Use of Anaerobically Digested Swine Manure in Corn Production

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Impact of Raw and Anaerobically Digested Swine Manure on Extractable Soil Phosphorus and Inorganic Nitrogen

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INTRODUCTION

Swine manure is an important source of nitrogen (N), phosphorus (P), and other nutrients for crop production. Processing of manure in an anaerobic digester is only a partial manure degradation process (Sweeten et al., 1990). During anaerobic digestion, chemical oxygen demand is reduced, but many organic compounds remain or are reduced to a lower molecular weight. Inorganic nutrients are still present, with some forms like NH_4 increasing. Also, the volume of manure remains constant (Kirchmann and Witter, 1989). Therefore, producers typically still need to utilize the material remaining after digestion as a source of plant nutrients.

Anaerobic digestion of animal manures has been extensively investigated during the last two decades (Williams, 1995). During anaerobic digestion, bacteria break down organic matter in an oxygen-free environment, resulting in fewer organic nutrient forms and more inorganic forms. Kirchmann and Lundvall (1993) reported increases of inorganic N (increase less than 10%). However, limited information is available regarding the impact of anaerobic digestion on nutrient content and crop nutrient availability.

Due to a potential increase in the use of anaerobic digestion systems for energy production, there is need for a reliable estimate of crop-available N and P in digested swine manure. Evaluation as a crop nutrient source requires determination of the effects of digestion on nutrient content and the ability to furnish crop-available nutrients when the material is applied to land.

Nutrient release when crops cannot assimilate them can cause low crop nutrient use and poor crop response. Binder et al. (1996) state the importance of synchronizing manure-nutrient mineralization with crop use. Also, environmental loss of nutrients can occur when supply does not match crop demand. One problem in manure management is the uncertainty of organic matter mineralization rate. Specific animal digestion processes (monogastric or ruminant), feed preferences and rations of different species, and overall handling of the manure are responsible for differences in manure nutrient concentrations and impacts on availability to crops (Bailey and Buckley, 2001).

To evaluate the impact of anaerobic digestion of swine manure on N and P when soil applied, it is important to know how these sources affect soil test P (STP), how they influence inorganic N levels and transformations, and how they compare to inorganic fertilizer sources. Incubation studies provide information that reflect field conditions, estimate nutrient changes in soil after application, and indicate rates that maximize crop production and reduce the risk of over-application (Rogers et al., 2001). Our objective was to compare the effects of anaerobically digested swine manure and raw swine manure on change in soil test P and inorganic-N.

MATERIALS AND METHODS

Soil

A bulk amount (0 to 15cm depth) of Webster soil (fine-loamy, mixed, mesic Typic Haplaquoll) was collected in November from a field that had been in a corn-soybean rotation. After collection, the soil was partially air-dried for 1 day at 22 ºC, sieved (5 mm), and stored at 2 ºC until the beginning of the incubation period. Chemical characteristics of the soil before incubation are presented in Table 1.

Source of Nutrients

Three nutrient sources were used: raw swine manure, anaerobically digested swine manure, and inorganic soluble fertilizer N and P. The inorganic fertilizer N and P source was a solution made of urea (44%), ammonium sulfate (44%), and ammonium phosphate (12%), for a final concentration of 1000 mg P L^{-1} and 4000 mg N L^{-1}. The raw and digested swine manures were collected from the same swine production facility; a commercial 5,000 sow-gestation-farrowing unit in southern Iowa. The manure sources were collected immediately before and after anaerobic digestion (15 days in a mesophilic anaerobic digester) and then stored in a plastic container at –5 ºC until application.

After thawing and thorough mixing, subsamples of the manures were chemically analyzed at the Iowa State University Analytical Services Laboratory for total N, ammonia - N, total K, total P, total solids, volatile solids, chemical oxygen demand (COD), and pH (American Public Health Association, 1995). The chemical characteristics of the manure sources are listed in Table 2.

Five rates of total N and P from each source were applied to the soil. Rates for P were 0, 12.5, 25, 37.5, 50 mg kg^{-1} and for N were 0, 50, 100, 150, 200 mg kg^{-1}. Phosphorus applications rates were matched for each source. However, due to differences in the total N:P ratio between manure sources, there were small differences in the applied N amount for the manure sources. The treatments were a complete factorial combination of nutrient sources and rates, replicated three times in a completely randomized design.

Incubation

Treatments were applied to the soil using the following procedure. Soil (1 kg, oven-dry basis) was spread on top of a brown paper sheet (40 x 40 cm) in a thin layer. Each specific treatment was prepared by adding to the fertilizer or manure solution a calculated amount of distilled water that would adjust the soil to approximately 80% water holding capacity. The solution (treatment + distilled water) was uniformly spread on top of the soil layer and then well mixed with the soil by moving up and down the corners of the paper sheet. The treated soil was transferred to a polyethylene bag, mixed again by shaking the bag for about 1 min, and incubated at approximately 22 ºC on a laboratory counter. The polyethylene bag top was left open (50%) to maintain air exchange. Moisture content was maintained at 80% water holding capacity by checking the weight of the bag every week and adding distilled water as needed. The soil was incubated for a total of 112 d.

Two soil subsamples were collected from each bag by scooping out 50 g of amended soil at 1, 7, 14, 28, 56, 84, and 112 d after treatment applications. One sample was designated for inorganic-N (NH_4-N and NO_2+NO_3-N) analysis, and the other for routine soil

P tests and pH. Hereafter the NO_2+NO_3-N concentration is referred to as NO_3-N. The subsamples for N analysis were stored in polyethylene bags and frozen at –5 ºC. The other subsamples were air-dried and stored in paper bags at room temperature until analysis.

Soil Analyses

Extractable P (soil test P or STP) was determined with the Olsen-P, Bray 1-P, and Mehlich 3-P availability indices (Frank et al., 1998). Changes in extractable P concentrations were estimated by subtracting the extractable P measured in each control soil for each sampling date. The percentage of added P reflected in the STP change was calculated by: (average P treatment STP concentration - control STP average P concentration) x 100/ P applied. This was calculated at 7 and 112 d and after application (Table 3).

Inorganic-N was determined by extracting 10 g of soil (moisture adjusted) with 2M KCl. The NH_4-N and NO_3-N contained in the KCl extract was determined by Lachat flow-injection procedure (Lachat Instruments, Milwaukee, WI) (Gelderman and Beegle, 1998). Extractable NH_4-N and NO_3-N was adjusted by subtracting the NH_4-N and NO_3-N measured in each control soil at each sampling date. Soil pH was determined on a 1:1 water soil paste using an electronic pH meter (Watson and Brown, 1998).

Data were analyzed by using the Proc Mix procedure of the Statistical Analysis System (SAS Institute, 1992). Repeated measurements analysis was utilized to compare treatment effects at different sampling dates.

RESULTS

Nitrogen

Soil inorganic-N was affected by the source x rate x time of incubation interaction ($P \leq 0.05$). Among all treatments, higher concentrations of NH_4-N and lower concentrations of NO_3-N were found the first day after treatment application (Fig. 1). During the next two weeks a rapid rate of NH_4-N disappearance and NO_3-N formation was evident among all treatments. No differences were found between raw and digested manure sources in most cases.

The decrease in concentration of extractable NH_4-N was not different between raw and digested swine manure at all rates, and both reached background levels between day 14 and 28 depending on the application rate (Fig. 1). However, significant differences between fertilizer and the manures were evident before day 28 at additions of 150 and 200 mg N kg^{-1}. In this period the manure sources had lower NH_4-N concentrations than the fertilizer and returned to background levels, whereas the fertilizer source still maintained some NH_4-N.

No differences in NO_3-N formation between manure sources were found for most of the sampling dates (Fig. 1). Nitrate-N concentrations were similar for all sources through day 7. Concentrations continued to increase until day 14 for the lowest application rates (50 and 100 mg N kg^{-1}) and until day 28 for the greater application rates (100 and 150 mg N kg^{-1}), the same time when NH_4-N concentrations returned to background levels. Differences between fertilizer and manure were measured from day 14 to the end of incubation. After peak NO_3 formation, concentrations were greater with fertilizer than either manure source. Nitrate concentrations increased slightly from 28 to 56 days for the fertilizer source, but did not increase further with subsequent sampling dates. With both manure sources, the NO_3-N concentrations slowly increased with time after the initial rapid increase. The maximal NO_3-N concentration measured for all rates with the fertilizer source was nearly 100% of applied N. However, the maximal NO_3-N concentration was approximately 80% of the applied N from the manure sources (Fig. 1).

