Published online April 11, 2006

Tillage and Nitrogen Source and Rate Effects on Corn Response in Corn–Soybean Rotation

David Kwaw-Mensah and Mahdi Al-Kaisi*

ABSTRACT

Conservation tillage systems present a challenge for integrating an efficient fertilizer program for corn (*Zea mays* L.) production in the U.S. Midwest and elsewhere. The objective of this study was to evaluate corn response to three tillage systems (no-tillage, strip-tillage, and chisel plow) and four N rates (0, 85, 170, and 250 kg N ha^{-1}) of liquid swine manure and commercial fertilizer in a corn–soybean [*Glycine max* (L.) Merr.] rotation. A 3-yr study from 2002 to 2004 was conducted on a Kenyon soil (fine-loamy, mixed, mesic Typic Hapludoll) at the Iowa State University Northeast Research and Demonstration Farm near Nashua, IA. The experimental design was a randomized complete block with split plots. Tillage and N rates were randomly assigned as main plot and subplot treatments, respectively. Corn grain yield and aboveground biomass response to different tillage systems were not significantly different for all N rates of both N sources; however, the biomass yield at different growth stages with different N sources, tillage, and N rates were inconsistent. There were no interaction effects of tillage and N rates on yields, except in a few cases. The 3-yr average of maximum (MNR) and economic optimal (EONR) N rates (182 and 174 kg N ha^{-1}, respectively) across all tillage systems with liquid manure produced identical maximum (MGY) and economic optimum (EOGY) grain yields of 11.7 Mg ha^{-1}. In contrast, the MNR and EONR (176 and 144 kg N ha^{-1}, respectively) with commercial fertilizer N produced a MGY and an EOGY of 11.2 and 11.1 Mg ha^{-1}, respectively.

For many years, tillage systems have been evolving to better conserve soil and moisture through less intensive or no-tillage operations (Jones et al., 1969; Blevins et al., 1971). The use of conservation tillage systems, and no-tillage in particular, have presented problems with early growth of spring-seeded crops in cooler and wetter soils, which may create conditions that reduce early nutrient uptake and growth (Al-Darby and Lowery, 1987; Kaspar et al., 1990). Despite these production problems, many studies have shown that no-tillage can produce corn with equal or superior nutrient uptake and grain yield to conventional tillage systems due to better moisture conditions (Singh et al., 1966; Triplett and Van Doren, 1969; Shear and Moschler, 1969; Belcher and Ragland, 1972; Moschler et al., 1972). Differences in corn response to different tillage systems has also been documented in long-term tillage studies conducted at multiple locations in Iowa, where no significant corn yield differences between no-tillage and conventional tillage systems were observed, especially in well-drained areas (Al-Kaisi and Yin, 2004; Al-Kaisi and Licht, 2004).

Dep. of Agronomy, Iowa State Univ., Ames, IA 50010-1010. Received 14 June 2005. *Corresponding author (malkaisi@iastate.edu).

Published in Agron. J. 98:507–513 (2006).
Nitrogen Management
doi:10.2134/agronj2005.0177

Tillage as a practice in crop production systems can affect soil environment components that are important to plant growth, such as N pool status and N availability. The effect of any tillage system on maintaining adequate nutrient levels in the soil system, particularly N for crop production, is therefore critical to the sustainability of crop production systems. The integration of appropriate tillage and N management systems for sustainable crop production thus presents a significant challenge. The interaction of tillage and N is not well documented due to the dynamics and complexity of such an interaction, which involves complex biochemical and physical processes.

Tillage operations and soil disturbance generally can cause an increase in soil aeration, residue decomposition, organic N mineralization, and the availability of N for plant use (Rice et al., 1987; McCarthy et al., 1995; Halvorson et al., 2001; Sanju and Singh, 2001; Dinnes et al., 2002). In contrast, no-tillage systems cause minimal soil disturbance and increase the buildup of surface residue, which may increase both N immobilization and possible N losses through leaching and denitrification (Gilliam and Hoyt, 1987; Tyler and Thomas, 1977). Many studies have reported that no-tillage reduced the availability of N from chemical fertilizer, presumably due to greater immobilization (House et al., 1984; Carter and Rennie, 1987; Varco et al., 1993). Therefore, the type of tillage system adopted for corn production can influence the performance of plant growth and grain yield. In central Iowa, corn grain yields of no-tillage, strip-tillage, and chisel plow with different application timing of commercial fertilizer N showed that strip-tillage corn yielded favorably compared with that of chisel plow, and both the strip-tillage and chisel plow systems produced greater yields than no-tillage regardless of spring or fall N application (Al-Kaisi and Licht, 2004). In the northern Great Plains, a long-term tillage study with spring wheat (*Triticum aestivum* L.) using conventional tillage, minimum tillage, and no-tillage along with three N rates of 0, 22, and 45 kg N ha^{-1} showed that spring wheat yield response to N fertilizer tended to be the greatest under conventional and minimum tillage systems for all N rates in years when precipitation was high (Halvorson et al., 2000).

