AMMONIA VOLATILIZATION LOSSES DURING SPRINKLER IRRIGATION OF ANIMAL MANURE

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ABSTRACT

Recent work at Clemson University has provided 32 new data sets of ammonia volatilization losses during sprinkler irrigation of liquid manure. These 32 observations were pooled with 23 additional data sets that were available in the literature. The combined data includes losses from traveling gun, center pivot, and impact sprinkler irrigation of dairy, swine, and beef manure. Manure type did not affect volatilization losses. Total ammoniacal nitrogen (TAN = NH_3-N + NH_4^+-N) concentration differences between samples collected from the irrigated wastewater and samples collected in containers placed on the ground were measured as an estimate of ammonia volatilization loss. The TAN concentrations of the ground collected samples were not statistically different from TAN concentrations of the irrigated waste. In addition, it was determined that evaporation and drift were not major factors in the quantification of TAN losses. Therefore, volatilization loss from manure during the irrigation event was not found to be significant.

INTRODUCTION

Sprinkler irrigation of animal manure and wastewater onto crop, forage, and pasture land to recycle plant nutrients is a common practice in many regions of the United States. The total ammoniacal nitrogen (TAN = NH_4^+-N + NH_3-N) in liquid animal manure can account for 28% to 85% of the total Kjeldahl nitrogen (Chastain, et al., 2001; Montes, 2002) depending on the moisture content and animal species. A portion of the TAN can potentially be lost as a part of the land application process as ammonia volatilization. Ammonia volatilization loss during irrigation of manure and wastewater is an important issue due to the fact that regulatory agencies in the United States, Canada, and Europe either have prohibited the use of irrigation as a land application method or are considering the prohibition of this land application technique in order to reduce ammonia emissions from agriculture.

Volatilization losses can potentially occur during collection, transfer, storage, treatment, and land application. The majority of the volatilization losses are associated with storage, treatment, and land application of manure (MWPS, 1985; Chastain et al., 2001; and Montes, 2002). The ammonia-N losses associated with land application can occur during the application process, or over a 1 to 4 day period following application (Meisinger, and Jokela, 2000; Montes, 2002). The available data indicates that the majority of the volatilization losses associated with land application occur following the application event (Meisinger, and Jokela, 2000; Montes, 2002).

Many extension publications (e.g. MWPS, 1985; Dougherty et al., 1998) consider the ammonia loss due to irrigation to be greater than for land applied slurries and solid manure. However, extensive review of the literature (Chastain et al., 2001; Montes, 2002) and recent work on the ammonia losses following irrigation of lagoon effluent (Montes and Chastain, 2003) indicate that the losses following irrigation are no greater than for other land application methods. The volatilization losses following irrigation of dilute liquid manures, such as lagoon supernatant, are much lower than for other land application scenarios (≈ 2% of TAN applied). The mass of TAN lost is a function of the solids content of the manure, application depth, and the amount of manure intercepted by plant foliage or residue (Chastain et al., 2001; Montes, 2002).

The percentage of the TAN in the ammonia form is strongly dependent on pH. Most manure has a pH in the range of 7.0 to 8.0. About 8% to 10% of the TAN is in the ammonia form for most liquid manures (Jayaweera and Mikkelsen, 1990; Zhang, 1992; American Petroleum Institute, 1981; 1995; Ruxton, 1995; Cumby et al., 1995; Denmead et al., 1982). Therefore, only a small fraction of the TAN has the potential to be lost during the irrigation process.

Several studies have reported ammonia volatilization losses of 10 to 25% during irrigation of liquid swine manure (Sharpe and Harper, 1997; Westermann et al., 1995; Safley et al., 1992). Safley et al. (1992) attributed the majority of the irrigation losses to the influence of evaporation and drift. Earlier work by Welsh (1973), concluded that volatilization losses during the irrigation of dairy slurry, liquid swine manure, and effluent from an oxidation ditch were insignificant. Recent work at Clemson University (Montes and Chastain, 2000; Montes, 2002) supported the observations by Welsh.

Only three studies (Montes, 2002; Safley et al., 1992; and Welsh, 1973) had the quantification of ammonia losses during irrigation as a primary objective and the conclusions are mixed with regards to the importance of ammonia volatilization losses during the irrigation event. Only one of these studies (Montes, 2002) included rigorous statistical and error analyses.

The objectives of this paper are to:

- perform a pooled statistical analysis of the available data related to ammonia volatilization losses during irrigation of animal manure, and
- perform a critical analysis of the impact of evaporation and drift on volatilization losses during the irrigation event.

