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Recovery of Point-Injected Labeled Nitrogen by Corn as Affected by Timing, Rate, and Tillage

D. R. Timmons and J. L. Baker*

ABSTRACT

Point-injection technology is being developed to improve fertilizer management, particularly N management. This study was conducted to evaluate the effects of the rate (number) and timing of point-injections of an ammonium nitrate (NH_4NO_3) solution on N uptake and corn growth and to measure any differences due to tillage. Nitrogen-15 depleted NH_4NO_3 (AN) was hand-injected beside individual plants at the V1, V5, and/or V9 growth stages at rates of 50, 100, and/or 200 kg N ha^{-1} with fall moldboard plow (MP), fall chisel plow (CP), and ridge-till (RT) systems. While MP had the highest grain and total dry matter production (but with the lowest N concentrations in those materials), tillage was not a significant factor in either the percentage of the total plant N derived from labeled AN (N_F) or its recovery (N_R) for any stage sampled. Generally the year (i.e. different environmental conditions) and application timing or a timing-by-year interaction had the greatest influence on N_F and N_R. Although plants sampled at the V9 stage on the average recovered more N from the V1 application (39%) vs the V5 application (27%), at maturity N_R values for grain (35%) and total dry matter (47%) were the same for both V1 or V5 applications (when only two applications were made). However when three applications were made (at the V1, V5, and V9 stages), N_R values decreased with time of application for both grain (38, 31, and 26%, respectively) and total dry matter (53, 43, and 33%, respectively). Across application timing, grain N_R values were 34 and 31%, respectively, for MP and RT. Compared with preplant knifed-in labeled N for MP and RT systems in an adjacent simultaneous study, grain N_R values for point-injected N in this study were 16 and 6% greater, respectively, indicating that multiple injections of fertilizer N improved N-use efficiency.

POINT-INJECTION TECHNOLOGY has been developed in part to increase N-use efficiency by crops and minimize NO_3-N leaching below the root zone, particularly for conservation tillage (Baker et al., 1989). Improved management of agricultural chemicals is now becoming increasingly important with greater emphasis on protecting surface and groundwater quality. Research has covered N source, placement, method of application, time of application, and rates in various combinations for different soils and climatic conditions. Nitrogen sources studied have included KNO_3 (KN), NH_4NO_3 (AN), $(NH_4)_2SO_4$ (AS), urea (U), urea-NH_4NO_3 (UAN), and anhydrous NH_3 (AA). After 12 yr of continuous corn (fall moldboard plow tillage), Nelson and MacGregor (1973) found that AN and U sources of N were equivalent at the 90 and 180 kg N ha^{-1} rates. Also, for conventionally tilled corn, Jung et al. (1972), Stevenson and Baldwin (1969), and Mengel et al. (1982) found no differences between AN, U, and AA; AA and U; and UAN and AA sources of N, respectively. No-till corn which received surface-applied N exhibited differences among N sources, with U generally the least efficient (Bandel et al., 1980; Eckert et al., 1986; Fox and Hoffman, 1981; Fox et al., 1986; Touchton and Hargrove, 1982).

With respect to time and method of N applications, Nelson and MacGregor (1973) observed no corn yield differences (12-yr average) between fall plow down, spring top dress, and sidedress N (except for U at 90 kg N ha^{-1} rate). Higher corn yields for spring-applied N (preplant or side dress) compared with fall-applied N have been reported by Miller et al. (1975) and Stevenson and Baldwin (1969), whereas Welch et al. (1971) observed considerable year-to-year variation in the relative efficiency of fall, spring, and sidedress N in their study. During 10 yr of continuous corn (fall moldboard plow) in Iowa, grain yield for spring incorporated N averaged 15% higher than for fall incorporated N (J.R. Webb, 1988, personal communication). With irrigation, Jung et al. (1972) found that N applied during either the fifth, sixth, seventh, or eighth week after planting was most effective for maximum yields. Depending on N rate and planting time, Russelle et al. (1983) found some yield advantage and greater fertilizer N accumulation in grain when N was applied at the 4-, 8-, or 16-leaf stages than at planting.

No-till corn yields (3-yr average) were significantly increased by N application at the V5 through V6 growth stage compared to N application at planting or when injected instead of surface broadcast (Fox et al., 1986). Touchton and Hargrove (1982) compared three UAN application methods for no-till corn. They observed little yield differences between surface and incorporated bands, but found considerably lower yields for surface broadcast spray.

Point-injection technology was developed to be compatible with conservation tillage systems since there is only a slight disturbance of surface crop residue during fertilizer application. Because the liquid

D.R. Timmons, USDA-ARS, National Soil Tilth Laboratory, and J.L. Baker, Agricultural and Biosystems Engineering Dep., Iowa State Univ., Ames, IA 50011. Joint contribution: The National Soil Tilth Laboratory, and Journal Paper no. J-14071 of the Iowa Agriculture and Home Economics Experiment Station, Ames, Project no. 2445. 29 Aug. 1990. *Corresponding author.

