Simulating the Fate of Fall- and Spring-Applied Poultry Litter Nitrogen in Corn Production

Gary Feng*
Haile Tewolde
USDA–ARS
Genetics and Sustainable Agricultural Research Unit
Mississippi State, MS 39762

Liwang Ma
USDA–ARS
Agricultural Systems Research Unit
Fort Collins, CO 80526

Ardeshir Adeli
USDA–ARS
Genetics and Sustainable Agricultural Research Unit
Mississippi State, MS 39762

Karamat R. Sistani
USDA–ARS
Food Animal Environmental Systems Research Unit
Bowling Green, KY 42104

Johnie N. Jenkins
USDA–ARS
Genetics and Sustainable Agricultural Research Unit
Mississippi State, MS 39762

Knowledge of the fate of manure N is important to effectively manage it and minimize its environmental impact. The system model RZWQM2 was calibrated and evaluated using 3 yr of data to simulate the mineralization and fate of fall- and spring-applied poultry litter N. Litter (18 Mg ha^{-1}) and, for comparison, NH_4NO_3 (202 kg N ha^{-1}) were applied in fall and spring from 2006 to 2008 in a corn (*Zea mays* L.) field near Starkville, MS. The model estimated that 57% (279 kg ha^{-1}) of the total litter N applied in the fall and 51% (249 kg ha^{-1}) of that applied in the spring had mineralized by the end of the first year in November. The loss of mineralized litter N by the end of the first year was 24 vs. 9% of the total applied for the fall vs. spring applications, respectively. At the end of the experiment in November 2008, 88% of the total 1507 kg ha^{-1} litter N applied in the previous three falls and 72% of that applied in the previous three springs was mineralized. The loss of mineralized litter N averaged across the 3 yr was 162 kg ha^{-1} (37% of the total mineralized) if applied in the fall and only 55 kg ha^{-1} (15% of the total mineralized) if applied in the spring. The primary avenue of litter N loss was leaching if applied in the fall and denitrification if applied in the spring. These results clearly demonstrate that spring is the best time to apply litter in the southeastern United States.

Nearly half of the US broiler chicken production is located in the southeastern region. Georgia, Arkansas, Alabama, and Mississippi are the top four states with the highest broiler chicken production and associated manure generation. An estimated 25 million Mg of poultry litter, which accounted for 48% of the total litter in the United States, was generated in these four states (National Agricultural Statistics Service, 2009). More than 10% of the nation's poultry supply was from Mississippi, which generated approximately 5 million Mg of broiler litter annually, containing about 28,480 Mg of total N and 6300 Mg of total P (Oldham, 2011).

The large volume of poultry litter, as a nutrient-rich fertilizer and soil amendment, is commonly land applied to pastures and row crops. Correct timing of application can maximize the fertilizer value of the litter and also improve soil organic matter and quality. Inappropriate timing of application on agricultural lands can result in potential contamination of the atmosphere, groundwater, and surface water bodies. Development of sound manure management practices for land application requires determining the right time and the right rate for a site-specific amount of manure application to meet the nutrients needs of different crops at each growth stage.

In the humid Mid-South region, due to an average total precipitation of 437 mm between January and April, the land is soggy most of the time, with only a short window for field operations in the spring. Therefore, farmers choose to apply litter before this period in the fall. However, the loss of nutrients to the environment during the fall and winter months following fall litter application and before

Soil Sci. Soc. Am. J. 79:1804–1814
doi:10.2136/sssaj2015.06.0211
Received 1 June 2015.
Accepted 25 Sept. 2015.
*Corresponding author (Gary.Feng@ars.usda.gov).

planting is a great concern. The mild fall and winter temperatures in the southeastern region will probably cause mineralization of fall-applied litter N, increasing the vulnerability of the N to loss. Knowledge of the degree of mineralization and loss of the mineralized N through different pathways is critical to properly manage N if litter is applied in the fall. Such knowledge, however, is scarce, partly because it is difficult or expensive to monitor N mineralization and quantify the loss by leaching, volatilization, and other pathways during such an extended period. Computer simulation models can help understand the interactions among various N processes in the soil–plant system and determine the fate of applied N.

A well-calibrated modeling system using short-term, site-specific experimental results can help determine the fate of fall-applied litter N and extend the results to other soils and weather conditions. The Root Zone Water Quality Model 2 (RZWQM2) is such an agricultural system model developed by the USDA–ARS (1992) for assessing agriculture sustainability and many other agricultural applications, with emphasis on water and nutrient management effects on both water and soil quality and crop production (e.g., Blicher-Mathiesen et al., 2014; Kladivko et al., 2014; Malone et al., 2014).

The RZWQM2 model has been applied to simulate crop production and water quality as affected by manure management. Ma et al. (1998b) evaluated the soil NO_3 response to beef-manure application on a corn field and tested the RZWQM (the older version of RZWQM2) for manure management in Colorado. In Iowa, Kumar et al. (1997) applied RZWQM to a corn–soybean [*Glycine max* (L.) Merr.] production system and Bakhsh et al. (1999) applied it to a continuous-corn production system to simulate the effect of swine manure application on NO_3–N losses with subsurface drainage water. Ma et al. (1998a) used RZWQM to simulate water and NO_3–N movement in a tall fescue (*Festuca arundinacea* Schreb.) field after broiler litter applications in Arkansas. Since then, many improvements have been made for most components of the RZWQM, and many new features have been added to the model (Ma et al., 2012). The model has not been used to study the fate of broiler litter N in cropland in the Mid-South, although field poultry litter application as fertilizer on agricultural lands in the region has been used for decades. In addition, poultry litter N transformation and the multiple pathways by which N may be lost following fall application of manure need to be studied in terms of N leaching and the residual N for the following crop. The objectives of this study were to: (i) calibrate and validate the RZWQM2 (Version 2.60.3) using 3 yr of experimental data in a corn field after poultry litter applications; (ii) apply the model to develop better timing of litter application; and (iii) analyze and quantify simulated litter N mineralization and loss from litter applied in the fall vs. spring.

