Effect of Tillage and Nitrogen Rate on Corn Yield and Nitrogen and Phosphorus Uptake in a Corn-Soybean Rotation

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ABSTRACT

Understanding tillage, N, and P interactions can contribute to improved N and P utilization and crop response. This study examined the interaction effects of tillage and N rate of two N sources on N and P uptake by corn (*Zea mays* L.). The study was conducted on Kenyon loam (fine loamy, mixed, mesic Typic Hapludolls) soil at the Iowa State University Northeast Research and Demonstration Farm near Nashua, IA. A randomized complete block design with a split-plot arrangement in three replications was used for the two separate N source experiments. The tillage systems consist of no-tillage (NT), strip-tillage (ST), and chisel plow (CP) as main plots. Within each tillage four N rates (0, 85, 170, and 250 kg N ha^{-1}) were assigned as subplots for each N source of manure (total N) and fertilizer (anhydrous ammonia) in a corn-soybean [*Glycine max* (L.) Merr.] rotation. Tillage and increase in N rate beyond 85 kg ha^{-1} had no effect on corn grain yield with both N sources. Tillage × N rate had a significant effect on plant N and P uptake, especially at early growth stages with both N sources. Recovery percentage of applied N across all tillage systems and N rates was 40% and 27% for manure and fertilizer sources, respectively, at the 12th-leaf growth stage of corn (V12). Plant N and P uptake at V12 growth stage was 44% and 37%, respectively, across tillage systems, N sources, and N rates. The findings indicate that the N rate and seasonal variability have more influence on plant N and P uptake than does the tillage system.

Soil tillage and fertility management influence both nutrient and soil moisture dynamics in the soil–plant system, which in turn affect nutrient use efficiency in a cropping system. Some of the tillage functions are to incorporate fertilizer and crop residues in the soil, improve soil aeration, and subsequently promote organic N and P mineralization (Carter and Rennie, 1987; Dinnes et al., 2002; Groffman et al., 1987; House et al., 1984; Huntington et al., 1985; McCarthy et al., 1995; Rice et al., 1987; Varco et al., 1993; Yoong et al., 2001). The tillage system can influence soil N availability due to its impact on soil organic C and N mineralization and subsequent plant N use or accumulation (Dinnes et al., 2002; Al-Kaisi and Licht, 2004; Licht and Al-Kaisi, 2005a; Gilliam and Hoyt, 1987; Mehdi et al., 1999; Sanju and Singh, 2001). Compared with NT, the conventional tillage (CT) system can significantly change the mineralizable C and N pools (Woods and Schuman, 1988). However, a long-term NT system has potentially greater mineralizable C and N pools compared with CT (Doran, 1980).

The plant N use can be altered by the different management practices and interactions between tillage system, N rate, and N application timing. The interactive effects of different tillage systems, such as, NT, CT, or minimum tillage and N rate on grain N uptake was significant in increasing N removal with increasing N rate (Halvorson et al., 2001). Similarly, corn response to other management practices, such as the use of starter fertilizer with CT and ST systems, showed that corn silage and grain yields in CT systems were lower than those in ST; however, both silage and grain yields of both tillage systems increased with additional N applications (Mullins et al., 1998). An understanding of tillage and N source effect on the dynamics of N availability in soil and plant N uptake through the growing season at different growth stages is essential for determining the efficiency of N management. As the N availability is affected by the tillage system, P availability can equally be affected, leading to a P deficiency in many cropping systems. Many soils have large reserves of total P, but low levels of available P (Ortiz-Monasterio et al., 2002). On soils testing low in available P, application of P fertilizer or liquid manure can increase crop yields, especially for corn and soybean (deMooy et al., 1973; Mallarino et al., 1991; Obreza and Rhoads, 1988; Webb et al., 1992). However, plant P uptake varies with soil P and moisture availability, and the concentration of P in plant tissue decreases with plant age and water stress (Payne et al., 1995). It was found that banded P (deep or shallow) increased early corn growth and P uptake compared with broadcast placement with NT (Mallarino et al., 1999). Liquid manure can be a valuable source for plant P nutrient need. In a study comparing liquid swine manure with chemical N and P fertilizer sources, it was found that corn yield and N and P uptake was similar for both N sources (Al-Kaisi and Waskom, 2002).

The value of liquid manure as a nutrient source to plant growth and the proximity of such source to field crop production can help reduce the cost of corn production as producing and transporting chemical fertilizers is costly. Therefore, this research explored this alternative source for N and P. Information on tillage and N source effects on N and P use efficiency in corn is limited. Our objective was to examine the interactive effects of three tillage systems (NT, ST, and CP) and four N rates of liquid swine manure and N fertilizer on corn response and N and P use efficiencies.

MATERIALS AND METHODS

Site Description

This study was conducted on a 16-ha site at the Iowa State University Northeast Research and Demonstration farm near

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Abbreviations: CP, chisel plow; CT, conventional tillage; NT, no-tillage; R6, physiological maturity stage of corn; ST, strip-tillage; V6, sixth-leaf stage of corn; V12, 12th-leaf stage of corn; VT, tassel stage of corn.

Nashua, IA (43°0′ N, 92°30′ W) from 2002 to 2004. The previous tillage system on this site was CP as primary tillage with field cultivation as a secondary tillage before implementing the three tillage treatments of NT, ST, and CP in year 2000. The 16-ha site was divided into two 8-ha areas (east and west sites) for corn and soybean rotations. The soil at the site is a nearly level to gently sloping Kenyon loam (fine loamy, mixed, mesic Typic Hapludolls). The average annual precipitation in northeastern Iowa is 896 mm with a growing season rainfall average of 701 mm. Initial values of total soil P (Bray and Kurtz, 1945), K (Thomas, 1982), NO_3–N (Mulvaney, 1996), organic matter by dry combustion using a LECO CHN-2000 analyzer, and pH (McLean, 1982) in the top 15 cm were 35, 163, and 11 mg kg^{-1}, 580 g kg^{-1}, and 6.4, respectively.

This study focused on corn response in a corn-soybean rotation. During the corn year, the 8-ha site was split into two 4-ha sites (north and south sites) for applying two sources of N. At one site (4 ha), corn received liquid swine manure, which will be referred to as *manure* at four different N rates based on total N (0, 85, 170, and 250 kg N ha^{-1}), while on the adjacent 4-ha site, chemical fertilizer (anhydrous ammonia) was applied at the same N rates, which will be referred to as *fertilizer*.

The experimental design for each corn-N source and tillage experiment was a randomized complete block with split-plots arranged in three replications. Three tillage systems of NT, ST, and CP were randomly assigned to each replication as the main plot treatments, and the four N rates were assigned randomly to each tillage treatment as subplot treatments during each corn year. Each tillage plot was approximately 56 m long by 21 m wide, with subplots of each N rate within main tillage plots being 56 m long by 5 m wide. Each tillage treatment stayed on the same plot for the duration of the study.

In 2002, the eastern half of the experimental site was planted to corn and the western half planted to soybean. In 2003 and 2004, corn and soybean crops were planted in the order of soybean following corn on these two sites to establish the corn-soybean rotation. The soybeans were planted in a 76-cm row spacing at a seeding rate of 420,000 plants ha^{-1} using the same tillage treatments as in corn every year.