METHODS

A summary of the available data on ammonia volatilization losses during irrigation of animal manure is presented in Table 1. Ammonia volatilization losses were calculated from the data reported by the authors based on the difference in TAN concentration before and after irrigation. These losses ranged from -33% to 26%. The mean ammonia loss ranged from -2.5% to 13% with an overall mean of 4.0% of the TAN applied.

Negative ammonia loss values imply that NH_3 was gained during the irrigation process. While this is obviously impossible, it indicates a significant amount of uncertainty in the quantification of ammonia losses. The factors that have been proposed to affect the magnitude of ammonia loss during irrigation include: air temperature, relative humidity, irrigation pressure, drop diameter, spray velocity, TAN content of the irrigated manure, and pH (Pote et al., 1980; Denmead et al., 1982; Brunke et al., 1988; Sharpe and Harper, 1997). These factors have been suggested as the cause of the variability in measuring ammonia volatilization losses. However, most of the authors did not perform any type of error analysis on their data collection procedures.

Table 1. Summary of available data on volatilization losses during sprinkler irrigation of manure.

Description	**Irrigated TAN (mg/L)**	**Irrigated (TS %)**	**pH**	**Ammonia Loss (%)**	**n**	**Reference**
Big Gun: Dairy, Beef, Swine	187 to 850	0.3 to 8.4	7.4 to 7.9	-2.5 (-12.4 to 9.8)	5	Welsh (1973)
Center Pivot: Swine	299 to 327	0.14 to 0.17	7.4 to 7.5	4.9 (-2.1 to 18.4)	12	Safley et al. (1992)
Big Gun: Swine	214 to 510	0.11 to 0.37	7.1 to 7.7	2.9 (0.5 to 9.4)	6	Safley et al. (1992)
Big Gun: Swine	242 [1]	NR [2]	NR	5.7 (-5.0 to 24)	3	Westermann et al. (1995)
Solid Set: Swine	53 [1]	NR	NR	13	NR	Sharpe and Harper (1997)
Solid Set: Swine	109 to 1183	0.05 to 0.57	7.6 to 8.6	0.3 (-33 to 26)	32	Montes (2002)

[1] Not given directly, estimated from application data given in reference.
[2] NR = not reported

In the investigation by Welsh (1973), samples were taken from the manure storage structure before irrigation and from ground collected samples following the irrigation event. The difference in TAN concentration was used to estimate NH_3 loss due to the irrigation process. The study, conducted in Minnesota, included four different manure types with very different characteristics as is reflected by the large range in total solids and TAN concentration shown in Table 1. The average ammonia loss was -2.5% and was not significantly different from zero.

Safley et al. (1992) studied ammonia losses during sprinkler irrigation of swine lagoon effluent using center pivot and traveling gun irrigation equipment in North Carolina. Ammonia losses were estimated by calculating the difference in TAN concentration between samples taken from the lagoon and samples taken from liquid caught on the ground during irrigation. The TAN concentration difference between irrigated and ground collected samples in the data presented by Safley et al. (1992) ranged from -2.1% to 18.4% with a mean of 3.9%.

The studies by Westermann et al. (1995), and Sharpe and Harper (1997) did not include all of the data required to be included in the present study. The TAN concentrations in the irrigated manure were estimated from nutrient application rate information provided in the publications. Consequently, these data were not included in the pooled statistical analysis.

Montes (2002) collected similar ammonia volatilization data for sprinkler irrigation from two swine lagoons in South Carolina. Montes collected irrigated lagoon water samples from a sampling port in the irrigation pipe on the discharge side of the irrigation pump. The ground collected samples were the composite of samples collected in 8 locations within the irrigated plots.

The data from the studies by Welsh (1973), Safley et al. (1992), and Montes (2002) were pooled into common statistical analyses. The quantities that were included were: TS, TAN, TKN (total Kjeldahl nitrogen), and pH. The change in TS between the irrigated and ground collected samples was included to provide a measure of evaporation losses. Both TAN and TKN were included since a significant reduction in TAN during irrigation would also result in a reduction in TKN. Data on pH were included since the fraction of TAN that is in the ammonia form depends on manure pH.

