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A Model to Estimate Ammonia Loss Following Application of Animal Manure

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Abstract. *A model of ammonia volatilization loss following application of animal manure and granular fertilizer has been developed based on data from the literature and new data obtained by researchers at Clemson University. The model provides estimates of the plant available nitrogen (PAN), ratio of PAN to total nitrogen (TN), and the mass of ammonia-N lost per hectare following application.*

The new model was used to estimate the ammonia-N losses following application of granular fertilizer, lagoon supernatant, broiler litter, and untreated dairy slurry to a field covered with crop residue. Broadcast application of 100 kg PAN/ha resulted in ammonia-N losses ranging from 0.4 kg NH_3-N/ha for lagoon supernatant to 48 kg NH_3-N/ha for dairy slurry. The ammonia-N loss for granular fertilizer (25 kg NH_3-N/ha) was greater than for poultry litter (7.4 kg NH_3-N/ha).

The influence of application methods such as band spreading, band spreading with immediate soil coverage, direct injection, and immediate incorporation with light tillage was studied using the model. The results indicated that these practices could reduce the mass of ammonia-N lost per hectare by 51% to 94%. Model results indicate that the time lag between application and incorporation should be no more than 24 h for granular fertilizer, 6 h for poultry litter, and 12 h for dairy slurry.

Model results point out that new types of spreading equipment are needed to allow agricultural producers to achieve optimum soil conservation benefits, while minimizing volatilization loss following application of animal manure.

Keywords. Ammonia volatilization, land application, manure management

Introduction

Animal manure is commonly used to fertilize hay fields, pastures, and row crops. In all cases, nitrogen will be lost to the atmosphere by ammonia volatilization to some extent. Volatilization loss of nitrogen equates to a financial loss to the farmer, and is also an environmental concern due to the potential for acid rain formation and deposition into sensitive ecosystems.

Manure is typically applied to hay fields, pastures, or no-till fields using some type of broadcast method without mechanical incorporation (e.g. tillage). Current conservation tillage practices generally do not include tillage to incorporate animal manure or fertilizer. Therefore, the amount of nitrogen lost to the air by volatilization can be significant.

The economic and environmental impacts associated with ammonia losses have given rise to a need for better estimates of the amount of ammonia-N lost from crop fields and grasslands. Better estimates of ammonia-N loss can be used to evaluate practices to reduce the release of ammonia to the atmosphere.

A significant amount of work has been conducted at Clemson University to better quantify ammonia volatilization associated with application of animal manure. Recent data by Montes (2002) and analysis presented by Chastain and Montes (2004), have indicated that ammonia volatilization losses during irrigation of animal manure is insignificant at the 95% level of probability. In addition, new data have been obtained to quantify ammonia-N losses following application of lagoon supernatant and poultry litter on forestland (Montes, 2002; Montes and Chastain, 2003; Montes and Chastain, 2005). Pooled analysis of the new data with data from the literature indicated that ammonia-N loss from the forest floor, hay, grass, and crop residue were not significantly different. All available data were combined to develop a model to estimate ammonia volatilization losses following application of animal manure. Losses following application of granular ammonium-N fertilizer were included for comparison.

The objectives of this paper are to: (1) provide a summary of the ammonia volatilization model, (2) compare the model to current Clemson University Extension recommendations, and (3) compare the ammonia-N losses following application of lagoon supernatant, poultry litter, dairy slurry, and granular ammonium fertilizer using various application methods.

Model Description

Nitrogen can be present in manure as ammonium-N, ammonia-N, organic-N, and nitrate-N. Not all of the nitrogen in manure is immediately available for plant use. The nitrogen that is available for plant use is called the plant available nitrogen (PAN).

Most animal manure contains very little nitrate-N and as a result it is typically not measured. However, manure that receives aerobic treatment, i.e. composting or aeration, should be analyzed for nitrate-N.

Most laboratories measure the total ammoniacal nitrogen content (TAN) of animal manure, which is NH_4^+-N + NH_3-N. The total ammoniacal nitrogen concentration is often reported by university laboratories as ammonium-N (NH_4^+-N).