MATERIALS AND METHODS

Field Experiment

The experimental site was located at the R.R. Foil Plant Science Research Center of Mississippi State University near Starkville in Oktibbeha County, Mississippi, on a Leeper silty clay loam (a fine, smectitic, nonacid, thermic Vertic Epiaquept) soil with total N of only 0.6 g kg^{-1} and a C/N ratio of 12.0 before the experiment (Table 1). The 0.4-ha field was almost level (slope and aspect = 0, elevation = 104 m asl, 33°38′ N, 88°46′ W). Daily weather data including maximum and minimum air temperature, solar radiation, wind run, relative humidity, and precipitation were recorded on site with a standard NRCS Agricultural Meteorological Network weather station (site no. 2064; http://www.wcc.nrcs.usda.gov/nwcc/site?sitenum=2064&temp_unit=9). The simulation period comprised both wet years (1402 mm in 2006 and 1303 mm in 2008) and a dry year (860 mm in 2007).

Broiler chicken litter (18 Mg ha^{-1}) and NH_4NO_3 (202 kg N ha^{-1}) were applied to the same plots in the fall and spring of the 2006, 2007, and 2008 corn growing seasons in a 2 × 2 factorial combination. As shown in Table 1, there were five treatments including an unfertilized control in a randomized complete block design with four replications. Each plot consisted of six, 17-m-long rows.

Table 1. Description of treatments and moisture, N, and C concentrations of poultry litter and soil (background sampled on 2 Dec. 2005).

Treatment	Applied poultry litter	Applied NH_4NO_3	Application date 2005	2006	2007	2008	Application method
	Mg ha^{-1}	kg N ha^{-1}					
Control	0	0	–	–	–	–	–
L18F	18	0	10 Nov.	13 Nov.	8 Nov.		broadcast
L18S	18	0		12 Apr.	30 Mar.	15 Apr.	broadcast
F202F	0	202	10 Nov.	13 Nov.	8 Nov.		knifed
F202S	0	135		9 May	25 May	5 June	knifed
			Soil	Litter			
			g kg^{-1}				
Moisture			–	352	405	195	
Total N			0.6	27.3	23.7	32.7	
NH_4–N			0.0	5.0	5.9	3.1	
NO_3–N			0.0	0.0	0.0	0.2	
Total C			7.2	241	224	307	
C/N ratio			12.0	8.8	9.5	9.4	

The litter was obtained from a local operation in November of each season and applied immediately by hand for the fall treatment. Litter from the same batch was placed in large, double-layered plastic bags and stored in large plastic tubs with lids under shade during the winter until application for the spring treatment. The litter was incorporated into the soil on the same day with an incorporation intensity of 1.0, which means the litter was assumed to be completely incorporated into the soil. The litter was analyzed for total C and total N by the dry combustion method after treating with HCl, drying at 65°C, and grinding to pass a 1-mm screen (Table 1).

The fall NH_4NO_3 was applied at the same time as the fall litter. This treatment, which supplied N in 100% mineral form, was included to estimate the magnitude of loss of litter N applied in the fall. A third of the spring-applied NH_4NO_3 was applied on the same day as the spring-applied litter, and the remaining two-thirds was applied later around the six-leaf stage. The NH_4NO_3 treatments received K as KCl and P as triple superphosphate as needed based on soil analysis. Pioneer 33M53 RR corn was planted every year at 69,000 seeds ha^{-1} to a depth of 5 cm. Supplemental irrigation was applied in 2006 and 2007 as needed but not in 2008. The crop was managed following locally established management practices for weed control during each growing season.

Grain yield was measured by harvesting all four middle rows with a small-plot combine on 11 Sept. 2006, 6 Sept. 2007, and 10 Sept. 2008. Corn was harvested at ~0.95 harvest efficiency (5% grain was lost during harvest). The height of stubble left in the field after harvest was about 30.5 cm. Grain water content, used to adjust the grain yield to 15.5% moisture content, was determined by drying 100 g of grain from each plot at 103°C for 72 h in an oven. The aboveground biomass was measured by harvesting plants from 1-m row sections of the middle four rows at physiological maturity on 20 July 2006, 8 Aug. 2007, and 7 Aug. 2008. These samples were dried in a forced-air oven at 80°C to constant weight and weighed. Leaf area index (LAI) was measured on a pair of the middle four rows using an AccuPAR Model PAR-80 (Decagon Devices), which calculates LAI based on measurements of canopy light interception. Additional management practices, such as planting, harvest, tillage, and irrigation, are listed in Table 2.

Soil moisture in the upper 20-cm profile was measured by an ECH_2O-20 probe (S-SMA-M003, Decagon Devices). Soil temperature in the upper 10-cm profile was measured by a 12-bit HOBO onset temperature sensor (S-TMB-M006). Both data sets were recorded hourly on site by a HOBO datalogger. Additional details on experimental management and operation were provided by Tewolde et al. (2013).