ANALYSIS AND RESULTS

Pooled linear regression analyses were performed for the irrigated and ground collected concentrations of TS, TAN, and TKN. The least-squares best fit for each constituent was represented by the following equation form:

$$C_G = b\, C_I \,. \tag{1}$$

Where:
C_I = the concentration of TS, TAN, or TKN in the irrigated material,
C_G = the concentration of TS, TAN, or TKN in the ground collected material, and
b = the slope of the line.

Theoretically, the intercept of equation 1 is zero in all cases and the intercept was not significantly different from zero for all three constituents. Therefore, the analysis was performed so as to force the equation through the origin.

An analysis of variance (ANOVA) was performed for each regression. The slope of the equation, b, was compared to 1 using a t-test at the 95% confidence level since a slope of 1 represents no change in concentration during the irrigation process. The results of the three analyses of variance are given in Table 2.

Table 2. Results of the analysis of variance of the regression using equation 1 for comparison of irrigated and ground collected concentrations of TS, TAN, and TKN.

Constituent	**R^2**	**n**	**RDF [1]**	**b**	**SE b [2]**	**C.I. (b) [3]**	**SE y [4]**
TS	0.9991	57	56	1.0244 *	0.004 %	± 0.008 %	0.046 %
TAN	0.9844	55	54	0.9999	0.010 ppm	± 0.021 ppm	39.3 ppm
TKN	0.9915	55	54	0.9846	0.009 ppm	± 0.018 ppm	56.0 ppm

[1] Residual degrees of freedom.
[2.] Standard error of b.
[3.] 95% confidence interval about b.
[4.] Standard error of the y-estimate.
* Significantly different from 1 at the 95% level.

Influence of Irrigation on TS – Evaporation Loss

The correlation between the ground collected and irrigated concentrations of total solids is given in Figure 1. The ANOVA results are given in Table 2. A t-test on the slope for the TS relationship indicated that a slope of 1.0244 was significantly different from 1 (Table 2). Therefore, evaporation during irrigation increased the TS of the ground collected sample by 2.44%. Both empirical and modeling studies have shown that evaporation losses from irrigation systems vary from 1 to 3.5% (Heermann and Kohl, 1980; Thompson et al., 1993). The observation from this study is in agreement with the literature.

Influence of Irrigation on TAN

The affect of the irrigation process on the TAN concentration of animal manure is shown in Figure 2. The slope of the regression line was not significantly different from 1 at the 95% level (Table 2). As a result, the pooled analysis of 55 observations from 3 states (South Carolina, North Carolina, and Minnesota) indicated that ammonia volatilization loss during irrigation did not occur for manures with TS ranging from 0.04 to 8.4% TS, and TAN concentrations ranging from 11 to 1183 ppm.

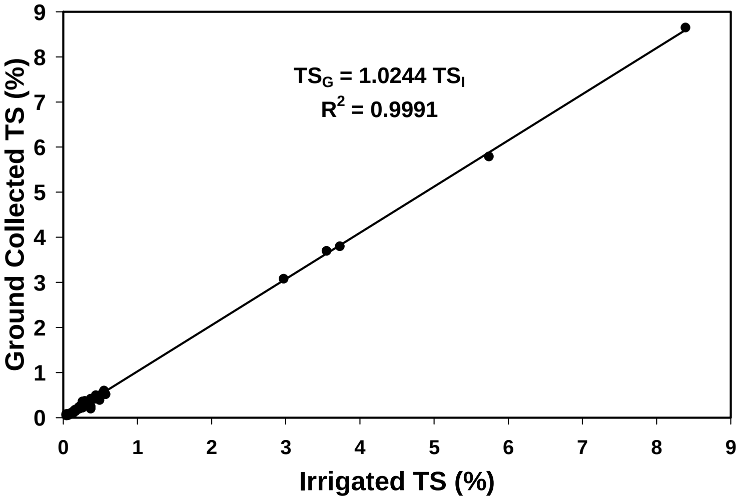

Figure 1. Change in TS concentration during irrigation of animal manure.