The plant available nitrogen in animal manure, compost, or sludge can be estimated as:

$$\text{PAN} = A_f \, \text{TAN} + m_f \, \text{Organic-N} + \text{Nitrate-N}. \quad (1)$$

Where:

A_f = the ammonium-N availability factor, and
m_f = the organic-N mineralization factor.

Therefore, the plant available nitrogen is the sum of the TAN that is not lost by volatilization, the portion of the organic-N that is mineralized during the growing season, and all of the nitrate nitrogen.

The fraction of the TAN that can be used by a crop is represented by the ammonium-N availability factor (A_f). The ammonium-N availability factor is calculated from the ammonia-N lost as:

$$A_f = (1- AL(t)) / 100. \quad (2)$$

Where,

AL(t) = the ammonia-N lost following application expressed as percentage of TAN applied
= 100 (NH_3-N(t) /TAN-applied), and
t = time following application (h).

The current recommendations by Clemson University Extension for A_f are (CAMM, 2005):

- 0.5 for surface applied manure with no incorporation,
- 0.8 for surface application followed by incorporation within 24 hours,
- 0.8 for irrigation of lagoon supernatant or liquid manure, and
- 1.0 for direct injection or immediate incorporation.

The relationship used to describe the ammonia-N loss following application of animal manure or granular fertilizer is:

$$AL(t) = f_S \; f_A \; AL_{\max}\left(1 - e^{-Kt}\right). \quad (3)$$

Where,

f_S = a soil contact factor that ranges from 0.7 to 1.0, Table 1,
f_A = application method factor that depends on the method of application, Table 2,
AL_{max} = the maximum ammonia-N loss possible,100 (NH_3-N/TAN-applied), Table 3, and
K = a rate constant that is a function of manure type and wind speed (h^{-1}), Table 4.

The basic form of equation 3 was first used by Demeyer et al. (1995) for fertilizer, and was later shown to be valid for manure by Montes (2002; Montes and Chastain, 2003; Montes and Chastain, 2005).

Values and relationships for f_S , f_A , AL_{max}, and K are summarized in Tables 1 through 4 for a variety of application methods, several types of animal manure, and granular fertilizer.

Table 1. Soil contact factors for use with equation 3 (based on review by Montes, 2002).

Description	f_S
Application to grass, crop residue, forest floor, or standing crop (any material)	1.0
Application to bare soil	
Fertilizer or manure with TS ≤ 2%	1.0
Manure with TS = 3.5%	0.9
Manure with TS = 5.0%	0.8
Manure with TS ≥ 10 %	0.7

Table 2. Application method factors (based on Chastain et al., 2001 and Montes, 2002).

Application Method	f_A
Broadcast or irrigation	1.0
Band spreading (drop or trail hose)	0.5
Trenching with sliding foot	0.12
Shallow injection	0.10
Direct injection or immediate incorporation	0.08

Table 3. Recommended values for the maximum ammonia-N loss following application of animal manure and granular fertilizer (based on reviews and data by Chastain et al., 2001; Montes, 2002; Montes and Chastain, 2003; Montes and Chastain, 2005).

Material	Recommended Values for AL_{max} (%)	Variable Range
Lagoon Water	$AL_{max} = 14.30\ TS - 4.74$ ($R^2 = 0.791$, n = 12, $SE_y = 0.57\%$)	$0.39\% \leq TS \leq 0.57\%$
Swine Manure	$AL_{max} = 3.284\ TS$ ($R^2 = 0.875$, n = 23, $SE_y = 7.35\%$)	$0.57\% < TS \leq 19\%$
Dairy Manure	$AL_{max} = 20.87\ TS^{0.461}$ ($R^2 = 0.811$, n = 18, $S_{RES} = 10.45\%$)	$0.9\ \% < TS \leq 22\%$
Poultry Litter (bedded)	$AL_{max} = 4.387\ TS - 306.5$ ($R^2 = 0.658$, n = 10, $SE_y = 8.92\%$)	$71\% \leq TS \leq 79\%$
Poultry Manure (Layer or unbedded)	$AL_{max} = 85.1 - 0.938\ TS$ ($R^2 = 0.584$, n = 5, $SE_y = 18.2\%$)	$16\% \leq TS \leq 61\%$
Urea, $(NH_4)_2SO_4$	$AL_{max} = 20$ (S = 14.3%, n = 13)	$3.5\% \leq AL_{max} \leq 50\%$