Soil pH

Soil pH was affected by the source x rate x time interaction ($P \leq 0.05$). Initially after application soil pH was increased with both manure sources, but over time pH decreased (Fig. 2). Soil pH decrease was similar between the raw and digested manure, but was not as large as for the inorganic fertilizer treatments (Fig. 2). The greatest decline was found by day 28. The decrease in soil pH is evidence of nitrification, and was low enough to potentially slow nitrification at the highest fertilizer rates.

Phosphorus

For all soil P tests, the change in extractable P was affected by the source and rate of P applied ($P \leq 0.05$) (Fig. 3). Also, the interaction with sample date was different for the Olsen-P and Mehlich 3-P tests ($P \leq 0.05$), but not different for Bray-1P ($P = 0.0638$).

The increase in STP was similar and remained fairly constant for each manure source over the incubation period. However, with fertilizer P application the change in STP declined slowly from the initial maximum levels found at days 1 to 28 (Fig. 3).

The impact on P recovery from the P sources (measured as percentage change in extractable P) was not affected by the application rate. However, recovery was affected by source x sampling date x STP ($P \leq 0.05$). This is evident with greater recovery for the fertilizer source among all three tests, even though the percentage increase in Olsen-P test was lower than the other two soil P tests (Table 3). Also, the mean increase was the same for both manure sources, except for the Mehlich-3 test at day 7 where the digested manure had a greater recovery.

DISCUSSION

From our incubation study, we observed no differences between raw and anaerobically digested swine manure in regard to initial NH_4-N supply, disappearance of NH_4-N, NO_3-N formation, pH suppression, or change in soil test P. However differences between inorganic fertilizer and the manures were found in all cases.

At the first sampling date, NH_4-N was increased but NO_3-N concentrations were not different than the control in all treatments. This indicates that the dominant inorganic-N form applied for all sources was NH_4-N. Kirchmann and Lundvall (1993), working with raw and digested swine manure, observed no NO_3-N and 75 to 85% of N as NH_4-N, respectively. This is similar to our findings. The rapid decrease in extractable NH_4-N and the increase in NO_3-N concentrations are a result of nitrification. The inorganic N transformation and time period for conversion were similar to those with liquid beef manure found by Schmitt et al. (1992) when incubated with soil and by Sawyer and Hoeft (1990a,b) with simulated band injection. It is possible that microbial immobilization would occur to a greater extent with manure application than inorganic sources due to the presence of organic carbon in the manures. A temporary and slight decrease in total inorganic-N was observed shortly after application (data not shown) in the manure sources, but not in the fertilizer. These findings are consistent with those of other researchers who have studied N mineralization and transformation from sources with varying organic content (Chae and Tabatabai, 1986; Duffera et al., 1999; Kirchmann and Lundvall, 1993).

The maximum NO_3-N concentration measured with all rates for both manure sources was only approximately 80% of the applied total N. However, the maximal NO_3-N concentration in the fertilizer source was nearly 100%. This reflects the lower proportion of total N as NH_4-N initially present in the different sources (Table 2), and explains why the inorganic fertilizer source responded with a greater immediate supply of plant-available N (Fig. 1). Despite high NH_4-N in both manure sources, a pool of organic-N continued mineralizing during incubation, releasing NH_4-N that also quickly nitrified. Thus, NO_3-N continued to increase whereas NH_4-N did not. However, in the 112 d of incubation, there was not an equivalent release of total inorganic-N from the manures, as was for the fertilizer. Thus some organic-N apparently was not mineralized in 112 days.

The pH of the soil treated with different manure sources showed a similar initial increase and subsequent suppression, with the greatest decline through day 28 (Fig. 2). This paralleled the nitrification process (Fig. 1), during which an acidifying effect due to proton formation occurs (Bernal and Kirchmann, 1992). The smaller decrease in pH found for soil treated with manure (Fig. 2) could be due to a greater buffer capacity as a consequence of organic matter content (Fordham and Schwertmann, 1977), use of ammonium sulfate in the fertilizer source, or less nitrification.

Typically 65 to 75% of the P in raw swine manure is in organic forms and only 25 to 35% is in inorganic forms (Reddy et al., 1980). The anaerobic digestion process apparently did not impact the swine manure to an extent that would affect P availability to change STP. Fig. 3 (A1, A2, A3 and C2) shows only a few exceptions where differences in STP were evident between the two manure sources. Compared to inorganic P application (where 100% of the P was orthophosphate), lower increases in STP with the manure sources were found at several sampling dates, most shortly after application.

Mineralization and adsorption govern net P trends and soil test changes when soils are amended with P (Taylor et al., 1978). Over time, manure-P will undergo both processes whereas inorganic fertilizer (orthophosphates) would be influenced primarily by the adsorption process. The initial increase in STP was greater with the fertilizer P addition than with either manure source. However, 28 days after application the extractable levels were similar for all sources and rates. When inorganic-P is added, all of the P is immediately available for soil chemical reactions or for soil test extraction; therefore the speed of soil interactions will govern the STP measured. Manure-P has inorganic-P, grain-P, and microbial-P (Poulsen, 2000); therefore P available to immediately influence STP is different than inorganic sources, and the P available to interact with the soil is also different than the inorganic sources. From this, the initial increase in soil test P should be lower with manure sources, as was measured in this study, but the slower supply from organic manure-P may help to maintain a more constant level of plant-available P or soil test P, also measured across the duration of this study.

As the rate of application increased, the change in extractable P also increased among all sources (Fig. 3). This is consistent with work by Reddy et al. (1980) who concluded that an increase in animal waste application increases plant-available P. However, in terms of percentage change in extractable P, no consistent differences in application rates were found. All three soil-P tests predicted similar estimates of the change in P from the manure-amended soils (Table 3). Because of the greater inorganic P content, fertilizer application showed a greater percentage change in STP, similar to results of Baxter et al. (1998). After 112 days, the percentage of applied P measured in STP increase averaged approximately 30 to 40% for the fertilizer and 15 to 30% for both manure sources. These are more similar than expected considering the widely differing P sources.

SUMMARY

On the short term with field application (less than one month) crop P availability would be expected to be less from the swine manure sources than soluble inorganic fertilizer P. One would expect, however, similar crop P availability from both manure sources and fertilizer over time. Both raw and digested swine manure provided similar and large amounts of inorganic-N, but within 4 months of application approximately 20% less than total manure-N, and less than the all inorganic fertilizer N. The initial nitrification of the manure NH_4-N parallels nitrification of fertilizer NH_4-N, and implies management should be similar to fertilizer based NH_4-N. We conclude that digested swine manure is a valuable nutrient source that producers can use for crop production, and they should manage it as they would raw swine manure.

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Table 1. Selected chemical characteristics of the soil before incubation.

Characteristic	Values
Bray 1-P (mg P kg^{-1})	47
Mehlich 3-P (mg P kg^{-1})	50
Olsen-P (mg P kg^{-1})	25
Exchangeable K (mg K kg^{-1}) †	245
Exchangeable Ca (mg Ca kg^{-1})†	3,856
Exchangeable Mg (mg Mg kg^{-1}) †	572
Exchangeable NH_4-N (mg N kg^{-1})	3
NO_3-N (mg N kg^{-1})	24
Organic matter (g kg^{-1})	7.0
pH	5.8

† Extracted by: (1M NH_4OAc, at pH 7.0)

Table 2. Selected chemical analyses of the swine manure sources. Values are means of four samples collected immediately before and after anaerobic digestion.

Characteristic	Raw Manure	Digested Manure
Total solids, mg L^{-1}	11,250	12,500
Total P, mg P L^{-1}	661	777
Total Kjeldahl Nitrogen (TKN), mg N L^{-1}	2,880	2,655
Measured as Ammonia-N, mg N L^{-1}	1,440	1,500
Total K, mg K L^{-1}	1,166	1,117
Chemical Oxygen Demand (COD), mg L^{-1}	12,600	5,600
pH	7.8	8.1

Table 3. Percentage change in extractable P for each soil test P method at sampling date 7 and 112, mean of all P application rates.