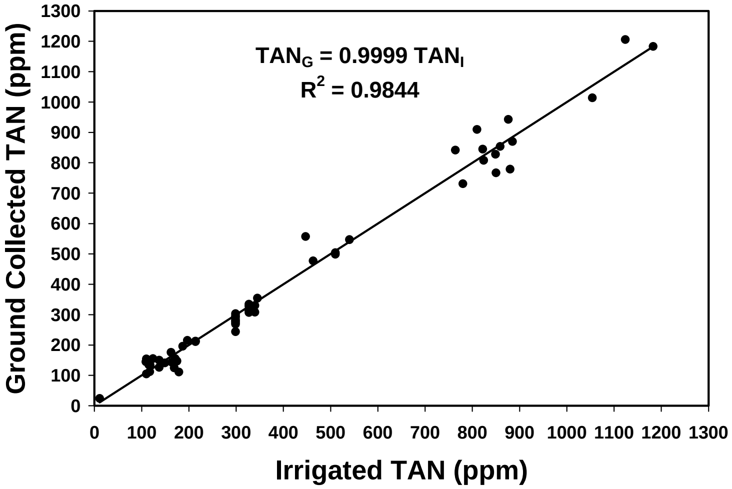

Figure 2. Variation of TAN as a result of irrigating animal manure.

Influence of Irrigation on TKN

Total Kjeldahl nitrogen is the sum of TAN and organic nitrogen. Therefore, the TKN concentration in the ground collected sample would be expected to be slightly higher even if ammonia volatilization did not occur due to small, but significant, evaporation losses. However, the data shown in Figure 3 and the statistical analysis (Table 2) indicated that the TKN concentration was not significantly affected by irrigation at the 95% level. In fact, TKN in the ground collected sample was slightly lower than TKN of the irrigated material on the average.

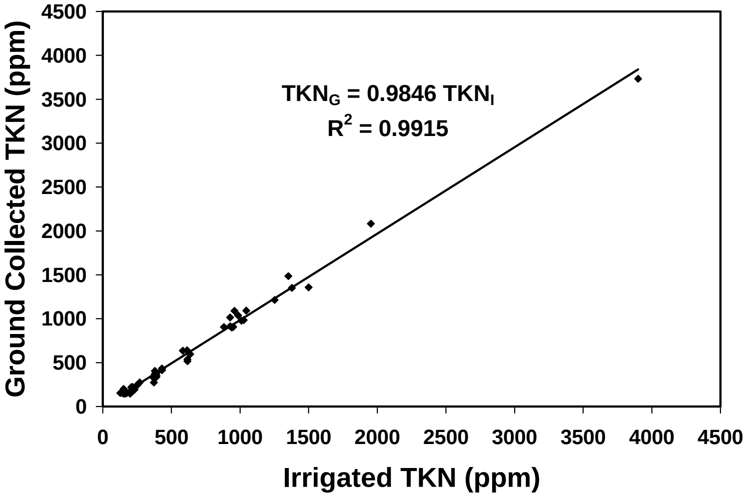

Figure 3. Variation of TKN as a result of irrigating animal manure.

Uncertainty in the Calculation of Volatilization Loss

The differences between TAN concentrations in irrigated and ground collected samples were sometimes negative as indicated in Table 1. Since it is impossible to gain TAN during irrigation, these negative values are due to the uncertainty, or lack of accuracy, in the measurements of TAN concentration.

The procedure to determine TAN concentration for irrigated and ground collected samples includes the following potential sources of error: sampling in the field, sub-sampling in the laboratory to prepare for chemical analysis, and executing the chemical analysis procedure. Each step has an associated error that contributes to the overall error in determining TAN concentration.

An estimate of the magnitude of overall error in determining TAN can be made based on the variability in TAN concentration of samples taken from similar materials and conditions. The estimate of uncertainty in TAN measurements was based on the pooled variance of 62 observations of TAN provided by Montes (2002). The pooled variance in TAN for the study by Montes (2002) was 965.3 $(mg/L)^2$. Therefore, the estimate of uncertainty in TAN concentration was the pooled standard deviation of ± 31.1 mg/L.

Calculation of the volatilization loss in percent requires taking the difference between the irrigated and ground collected concentrations. The uncertainty in the difference between two measured values can be estimated as (Taylor, 1997; Holman, 1993):

$$u_{(a-b)} = \sqrt{(u_a)^2 + (u_b)^2}\ . \qquad (2)$$

Where:
$u_{(a-b)}$ = uncertainty in knowing the difference between a and b,
u_a = uncertainty in measuring a, and
u_b = uncertainty in measuring b.

Using equation 2, and the defined uncertainty for TAN, it can be shown that the uncertainty in percent difference in concentrations between irrigated and ground collected samples can be expressed as:

$$U_{\Delta TAN} = (\pm 44\ mg/L \div TAN_I) \times 100, \tag{3}$$

Where:
$U_{\Delta TAN}$ = uncertainty in calculated loss of ammoniacal-N (%), and
TAN_I = concentration of TAN in irrigated manure (mg/L).