Table 4. Recommended rate constants (K) for ammonia-N loss following application of animal manure and granular fertilizer (based on data and literature review by Montes, 2002).

Material	Recommended Values for K (h^{-1})	Range (h^{-1})
Lagoon Water	0.750 (S = 0.119, n = 12)	$0.528 \leq K \leq 2.09$
Animal Manure (Swine, Dairy, Poultry)	$K = 0.073 + 0.00103\ TS$ ($R^2 = 0.960$, n = 5, $SE_y = 0.007$)	$0.019 < K \leq 0.18$ ($3.9\% \leq TS \leq 74\%$)
Poultry Litter	0.150 (S = 0.119, n = 9)	$0.105 < K \leq 0.184$
Urea, $(NH_4)_2SO_4$	0.032	$0.02 < K < 0.20$

At the present, Clemson University Extension recommends that a value of 0.6 be used for the mineralization factor, m_f, for all types of animal manure. Therefore, 60% of the organic-N is assumed available in all cases using Clemson Extension's recommendations.

Evanylo (2000) provided a detailed review of research related to factors that effect mineralization of animal manure. The actual amount of organic-N that will be mineralized depends on manure type, level of treatment, soil pH, soil temperature, soil moisture content, and soil type. Evanylo concluded that animal species and manure treatment were the main factors that should be considered to estimate values for m_f.

The model includes the results of Evanylo's review and a few other reviews of the literature. The values of m_f recommended for use with equation 1 are given in Table 5. The ranges of m_f are also given to indicate the large amount of variation in the available data.

Table 5. Estimates of organic-N mineralization factors (Evanylo, 2000; Mikkelsen, et al., 1995; and Rynk et al., 1992).

Material	Recommended value of m_f (range)
Dairy and beef manure (untreated)	0.4 (0.13 to 0.51)
Swine manure (untreated)	0.5 (0.25 to 0.50)
Poultry manure (litter and untreated layer manure)	0.6 (0.47 to 0.90)
Lagoon supernatant	0.7 (0.5 to 0.9)
Anaerobically treated manure or sludge	0.6 m_f (based on species)
Compost	0.12 (0.06 to 0.12)

The nutrient content of animal manure varies significantly based on species, amount of water added for handling, and level of treatment. Representative animal nutrient data are provided for common types of animal manure used in the Southeastern US in Table 6. Additional information on the nutrient content of animal manure is provided in the manuals of the Confined Animal Manure Managers Program (CAMM, 2005).

Table 6. Nutrient and solids content of selected types of animal manure (Chastain et al. 2001; broiler litter data from Coloma, 2005).

TS =	0.37%	2.0%	7.0%	75.6%
	Swine Lagoon Supernatant	Untreated Swine Manure[1]	Untreated Dairy Slurry	Broiler Litter
Constituent	--------------	kg /1000 L	--------------	kg / 1000 kg
TAN [2]	0.41	1.37	1.13	5.0
Organic - N	0.17	0.67	1.63	22.0
TN [3]	0.58	2.04	2.76	27.0
P_2O_5 [4]	0.34	1.61	1.68	33.0
K_2O [5]	0.73	1.70	2.52	28.5
Ca	0.10	0.44	1.20	22.0
Mg	0.055	0.288	0.575	4.5
Zn	0.004	0.034	0.025	0.3
Cu	0.002	0.031	0.006	0.3
Mn	0.001	0.014	0.022	0.3
S	0.037	0.156	0.371	5.3
Na	0.22	0.30	0.38	6.7

[1] The total solids content from flush and pit-recharge buildings will vary from 1.5% to 2.6% depending on building design and animal weight. A mean value of 2% is shown.
[2] TAN = NH_4^+-N + NH_3-N
[3] TN = Organic-N + TAN
[4] Total phosphorus expressed as P_2O_5. To get elemental P multiply by 0.44.
[5] Total potassium expressed as K_2O. To get elemental K multiply by 0.83.