Soil P test	Sampling date	Raw Manure	Digested Manure	Fertilizer
	days	- - - - Percent change in Extractable P[†] - - - -		
Olsen-P	7	19a,a,a[‡§¶]	19a,a,a	38a,b,a
Bray1-P	7	29a,a,a	27a,ab,a	44ab,b,b
Mehlich 3-P	7	23a,a,a	44b,b,a	56b,b,a
Olsen-P	112	18a,a,a	29a,a,a	29a,a,a
Bray1-P	112	22a,a,a	24a,a,a	41a,b,b
Mehlich 3-P	112	16a,a,a	19a,ab,b	34a,b,b

† Percentage change was calculated by: 100*(soil test P mg P kg^{-1} - soil test P control)/P applied mg P kg^{-1}.

‡ At the same sampling date, numbers in columns followed by different first letter are significantly different, ($P \leq 0.05$) Tukey-Kramer least square means test.

§ At the same sampling date, numbers in rows followed by different second letter are significantly different, ($P \leq 0.05$) Tukey-Kramer least square means test.

¶ At different sampling date, but same soil test method, numbers in columns followed by different third letter are significantly different, ($P \leq 0.05$) Tukey-Kramer least square means test.

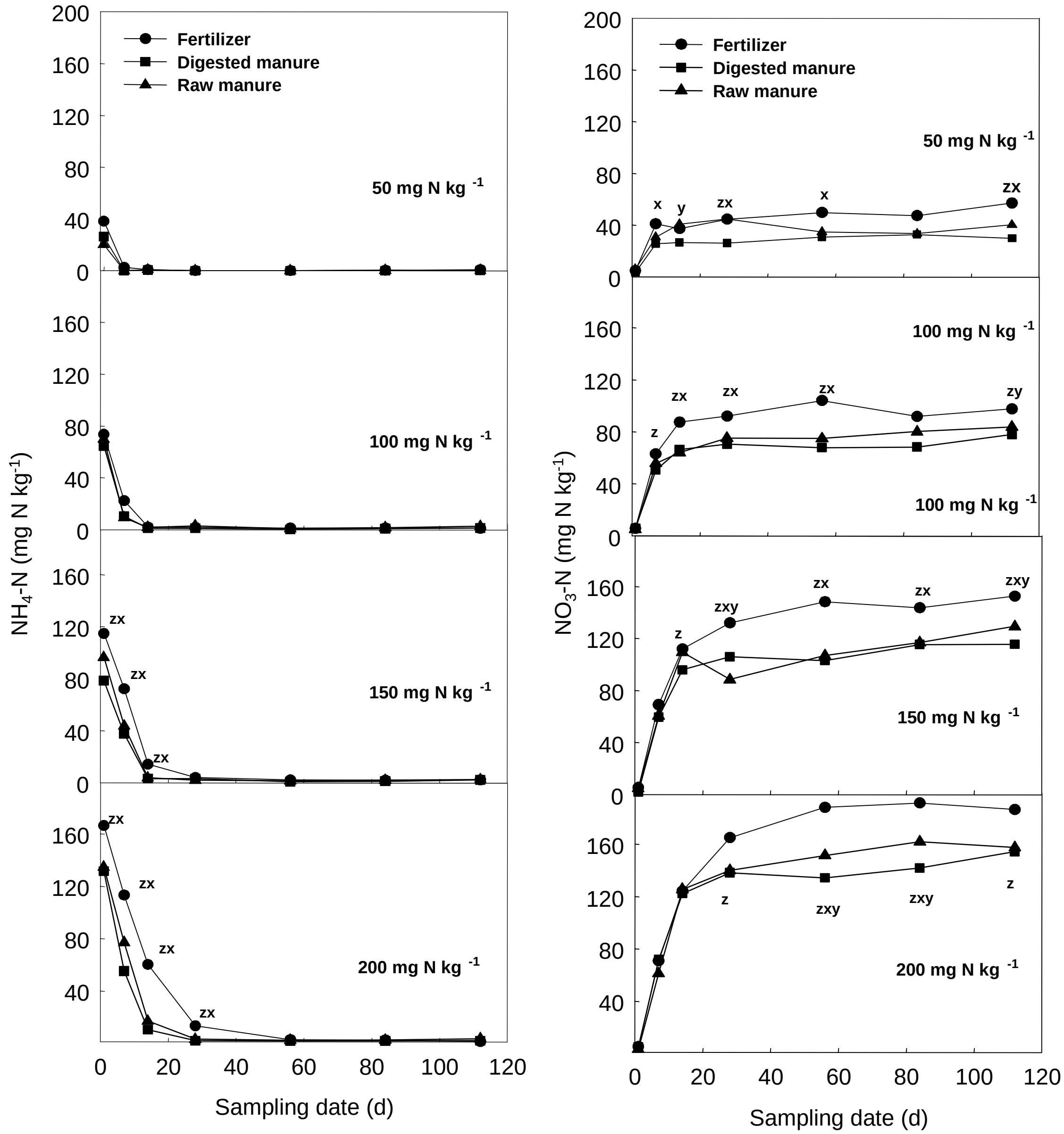

Fig. 1. Extractable NH_4-N and NO_3-N over time for each nutrient source and application rate. At each sampling date the NH_4-N or NO_3-N concentration in the control soil was subtracted from each sample. Comparisons ($P \leq 0.05$) using Tukey-Kramer least square means between N sources at each sampling date are indicated by: [z] fertilizer and digested manure; [x] fertilizer and raw manure; [y] raw and digested manure.