The integration between tillage, N rate, and N source is an important issue from production, economical, and environmental perspectives. The integration of these three components in corn production is not well documented or consistent due to the complexity of tillage

Abbreviations: CP, chisel plow; EOGY, economic optimum grain yield; EONR, economic optimum nitrogen rate; MGY, maximum grain yield; MNR, maximum nitrogen rate; NT, no-tillage; R6, physiological maturity stage of corn; ST, strip-tillage; VT, tassel stage of corn; V6, sixth-leaf stage of corn; V12, 12th-leaf stage of corn.

system effects on soil nutrient availability. A study of liquid manure as a source of N and P coupled with different tillage systems can help elucidate the value of liquid manure as an alternative source of nutrients for corn production in Iowa and the Midwest given the economic challenges of the rising cost of commercial fertilizer. The objective of this study was to evaluate the response of corn to three tillage treatments and four N rates of both liquid swine manure and commercial fertilizer N.

MATERIALS AND METHODS

Site Description

The study was conducted at the Iowa State University Northeast Research and Demonstration Farm near Nashua, IA. The experimental site is nearly level to gently sloping with a Kenyon soil. The average annual precipitation in northeastern Iowa is 896 mm, with a growing season average of 701 mm.

The experiment was conducted from 2002 to 2004. The 16-ha site was divided into two main 8-ha sites (east and west sites) for corn and soybean rotations. During the corn year, the 8 ha was split into two 4-ha sites (north and south sites) for application of two different N sources. At one site, corn received liquid swine manure at four different N rates (0, 85, 170, and 250 kg N ha^{-1}), while on the adjacent 4-ha site, commercial fertilizer N was applied at the same N rates. The experimental design for each corn experiment with different N sources was a randomized complete block with split plots arranged in three replications. Three tillage systems of chisel plow (CP), strip-tillage (ST), and no-tillage (NT) were randomly assigned to each replication as the main-plot treatments and the four N rates of 0, 85, 170, and 250 kg N ha^{-1} were assigned randomly to each tillage treatment as subplot treatments during each corn year. The size of each tillage plot was 56.1 m long by 21.3 m wide. The subplot size of each N rate within the main tillage plots was 56.1 m long by 5.3 m wide.

In 2002, the eastern half of the experimental site was planted with corn and the western half planted with soybean. In 2003, corn and soybean were planted in the 2002 soybean and corn residues, respectively, and vice versa in 2004.

In November of each year after harvest, CP and ST treatments were implemented in the corn and soybean plots. The chisel plow was equipped with straight disks in front of the chisel points to cut through residue. The strip-tillage unit was outfitted with mole knives attached to toolbar shanks, which create 20-cm-deep tilled zones, and has 46-cm-diam. closing disks, which created an 8-cm berm over a 20-cm-wide tilled zone. Liquid swine manure was applied before the CP and ST operations in the previous year's soybean plots at the rates of 0, 85, 170, and 250 kg N ha^{-1} using a commercial liquid manure applicator. The liquid swine manure was analyzed each year for total C, N, P_2O_5, K_2O, and NO_3–N concentrations using the macro Kjeldahl method (Kane, 1999), AOAC 965.17 photometric method (AOAC, 1997), the USEPA 7610 atomic absorption method (USEPA, 1986), and the USEPA 353.3 automated Cd reduction method (USEPA, 1974), respectively. Three-year averages of manure analysis were: total N, 6.8 g L^{-1}; P_2O_5, 4.9 g L^{-1}; K_2O, 4.6 g L^{-1}; total C, 47 g kg^{-1}; NH_4–N, 5.0 g L^{-1}; and NO_3–N, 4.5 mg L^{-1}. The manure applicator was modified to cause minimum disturbance in NT plots.

Anhydrous NH_3 was applied at the same rates as the liquid manure N in April of each year on the other 4-ha site of the corn experiment using a six-row pull-type anhydrous NH_3 injection knife applicator. In May of each year during planting, a starter fertilizer was applied to the anhydrous NH_3 plots by applying 29 kg P_2O_5 ha^{-1} as $NH_4H_2PO_4$ (11–52–0) and 35 kg K_2O ha^{-1} of K (0–0–62) 5 cm deep and 5 cm from the row center to bring P and K levels similar to the liquid swine manure plots.

Field cultivation of the CP system plots was conducted in the spring before planting corn to control weeds and level the soil surface. Corn was planted in early May each year using DeKalb 537 non-*Bacillus thuringiensis* (non-Bt) corn at a plant population of 84000 plants ha^{-1}. During planting, the corn experiment was simultaneously sprayed with a pre-emergence 189-mL emulsifiable concentrate (EC) acetochlor herbicide [2-chloro-*N*-(ethoxymethyl)-*N*-(2-ethyl-6-methylphenyl)acetamide] at a rate of 189 L ha^{-1}. At maturity, corn was harvested using a combine with a scale for yield monitoring.