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Abbreviations: AA, anhydrous ammonia; AN, ammonium nitrate; AS, ammonium sulfate; KN, potassium nitrate; U, urea; UAN, urea-ammonium nitrate; N_F, labeled N taken up by plants divided by total plant N; N_R, labeled N taken up by plants divided by total labeled N applied; CP, chisel plow; MP, moldboard plow; and RT, ridge-till.

fertilizer solution is injected about 10 cm deep (Baker et al., 1989), volatilization loss of NH_3 from urea-containing solutions would be negligible. The configuration of point-injected fertilizer differs from that of knifed-in fertilizer in that the solution is distributed in small volumes of soil about 20 cm apart rather than in a continuous band. Thus, the uptake of plant nutrients during early corn growth may be influenced by the time of application since the plant root development and distribution will be different. Since existing information about point-injected N is very limited, this study was performed to (i) evaluate the effects of labeled N rate (number) and timing of point-injections of an AN solution on plant N uptake and recovery by corn, (ii) determine any differences in N-use efficiency of point-injected fertilizer due to tillage, and (iii) compare use efficiency of point-injected N with other application methods in adjacent simultaneous studies.

Table 1. Amounts of N point-injected at different corn growth stages, unlabeled (1981–1982) and labeled (1983–1985) N treatments, and plant sampling stages.

No. of injections	Growth stages	N injection rate† V1	V5	V9	total	Sampling stages V5	V9	R6
		kg ha^{-1}						
0	–	0	0	0	0	x	x	x
1	V1	50	0	0	50	x	–	x
		50‡	0	0	50	x	–	x
2	V1, V5	50	50	0	100	–	x	x
		50‡	50	0	100	–	x	x
		50	50‡	0	100	–	x	x
		50‡	50‡	0	100	–	x	x
3	V1, V5, V9	50	50	100	200	–	–	x
		50‡	50	100	200	–	–	x
		50	50‡	100	200	–	–	x
		50	50	100‡	200	–	–	x
		50‡	50‡	100‡	200	–	–	x

† 6.25 kg P ha^{-1} and 18.75 kg K ha^{-1} also injected with each 50 kg N ha^{-1}.
‡ Indicates ^{15}N-depleted NH_4NO_3 (99.99% ^{14}N) applied.

MATERIALS AND METHODS

This study was conducted from 1981 to 1985 at the Agronomy and Agricultural Engineering Research Center near Ames, IA, on a predominantly Nicollet loam (fine-loamy, mixed, mesic Aquic Hapludolls) with some associated Webster silty clay loam (fine-loamy, mixed, mesic, Typic Haplaquolls). The three tillage systems compared in this study were fall moldboard plow (MP), fall chisel plow (CP), and ridge-till (RT), all established in 1975. For both MP and CP, corn stalks were shredded before fall tillage and depth of tillage was approximately 20 cm; both systems included disk harrowing and/or field cultivation in the spring before planting. The chisel plow used had 7.6-cm twisted points on 38-cm spacings. All areas were mechanically cultivated once or twice each year, as needed to control weeds. No preplant tillage was used for the RT system; ridges were rebuilt each year at final cultivation with a rolling or disk cultivator. The experimental area was cropped with a corn-soybean rotation during 1975 to 1979, and continuous corn 1980 to 1985. Each tillage area was 96 by 27 m, and tillage systems were randomized within each of three replications. Plot areas received their last N application (knifed-in anhydrous ammonia) in spring, 1979, and their last P and K application (broadcast) in fall, 1979. At the beginning of this experiment, Bray's no. 1 extractable P and exchangeable K concentrations in the soil (upper 30 cm) were at the high test levels in each of the tillage systems.

In 1981, three unlabeled N treatments (plus a check treatment, Table 1) were randomized within a 3-by-10 m area for each tillage system with that area not having been fertilized since 1979. In 1982, these treatments were imposed on adjacent areas within the same tillage subplot that also had not been fertilized since 1979. In 1983 through 1985, the eight labeled N treatments shown in Table 1 (plus a check treatment) were imposed on additional adjacent areas within the same tillage subplot, each time on an area that had not been fertilized since 1979. Buffer zones to satisfy the minimum distances observed by Sanchez et al. (1987) were used to assure that no lateral movement of the labeled N occurred (^{15}N analysis of plants not receiving labeled N applications showed that no lateral movement occurred along or between rows). The labeled material used to make the fertilizer solution that was injected was ^{15}N-depleted AN (99.99% ^{14}N).

The concentration of the fertilizer solution was such that when applied at 1200 L ha^{-1}, it would supply 200 kg N ha^{-1} (as NH_4NO_3), 25 kg P ha^{-1} (as K_2HPO_4), and 75 kg K ha^{-1} (as KCL and K_2HPO_4). This solution was injected next to all corn plants at the V1 corn growth stage (excepting those in the check treatment), at the V5 stage next to those plants that were to receive two or three injections; and at the V9 stage next to those plants that were to receive three injections and had already received injections at the V1 and V5 stages. For three injections, assuming a plant population of 60 000 plants ha^{-1}, a total volume of 20 mL of the fertilizer solution per plant was injected using a hand-operated volumetric syringe; for two injections 10 mL was injected, and for one injection, 5 mL was injected. Therefore, at the V1 stage, 5 mL of solution (50 kg N ha^{-1}) was injected 5 cm from the plant and 5 cm deep; and depending on the N treatment, at the V5 stage, an additional 5 mL of solution (50 kg N ha^{-1}) was injected 10 cm from the plant and 10 cm deep; and at the V9 stage, a final 10 mL of solution (100 kg N ha^{-1}) was injected 10 cm from the plant and 10 cm deep. The greater depth and distance from the plant for injections at V5 and V9 more closely matches what is feasible with a field point-injector applicator when the crop canopy has begun to develop. At the V1 stage, the needle of the hand syringe was inserted directly into the soil and the 5 mL of solution slowly dispensed. At the V5 and V9 stages, a pointed steel rod 12 mm in diameter was inserted into the soil to the 10-cm depth to create a cavity and the solution was slowly dispensed by syringe into that cavity. After the fertilizer solution was dispensed, each hole was filled with soil. The growth stages at which fertilizer was applied and samples were taken were identified according to the classification scheme of Richie and Hanway (1982); care was taken not to miss desiccated lower leaves at the V5 and V9 stages.