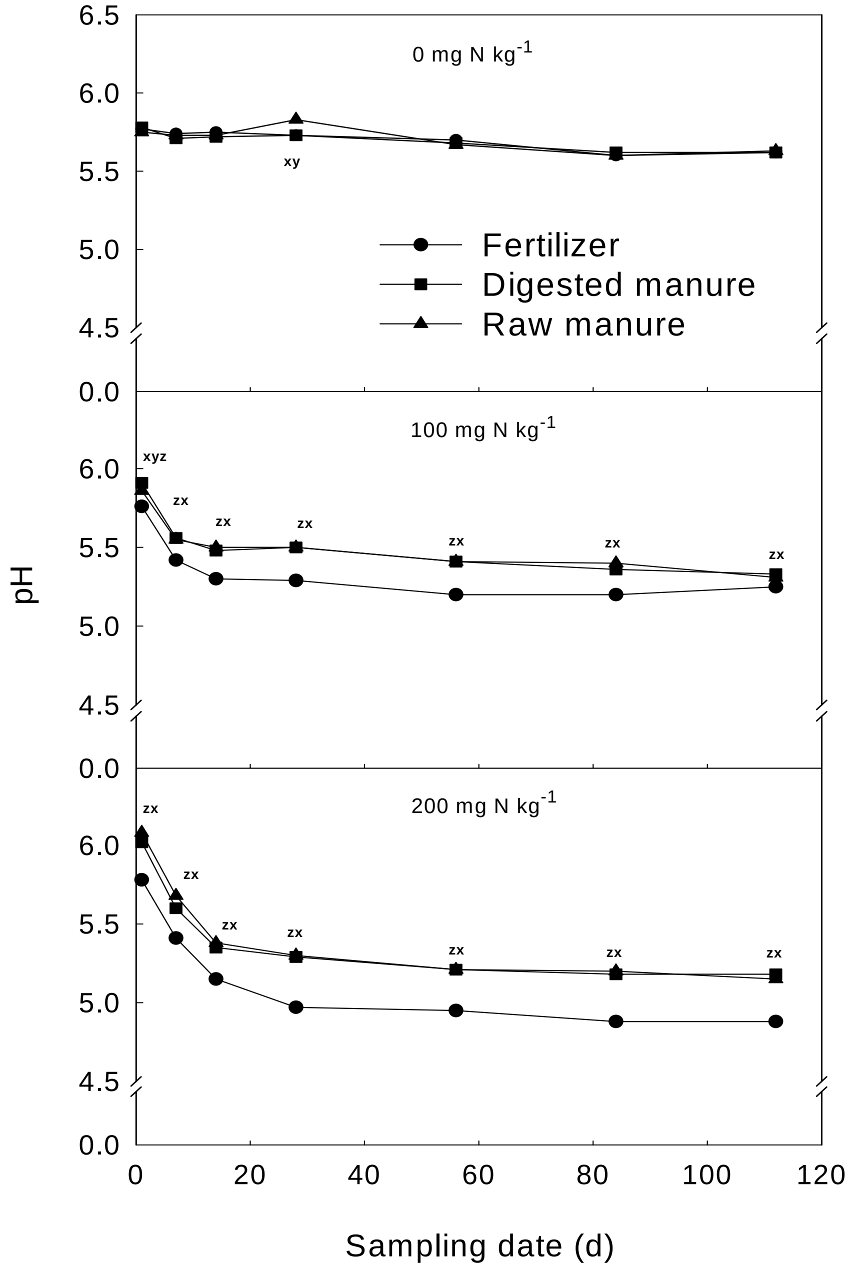

Fig. 2. Impact of manure source and application rate on soil pH. Comparisons ($P \leq 0.05$) using Tukey-Kramer least square means between nutrient sources at each sampling date are indicated by: [z] fertilizer and digested manure; [x] fertilizer and raw manure; [y] digested and raw manure.

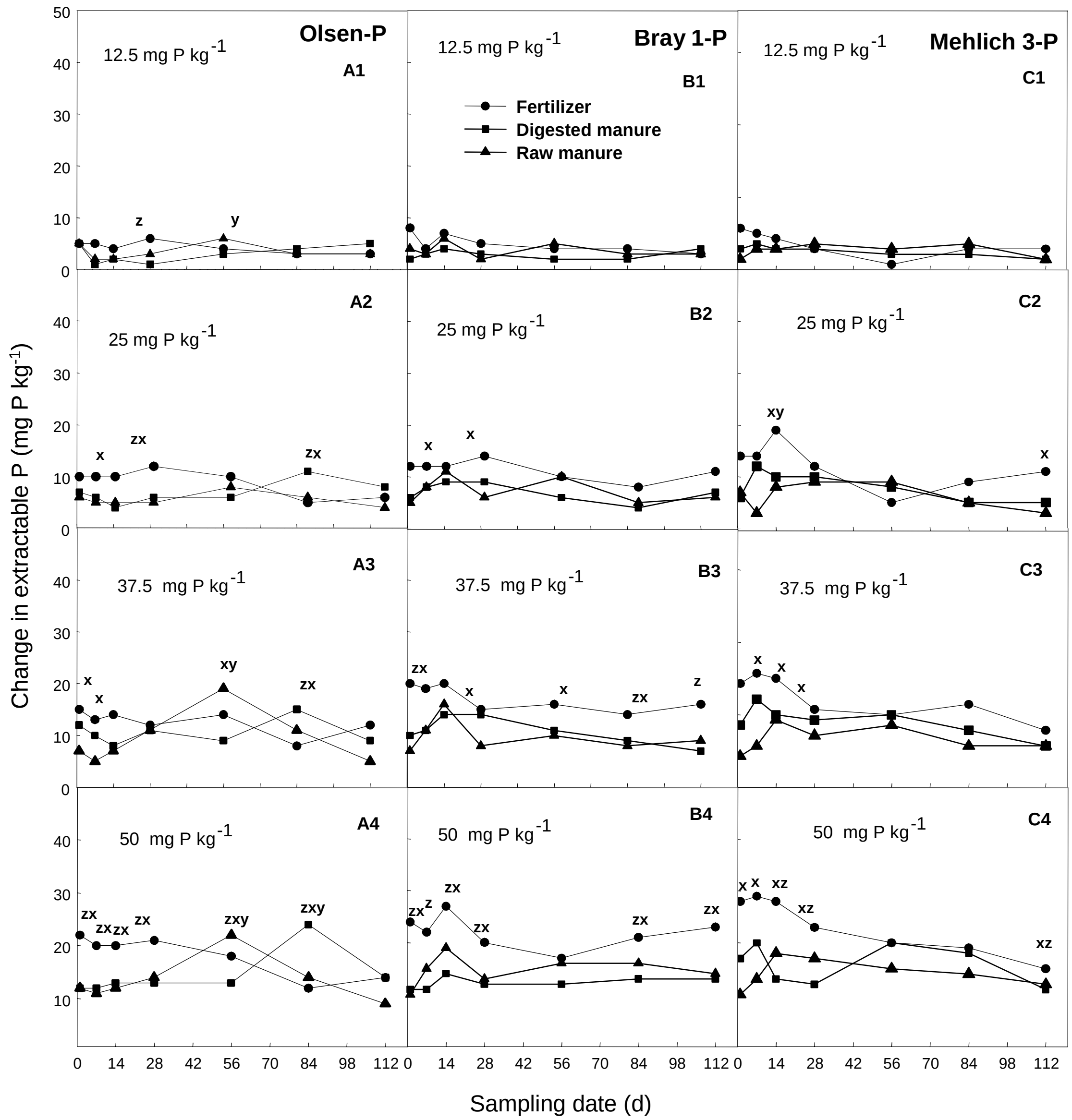

Fig. 3. Change in extractable P over time for each nutrient source and application rate. At each sampling date the STP concentration in the control treatment was subtracted from each sample to calculate the change in extractable P. A1, A2, A3 and A4; B1, B2, B3 and B4; C1, C2, C3 and C4; represent Olsen-P, Bray 1-P and Mehlich 3-P at 12.5, 25, 37.5, and 50 mg P kg^{-1}, respectively. Comparisons ($P \leq 0.05$) using Tukey-Kramer least square means between P sources are indicated by: ^{z} fertilizer and digested manure; ^{x} fertilizer and raw manure; ^{y} digested and raw manure.

Use of Anaerobically Digested Swine Manure as a Nitrogen Source in Corn Production

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INTRODUCTION

In the last three decades the concept of extracting energy from animal manure has gained renewed interest. Anaerobic digestion of animal manures for production of biogas has increased (Williams, 1995) and been taken more seriously because of potential tax cuts and problematic energy supply, similar to the USA energy crisis in the 1970's. Also, concerns about environmental hazards in regard to disposal of manure have increased (Goodrich, 2001). In general there are many scientific publications related to the performance of digester designs for energy production (Goodrich, 2001); however little information is available regarding the impact of digestion on manure related to nutrient content, potential availability for crop production, and soil chemical changes (Sutton et al., 1978).

Nutrient availability questions are more complicated than they may seem because crop uptake is a season-long process (Schepers et al., 1998). A large problem in manure management is the uncertain potential availability of the organic nutrient forms (Killorn, 1998). Better estimates of manure nutrient availability to crops are needed to help farmers improve manure nutrient management, especially for manures that have been chemically or physically manipulated, like anaerobically digested manure.

Binder et al. (1996) states the importance of manure mineralization and the synchronization of nutrient release with crop demand. Swine manure is considered a valuable nutrient source that can increase yields when applied to soil at rates commensurate with good agronomic practices (Duffera et al., 1999). This is attributed to improved soil physical properties such as aggregate stability, water holding capacity, and decreased bulk density, as well as enhanced nutrient availability.

In the anaerobic digestion process, bacteria break down organic matter in an oxygen-free environment, typically resulting in higher amounts of inorganic nutrient forms and lower organic matter (Kirchmann and Lundvall, 1993). Sutton et al. (1978) reported that generally anaerobically treated wastes contain higher concentration of Kjeldahl N (TKN) and NH_4-N on a wet basis than aerobically treated wastes. Across a multi-year sampling J. Lorimor (personal communication, 2002) found a 13% larger proportion in the NH_4 (measured as ammonia-N) form (76% raw, 89% digested) after swine manure went through an anaerobic digestion process, but a 10% higher TKN with raw manure. This transformation in the chemical characteristics of the manure could necessitate a change in agronomic utilization.