RZWQM2 Model Initialization and Calibration

Soil properties for the study site were obtained from the NRCS soil database (Table 3; (http://www.wcc.nrcs.usda.gov/nwcc/pedon). A 1.8-m-deep soil profile was considered for model simulations. This soil profile was divided into seven horizons. Soil hydraulic properties for each soil horizon were estimated by the RZWQM2 based on bulk density, soil water content at field capacity (33 kPa), and soil texture (Ahuja et. al., 2000). The albedo values of wet and dry soil of 0.11 and 0.21 as measured by Post et al. (2000) were used in this study. Nitrate-nitrogen and NH_4–N in the precipitation were estimated to be 0.7 and 0.2 mg L^{-1}, which are the approximate average annual concentrations for Mississippi (National Atmospheric Deposition Program; http://nadp.sws.uiuc.edu/).

Because the region normally has a wet spring, initial soil water contents were set at field capacity in the beginning of the simulations but calibrated later to ensure that the model-simulated soil moisture matched the observed data in the field. Soil organic pools were initialized according to Ma et al. (1998b) by conducting a "warm-up" run of 15 yr based on measured soil C for each soil layer. Inter-pool transfer coefficients were the same as those calibrated by Ma et al. (1998a, 1998b) for manure. Initial soil NO_3–N and NH_4–N were measured at the beginning of the experiment on 2 Dec. 2005 (Table 4).

Soybean residue of 1.9 Mg ha^{-1} was estimated as the initial surface residue cover. Initialized soil organic matter pools are shown in Table 4. For the top 30 cm of soil, there was 2% for the fast pool, 11% for the intermediate pool, and 87% for the slow pool, with a total soil organic matter content of 1.7%.

The parameter estimation software PEST was used to calibrate the Decision Support System for Agrotechnology Transfer

Table 2. Details on tillage and management practices of an experiment that tested the effectiveness of fall- and spring-applied poultry litter on corn production near Starkville, MS, in 2005 to 2008.

Year	Date	Tillage and field operation
2005	10 Nov.	fall litter and NH_4NO_3 treatments broadcast and incorporated using a bedder ridge
2006	12 Apr.	spring litter and NH_4NO_3 fertilizer treatment applied as broadcast, incorporated using field cultivator; corn planted
2006	14 June	furrow irrigated, 45 mm
2006	12 July	furrow irrigated, 50 mm
2006	20 July	harvested corn
2006	13 Nov.	fall litter and NH_4NO_3 treatments broadcast and incorporated using a bedder ridge
2007	30 Mar.	spring litter and NH_4NO_3 treatments broadcast and incorporated using a bedder ridge
2007	17 Apr.	corn planted
2007	1 May	drip irrigated, 38 mm
2007	19 May	drip irrigated, 38 mm
2007	25 May	broadcast incorporated
2007	15 June	furrow irrigated, 51 mm
2007	8 Aug.	corn harvested
2007	12 Oct.	bedder ridge
2007	8 Nov.	fall litter and NH_4NO_3 treatments broadcast applied and incorporated
2008	15 Apr.	spring litter and NH_4NO_3 treatments broadcast applied and incorporated using a bedder ridge
2008	17 Apr.	harrow with a spike-tooth harrow, corn planted
2008	7 Aug.	corn harvested

Table 3. Properties of a Leeper silty clay loam soil used as model input parameters for modeling the effectiveness of fall- and spring-applied poultry litter on corn production near Starkville, MS, in 2005 to 2008 (data from the NRCS, http://www.wcc.nrcs.usda.gov/nwcc/pedon).

				Particle Size				Soil volumetric water content					
Horizon	Depth	Bulk density	Porosity	Sand	Silt	Clay	Texture†	Saturated	33 kPa	1500 kPa	Residual‡	K_{sat}§	Bubbling pressure‡
	cm	Mg m^{-3}	m^3 m^{-3}		%				%			cm h^{-1}	cm
1	15	1.35	0.491	39	33	28	CL	49	33	20	7.5	0.823	−26.8
2	30	1.36	0.487	39	31	30	CL	49	35	20	7.5	0.281	−38.2
3	60	1.37	0.483	43	29	28	CL	48	29	18	7.5	0.334	−10.9
4	90	1.38	0.479	49	25	27	SCL	48	26	14	6.8	0.643	−15.8
5	120	1.39	0.475	40	32	29	CL	48	40	23	7.5	0.589	−113.5
6	150	1.40	0.471	40	32	28	CL	47	40	23	7.5	0.529	−122.3
7	180	1.40	0.471	40	32	28	CL	47	33	20	7.5	0.639	−34.5

† CL, clay loam; SCL, sandy clay loam.

‡ Residual water content and bubbling pressure are parameters of the water retention–matric potential relationship required in the Brooks and Corey (1966) equation that is used in RZWQM2. Residual water content is the water content at the residual state , where the water phase is discontinuous and isolated, with thin films of water surrounding the soil and air. Brooks and Corey (1966) defined residual water content as the water content at which suction reaches infinity.

§ Saturated hydraulic conductivity.

(DSSAT) CERES-Maize model in RZWQM2 (Ma et al., 2012). The model was initially calibrated for the spring litter (L18S) treatment from 2006 to 2008 in terms of phenology, LAI, biomass, crop yield, plant N uptake, soil NO_3–N, and soil water and then evaluated for the other treatments (the control, fall litter [L18F], fall fertilizer [F202F], and spring fertilizer [F202S]). The final calibrated plant parameters are listed in Table 5.