A 110-d relative maturity corn hybrid was planted at about 65 700 seeds ha^{-1} in 0.76-m rows with a John Deere Model 71 Maximerge[1] slot planter. A recommended insecticide was applied with the corn seed at planting, and recommended herbicides were broadcast before emergence. Actual plant stands for the five growing seasons averaged 60 038, 59 507, and 57 905 plants ha^{-1} for MP, CP, and RT, respectively. These differences were not significant, but the trend is the same as an earlier study where it was stated "reasons for the variation in final plant population among tillage systems from year to year are not clear but may be due to interactions between planter performance, weather, and tillage (Erbach, 1982)."

The above ground portions of five corn plants that received 50 kg N ha^{-1} (one fertilizer injection) were harvested at the V5 stage (at the same time as the second fertilizer injection), and similarly, five corn plants that received 100 kg N ha^{-1} (two fertilizer injections) were harvested at the V9 stage (at the same time as the third fertilizer injection). After drying at 65 °C to measure dry matter, these samples were

[1]Reference to a trade or company name is for specific information only and does not imply approval or recommendation of the company or product by the USDA or Iowa State University, to the exclusion of others that may be suitable.

hand-chopped and ground in a Cyclone mill (UDY Corp., Fort Collins, CO) for chemical and isotope analyses. At physiological maturity (R6 stage), 10 corn plants (above ground portion) were harvested, dried at 65 °C, and then separated into grain and stover (including cobs) components. Corn stover was chopped by hand and ground in a Cyclone mill, and corn grain was shelled by hand and ground in a hammer mill for chemical and isotope analyses.

Total N in the ground corn was determined by the permanganate-reduced iron modification of the Kjeldahl procedure (Bremner and Mulvaney, 1982). Separate distillates for isotopic N forms were collected in dilute H_2SO_4, concentrated to about 2 mL volume, and reacted with sodium hypobromite in an evacuated Rittenberg flask. A Finnegan MAT 250 (Finnegan MAT, San Jose, CA) mass spectrometer (in the Agronomy Dep., Iowa State Univ.) was used to measure the $^{15}N/^{14}N$ ratio of the resulting N gas. Based on these determinations, total plant N uptake, labeled fertilizer N uptake (N_F), and labeled fertilizer N recovery (N_R) were calculated as detailed by Blackmer and Sanchez (1988). The symbol N_F equals the mass of labeled N taken up by plants divided by the total mass of N in those plants; N_R equals the mass of labeled N taken up by plants in a certain area divided by the total labeled N applied to that area.

Table 2. Precipitation data for the Iowa Agronomy-Agricultural Engineering Research Center.

Period	1981	1982	1983	1984	1985	LTA†
	Precipitation					
	mm					
Jan.-Mar.	31	133	135	63	90	96
April	48	70	80	173	31	86
May	25	155	158	129	32	111
June	104	66	232	167	86	130
July	101	146	97	86	36	88
August	147	88	107	8	129	99
September	61	48	81	101	102	82
October	42	67	159	92	87	59
Nov.-Dec.	77	183	147	95	49	56
annual	636	956	1196	915	642	807

† Long-term average from "Climatological Data Annual Summary, Iowa, 1986," National Oceanic and Atmospheric Administration, for Ames 8WSW station.

The ANOVA models were based on a split-block design for tillage and years with the fertilizer treatments conducted as a subunit within the tillage-year whole unit treatment combinations. The ANOVA model for the two and three injection experiments was:

$$Y_{ijk} = u + R_i + T_j + a_{(ij)} + Y_k + b_{(ik)} + T \times Y_{jk} + c_{(ijk)} + AS_l + T \times AS_{jl} + Y \times AS_{kl} + T \times Y \times AS_{jkl} + d_{(ijkl)},$$

where:

R_i = blocked replicate (random), i = 1 to 3;
T_j = tillage treatment (fixed), j = 1 to 3;
a_{ij} = whole unit error for tillage;
Y_k = year (random), k = 1 to 3 or 1 to 5;
$b_{(ik)}$ = whole unit error for year;
$c_{(ijk)}$ = error for tillage and year;
AS_l = N treatment (fixed), l = 1 to 2 or 1 to 3;
$d_{(ijkl)}$ = subunit error.

All error terms were tested for pooling; errors *a* and *b* were pooled into error *c*. Year was considered to be a random factor as the tillage practices had been in place on the experimental units for 5 yr prior to the start of this experiment. The year interaction was used to test each corresponding fixed treatment effect. For the one injection experiment with no AS variable, the ANOVA model was reduced to just the first eight terms of the model given above.