In the USA swine production is being concentrated at both regional and farm levels (Bailey and Buckley, 2001). The states of Iowa, North Carolina, Minnesota, and Illinois lead the country, accounting for more than 50% of the USA swine production. Also 52% of the

58 million swine population is fed in concentrated operations (5,000 head or larger) (USDA Hogs and Pigs report, 2002). All this controlled and large source of potential nutrients and energy as manure from these facilities must be utilized in some manner --most logically land application for crop nutrient use. But at the same time energy production before land application could help to save fossil fuel reserves and decrease the synthetic fertilizer budget.

The objective of this study was to compare the N supply from raw and anaerobically digested swine manure for corn (*Zea mays* L.) production. Field studies were designed to determined soil N, plant N uptake, and grain yield responses to applications of raw swine manure, digested swine manure, and inorganic N.

MATERIALS AND METHODS

Field studies were conducted in the 2000-2002 crop years on a Clarion-Nicollet Webster soil association (Fine -loamy, mixed, mesic, Typic Haplaquolls) at adjacent sites at the Agronomy Research and Demonstration Farm, located near Boone, IA. The same site was used in 2002 as in 2000. Soil chemical characteristics of the sites are listed in Table 1.

Raw and anaerobically digested liquid swine manures used in this study were obtained from Bell farms, a commercial sow-farrowing swine facility located in Southern Iowa. The anaerobic digested manure source was liquid swine manure that had been exposed to a 15 d residence digestion in a mesophilic anaerobic digester. Chemical analyses of manure samples collected before each application were conducted by the Iowa State University Analytical Service Laboratory for ammonia-N, total P, TKN, total solids, volatile solids, and pH (APHA, 1995). Manure NO_3-N was not included due to previous experience that indicated very little NO_3-N in liquid swine manure. Table 2 shows the chemical analysis of the manure sources.

The manure was applied in the late fall each year (early Nov.) with a sweep injector applicator (76-cm sweep spacing) that had injection knives mounted on the back of the applicator. Maximum injection depths were 15 to 20 cm, and resulted in a band of manure vertically and horizontally distributed. The applicator was run through the control plots (no manure application) to negate effects of injection tillage. The rates of manure and N applied are presented in Table 3.

The study utilized a split-split plot treatment arrangement in a randomized complete block design, with four replications. Main plots (22.8 by 73.2m) were manure sources (raw swine manure and anaerobically digested swine manure). Sub-plots (7.6 by 73.2m) were manure rate (none, medium, high). Sub-sub plots (3.8 by 12.2m) received surface-broadcast NH_4NO_3 fertilizer at rates of 0, 45, 90, 135, 180 and 225 kg N ha^{-1} immediately after corn planting.

Soil was sampled for routine soil test P, K, and pH in the spring before planting to determine fertilizer needs. Phosphorus or K fertilizers were applied to non-manure plots when soil tested at or below a very high-test category to negate effects of P and K applied with manure. All cultural practices of planting, herbicide and insecticide applications were typical for the region. Corn was planted (72,000 plant ha^{-1} in 76.2 cm rows) in early May each year with adapted hybrids. Hybrids were Pioneer® 34R07 in 2000 and NK® N58-D1 in 2001 and 2002. Corn stands were counted and thinned to uniform population each year.

Sampling and Analysis

Leaf greenness (LG) was measured with a chlorophyll meter (Minolta® SPAD 502 meter) to evaluate the N status of corn plants during the growing season. All measurements were taken on 30 randomly selected plants from the middle three rows of each sub-subplot. Readings were taken at the V8, V15, R1, and R3 growth stages using the procedure of Peterson et al. (1993). Readings were taken from the newest fully expanded leaf that had a collar exposed until the R1 stage, when the ear leaf was measured. Only results for the R1 stage are presented.

End of season cornstalk NO_3 concentrations (Binford et al., 1992) were determined on lower stalk samples (10 stalk segments per plot) collected at physiological maturity.

The middle three rows of each plot were harvested for grain yield with a plot combine. In 2000 some plots were harvested by hand because of lodging from wind damage. Grain yields were adjusted to 155 g kg^{-1} moisture content.

Soil samples were collected in a pattern across the manure application from each manure source and rate (zero fertilizer N) at 0, 19, and 38 cm away from the band and increments of 15 cm to a depth of 45 cm. Only results for the 0-15 cm depth at the center of the band are reported. Samples were collected in first week of December of 1999, second week of May and June of 2000 and second week of May of 2001. Due to adverse weather conditions samples could not be collected in December of 2000 and 2001. Also after analysis of the first year samples, no differences between May and June samples were found. Therefore, in 2001 and 2002 spring samples were only colleted in early spring. Samples were sieved (5 mm) and placed in plastic bags and frozen at –5 ˚C until inorganic N (NH_4-N and NO_3+NO_2-N) analysis by accelerated diffusion methods of Khan et al. (1997). Moisture content was determined gravimetrically.

Late spring soil nitrate test (LSNT) samples were collected in early June (when corn plants were 15 to 30 cm tall). Samples were collected from the 0 to 30 cm layer of selected treatments in three sets of eight 3.2 cm diam. cores across the application direction. The soil samples were dried in a forced-air oven at 50 ˚C and analyzed for NO_3-N (Gelderman and Beegle, 1998).

Statistical analyses were carrying out by Statistical Analysis System (SAS Institute, 1992) using GLM and Mixed procedures. The analyses of variance for the measured variables were conducted in a manner consistent with the split-split plot treatment arrangement in a randomized complete block design, with four replications. When deemed significant, responses to fertilizer N rate were fitted by the NLIN procedure to the quadratic plateau model. The Mixed statistical procedure was modified when only selected plots were sampled (LSNT and cornstalk NO_3), separating manured from fertilized plots in independent analyses and calculating Fisher protected least significant difference (FLSD).

RESULTS AND DISCUSSION

Climatic conditions varied between the years and impacted overall productivity and response to applied N. The 2000 growing season was dryer and warmer than the 2001 and 2002 seasons. The 2000 growing season started with low precipitation and warm temperatures in early spring, a warm summer with temperatures reaching almost 30˚C and weekly distribution of rain providing adequate moisture. A hot-dry period in late August rapidly accelerated plant maturity. The 2001 and 2002 growing seasons started wetter and cooler (March and May) than 2000. The corn was slow to reach maturity and for the grain to dry down for harvest in 2001. Also, each late fall was warm enough after manure application to allow nitrification. All measured parameters were statistically analyzed by individual year.

Soil inorganic-N

Inorganic N in Manure Band

Elevated concentrations of NH_4-N and NO_3-N were found in samples collected at the center of the injection zone in the surface to 15 cm depth (Table 4) at the December 1999 sampling. No differences between raw and digested manure were found. The control in Table 4 represents background NH_4-N, and NO_3-N values at each sampling date. It would be expected to find increased NH_4-N due to the composition of the manure, and apparent rapid nitrification took place as a result of warm temperatures after application. In each year, by the early spring sample date, NH_4-N levels decreased to background levels and in 2001 NO_3-N had also. Inorganic-N concentrations are reported only for the center of the application zone as that was the zone of highest concentration. These results indicate that the fall-applied raw or digested manure NH_4-N could easily be converted to NO_3-N by early spring. The rapid conversion from NH_4-N to NO_3-N is similar to that measured by Sawyer et al. (1990) with spring applied liquid beef manure.

Late Spring Soil Nitrate (LSNT)

In each year the LSNT values were not different between manure sources, however manure rate and N rate significantly affected LSNT values (Table 5). Higher values were measured in 2000 and 2002 than 2001. It is interesting that the values from the manured plots are lower than from the fertilized plots even though the applications supplied similar amounts of total N. Also, despite low LSNT values each year with the high manure rate, adequate N was apparently available for corn production as there was no yield response with additional fertilizer N (Figs. 1-3). Similar response occurred for the low manure rate in 2000. Others have noted that less inorganic N was present in the soil following manure injection than surface-broadcast fertilizer treatments (Sutton et al., 1978). Suggested critical LSNT values are lower with manure application than fertilizer application (Blackmer et al., 1997). Also, the manure was fall applied while the fertilizer treatments were spring applied. Differences in mineralization, NO_3-N movement out of the top foot of soil, or loss may explain part of the difference in LSNT values. The cooler and wetter 2001 spring may have also impacted differences between years.