The coefficient of determination (R^2), index of agreement (d), modeling efficiency (EF), and root mean square error (RMSE) are widely used statistical parameters for model evaluation:

$$d=1.0-\left[\frac{\sum_{i=1}^{n}\left(P_i-O_i\right)^2}{\sum_{i=1}^{n}\left(\left|P_i-\bar{O}\right|+\left|O_i-\bar{O}\right|\right)^2}\right]$$

where P is the predicted value, O is the observed or measured value, n is the number of comparisons, and d varies from 0 to 1.0;

$$\mathrm{EF}=\frac{\sum_{i=1}^{n}\left(O_i-\bar{O}\right)^2-\sum_{i=1}^{n}\left(P_i-O_i\right)^2}{\sum_{i=1}^{n}\left(O_i-\bar{O}\right)^2}$$

where $\bar{O}$ is the mean observed value; the EF can be negative and have a maximum value of 1.0—a negative EF value indicates that the averaged measured values give a better estimate than the simulated values, while higher EF values indicate better agreement between simulated and measured values;

$$\mathrm{RMSE}=\left[\frac{\sum_{i=1}^{n}\left(P_i-O_i\right)^2}{n}\right]^{1/2}$$

Table 4. Initialized soil organic C pools classified as slow, intermediate, and fast, inorganic N, and microbial type and population in the soil profile as required by RZWQM2.

			Residue pool		Humus pool			Microbial population			N conc.		
Horizon	Depth	Organic C	Slow	Fast	Fast	Intermediate	Slow	Aerobic heterotrophs	Autotrophs	Anaerobic heterotrophs	Urea	NO_3	NH_4
	cm	mg kg^{-1} soil			mg C kg^{-1}soil				no. of organisms g^{-1} soil			– mg N kg^{-1} soil –	
1	15	7180	24.2	5.7	140.0	363.9	7261	367,671	6003	136,106	0	8.842	4.908
2	30	6140	0.4	0.0	65.6	452.9	6117	82,000	3465	30,000	0	2.704	3.836
3	60	5840	0.5	0.0	54.8	407.5	5825	82,000	3440	27,000	0	1.079	2.475
4	90	4790	0.9	0.1	54.5	346.9	4775	58,214	2958	29,000	0	1.012	2.537
5	120		0.9	1.5	85.7	302.3	3972	37,000	2011	98,000	0	1.012	2.537
6	150		0.1	0.0	25.4	123.8	2506	8849	1916	42,000	0	1.012	2.537
7	180		0.1	0.1	1.2	0.0	1530	4002	1695	16,000	0	1.012	2.537

Table 5. Calibrated physiological parameters of corn growth and development for DSSAT.

Species or cultivar input	Description	Value
P1	thermal time from seedling emergence to the end of the juvenile phase (above 8°C base temperature), °C d	114
P2	Delay in development for each hour that daylength is >12.5 h, d h^{-1}	0.6
P5	thermal time from silking to physiological maturity (above 8°C base temperature), °C d	615
G2	maximum possible kernels per plant, no. $plant^{-1}$	690
G3	grain-filling rate during the linear grain-filling stage and under optimum conditions, mg d^{-1}	9.6
PHINT	phyllochron interval, the interval in thermal time between successive leaf tip appearances, °C d	38.9

where RMSE = 0 indicates a perfect fit.

RESULTS AND DISCUSSION

RZWQM2 Calibration

The calibrated crop phenology, in general, matched the observed emergence, anthesis, and physiological maturity dates. The calibrated vs. observed values averaged across the 3 yr, respectively, were 7 vs. 5 DAP (days after planting) for emergence, 65 vs. 69 DAP for anthesis, and 108 vs. 103 DAP for maturity. The differences between calibrated and measured grain yield, biomass, soil NO_3 concentration, and plant N uptake for the L18S treatment from 2006 to 2008 were within the standard error of the observed values (Fig. 1–4). The maximum mean relative errors [defined as 100(measured – simulated)/measured] of simulated grain yield, biomass, and plant N uptake from 2006 to 2008 were 4, 11, and 4%, respectively.

Model Evaluation for Simulations of Litter and Fertilizer Effects

Overall, the differences between simulated and measured values were within the standard error of their respective observed values in 3 yr (Fig. 1–4). The maximum averaged relative errors of simulated grain yield, biomass, and plant N uptake across all treatments across the 3 yr were 12, 10, and 31%, with the best simulation results obtained in 2008 and the poorest simulation results in 2006. Corn grain yield of the control treatment averaged across the 3 yr was among the least accurately simulated (underpredicted by 502 kg ha^{-1}). The litter from the L18S treatment in the first year in 2006 did not provide sufficient plant-available N and therefore resulted in 24% lower measured grain yield than the F202S treatment (Fig. 2; Tewolde et al., 2013), an observation correctly simulated by the RZWQM2. The grain yield reduction of the L18S relative to the F202S treatment as predicted by the RZWQM2 model was 18% (Fig. 2). The model overpredicted the grain yield of the L18F treatment in the first year. Repeating both the L18F and L18S treatments in the same plots in the subsequent 2 yr produced higher measured and simulated grain yield than the F202F and F202S treatments,