Crop Measurements

Corn plant samples were collected at the sixth-leaf (V6), 12th-leaf (V12), tassel (VT), and physiological maturity (R6) growth stages for each tillage treatment and N rate for dry matter production estimation (Al-Kaisi and Yin, 2003). The sampling area per plot was 4.6 m long, which was divided into three 1.53-m segments. At each of the four growth stages, one plant per 1.53-m segment of the sampling area was cut at ground level. A total of three plants were cut per 4.6-m-long plot. Each plant was cut from an area with two plants on each side of it. Plant samples were oven-dried at 60°C for 8 d to achieve a constant dry mass. Corn grains were harvested with a combine and grain moisture was adjusted to 15% when final yield was estimated. Relative grain yield was calculated by dividing the individual N rate yield for each tillage by the that of the 250 kg ha^{-1} N rate treatments where no interaction between tillage and N rate occurred. The corn harvest index (HI) was determined as a ratio of corn grain yield to aboveground dry matter without corn grain at physiological maturity for each tillage treatment and N rate. Economic optimum N rate (EONR) and maximum N rate (MNR) in relation to corn grain yield were determined for both N sources for each tillage system and across all tillage systems and years for each year of the study.

Economic optimum and maximum N rates were determined using the following quadratic equation to generate a yield response curve as a function of N rate:

$$y = a + bx - cx^2 \quad [1]$$

where y is corn yield and x is N rate. To determine MNR, the first derivative of Eq. [1] was equated to zero to solve for the value of x, which represents the MNR to achieve maximum corn yield:

$$dy/dx = b - 2cx \quad [2]$$

$$0 = b - 2cx \quad [3]$$

Therefore, MNR or x can be determined from the following equation:

$$\text{MNR or } x = (b/2c) \quad [4]$$

Similarly, the EONR was estimated by equating the first derivative of Eq. [1] to the N fertilizer price/corn price ratio (N/corn ratio). The N/corn ratio used in determining EONR was based on the assumptions that the unit price of commercial fertilizer N was \$0.44 kg^{-1} (or \$0.22 per pound, based on the actual N price during the study) of actual N and the unit price of corn was \$78.74 Mg^{-1} of corn (or \$2.00 per bushel during the study). Similarly, the N/corn ratio for liquid swine manure

Table 1. Effect of no-tillage (NT), strip tillage (ST), and chisel plow (CP) systems and four N rates of two N sources on aboveground corn biomass at six-leaf (V6), 12-leaf (V12), tasseling (VT), and physiological maturity (R6) growth stages averaged across the growing seasons of 2003 and 2004.

		Aboveground corn biomass							
		Liquid swine manure, kg ha^{-1}				Commercial fertilizer, kg ha^{-1}			
Growth stage	Tillage system	0	85	170	250	0	85	170	250
		Mg ha^{-1}							
V6	NT	0.3Aa†	0.4ABab	0.3Aa	0.5Ab	0.2Aa	0.3Aab	0.4Ab	0.3Aab
	ST	0.3Aa	0.3Ba	0.5Bb	0.5Ab	0.3ABa	0.3Aa	0.3Aa	0.3Aa
	CP	0.3Aa	0.5Ab	0.5Bb	0.5Ab	0.4Ba	0.4Aa	0.4Aa	0.5Ba
V12	NT	3.3Aa	4.1Aa	4.3Aa	5.9Ab	2.8Aa	3.7Aab	3.9Ab	3.9Ab
	ST	3.3Aa	4.5Ab	5.7Bc	6.3Ac	3.1ABa	3.8Aab	4.8ABb	4.3ABb
	CP	3.5Aa	5.8Bb	6.2Bb	5.6Ab	3.9Ba	4.5Aab	5.2Bb	5.1Bb
VT	NT	6.8Aa	8.2Aa	8.1Aa	10.3Ab	5.0Aa	7.2Ab	8.2Ab	6.7Ab
	ST	6.5Aa	8.0Aa	9.8Bb	9.8Ab	6.1ABa	7.3ABab	8.0Ab	7.7Aab
	CP	7.5Aa	9.0Aab	10.0Bb	9.9Ab	7.7Ba	8.9Bab	10.9Bc	9.4Bbc
R6	NT	10.8Aa	13.0Aab	14.2Ab	15.3Ab	9.3Aa	12.3Ab	9.7Aab	10.8Aab
	ST	12.5Aa	12.6Aa	15.7Ab	15.4Ab	12.1Ba	11.0Aa	12.3Ba	12.6Aa
	CP	11.8Aa	14.8Ab	14.4Ab	13.3Aab	10.4ABa	12.3Aab	13.3Bb	12.3Aab

† Means in columns within each N rate and growth stage with the same uppercase letter are not significantly different according to Tukey's least-square means adjusted for multiple comparisons. Means in rows within each growth stage and tillage system with the same lowercase letter are not significantly different according to Tukey least-square means adjusted for multiple comparisons at $P \leq 0.05$.

was estimated based on the unit price of \$0.22 kg^{-1} of actual N from liquid swine manure (based on the current market value set by the applicators for delivering and applying liquid manure).

Equation [2] was rewritten as follows:

$$dy/dx = \text{N/corn ratio} = b - 2cx \qquad [5]$$

The N/corn ratio based on the unit price of either commercial fertilizer or liquid swine manure N was used to solve for the value of x:

$$\text{EONR or } x = (b - \text{N/corn})/(2c) \qquad [6]$$

Statistical Analysis

The GLM procedure of the SAS statistical software package (Version 9.1) was used to perform an analysis of variance appropriate for a randomized complete block design with a split-plot arrangement (SAS Institute, 2003). Separate statistical analyses were done for dependent variables for each year of the study. Tukey's least-square means adjustment for multiple comparisons was used to compare treatment effects. Probability levels ≤0.05 were considered significant.

