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Swine Manure Rate, Timing, and Application Method Effects on Post-Harvest Soil Nutrients, Crop Yield, and Potential Water Quality Implications in a Corn-Soybean Rotation

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Abstract

Management practices for applying liquid swine manure to minimize surface runoff water pollution and improve crop production can be evaluated by conducting long-term field studies. This article documents results from a six-year (1996-2001) central Iowa field study that evaluated the effects of swine manure application management practices on soil nutrients, organic matter, pH, crop yield, and discusses potential water quality implications. Swine manure management practices included single-rate (SR) and double-rate (DR) nitrogen (N) based application rates (168 and 336Â kg N ha^{-1}, respectively), three timings (fall injection [FI], winter broadcast [WB], and spring injection [SI]), and two methods (broadcast and injection) of liquid swine manure. Analysis of these practices involved comparing levels of residual soil total phosphorus (P) as Bray-1 available P (RSP), residual soil nitrate-nitrogen (RSN), percent organic matter (OM%), pH, carbon:nitrogen (C:N) ratio, and crop yields (kg ha^{-1}) in a corn-soybean rotation cropping practice. Manure application rates were based on standard crop-available N levels as applied to corn plots and were adjusted for environmental losses. Soil samples were collected immediately prior to commencing the study and after harvest each year and analyzed for RSP, RSN, OM%, pH, and C:N ratio at selected depths in the top 0.30 m of the soil profile. Deep soil core (0-1.22 m) samples also were collected after harvest in 1996 and 2000 and analyzed for RSN as a function of depth in the soil profile. When averaged over the six project years and manure application times for corn plots, these findings showed that DR application plots had significantly higher accumulation of RSP and RSN (32.6% and 36.5%, respectively) versus SR application plots in the top 0.30 m of the soil profile. The RSP for the SI (38.2%) and WB (32.8%) treatments was significantly higher than for the FI treatment on corn plots. The RSN accumulation also was found to be significantly higher for the SI (33.4%) and WB (17.4%) treatments than for the FI treatment on corn plots. The 0-1.22 m deep soil core analysis indicated a higher RSN accumulation in up to 88% of the 1.22 m soil profile depth range for the DR and SI treatments. When averaged across the six years and application rates, corn yield was significantly higher for SI plots (9,596 kg ha^{-1}) versus FI plots (9,236 kg ha^{-1}). The reduction in FI plot corn yield results may have been due largely to excessive leaching of nutrients through the soil profile from post-harvest rainfall during the fall-spring duration. Swine manure SI plots with the higher DR application rate produced the highest average corn yield (10,093 kg ha^{-1}). When averaged over project years and application times, the SI treatment showed an increase of 4.0% in corn yield over the FI treatment. While there were short-term significant increases in OM% for the SI1 treatment during 1996 and 1997, there were no significant cumulative differences in OM% as well as pH and C:N ratio in the soil profile after six years of N management practices at the study site. Although no manure was applied to soybean plots, residual effects of N management practices using the WB and SI application methods in the DR treatment plots during corn years significantly increased average values of RSP, RSN, and soybean yield. Results of this study indicate that long-term application of higher liquid swine manure rates during winter and spring application times resulted in significantly higher post-harvest accumulation of residual P and N in the soil profile. These results also show that incorporation of swine manure during the spring application time produced significantly higher corn yields compared with fall and winter application times. Overall results suggest that while residual soil P and N content may be significantly higher from spring versus fall manure application times, these nutrient runoff losses and the potential threat to surface water quality may be substantially lower during spring and summer compared with fall and winter due to effects from crop nutrient uptake, microbial activity, leaching, and evapotranspiration during the growing season.

Keywords
best management practices, corn-soybean rotation, cover crops, manure application, nitrogen and phosphorus, soil nutrient content, water quality implications

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SWINE MANURE RATE, TIMING, AND APPLICATION METHOD EFFECTS ON POST-HARVEST SOIL NUTRIENTS, CROP YIELD, AND POTENTIAL WATER QUALITY IMPLICATIONS IN A CORN-SOYBEAN ROTATION

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ABSTRACT. *Management practices for applying liquid swine manure to minimize surface runoff water pollution and improve crop production can be evaluated by conducting long-term field studies. This article documents results from a six-year (1996-2001) central Iowa field study that evaluated the effects of swine manure application management practices on soil nutrients, organic matter, pH, crop yield, and discusses potential water quality implications. Swine manure management practices included single-rate (SR) and double-rate (DR) nitrogen (N) based application rates (168 and 336 kg N ha^{-1}, respectively), three timings (fall injection [FI], winter broadcast [WB], and spring injection [SI]), and two methods (broadcast and injection) of liquid swine manure. Analysis of these practices involved comparing levels of residual soil total phosphorus (P) as Bray-1 available P (RSP), residual soil nitrate-nitrogen (RSN), percent organic matter (OM%), pH, carbon:nitrogen (C:N) ratio, and crop yields (kg ha^{-1}) in a corn-soybean rotation cropping practice. Manure application rates were based on standard crop-available N levels as applied to corn plots and were adjusted for environmental losses. Soil samples were collected immediately prior to commencing the study and after harvest each year and analyzed for RSP, RSN, OM%, pH, and C:N ratio at selected depths in the top 0.30 m of the soil profile. Deep soil core (0-1.22 m) samples also were collected after harvest in 1996 and 2000 and analyzed for RSN as a function of depth in the soil profile. When averaged over the six project years and manure application times for corn plots, these findings showed that DR application plots had significantly higher accumulation of RSP and RSN (32.6% and 36.5%, respectively) versus SR application plots in the top 0.30 m of the soil profile. The RSP for the SI (38.2%) and WB (32.8%) treatments was significantly higher than for the FI treatment on corn plots. The RSN accumulation also was found to be significantly higher for the SI (33.4%) and WB (17.4%) treatments than for the FI treatment on corn plots. The 0-1.22 m deep soil core analysis indicated a higher RSN accumulation in up to 88% of the 1.22 m soil profile depth range for the DR and SI treatments. When averaged across the six years and application rates, corn yield was significantly higher for SI plots (9,596 kg ha^{-1}) versus FI plots (9,236 kg ha^{-1}). The reduction in FI plot corn yield results may have been due largely to excessive leaching of nutrients through the soil profile from post-harvest rainfall during the fall-spring duration. Swine manure SI plots with the higher DR application rate produced the highest average corn yield (10,093 kg ha^{-1}). When averaged over project years and application times, the SI treatment showed an increase of 4.0% in corn yield over the FI treatment. While there were short-term significant increases in OM% for the SI1 treatment during 1996 and 1997, there were no significant cumulative differences in OM% as well as pH and C:N ratio in the soil profile after six years of N management practices at the study site. Although no manure was applied to soybean plots, residual effects of N management practices using the WB and SI application methods in the DR treatment plots during corn years significantly increased average values of RSP, RSN, and soybean yield. Results of this study indicate that long-term application of higher liquid swine manure rates during winter and spring application times resulted in significantly higher post-harvest accumulation of residual P and N in the soil profile. These results also show that incorporation of swine manure during the spring application time produced significantly higher corn yields compared with fall and winter application times. Overall results suggest that while residual soil P and N content may be significantly higher from spring versus fall manure application times, these nutrient runoff losses and the potential threat to surface water quality may be substantially lower during spring and summer compared with fall and winter due to effects from crop nutrient uptake, microbial activity, leaching, and evapotranspiration during the growing season.*

Keywords. *Best management practices, Corn-soybean rotation, Cover crops, Manure application, Nitrogen and phosphorus, Soil nutrient content, Water quality implications.*

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The animal production industry in Iowa has posed a serious threat to the state's surface and groundwater quality (USDA-IFB, 1998), and nonpoint-source (NPS) pollution from agricultural nutrients continues to be recognized as a significant contributor to poor water quality throughout much of the U.S. (USEPA, 2009; USGS, 2010). Iowa is the leading pork producer in the U.S. (USDA-NASS, 2011), generating a large volume of swine manure and prompting a need for new manure management strategies. These strategies include improved storage and handling of manure to minimize off-site impacts of manure management. One step toward a more sustainable approach to enhancing soil and water quality is through the efficient use of livestock manure on cropland and pasture areas.