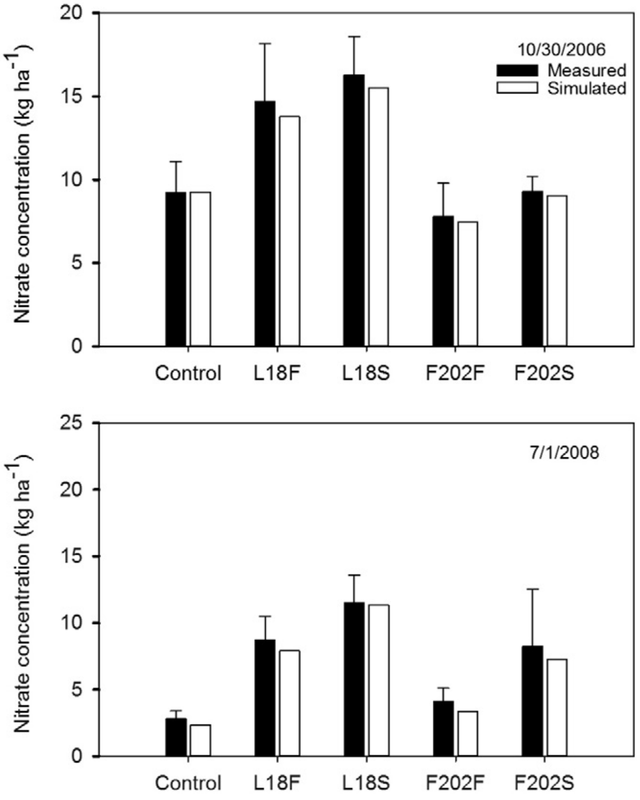

Fig. 1. Simulated and measured soil NO_3–N concentration in the top 30-cm soil profile from a corn field fertilized with poultry litter at 18 Mg ha^{-1} (L18) or NH_4NO_3 at 202 kg N ha^{-1} (F202) applied in the fall (F) or spring (S) near Starkville, MS.

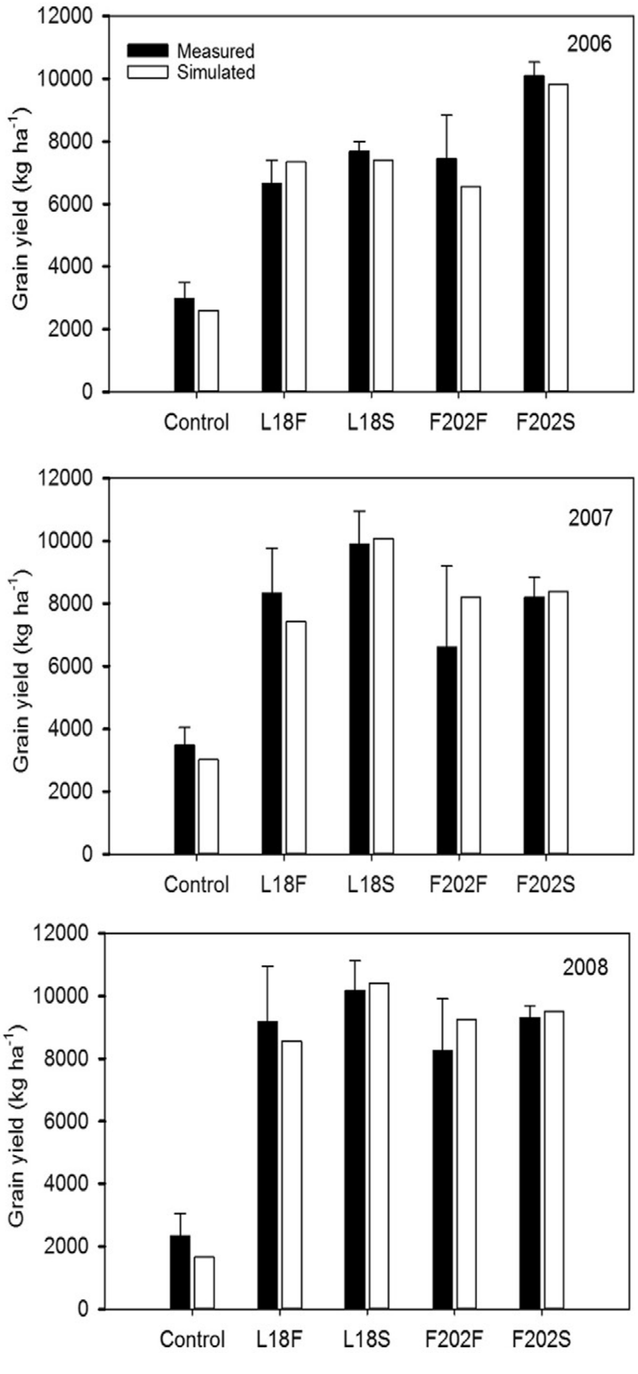

Fig. 2. Simulated and measured grain yield of corn fertilized with poultry litter at 18 Mg ha^{-1} (L18) or NH_4NO_3 at 202 kg N ha^{-1} (F202) applied in the fall (F) or spring (S) near Starkville, MS.