Grain Yield

Corn grain yields are presented in Figs. 1-3. Grain yields were higher in 2000 than in 2001 and 2002. Yield differences between growing seasons could be attributed to several factors, like genetics (change in hybrid) and weather conditions. The manure source x manure rate x N rate interaction was significant for corn grain yield in 2000, and the manure rate x N rate interaction was significant in 2001 and 2002. Also, the main effects of N rate and manure rate were significant each year. These results indicate that the significance of the triple interaction in 2000 was influenced mostly by manure rate and N rate. The main effect of manure source, and interactions with manure source, were not significant either year. Therefore, for all years the effect of manure source was considered not significant and results are averaged across sources. This is consistent with work by Fischer et al. (1984) who reported that when effluent of anaerobically digested swine manure and raw manure are applied to the soil at the same N rate, corn response was similar.

In order to quantify manure impact on yield and N availability to corn, we pooled the manure source data. Quadratic-plateau regression equations (when significant) were fit to the N rate responses, and maximum plateau values were determined for the different manure rates (Figs. 1-3). Jokela (1992) suggested this method to quantify the fertilizer N equivalence to a given rate of manure by developing best fit regression lines for the response variable (grain yield) to N fertilizer and determining the fertilizer rate that would produce similar yield as manure. We have the benefit of having all fertilizer N rates applied along with each manure rate, which helps negate other manure effects.

For the no-manure regression fit-lines, maximum yields (plateau join point) were obtained at 90 kg fertilizer-N ha^{-1} in 2000, 105 kg fertilizer-N ha^{-1} in 2001, and 128 kg fertilizer-N ha^{-1} in 2002. In 2000, the low rate of manure (average 85 kg total manure-N ha^{-1}) yielded approximately the same as the 90 kg N ha^{-1} from fertilizer, with no yield increase when fertilizer N was applied on top of the manure N. This indicates that equivalence of N supply from the manure was 100% in 2000. High equivalence would be expected due to the high fraction as NH_4-N in both manure sources, and conditions not conducive to N loss. In 2001, the plateau yield (Fig. 2) was reached at 65 kg fertilizer-N ha^{-1} with the regression fit-line of the low manure rate (average 80 kg total manure-N ha^{-1}) and at 105 kg fertilizer-N ha^{-1} with no manure. This suggests that the difference in rates between the maximum yields in terms of N is the quantity delivered by the manure (40 kg N ha^{-1}) which gives approximately 50% equivalence N supply from fall-applied manure compared to the spring-applied inorganic fertilizer for the 2001 year. In 2002, the plateau yield (Fig. 3) was reached at 72 kg fertilizer-N ha^{-1} with the regression fit-line of the low manure rate (average 94 kg total manure-N ha^{-1}) and at 128 kg fertilizer-N ha^{-1} with no manure. This suggests that the difference in rates between the maximum yields in terms of N is the quantity delivered by the manure (56 kg N ha^{-1}) which gives approximately 60% equivalence N supply from fall-applied manure compared to the spring-applied inorganic fertilizer for the 2002 year. The difference in equivalence of N supply could be attributed to varying growing seasons and loss potential from time of fall application. In none of the three years was there additional yield increase to fertilizer N when applied in conjunction with the high manure rate.

The impact of manure application on corn grain yield is reflected in the large yield increase each year with manure application when no fertilizer-N was applied (Figs. 1-3). The largest yield increase occurred with the low rate, with smaller increase from the low to high rate. Differences in yield increase from manure application were found each year, which reflects differences in background soil N supply, climate, and crop responsiveness to N.

Plant N

Leaf greenness (LG)

Leaf greenness, as determined by chlorophyll meter readings, is a useful measurement to monitor the in-season N status of corn because chlorophyll content is highly correlated with leaf N concentration (Schepers et al., 1992). As available soil N increases, more leaf chlorophyll is produced and the plant displays increasingly greener leaves. (Bullock and Anderson, 1998). However, a maximum greenness is reached, so excess N cannot be detected (Schepers et al., 1992). But LG can be used to detect N deficiency.

The time surrounding pollination is critical for high yield and stress can significantly influence pollination and seed set. The LG at the R1 stage was maximized at 90, 110, and 120 kg fertilizer-N ha^{-1} with no applied in manure in 2000, 2001, and 2002, respectively (Figs. 1-3). These N rates are close to the maximal rates measured in grain yield response. There was no increase in LG with fertilizer N application to either manure rate in 2000, but there was LG response with the half rate in 2001 and 2002, to approximately the same fertilizer N rate as with grain yield. Only in 2002 was there an increase in LG when fertilizer-N was applied with the high manure rate, but the increase was small and LG with no fertilizer N was high. In all three years, corn response to manure-N was indicated by the large increase in LG when no fertilizer N was applied; a response similar to that for yield increase. Manure-N supply, and associated magnitude of yield response, was not consistently predicted by the LSNT but was by LG (Table 5 and Figs. 1-3). With above maximal fertilizer-N application rates, LG tended to be higher with manure applications. This may indicate a plant greenness response to something besides N.

Peterson et al. (1993) and Blackmer and Schepers (1995) indicated N deficiencies detected late in the season by LG were highly correlated with yield, and it appears that LG at R1 was a good indicator of the rate of N to achieve plateau yield as found by Varvel et al. (1997).

End of Season Stalk Nitrate

Concentration of NO_3-N in the lower stalk at maturity has the potential for evaluating excess N status (Bindford et al., 1990). In 2000, stalk NO_3 was affected by manure rate and N rate while in 2001 and 2002 only by N rate (Figs. 1-3). More NO_3-N accumulation was found with N fertilizer application and with manure applications in 2000 than 2001 or 2002. Comparing years, at N applications above the rate when maximum grain yield was obtained, an indication of excess NO_3 occurred in 2000 and 2001 (concentration above approximately 2000 mg kg^{-1}) (Binford et al., 1992; Varvel et al., 1997; Brouder et al., 2000), but this occurred at a lower N rate in 2000 than 2001 (Figs. 1 and 2). In 2002 the stalk NO_3-N was increased at high N rates, but was well below 2000 mg kg^{-1} even with N application in excess of the maximal response rate. High concentration was measured for the high manure rate in 2000, but not in 2001 or 2002.

SUMMARY

Anaerobically digested swine manure is a valuable source of nutrients that can be used in crop production. Exposing the raw swine manure to anaerobic digestion had only a small impact on total nutrient content and no apparent impact on crop available N. Results from three growing seasons indicated no difference between raw and digested swine manure as a plant N source. Apparent N availability from both raw and digested swine manure to corn varied between years, with estimated availability from 50% in 2001 to100% in 2000. This difference was attributed to varying growing seasons and loss potential from time of fall application. Late fall and early spring sampling indicated rapid N conversion to NO_3-N.

From this work, digested swine manure can readily supply adequate N for corn production. Management of digested swine manure for crop production should be similar as with raw manure.

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Table 1. Soil chemical characteristics.

	Year		
	2000	2001	2002
Bray 1-P (mg P kg^{-1})	60	67	60
Exchangeable K (mg K kg^{-1})†	174	143	174
Organic matter (g kg^{-1})	50	40	50
pH	6.0	6.0	6.0

† Extracted by 1M NH_4OAc, pH 7.0

Table 2. Characteristics of the digested and raw swine manure.

Source	TKN	NH_4-N†	Total P	Total K	Solids	COD	V. Solids‡	pH
	-----------------	-----	------ $g\ L^{-1}$	-----	-----	-----	-----------------	
2000								
Digested	2.7	2.6	1.0	1.5	16.0	16	8.7	8.1
Raw	3.4	2.7	1.3	2.0	25.6	38	16.2	7.3
2001								
Digested	2.9	1.5	0.7	1.1	12.5	6	3.7	8.1
Raw	2.7	1.4	0.7	1.1	12.7	13	5.9	7.8
2002								
Digested	3.2	2.6	1.1	1.5	14.7	15	7.2	8.3
Raw	3.4	2.6	1.2	1.7	18.4	24	10.3	7.9

† Measured as NH_3-N.