The uncertainty interval for TAN losses defined by equation 3 is plotted in Figure 4 with all of the data included in the present study. The upper and lower limits of the uncertainty band were limited to ± 100%. As a result a few points are not shown in the plot. These results indicate that volatilization losses were well distributed about zero. Only 10 of the 55 data points were not contained within the uncertainty interval for TAN. Furthermore, they were uniformly distributed about the line of zero difference. These results support the statistical conclusion and indicate that volatilization losses were zero within the errors induced by calculation of a percent loss and the errors associated with measurement.

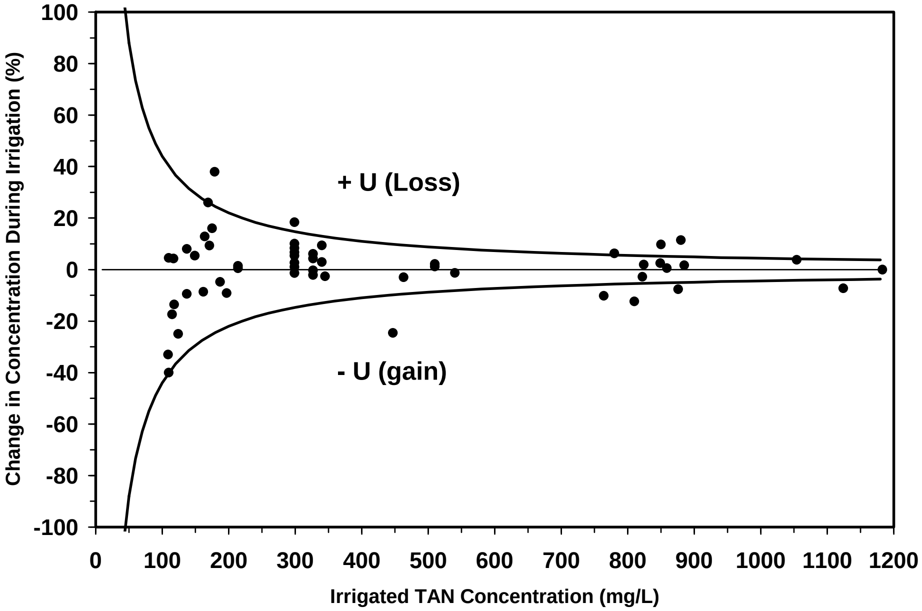

Figure 4. Comparison of the change in total ammoniacal nitrogen concentration during irrigation with the uncertainty associated with the calculation of percent differences (± U).

Influence of Evaporation and Drift

Safley et al. (1992) attempted to incorporate the influence of evaporation and drift losses into the estimation of ammonia losses during sprinkler irrigation using a center pivot. Safley reported that the ammonia losses during irrigation ranged from13.9% to 37.3 % if evaporation and drift were included. However, their concentration data indicated that volatilization losses averaged 4.9% (Table 1).

The irrigate-catch technique to estimate volume loss during irrigation was used by Safley et al. (1992). Volume loss results obtained by this technique need to be interpreted with caution since all errors are counted as an irrigation volume loss (Heermann and Kohl, 1980). The error in the irrigate-catch technique can be described as a recovery error defined as:

$$R_e = \left(1 - \frac{A_c}{A_T}\right) \times 100 . \qquad (4)$$

Where:
R_e = recovery error (%),
A_c = measured application depth (cm),
A_T = theoretical application depth (cm) based on flow measurements in the main irrigation pipe and the application area, and
A_c/A_T = fraction recovered in containers on the ground.

The recovery error includes the following effects: (1) collection error, E_C; (2) error due to the lack of uniformity of the irrigation system, E_U; and (3) error caused by evaporation losses from the sprinkler spray, E_E.

The collection error, E_C, is caused by liquid that drifts away from the collection containers, liquid that strikes the collection containers but is not trapped, liquid lost by splashing out of the collection containers, and evaporation from the collection containers. A collection error related to the type of container used was explicitly measured by Kohl (1972). Kohl showed that the collection error for 76-mm diameter rain gages ranged from 85% at an application rate of 0.09 cm/h to 12% at a rate of 0.94 cm/h when compared with a precise collecting device ($E_C \approx 0$).

The error induced by lack of uniformity, E_U, is directly related to the design of irrigation equipment and the number and distribution of collection containers used to capture the spray. Center pivot irrigation equipment typically provides an application uniformity that varies between 70 to 90% (Kruse et al., 1990; Rolland, 1982). For design purposes, 80% is typically used as the application uniformity (Kruse et al., 1990; Valmont, 2000) which yields an E_U of 20%.