The material application rate (MAR, 1000 kg/ha or L/ha), or the amount of manure needed per hectare to provide the N requirement, is calculated as:

$$\text{MAR} = \text{N requirement (kg/ha)} \div \text{PAN}. \quad (4)$$

Where,

PAN = Plant available nitrogen content, kg PAN / 1000 kg or kg PAN / 1000 L.

The amount of ammonia-N lost per hectare following application of animal manure or fertilizer was calculated as:

$$M_{AL} = (AL(\text{t})/100) \cdot \text{TAN} \cdot \text{MAR}. \quad (5)$$

Where,

M_{AL} = mass of ammonium-N lost (kg/ha), and
TAN = kg TAN/ 1000 kg or kg TAN / 1000 L.

Results

Comparison of Extension Recommendations with the New Model

The estimates of A_f , m_f , and PAN/TN based on Clemson University Extension recommendations and the model are compared for four types of animal manure and granular fertilizer in Table 7. In all cases, the manure or fertilizer was assumed to be broadcast on a hay field, or a field covered with crop residue. It was also assumed that no tillage, rain or irrigation for seven days. Therefore, these results reflect the maximum ammonia-N loss.

Table 7. Comparison of ammonia availability factors (A_f), mineralization factors (m_f), and PAN/TN values for application of animal manure and fertilizer on grassland or residue covered fields (no incorporation, irrigation or rain for seven days).

	Clemson Extension [1]			New Model [2]		
Material	A_f	m_f	PAN/TN	A_f	m_f	PAN/TN
Untreated Dairy Slurry (TS = 7%)	0.50	0.6	0.56	0.49	0.4	0.44
Untreated Swine Manure (TS = 2%)	0.50	0.6	0.53	0.93	0.5	0.79
Broiler Litter (TS = 75.6%)	0.50	0.6	0.58	0.75	0.6	0.63
Lagoon Supernatant (TS = 0.37%)	0.80	0.6	0.74	0.99	0.7	0.91
Granular Fertilizer	1.0	NA[3]	1.0	0.80	NA	0.80

[1] Based on current recommendations from Clemson University Extension (CAMM, 2005).
[2] Based on equations 1 and 2.
[3] Not applicable

The greatest difference between the two methods is in the estimate of ammonium-N availability. The differences in A_f range from 2% for untreated dairy slurry to -86% for untreated swine manure. The Clemson Extension value over predicts ammonia-N losses, (1 - A_f), for irrigation of swine lagoon supernatant by 95% as compared to the new model.

Mineralization rates differed between the two methods by 0% to 33%. The best agreement was for broiler litter and the worst agreement was for dairy slurry.

The value of PAN/TN encompasses the overall differences in the two methods, and is directly related to the economic value of manure. The differences in PAN/TN estimates ranged from -23% for lagoon supernatant to 21% for dairy slurry. The best agreement in PAN/TN estimates was for broiler litter.

At the present, ammonia volatilization loss following application of granular fertilizer is ignored by many extension publications. The model uses a mean value for A_f of 0.80. Therefore, 20% of the purchased N would be lost following broadcast application onto a residue covered field or pasture.

Variation in Ammonia Loss with Time Following Application

The model provides a method to estimate the rate of ammonia-N loss following application of manure or granular fertilizer. The rate of ammonia-N loss is controlled by the rate constant, K, in equation 3. The value of K varies with the material and wind speed. At the present, variation in wind speed is not included in the model. However, as wind speed increases, K increases in magnitude. Recommended values for the rate constant for different types of manure and granular fertilizer were given in Table 4.