RESULTS AND DISCUSSION

Corn Biomass Response to Tillage and Nitrogen Management

Corn biomass yield was generally not affected by tillage system with liquid manure as the N source, except for some inconsistent effects at V6 to VT with the 85 and 170 kg ha^{-1} N rates, and with less biomass yield with the NT system than CP or ST at V6 to VT with the 170 kg ha^{-1} N rate (Table 1). When commercial fertilizer N was the N source, however, the tillage system effects on biomass yield were more frequent than with liquid manure N. These effects occurred at all N rates, although inconsistently. Generally, biomass yield with the commercial fertilizer N treatment was greater with CP than with NT where differences occurred, but biomass yield with ST was greater than with NT at R6 with the 0 and 170 kg ha^{-1} commercial fertilizer N rates.

Corn biomass yield generally increased with at least one rate of N application for both liquid manure and commercial fertilizer N compared with the 0 kg ha^{-1} N rate at all growth stages. The N rate effect was, however, highly inconsistent and variously linear to quadratic. Although inconsistent during early growth stages and with both N sources, better yield biomass with CP and ST systems may be attributed to better soil conditions early in the season and consequently improved early corn growth compared with the NT system (Al-Kaisi and Licht, 2004). Generally, the interaction effect of N rates and tillage systems with both N sources appears to be inconsistent, but more frequent with CP and ST than NT for some N rates at the V6 to VT growth stages. Also, the interactions of tillage × N rate and tillage × N rate × N source were not significant at any growth stages, and the interaction of tillage × N type was only significant at the V12 and VT growth stages (Table 2). This is consistent with the findings of some researchers that tillage operations and soil disturbance generally can cause an increase in soil aeration, residue decomposition, organic N mineralization, and the availability of N for plant use (Rice et al., 1987; McCarthy et al., 1995; Halvorson et al., 2001; Sanju and Singh, 2001; Dinnes

Table 2. Analysis of variance of the interaction effects of tillage, N rate, and N source on corn biomass at the six-leaf (V6), 12-leaf (V12), tasseling (VT), and physiological maturity (R6) growth stages for the growing seasons of 2002 to 2004.

Growth stage	Source	df	Mean square	$P > F$ (0.05)
V6	Tillage × N rate	6	0.0090	0.8057
	Tillage × N source	3	0.0432	0.0709
	Tillage × N rate × N source	9	0.0220	0.2841
V12	Tillage × N rate	6	0.7109	0.6469
	Tillage × N source	3	13.1095	0.0001
	Tillage × N rate × N source	9	1.5024	0.1617
VT	Tillage × N rate	6	2.1303	0.5638
	Tillage × N source	3	18.5442	0.0002
	Tillage × N rate × N source	9	2.9904	0.3428
R6	Tillage × N rate	6	1.9704	0.6399
	Tillage × N source	3	34.3620	0.0934
	Tillage × N rate × N source	9	7.9960	0.8646