After harvest in mid-November of each year, CP and ST treatments were performed to both corn and soybean plots. A straight-disc coulter was used in front of the chisel points to cut through residue. Strip-tillage was performed with a six-row ST unit equipped with mole knives attached to a toolbar and centered between two 46-cm-diameter closing disks. These attachments created a 20-cm-deep tilled zone with 8-cm berms.

Each year before field application of manure, three representative liquid swine manure samples were collected in a plastic container from the manure applicator. The manure samples were mixed well and then 500-mL subsamples were collected in plastic bottles and placed in a cooler with ice for transfer to the laboratory for the same-day analysis, or were stored in a −4°C freezer. During each year, the three manure samples were analyzed individually for total C, total N, total P, total K, ammonium nitrogen (NH_4–N), and nitrate nitrogen (NO_3–N) concentrations using the macro Kjeldahl (Kane, 1999), AOAC-965.17 photometric method (AOAC, 1997), the EPA-7610 atomic absorption method (EPA, 1986), and the EPA-353.3 automated cadmium reduction method (EPA, 1974), respectively. Three-year averages of manure analysis were: total C, 47 g kg^{-1}; total N, 6.8 g L^{-1}; total P, 4.9 g L^{-1}; total K, 4.6 g L^{-1}; NH_4–N, 5.0 g L^{-1}; and NO_3–N, 4.5 mg L^{-1}. Each manure application rate was based on the average of the three samples of total N concentration. Each year, manure was injected 10 to 15 cm below the soil surface on 15, 23, and 27 Nov. 2002, 2003, and 2004, respectively, at the rates of 0, 85, 170, and 250 kg N ha^{-1} in each corn year using a Badger 5800 L manure applicator (Badger Northland, Inc., Kaukauna, WI) equipped with a modified injection knife to cause minimum soil disturbance in the same direction and location of previous rows in all tillage systems. No manure was applied after corn harvest or during the soybean season.

Anhydrous ammonia was knifed in early April of each year using a six-row, pull-type anhydrous ammonia injection knife applicator. The anhydrous ammonia was injected 10 to 15 cm deep with modified injection knives to cause minimum soil disturbance. Corn was planted on the manure and anhydrous ammonia bands in all tillage systems. During planting in May of each year, starter fertilizer was applied to the anhydrous ammonia plots by applying 29 kg P ha^{-1} as $NH_4H_2PO_4$ and 35 kg K ha^{-1} as KCl, placed 5 cm deep and 5 cm from the row center.

The CP system plots were field cultivated in the spring before planting corn to control weeds and level the soil surface. In all tillage systems, corn was planted in early May of each year using DeKalb 537 non-*Bacillus thuringiensis* corn at a seeding rate of 84,000 plants ha^{-1} and 76-cm row spacing. Corn was planted over the disturbed application zone of manure and anhydrous ammonia of all tillage systems. During planting, the area was simultaneously sprayed with 189 mL ha^{-1} acetochlor [2-chloro-*N*-(ethoxymethyl)-*N*-(2-ethyl-6-methylphenyl) acetamide]. Corn was harvested using a combine with a scale yield monitor. Harvested corn grain was adjusted to 150 g kg^{-1} moisture to estimate final yield.

Crop Measurements

Plant samples of corn were collected at the sixth–leaf (V6), 12th–leaf (V12), tassel (VT), and physiological maturity (R6) growth stages for each split-plot to estimate dry matter production (Ritchie et al., 1993; Al-Kaisi and Yin, 2003). The sampling area per split-plot was 4.6 m long, which was divided into three 1.53-m segments. A separate area was maintained for yield harvest. At each of the four growth stages, one plant per 1.53-m segment of the sampling area was cut at ground level having two plants on both sides of the harvested plant. A total of three plants were cut at ground level from the 4.6-m-long row at each growth stage. Plant samples were oven-dried at 60°C for 8 d to achieve a constant dry mass. Oven-dried plant samples were ground using a Wiley Mill Model 2 carbon steel pulverizer (Arthur H. Thomas Co., Philadelphia, PA). Ground samples were placed in plastic-lined paper bags before analysis. Concentrations of total N and total P were determined by dry combustion using a LECO CHN-2000 C-N analyzer and the microwave digestion and inductively coupled plasma (ICP) method, respectively. Plant and corn grain N and P uptake were estimated as products of total plant dry matter or grain yield and their respective total N and total P concentrations.

The recovery percentages of applied N and P by grain and corn plant at different growth stages were calculated by using the following relationship:

$$\text{N or P recovery \%} = [(\text{N or P treatment uptake} - \text{control uptake})/(\text{N or P}) \text{ of applied N or P rate}] \times 100$$

The 3-yr averages of applied P corresponding to the N rates of 0, 85, 170, and 250 kg N ha^{-1} of manure were 0, 56, 113, and 178 kg P ha^{-1}, respectively. These values were used in calculating total P recovery from manure. For the fertilizer experiment, the applied rate of 29 kg P ha^{-1} was used in calculating the total P recovery.

Late Spring Soil NO_3–N Concentration

Late spring NO_3–N test is a N management tool used to manage N application more efficiently. Soil samples were collected at the V6 growth stage for all treatments to measure late spring soil NO_3–N concentration. A 30-cm-long soil probe with a hardened cutting tip with an inside diameter of 1.9 cm was used for soil sampling. Soil samples were collected from a 4.6-m-long row in the center of each plot. This area was divided into three 1.53-m-long sections. Soil sampling was conducted at two depths, from 0 to 30 and from 30 to 60 cm during the time of plant sampling. Ten to 12 soil cores were collected for each soil depth from each 1.53-m section of the sampling area within and between rows of each plot and kept in plastic-lined paper bags and frozen. The soil samples from each 1.53-m section were air-dried and analyzed separately for NO_3–N concentration using the KCl extraction method (Mulvaney, 1996). The average of the soil NO_3–N concentration of the three soil sample sections for each plot was used in data analysis.

Fall Stalk NO_3–N Concentration

The fall stalk NO_3–N test was used to evaluate the efficient utilization of N by corn. Nitrate-N concentration in the corn stalk was evaluated according to criteria that were established to evaluate a N fertilization program for the following season (Blackmer and Mallarino, 1996). Fall corn stalk NO_3–N concentration was determined by collecting corn stalk samples from all treatments after corn reached R6 growth stage, when at least 80% of the kernels of most ears had black layer (physiological maturity) (Blackmer and Mallarino, 1996). A 20-cm-long segment of each corn stalk was taken 15 to 35 cm above ground level, and leaf sheaths were removed from samples. A total of 15 corn stalks were collected from each treatment and placed in a paper bag for drying. Corn stalk samples were oven-dried at 60°C for 8 d to attain a constant dry mass before grinding with the carbon steel pulverizer. The ground corn stalks were sealed in plastic-lined paper bags for storage before analysis. Samples were analyzed for corn stalk NO_3–N concentrations using the 2M potassium chloride (KCl) extraction method (Mulvaney, 1996) using a Lachat QuickChem FAI+8000 series with cadmium reduction column. Corn stalk nitrate concentrations were expressed as mg NO_3–N kg^{-1} of dry corn stalk.

