CHALLENGES OF MANAGING LIQUID SWINE MANURE

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ABSTRACT. *Liquid swine manure can be a resource for providing essential plant nutrients and building soil resources, but its management for maximum productivity with minimum environmental impact is often very difficult. Failure to understand the challenges may result in expectations or even regulations that are impossible to achieve. Our objective is to provide producers and policy makers with information regarding agronomic and environmental challenges of liquid swine manure management based on results from a 6−year study with continuous corn (*Zea mays *L.) and a corn−soybean [*Glycine max *(L.) Merr.] rotation in Iowa. Challenges that we encountered are openly discussed to increase the awareness of those people who may ultimately be developing policy and writing manure management legislation. Drainage volume, NO_3−N concentrations, and NO_3−N leaching loss were spatially variable, being influenced by seasonal precipitation as well as current and past manure application rates. Annual manure applications for continuous corn increased soil−test P and K values because more nutrients were supplied than removed through grain harvest. Biennial applications also increased soil−test P but not K. We suggest developing local manure nutrient databases to guide application rates, using total Kjeldahl N (TKN) values to estimate plant−available N, monitoring manure loads to quantify variability and actual loading rates, and routinely using soil−testing to determine if application rates should be based on P rather than N content in the manure.*

Keywords. *Manure management, N leaching, Nutrient balance, Tile drainage, Crop rotation.*

Poor manure management can result in pollution (Hatfield et al., 1998; Bakhsh et al., 1999), but by understanding how the entire soil−, manure−, and crop−management system functions, liquid swine manure can be used as a resource in an agronomically, environmentally, and economically sustainable manner. During the 1990s, manure management research focused on changing people's perceptions of swine manure from a waste needing disposal to a resource that can be utilized in an environmentally sound and economically profitable manner (Hatfield and Stewart, 1998; Wright et al., 1998; Janzen et al., 1999). Changing this perception was very important because as Nowak et al. (1998) concluded "altering patterns and consequences of manure management are predicated on the ongoing process of changing human behavior."

The total number of swine being raised in the United States has remained relatively unchanged for several years, but production practices have changed dramatically over the last two decades (Jackson et al., 2000). Many small− and medium−sized operations throughout the United States have been replaced at a steady rate by concentrated animal feeding operations (CAFOs). Although odor, manure spills, fish kills, and other environmental problems are not unique to CAFOs, they exacerbate these problems because of the high concentration of animals and manure in relatively small areas. Public demand for more environmentally sound manure management practices has increased as the number of CAFOs have increased.

Manure management problems can occur in all animal operations regardless of size, but in response to increasing public concerns regarding CAFOs, many states now require manure management plans. Developing economically and environmentally sound plans is essential for sustainable swine production (Honeyman, 1996; Coffey, 1999; Jackson et al., 2000). Unfortunately, it is not always a simplse task.

Achieving optimum manure management can be difficult because daily manure production ranges from 1 to 10 kg hog^{-1} depending upon the animal's size, type, and ration. Variability among soils in fields where the manure is applied or in nutrient content from year to year (or even load to load), a manure N−P−K ratio that does not match crop needs (O'Dell et al., 1995; Jackson et al., 1996), and engineering problems resulting in uneven rates of application can all hinder implementation of best management plans (BMPs). As a result, it was not surprising that Shepard (2000) found that among 1928 Wisconsin livestock farmers, two out of three routinely apply excess N and four out of five apply excess P to their cropland. Unfortunately, such survey results are often used to imply that farmers using liquid swine manure as a nutrient source are not good stewards of their land (Jackson et al., 2000). This study was conducted to provide producers and policy makers with information regarding agronomic and environmental opportunities and challenges associated with liquid swine manure.

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Materials and Methods

The study was conducted between 1993 and 1998 at the Northeast Iowa Research and Demonstration Farm near Nashua, Iowa. Continuous corn (C−C−C−C−C−C) and both phases of a corn−soybean rotation (i.e. C−S−C−S−C−S or S−C−S−C−S−C)were each replicated three times in 0.4−ha plots. The predominant soils are Floyd loam (fine−loamy, mixed, mesic Aquic Hapludolls), Kenyon silty clay loam (fine−loamy, mixed, mesic Aquic Hapludolls), and Readlyn loam (fine−loamy, mixed, mesic Aquic Hapludolls). The Natural Resources Conservation Service (NRCS) soil survey (Voy, 1995) indicates that all three soils contain 30− to 40−g kg^{-1} (3% to 4%) organic matter, are moderately well to poorly drained, and have seasonally high water tables.

Subsurface drainage tiles were installed at a depth of 1.2 m between and in the center of each plot in 1979. Drain−tile spacing was 29.3 m, regardless of topographical position or apparent need for drainage. Border−tile lines are assumed to prevent cross contamination from surrounding plots. The center tile line in each plot was intercepted and connected to individual sumps for measuring subsurface drainage (tile flow) and collecting water samples for chemical analysis (Kanwar et al., 1999). Approximately 0.2% of the tile water was diverted into a sampling bottle whenever water was pumped from the sump. The water samples were analyzed to determine NO_3−N concentrations with a Lachat Model AE ion analyzer (Lachat Instruments, Milwaukee, Wis.). Nitrate leaching was computed by multiplying concentration data by drainage volume.