Swine, cattle, and poultry manures are valuable resources as fertilizers and soil amendments. However, several studies have documented that manure and inorganic fertilizer applications are significant sources of excessive soil nitrogen (N) and phosphorus (P), resulting in increased leaching of nitrate-N (NO_3-N) and runoff losses of P if not properly managed (Sims, 1987; Roth and Fox, 1990; Gilley et al., 2002; Daverede et al., 2004; Gessel et al., 2004; Bakhsh et al., 2005; Ball Coelho et al., 2007; Allen and Mallarino, 2008; Wienhold and Gilley, 2010), and can lead to hypoxic conditions in the Gulf of Mexico (David et al., 2010; Jacobson et al., 2011). Khaleel et al. (1980) found that feedlot runoff data suggest that snowmelt runoff contains about two to three times more nutrient (N and P) concentrations compared to rainfall runoff, and feedlot pollutant concentrations were significantly greater than runoff from land application sites. A study by van Es et al. (2006) found that significant N leaching was preceded by dry growing seasons, where high residual N levels contributed to high leaching concentrations.

Kanwar et al. (1996) reported that swine manure and other N management systems can be successfully used to reduce leaching of NO_3-N to shallow groundwater without sacrificing crop yields, and Ferguson et al. (2005) found that repeated annual manure applications resulted in acceptable soil profile NO_3-N concentrations over the short term. Several studies have also shown that livestock manure management strategies and conditions may reduce water pollution, including the rate, method, and timing of manure application as well as the soil type, tillage practices, crop rotation, rainfall conditions, and livestock feeding rations (Boddy and Baker, 1990; Ahmed and Kanwar, 1997; Xue et al., 1999; Bakhsh et al., 2000; Pote et al., 2001; Kleinman and Sharpley, 2003; Zhu and Fox, 2003; Allen and Mallarino, 2006; van Es et al., 2006; Gilley et al., 2007; Shigaki et al., 2007; Wu and Powell, 2007; Pappas et al., 2008; Powell and Grabber, 2009).

The rate, method, and timing of application of organic and inorganic fertilizers also affect concentration of residual soil N (RSN) in the soil profile and movement to shallow groundwater (Gast et al., 1978; Kanwar et al., 1985; Jokela, 1992). Randall et al. (1997) reported that late-season N applications resulted in the highest RSN compared to spring application in the top 0-1.0 m of the soil profile. Gilley et al. (2007) found that tillage appeared to have less of an impact on runoff nutrient transport from cropland areas than length of time since manure application. Qian and Schoenau (2000) also found that manure applications significantly increased N and P supply rates in soil not otherwise fertilized. Some other studies in North America showed that soil nutrient accumulation in the soil profile was related to soil texture (Eghball et al., 1996) and high water tables (Simard et al., 1995). Mallarino and Wittry (2010) studied the effects of fixed and variable rates of liquid swine manure on crop yield and soil P within a corn (*Zea mays* L.) and soybean (*Glycine max* L.) cropping system. They reported that manure rates did not significantly affect crop yield; however, variable-rate manure application reduced P accumulation in the soil profile.

Schoenau et al. (1999) reported that manure application rates higher than the crop's nutrient demands resulted in post-harvest accumulation of nutrients in the soil profile and posed an environmental concern. Vadas et al. (2007) also determined that management practices for water quality must consider the potential for manure P transformations to contribute dissolved P to runoff long after manure is applied. A six-year swine manure application study by Novak et al. (2000) showed that accumulation and additional leaching of residual soil P (RSP) in plots where manure was applied were not significantly different from the control plots. Kleinman et al. (2002) determined that mixing mineral and manure P sources into the soil significantly decreased P losses relative to surface P application. Although Gangbazo et al. (1997) found that swine manure applications were no greater threat to the environment than mineral fertilizers, Barbazan et al. (2009) found no evidence supporting a reduction in crop P availability from liquid swine manure versus fertilizer P applications. However, other more recent studies tend to support the assertion that manures are more environmentally sustainable than inorganic fertilizers (Sharpley et al., 2001; Tabbara, 2003; Loecke et al., 2004; Smith et al., 2007). Nayak et al. (2009) conducted a six-year field study to investigate the effects of swine manure application on P accumulation in the soil profile and found that nutrients from inorganic fertilizer are more susceptible to leaching to tile drains than nutrients from manure; however, P from manure was determined to increase in the surface soil by two to six times higher than the agronomic optimum range.

Patni et al. (1999) found a low potential of NO_3-N leaching in manured plots, and Ball Coelho et al. (2007) reported that injected liquid swine manure supplied adequate crop nutrients without compromising drainage water quality. Jokela (1992) documented that there was very little difference in RSN between manure and fertilizer N applied plots, and Kwaw-Mensah and Al-Kaisi (2006) reported that liquid swine manure N source should be considered a strong alternative to commercial N fertilizer, depending on its availability and logistics of application. Meng et al. (2005) also determined that manure added to a soil did not result in greater N_2O emissions than a treatment with an N-containing fertilizer, but manure conferred greater benefits for soil fertility and the environment.

Following a comprehensive literature review of manure management technologies in no-till and forage systems, Maguire et al. (2011) reported that while improvements have been made to manure land application and farming system sustainability with alternatives to surface broadcasting, many questions remain concerning which technologies work best for particular soils, manure types, and farming and cropping systems.

Continuous application of manure to agricultural lands also can affect other soil characteristics. Soil organic matter (OM) has long been recognized as a key element in soil quality (Reeves, 1997); which helps maintain soil in an uncompacted condition with a lower bulk density, improving air and water movement and storage in soil. Haynes and Naidu (1998) reported that the addition of organic manures resulted in increased soil OM, porosity, water holding capacity, and hydraulic conductivity. Slevinsky and Small (1997) investigated physical and chemical changes in a clay soil after repeated applications of swine manure and reported higher electrical conductivity, higher OM, and lower pH in manured soils than in non-manured soils. Kingery et al. (1994) found that application of poultry manure increased organic carbon (C) and total N to depths of 0.15 and 0.30 m, respectively. However, Whalen and Chang (2002) determined that long-term manure applications reduced OM aggregate size and increased C, N, and P concentrations, possibly increasing the risk of soil and nutrient losses through wind erosion.

Many researchers have studied the effect of manure application on crop yield. Mathers and Stewart (1974) determined that sorghum (*Sorghum bicolor* L.) yield was reduced by high rates of manure applications. Another study found that corn yield was decreased when high rates of liquid and solid dairy manure were applied (Sutton et al., 1986). Daliparthy et al. (1995) evaluated the effect of dairy manure on alfalfa (*Medicago sativa* L.) yield and found no adverse effect or economic risk. Jokela (1992) reported that corn yield and N uptake were increased by both manure and fertilizer N applications. A study by Schmidt et al. (2001) reported an average soybean yield increase with an increase in manure application rate. Spring application of manure increased corn yield by 5% when compared with fall application yield results (Randall et al., 1999). However, Loecke et al. (2004) found that fall application of manure increased corn grain yield more than spring application, with spring application providing no yield response beyond the unamended control.

Some alternative N management practices include the use of a legume in a crop rotation and a grass species in a cover crop planting, and several studies have shown the economical and environmental benefits of a corn-soybean rotation when compared to continuous corn (Bundy et al., 1993; Karlen et al., 1994; Katupitiya et al., 1997). Corn after soybean or alfalfa typically requires less N fertilizer than continuous corn to attain optimum yields (Fox and Piekielek, 1988). Increased crop yields also resulted in increased removal of available N in the soil (Lory et al., 1995). Parkin et al. (2006) reported that the use of a rye (*Secale cereale* L.) cover crop reduced N load in drainage water when manure was applied to soils. Kovar et al. (2011) determined that liquid swine manure applied with a low-disturbance injection system (in a corn-soybean rotation with a winter wheat/oat cover crop) increased P uptake (due to reduced cover crop damage), increased crop P availability, and reduced P losses in surface runoff. Rotz et al. (2011) also determined that shallow disk injection of liquid dairy cow and swine manures into corn and grass/alfalfa crop systems provided the greatest environmental benefit at the least cost (and greatest profit) for the producer. Other studies showed the benefits of a corn-soybean rotation in reducing NO_3-N leaching and losses in surface and subsurface drainage (Randall et al., 2003; Zhu and Fox, 2003; Randall and Vetsch, 2005).

Knowing how long-term manure application affects crop production, soil, and water quality may increase our understanding and ability to make appropriate decisions concerning nutrient management. Improved manure management for maximizing crop production and minimizing environmental pollution may be achieved by conducting intensive long-term research. Efficient manure management depends on many environmental, biological, and storage handling conditions, and manure application should be evaluated within the limitations of the livestock industry and other local conditions. Consequently, the primary research objective of this central Iowa study was to evaluate the long-term effects of liquid swine manure application rate, timing, and method in a corn-soybean rotation. Specific objectives included determining these long-term manure management effects on levels of residual soil total P, nitrate-N, percent OM, pH, carbon:nitrogen ratio, crop yield, and discussing potential water quality implications.