The influence of the rate constant on ammonia-N loss rates following broadcast of animal manure and granular fertilizer are compared in Figure 1. The ammonia-N loss, in the figure, was expressed as the fraction of maximum ammonia-N Loss as $AL(t) / AL_{max}$.

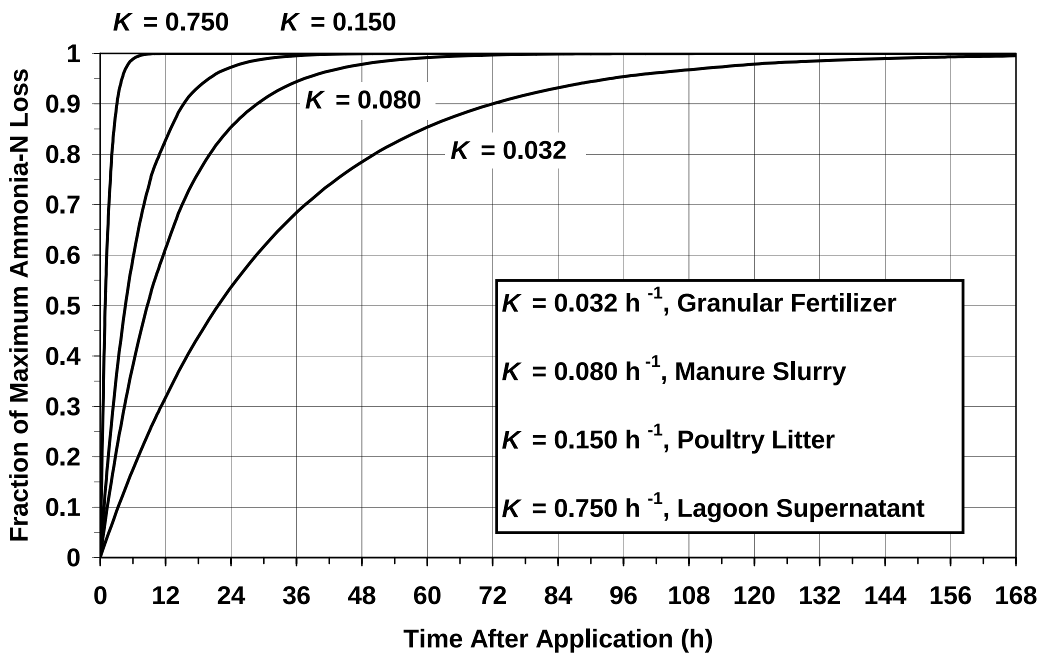

Figure 1. Rate of ammonia-N loss as determined by the value of the rate constant (*K*).

The results in the figure indicate that the rate of ammonia-N loss is slowest for granular fertilizer. Therefore, substantial nitrogen savings can be obtained by providing incorporation by either a light tillage operation, or irrigation of at least 13 mm of water within 6 to 24 hours following a broadcast application.

Ammonia volatilization occurs more quickly for animal manure than granular fertilizer and the rate depends on manure consistency and the amount of liquid that can infiltrate into the soil. Lagoon supernatant quickly infiltrates into the soil, and as a result, volatilization only occurs for about 6 hours. The high porosity of poultry litter permits ammonia to be released more slowly than lagoon supernatant, but still much faster than a slurry (K = 0.08, TS = 7%).

The variation in K greatly influences incorporation timing after a broadcast application. Incorporation of poultry litter must occur within 6 hours following application if a substantial savings of N is to be obtained. Incorporation of manure slurry should occur within 8 to 12 hours after a broadcast application to reduce volatilization losses by 40% to 50%. No incorporation can follow irrigation.