Statistical Analysis

Statistical analysis of the data was performed using a statistical analysis system package (SAS Institute, 2003). Data from each N-source experiment were analyzed separately for the main and interaction effects between year, tillage, and N rate by using the GLM procedure for analysis of variance appropriate for a randomized complete block design with a split-plot arrangement. Mean separations were performed by using the least significant difference ($P \leq 0.05$). The interaction effects of treatments were presented for both N sources.

RESULTS AND DISCUSSION

Grain Yield Response to Tillage and N Rate

The main effect of tillage on grain yield was not significant with all N rates of both N sources (Table 1). Regardless of tillage system or N source, increasing the N rate above 85 kg N ha^{-1} had no significant effect in increasing grain yield. This is in agreement with N recommendations for corn after soybean in Iowa, where it ranges from 100 to 145 kg ha^{-1} (Blackmer et al., 1997). Also, these findings are in agreement with those by Licht and Al-Kaisi (2005a) for the same tillage systems. Generally, all tillage systems showed lower grain yields with zero N rate compared with high N rates regardless of N source. The corn response to different tillage systems and N management showed that type of tillage system has little effect on corn yield despite the initial differences in corn germination due to increases in soil temperature of 1.2 to 1.4°C for ST and CP over NT in the top 5 cm (Licht and Al-Kaisi, 2005b). It was reported by others that the poor early season vegetative growth in the NT was due to low N availability (increased N immobilization, denitrification, and reduced organic N mineralization) and reduction in nutrient uptake by plants, which subsequently reduced crop yield compared with the ST and CP systems (Griffith et al., 1977; Ketchenson, 1980; Karlen et al., 1991; Mallarino et al., 1999). Regardless of tillage system, corn grain yield response depicted N poverty adjustment, where grain yield increased with additional 85 kg N ha^{-1} with no significant increase in yield above that N rate (Macy, 1936; Cerrato and Blackmer, 1990; Al-Kaisi and Waskom, 2002).

Table 1. Effect of tillage systems and N rates of two N sources on corn grain yield in 2002–2004.

N source	Tillage system†	N rate, kg ha^{-1}			
		0	85	170	250
		grain yield, Mg ha^{-1}			
Manure	NT	6.7Ab‡	9.3Aa	10.5Aa	10.7Aa
	ST	7.0Ab	9.7Aa	10.4Aa	10.8Aa
	CP	8.0Ab	10.7Aa	11.0Aa	11.3Aa
Fertilizer	NT	6.5Ab	10.1Aa	10.6Aa	10.5Aa
	ST	8.6Ab	10.1Aa	10.3Aa	10.3Aa
	CP	7.9Ab	10.0Aa	10.5Aa	10.6Aa

† NT, no-tillage; ST, strip-tillage; CP, chisel plow.
‡ Means in columns within each N rate with the same uppercase letter are not significantly different according to least-square means for tillage and N rate interactions adjusted for multiple comparisons at $P \leq 0.05$. Means in rows within each tillage system with the same lowercase letter are not significantly different according to least-square means for tillage and N rate interactions adjusted for multiple comparisons at $P \leq 0.05$.

Tillage and N Rate Effects on Grain N and P Uptake

Grain N and P uptake showed no significant differences between tillage systems for all N rates with manure (Table 2). In the manure source plots, regardless of tillage system, the grain N and P uptake had significantly increased with additional N application and the greatest N and P uptake was achieved with 250 kg N ha^{-1} of manure. The control treatment had the lowest grain N uptake (Table 2). The increase in N and P accumulation in grain can be attributed to greater yield response and N and P availability at the high manure application rate. The results showed that even with the increase of N application rate, which led to an increase in P application with manure source (manure application rate based on total N content), the increase in applied P had no effect on increasing grain P uptake or accumulation in the grain.

Table 2. Grain N and P uptake with different tillage systems and N rates of manure and fertilizer in 2002–2004.

N source	Tillage system†	N rate, kg ha^{-1}				N rate, kg ha^{-1}			
		0	85	170	250	0	85	170	250
		total N uptake, kg ha^{-1}				total P uptake, kg ha^{-1}			
Manure	NT	79.7Ad‡	101.8Ac	122.1Ab	137.3Aa	11.7Ac	17.0Ab	17.1Ab	21.5Aa
	ST	82.5Ac	112.3Ab	126.0Aa	134.4Aa	13.1Ab	18.7Aa	17.0Aab	19.9Aa
	CP	82.7Ac	113.8Ab	115.6Ab	143.4Aa	11.6Ab	19.7Aa	17.9Aa	19.7Aa
Fertilizer	NT	76.6Bc	122.4Bb	144.5Aa	142.5Aa	10.2Ab	16.3Aa	16.6Aa	16.6Aa
	ST	99.4Ab	135.0Aa	130.5Ba	139.1Aa	11.0Ab	14.1Aab	16.0Aa	14.7Aab
	CP	86.9ABb	116.6Ba	126.0Ba	131.1Aa	12.0Ab	16.7Aa	15.5Aab	15.9Aab

† NT, no-tillage; ST, strip-tillage; CP, chisel plow.
‡ Means in columns within each N rate with the same uppercase letter are not significantly different according to least square means for tillage and N rate interactions adjusted for multiple comparisons at $P \leq 0.05$. Means in rows within each tillage system with the same lowercase letter are not significantly different according least square means for tillage and N rate interactions adjusted for multiple comparisons at $P \leq 0.05$.

In the fertilizer source plots, ST grain N uptake was greater compared with NT and CP, especially at 0 and 85 kg N ha^{-1} (Table 2). However, grain P uptake with different tillage systems was not significantly different regardless of N rate. The only difference in P uptake with fertilizer source was observed between zero and other N rates across all tillage systems. The greater grain N uptake with the fertilizer source in ST compared with the NT can be attributed to better soil conditions associated with the ST system, where early spring increase in soil temperature in poorly drained soils improved corn germination, compared with NT as documented by Licht and Al-Kaisi (2005b).

Tillage and N Rate Effects on Grain Recovery of Applied N and P

The grain recovery of applied N from both N sources was generally greater with the 85 kg N ha^{-1} rate compared with the other two higher application N rates in all tillage systems (Table 3). However, it was observed that both ST and CP improved grain N recovery, especially with manure source at the 85 kg N ha^{-1} rate. The increase in N application rate beyond 85 kg N ha^{-1} did not increase grain N recovery with all tillage systems. It was observed that grain N recovery of applied N fertilizer with NT was greater compared with ST and CP at 85 and 170 kg N ha^{-1} rates. These finding are consistent with those by Al-Kaisi and Waskom, 2002. It appears that the increase in N rate beyond 85 kg N ha^{-1} did not contribute significantly to recovering applied N with both N sources regardless of tillage system. The grain P recovery was significantly greater with CP treatment compared with the NT or ST with manure at 85 kg N ha^{-1} rate. The increased amount of applied P with manure did not lead to greater grain P recovery, where manure N rate application was based on total N content.