RESULTS AND DISCUSSION

Growth Conditions

At the beginning of each growing season, the soil water content to 1.5-m depth was either near or at field capacity. Because of adverse weather conditions during at least 3 yr (see precipitation data, Table 2), corn yields during the 5-yr period were less than the 11.0 Mg ha^{-1} yield that might be expected in the region

Table 3. Corn grain yields and total mature dry matter as affected by application stage and tillage (1981–1985) or year (1983–1985).

Stage(s) N applied	Total N applied	Grain‡				Mature plants			
Tillage:		MP§	CP	RT	(avg.)	MP	CP	RT	(avg.)
	kg ha^{-1}	Mg ha^{-1}							
check	0	4.1	2.3	2.3	(2.9)	8.5	6.6	6.2	(7.1)
V1	50	6.4	5.5	5.5	(5.8)	11.3	10.1	9.5	(10.3)
V1, V5	100	6.9	6.6	6.7	(6.7)	12.1	11.5	11.2	(11.6)
V1, V5, V9	200	8.5	7.5	7.6	(7.9)	13.9	12.5	12.4	(12.9)
(avg.)		(6.5)	(5.5)	(5.5)	(5.8)	(11.4)	(10.2)	(9.8)	(10.5)
Year:		*1983*	*1984*	*1985*	(avg.)	*1983*	*1984*	*1985*	(avg.)
	kg ha^{-1}	Mg ha^{-1}							
check	0	1.2	1.9	2.9	(2.0)	6.0	5.0	7.3	(6.1)
V1	50	3.8	4.4	6.8	(5.0)	8.8	7.4	10.4	(8.8)
V1, V5	100	5.7	5.3	7.8	(6.3)	11.0	8.5	11.9	(10.4)
V1, V5, V9	200	6.7	5.8	8.9	(7.2)	12.6	9.1	13.5	(11.7)
(avg.)		(4.4)	(4.4)	(6.6)	(5.1)	(9.6)	(7.5)	(10.8)	(9.3)
Statistical Data									
Source	df	Grain	Mature Plants						
Tillage (T)	2	†	*						
Year (Y)	4	**	**						
T × Y	8	NS	NS						
N Rate (R)	2	**	**						
T × R	4	NS	NS						
Y × R	8	NS	NS						
T × Y × R	16	NS	NS						

**, *, and † show significance at the 0.01, 0.05, and 0.10 probability levels, respectively, and nonsignificance at $P > 0.10$. The ANOVA only includes the fertilized treatments.
‡ Mass of grain reported here is as no. 2 corn which includes 155 g kg^{-1} moisture; elsewhere grain is adjusted to 0 g kg^{-1} moisture.
§ MP (moldboard plow), CP (chisel plow), and RT (ridge till).

with sufficient fertility. Excessive rainfall in May 1982, delayed planting until 3 June resulting in decreased yields. In 1983, only 40 mm of rainfall from 5 July to 21 August combined with an average August maximum air temperature of 32.5 °C reduced yields. In 1984, less than 10 mm of rainfall was received from 27 July to 31 August (grain filling period) and yields were depressed even more severely than in 1983. Of the five seasons, crop growth conditions were most favorable during 1981 and 1985.

Grain and Dry Matter Production

Grain yields (5-yr averages) for fertilized corn ranged from 5.5 to 8.5 Mg ha^{-1} depending on tillage system and injected N rate (number of fertilizer injections); the greatest yields were obtained with MP tillage (Table 3; yields for the three individual years labeled N was used are also shown for later reference). Yield response to injected N was observed for each tillage system during each growing season, and MP tillage also produced the greatest yield without N fertilization. When averaged across tillage, total application of 50 kg N ha^{-1} (one injection), 100 kg N ha^{-1} (two injections), and 200 kg N ha^{-1} (three injections) increased grain yields by 99, 17, and 17% compared to the next lower N rate, respectively, for a typical diminishing response. Applied P and K fertilizers should not have been a factor because soil tests showed that neither available P nor exchangeable K in the soil were limiting. Corn grain yields were influenced by year, rate of injected N, and tillage; no N rate by tillage interactions were observed (Table 3). Yield differences due to tillage were greatest at the 50 (one injection) and 200 (three injections) kg N ha^{-1} rates with yields for MP tillage greater than those for CP and RT.

Total dry matter at physiological maturity (R6 stage), like grain production, increased with rate of injected N regardless of tillage, and no N rate-by-tillage interactions were observed (Table 3). Total dry matter was greatest with MP tillage for each injected N increment.

Total and Labeled Nitrogen in Corn

During the three seasons in which labeled N was applied (1983–1985), corn plants sampled at the V5 and V9 growth stages showed no tillage effect on N concentration and averaged 4.3 and 2.3 g N kg^{-1} dry matter, respectively (data not shown in Tables). At physiological maturity (R6 stage), grain N concentrations for fertilized corn averaged over tillage and years ranged from 13.1 (50 kg ha^{-1}) to 16.9 (200 kg ha^{-1}) g N kg^{-1} dry grain (Table 4). Based on the 15.4 g kg^{-1} dry grain sufficiency level for maximum yields suggested by Pierre et al. (1977), 200 kg N ha^{-1} (three injections) for each tillage system provided adequate N. However, 100 kg N ha^{-1} (two injections) satisfied this sufficiency level only for CP.