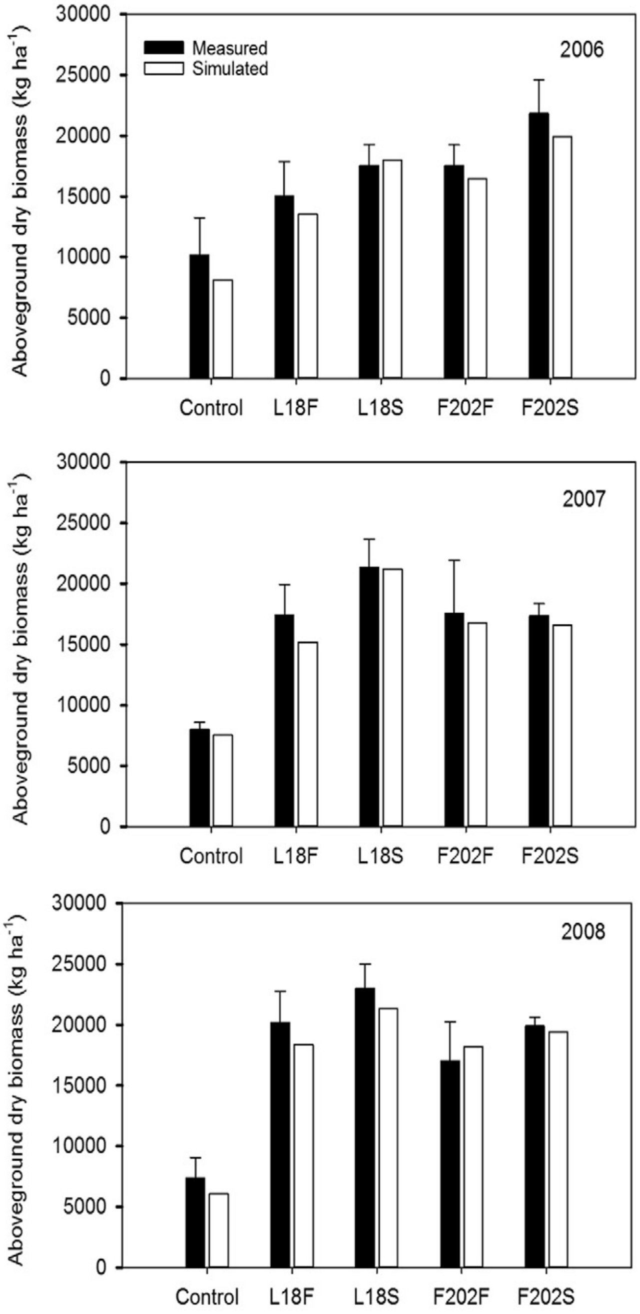

Fig. 3. Simulated and measured total aboveground dry biomass of corn fertilized with poultry litter at 18 Mg ha^{-1} (L18) or NH_4NO_3 at 202 N kg ha^{-1} (F202) applied in the fall (F) or spring (S) near Starkville, MS.

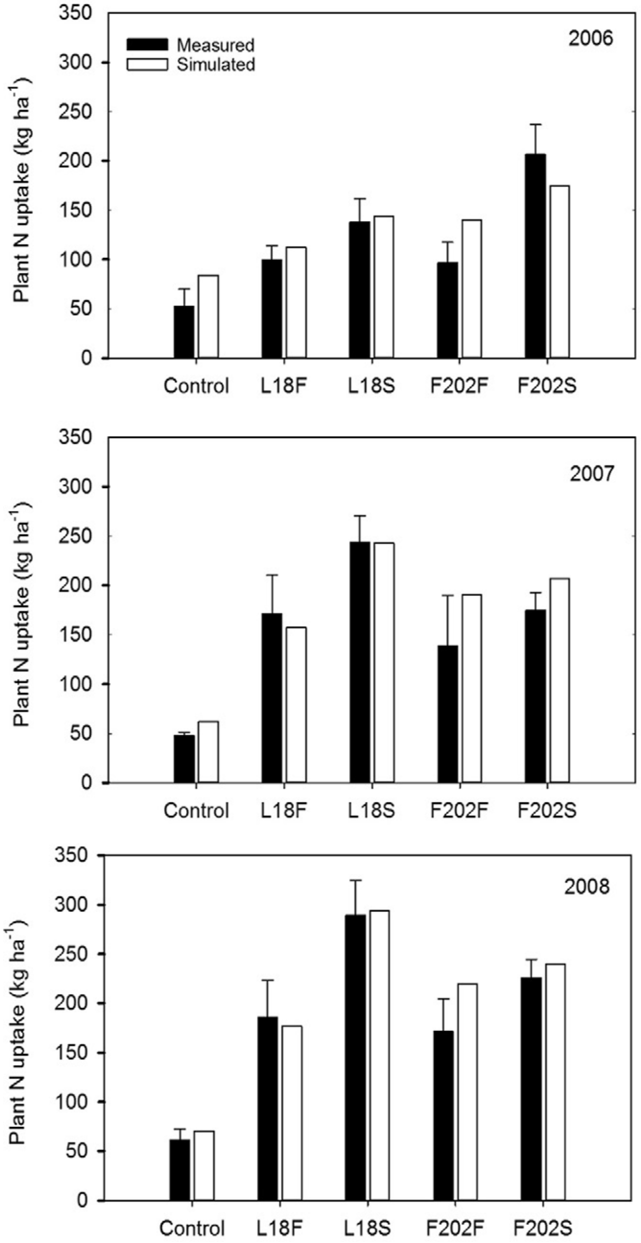

Fig. 4. Simulated and measured total N uptake by aboveground biomass of corn fertilized with poultry litter at 18 Mg ha^{-1} (L18) or NH_4NO_3 at 202 kg N ha^{-1} (F202) applied in the fall (F) or spring (S) near Starkville, MS.

respectively, which is consistent with the higher soil mineral N and plant N uptake (Table 6). The model underpredicted biomass for all treatments in all 3 yr by 459 to 2250 kg ha^{-1} (Fig. 3). Overall, however, the calibrated model responded very well to the application of both litter and NH_4NO_3 at either timing.