However, NT grain P recovery in the fertilizer source plots was significantly greater than that with ST or CP at all N rates (Table 3). These findings are in agreement with those described by Al-Kaisi and Licht (2004) for the same tillage systems.

Effects of Tillage, N Rate, and Season Interactions on Grain N and P Uptake and Recovery

Interaction effects of tillage × N rate, tillage × year, and N rate × year on grain N and P uptake were frequently observed with both N sources, although inconsistent (Table 4). The only significant interaction between tillage and N rate was observed with grain N uptake for the fertilizer source. The tillage × year interaction had a significant effect on grain N and P uptake of manure source and on grain N uptake with fertilizer source. However, the N rate × year interaction had a significant effect on grain N and P uptake with manure and fertilizer sources, respectively (Table 4). Even though these interactions are inconsistent with both N sources, they reflect the seasonal variability effect on grain N and P uptake with different tillage systems. Generally, there was an insignificant three-way interaction of tillage × N rate × year effect on grain N and P uptake with both N sources. These finding are consistent with observations described by Dharmakeerthi et al. (2006), where N fer-

Table 3. Grain N and P recovery with various tillage systems and N rates of manure and fertilizer in 2002–2004.

N source	Tillage system†	N rate, kg ha^{-1}							
		0	85	170	250	0	85	170	250
		N recovery, %				P recovery, %			
Manure	NT	–	26.0Ba‡	25.0Aa	23.1Aa	–	9.5Ba	4.7Ab	5.5Ab
	ST	–	35.1Aa	25.6Ab	20.8Ab	–	9.9Ba	3.4Ab	3.8Ab
	CP	–	36.6Aa	19.4Ac	24.3Ab	–	14.3Aa	5.5Ab	4.5Ab
Fertilizer	NT	–	53.9Aa	40.0Ab	26.4Ac	–	21.4Aa	22.2Aa	22.4Aa
	ST	–	41.9Ba	18.3Bb	15.9Ab	–	10.6Bb	17.3Aa	12.9Bab
	CP	–	34.9Ba	23.0Bb	17.7Ac	–	16.1ABa	11.8Bb	13.3Bb

† NT, no-tillage; ST, strip-tillage; CP, chisel plow.
‡ Means in columns within each N rate with the same uppercase letter are not significantly different according to least square means for tillage and N rate interactions adjusted for multiple comparisons at $P \leq 0.05$. Means in rows within each tillage system with the same lowercase letter are not significantly different according least square means for tillage and N rate interactions adjusted for multiple comparisons at $P \leq 0.05$.

Table 4. Interaction effects of tillage, N rate, and year on N and P uptake by corn plant and grain with manure and fertilizer N sources.

Growth stage†	Source	Manure N uptake	Manure P uptake	Fertilizer N uptake	Fertilizer P uptake
		P > *F*			
V6	tillage × N rate	0.001	0.034	0.005	0.001
	tillage × year	0.008	0.074	0.019	0.002
	N rate × year	<0.0001	0.006	<0.0001	<0.0001
	tillage × N rate × year	0.214	0.257	0.073	0.0468
V12	tillage × N rate	0.077	0.158	0.329	0.926
	tillage × year	0.496	0.047	0.113	0.556
	N rate × year	<0.0001	0.350	0.029	0.196
	tillage × N rate × year	0.365	0.264	0.280	0.175
VT	tillage × N rate	0.887	0.293	0.016	0.973
	tillage × year	0.559	0.004	0.216	0.741
	N rate × year	<0.0001	0.026	0.003	0.746
	tillage × N rate × year	0.332	0.530	0.576	0.985
R6	tillage × N rate	<0.0001	0.001	0.535	0.015
	tillage × year	0.950	0.043	0.973	0.320
	N rate × year	0.002	0.002	0.005	0.101
	tillage × N rate × year	0.225	0.020	0.098	0.002
Grain	tillage × N rate	0.251	0.813	0.004	0.830
	tillage × year	<0.0001	0.049	0.006	0.715
	N rate × year	0.110	0.008	0.021	0.927
	tillage × N rate × year	0.149	0.265	0.047	0.978

† V6, sixth-leaf stage of corn; V12, 12th-leaf stage of corn; VT, tassel stage of corn; R6, physiological maturity stage of corn. Significant level ($P \leq 0.05$).

tilizer level and tillage interaction effect was not significant during any growth stage.

The grain N and P recovery interactions are summarized in Table 5. Tillage × N rate, tillage × year, N rate × year, and tillage × N rate × year interactions had no significant effect on grain N and P recovery with both N sources, except in a few cases. It appears that tillage × year had a significant effect on grain P and N and P recoveries with manure and fertilizer sources, respectively (Table 5). This can be attributed to tillage effect on both N and P availability and N and P uptake. It was found that banded P (deep or shallow) increased early corn growth and P uptake more than broadcast placement with NT (Mallarino et al., 1999).

Tillage and N Rate Effects on Plant N and P Uptake at Different Growth Stages

Generally, plant N uptake was significantly greater with the CP system compared with NT at 85 and 170 kg N ha^{-1} rates of manure source at V6 to R6 growth stages (Table 6). The observed tillage effect on the plant N uptake may be attributed to the differences in crop growth rates because N uptake is controlled by N availability and crop growth rate (Devienne-Barret et al., 2000). The plant N uptake at the 250 kg N ha^{-1} N rate was inconsistent during all growth stages. The differences in plant N uptake between N rates within each tillage system showed generally greater plant N uptake with the increase in N rate up to 170 kg N ha^{-1} for the manure source. These findings are in agreement with those by Dharmakeerthi et al. (2006), where plants growing in treatments with higher N application took up significantly more N than zero-N treatments at all growth stages.

The plant P uptake was generally not significantly different for all tillage systems at 0 kg N ha^{-1} rate during all growth stages with manure source (Table 6). However, the increase in application of N rate showed inconsistent differences between tillage systems for plant P uptake with some advantages for CP and ST systems over NT. The increase in manure application rate that led to a greater amount of P application did not cause significant differences in plant P uptake between tillage treatments. These findings are not surprisingly unexpected due to high soil-P test of the site.

In the fertilizer source plots, the tillage effect on plant N uptake with different N rates was highly variable during all growth stages (Table 7). At the V6 to R6 growth stages, the difference in plant N uptake was only significant between zero and high N rates across all tillage systems. It was noticeable at the VT growth stage that a maximum N accumulation was reached and greater plant N uptake was observed at all fertilizer N rates for the CP tillage system, except at the 250 kg N ha^{-1} (Table 7).

Generally, at the V6 to R6 growth stages, plant P uptake was not significantly different between zero and

Table 5. Interaction effects of tillage, N rate, and year on applied N and P recovery by corn plant and grain with manure and fertilizer N sources.