‡ V. Solids = Volatile Solids.

Table 3. Digested and raw swine manure application volumes and total N rates.

Manure Source	2000	2001	2002
Rate applied		- - - - - - - - - - L ha^{-1} - - - - - - - - -	
Digested manure low	28,000	29,900	31,800
Raw manure low	28,000	28,900	31,800
Digested manure high	56,000	59,700	58,000
Raw manure high	56,000	57,900	58,000
Total N applied		- - - - - kg Total-N ha^{-1} - - - - - -	
Digested manure low	76	86	92
Raw manure low	94	76	95
Digested manure high	154	172	167
Raw manure high	188	152	174

Table 4. Effect of manure source and rate of application on the concentration of soil inorganic-N in the 0-15 cm depth of soil collected from the center of the application zone.

	Sampling date				
Source	Dec-99	May-00	Jun-00	May-01	Apr-02
	---------- mg NH_4-N kg^{-1} -------------				
Digested High	63	11	21	14	6
Digested Low	54	13	14	11	5
Raw High	57	17	14	13	6
Raw Low	39	11	13	17	6
Control†	12	11	13	8	4
FLSD‡	23	NS	NS	NS	NS
	---------- mg NO_3-N kg^{-1} ------------				
Digested High	50	52	22	33	22
Digested Low	42	54	30	29	11
Raw High	58	54	30	27	13
Raw Low	64	33	19	28	11
Control	35	31	31	20	4
FLSD	NS	10	NS	NS	5

† Samples collected 38 cm away from the band, 0-15 cm depth.

‡ Fisher protected LSD for significant differences between NH_4-N and NO_3-N concentration within a sampling date, $P \leq 0.10$.

Table 5. Effect of manure source, rate, and fertilizer N rate on late spring soil nitrate test concentrations.

Manure		Fertilizer	Year		
Source	Rate	N rate	2000	2001	2002
		kg N ha^{-1}	- - - mg NO_3-N kg^{-1} - - -		
Digested	Low	0	10	5	8
	High	0	16	5	10
Raw	Low	0	12	4	9
	High	0	16	9	11
None	None	0	7	4	7
	None	90	24	23	29
	None	180	38	35	45
FLSD†			3	4	6

† Fisher protected LSD for significant differences between soil NO_3-N concentration, $P \leq 0.10$.

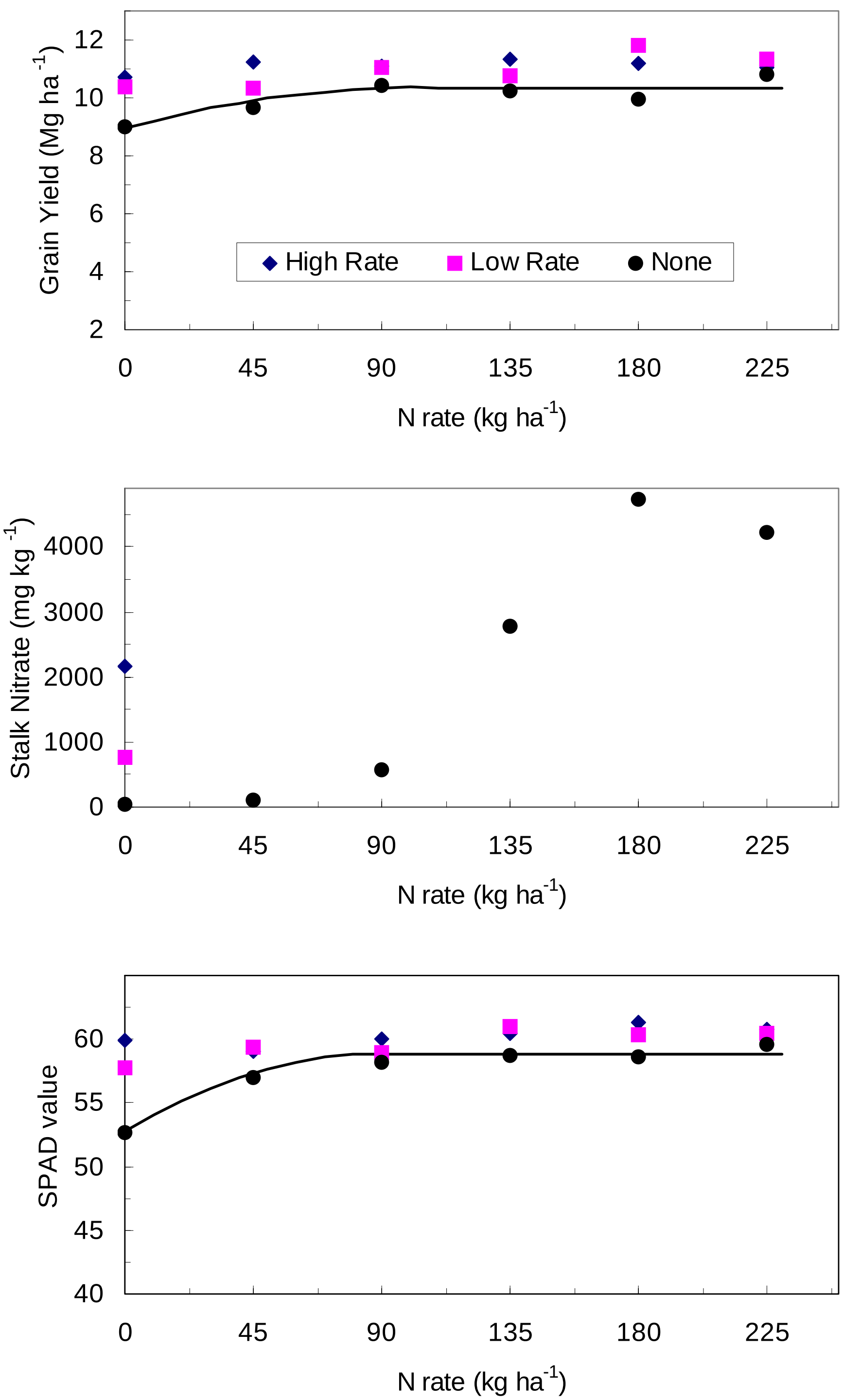

Fig. 1. Corn grain yield, cornstalk nitrate at maturity, and leaf greenness (R1 growth stage SPAD reading) as affected by fertilizer N rate and manure rate in 2000. Mean of both manure sources.