Evaporation loses from sprinkler spray, E_E, are considered insignificant when compared with the effects of irrigation uniformity (Heermann and Kohl, 1980). Evaporation losses from sprinkler spray have been typically overestimated when the difference between irrigated and collected volume is used. Empirical and modeling studies have shown that evaporation losses from irrigation systems vary from 1 to 3.5% (Heermann and Kohl, 1980; Thompson et al., 1993). The results of this study indicated an average value of 2.4%. Therefore, E_E is in the range of 1 to 3.5%.

The recovery error, R_e, was estimated from these three independent uncertainties as (Holman, 1997):

$$R_e = \sqrt{(E_C)^2 + (E_U)^2 + (E_E)^2} . \qquad (5)$$

Safley used 95 mm rain gages to measure the application depth, A_C, from a Valmont Model 4871 center pivot irrigation system with an average application rate of 1.1 cm/h. The irrigation system was rated to give 80% uniformity according to the manufacturer (Valmont, 2000). Assuming a collection error of 12%, a uniformity error of 20%, and an evaporation error of 2% in equation 5 yields a recovery error of 23.4% for a center pivot irrigation system. Evaporation from the sprinkler spray accounts for only 0.7% of the total recovery error while uniformity error contributes 73%.

Setting R_e equal to 23.4% in equation 4, and solving for the fraction recovered (A_C / A_T) indicates that one would expect to recover 0.77 A_T for a typical center pivot irrigation system. However, only a tiny fraction of the total water applied would not reach the ground since the majority of the discrepancy is due to errors in the irrigate-catch technique and not a combination of evaporation and drift.

The average recovery fraction observed by Safley et al. (1992) was 0.77 indicating that their center pivot performed as expected. Safley erroneously attributed the 23% volume not collected, or recovery error, to evaporation and drift losses during irrigation using the following relationship:

$$TAN_L = \left[1 - \frac{A_c C_c}{A_T C_L} \right] \times 100 \quad . \tag{6}$$

Where:
TAN_L = total ammonia loss (%),
A_c = collected application depth (cm),
C_c = TAN concentration in the captured liquid (mg/L),
A_T = theoretical application depth (cm), and
C_L = TAN concentration in lagoon supernatant (mg/L).

As shown in Table 1, the average change in TAN concentration for Safley's center pivot study was 4.9%, which makes C_C / C_L equal to 0.951, and the mean value of A_C / A_T was 0.77. As a result, the average TAN loss reported by Safley et al. (1992) using equation 6 was 26.8%. However, the majority of the average ammonia loss predicted using equation 6 was due to error in the irrigate-catch technique and not evaporation and drift as assumed by Safley et al. (1992).

The difference in total solids concentration between samples collected from the liquid before irrigation and samples collected in containers placed on the ground during irrigation is a more accurate method to estimate the volume loss due to evaporation. The data reported by Safley et al. (1992) indicated no significant difference in total solids concentration before and after irrigation (Montes, 2002). Therefore, evaporation loss was insignificant for their data set.

Influence of Irrigation on pH

The studies by Welsh (1973) and Safley et al. (1992) provided 24 paired observations of pH of irrigated and ground collected samples. The average pH of the irrigated manure was 7.47 and the average pH of the ground collected samples was 8.04. The pooled standard deviation of the data set was 0.19. The least significant difference at the 95% level was 0.109 (error df = 46, SE diff = 0.054). Therefore, the pH of the irrigated and ground collected samples was significantly different. Irrigation increased the pH of the manure by 7.6%.

Montes (2002) only measured the pH of irrigated lagoon supernatant. The pH of the two swine lagoons in the study by Montes ranged from 7.62 to 8.55 with a mean of 8.05 and pooled standard deviation of 0.23.

CONCLUSIONS

- Irrigation of animal manure increased the TS concentration by 2.4%. Evaporation was small but statistically significant.
- Irrigation of animal manure did not influence the concentration of TAN or TKN in the ground collected samples.
- Evaporation and drift does not contribute to ammonia volatilization losses.
- The pH of manure was increased by 7.6% during the irrigation process.
- Ammonia volatilization losses during irrigation was not significant at the 95% level.
- The percent difference between irrigated and ground collected TAN concentrations was within the errors associated with the calculation of percent differences.

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