Grain N concentrations were influenced by year, injected N rate, and tillage, and a N rate-by-year interaction was observed. For a constant fertility treatment, the year of highest grain N concentration was associated with the year of the lowest yield. For each tillage system, grain N concentrations increased as N rate increased, and the tillage effect was due to higher grain N concentrations for CP and mostly at 100 kg N ha^{-1}. Comparisons to different methods of applications and N sources show that the average (1983–1985) grain N concentrations for 200 kg N ha^{-1} (three injections) with MP and RT systems, 16.6 and 17.0 g N kg^{-1}, respectively, were similar to those that received 224 kg N ha^{-1} of preplant knifed-in UAN solution in an adjacent simultaneous study where MP and RT averaged 16.7 and 17.4 g N kg^{-1}, respectively (Timmons and Cruse 1990, 1991). In addition, Blackmer and Sanchez

Table 4. Nitrogen concentrations in corn grain and mature plants as affected by application stage and tillage or year.

Stage(s) N applied	Total N applied	Grain				Mature plants			
Tillage:		MP§	CP	RT	(avg.)	MP	CP	RT	(avg.)
	kg ha^{-1}	g N kg^{-1}							
check	0	12.0	11.3	11.3	(11.5)	6.6	7.4	7.2	(7.1)
V1	50	12.9	13.4	12.8	(13.1)	8.2	8.4	8.2	(8.2)
V1, V5	100	14.4	15.7	15.0	(15.0)	9.7	10.5	10.1	(10.1)
V1, V5, V9	200	16.6	17.1	17.0	(16.9)	11.7	11.8	11.8	(11.8)
(avg.)		(14.0)	(14.4)	(14.0)	(14.1)	(9.0)	(9.5)	(9.3)	(9.3)
Year:		*1983*	*1984*	*1985*	(avg.)	*1983*	*1984*	*1985*	(avg.)
	kg ha^{-1}	g N kg^{-1}							
check	0	12.4	10.3	11.7	(11.5)	6.9	6.3	8.1	(7.1)
V1	50	13.6	13.3	12.2	(13.1)	7.7	8.4	8.7	(8.2)
V1, V5	100	14.4	15.8	14.9	(15.0)	9.1	10.2	10.9	(10.2)
V1, V5, V9	200	16.5	17.2	17.1	(16.9)	10.9	11.7	12.7	(11.8)
(avg.)		(14.2)	(14.2)	(14.0)	(14.1)	(8.6)	(9.2)	(10.1)	(9.3)

Statistical Data

Source	df	Grain	Mature Plants
Tillage (T)	2	*	†
Year (Y)	2	*	**
T × Y	4	NS	NS
N Rate (R)	2	**	**
T × R	4	NS	NS
Y × R	4	**	**
T × Y × R	8	NS	NS

**, *, and † show significance at the 0.01, 0.05, and 0.10 probability levels, respectively, and nonsignificance at $P > 0.10$. The ANOVA includes only the fertilized treatments.

‡ MP (moldboard plow), CP (chisel plow), and RT (ridge till).

(1988) reported 3-yr averages of 15.5 and 16.8 g N kg^{-1}, respectively, for 112 and 224 N kg ha^{-1} as AA applied to continuous corn with MP tillage on the same experimental site.

Mature plant N concentrations also were influenced by year, injected N rate, and tillage, with a N rate-by-year interaction (Table 4). Unlike for grain, the year of highest dry matter N concentrations was associated with the year of the highest dry matter production. Similar to grain N concentrations, plant N concentrations within each tillage increased as injected N rate increased, and the tillage effect was due to higher plant N concentrations for CP and mostly at 100 kg N ha^{-1}. Plant N concentrations of 11.7 and 11.8 g N kg^{-1} for MP and RT systems, respectively, that received 200 kg N ha^{-1} in this study were slightly higher than for 224 kg N ha^{-1} of preplant knifed-in UAN in an adjacent simultaneous study where N concentrations averaged 10.6 and 10.9 g N kg^{-1}, respectively (Timmons and Cruse 1990; 1991).

Corn that received 50 kg ha^{-1} of labeled N (one injection) at the V1 stage and sampled at the V5 stage showed no tillage effects on the percent of N derived from fertilizer, N_F, or on the fertilizer N recovery, N_R (Table 5). Although the N_F by year ranged from about 53 to 59%, the N_R was low, ranging from 4 to 21%, because average total N uptake at the V5 stage was only 10 kg ha^{-1}. Corn that received 100 kg N ha^{-1} in two injections (50 kg ha^{-1} of labeled N at either the V1 or V5 stage) and was sampled at the V9 stage showed an effect due to year and application stage by year but no tillage effect for either N_F or N_R (Table 5). The year effect was greatest in 1985 when only 12% of the labeled N applied at the V5 stage was recovered at the V9 stage. That year there was a dry spring and only 28 mm of rain fell in the 19 d between the V5 and V9 stages, possibly leaving the applied N positionally unavailable in dry soil. However, as shown later, N_R values at maturity were approximately equal for the V1 and V5 applications. An average of 10.8% of the labeled N applied at the V1 stage was recovered from V1 to the V5 stage, and by difference, another 28% was recovered from the V5 to V9 stage. This compares with an average of 27.3% of the labeled N applied at the V5 stage and recovered at the V9 stage.