Growth stage†	Source	Manure N recovery	Manure P recovery	Fertilizer N recovery	Fertilizer P recovery
		P > *F*			
V6	tillage × N rate	0.098	0.324	0.0381	0.001
	tillage × year	0.786	0.102	0.0104	0.154
	N rate × year	<0.0001	0.031	0.0001	<0.0001
	tillage × N rate × year	0.491	0.181	0.0250	0.012
V12	tillage × N rate	0.007	0.147	0.1551	0.822
	tillage × year	0.235	0.063	0.2379	0.058
	N rate × year	0.010	0.765	0.3857	0.051
	tillage × N rate × year	0.075	0.078	0.5653	0.027
VT	tillage × N rate	0.928	0.626	0.5054	0.969
	tillage × year	0.894	0.567	0.4870	0.314
	N rate × year	<0.0001	0.179	0.0903	0.723
	tillage × N rate × year	0.267	0.352	0.7687	0.982
R6	tillage × N rate	<0.0001	0.273	0.2602	0.002
	tillage × year	0.001	0.572	0.5690	0.825
	N rate × year	<0.0001	0.001	0.0007	0.023
	tillage × N rate × year	0.152	0.074	0.060	<0.0001
Grain	tillage × N rate	0.272	0.642	0.142	0.505
	tillage × year	0.769	0.047	0.091	0.032
	N rate × year	0.197	0.24	0.001	0.726
	tillage × N rate × year	0.493	0.018	0.642	0.793

† V6, sixth-leaf stage of corn; V12, 12th-leaf stage of corn; VT, tassel stage of corn; R6, physiological maturity stage of corn. Total N determined at R6 for plant biomass only without grain. Significant level ($P \leq 0.05$).

Table 6. Corn plant N and P uptake with three tillage systems and four N rates of manure at four growth stages in 2002–2004.

		N rate, kg ha^{-1}							
Growth stage†	Tillage system‡	0	85	170	250	0	85	170	250
		N uptake, kg ha^{-1}				P uptake, kg ha^{-1}			
V6	NT	4.9Ad§	12.4ABb	8.8Bc	16.5ABa	0.6Ac	1.0Ab	1.1Bb	1.6Aa
	ST	5.3Ac	10.7Bb	10.6Bb	18.7Aa	0.6Ab	0.9Ab	1.4Aa	1.3Aa
	CP	7.5Ab	14.2Aa	15.5Aa	15.2Ba	0.7Ac	1.2Ab	1.7Aa	1.5Aa
V12	NT	53.2Ab	72.3Bb	116.9Ba	97.6Aa	7.0Ac	9.1Bbc	10.1Bab	11.9Aa
	ST	55.5Ab	109.2Aa	125.7Aa	118.4Aa	7.3Ab	10.4ABa	12.2Aa	12.8Aa
	CP	69.3Ac	122.4Aa	126.9Aa	103.3Ab	7.6Ab	11.9Aa	12.6Aa	11.0Aa
VT	NT	81.8Bc	137.9Bb	167.5Ca	121.7Bb	12.5Ab	16.8Aa	17.4Ba	18.1Aa
	ST	76.8Bc	151.4Bb	188.5Ba	145.5Ab	12.1Ab	17.9Aa	20.0ABa	17.3Aa
	CP	101.8Ad	171.8Ab	211.7Aa	141.0Ac	14.4Ac	19.9Ab	23.1Aa	17.8Ab
R6	NT	69.9ABb	105.0Ba	111.0Ba	108.8ABa	11.5Ab	23.4Ba	20.2Ba	23.8Aa
	ST	77.0Ab	110.6Ba	108.8Ba	117.2Aa	14.4Ac	27.3Aa	19.7Bb	22.7Ab
	CP	53.0Bb	124.5Aa	138.6Aa	93.5Bc	13.8Ac	27.5Aa	24.6Aa	18.7Bb

† V6, sixth–leaf stage of corn; V12, 12th–leaf stage of corn; VT, tassel stage of corn; R6, physiological maturity stage of corn.
‡ NT, no-tillage; ST, strip-tillage; CP, chisel plow. Total N determined at R6 for plant biomass only without grain.
§ Means in columns within each N rate with the same uppercase letter are not significantly different according to least square means for tillage and N rate interactions adjusted for multiple comparisons at $P \leq 0.05$). Means in rows within each tillage system with the same lowercase letter are not significantly different according least square means for tillage and N rate interactions adjusted for multiple comparisons at $P \leq 0.05$).

high N rates of fertilizer source regardless of the tillage system (Table 7). Plant P uptake exhibited a similar pattern, where corn plant P uptake in the CP tillage system was greater at the VT growth stage than ST and NT for all N rates (Table 7). This may be attributed to the effect of tillage on N and P availability by increasing soil temperature, increasing crop growth rate early in the season, and increased availability of N and P (Devienne-Barret et al., 2000; Licht and Al-Kaisi, 2005b). Mallarino et al. (1999) found also that deep banded P (deep or shallow) increased early corn growth and P uptake more than broadcast placement with NT.

The plant N uptake at the V12 growth stage across all tillage systems was calculated as a percentage of total N uptake (grain + plant) using data from Tables 2 and 6 for manure source; the N uptake was 42, 41, 50, and 43%, for 0, 85, 170, and 250 kg N ha^{-1} N rates, respectively. Similarly, N uptake was calculated as a percentage of total N uptake (grain + plant) using data from Tables 2 and 7 at the V12 growth stage across all tillage systems with fertilizer source; the N uptake was 41, 44, 47, and 41% for 0, 85, 170, and 250 kg N ha^{-1}, respectively. The P uptake at the V12 growth stage across all tillage systems as a percentage of total P uptake (grain + plant) was 37, 42, 41, and 36%, and 35, 33, 36, and 33% for the above N rates of manure and fertilizer N sources, respectively.

Tillage and N Rate Effects on Plant Recovery of Applied N and P at Different Growth Stages

The recovery of applied N and P from both manure and fertilizer sources by corn plant progressively increased with corn growth through VT growth stage (Tables 8 and 9). However, the greatest N recovery was observed at the 85 kg N ha^{-1} N rate across all tillage systems with both N sources at the VT growth stage

Table 7. Corn plant N and P uptake with three tillage systems and four N rates of fertilizer at four growth stages in 2002–2004.

		N rate, kg ha^{-1}							
Growth stage†	Tillage system‡	0	85	170	250	0	85	170	250
		N uptake, kg ha^{-1}				P uptake, kg ha^{-1}			
V6	NT	7.1Bb§	12.8Ba	12.2Aa	11.2Ba	0.5Ac	1.0Aa	0.8Ab	1.0Ba
	ST	7.7ABb	11.8Ba	11.7Aa	10.4Ba	0.5Ab	0.9Ba	0.8Aa	0.8Ca
	CP	9.5Ac	16.5Aa	12.8Ab	17.5Aa	0.6Ad	1.1Ab	0.9Ac	1.3Aa
V12	NT	52.2Ab	70.8Bb	110.8Aa	82.7Aa	5.2Ab	7.4Aa	7.6Aa	7.7Aa
	ST	65.1Ac	115.9Aba	130.5Aa	99.6Ab	5.3Ab	8.3Aa	9.4Aa	7.9Aa
	CP	70.5Ab	111.3Aa	114.2Aa	106.8Aa	6.3Ab	9.1Aa	9.6Aa	9.1Aa
VT	NT	87.6Bc	147.3Bb	184.8Ba	151.9Bb	9.7Bb	14.7Ba	14.6Ba	13.7Ba
	ST	74.0Bc	149.5Bb	173.0Bb	202.8Aa	10.3Bb	14.8Ba	15.2Ba	14.9Ba
	CP	117.1Ac	191.4Aba	213.7Aa	159.9Bb	13.0Ab	17.5Aa	19.3Aa	18.4Aa
R6	NT	52.9Ac	94.0Aab	113.4Ba	77.7Ab	6.0Ab	15.8Aa	12.9ABa	12.2Aa
	ST	42.3Ab	91.1Aa	96.8Ba	89.9Aa	5.8Ab	13.9Aa	8.3Bb	13.5Aa
	CP	53.2Ac	79.4Ab	124.4Aa	74.3Ab	4.9Ab	8.8Bb	16.3Aa	9.2Ab