Two different local cooperators provided liquid swine manure for this study. The first location (Farm 1) supplied manure from a farrow to finish operation for the 1993 and 1994 growing seasons but then due to an increase in farm size could no longer do so for 1995 through 1998. The second location (Farm 2) supplied manure for final four years from a new farrow−to−finish operation. Each year, manure was injected at a depth of 15 to 20 cm (6 to 8 in.). To ensure the manure tracks were covered and to disrupt any wheel traffic patterns associated with the manure application, both the continuous corn and the rotated plots receiving manure were chisel plowed. Manure applications were generally made in late November or early December, although in 1996 only two of the continuous corn plots were fertilized prior to a severe winter storm. The third continuous corn plot and all three rotated plots were treated with liquid swine manure in early April of 1997. Manure samples were collected from several loads of manure each year. Total Kjeldahl N (TKN) was quantified using a colorimetric measurement with an Auto-Analyzer while ammonia−N was measured using an electrode. Total P was also quantified using a colorimetric AutoAnalyzer method, while total K was determined using atomic absorption. The percent solids in the manure were also determined. All manure analyses were carried out at the ISU Analytical Services Laboratory.

Corn (‘Golden Harvest 2343’) was planted in 75−cm rows after preparing a seedbed with a field cultivator. Soybeans (‘Sands of Iowa 237’) were drilled in 20−cm rows directly into corn stover. Grain yield was measured each year by harvesting a 3−row corn strip or 3.8−m soybean strip across each plot, weighing the grain, and subsampling for moisture determinations. Grain N concentrations were measured with the Carlo−Erba Model 1500 NCS analyzer (Haake Buchler, Patterson, N.J.) after grinding the grain to pass a 0.5−mm stainless steel screen. Nitrogen removal was computed by multiplying grain dry weight by the measured grain N concentrations. Annual P and K removal were estimated similarly but using average P and K concentrations for corn and soybean grain (Voss et al., 1999).

Changes in pH (1:1 soil:water), Bray P1, 1*M* ammonium acetate exchangeable K, total organic C, and total N were determined by collecting 20 soil cores (0 to 20 cm in depth) from each plot in a random pattern prior to applying liquid swine manure (1992) and again in 1998 after three (rotated plots) or six (continuous corn) years of manure application. Prior to measuring total C and N by dry combustion with the NCS 1500 analyzer, the soil samples were checked for the presence of free carbonates but none were found. A partial nutrient budget was computed by subtracting grain removal, drainage tile loss, and soil−test changes from the quantity of manure−applied nutrients. The analysis of variance (ANOVA), mean values, standard deviations, and correlation coefficients were computed using SAS statistical software (SAS Institute, 1999).

Results and Discussion

Agronomic Response

Annual rates of liquid swine manure, applied nutrients, crop yield, and nutrient removal are summarized in table 1. Expected corn and soybean yields were 9.4 and 3.0 Mg ha^{-1} (150 and 45 bu $acre^{-1}$), respectively (Voy, 1995). The target N application rates were 157 and 134 kg N ha^{-1} for continuous and rotated corn, respectively. Those rates were based on average corn yields for the previous five years at the research site (Kanwar et al., 1997) but were also about 15 kg ha^{-1} less than ISU recommendations because the research team was very focused on reducing NO_3−N loss through tile drainage. That goal was important because previous research at this site with annual fertilizer N rates of 202 and 162 kg N ha^{-1} yr^{-1} consistently resulted in tile drainage water nitrate concentrations that exceeded 10 mg L^{-1} (Kanwar et al., 1997). When this study was initiated, there was also no consistent recommendation for estimating plant available N from liquid swine manure (S.W. Melvin, personal communication, 1993), so we assumed that all of the ammonia N and one−half of the total N minus the ammonia N would be available to the plants during the first year after the liquid swine manure was applied (eq. 1).

$$\text{Plant Available N} = \text{ammonia−N} + ((\text{TKN}-\text{ammonia−N})/2) \quad (1)$$

For consistency, equation 1 was used throughout this 6−year study. However, based on our results and that of others since then, we agree with Killorn and Lorimor (1999) that provided volatilization losses are prevented through subsurface injection and covering of the liquid swine manure, plant available N can more easily be estimated using only the TKN concentration. Seasonal results enabling us to support their recommendation are presented in table 1 and summarized below.

Table 1. Liquid swine manure application rates, nutrients applied, crop yields, nutrients removed, and drainage−tile NO_3−N losses for continuous corn and corn−soybean rotations in six−year study in northeastern Iowa.

