship for predicting relative grain yield, even when N losses and N deficiency symptoms occurred for fall-applied N.

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