† V6, sixth-leaf stage of corn; V12, 12th-leaf stage of corn; VT, tassel stage of corn; R6, physiological maturity stage of corn.
‡ NT, no-tillage; ST, strip-tillage; CP, chisel plow. Total N determined at R6 for plant biomass only without grain.
§ Means in columns within each N rate with the same uppercase letter are not significantly different according to least square means for tillage and N rate interactions adjusted for multiple comparisons at $P \leq 0.05$). Means in rows within each tillage system with the same lowercase letter are not significantly different according least square means for tillage and N rate interactions adjusted for multiple comparisons at $P \leq 0.05$).

Table 8. Corn plant N and P recovery with various tillage systems and N rates of manure at four growth stages in 2002–2004.

		N rate, kg ha^{-1}							
Growth stage†	Tillage system‡	0	85	170	250	0	85	170	250
		N recovery, %				P recovery, %			
V6	NT	–	8.9Aa§	2.3Ab	4.7Ab	–	0.7ABa	0.4Bb	0.5Aab
	ST	–	6.4Ba	3.1Ab	5.3Aa	–	0.5Ba	0.6ABa	0.4Aa
	CP	–	7.9Aa	4.7Ab	3.1Ab	–	0.9Aa	0.9Aa	0.5Ab
V12	NT	–	22.4Bb	37.4Aa	17.7ABb	–	3.8Ba	2.8Aa	2.8Aa
	ST	–	63.2Aa	41.3Ab	25.1Ac	–	5.5ABa	4.3Aa	3.1Ab
	CP	–	62.5Aa	33.9Ab	13.6Bc	–	7.5Aa	4.4Ab	1.9Ac
VT	NT	–	66.0Ba	50.4Aa	16.0Bb	–	7.4Aa	4.3Ab	3.1Ab
	ST	–	87.7Aa	65.7Ab	27.5Ac	–	9.7Aa	6.9Ab	2.9Ac
	CP	–	82.4Aa	64.7Ab	15.7Bc	–	9.8Aa	7.7Ab	1.9Ac
R6	NT	–	41.3Ba	24.2Bb	15.6Ac	–	21.3Aa	7.7Ab	6.9Ab
	ST	–	39.6Ba	18.7Bb	16.1Ab	–	23.1Aa	4.7Ab	4.7Ab
	CP	–	84.1Aa	50.3Ab	16.2Ac	–	24.5Aa	9.6Ab	2.8Ac

† V6, sixth–leaf stage of corn; V12, 12th–leaf stage of corn; VT, tassel stage of corn; R6, physiological maturity stage of corn.
‡ NT, no-tillage; ST, strip-tillage; CP, chisel plow.
§ Means in columns within each N rate with the same uppercase letter are not significantly different according to least square means for tillage and N rate interactions adjusted for multiple comparisons at $P \leq 0.05$). Means in rows within each tillage system with the same lowercase letter are not significantly different according least square means for tillage and N rate interactions adjusted for multiple comparisons at $P \leq 0.05$).

(Tables 8 and 9). Generally, increased N rate resulted in a decrease in plant N and P recovery with all tillage systems.

The low recovery of P by the corn plant at all growth stages with both manure and fertilizer sources may be attributed to the lack of corn response to any additional P application due to high soil P test (>35 mg kg^{-1}). It was found that P absorption by soil particles in surface layers in NT are often reduced compared with CP, where soil surface disturbance helped incorporate P and increase opportunities for soil-P reaction (Edwards et al., 1988; Guertal et al., 1991). It was always believed that NT might have a disadvantage in nutrient availability and the need for additional N and P applications compared with CT systems. However, these findings showed the limited effect that increased N or P applications have on increasing the utilization or recovery of these two nutrients by corn grown in all tillage systems.

Effects of Tillage, N Rate, and Season Interactions on Plant N and P Uptake and Recovery

The interactions of tillage × N rate, tillage × year, and N rate × year had a significant effect on plant N and P uptake during the early growth stage (V6), but tillage × N rate × year had only a significant effect on plant P uptake with fertilizer source (Table 4). Changes in soil conditions because of different tillage along with seasonal variability may contribute to the change in N and P availability early in the growing season. Thus, a significant tillage effect on plant N uptake could often be observed during the early parts of the growing season

Table 9. Corn plant N and P recovery with various tillage systems and N rates of fertilizer at four growth stages in 2002–2004.

		N rate, kg ha^{-1}							
Growth stage†	Tillage system‡	0	85	170	250	0	85	170	250
		N recovery, %				P recovery, %			
V6	NT	–	6.7Aa§	3.0Ab	1.6Bc	–	1.8Aa	0.8Ab	1.6Ba
	ST	–	4.9Ba	2.3Ab	1.1Bb	–	1.2Ba	1.0Aa	1.0Ca
	CP	–	8.2Aa	1.9Ab	3.2Ab	–	1.5ABb	0.9Ac	2.2Aa
V12	NT	–	21.9Bb	34.5Aa	12.2Ac	–	7.7Aa	8.3Ba	8.7Aa
	ST	–	59.8Aa	38.5Ab	13.8Ac	–	10.3Ab	14.2Aa	8.9Ab
	CP	–	48.0Aa	25.7Ab	14.5Ac	–	9.8Aa	11.5Aa	9.7Aa
VT	NT	–	70.2Aa	57.1Ab	25.7Bc	–	17.3Aa	16.9Aa	13.7Ab
	ST	–	88.8Aa	58.2Ab	51.5Ab	–	15.4Aa	17.0Aa	15.8Aa
	CP	–	87.3Aa	56.8Ab	17.1Bc	–	15.5Ab	21.5Aa	18.4Aab
R6	NT	–	48.3Aa	35.6Ab	9.9Bc	–	33.8Aa	23.5Bb	21.1ABb
	ST	–	57.4Aa	32.1Ab	19.0Ac	–	27.9Aa	8.4Cb	26.6Aa
	CP	–	30.8Bb	41.9Aa	8.4Bc	–	13.7Bb	39.5Aa	14.9Bb

† V6, sixth–leaf stage of corn; V12, 12th–leaf stage of corn; VT, tassel stage of corn; R6, physiological maturity stage of corn.
‡ NT, no-tillage; ST, strip-tillage; CP, chisel plow.
§ Means in columns within each N rate with the same uppercase letter are not significantly different according to least square means for tillage and N rate interactions adjusted for multiple comparisons at $P \leq 0.05$). Means in rows within each tillage system with the same lowercase letter are not significantly different according least square means for tillage and N rate interactions adjusted for multiple comparisons at $P \leq 0.05$).