Materials and Methods

This study was conducted at the Iowa State University Agronomy and Agricultural Engineering Research Center, 8 km (5 mi) west of Ames, Iowa (42.020° N, 93.780° W). Soils at the research site are predominantly Nicollet, a fine loamy, mixed, mesic Aquic Hapludolls in the Clarion-Nicollet-Webster Soil Association (Andrews and Dideriksen, 1981). The soils are classified as moderately permeable and somewhat poorly drained, with selected soil physical properties given in table 1. Table 2 shows experimental sources of variation that include N management treatments and application practices conducted at the research site. Rainfall data (table 5) were collected at an on-site National Oceanic and Atmospheric Administration (NOAA) certified weather station throughout the duration of the study period (1996-2001).

A randomized block design was used with three replications of seven treatments. Each plot was 7.6 m (25 ft) wide × 22.9 m (75 ft) long to accommodate an annual rotation of five 76 cm (30 in.) rows of corn in half of the plot and five rows of soybean in the other half. All field work was conducted over the length of the plot, up and down the slope. A 3.7 m (12 ft) wide field cultivator was used for spring preplant tillage. Crops were planted with a five-row modified John Deere 7000 planter.

Table 1. Selected soil physical properties at the Iowa State University Agronomy and Agricultural Engineering Research Center (Kanwar et al., 1988; Blanchet, 1996). Percent organic matter, bulk density, and hydraulic conductivity are denoted as OM, BD, and *k*, respectively.

Depth (m)	Clay (%)	Silt (%)	Sand (%)	OM (%)	BD (g cm^{-3})	Porosity (%)	*k* (cm d^{-1})
0-0.15	22.8	35.2	42.0	4.0	1.48	44	3.5
0.15-0.30	27.6	38.2	35.7	4.0	1.35	49	3.5
0.30-0.45	27.5	38.4	34.1	3.2	1.30	51	3.0
0.45-0.91	26.0	36.0	38.0	2.6	1.35	49	2.5
0.91-1.22	21.7	25.2	53.1	0.5	1.43	46	2.0

Table 3. Liquid swine manure slurry analysis (average yearly data, 1996-2001).

	Volume		Total N		P_2O_5		K_2O	
Year	m^3 plot^{-1}	m^3 ha^{-1}	kg plot^{-1}	kg ha^{-1}	kg plot^{-1}	kg ha^{-1}	kg plot^{-1}	kg ha^{-1}
1996	0.89	16.67	2.85	54	0.97	18	0.95	18
1997	0.77	15.22	3.11	58	0.50	9.0	2.42	45
1998	0.86	14.60	3.09	58	1.44	26	2.00	38
1999	0.60	12.91	2.69	51	1.61	29	1.39	26
2000	0.73	10.93	2.31	43	1.28	21	1.78	32
2001	0.45	11.01	2.65	50	1.71	31	1.33	25

Metalochlor herbicide was applied at the rate of 2.2 kg ha^{-1} (2.0 lb ac^{-1}), and row cultivation was used for additional weed control on all plots. All plots were outfitted with subsurface drainage and surface runoff collection systems and are described by Warnemuende et al. (2001). The subsurface drainage collection system included a 7.6 cm (3.0 in.) diameter tile drain placed 1.2 m (4.0 ft) deep through the center of each plot. The surface runoff collection system included earthen berms surrounding each plot to protect against cross-contamination due to surface runoff from adjacent plots.

Fall application of liquid swine manure was included as a treatment because it is a common practice in this area due in part to storage issues and ease of application after crop harvest. Table 2 shows the six experimental treatments used to evaluate effects of manure application timing (spring, late fall, and late winter), rate (168 and 336 kg N ha^{-1} [150 and 300 lb N ac^{-1}]), and method (broadcast and inject) on RSP, RSN, percent OM (OM%), and yields of the rotated corn and soybean crops. These crop-available N rates are standard levels applied to corn plots and were adjusted for environmental losses. An additional control treatment was included in the plots that received 168 kg N ha^{-1} as 28% urea ammonium nitrate (UAN) solution. Manure was injected in the fall using a four-row applicator with 46 cm (18 in.) wide sweeps at a depth of 15 to 20 cm (6 to 8 in.) and was surface broadcast onto frozen soil in late winter. Manure also was injected using the same application method in spring. The manure application rates were 168 kg N ha^{-1} as a single rate (SR) and 336 kg N ha^{-1} as a double rate (DR) for all six years of the study.

The manure in this study was obtained from the Iowa State University Swine Nutrition Farm, a finishing facility near Ames, Iowa, and the Iowa State University Swine Breeding Farm near Madrid, Iowa. Manure samples were analyzed for nutrient content by the Iowa Testing Laboratories, Eagle Grove, Iowa, to calculate manure application rates for the experimental treatments (table 3) and are averaged over the six-year study period (1996-2001).

Table 2. Nitrogen (N) management treatment and application practice sources of variation conducted at the study site.

Treatment	Application Rate (kg N ha^{-1})	Application Timing	Application Method
Spring UAN (UAN)[a]	168	Spring	Broadcast[b]
Fall 1× (FI1)	168	Fall	Inject
Fall 2× (FI2)	336	Fall	Inject
Winter 1× (WB1)	168	Late winter	Broadcast
Winter 2× (WB2)	336	Late winter	Broadcast
Spring 1× (SI1)	168	Spring	Inject
Spring 2× (SI2)	336	Spring	Inject

[a] Control.
[b] With field cultivator.

Soil Sampling

Soil samples were collected on 23 August 1996 (prior to all manure and UAN applications) to determine P, N, potassium (K), pH, and OM% in the soil profile (table 4). To determine the impact of liquid swine manure applications on soil nutrients, two different sets of soil cores (0-0.30 and 0-1.22 m [0-0.98 and 0-4.00 ft] deep) were collected after harvest for every year during the six-year study (1996-2001).

In the first set of soil cores, soil samples were collected annually in late fall (post-harvest). Subsamples for this first set of soil cores were collected from five different locations in each plot for all six years (1996-2001) of the study. The second set of soil cores was collected post-harvest from the top 0-1.22 m of the soil profile from the third (middle) row of both corn and soybean halves of the plots, and 7.6 m (25 ft) from the bottom edge, from 1996 to 2001. A hand sampler was used to collect the 0.30 m (12.0 in.) long × 22.2 mm (0.90 in.) diameter soil cores. A zero contamination power sampler was used to collect the 1.22 m (48 in.) long × 38.1 mm (1.50 in.) diameter soil cores. As the sampler was pushed into the soil, the soil core entered a liner made of polyethylene terephthalate glycol-modified (PETG) plastic. All soil samples were frozen immediately after collection.

The 0-0.30 m soil samples were cut in half for soil depths of 0-0.15 and 0.15-0.30 m. Five cores for each depth were combined into one composite soil sample for each plot. All 0-0.30 m-depth soil samples were analyzed for TP, NO_3-N, OM%, and pH in the soil profile. The 1.22 m soil cores were fractioned into five depth increments of 0-0.15, 0.15-0.30, 0.30-0.61, 0.61-0.91, and 0.91-1.22 m. All soil samples were wrapped in labeled plastic-lined bags and kept frozen until laboratory analysis. The soil cores (0-1.22 m) collected in 1996 and 2000 were analyzed for RSN in the soil profile. The soil cores (0-1.22 m) collected in 1997, 1998, and 1999 were analyzed for carbon:nitrogen

Table 4. Initial soil sampling average data (sampling date 23 August 1996, prior to all manure/UAN applications).

Crop	Core Depth (cm)	Total P (ppm)	Nitrate N (ppm)	K (ppm)	Soil (pH)	Buffer (pH)	OM (%)
Corn	0-15	21	5	115	6.64	6.84	3.0
	15-30	7	2	114	6.33	6.72	2.7
Soybean	0-15	15	4	113	6.72	6.90	2.9
	15-30	6	2	108	6.38	6.74	2.6

(C:N) ratio at selected depths for the corn plots. The soil samples were analyzed at Iowa State University's Soil Testing Laboratory and the USDA National Laboratory for Agriculture and the Environment, both in Ames, Iowa.

Chemical Analysis

The soil was analyzed for total P (TP) using the ascorbic acid method and the Bray-Kurtz P-1 procedure (Bray and Kurtz, 1945), and TP content was determined by mixing dilute ammonium fluoride with 250 mL of 1.0 M HCl. A 1:10 soil-to-solution ratio mixture was shaken at approximately 200 excursions per minute for 5 min at 24°C to 27°C. Extracts were filtered through Whatman No. 42 filter paper, and 2 mL of aliquot extract were added with 8 mL of working solution for mixing and color development. Measurements were made with a colorimeter at a wavelength of 882 nm. Concentrations of TP in samples were determined from intensity and standard curves by using the concentrations in soil extracts (Black, 1965).