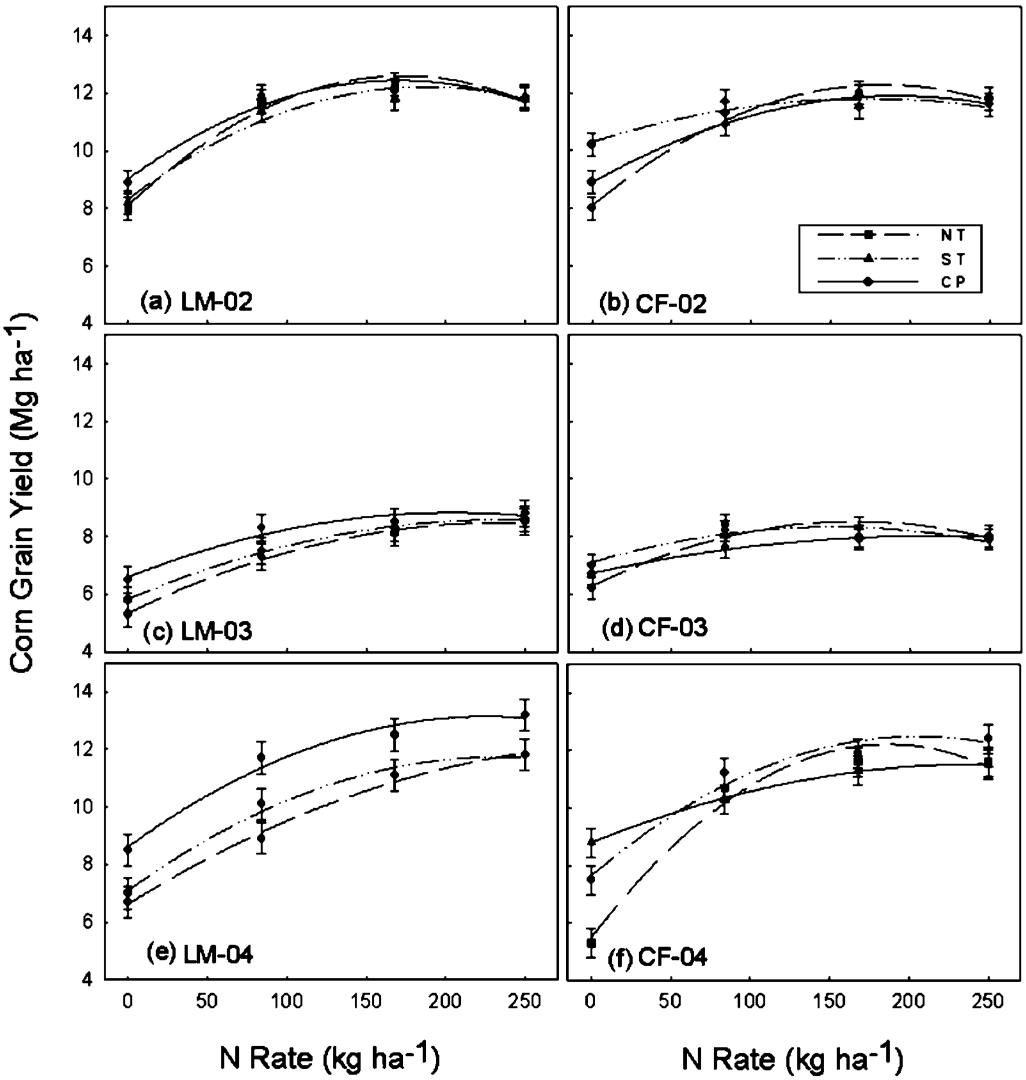

Fig. 1. Corn grain yield as a function of N rate of liquid swine manure (LM) and commercial fertilizer N (CF) under no-tillage (NT), strip tillage (ST), and chisel plow (CP) systems at Nashua, IA: (a) LM in 2002, (b) CF in 2002, (c) LM in 2003, (d) CF in 2003, (e) LM in 2004, and (f) CF in 2004. Error bars represent ±1 SE.

Table 3. Parameters of quadratic function ($y = a + bx - cx^2$) curves fitted through data points of Fig. 1a–1f.

Figure	Tillage†	Function parameters *a*	*b*	*c*	r^2
1a	NT	0.0512	0.00015	8.097	0.98
	ST	0.0416	0.00011	8.322	0.97
	CP	0.0433	0.00012	9.012	0.96
1b	NT	0.0459	0.00013	8.082	0.99
	ST	0.0174	0.00005	10.298	0.87
	CP	0.0315	0.00008	8.884	0.99
1c	NT	0.0267	0.00006	5.339	0.99
	ST	0.0234	0.00005	5.820	0.99
	CP	0.0220	0.00005	6.584	0.96
1d	NT	0.0273	0.00008	6.273	0.96
	ST	0.0163	0.00005	7.103	0.79
	CP	0.0122	0.00003	7.720	0.99
1e	NT	0.0341	0.00005	6.627	0.99
	ST	0.0399	0.00009	7.089	0.99
	CP	0.0402	0.00009	8.613	0.98
1f	NT	0.0722	0.00019	5.476	0.98
	ST	0.0224	0.00005	8.785	0.99
	CP	0.0471	0.00011	7.637	0.97

† NT = no-tillage, ST = strip tillage, CP = chisel plow.

et al., 2002). Therefore, ST and CP biomass responses may be influenced by an interaction between tillage and N dynamics.

Grain Yield Response to Tillage and Nitrogen Management

During the 3 yr of the study, the interactions between tillage systems and N rates of liquid swine manure and commercial fertilizer N did not cause significant differences in corn grain yield (Fig. 1a–f). Generally, yearly corn grain yield response curves to tillage and N rates were nonlinear (quadratic to quadratic plus plateau; Table 3) where the corn yield under CP, ST, and NT with 85, 170, and 250 kg N ha^{-1} of liquid swine manure were significantly greater than 0 kg N ha^{-1}. It appears that corn grain yield is mostly affected by N rate and shows significant differences between tillage systems across all years with liquid manure.