Crop Sequence[a]	Target Manure Rate ($L\ ha^{-1}$)	Actual Manure Rate ($L\ ha^{-1}$)	Target N Rate	Nutrients Applied[b]			Crop Yield	Nutrients Removed[c]			Drainage NO_3−N Loss
				N ($kg\ ha^{-1}$)	P ($kg\ ha^{-1}$)	K ($kg\ ha^{-1}$)		N ($kg\ ha^{-1}$)	P ($kg\ ha^{-1}$)	K ($kg\ ha^{-1}$)	
1993 (seasonal[d] rainfall = 1026 mm)											
C−C−C−C−C−C	37400	28985	157	69	52	62	2775	29	8	12	48
C−S−C−S−C−S	32725	27115	134	81	59	79	5545	55	17	24	35
S−C−S−C−S−C	0	0	0	0	0	0	2640	126	25	37	33
1994 (seasonal rainfall = 756 mm)											
C−**C**−C−C−C−C	79475	79475	157	262	215	373	7250	106	21	33	10
S−**C**−S−C−S−C	67790	67790	134	236	176	188	8400	126	25	37	12
C−**S**−C−S−C−S	0	0	0	0	0	0	3235	172	19	67	4
1995 (seasonal rainfall = 802 mm)											
C−C−**C**−C−C−C	51425	52460	157	302	147	143	4810	73	14	21	38
C−S−**C**−S−C−S	42100	44975	134	218	87	117	5575	82	17	25	13
S−C−**S**−C−S−C	0	0	0	0	0	0	3030	160	18	63	39
1996 (seasonal rainfall = 683 mm)											
C−C−C−**C**−C−C	16400	19650	157	101	37	53	8373	124	25	37	11
S−C−S−**C**−S−C	14025	14615	134	83	25	36	8880	122	26	39	13
C−S−C−**S**−C−S	0	0	0	0	0	0	3900	212	23	81	8
1997 (seasonal rainfall = 747 mm)											
C−C−C−C−**C**−C	32725	21840	157	103	34	53	7450	82	22	33	7
C−S−C−S−**C**−S	28050	15915	134	85	28	45	9180	91	27	41	8
S−C−S−C−**S**−C	0	0	0	0	0	0	3630	192	21	75	15
1998 (seasonal rainfall = 974 mm)											
C−C−C−C−C−**C**	32725	33990	157	141	48	78	7495	95	22	34	41
S−C−S−C−S−**C**	28050	26715	134	106	36	63	9750	123	29	43	40
C−S−C−S−C−**S**	0	0	0	0	0	0	3895	228	23	80	18
Six−year average (rainfall = 865 mm)											
C−C−C−C−C−C	41690	39385	157	163	89	127	6376	85	19	28	26
C−S−C−S−C−S[e]	35450	32855	134	135	69	88	7888	100	24	35	14
S−C−S−C−S−C[f]	0	0	0	0	0	0	3388	182	22	67	25

[a] Bold letter indicates the current crop for a specific year (i.e. C = corn; S = soybean).
[b] Calculated by multiplying the manure application rate and plant−available N (eq. 1), P, and K concentrations.
[c] Calculated based on measured N concentrations and estimated (Voss et al., 1999) P and K composition data.
[d] Rainfall received from 1 March through 30 November 30 compared to an average of 772 mm (Voy, 1995).
[e] Average values for the corn phase of the two−year rotation.
[f] Average values for the soybean phase of the two−year rotation.

1993 Cropping Season

The target manure application rates for 1993 were based on an estimated N content of 4.2 g N L^{-1} (35 lb N per 1000 gal), a "book value" consistent with those recommendations reported by the Midwest Plan Service (1993) and Sutton et al. (1983). The actual N application rates (69 and 81 kg N ha^{-1} for continuous and rotated treatments, respectively) were lower than desired primarily because the ammonia N values from Farm 1 were 10−times lower than the anticipated values. Our research plan for 1993 was also compromised when our cooperator had an insufficient supply of swine manure to meet our research needs. Furthermore, even though a greater volume of manure was applied to the continuous corn plots than to the rotated plots (table 1), load−to−load variability in nutrient content of the manure (table 2) resulted in less N being applied for continuous corn than for rotated corn.

Our first year of research was further complicated because throughout the Midwest, rainfall during the 1993 growing season was 50% to 100% above normal. At this site, growing−season (March through November) rainfall totaled 1026 mm compared to an average of 772 mm (Voy, 1995). As

Table 2. Liquid swine manure composition throughout a six−year study in northeast Iowa.