Average N_F values for mature corn (R6 stage) that received 50, 100, and 200 kg N ha^{-1} (one, two, and three injections, respectively) are presented in Tables 6 and 7. The N_F values for both corn grain and whole plants that received 50 kg N ha^{-1} at the V1 stage (one injection) were not affected by tillage (ANOVA not shown). With 50 kg N ha^{-1} injected at both the V1 and V5 stages (two injections, only one of which was of labeled N), year was a factor with the largest N_F value occurring in the year of greatest production. No effects on N_F due to tillage or application stage (timing) were observed for grain and whole plants (except for $p < 0.10$ for application stage on mature plants; Table 6). This indicates that the point-injected N was equally available for corn growth regardless of tillage when

Table 5. Percentage of total N from labeled N (N_F) and recovery of labeled N (N_R) in corn at the V5 and V9 stages as affected by application stage and year.

Stage(s) N‡ applied	Amt N‡ applied	V5 Stage 1983	V5 Stage 1984	V5 Stage 1985	V5 Stage (avg.)	V9 Stage 1983	V9 Stage 1984	V9 Stage 1985	V9 Stage (avg.)
	kg ha^{-1}	%N_F							
V1‡	50	58.8	61.4	52.7	(57.6)	–	–	–	–
V1‡, V5	50	–	–	–	–	37.6	43.4	47.7	(42.9)
V1, V5‡	50	–	–	–	–	30.7	45.0	12.1	(29.3)
(avg.)		–	–	–	–	(34.1)	(44.2)	(29.9)	(36.1)
V1‡, V5‡	100§	–	–	–	–	69.1	61.8	62.4	(64.4)
Statistical Data									
Source		df	V5 Stage	df	V9 Stage				
Tillage (T)		2	NS	2	NS				
Year (Y)		2	**	2	**				
T × Y		4	NS	4	†				
Applic. Stage (AS)		–		1	NS				
T × AS		–		2	NS				
Y × AS		–		2	**				
T × Y × AS		–		4	†				
	kg ha^{-1}	%N_R							
V1‡	50	4.0	20.8	7.0	(10.8)	–	–	–	–
V1‡, V5	50	–	–	–	–	38.3	34.3	43.7	(38.8)
V1, V5‡	50	–	–	–	–	31.4	38.9	11.8	(27.3)
(avg.)		–	–	–	–	(34.8)	(36.6)	(27.8)	(33.1)
V1‡, V5‡	100§					32.9	23.8	25.0	(27.2)
Statistical Data									
Source		df	V5 Stage	df	V9 Stage				
Tillage (T)		2	NS	2	NS				
Year (Y)		2	**	2	*				
T × Y		4	NS	4	NS				
Applic. Stage (AS)		–		1	NS				
T × AS		–		2	NS				
Y × AS		–		2	**				
T × Y × AS		–		4	NS				

**, *, and † show significance at the 0.01, 0.05, and 0.10 probability levels, respectively, and nonsignificance (NS) at $P > 0.10$.

‡ ^{15}N-depleted double label NH_4NO_3 solution; for V1, V5 total N applied was 100 kg ha^{-1}.

§ Data for all N applied as labeled N included for check of consistency; they are not included in the ANOVA.

applied at the V1 or V5 growth stages. Data also were taken as an experimental check for the case where both the V1 and V5 applications were made with labeled N. As shown, the N_F values for grain (average of 45.8%) and mature plants (46%) should, and essentially do, equal the sums of N_F values for applications of labeled N made at V1 and V5 (grain: 22.8 + 23.9 = 46.7%; mature plants: 23.1 + 23.7 = 46.8%).

Average N_F values for corn grain and mature whole plants (R6 stage) that received 50, 50, and 100 kg N ha^{-1} at the V1, V5, and V9 stages, respectively (three injections), were not affected by tillage (Table 7). However, application stage (timing), and application stage interactions with tillage and year had significant effects. If the results for the 100 kg ha^{-1} of labeled N applied at V9 are normalized to 50 kg N ha^{-1} (i.e. by dividing N_F by 2), there is a trend of decreasing N_F as application is delayed. The tillage-by-application stage interaction occurred because the N_F values for MP tillage were lowest with the V1 application and highest with the V9 application for both grain and whole plants (data not shown). Data are again shown as an experimental check for the case where the V1, V5, and V9 applications were all made with labeled N. The N_F values for grain (62.1%) and mature plants (61.3%) essentially equal the sums for applications of labeled N made at V1, V5, and V9 (grain: 17.9 + 14.4 + 26.8 = 59.2; mature plants: 18.5 + 15.5 + 25.5 = 59.5).

No major differences in the N_F values were found between grain and mature plants as effected by timing, year (Tables 6 and 7), or tillage (data not shown). For the 200 kg ha^{-1} total N rate (Table 7), there was a very slight trend that N applied at the V1 stage was more concentrated in the mature plant than in the grain (18.5 vs. 17.9% N_F values averaged across year and tillage); the same was true for N applied at the V5 stage (15.5 vs. 14.5% average N_F values). For N applied at the V9 stage, however, this trend was reversed (25.6 vs. 26.8% average N_F values). Based on the timing of corn ear development with respect to N injections, this difference might be expected.