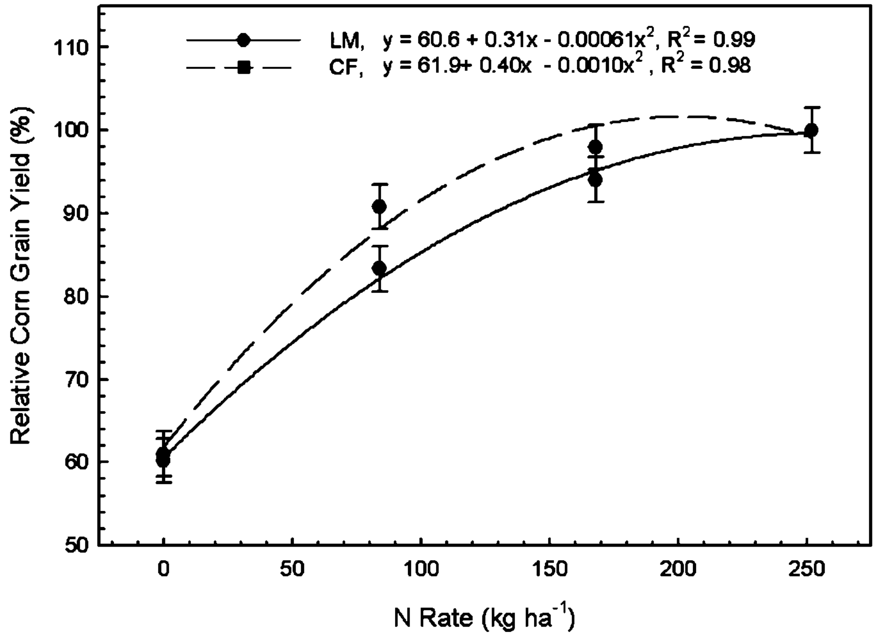

Fig. 2. Relative corn grain yield averaged across 3 yr and three tillage systems as a function of N rate of liquid swine manure (LM) and commercial fertilizer N (CF). Error bars represent ±1 SE.

Similarly, corn grain yields with the commercial fertilizer N treatments showed an identical nonlinear response to the tillage × N interaction; high N rates in the CP and NT systems had greater yields than with 0 kg N ha^{-1}. High grain yield variability was observed from year to year, with the only significant differences in yields between 0 kg ha^{-1} and high N rates (85, 170, and 250 kg N ha^{-1}) with all tillage systems. Generally, corn grain yield response to the tillage × N rates interaction of both N sources was variable and nonlinear, with greater performance of the CP and ST systems, averaged across all N rates, than the NT system.

Relative corn grain yields of commercial fertilizer N averaged across 3 yr and across all tillage systems showed improvement over those of the liquid manure at all N rates except the highest N rate of 250 kg N ha^{-1} (Fig. 2). Three-year averages of MNR or EONR, maximum grain yield (MGY), and economic optimum grain yield (EOGY) of liquid manure for all tillage systems were not significantly different (Table 4, Fig. 3). This may be due to the residual effects of manure organic N mineralization from the previous year of application. The MNR and EONR of commercial fertilizer N with CP, however, were significantly greater than with ST, but both MGY and EOGY of commercial fertilizer N with all tillage systems were not significantly different. Corn yield performance in general showed a similar response to both N sources with different N rates regardless of tillage system; however, MGY and EOGY with liquid manure appear to be numerically greater than with commercial fertilizer N. This can be attributed to the low cost of N of liquid manure. It must be noted also that the results of this study showed clearly that there was an interaction of tillage, N rate, and N source, although inconsistent; however, the inconsistent response of grain yield or biomass to tillage, N rate, and N source reveals the complex relationship between these parameters.

Corn Harvest Index

Harvest index was inconsistently affected by the tillage × N rate interaction for both N sources, as was observed for biomass and grain yields (Table 5). For the liquid manure N source and NT system, HI was greater with the 250 kg ha^{-1} N rate than the 0 kg ha^{-1} N rate and greater with the 85 kg ha^{-1} N rate with ST. For the commercial fertilizer N, the only significant N rate × tillage treatment interaction effect on HI occurred with NT, where the 250 kg ha^{-1} N rate had a greater HI than the 0 kg ha^{-1} N rate. Except for these effects, tillage and

Table 4. Maximum (MNR) and economic optimum (EONR) N rates of two N sources and maximum (MGY) and economic optimum (EOGY) corn grain yields averaged across 3 yr for no-tillage (NT), strip tillage (ST), and chisel plow (CP) systems at Nashua, IA.

	Liquid swine manure				Commercial fertilizer			
Tillage system	**MNR**	**EONR**	**MGY**	**EOGY**	**MNR**	**EONR**	**MGY**	**EOGY**
	kg N ha^{-1}		Mg ha^{-1}		kg N ha^{-1}		Mg ha^{-1}	
NT	**175a†**	**166a**	**12.6a**	**12.5a**	**179ab**	**156a**	**11.0a**	**11.0a**
ST	**190a**	**175a**	**11.1a**	**11.1a**	**162b**	**112b**	**10.5a**	**10.3a**
CP	**181a**	**182a**	**11.5a**	**11.5a**	**188a**	**163a**	**12.0a**	**12.0a**

† Means in columns with the same letter are not significantly different according to Tukey's least-square means adjusted for multiple comparisons at $P \leq 0.05$.