The compounds nitrate-N (NO_3-N) + nitrite-N (NO_2-N) were analyzed by the automated flow injection cadmium reduction method using a Lachat Quickchem 2000 Automated Ion Analyzer system according to Standard Methods (APHA, 1998). Nitrate-N was reduced to NO_2-N by a cadmium/copper column. Nitrite-N was diazotized with sulfanilamide and then reacted with N-(1-naphthyl-)-ethylenediamine dihydrochloride at a pH of 8.5 to form a colored (pink to red) azo compound in an intensity proportional to the amount of NO_3-N + NO_2-N in the sample. Measurements were made with a colorimeter at a wavelength of 520 nm. Concentrations of NO_3-N and NO_2-N in the samples were determined by comparing sample absorbance with absorbance values obtained from a calibration curve comprised of standards containing NO_3-N concentrations of 0.25 to 20.0 mg N L^{-1}.

Organic matter (OM) was analyzed as percent OM (OM%) using the Walkley-Black method (Walkley and Black, 1934). Soil sample OM% was calculated by assuming 77% oxidation of organic C and that OM% was 58% C (OM% = %C × 1.72). Soil pH was determined using the modified Dumas method (Thomas, 1996). Nitrate-N and TP concentrations were reported in ppm. The concentrations of nutrients were changed to kg ha^{-1} for that soil horizon by multiplying bulk density of soil (g cm^{-3}) by soil depth increment (m) and correcting for appropriate unit conversions. Corn and soybean yield data (kg ha^{-1}) collected from each plot were tested for moisture content and adjusted to a constant water content of 150 g kg^{-1} (15%) for corn and 130 g kg^{-1} (13.0%) for soybean.

The significance among treatments was determined using the general linear model (GLM) procedure at the 5% probability level ($p \leq 0.05$) with SAS version 8.2 (SAS, 1985). Fisher's least significant difference (LSD) test, standard error of the mean (SE), and contrast method also were used to statistically analyze differences among the N management treatments.

Table 5. Seasonal rainfall monthly and annual total and average values (mm) for the six-year study period (1996-2001).

Month	1996	1997	1998	1999	2000	2001	Avg.[a]
Jan.	30.0	14.0	21.1	21.6	9.40	28.2	20.7
Feb.	4.30	28.2	36.3	13.7	41.4	32.5	26.1
Mar.	36.3	48.8	70.4	20.8	11.2	27.9	35.9
Apr.	32.8	85.6	80.8	207	20.8	96.0	87.2
May	194	61.2	92.2	150	120	190	135
June	132	92.7	274	185	104	49.8	140
July	104	100	68.1	162	72.1	48.3	92.4
Aug.	125	39.1	0.00	151	33.8	73.9	70.5
Sept.	81.0	56.1	23.6	61.0	25.7	149	66.1
Oct.	71.0	91.2	102	8.60	50.0	65.0	64.6
Nov.	103	38.1	22.9	23.6	60.5	36.3	47.4
Dec.	22.0	12.4	4.10	13.2	38.1	9.70	16.6
Total[b]	935	668	796	1018	587	807	802[c]
Avg.[d]	77.9	55.7	66.3	84.8	48.9	67.3	

[a] Six-year monthly average rainfall (1996-2001).
[b] Annual total rainfall.
[c] Six-year annual average rainfall (1996-2001).
[d] Monthly average rainfall.

Results and Discussion

Rainfall Amounts

The total monthly and annual average rainfall amounts for the six-year study period (1996-2001) are given in table 5 (NOAA, 1996-2001). The long-term annual average rainfall for the study site is approximately 824 mm (32.4 in.), with 561 mm (22.1 in.) occurring during the spring and summer months. The amount of annual total rainfall varied during the study period from 587 (2000) to 1018 mm (1999) (23.1 to 40.1 in.), with a six-year annual average of 802 mm (31.1 in.). These data indicate that observed variations in rainfall amounts may have been a factor affecting crop yields and nutrient accumulations in the soil profile.

Residual Soil P (RSP)

Figure 1 shows the effect of N management practices on RSP for corn plots averaged over the six-year project period for two soil profile depth increments (0-0.15 and 0.15-0.30 m). The amounts of accumulated RSP ranged from 32.6 kg ha^{-1} (FI1) to 104.1 kg ha^{-1} (WB2) among treatments for the 0-0.15 m depth (fig. 1). The amounts of RSP in WB2 and SI2 plots were also significantly higher ($p \leq 0.05$) than in UAN and other manure-treated plots, indicating the effects of application timing and higher manure rate on the amount of RSP. The higher RSP accumulations in manure plots

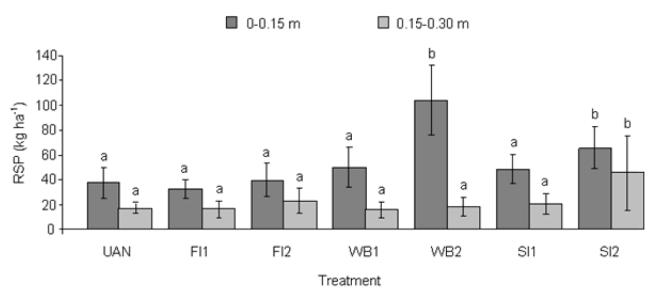

Figure 1. Effect of N management practices on residual soil phosphorus (RSP, kg ha^{-1}) at 0-0.15 m and 0.15-0.30 m soil profile depths for corn plots averaged for six years (1996-2001). Different letters indicate significant differences ($p \leq 0.05$) among treatments within selected soil depths, and error bars represent ±1 standard deviation of the mean.

versus UAN plots were attributed to the contribution of manure to available P. Lindo et al. (1993) found that large applications of P to soil are generally subjected to rapid fixation. The effect of mineralization of organic P also contributed to greater accumulation in the double-rate (FI2, WB2, and SI2) plots. However, the 0.15-0.30 m depth plots (fig. 1) show that only SI2 plots (44.2 kg ha^{-1}) had significantly higher ($p \leq 0.05$) P accumulation.

It is well known that surface and near-surface applied P generally adsorbs to soil particles and accumulates in the top layer (0-0.30 m) of the soil profile (Chang et al., 1991; Gangbazo et al., 1999). A similar trend of P accumulation was observed during this study, indicating that the 0-0.15 m depth increment had significantly higher ($p \leq 0.05$) RSP than the 0.15-0.30 m depth increment of the soil profile. Eghball et al. (1996) and Graetz et al. (1999) also reported significantly higher accumulation and movement of P from 0-0.15 m depth to deeper depths in highly manured plots. However, Tabbara (2003), Gessel et al. (2004), Allen and Mallarino (2008), and Ball Coelho (2007) found that incorporated manure significantly reduced runoff P losses.

The cumulative effect of rate, timing, and method of manure application on RSP was compared for all six years in the 0-0.30 m soil profile for corn plots (tables 6 and 7). Table 6 indicates no significant difference ($p \leq 0.05$) in a comparison of single-rate (SR) plots (six-year average of SR plots FI1, WB1, and SI1) and the UAN treatment. For double-rate (DR) plots (six-year average of DR plots FI2, WB2, and SI2) versus UAN, RSP was significantly higher ($p \leq 0.05$) at 44.8% for DR plots. Sallade and Sims (1997), Novak et al. (2000), and Gessel et al. (2004) reported similar results for significant RSP accumulation in the soil profile. The amount of RSP also was significantly higher ($p \leq 0.05$) by 38% for DR versus SR manure rates (97.9 vs. 60.7 kg ha^{-1}, respectively) for corn plots (table 6). Similarly, Qian and Schoenau (2000) found less accumulation of P in soil from SR versus DR manure applications.

Comparison of SI versus FI and WB versus FI treatments for corn plots averaged over six years and manure application rates showed significantly higher ($p \leq 0.05$) accumulations for RSP in SI and WB treatments, 30.6% and 33.8% respectively, compared to the FI treatment (table 6). However, comparison of SI versus WB showed no significant differences ($p \leq 0.05$) in manure application method and/or timing for corn plots. Daverede et al. (2004) determined that injected manure reduced runoff P losses, decreased runoff volumes, and increased time to runoff, minimizing potential risk of surface water contamination. Tables 6 and 8 show that RSP was significantly higher ($p \leq 0.05$) by 23.1% for DR versus SR (73.8 vs. 56.7 kg ha^{-1}, respectively) for soybean plots. The RSP for soybean plots also was significantly higher ($p \leq 0.05$) by 29.6% for SI versus FI (74.3 vs. 52.3 kg ha^{-1}, respectively), and RSP was significantly higher ($p \leq 0.05$) by 28.8% for WB versus FI (73.5 vs. 52.3 kg ha^{-1}, respectively).