Source	Sample Date	Samples Collected	Total N ($g\ L^{-1}$)	Ammonia N ($g\ L^{-1}$)	Total P ($g\ L^{-1}$)	Total K ($g\ L^{-1}$)	Solids ($g\ kg^{-1}$)
Farm 1	Fall 1992	4	4.9 ± 0.6	0.3 ± 0.1	1.9 ± 0.4	2.4 ± 0.4	64 ± 8
Farm 1	1993 Pit[a]	3	3.5 ± 0.01	0.2 ± 0.00	0.6 ± 0.01	1.9 ± 0.06	17 ± 0.5
Farm 1	Fall 1993	4	6.0 ± 0.5	0.5 ± 0.1	2.6 ± 0.7	3.6 ± 1.1	78 ± 29
Farm 2	Fall 1994	17	5.3 ± 0.5	4.9 ± 0.2	2.6 ± 0.7	2.8 ± 0.2	82 ± 24
Farm 2	Fall 1995	8	5.9 ± 0.2	4.8 ± 0.6	1.8 ± 0.2	2.6 ± 0.3	54 ± 4
Farm 2	Fall 1996	3	6.1 ± 0.04	4.9 ± 0.03	1.8 ± 0.2	2.8 ± 0.5	54 ± 4
Farm 2	Spring 1997	4	5.9 ± 0.1	4.9 ± 0.2	1.8 ± 0.02	2.8 ± 0.1	63 ± 3
Farm 2	Fall 1997	8	5.8 ± 0.4	3.8 ± 0.3	1.4 ± 0.07	2.3 ± 0.1	84 ± 23

[a] Samples collected approximately 1 month before application.

a result, yields for rotated and continuous corn were 40% to 70% below average (9410 kg ha^{-1}) and soybean yields were 13% below average (3025 kg ha^{-1}). The continuous corn plots were also visually N deficient throughout the growing season confirming that plant available N was not adequate.

1994 Cropping Season

In response to the visual N deficiency symptoms and to ensure that an adequate amount of N was applied for the 1994 crop, we collected manure samples about one month before application and had them analyzed by the ISU Analytical Services Laboratory. The manure storage pits were agitated for more than three days before collecting the samples. As in 1993, ammonia and TKN values were lower than expected (table 2), but the latter were within the normal range (3.4 to 6.6 g L^{-1}) for liquid swine manure (Sutton et al., 1983). Unfortunately, we did not notice at that time that the percent solids and total P concentrations were also below normal (2% to 7% solids and 0.7 to 1.6 g L^{-1} P). Those data confirm that despite agitating for more than 72 hours before sampling, the pits were still not adequately mixed.

The manure application rates were calculated to be 68,000 and 80,000 L ha^{-1} (7000 and 8000 gal acre^{-1}) for the rotated and continuous corn crops, respectively, using equation 1 and the pre−application analytical results. We recognized the values were higher than anticipated, but our cooperator provided sufficient manure to achieve the target rates (table 1). To confirm the actual nutrient application rates, another set of samples were collected and analyzed (table 2, Fall 1993). The ammonia−N values were slightly higher than in the pre−application samples but still nearly 10 times lower than expected. The TKN values, however, were nearly double those concentrations measured prior to application. Those factors resulted in N application rates that were much greater than the target values (table 1).

Nutrient application rates certainly were not limiting in 1994, but rainfall was below average (table 1) and grain yields for continuous and rotated corn were below average (9410 kg ha^{-1}) for well−managed Floyd, Kenyon, and Readlyn soils (Voy, 1995). Soybean yield, however, was above average (3025 kg ha^{-1}). Grain removal based on TKN levels accounted for the equivalent of 22% and 29% of the N applied to continuous or rotated corn, respectively. This low level of N recovery is not unusual and is one reason why agriculture has been implicated as a major contributor to non−point pollution (Dinnes et al., 2002).

1995 Cropping Season

The cooperator who supplied liquid swine manure for 1993 and 1994 (Farm 1) could no longer provide manure for our research because of an expansion in personal farming operations. Therefore, arrangements were made with a second cooperator (Farm 2) to provide manure for the remainder of the study. Also, rather than continuing to use "book values" (e.g. Sutton et al., 1983; Midwest Plan Service, 1993) or trying to sample the manure pits and measure ammonia and TKN levels prior to application, we decided to develop a local database using the average nutrient values for samples collected each year. The mean values were used in equation 1 to establish target application rates (table 1), and the database was updated each year as additional manure samples were analyzed.

Despite our rigorous efforts to develop a manure management plan that would ensure we achieved our target application rates, the laboratory results for the 1995 crop year showed that ammonia levels in the liquid swine manure from Farm 2 were an order of magnitude (10x) greater than those for Farm 1 and nearly 60% higher than the average (3.1 g L^{-1}) given by Sutton et al. (1983). TKN concentrations (table 2) were also above the average (4.3 g L^{-1}) given by Sutton et al. (1983). As a result, the actual N application rates for the 1995 cropping season were once again about 40% greater than desired (table 1).

Corn and soybean yield for 1995 were again below average for well−managed Floyd, Kenyon, and Readlyn soils (Voy, 1995) even though seasonal rainfall (table 1) was above average. The primary reason for the low yields was a severe hailstorm that occurred in July during the R1 (silking) growth stage (Ritchie et al., 1996) for corn and the R1 (beginning bloom) growth stage for soybean (Ritchie et al., 1994). The storm destroyed many of the leaves that would have provided photosynthate to the developing ears of corn and stripped many leaves and flowers from the soybean plants. As a result, N removal with the corn grain once again accounted for the equivalent of only 26% to 39% of the applied N.