Because the top 30 cm of soil is the critical zone where poultry litter increases soil nutrient and corn N uptake in the humid Mid-South (Watts et al., 2010), measured and simulated soil NO_3–N in the top 30-cm layer in the first and last year of the experiment were compared (Fig. 1). The model underpredicted soil NO_3–N to some degree for all treatments on the two sampling dates. On average, the difference between measured and simulated soil NO_3–N concentrations was 7%. The maximum difference was 0.95 kg ha^{-1}, which is acceptable considering that the mean NO_3–N concentration across all treatments during the 3 yr was 2.6 kg ha^{-1}. The average measured soil NO_3–N (± standard error) across all treatments in 2006 and 2008 were 11.4 ± 2.2 and 6.7 ± 1.7 kg ha^{-1}, respectively (Fig. 1).

Averaged across the 3 yr and all treatments, the RMSE of the simulated yield, biomass, plant N uptake, and soil NO_3–N were 1333, 2516, 41, and 47 kg ha^{-1}, respectively (Table 7). Moriasi et al. (2007) rated model performance as acceptable for $R^2 > 0.5$, EF > 0.5, and $d > 0.65$. Table 7 shows that the R^2 and EF values of all simulated results were >0.5 and d values were>0.65

Table 6. Simulated dynamics of soil mineral N in the 0- to 1.8-m depth in a soil that received poultry litter or NH_4NO_3 in the fall or spring of 2005 to 2008. The starting and ending dates of each period in each year were given in Table 8.

	Preplant period					Growing season					Postharvest	
Treatment†	Starting mineral N	Total N applied at start	Mineralized N in period	Total N loss in period	Ending total mineral N	Total N applied at start	Mineralized N in period	Corn plant N uptake	Total N loss in period	Ending total mineral N	Mineralized N in period	Total N loss in period
	kg N ha^{-1}											
						2005–2006						
Control	112	0	48	59	101	0	44	84	10	51	49	7
L18F	112	491	201	115	198	0	110	106	64	138	109	16
F202F	111	202	46	95	264	0	44	140	26	142	82	15
L18S	111	0	98	57	152	491	169	151	18	152	173	45
F202S	111	0	48	59	100	202	43	175	45	125	90	16
						2006–2007						
Control	93	0	26	29	90	0	50	62	7	71	40	9
L18F	231	427	241	74	398	0	192	171	60	359	127	38
F202F	209	202	47	94	364	0	61	191	36	198	136	51
L18S	280	0	109	36	353	427	257	230	30	350	115	34
F202S	199	0	38	52	185	202	61	207	42	199	113	39
						2007–2008						
Control	102	0	29	23	108	0	53	71	10	80	39	4
L18F	448	589	310	167	591	0	238	190	91	548	170	20
F202F	283	202	38	108	415	0	59	220	41	213	95	6
L18S	431	0	101	42	490	589	354	281	31	532	144	28
F202S	273	0	44	77	240	202	67	240	61	208	99	7

† L18, poultry litter applied at 18 Mg ha^{-1}; F202, NH_4NO_3 fertilizer applied at 202 kg N ha^{-1}; final F, fall application; final S, spring application.

except for soil water content, which might be because only one soil moisture probe was used. Although RMSE values across all six treatments in all 3 yr appear high, they were comparable to the experimental errors of the measured data.

Simulated Mineralization of Litter Nitrogen

The litter used in this study contained only 5.0, 5.9, and 3.3 g kg^{-1} inorganic N in 2006, 2007, and 2008, respectively (Table 1). We calibrated the litter mineralization rate and pool transfer rates from the fast pool to the intermediate pool and from the intermediate pool to the slow pool in the model assuming 100% organic N in the litter to minimize model uncertainty associated with volatilization loss of NH_3 during application. This calibration method allowed the model to release inorganic N from the litter more quickly after application to compensate for the assumption. Good agreement between observed and simulated soil inorganic N and plant N uptake indicate that the purpose was achieved (Table 7; Fig. 1 and 4).

The change in soil N level was simulated in three distinct periods (Table 8). The first is the preplant period beginning in November when the litter was applied and ending 1 d before planting corn in April each year. The second period is the growing season, which began on the planting date in April and ended on the day corn was harvested in July or August. The last is the postharvest period, which began a day after corn was harvested and ended just 1 d before litter was applied in November.

Litter N underwent substantial mineralization in all three periods. Each year, N mineralization was simulated to be the largest in the period that followed litter application (Table 6). For example, mineralization from the fall-applied litter was the largest in the preplant period, although the average soil and air temperatures during this period overall are the lowest of all three periods. Nitrogen mineralization from the spring-applied litter was also the largest during the growing season. This suggests that the remaining components were less easily mineralized once the easily mineralizable N transformed into mineral forms shortly after application.

Table 7. Comparison using the coefficient of determination (R^2), modeling efficiency (EF), index of agreement (d), root mean squared error (RMSE), and the standard deviation (SD) of measured and simulated grain yield, biomass, soil NO_3–N, and soil moisture for corn that received poultry litter or NH_4NO_3 fertilization in the fall or spring of 2006 to 2008. The mean values are averages of all treatments across the 3 yr except the spring litter treatment, which was used for validation.