Tables 7 and 8 show the cumulative effect of manure applications on RSP in corn and soybean plots, respectively, for the 0-0.30 m soil profile. There was a general trend of accumulation for RSP with time (1996 to 2001) in the soil profile for the plots that received DR versus SR. The RSP in 2001 was found to be the highest (207.6 kg ha^{-1}) in the WB2 plot (table 7) when compared

Table 6. Comparison of percent differences (% diff) and p-values of N management practices on residual soil phosphorus (RSP) and residual soil nitrogen (RSN) at 0-0.30 m depth in the soil profile for corn and soybean plots averaged over six years (1996-2001).[a]

	Corn				Soybean			
	RSP		RSN		RSP		RSN	
Treatment[b]	% Diff	p-Value	% Diff.	p-Value	% Diff.	p-Value	% Diff.	p-Value
SR vs. UAN	10.9	NS	-8.40	NS	-1.20	NS	-0.60	NS
DR vs. UAN	44.8	0.00	31.0	0.00	22.2	0.00	3.80	NS
DR vs. SR	38.0	0.00	36.3	0.00	23.1	0.00	4.40	NS
SI vs. FI	30.6	0.00	26.5	0.00	29.6	0.00	14.3	0.01
WB vs. FI	33.8	0.00	8.00	NS	28.8	0.00	16.2	0.00
SI vs. WB	-4.90	NS	20.0	NS	1.10	NS	-2.20	NS

[a] % Diff = percent difference between treatments, e.g., SR vs. UAN = (1 - UAN/SR) × 100. NS = not significant ($p > 0.05$).

[b] UAN = UAN application single rate (168 kg N ha^{-1}); SR and DR = average across time and method of all manure applied plots with single (168 kg N ha^{-1}) and double rate (336 kg N ha^{-1}), respectively; FI = average across rates of all manure injected plots in fall; WB = average across rates of all manure broadcast plots in winter; and SI = average across rates of all manure injected plots in spring. Contrast analysis using SAS software.

Table 7. Effect of N application management practices by year on residual soil phosphorus (RSP, kg ha^{-1}) at 0-0.30 m depth for corn plots.[a]

Treatment	1996	1997	1998	1999	2000	2001	Average
UAN	54.4 bc	33.0 c	58.6 bc	67.2 bc	53.8 c	56.9 c	53.9 c
FI1	38.7 c	54.2 bc	38.4 c	56.6 c	44.4 c	58.9 c	48.5 c
FI2	53.1 b	60.5 bc	52.1 c	74.1 bc	54.7 c	76.6 c	61.8 bc
WB1	68.3 ab	66.5 ab	55.5 bc	83.6 bc	58.6 bc	58.2 c	65.1 bc
WB2	82.7 a	89.1 ab	84.7 bc	152.2 a	115.2 ab	207.6 a	121.9 a
SI1	67.1 ab	55.3 bc	66.8 bc	63.1 bc	68.9 abc	88.8 bc	68.3 b
SI2	57.9 c	107.2 a	106.6 a	104.2 b	120.0 a	163.4 ab	109.9 a
Average	60.3	66.5	66.1	85.8	73.6	101.5	75.7
CV[b]	18.4	43.3	25.4	30.4	43.6	44.5	33.0
SE	19.1	25.7	14.9	16.9	9.5	21.3	14.2
$LSD_{0.05}$	19.8	51.3	29.9	46.5	57.2	80.4	16.6

[a] Means in the same column followed by the same letter are not significantly different ($p \leq 0.05$).

[b] CV = coefficient of variance, SE = standard error, and LSD = least significant difference.

Table 8. Effect of N application management practices by year on residual soil phosphorus (RSP, kg ha^{-1}) at 0-0.30 m soil for soybean plots.[a]

Treatment	1996	1997	1998	1999	2000	2001	Average
UAN	41.9 a	37.2 b	63.1 ab	89.1 a	60.3 c	52.8 c	57.4 bc
FI1	37.7 a	39.6 b	42.5 b	40.8 c	55.1 c	46.2 c	43.6 d
FI2	41.8 a	41.7 b	61.1 ab	52.5 bc	57.3 c	59.7 c	52.3 cd
WB1	52.1 a	68.5 a	42.5 b	66.8 abc	73.5 bc	56.4 c	60.2 cb
WB2	50.9 a	78.0 a	62.7 ab	87.8 a	102.2 ab	139.5 a	86.8 a
SI1	47.1 a	71.6 a	79.8 a	72.0 ab	69.1 bc	58.5 c	66.3 b
SI2	33.9 a	60.2 ab	80.2 a	85.7 a	136.8 a	96.7 b	82.2 a
Average	43.6	56.7	61.8	70.6	79.2	72.8	64.1
CV[b]	32.4	24.8	26.9	24.5	27.9	27.7	24.3
SE	15.0	26.7	16.3	10.9	21.8	15.7	15.9
$LSD_{0.05}$	25.2	25.0	29.7	30.8	39.3	35.9	10.4

[a] Means in the same column followed by the same letter are not significantly different ($p \leq 0.05$).
[b] CV = coefficient of variance, SE = standard error, and LSD = least significant difference.

Table 9. Effect of N application management practices by year on residual soil nitrogen (RSN, kg ha^{-1}) at 0-0.30 m depth for corn plots.[a]

Treatment	1996	1997	1998	1999	2000	2001	Average
UAN	13.7 b	3.3 a	7.8 b	14.0 ab	27.8 a	17.8 bc	14.1 bc
FI1	11.1 b	2.8 a	8.1 b	15.9 ab	22.5 a	12.8 c	12.2 c
FI2	8.6 b	15.1 a	12.4 ab	15.1 ab	24.5 a	13.8 c	14.9 bc
WB1	12.4 b	2.7 a	7.7 b	19.2 ab	20.1 a	16.2 c	13.1 bc
WB2	16.6 b	4.2 a	14.1 ab	22.9 a	32.8 a	26.0 ab	19.4 b
SI1	16.6 b	17.4 a	10.6 ab	10.4 b	14.2 a	13.2 c	13.7 bc
SI2	31.2 a	28.9 a	16.2 a	18.1 ab	36.1 a	30.8 a	26.9 a
Average	15.7	10.6	11.0	16.5	25.4	18.6	16.3
CV[b]	29.4	152.6	40.7	32.2	53.0	28.8	59.3
SE	7.1	5.6	5.9	1.3	3.6	3.8	1.3
$LSD_{0.05}$	8.2	28.9	7.9	9.4	24.0	9.6	6.4

[a] Means in the same column followed by the same letter are not significantly different ($p \leq 0.05$).
[b] CV = coefficient of variance, SE = standard error, and LSD = least significant difference.

with the other treatment plots. Qian and Schoenan (2000) also found less accumulation of P in the soil with a single application of manure. Manure application in the fall consistently resulted in less accumulation of RSP in the soil profile than winter and spring applications (table 7). One factor that significantly affected the residual amount of nutrients is the movement of nutrients to deeper depths from November to April, which was most likely due to post-harvest rainfall and snowmelt infiltration.

Residual Soil N (RSN)

When averaged over six years for corn plots, the amount of RSN for the 0-0.15 m depth ranged from 7.5 to 14.5 kg ha^{-1} among the treatments (fig. 2). The RSN values for the SI2 (14.5 kg ha^{-1}) and WB2 (13.4 kg ha^{-1}) treatments were significantly higher ($p \leq 0.05$) than for all other treatments. However, timing of application did not affect RSN for the single-rate (FI1, WB1, and SI1) plots. For the 0.15-0.30 m depth, only the SI2 (12.4 kg ha^{-1}) treatment was found to be significantly higher ($p \leq 0.05$) than the other treatments (fig. 2). Zhu and Fox (2003) determined that RSN in the top 0.25 m soil layer after harvest was not significant at 0 to 100 kg N ha^{-1}, but was significant at the higher 100 to 200 kg N ha^{-1} rate. As shown in table 6, significantly higher ($p \leq 0.05$) accumulation (26.5%) was observed for RSN in the SI versus FI treatments in corn plots. However, Loecke et al. (2004) found that the mean N supply efficiency (defined as N fertilizer equivalency value as a percentage of total N applied) was 24.3% and 10.9% for fall- and spring-applied swine manure, respectively. The reason for this trend may be that manure applications in fall allow more time (approx. one year) for manure decomposition, leaching, denitrification, and other physical and chemical activities than spring or winter applications (six to eight months). Fall manure applications also include additional time for crop uptake of nutrients that occurs before annual soil sampling.