(Dharmakeerthi et al., 2006). The interaction effect of tillage × N rate, tillage × year, and N rate × year after the V6 growth stage on plant N and P uptake was inconsistent with both N sources. These interaction effects on plant N and P uptake were insignificant, particularly late in the season where tillage systems have very limited effect on plant N or P uptake. These observations are similar to those by Dharmakeerthi et al. (2006), where plant N uptake between V6 growth stage and silking is not significantly affected by tillage system. The few cases of increase in plant N and P uptake that were observed with CP tillage system with both N sources is highly related to soil temperature increase and enhanced early plant growth compared with NT (data not presented). The cool soil conditions associated with the NT system tend to reduce early plant growth and nutrient uptake (Licht and Al-Kaisi, 2005b; Kaspar et al., 1990). It was observed that at the R6 all interactions of tillage, N rate, and year in affecting plant N and P uptake were inconsistent with both N sources. Tillage × N rate and N rate × year were significant at the R6 growth stage in affecting plant N and P uptake with manure source, and only N rate × year was significant in affecting plant N uptake with fertilizer source (Table 4). The three-way interaction of tillage, N rate, and year had a significant effect on plant P uptake at the V6 growth stage with fertilizer N source and at the R6 growth stage with both N sources (Table 4). These interactions indicate that the N rate and seasonal variability have more effect on plant N and P uptake later in the growing season than the tillage system. Dharmakeerthi et al. (2006) found that N uptake was affected by fertilizer N management during the V6 growth stage to maturity.

The only significant interaction in affecting plant N and P recovery of applied N and P was tillage × N rate at the V6 growth stage with both N sources (manure and fertilizer). It was observed that 31, 13, and 69% of the two-way interactions of tillage × N rate, tillage × year, and N rate × year, respectively, have a significant effect ($P < 0.05$) on N and P recovery from V6 to R6 growth stages (Table 5). However, only 25% of the three-way interaction effects of tillage × N rate × year on N and P recovery were significant ($P < 0.05$) from V6 to R6 growth stages (Table 5).

Tillage and N Rate Effects on Fall Corn Stalk NO_3–N Concentration

Three-year averages of fall corn stalk NO_3–N concentration increased linearly with increasing N application rate with both N sources regardless of tillage system (Fig. 1a and 1b). The relationship between corn stalk NO_3–N concentration and N application rate within each tillage system of both N sources is well described by linear functions, but not significantly different in slopes with manure source. This relationship also explains the effect of each tillage system on potential NO_3–N accumulation in corn stalks at maturity, where corn stalks had similar NO_3–N concentrations (Fig. 1a). The slopes of linear functions with manure source are not significantly different ($P < 0.05$), which means the rate of

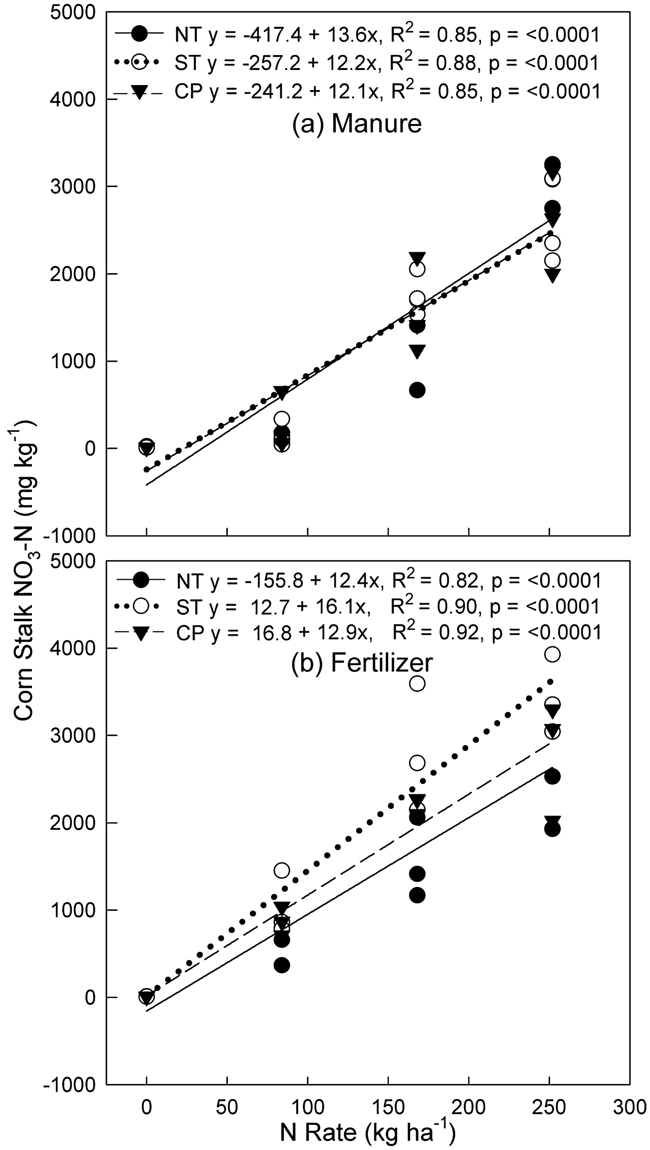

Fig. 1. Fall corn stalk NO_3–N concentration as a function of N rate of manure and fertilizer treatments with three tillage systems over 3 yr.

NO_3–N accumulation is identical with all tillage systems. Fall stalk NO_3–N concentration and slope were highest in the ST system for the fertilizer source at the 170 and 250 kg N ha^{-1} N rate compared with NT and CP (Fig. 1b).

The intercept of different tillage linear functions of manure and fertilizer sources indicates that stalk NO_3–N accumulation is much lower with NT than that with ST and CP. This may be attributed to the influence of tillage system on N mineralization and the increase of potential N availability, where ST and CP can contribute to the increase of soil temperature compared with NT (Licht and Al-Kaisi, 2005b; Doran, 1980). Generally, the high N rate application caused an increase in corn stalk NO_3–N concentration above the critical range of 750–2000 mg kg^{-1} (Macy, 1936; Blackmer and Mallarino, 1996) in corn plants, and luxury N consumption by corn was observed with both N sources and tillage systems. The greater NO_3–N accumulation as N rate increases indicates the inefficient N utilization for grain production leading to luxury N consumption and accumulation in stalks from over N application. The maximum corn stalk NO_3–N concentration with manure source occurred at 250 kg N ha^{-1} for all tillage systems, while it occurred at 170 and 250 kg N ha^{-1} with ST and at 250 kg N ha^{-1} with NT and CP. The results revealed that regardless of tillage system, NO_3–N accumulation in corn stalks with manure was in the same range in response to N application rate.