Influence of Land Application Techniques on Ammonia-N Loss per Hectare

Several application techniques can be used with animal manure and granular fertilizer to reduce ammonia-N losses from no-till or strip-till fields. Spreaders that place bands of fertilizer (drop/side dress) or manure (trail hose) on the surface can be used. Irrigation with a least 13 mm of water within a few hours of spreading manure or fertilizer can also wash ammonium-N into the soil and greatly reduce volatilization losses. Towed hose or tank injectors are available to allow immediate incorporation of bands of liquid or slurry manure with minimal disturbance of crop residues.

The ammonia volatilization model was used to calculate the ammonia-N lost following application of 100 kg of plant available nitrogen per hectare for several application methods. Model results are compared for application of granular fertilizer, lagoon supernatant, broiler litter, and dairy slurry to residue covered fields in Table 8. The values of f_A used in equation 3 were given in Table 2. Nutrient data used were from Table 6, and the granular fertilizer was assumed to be 17% ammonium-N.

Table 8. Comparison of ammonia nitrogen loss estimates following application of granular fertilizer and animal manure to provide 100 kg PAN/ha to fields covered with crop residue.

Description of Application	Granular Fertilizer	Lagoon Supernatant (TS = 0.37%)	Broiler Litter (TS = 75.6%)	Untreated Dairy Slurry (TS = 7%)
Method	------------------ Ammonia-N Loss (kg N/ha) ------------------			
Broadcast [1]	25	0.4	7.4	48
Band / trail hose	11	0.2	3.6	19
Trench with sliding foot	N/A	N/A[2]	N/A	4.0
Shallow injection	N/A	N/A	N/A	3.4
Injection or immediate incorporation	1.6 [3]	N/A	0.6	2.7

[1] Assumes no rain or irrigation for 7 days.
[2] Not applicable.
[3] No-till drill with band spreading and soil coverage with coulters.

The material that had the highest ammonia nitrogen loss following a broadcast application was dairy slurry. The losses were the highest because dairy manure had the lowest ammonium-N availability and the lowest organic-N mineralization rate (Table 5). All of the alternative spreading methods given in Table 8 significantly reduced nitrogen losses as compared to broadcast. The reductions in nitrogen loss ranged from 60% for band spreading to 94% for direct injection.

Direct injection is one of the best options currently available for reduction in ammonia volatilization. However, it is best used with liquid or slurry manure. It is not recommended for lagoon supernatant due to the higher cost, and lack of N conservation benefits.

The quantities of ammonia-N lost per hectare following application of litter was much lower than expected. The reason was the much lower value of A_f used for the model as compared to most extension recommendations (e.g. Table 7; MWPS, 1993; NRAES, 1999). However, if it is possible to band spread poultry litter, or to provide immediate incorporation, the nitrogen loss could be reduced by 51% (band spreading) to 92% (immediate incorporation).

Broadcast application of granular NH_4^+-N fertilizer is a poor choice for conservation tillage systems. For every 100 kg of PAN spread, 25 kg of nitrogen would be wasted. The results given in the table indicate that band or side dress spreading, or use of a no-till drill that band spreads and covers fertilizer with soil should be used. Incorporation could also be achieved by providing 13 mm of water soon after a broadcast application.

Influence of Time Lag Between Broadcast and Incorporation on Ammonia-N Loss

If irrigation or some sort of light tillage operation will be used to reduce nitrogen losses following application of fertilizer, poultry litter or dairy slurry the rate of volatilization needs to be considered. If too much time elapses between application and incorporation, no benefit will be realized.

The affect of time lag between broadcast application and incorporation of fertilizer, broiler litter, and dairy slurry is provided in Table 9.

Table 9. Affect of time lag between broadcast application and incorporation on ammonia nitrogen loss from residue covered fields fertilized to provide 100 kg PAN/ha.

Time between broadcast and incorporation or irrigation [1] (h)	Granular Fertilizer	Broiler Litter (TS = 75.6%)	Untreated Dairy Slurry (TS = 7%)
	----- Ammonia-N Loss (kg N/ha) -----		
0	1.6	0.6	2.7
4	2.5	3.2	9.8
8	4.7	5.1	18
12	6.8	6.1	25
24	12	7.2	38
36	16	7.4	44
48	19	7.4	47
No incorporation [1]	25	7.4	48

[1] Assumes no rain or irrigation for 7 days.