Corn grain N_F values for 200 kg N ha^{-1} point-injected averaged 62 and 63%, respectively, for MP and RT tillage systems; for comparison, N_F values for 112 and 224 kg N ha^{-1} as AA with MP tillage averaged (3-yr) 35 and 46%, respectively (Blackmer and Sanchez, 1988). Preplant knifed-in 28% UAN at 224 kg N ha^{-1} rate resulted in corn grain N_F values of 49 and 56%, respectively, for MP and RT systems (Timmons and Cruse, 1990).

Depending on year, injected N rate (number of injections), and growth stage (timing), average recovery of injected labeled N (N_R) ranged from 19 to 55% for corn grain and from 24 to 74% for mature plants (Tables 6 and 7). The N_R value for corn grain and MP tillage with two N injections at the V1 and V5 stages

Table 6. Percentage of total N from labeled N (N_F) and recovery of labeled N (N_R) in grain and mature plants as affected by two application stages and year.

Stage(s) N‡ applied	Amt N‡ applied	Grain 1983	Grain 1984	Grain 1985	Grain (avg.)	Mature plants 1983	Mature plants 1984	Mature plants 1985	Mature plants (avg.)
	kg ha^{-1}	%N_F							
V1‡, V5	50	19.4	24.4	24.6	(22.8)	19.6	24.2	25.4	(23.1)
V1, V5‡	50	19.6	25.7	26.5	(23.9)	20.0	25.1	25.9	(23.7)
(avg.)		(19.5)	(25.1)	(25.5)	(23.4)	(19.8)	(24.7)	(25.7)	(23.4)
V1‡	50§	23.6	25.2	29.5	(26.1)	25.1	25.9	30.8	(27.3)
V1‡, V5‡	100§	43.3	44.4	49.7	(45.8)	42.9	45.1	50.2	(46.0)
Statistical Data									
Source		df	Grain	Mature Plants					
Tillage (T)		2	NS	NS					
Year (Y)		2	**	**					
T × Y		4	†	NS					
Applic. Stage (AS)		1	NS	†					
T × AS		2	NS	NS					
Y × AS		2	NS	NS					
T × Y × AS		4	NS	NS					
	kg ha^{-1}	%N_R							
V1‡, V5	50	23.8	33.2	49.1	(35.4)	35.9	40.6	64.6	(47.0)
V1, V5‡	50	26.7	32.2	47.4	(35.4)	39.8	38.1	61.9	(46.6)
(avg.)		(25.2)	(32.7)	(48.3)	(35.4)	(37.9)	(39.4)	(63.3)	(46.8)
V1‡	50§	22.4	26.2	44.7	(31.1)	34.5	34.1	59.0	(42.5)
V1‡, V5‡	100§	29.6	32.5	48.8	(36.9)	42.3	41.2	66.1	(49.9)
Statistical Data									
Source		df	Grain	Mature Plants					
Tillage (T)		2	NS	NS					
Year (Y)		2	**	**					
T × Y		4	*	**					
Applic. Stage (AS)		1	NS	NS					
T × AS		2	NS	NS					
Y × AS		2	NS	NS					
T × Y × AS		8	NS	NS					

**, *, and † show significance at the 0.01, 0.05, and 0.10 probability levels, respectively, and nonsignificance (NS) at $P > 0.10$.

‡ ^{15}N-depleted double label NH_4NO_3 solution; for V1, V5 total N applied was 100 kg ha^{-1}.

§ Data for all N applied as labeled N included for check of consistency; they are not included in the ANOVA.

Table 7. Percentage of total N from labeled N (N_F) and recovery of labeled N (N_R) in grain and mature plants as affected by three application stages and year.

Stage(s) N‡ applied	Amt N‡ applied	Grain 1983	Grain 1984	Grain 1985	Grain (avg.)	Mature Plants 1983	Mature Plants 1984	Mature Plants 1985	Mature Plants (avg.)
	kg ha⁻¹				%N_F				
V1‡, V5, V9	50	15.0	19.0	19.7	(17.9)	15.7	19.3	20.4	(18.5)
V1, V5‡, V9	50	12.6	15.6	15.1	(14.5)	14.0	15.4	17.0	(15.5)
V1, V5, V9‡	100	30.8	23.1	26.6	(26.8)	28.5	22.3	25.8	(25.5)
(avg.)		(19.5)	(19.2)	(20.5)	(19.7)	(19.4)	(19.0)	(21.1)	(19.8)
V1‡, V5‡, V9‡	200§	62.7	61.5	62.2	(62.1)	60.5	61.1	62.4	(61.3)
Statistical Data									
Source		df	Grain	Mature Plants					
Tillage (T)		2	NS	NS					
Year (Y)		2	NS	NS					
T × Y		4	NS	NS					
Applic. Stage (AS)		2	*	*					
T × AS		4	*	†					
Y × AS		4	**	**					
T × Y × AS		8	*	†					
	kg ha⁻¹				%N_R				
V1‡, V5, V9	50	28.5	33.0	54.8	(38.7)	43.7	41.7	73.7	(53.0)
V1, V5‡, V9	50	25.1	27.9	40.2	(31.1)	40.0	34.4	53.7	(42.7)
V1, V5, V9‡	100	26.5	18.9	31.2	(25.5)	35.3	23.6	40.1	(33.0)
(avg.)		(26.7)	(26.6)	(42.0)	(31.8)	(39.6)	(33.2)	(55.8)	(42.9)
V1‡, V5‡, V9‡	200§	28.1	24.8	37.3	(30.0)	40.2	31.4	51.0	(40.8)
Statistical Data									
Source		df	Grain	Mature Plants					
Tillage (T)		2	NS	NS					
Year (Y)		2	**	**					
T × Y		4	NS	NS					
Applic. Stage (AS)		2	†	*					
T × AS		4	NS	NS					
Y × AS		4	**	**					
T × Y × AS		8	**	**					