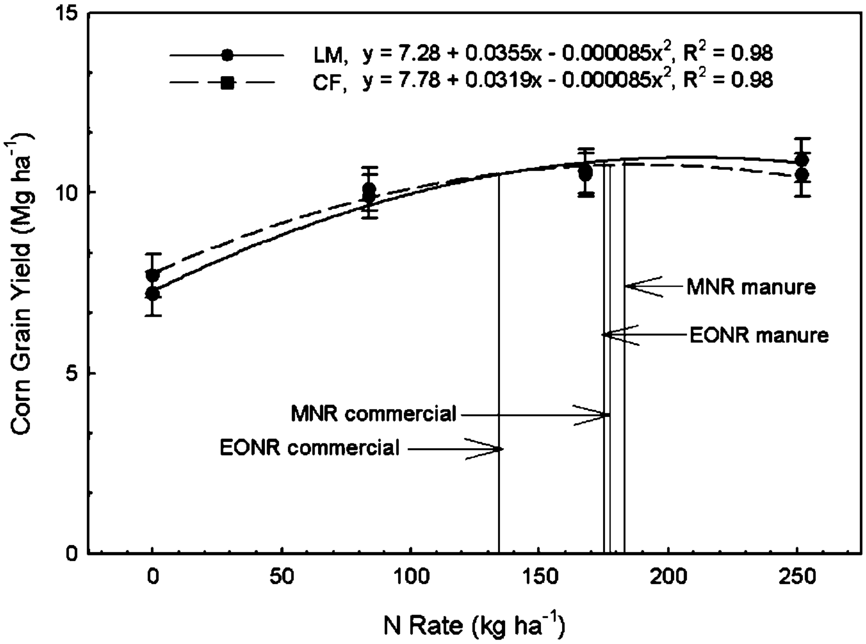

Fig. 3. Corn grain yield averaged across 3 yr and across all tillage systems as a function of N rate of liquid swine manure (LM) and commercial fertilizer N (CF or commercial). Points of maximum (MNR) and economic optimum (EONR) N rates and maximum (MGY) and economic optimum (EOGY) grain yields are shown. Error bars represent ±1 SE.

N rate did not affect HI with either N source. It appears that the increase in N rate has little effect on HI values with either ST or CP systems with either N source, but HI showed an improvement with increasing N rate, especially at 250 kg ha^{-1}. This may be attributed to the effect of both ST and CP in providing additional N through organic N mineralization (Rice et al., 1987; McCarthy et al., 1995; Halvorson et al., 2001; Sanju and Singh, 2001; Dinnes et al., 2002). It must be noted also that the high HI values, particularly with commercial fertilizer N, can be attributed to the lower biomass yield compared with liquid manure across all tillage systems.

CONCLUSIONS

The interaction effects of tillage, N rate, and N source on biomass yield were generally inconsistent with both liquid manure and commercial fertilizer N. It appears that the interaction effects of tillage and N rate were more frequent with commercial fertilizer N treatment, where most growth stages showed a favorable response to tillage and N rates, especially with N rates between 85 and 170 kg ha^{-1} with CP and ST tillage systems. It is also to be noted that the increase in N rate beyond 170 kg ha^{-1} did not show significant advantages in biomass yield or grain yield regardless of tillage system, N rate, or N source. The economic optimum N rate of liquid manure was 10 to 13 kg N ha^{-1} greater than that of commercial fertilizer N and produced 5.5 and 0.8 Mg ha^{-1} more grain than commercial fertilizer N with NT and ST, respectively, but underproduced by 0.8 Mg ha^{-1} with CP. It was also found that the difference between MNR and EONR is much smaller with liquid manure than commercial fertilizer regardless of tillage system. Therefore, based on the N cost and grain yield advantages of liquid manure, this N source should be considered a strong alternative to commercial fertilizer N, depending on its availability and the logistics of application. The other aspect of examining the interaction effects of tillage and N rates is the HI, where commercial fertilizer N treatments generally produced a greater HI (0.60 compared with 0.50 with liquid manure) across all tillage systems. It appears that the high HI with commercial fertilizer N was influenced generally by the low

Table 5. Harvest index of corn with four N rates of two N sources under no-tillage (NT), strip tillage (ST), or chisel plow (CP) systems averaged across 3 yr at Nashua, IA.

	Corn harvest index							
	Liquid swine manure, kg ha^{-1}				Commercial fertilizer, kg ha^{-1}			
Tillage system	0	85	170	250	0	85	170	250
NT	0.43Aa†	0.50Aab	0.53Aab	0.55Ab	0.47Aa	0.60Ab	0.60Ab	0.65Ab
ST	0.40Aa	0.55Ab	0.50Aab	0.50Aab	0.53Aa	0.60Aa	0.55Aa	0.60Aa
CP	0.47Aa	0.50Aa	0.50Aa	0.60Aa	0.53Aa	0.60Aa	0.57Aa	0.60Aa

† Means in columns within each N rate with the same uppercase letter are not significantly different according to Tukeys least-square means 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 Tukey's least-square means adjusted for multiple comparisons at $P \leq 0.05$.

biomass yield compared with liquid manure treatments. Generally, the tillage system × N rate interaction has a limited and inconsistent impact on corn performance.

ACKNOWLEDGMENTS

We would like to acknowledge the funding provided by the Division of Soil Conservation, Iowa Department of Agriculture and Land Stewardship, to conduct this research.

REFERENCES

Al-Darby, A.M., and B. Lowery. 1987. Seed zone soil temperature and early corn growth with three conservation tillage systems. Soil Sci. Soc. Am. J. 51:768–774.

Al-Kaisi, M., and M.A. Licht. 2004. Effect of strip tillage on corn nitrogen uptake and residual nitrate accumulation compared with no-tillage and chisel plow. Agron. J. 96:1164–1171.