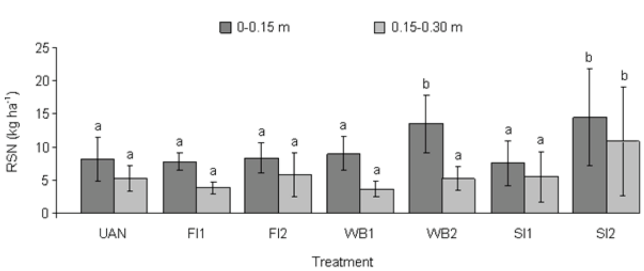

Figure 2. Effect of N management practices on residual soil nitrogen (RSN, kg ha^{-1}) at 0-0.15 m and 0.15-0.30 m soil profile depths for corn plots averaged for six years (1996-2001). Different letters indicate significant differences ($p \leq 0.05$) among treatments within selected soil depths, and error bars represent ±1 standard deviation of the mean.

Significantly higher ($p \leq 0.05$) RSN at 26.5% was determined for SI versus FI treatments in corn plots (table 6). Nevertheless, the comparison of WB versus FI and SI versus WB treatments for RSN showed no significant differences ($p \leq 0.05$) for manure application method and/or timing for corn plots (tables 6 and 9). The primary reason could be that winter and spring application timings were approximately one month apart for most of the study years. Relatively colder weather conditions during winter and spring months (November to April) also limited soil-water functions such as manure decomposition, leaching, surface water runoff, subsurface drainage flow, and reduction in microbial activity. Khaleel et al. (1980) determined that snowmelt-runoff from field plots receiving manure during winter and spring consisted of high concentrations of organic-bound N and P. These data are in contrast to results from manure applications conducted in summer and fall (subject to rainfall-runoff) that readily undergo decomposition, significantly reducing concentrations of organic components in runoff water.

Similarly, Gilley et al. (2007) found that significant N leaching occurred after harvest (30 September) from corn residue and resulted in increased NO_3-N in runoff. Other studies also determined that NO_3-N concentrations and losses in drainage from corn were greatest for fall-applied N (Randall et al., 2003; Randall and Vetsch, 2005). Zhu and Fox (2003) reported that while RSN leaching potential was similar for corn and soybean at recommended N rates, it was greater under soybean than corn at less than 100 kg N ha^{-1}. Soil data from soybean plots (table 4) also reflected effects of the previous year's manure/UAN applications on RSN in the 0-0.30 m soil profile (table 10). Randall et al. (2003) found that NO_3-N losses from soybean were affected more by residual soil NO_3-N following corn than by N treatments alone.

The deep soil core (0-1.22 m) RSN analysis in 1996 and 2000 (during corn years) showed that effects of rate and timing were significant ($p \leq 0.05$) on RSN at the 0-0.15 and 0.91-1.22 m depths in the soil profile (table 11). These data also show that five years (1996-2000) of manure application significantly increased ($p \leq 0.05$) the amount of RSN for the 0-0.15 m depth of the soil profile (fig. 2; tables 9 and 11). The amount of RSN also significantly increased ($p \leq 0.05$) with increasing depth, indicating UAN- and manure-derived NO_3-N movement through the soil profile. The differences in RSN between DR versus SR were found to be significant ($p \leq 0.05$) for soil depth increments 0-0.5, 0.30-0.61, 0.61-0.91, and 0.91-1.22 m (table 11). The SI versus FI treatment differences also were significant ($p \leq 0.05$) at the 0-0.15 and 0.91-1.22 m soil depth increments (table 11).

The two-year (1996 and 2000) RSN average manure application rate for corn plots was used to evaluate the effect of application timing. The resulting RSN average values indicate significantly higher ($p \leq 0.05$) SI (73.4 kg ha^{-1}) and WB (67.1 kg ha^{-1}) treatments (34.2% and 27.9%, respectively) (table 11). The SI and WB treatments also were significantly higher ($p \leq 0.05$) than FI (48.3 kg ha^{-1}) at the 1.22 m soil profile depth. The comparison of RSN for application rates DR versus SR (82.7 vs. 43.1 kg ha^{-1}, respectively) also showed a significant difference ($p \leq$ 0.05) between the treatments (table 11). Overall, these results indicate that RSN was found in both UAN- and manure-applied plots.

Table 11. Comparison of p-values for N management practices on residual soil nitrogen (RSN) at selected depths in the soil profile for corn plots averaged over two years (1996 and 2000). NS = not significant (p > 0.05).

	Soil Profile Depth (m)				
Treatment	0-0.15	0.15-0.30	0.30-0.61	0.61-0.91	0.91-1.22
SR vs. UAN	NS	NS	NS	NS	NS
DR vs. UAN	NS	NS	NS	0.03	NS
DR vs. SR	0.03	NS	0.05	0.03	0.03
SI vs. FI	0.00	NS	NS	NS	0.03
WB vs. FI	NS	NS	NS	NS	0.04
SI vs. WB	NS	NS	NS	NS	0.01

The accumulation of RSN at selected depths over time may be attributed to N applications as UAN or swine manure and rainfall conditions. The reduced NO_3-N transport to deeper depths (0.61-0.91 and 0.91-1.22 m depth increments) for 2000 may have been a function of less than average rainfall (587 mm [23.1 in.]; table 5) during the growing season. These drier conditions could have limited N transport, since NO_3-N accumulation in the soil profile and its leaching to deeper depths has been cited in many studies (Jokela, 1992; Weed, 1996; Mehdi and Madramooto, 1999; Randall et al., 1999; Bakhsh et al., 2000). Randall et al. (2003) also found that NO_3-N concentrations in drainage water were two to three times greater in the two years following a three-year dry period compared with preceding and succeeding years; and van Es et al. (2006) reported that high levels of concern are associated with periods following dry growing seasons, since high residual N levels contribute greatly to high leaching concentrations. Bakhsh et al. (2005) also suggested the need for better management of swine manure application during wet and dry growing seasons to reduce NO_3-N leaching into shallow groundwater systems to avoid contamination of drinking water supplies.

Averaged values from figure 3 show significant reductions ($p \leq 0.05$) in RSN at the 0-1.22 m soil depth from spring double-rate (SI2) application times between two years (1996 and 2000) for corn plots, and table 11 indicates significant differences ($p \leq 0.05$) in RSN in the 0.91-1.22 m soil depth increment. Chang et al. (1991) reported significant N accumulation to a depth of 0.50 m after 11 years of manure applications. Figure 3 shows the cumulative effect of N management on average RSN in the 0-1.22 m soil profile

Table 10. Effect of N application management practices by year on residual soil nitrogen (RSN, kg ha^{-1}) at 0-0.30 m depth for soybean plots.[a]

Treatment	1996	1997	1998	1999	2000	2001	Average
UAN	11.7 b	5.6 a	11.7 a	23.2 a	18.0 a	21.3 bc	15.2 bc
FI1	10.3 b	3.5 a	10.0 a	21.3 ab	22.2 a	19.5 bc	14.4 bc
FI2	9.6 b	3.1 a	10.6 a	19.3 ab	21.0 a	19.0 bc	13.8 c
WB1	11.1 b	3.7 a	12.2 a	22.9 a	24.2 a	17.5 c	15.2 abc
WB2	17.4 a	4.1 a	13.2 a	18.4 b	26.4 a	25.8 b	17.6 a
SI1	11.1 b	4.7 a	10.5 a	22.1 ab	25.5 a	20.6 bc	15.8 abc
SI2	11.7 b	2.7 a	14.6 a	20.1 ab	26.8 a	22.0 ab	16.3 ab
Average	11.8	3.9	11.8	21.0	23.4	20.8	15.5
CV[b]	20.6	42.8	27.9	11.5	22.2	11.2	22.2
SE	3.5	0.2	3.2	1.4	3.4	1.6	0.3
$LSD_{0.05}$	4.3	2.9	5.8	4.3	9.2	4.1	2.2

[a] Means in the same column followed by the same letter are not significantly different ($p \leq 0.05$).
[b] CV = coefficient of variance, SE = standard error, and LSD = least significant difference.

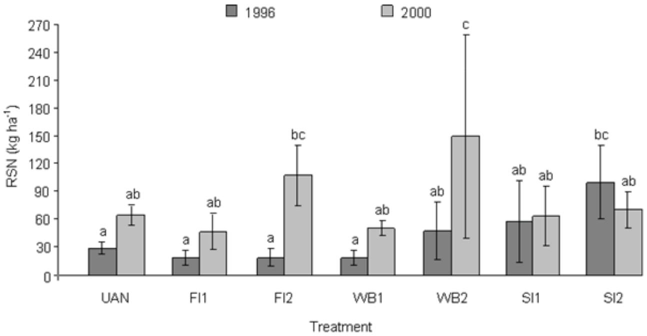

Figure 3. Effect of N management practices on residual soil nitrogen (RSN, kg ha^{-1}) between two years (1996 and 2000) for corn plots. Different letters indicate significant differences ($p \leq 0.05$) among treatments within years, and error bars represent ±1 standard deviation of the mean.