Assuming that the goal of incorporation is to reduce nitrogen losses by half, model results indicate that incorporation should occur within 24 h of application for fertilizer, within 6 h of application for poultry litter, and within 12 h of application for dairy slurry.

Incorporation of dairy slurry or poultry litter within 24 h is a common extension recommendation to reduce nitrogen loss. However, the results given in Table 9 indicate that such a practice may be of minimal benefit. Immediate incorporation using a second tractor with a light tillage implement would solve this problem. However, many producers are reluctant to use a second tractor due to increased fuel and labor costs. Using an irrigation system to stop volatilization losses may be impractical or impossible.

On a very windy day, the maximum allowable time lag between application and incorporation will be much shorter than indicated by the results given in Table 9. Windy conditions can cause the rate constant in the model to double or even triple. Model results, shown previously in Figure 1, point out that high *K*-values on the day of application may negate all benefits of a second trip across the field for manure incorporation. Equipment that provides application and immediate incorporation of solid and slurry manure, in a single trip across the field, is needed to maximize N utilization and minimize ammonia volatilization.

Additional research is needed to reduce volatilization losses from hay fields, pastures, and no-till fields. Quantification of soil conservation impacts of using minimum or strip tillage with animal manure as compared to no-till are needed. New types of spreading equipment are needed to allow agricultural producers to achieve optimum benefits of soil conservation, while minimizing the loss of N by volatilization following application of animal manure or fertilizer.

Summary and Conclusions

A model of ammonia volatilization losses following application of animal manure and granular fertilizer has been developed based on data from the literature and new data obtained by researchers at Clemson University. The model includes the affects of manure type, total solids content, characteristics of the soil surface (bare or covered with a crop or residue), application method, and rate of ammonia-N loss.

The model was combined with a range of organic-N mineralization factors from the literature to provide estimates of the plant available nitrogen (PAN), ratio of PAN to total nitrogen (TN), and the mass of ammonia-N lost per hectare.

Model predictions were compared with current Clemson University Extension recommendations. It was determined that, compared to the model, Clemson Extension recommendations over predict ammonia-N losses following irrigation of lagoon supernatant by 95%. The best agreement between the two methods was in the estimate of ammonia-N loss for dairy slurry (2%). The difference in mineralization factors used by the two methods ranged from 0% to 33%. The differences in estimates in the value of PAN/TN ranged from -23% to 21%.

The model was used to estimate the ammonia-N losses following application of granular fertilizer (17% ammonium-N), lagoon supernatant, broiler litter, and untreated dairy slurry to a residue covered field. Calculations were performed to determine the amount of material required to provide 100 kg PAN/ha. Broadcast application, with no rain or irrigation for 7 days, resulted in ammonia-N losses ranging from 0.4 to 48 kgNH_3-N/ha. The highest loss was for dairy slurry, and the lowest loss was for irrigation of lagoon supernatant. The ammonia-N loss for granular fertilizer (25 kg NH_3-N/ha) was greater than for poultry litter (7.4 kg NH_3-N/ha).

The influence of application methods such as band spreading, band spreading with immediate soil coverage, direct injection, and immediate incorporation with light tillage was studied using the model. The results indicated that these practices could reduce the mass of ammonia-N lost per hectare by 51% to 94% for all materials. Irrigation of lagoon supernatant was equivalent to immediate incorporation.

The model was also used to determine the affect of time lag between application and incorporation of fertilizer, broiler litter, and dairy slurry. Assuming that incorporation must reduce nitrogen losses by half, model results indicate that incorporation should occur within 24 h for fertilizer, 6 h for poultry litter, and 12 h for dairy manure. These short time periods may not be practical in many situations.

New types of spreading equipment are needed for use with solid and slurry manure to optimize soil conservation while minimizing ammonia volatilization losses.

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