Tillage and N Rate Effects on Late Spring Soil NO_3–N Concentration

The relationship between soil NO_3–N concentration in the top 30 cm of soil and N rate of manure and fertilizer sources of 3-yr averages of the three tillage systems was poorly described by a linear function ($P < 0.05$), except for NT with manure source and ST with fertilizer N source (Fig. 2a and 2b). The relationship was equally poorly described by nonlinear function as well (data not presented). The weak relationship between soil NO_3–N concentration and N rate is most likely due to high spatial variability of soil NO_3–N concentration. The slopes of the linear functions of the three tillage systems with manure are similar ($P < 0.05$) (Fig. 2a), which indicates a similar effect of all tillage systems on NO_3–N concentration in soil. However, differences in slopes of different tillage systems were more pronounced with fertilizer source, where it was greater with ST compared with both NT and CP slopes ($P < 0.05$) (Fig. 2b). The concentration of NO_3–N was low during early spring in 2002 and 2004, which is most likely caused by some deep leaching of NO_3–N due to above normal rainfall in early April (approximately 2.70 cm) (local weather station at the research farm). At all manure N rates, tillage systems did not cause significant differences in late spring soil NO_3–N concentration (Fig. 2a). Soil NO_3–N concentration of ST with fertilizer source was greater than that under both the NT and CP systems at the N rates of 170 and 250 kg N ha^{-1} at the top 30 cm (Fig. 2b). The high spatial and seasonal variability effect on soil NO_3–N concentration with both manure and fertilizer sources with all tillage systems is very evident and clearly highlights the inconsistency of tillage effect on NO_3–N status, and therefore, the reliability of this test for N application recommendations.

However, some studies have shown that CT systems can lead to an increase in soil NO_3–N concentration in the soil profile due to rapid mineralization of organic-N compared with the NT system (Philips et al., 1980; Brandt, 1992; Huntington et al., 1985; McCarthy et al., 1995; Halvorson et al., 2001; Sanju and Singh, 2001). These study results showed a significant effect for tillage systems on soil NO_3–N concentration with either N source, except for ST with fertilizer N source.

CONCLUSIONS

The findings of this research showed that regardless of the N source and tillage system, corn yield did not

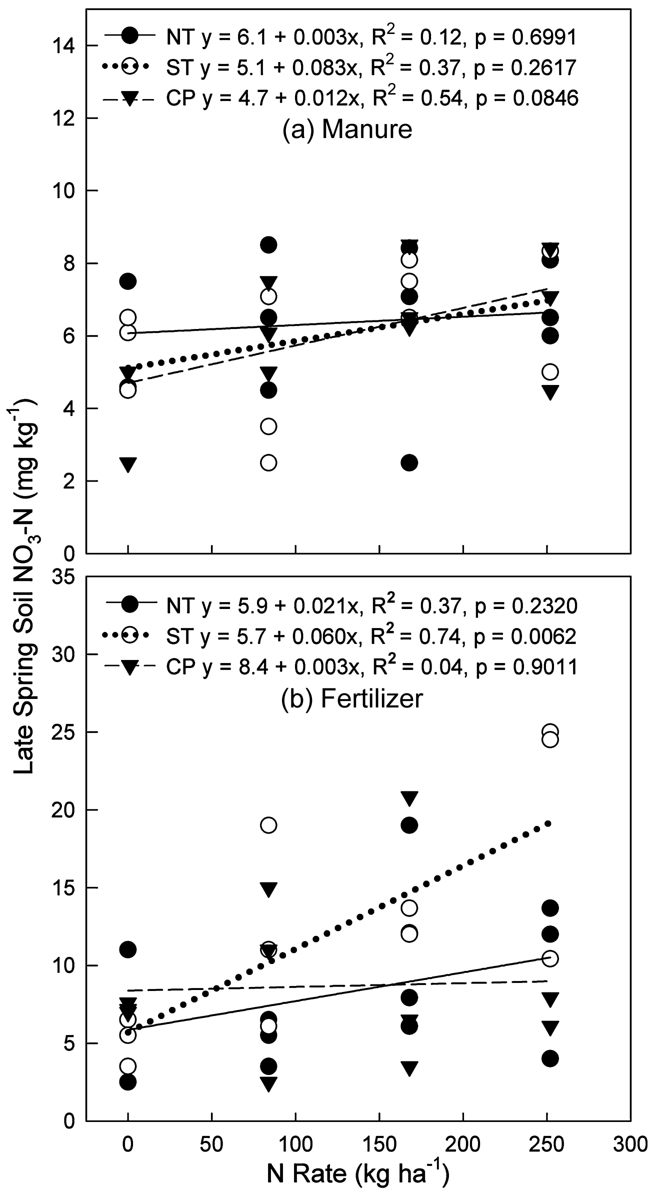

Fig. 2. Late spring soil NO_3–N concentration as a function of N rate of manure and fertilizer treatments with three tillage systems over 3 yr.

increase significantly with increasing N rate application above 85 kg N ha^{-1}. The effect of tillage system on grain N uptake at different N rates with both N sources was generally insignificant, except with fertilizer source, where ST had improved N uptake compared with NT and CP for the 0 and 85 kg N ha^{-1} rates. The interaction effect of tillage × N rate on grain N and P uptake was inconsistent, except for N uptake with fertilizer source. Across all tillage systems and N rates, plant N and P uptake percentages at the V12 growth stage represent 44 and 39% of total plant + grain N uptake, respectively with manure source, and 43 and 34%, respectively with fertilizer source.

The tillage × N rate effect on plant N and P recovery was only significant at the V6 growth stage with both N sources. However, most dominant interaction effect on plant N and P uptake and recovery was N rate × year from the V6 to R6 growth stages. This significant interaction effect on plant N and P uptake and recovery was consistent with both N sources at the V6 and R6 growth stages. This indicates that seasonal variability has more effect on N availability than the type of tillage system. The three-way interaction effect of tillage × N rate × year on plant N and P recovery was generally insignificant, and only 25% of this interaction was significant from the V6 to R6 growth stages.

Regardless of N source, the interaction effect of tillage × N rates influenced both corn stalk NO_3–N and soil NO_3–N concentrations. Generally, the relationships between either corn stalk NO_3–N concentration and the N application rate of both N sources was linear, increasing with the increase of N rate in all tillage systems. The soil NO_3–N and N rate showed a poor correlation due to high spatial variability of soil NO_3–N concentration. The interaction between tillage and N rate was inconsistent in influencing plant N and P uptake by corn plant and grains, but high N rates have an influence on yield response and corn stalk NO_3–N concentration regardless of the tillage system. The findings suggest that both N sources have a similar effect on yield and N and P uptake regardless of tillage type. Additional N application from both N sources did not increase N uptake or yield for one particular tillage system over another. The findings of this study also indicate that the most effect a tillage system can have on plant N and P uptake was early in the growing season with both N sources, and it had a limited effect on plant N and P uptake later in the growing season. It was always believed that NT might have a disadvantage in nutrient availability and the need for additional N and P applications compared with CT systems. However, these findings showed the limited effect that increased N or P application has on increasing the utilization or recovery of these two nutrients by corn grown with all tillage systems. Furthermore, the most dominant or significant two-way interaction effect on plant N and P uptake or recovery was N rate × year rather than tillage × N rate or tillage × year interactions. Another interesting observation from these results is the similarity of nutrient value of both N sources and corn response to these two N sources across all tillage systems.

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