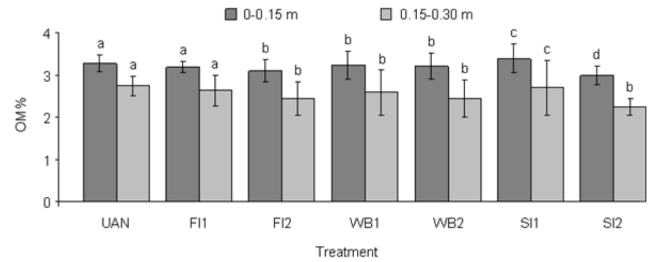

Figure 4. Effect of N management practices on percent organic matter (OM%) at 0-0.15 m and 0.15-0.30 m soil profile depths for corn plots averaged for six years (1996-2001). Different letters indicate significant differences ($p \leq 0.05$) among treatments within selected soil depths, and error bars represent ±1 standard deviation of the mean.

with time (1996 vs. 2000). Increases in accumulation of RSN from 1996 to 2000 ranged from 47.6 to 150.4 kg ha^{-1} for the manure treatments, with a significant increase ($p \leq 0.05$) in the WB2 treatment in the 0-1.22 m soil profile. There also was a significant increase ($p \leq 0.05$) in RSN (29.6 to 65.1 kg ha^{-1}) from 1996 to 2000 for the UAN treatment (fig. 3), and the highest RSN accumulation with time (47.9 to 150.0 kg ha^{-1}) was found in the WB2 treatment (fig. 3).

The accumulation of RSN in the relatively drier year of 2000 could be attributed to low crop N uptake, N mineralization, and below-average rainfall. When these data from figure 3 were averaged over the two years of sampling (1996 and 2000), WB2 and SI2 treatments had the highest RSN (99.1 and 85.8 kg ha^{-1}, respectively) and were found to be significantly higher ($p \leq 0.05$) than the other treatments. The FI1 treatment had the lowest RSN (33.3 kg ha^{-1}) in the soil profile. Although the FI2 treatment had a lower RSN level (63.4 kg ha^{-1}) than the WB2 and SI2 treatments, the differences were not significantly different ($p \leq 0.05$). These data from 2000 suggest that the amount of NO_3-N available for leaching in the fall can be significant due to the lack of crop N uptake, low evapotranspiration, below-average rainfall, and limited microbial activity. In addition, when averaged over the treatments, an increase in RSN accumulation was observed in the 0-0.30 m profile with time (table 9). RSN was found to be the highest in 2000 (25.4 kg ha^{-1}) for corn plots. This is verification of the effect of rainfall on the leaching of RSN through the soil profile during a dry year (the annual rainfall for 2000, 587 mm [23.1 in.], was the lowest during the six-year study). Randall et al. (2003) and Randall and Vetsch (2005) suggested that NO_3-N losses from a corn-soybean rotation into subsurface drainage can be reduced by approximately 14% using spring manure application timing. Another approach for reducing higher N levels in runoff uses a rye (*Secale cereale* L.) cover crop. Parkin et al. (2006) determined that this strategy increased N retention and reduced cumulative N_2O emissions and N load in drainage water when manure was applied to soils.

Percent Organic Matter (OM%), pH, and Carbon:Nitrogen (C:N) Ratio

The six-year average of soil OM% for the 0-0.15 and 0.15-0.30 m soil depths for corn plots ranged from 2.5% (SI2; 0.15-0.30 m depth) to 3.4% (SI1; 0-0.15 m depth) (fig. 4). Average OM% in the SI1 treatment was significantly higher ($p \leq 0.05$) than in other treatments (fig. 4), and the effects of N management on OM% in the 0-0.30 m depth soil profile for corn plots were significantly different ($p \leq 0.05$) among treatments only in 1996 and 1997. However, cumulative OM% did not significantly increase ($p \leq 0.05$) for both corn and soybean plots during the six-year study (1996-2001). Several studies have shown that increases in soil OM% can be achieved by long-term applications of UAN or organic manures (Lal and Kang, 1982; Sanchez et al., 1989; Haynes and Williams, 1992). Haynes and Naidu (1998) also reported that manure application increased OM content in the soil profile. However, Whalen and Chang (2002) found that long-term manure application in southern Alberta, Canada, increased soil C, N, and P concentrations and reduced OM aggregate size due to manure dispersive agents, possibly increasing the risk of soil and nutrient loss through wind erosion.

The effect of UAN and manure applications on pH in the soil profile was also evaluated during the six-year study period, resulting in no significant differences ($p \leq 0.05$) for average soil pH among treatments for both corn and soybean plots. The soil C:N ratio for the 0-1.22 m soil profile depth was determined for project study years 1997, 1998, and 1999 and was found to be approximately 15 at the 0.61 m depth for all treatments; and significantly increased ($p \leq 0.05$) below the 0.61 m depth as a function of lower percent N deeper in the soil profile during the three sampling years. Sauerbeck (1982) found that the greatest increase in soil organic carbon included a manure treatment when compared with straw and composted manure treatments. However, the cumulative effect of manure application on C:N ratio in the 0-1.22 m depth range averaged over three years (1997-1999) indicated that application rate, timing, and method did not significantly affect ($p \leq 0.05$) C:N ratio in the soil profile.

Corn and Soybean Yield Analysis

Crop yield analysis results indicate that the application of N management practices affected corn yields in all six years of the study (1996-2001). Average corn yields ranged from 5,275 kg ha^{-1} for UAN (control) in 2001 to 11,183 kg ha^{-1} for SI2 in 1997 (table 12). Significant reductions ($p \leq$

0.05) in average corn yields during 2000 and 2001 may have been caused by below-normal seasonal rainfall for the 2000 and 2001 growing seasons (table 5). However, using the same research site during roughly the same time period as this study, Loecke et al. (2004) determined that fall 2001 applications of swine manure increased corn grain yield more than the spring application time.

A trend of increased corn yields from the higher double-rate (DR) manure application plots (FI2, SI2, and WB2) versus the single-rate (SR) plots (FI1, SI1, and WB1) was observed throughout the study period, and the effect of DR versus SR was significantly different ($p \leq 0.05$) for every year except 1996 and 1998 (table 14). The average corn yield for DR plots also was significantly higher ($p \leq 0.05$) at 19.1% than for UAN application plots, and similar results of N management practices on crop yields have been documented by other researchers (Bundy, 1986; Blaylock and Cruse, 1992; Jokela and Randall, 1989). The effect of manure application timing (SI vs. FI treatments) on corn yields was significantly different ($p \leq 0.01$) in 1996, and the methods of application (SI vs. WB) resulted in significantly higher ($p \leq 0.05$) corn yields for SI plots during 1997 and 2001 (table 14). Blaylock and Cruse (1992) found higher corn yields and N recovery when UAN was injected versus broadcast applications in Iowa, and Daverede et al. (2004) reported that injected manure also reduced runoff P losses.

When averaged over the six years (1996-2001), corn yield for SI2 plots (table 16) was significantly higher ($p \leq 0.05$) among all treatments at 10,093 kg ha^{-1} (table 12). The average long-term corn yield in the area is 9,350 kg ha^{-1} (IAS, 2002). The lowest average corn yield was from the UAN plots (7,864 kg ha^{-1}) (table 12). While average corn yields for all manure treatments were improved above the UAN treatment over the six-year study period (table 16), the SI1 treatment produced significantly higher ($p \leq 0.05$) yields (9,099 kg ha^{-1}) (table 12) among the other two SR manure application treatments (FI1 and WB1).

Mallarino and Wittry (2010) found that liquid swine manure P always increased corn and soybean grain yield with soil test P (STP) very low (<16 mg Bray-P1 kg^{-1}) and only in three of nine sites with STP at optimum level (16 to 20 mg P kg^{-1}). Analysis of soybean yields by year showed that soybean yield was not significantly different ($p \leq 0.05$) due to the previous year's N management practices (tables 13 and 15). However, when yields from soybean followed by corn were averaged over the six years, WB2 and SI2 treatment plots had significantly higher ($p \leq 0.05$) yields than the other treatments (tables 13 and 16).

Although N management practices were not conducted on soybean plots, below-average rainfall conditions may have affected soybean yields during 2000 and 2001. Average soybean yields ranged from 1,865 kg ha^{-1} for SI1 in 2000 to 3,314 kg ha^{-1} for WB2 in 1997 (table 13). The long-term average soybean yield in the area is 2,890 kg ha^{-1} (IAS, 2002). Residual effects of N management practices were significantly different ($p \leq 0.05$) for all years except 1996 (first year of the study).