1996 Cropping Season

The research team was frustrated by not achieving the target N application rates in prior years. Therefore, in addition to continuing to develop the database, we also sampled and tested every load of manure in the field with a Hach (Hach Inc., Ames, Iowa) test kit prior to application. This effort was not very successful because of the very high dilution that was required for in−field manure analysis with the Hach kit. However, rates of manure application were determined using equation 1 with the "in−field" measured ammonia−N values and an average TKN value from the 1993, 1994, and 1995 manure samples. A second manure sample was also collected from each load for subsequent laboratory analysis.

The calculated N application rates for the 1996 continuous and rotated corn crops (using laboratory analyses in table 1) were approximately 45 kg N ha^{-1} lower than the target values for both cropping systems because of the manure sampling and dilution problems encountered with the in−field ammonia−N measurement. The lower N application rates did not appear to reduce grain yield in 1996, presumably because rainfall was below normal (table 1).

The lower than desired N application rates did result in estimated N recovery rates that exceeded 100% in 1996. Although this rate of recovery was good, it is important to realize that various other soil N pools, including residual N from prior manure applications probably supplied a portion of the N actually removed through grain harvest.

1997 Cropping Season

The laboratory analyses of the liquid swine manure from Farm 2 were similar for 1995 and 1996 (table 2). Therefore for 1997, we used the average ammonia−N and TKN values from those two years to calculate the target application rates. Once again the target rates were not achieved (table 1), but this time it was because of an early winter storm. As the soil froze, it became impossible to pull the applicator at the desired speed and depth. To prevent the liquid manure from ponding on the soil surface and running off, the rates of application were reduced. Furthermore, because of the storm, manure could be applied to only two of the six plots in November 1996. The remaining four plots received manure in April 1997.

To avoid further confounding the experiment, the spring 1997 application rate was kept the same as had been achieved on the plots treated in the fall. Another set of manure samples were submitted for laboratory analysis (table 2). Fortunately, TKN and ammonia−N concentrations were similar for the fall and spring, so manure nutrient composition did not create any additional inconsistencies for the 1997 crop. The lower N application rates did not appear to reduce yields for the rotated corn (table 1), but continuous corn yields were about 20% below average (9.4 Mg ha^{-1}) for these soils. The calculated N removal for continuous and rotated corn grain accounted for the equivalent of 52% and 68% of the applied N, respectively

1998 Cropping Season

After five years of experience, there were finally no problems with liquid manure application and the rates of application were within ±5% of the target rates for both cropping systems (table 1). However, based on the analytical results (table 2), the nutrient application rates were still above the target values (table 1). Seasonal rainfall in 1998 was above average (table 1) and yields for both corn and soybean from the rotated plots were above average for the Floyd, Kenyon, and Readlyn soils (9.4 and 3.0 Mg ha^{-1}, respectively). Yields for continuous corn were about 20% below average (Voy, 1995), despite having adequate rainfall and sufficient N rates. This response was consistent with prior results from this research site (Kanwar et al., 1997) and suggests that regardless of N source, corn rotated with soybean will have higher grain yield than continuous corn on these soils.

Table 3. Subsurface drainage volume, nitrate concentration, and nitrate load following liquid swine manure application to continuous corn or the corn phase of a corn−soybean rotation grown on loam and clay−loam soils in northeastern Iowa.

Year	Rotation[a]	Drainage Volume (mm)	Nitrate Concentration (mg L^{-1})	Nitrate Loss (kg ha^{-1})
1993	**C**−C−C−C−C−C	390 ± 57	12 ± 0.4	48± 6
1993	**C**−S−C−S−C−S	262 ± 116	13 ± 2.3	35 ± 19
1993	**S**−C−S−C−S−C	488 ± 251	7 ± 0.6	33 ± 19
1994	C−**C**−C−C−C−C	57 ± 21	17 ± 5.5	10 ± 6
1994	S−**C**−S−C−S−C	123 ± 107	11 ± 2.4	12 ± 8
1994	C−**S**−C−S−C−S	64 ± 23	7 ± 0.9	4 ± 1
1995	C−C−**C**−C−C−C	118 ± 29	32 ± 2.1	38 ± 11
1995	C−S−**C**−S−C−S	71 ± 37	18 ± 1.8	13 ± 7
1995	S−C−**S**−C−S−C	244 ± 106	17 ± 2.0	39 ± 27
1996	C−C−C−**C**−C−C	45 ± 15	24 ± 2.7	11 ± 5
1996	S−C−S−**C**−S−C	94 ± 78	16 ± 4.0	13 ± 7
1996	C−S−C−**S**−C−S	39 ± 17	20 ± 2.4	8 ± 4
1997	C−C−C−C−**C**−C	84 ± 38	8 ± 1.4	7 ± 4
1997	C−S−C−S−**C**−S	55 ± 29	13 ± 2.0	8 ± 4
1997	S−C−S−C−**S**−C	206 ± 155	8 ± 1.5	15 ± 10
1998	C−C−C−C−C−**C**	192 ± 40	21 ± 1.2	41 ± 8
1998	S−C−S−C−S−**C**	311 ± 211	14 ± 3.6	40 ± 21
1998	C−S−C−S−C−**S**	161 ± 102	11 ± 0.5	18 ± 12
		−−−−−−−−−− Six−year mean values −−−−−−−		
C−C−C−C−C−C		148	19	26
C−S−C−S−C−S		109	14	14
S−C−S−C−S−C		244	12	25
$LSD_{(0.1)}$		64	1	7