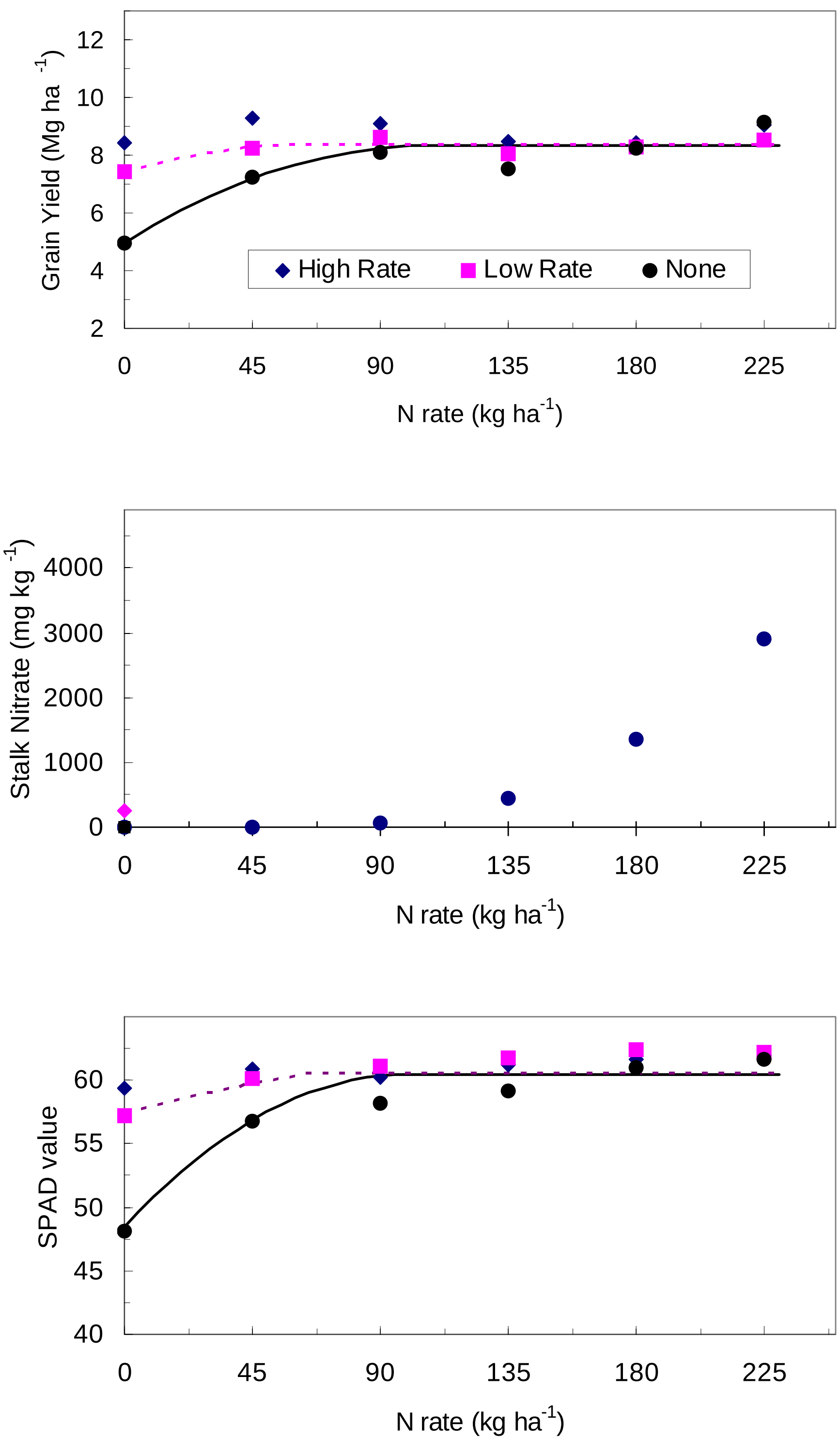

Fig. 2. Corn grain yield, cornstalk nitrate at maturity, and leaf greenness (R1 growth stage SPAD reading) as affected by fertilizer N rate and manure rate in 2001. Mean of both manure sources.

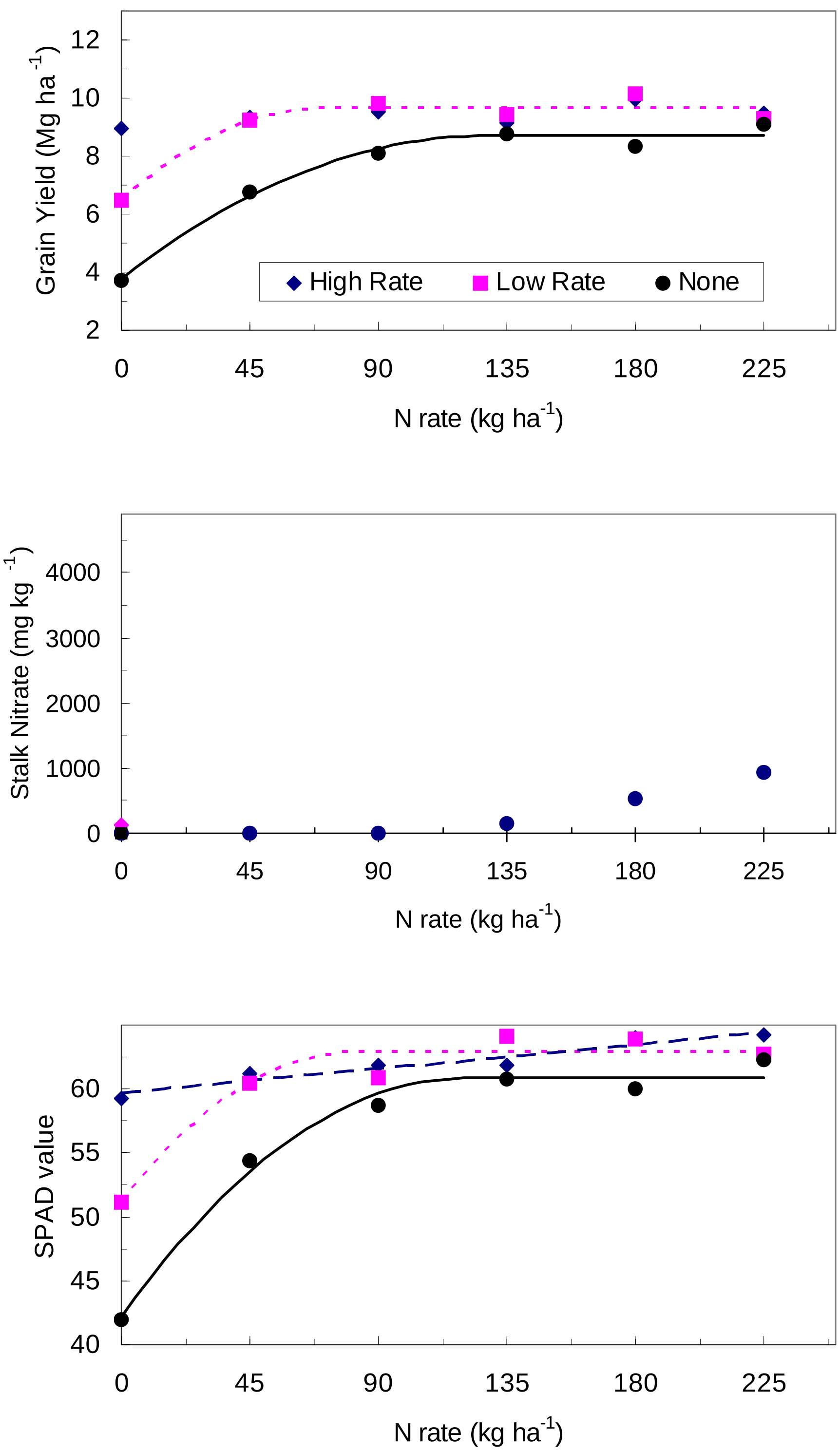

Fig. 3. Corn grain yield, cornstalk nitrate at maturity, and leaf greenness (R1 growth stage SPAD reading) as affected by fertilizer N rate and manure rate in 2002. Mean of both manure sources.

OVERALL CONCLUSION

The objectives of these studies were (1) to compare the effects of anaerobically digested liquid swine manure (15 d residence time in the digester) and raw swine manure on change in soil test P and soil inorganic-N and (2) to compare the N supply from raw and digested swine manure for corn production, determining soil N, plant-N, and grain yield responses.

From our incubation study, we observed no differences between raw and digested swine manure in regard to initial NH_4-N supply, disappearance of NH_4-N, NO_3-N formation, pH suppression, or change in soil test P. Some differences between inorganic fertilizer and the manure sources were found in regard to short term impact on soil test P, disappearance of NH_4-N, and formation of NO_3-N.

We conclude that digested swine manure is a valuable nutrient source that producers can use for crop production, and they should manage it as they would raw swine manure. One would expect similar crop P availability from both manure sources and fertilizer over time. On the short term, however (less than one month), P availability would be expected to be less from swine manure, either raw or digested. Both raw and digested swine manure provide large amounts of inorganic-N, but approximately 20% less than all inorganic fertilizer N (within 4 months of application). The initial nitrification of the manure NH_4-N parallels nitrification of fertilizer NH_4-N, and implies management should be similar to fertilizer based NH_4-N to best utilize this N component of swine manure.

Anaerobically digested swine manure is a valuable source of nutrients that can be use in crop production. Results indicated no difference between raw and digested swine manure as a plant N source. Apparent N availability from both raw and digested swine manure to corn varied between years, with estimated availability from 50% to 100%. This difference was attributed to varying growing seasons and loss potential from time of fall application, and not potential supply of inorganic N. From this work, digested swine manure can readily supply adequate N for corn production, and should be managed in a similar fashion as raw manure. Late fall and early spring sampling indicated rapid N conversion to NO_3-N form. Therefore application timing of digested swine manure should be similar as raw swine manure.