Table 12. Comparison of corn yield (kg ha^{-1}) for individual N management treatments by year (1996-2001).

Treatment	1996	1997	1998	1999	2000	2001	Avg.
UAN	7,923	7,724	9,860	8,442	7,959	5,275	7,864
FI1	7,858	9,364	10,149	8,320	8,505	9,122	8,886
FI2	8,226	10,565	10,004	9,185	9,227	10,305	9,585
WB1	9,553	8,782	9,104	8,177	8,093	8,310	8,670
WB2	10,599	9,681	9,612	8,738	8,702	9,677	9,502
SI1	9,958	9,557	9,330	8,312	8,087	9,351	9,099
SI2	10,002	11,183	10,924	9,681	8,646	10,122	10,093

Table 13. Comparison of soybean yield (kg ha^{-1}) for individual N management treatments by year (1996-2001).

Treatment	1996	1997	1998	1999	2000	2001	Avg.
UAN	2,658	3,071	2,897	2,765	2,037	1,894	2,554
FI1	2,760	2,955	2,658	2,700	2,064	1,930	2,511
FI2	2,751	2,859	2,850	2,845	2,325	2,233	2,644
WB1	2,859	2,856	2,890	2,968	2,102	2,173	2,641
WB2	2,745	3,314	2,863	3,176	2,309	2,354	2,794
SI1	2,756	3,158	2,734	2,687	1,865	1,965	2,528
SI2	2,738	3,265	3,035	2,993	2,289	2,506	2,804

Table 14. Comparison of p-values for N management practices on corn yield by year (1996-2001). NS = not significant ($p > 0.05$).

Treatment	1996	1997	1998	1999	2000	2001
SR vs. UAN	0.01	0.00	NS	NS	NS	0.00
DR vs. UAN	0.00	0.00	NS	NS	0.02	0.00
DR vs. SR	NS	0.00	NS	0.03	0.03	0.00
SI vs. FI	0.00	NS	NS	NS	NS	NS
WB vs. FI	0.00	NS	NS	NS	NS	0.02
SI vs. WB	NS	0.01	NS	NS	NS	0.02

Table 15. Comparison of p-values for N management practices on soybean yield by year (1996-2001). NS = not significant ($p > 0.05$).

Treatment	1996	1997	1998	1999	2000	2001
SR vs. UAN	NS	NS	NS	NS	NS	NS
DR vs. UAN	NS	NS	NS	NS	NS	0.00
DR vs. SR	NS	NS	NS	0.03	0.02	0.00
SI vs. FI	NS	0.00	NS	NS	NS	NS
WB vs. FI	NS	NS	NS	0.01	NS	NS
SI vs. WB	NS	NS	NS	NS	NS	NS

Table 16. Comparison of percent differences (% diff) and p-values for N management practices on crop yields averaged over six years (1996-2001). NS = not significant ($p > 0.05$).

	Corn Yield		Soybean Yield	
Treatment	% Diff	p-Value	% Diff	p-Value
SR vs. UAN	11.5	0.00	0.5	NS
DR vs. UAN	19.1	0.00	6.5	0.01
DR vs. SR	8.6	0.00	6.0	0.00
SI vs. FI	3.7	0.05	4.2	NS
WB vs. FI	-1.6	NS	6.5	0.03
SI vs. WB	5.3	0.01	-2.4	NS

Summary and Conclusions

The primary objective of this study was to evaluate long-term effects of liquid swine manure rate, timing, and application methods in a corn-soybean rotation cropping system. Specific objectives included determining post-harvest soil nutrient total P and NO_3-N levels, percent organic matter (OM%), pH, C:N ratio, and crop yields, and discussing potential water quality implications. Six consecutive years (1996-2001) of UAN and manure applications to soil showed a trend of significant increases in RSP and RSN in the 0-0.30 and 0-1.22 m soil profiles, respectively. Another trend of significantly higher crop yields was observed with the higher double-rate (DR, 336 kg N ha^{-1}) manure application versus the single-rate (SR, 168 kg N ha^{-1}) application. However, there were no significant effects on soil OM%, pH, and C:N ratio after six years of UAN/manure applications.

The two manure application treatments (SR and DR) significantly affected RSP and RSN in the soil profile. The trend of higher accumulation of RSP and RSN for the higher DR manure application was consistent throughout the study period, indicating that there may have been more manure P and crop-available N applied than the crop demanded. Consequently, a greater potential for significant environmental pollution exists for the higher DR manure application. While the amount of annual rainfall can affect crop nutrient uptake, leaching, and transport, the accumulation of average soil profile RSN levels was significantly higher for the years 2000 and 2001, which had below-average annual rainfall.

A comparison of injection versus broadcast manure application methods when averaged over the six project years and application rates showed more accumulation of RSP from the broadcast method and more RSN from the injection method in the soil profile. This could be a result of available P and N from manure and appeared to be related to conservation of NH_3 and mineralization of organic P and N, increasing the accumulation of residual P and N in the soil profile. The application methods also affected corn yield, with the winter broadcast method resulting in the lowest yield (9,086 kg ha^{-1}) and the spring injection method producing the highest yield (9,596 kg ha^{-1}) when averaged over all study years and manure application rates.

The analysis of three manure application timings (fall, winter, and spring) indicated that fall application had the lowest average RSP and RSN in the soil profile and lower crop yield. This demonstrated that fall manure application has the potential to be a significant threat to the soil-water environment due to reduction of crop P and N utilization, microbial activity, post-harvest rainfall, and evapotranspiration from November to April. Consequently, subsequent accumulations of nutrients in soil could move through the profile to deeper depths, possibly contaminating shallow groundwater.

The six-year average corn yield was significantly higher (10,093 kg ha^{-1}) when manure was injected with the higher DR application in spring. The lowest average corn yield was found with the UAN plots (7,864 kg ha^{-1}). Although no manure and UAN were applied to soybean plots, the residual effect of N management also increased soybean yields for the DR application. Below-average annual rainfall conditions during project years 2000 and 2001 may also have reduced corn and soybean yields.

Overall, these results indicate an accumulation of large amounts of RSP and RSN in higher DR manure application plots. Timing of manure application also influenced nutrient accumulation and leaching through the soil profile. Changing manure application time from fall to spring significantly increased average corn yield up to 4.0%. The reduction in corn yield for the fall application may have been due to denitrification of available N, low nutrient level in the root zone, movement of NO_3-N to deeper depths with infiltrated water, and leaching to shallow groundwater (subsurface drainage tile was 1.2 m below the soil surface). These results tend to indicate that more nutrient accumulation was observed in spring and winter application plots versus fall application plots. However, some studies indicated increased nutrient accumulation in fall and increased corn grain yield from fall N application, possibly due to below-average rainfall conditions that were experienced during this study in years 2000 and 2001.

The results of this study could provide better N management information for Midwest U.S. farmers and livestock producers. Manure N management practices must be evaluated in the context of economic and other production constraints faced by farmers and livestock producers. Fall manure application timing has been a common practice used to avoid issues related to spring application, such as minimal storage capacity, wet soil, soil compaction, and high labor and equipment costs. However, potentially higher yields obtained using the spring versus fall application time should be considered to offset increased operating expenses and management limitations.

Among N management practices evaluated in this study, manure injections in fall and spring resulted in average corn yields ranging from 9,236 to 9,596 kg ha^{-1}, respectively, indicating that spring application may be a more effective and profitable practice. Moreover, it is important to further investigate the effects of fall application on shallow groundwater to enhance the establishment of appropriate best management practices to minimize potential threats to the soil-water environment. It also is suggested that a long-term manure application study to determine nutrient mass balance values for corn and soybean under other crop production systems could provide useful data and information for researchers and farmers in the decision-making process. Other future long-term studies might include documenting potential effects of climate change, variable economic conditions, livestock dietary impacts on soil N cycling (Paschold et al., 2008; Powell and Grabber, 2009), and the use of matrix-based fertilizers (Entry et al., 2010) on N management practices, P and N leaching, and corn-soybean yields.

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NOMENCLATURE

UAN = UAN application single rate (168 kg N ha^{-1} [150 lb N ac^{-1}])

RSP = residual soil phosphorus

RSN = residual soil nitrate-nitrogen

OM% = percent organic matter

FI1 = fall application with single application rate

FI2 = fall application with double application rate (336 kg N ha^{-1} [300 lb N ac^{-1}])

WB1 = winter broadcast with single application rate

WB2 = winter broadcast with double application rate

SI1 = spring application with single application rate

SI2 = spring application with double application rate

SR = average across time and method of all manure applied plots with single application rate

DR = average across time and method of all manure applied plots with double application rate

FI = average across rates of all manure injected plots in fall

WB = average across rates of all manure broadcast plots in winter

SI = average across rates of all manure injected in spring