[a] Bold letter indicates the current crop for a specific year (i.e. C = corn; S = soybean).

ENVIRONMENTAL IMPACTS

Subsurface NO_3−N Drainage Loss

The potential environmental impact of the liquid swine manure treatments was evaluated by quantifying NO_3−N leaching loss from subsurface drainage lines. The drainage network at this research site was installed in 1979 to reduce plot variability because of the seasonally high water tables in the dominant soils (Voy, 1995) and to increase the crop yield potential. However, artificial drainage also increases vulnerability for NO_3−N leaching, a process that not only contributes to surface water contamination, regardless of the N source (Dinnes et al., 2002), but also increases production costs.

Table 3 shows that subsurface drainage accounted for 6% to 48% of the seasonal precipitation during this study. Drainage volume among replicates was highly variable, presumably because of subtle differences in slope and inherent soil characteristics. Among the six rotated plots (table 3), the three planted to soybean in odd years ('93, '95, and '97) and corn in even years ('94, '96, and '98) had a higher drainage volume each year than the three plots planted to corn in the odd years and soybean in the even years.

The amount of NO_3−N lost through subsurface drainage (table 3) was highly variable ranging from 4 to 48 kg ha^{-1} yr^{-1}. Annual losses were influenced by several factors including seasonal precipitation, drainage volume, current and past liquid swine manure application rates, and the crop being grown. Some researchers have suggested that fall application of liquid swine manure contributes substantially to NO_3−N loss through drainage and/or denitrification. This study did not include fall versus spring application comparisons so this question cannot be answered. However, the average monthly precipitation (Voy, 1995) indicates that N loss during the winter will generally not be a problem because 91% of the annual precipitation occurs between March and November. During this 6−year study, seasonal precipitation accounted for 81% to 116% of the average annual amount, with the low value occurring during a very dry year (1996).

The NO_3−N concentration data (table 3) show that during the first two years (1993 and 1994), the soybean plots that had no history of liquid swine manure application had the lowest NO_3−N concentrations and therefore the lowest NO_3−N loss through the drainage tile. The data also show that although NO_3−N concentrations were the same for soybean for 1993 and 1994, the higher drainage volume in 1993 resulted in much greater N leaching losses than in 1994, a relatively dry year.

In 1995, the NO_3−N concentration in drainage from the soybean plots was once again lower than from either continuous or rotated corn. The high drainage volume and presumably residual N from the 1994 manure application (table 1) resulted in a NO_3−N loss through subsurface drainage from soybean that was essentially the same (38 vs. 39 kg ha^{-1}) as from continuous corn. The latter (i.e. continuous corn) had nearly twice the NO_3−N concentration but less than 50% of the flow volume. This emphasizes the need to know both the concentration and flow volume to accurately assess the environmental impact of subsurface drainage. Furthermore, compared to 1994, the rotated corn plots in 1995 showed a substantial increase in NO_3−N concentration. This increase was presumably in response to the high rate of manure application in the fall of 1994 (table 1). Therefore, even though drainage volumes for 1994 and 1995 were similar (64 and 71 mm, respectively), NO_3−N loss through the subsurface tiles was more than three times higher in 1995 than in 1994.

Seasonal precipitation (table 1) was below average (772 mm) in 1996 and although NO_3−N concentrations were quite high, drainage volume and, therefore, NO_3−N loss was quite low (table 3). In 1997, seasonal precipitation was nearly normal, but because of lower manure N applications in both 1996 and 1997 (table 1), NO_3−N concentrations and leaching losses were quite low. In 1998, seasonal precipitation was above average and the manure N application rates were once again approximately 40% to 50% higher than in 1996 and 1997. The result was that NO_3−N concentrations and losses in drainage water from the corn plots were greater than from the soybean plots (table 3).