Al-Kaisi, M.M., and X. Yin. 2003. Effects of nitrogen rate, irrigation rate and plant population on corn and water use efficiency. Agron. J. 95:1475–1482.

Al-Kaisi, M.M., and X. Yin. 2004. Stepwise time responses of corn yields and economic returns to no-tillage systems. Soil Tillage Res. 78:91–101.

AOAC. 1997. Phosphorus in animal feed and pet food. Photometric method. p. 35–36. *In* P. Cunniff (ed.) Official methods of analysis. 16th ed. AOAC Int., Gaithersburg, MD.

Belcher, C.R., and J.L. Ragland. 1972. Phosphorus absorption by sod-planted corn (*Zea mays* L.) from surface applied phosphorus. Agron. J. 64:754–756.

Blevins, R.L., D. Cook, S.H. Philips, and R.E. Philips. 1971. Influence of no-tillage on soil moisture. Agron. J. 63:593–596.

Carter, M.R., and D.A. Rennie. 1987. Effects of tillage on deposition and utilization of ^{15}N residual fertilizer. Soil Tillage Res. 9:33–43.

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

Gilliam, J.W., and G.D. Hoyt. 1987. Effect of conservation tillage on fate and transport of nitrogen. p. 217–240. *In* T.J. Logan et al. (ed.) Effects of conservation tillage on groundwater quality: Nitrates and pesticides. Lewis Publ., Chelsea, MI.

Halvorson, A.D., A.F. Black, J.M. Krupinsky, S.D. Merrill, B.J. Wienhold, and D.L. Tanaka. 2000. Spring wheat response to tillage system and nitrogen fertilization within a crop–fallow system. Agron. J. 92:288–294.

Halvorson, A.D., B.J. Wienhold, and A.L. Black. 2001. Tillage and nitrogen fertilization influence grain and soil nitrogen in an annual cropping system. Agron. J. 93:836–841.

House, G.J., B.R. Stinner, D.A. Crossley, Jr., E.P. Odum, and G.W. Langdale. 1984. Nitrogen cycling in conventional and no-tillage agroecosystems in the southern Piedmont. J. Soil Water Conserv. 39:194–200.

Jones, J.N., J.E. Moody, and J.H. Lillard. 1969. Effects of tillage, no-tillage and mulch on soil water and plant growth. Agron. J. 61:719–721.

Kane, P.F. 1999. Method 987.02: Nitrogen (total) in fertilizers. p. 13–14. *In* P. Cunniff (ed.) Official methods of analysis. 16th ed. AOAC Int., Gaithersburg, MD.

Kaspar, T.C., D.C. Erbach, and R.M. Cruse. 1990. Corn response to seed-row residue removal. Soil Sci. Soc. Am. J. 54:1112–1117.

McCarthy, G.W., J.J. Meisinger, and F.M.M. Jenniskens. 1995. Relationship between total-N biomass and active-N under different tillage systems and N fertilizer treatments. Soil Biol. Biochem. 27: 1245–1250.

Moschler, W.W., G.M. Shear, D.C. Martens, G.D. Jones, and R.R. Wilmouth. 1972. Comparative yield and fertilizer efficiency of no-tillage and conventionally tilled corn. Agron. J. 64:229–231.

Rice, C.W., J.H. Grove, and M.S. Smith. 1987. Estimating soil net nitrogen mineralization as affected by tillage and soil drainage due to topographic position. Can. J. Soil Sci. 67:513–520.

SAS Institute. 2003. The SAS system for windows. Release 9.1. SAS Inst., Cary, NC.

Sanju, U.M., and B.P. Singh. 2001. Tillage, cover crop and kill-planting date effects on corn yield and soil nitrogen. Agron. J. 93:878–886.

Shear, G.M., and W.W. Moschler. 1969. Continuous corn by the no-tillage and conventional tillage method: A 6-year comparison. Agron. J. 61:524–526.

Singh, T.A., G.W. Thomas, W.W. Moschler, and D.C. Martens. 1966. Phosphorus uptake by corn (*Zea mays* L.) under no-tillage and conventional practices. Agron. J. 58:147–148.

Triplett, G.B., Jr., and D.M. Van Doren, Jr. 1969. Nitrogen, phosphorus and potassium fertilization of non-tilled maize. Agron. J. 61:637–639.

Tyler, D.D., and G.W. Thomas. 1977. Lysimeter measurements of nitrate and chloride losses from soil under conventional and no-tillage corn. J. Environ. Qual. 6:63–66.

USEPA. 1974. Nitrogen, nitrate–nitrite (spectrophotometer, cadmium reduction). Method 353.3. Rep. no. 600/4-79-02. USEPA, Washington, DC.

USEPA. 1986. Potassium (atomic absorption, direct aspiration). Method 7610. Rep. no. 600/4-82-055. USEPA, Washington, DC.

Varco, J.J., W.W. Frye, M.S. Smith, and C.T. MacKown. 1993. Tillage effects on legume decomposition and transformation of legume and fertilizer nitrogen-15. Soil Sci. Soc. Am. J. 57:750–756.