**, *, and † show significance at the 0.01, 0.05, and 0.10 probability levels, respectively, and nonsignificance (NS) at $P > 0.10$.
‡ ^{15}N-depleted double label NH_4NO_3 solution; for V1, V5, V9, total N applied was 200 kg ha⁻¹.
§ Data for all N applied as labeled N included for check of consistency; they are not included in the ANOVA.

totaling 100 kg N ha⁻¹ averaged 41% with 6.9 Mg ha⁻¹ yield (data not shown). For comparison, on the same experimental site with MP tillage, Sanchez and Blackmer (1988) reported an average (3-yr) grain N_R of 19% when 112 kg N ha⁻¹ as AA was applied preplant in the spring and 4.8 Mg ha⁻¹ corn yield.

When labeled AN was injected at the V1, V5, or V9 growth stages, year, application stage, and their interaction influenced fertilizer N recovery in grain and mature plants (Table 7). Year was a factor with the largest recovery in the year of greatest production. As with N_F values, N_R values averaged for application stage across tillage and years were in the order V1 > V5 > V9 for both grain and mature plants. Average N_R values decreased by 8% between the V1 and V5 injections and by 6% between the V5 and V9 injections. Data are again shown for the cases where all applications were made with labeled N to provide an experimental check on N_R values. For two applications (Table 6), average recoveries in grain (36.9%) and mature plants (49.9%) agree well with average N_R values for individual applications for grain [(35.4 + 35.4)/2 = 35.4%] and mature plants [(47.0 + 46.6)/2 = 46.8%]. For three applications (Table 7), average recoveries in grain (30.0%) and mature plants (40.8%) agree well with average N_R values for individual applications, weighted for the different amounts applied, for grain [(38.7 + 31.1 + 25.5 + 25.5)/4 = 30.2%] and mature plants [(53.0 + 42.7 + 33.0 + 33.0)/4 = 40.4%]. As shown in Tables 6 and 7, the extra growth caused by the addition of 50 kg N ha⁻¹ at V5 increased recovery of the 50 kg labeled N ha⁻¹ applied at V1 in the mature plant from 42.5 to 47.0% (averaged across years and tillage); further addition of 100 kg N ha⁻¹ at V9 increased recovery to 53.0%. "Dilution" of the labeled N with unlabeled N applied at V5 reduced %N_F from labeled N from 27.3 to 23.1%; further addition of 100 kg N ha⁻¹ at V9 reduced this percentage to 18.5%. For labeled N applied at 50 kg ha⁻¹ at V5, addition of 100 kg N ha⁻¹ at V9 reduced both recovery (from 46.6–42.7%) and %N_F (from 23.7–15.5%). The increased growth was not sufficient to overcome the "dilution" effect.

Compared with preplant knifed-in UAN solution in another study, N injected at the V1, V5, and V9 growth stages (three injections) was utilized more efficiently by corn grain with MP tillage (20 vs. 35% N_R) and RT (20 vs. 26% N_R) in continuous corn culture (Timmons and Cruse, 1990). Sanchez and Blackmer (1988) also reported an average N_R value for corn grain of 17% for continuous corn with MP tillage that was fertilized with 224 kg N ha⁻¹ preplant AA.

In summary, the additional corn growth with additional applied N that occurred for the conditions in this study, and the dilution of existing N in the soil-water system with additional applied N (or vice versa), combined to determine the effects of rate (or number of applications) and timing on uptake and recovery of labeled N by corn. For example, the recovery in both grain and mature plants of labeled N applied at the V1 stage increased with additional nonlabeled fertilizer applied at the V5 stage, and increased further with an additional increment of nonlabeled fertilizer applied at the V9 stage for all 3 yr of the study. Therefore the additional growth factor exceeded the dilution factor. On the contrary, the recovery of labeled N applied at the V5 stage (with nonlabeled N applied at the V1 stage) was decreased if an additional application of nonlabeled N was made at the V9 stage, despite an increase in growth.

When the total amount of 200 kg N ha^{-1} was applied over three applications, the recovery of labeled N decreased as it was applied later during the vegetative growth stages. When the total amount of 100 kg N ha^{-1} was applied over two applications, the recovery of labeled N was not affected whether it was applied at the V1 or V5 stage. When all the fertilizer applied was labeled N, maximum percent recovery occurred for the intermediate rate of 100 kg N ha^{-1}.

Tillage affected grain yields and dry matter production with MP having the highest values. However, tillage was not shown to have a significant effect on either N_F or N_R values within the variability of the study.

Comparison of the results from this study with other studies indicates that more precise placement and timing of fertilizer N applications attained by utilizing point-injection technology increased N recovery by corn. During the 3-yr period in which labeled N was injected (200 kg ha^{-1} N rate), the percentage of labeled N not recovered by mature corn (grain + stover) averaged 53, 61, and 64%, respectively, for MP, CP, and RT systems. Thus, there is potential for increased fertilizer N use-efficiency, which is important for both economic and environmental reasons.

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