Partial Nutrient Balance

Crop removal and changes in surface soil−test P and K for the continuous corn and both phases of the corn−soybean rotation are shown in table 4. Volatilization and denitrification were not determined and profile data below the surface 20 cm were not included in this analysis. The measured amount of N and estimated amount of P and K removed with the grain in the rotated plots (table 1) averaged 100, 23, and 35 kg ha^{-1} for corn and 184, 20, and 70 kg ha^{-1} for soybean. When averaged for the 6 years, grain removal in the rotated plots accounted for 150%, 70%, and 119% of the annual N, P, and K applications, respectively. With continuous corn, average annual nutrient removals were 85, 19, and 28 kg ha^{-1} or 38%, 21%, and 22% of the average annual N, P, and K applications, respectively. N removal in rotated plots presumably exceeded 100% because of the N fixation by soybean. Removal of more K through grain harvest than was applied through manure in the rotated plots was due to the relatively higher K concentration in soybean seed than in corn grain. Six years of liquid swine manure application for continuous corn showed an increase in soil−test P and K (table 4). Soil−test K in the rotated plots decreased, presumably because grain removal exceeded the application rate. The removal of less P than was applied suggests that soil test P should have increased in the rotated plots, even if liquid swine manure was applied only every other year. The decrease in this study presumably reflects sample variability.

Total C and N were measured in surface samples (20 cm) in autumn 1992 (prior to applying liquid swine manure) and again following the 1998 cropping season, but we were not able to detect any significant changes or account for any of the excess N applied to continuous corn plots (data not presented). Subsurface drainage accounted for 10% to 12% of the N applied through swine manure, but we suspect that some of this loss was not only from the manure N but also other soil N pools.

Table 4. Six year N, P, and K balance and soil−test changes for continuous corn and both phases of a corn−soybean rotation at a northeast Iowa research site fertilized with liquid swine manure.

	Nutrient Balance[b]			Surface (0−20 cm) Soil Test Change	
Crop Sequence[a]	N (kg ha^{-1})	P (kg ha^{-1})	K (kg ha^{-1})	P (mg kg^{-1})	K (mg kg^{-1})
C−C−C−C−C−C	49	72	100	20	82
C−S−C−S−C−S	−92	8	−13	−21	−6
S−C−S−C−S−C	−96	14	−6	−28	−13
$LSD_{(0.1)}$	12	11	8	16	20

[a] Crop sequence during the 6−year study (i.e. C = corn; S = soybean).
[b] N balance = Applied via manure – measured grain removed – measured drainage loss.
P balance = Applied via manure – estimated amount removed with grain.
K balance = Applied via manure – estimated amount removed with grain.

Soil−test P and K both increased in the continuous corn plots (table 4) because the average application rates exceeded crop removal by nearly 80%. Within the rotated plots, soil−test P declined from an initial level of 56μg g^{-1} even though the average annual P application was approximately 35% greater than the amount removed with the grain. The slight decline in soil−test K, from an initial level of 132 μg g^{-1} in the rotated plots, was consistent with the higher K removal with soybean than with corn grain. With regard to soil−test ratings these changes were minimal, with P remaining at the “very high” level and K at the “medium” level (Voss et al., 1999).

SUMMARY AND CONCLUSIONS

The numerous challenges encountered in this six−year field study with liquid swine manure are presented to help students, teachers, policy makers and others realize the difficulties encountered with manure management in continuous corn or corn and soybean production systems. Challenges included substantial differences in ammonia−N concentrations due to the operation that provided the manure. Efforts to measure manure nutrient levels one month prior to application were not successful because even though the storage pits were agitated for three days prior to sampling, the manure was not thoroughly mixed and nutrient concentrations in the samples were much different than in the manure that was subsequently applied. The use of Hach field−tests to measure ammonia−N just prior to manure application also proved to be unsuccessful because of the very high dilution that was required before analyzing the samples.

Subsurface drainage volume was highly variable among plots but proportional to seasonal precipitation, ranging from 6% to 14% in relatively dry years (e.g. 1996) to as much as 48% in wet years (e.g. 1993). Nitrate N concentrations were also variable being influenced by drainage volume, current and prior manure application rates, and the crop being grown. As a result, NO_3−N loss was also variable ranging from 4 to 48 kg NO_3−N ha^{-1} yr^{-1}. A six−year partial nutrient balance showed that for continuous corn 52% of the applied N was harvested in grain and 16% was lost through subsurface drainage. Averaged for the corn phase of a corn−soybean rotation, grain harvest accounted for 74% of the applied N with 10% being lost through drainage water. Soil−test P and K in the surface 20 cm both increased with annual manure applications but declined slightly for the rotation.

We conclude that despite the challenges associated with managing liquid swine manure, it is very important for producers to recognize its value as a resource and for policy makers and regulators to understand that manure management is not a simple task. Some recommendations for productive and environmentally acceptable manure management programs are to develop operation−specific manure nutrient databases to guide application rates, to use TKN values to estimate plant−available N, to monitor manure loads to quantify variability and actual loading rates, and to routinely use soil−testing to determine if application rates should be based on P rather than N content in the manure.

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REFERENCES

Bakhsh, A., R. S. Kanwar, and L. R. Ahuja. 1999. Simulating the effect of swine manure application on NO_3−N transport to subsurface drainage water. *Transactions of the ASAE* 42(3): 657−664.

Coffey, M. T. 1999. A swine integrator's perspective on nutrient management procedures. *J. Anim. Sci.* 77(2): 445−449.

Dinnes, D. L., D. L. Karlen, D. B. Jaynes, T. C. Kaspar, J. L. Hatfield, T. S. Colvin, and C. A. Cambardella. 2002. Nitrogen management strategies to reduce nitrate leaching in tile−drained midwestern soils. *Agron. J.* 94(1): 153−171.

Hatfield, J. L., and B. A. Stewart (eds.) 1998. *Animal Waste Utilization: Effective Use of Manure as a Soil Resource.* Chelsea, Mich.: Sleeping Bear Press.

Hatfield, J. L., M. C. Brumm, and S. W. Melvin. 1998. Swine manure management. In *Agricultural Uses of Municipal, Animal, and Industrial Byproducts*, eds. R. J. Wright, W. D. Kemper, P. D. Millner, J. F. Power, and R. F. Korcak, 78−90. Conserv. Res. Rpt. No. 44. Washington, D.C.: USDA−ARS.

Honeyman, M. S. 1996. Sustainability issues of U.S. swine production. *J. Anim. Sci.* 74(6): 1410−1417.

Jackson, L. L., G. Hallberg, R. L. Huffman, D. R. Keeney, L. E. Lanyon, N. Lynch, and D. D. Schulte. 1996. Water quality. In *Understanding the Impacts of Large−Scale Swine Production, Proc. Interdisciplinary Scientific Workshop*, ed. K. Thu, 11−46. Iowa City, Iowa: University of Iowa.

Jackson, L. L., D. R. Keeney, and E. M. Gilbert. 2000. Swine manure management plans in North−Central Iowa: Nutrient loading and policy implications. *J. Soil Water Conserv.* 55(2): 205−212.

Janzen, R. A., W. B. McGill, J. J. Leonard, and S. R. Jeffrey. 1999. Manure as a resource – Ecological and economic considerations in balance. *Transactions of the ASAE* 42(5): 1261−1273.

Kanwar, R. S., T. S. Colvin, and D. L. Karlen. 1997. Ridge, moldboard, chisel, and no−till effects on tile water quality beneath two cropping systems. *J. Prod. Agric.* 10(2): 227−234.

Kanwar, R. S., D. Bjorneberg, and D. Baker. 1999. An automated system to monitor the quality and quantity of shallow groundwater in artificially drained agricultural fields. *J. Agric. Eng. Res.* 73(2): 123−129.

Killorn, R., and J. Lorimor. 1999. Managing manure nutrients for crop production. Iowa State University Extension, Ames, Iowa.

O'Dell, J. D., M. E. Essington, and D. D. Howard. 1995. Surface application of liquid swine manure: Chemical variability. *Commun.Soil Sci. Plant Anal.* 26(19&20): 3113−3120.

Midwest Plan Service. 1993. *Livestock Waste Facilities Handbook*. Ames, Iowa: Iowa State University.

Nowak, P. R. Shepard, and F. Madison. 1998. Farmers and manure management: A critical analysis. In *Animal Waste Utilization: Effective Use of Manure as a Soil Resource*, eds. J. L. Hatfield and B. A. Stewart, 1−32. Chelsea, Mich.: Sleeping Bear Press.

Ritchie, S. W., J. J. Hanway, H. E. Thompson, and G. O. Benson. 1994. How a soybean plant develops. Spec. Rpt. No. 53, ISU Coop. Exten. Serv., Ames, Iowa.

Ritchie, S. W., J. J. Hanway, and G. O. Benson. 1996. How a corn plant develops. Spec. Rpt. No. 48. ISU Coop. Exten. Serv., Ames, Iowa.

SAS Institute. 1999. *Statistical Analysis Software*, Ver. 8. Cary, N.C.: SAS Institute.

Shepard, R. 2000. Nitrogen and phosphorus management on Wisconsin farms: Lessons learned for agricultural water quality programs. *J. Soil Water Conserv.* 55(1): 63−68.

Sutton, A. L., S. W. Melvin, and D. H. Vanderholm. 1983. Fertilizer value of swine manure. Purdue Univ. Coop. Exten. Serv., Pork Industry Handbook Fact Sheet. Purdue Univ., W. Lafayette, Ind.

Voss, R. D., J. E. Sawyer, A. P. Mallarino, and R. Killorn. 1999. General Guide for Crop Nutrient Recommendations in Iowa. Iowa State Univ. Coop. Ext. Serv., ISU, Ames, Iowa. Available at http://www.extension.iastate.edu/Publications/PM1688.pdf.

Voy, K. D. 1995. Soil survey of Floyd County, Iowa. USDA−SCS in cooperation with Iowa Agric. and Home Econ. Exp. Stn., Coop. Ext. Serv., Iowa State University, Ames, Iowa.

Wright, R. J., W. D. Kemper, P. D. Millner, J. F. Power, and R. F. Korcak (eds.) 1998. Agricultural uses of municipal, animal, and industrial byproducts. Conserv. Res. Rpt. No. 44. Washington, D.C.: USDA−ARS.