						Observed		Simulated	
Parameter	*n*	R^2	EF	*d*	RMSE	Mean	SD	Mean	SD
Yield, kg ha^{-1}	16	0.80	0.88	0.87	1333	6940	2299	6619	2551
Biomass, kg ha^{-1}	91	0.85	0.96	0.95	2516	7623	6050	8609	5314
Grain N, kg ha^{-1}	16	0.59	0.90	0.87	31	98	49	102	40
Plant N, kg ha^{-1}	70	0.72	0.61	0.89	41	74	66	95	61
Soil NO_3–N, kg N ha^{-1}	100	0.57	0.80	0.76	47	48	54	36	50
Leaf area index	160	0.60	0.82	0.85	0.71	2.35	0.84	2.51	1.09
Soil water content at 25-cm depth, m^3 m^{-3}	1042	0.56	0.62	0.57	0.16	0.29	0.07	0.34	0.06

Table 8. Duration of the three distinct periods in a study of poultry litter use in corn production in Mississippi.

	Preplant			Growing season			Postharvest		
Year	Start	End	Duration	Start	End	Duration	Start	End	Duration
			d			d			d
2006	10 Nov. 2005	11 Apr.	152	12 Apr.	20 July	99	21 July	12 Nov.	114
2007	13 Nov. 2006	16 Apr.	154	17 Apr.	8 Aug.	113	9 Aug.	7 Nov.	90
2008	8 Nov. 2007	16 Apr.	160	17 Apr.	8 Aug.	113	9 Aug.	7 Nov.	90

Preplant Nitrogen Mineralization

The percentage of N derived from fall-applied litter between November after litter application and April before planting corn was 31% in the first year, 2006 (Table 6). The L18F treatment during this period had a total of 201 kg ha^{-1} of mineralized N, which includes N derived from the soil reserve and fall-applied litter. Assuming that the 48 kg ha^{-1} N mineralization of the control treatment estimates N derived from the soil reserve, litter N that mineralized during the 5-mo preplant period for the L18F treatment was 153 kg ha^{-1}, which is 31.1% of the total applied in November 2006. This simulated N mineralization was similar to that reported by Thomsen (2004), who studied the fate of ^{15}N-labeled poultry manure applied in winter and found that only 15% of the ^{15}N in the poultry manure was taken up by the crop. The preplant mineralization of fall-applied litter N increased to 215 kg ha^{-1} in 2007 and 281 kg ha^{-1} in 2008 for the L18F treatment. This increase was attributed to the carryover of litter N that did not mineralize in the previous years. As a result, the amount of soil mineral N in April that can be attributed to fall-applied litter increased from 198 kg ha^{-1} in 2006 to 398 kg ha^{-1} in 2007 and to 591 kg ha^{-1} in 2008. Regardless of the source, mineralization of this magnitude is high considering that much of the time this took place was in the winter. However, the location of the research is characterized by wet and mild winters and early spring temperatures, which are ideal for organic N mineralization.

Growing-Season Nitrogen Mineralization

The L18F treatment had a total of 110 kg ha^{-1} of mineralized N during the growing season (April–July) in the first year (2006), out of which 66 kg ha^{-1} is considered to be litter derived. Adding the153 kg ha^{-1} mineralized during the preplanting period, a total of 219 kg ha^{-1} (44.6%) of the total 491 kg ha^{-1} litter N applied in November 2005 was mineralized by the end of the 2006 corn growing season (Table 6). Litter N that mineralized from the L18S treatment during the growing season in 2006 was almost twice (125 kg ha^{-1}) that of the L18F treatment (66 kg ha^{-1}). However, the sum of N mineralized from the L18F treatment during the preplanting period (153 kg ha^{-1}) and the growing season (66 kg ha^{-1}) was much higher than that of the L18S treatment (125 kg ha^{-1}). This difference between L18F and L18S continued for the growing seasons in 2007 and 2008. Further, the amount of litter N mineralized from both treatments during this period increased yearly, primarily because of carryover of litter N from year to year. The simulated average daily N mineralization rate during the growing season for the L18S treatment was 1.3, 1.8, and 2.7 kg ha^{-1} d^{-1} in 2006, 2007, and 2008, respectively. The peak values during the 3 yr ranged from 3 to 4 kg N ha^{-1} d^{-1}, which was in agreement with the measured 3.5 kg N ha^{-1} d^{-1} mineralization rate reported by Sistani et al. (2008).

Postharvest Nitrogen Mineralization

Nearly the same amount of N was mineralized during the postharvest period as in the growing season whether the litter was applied in the fall or spring in 2006 (Table 6). The L18F treatment in 2006 had 60 kg ha^{-1} mineralized N during the postharvest period compared with 66 kg ha^{-1} during the growing season. The corresponding values for the L18S treatment were 124 vs. 125 kg ha^{-1}. The amount of mineralized N was much greater during the growing season than during the postharvest period in the other 2 yr (2007 and 2008). This may be related to weather conditions and the age of litter in the soil, but these results show that litter N continues to mineralize throughout the year even after harvest of a full-season corn crop.

In total, more than half (57% for L18F and 61% for L18S) of the litter N applied in the first season (2006) mineralized between application and the end of the postharvest period, which marks 12 mo for the L18F treatment and 8 mo for the L18S treatment since the litter was applied. This mineralization rate is within the range of 42 to 64% reported by Preusch et al. (2002) and 39 to 69% reported by Sanchez and Mylavarapu (2011).

Simulated Losses of Litter Nitrogen

Nitrogen Loss during the Preplant Period

Of the 153 kg N ha^{-1} that mineralized during the preplant period in 2006 from the L18F treatment, 56.6 kg N ha^{-1} was lost from the root zone (Table 9). This loss was 37% of the total mineralized litter N or nearly 12% of the total litter N applied in the fall. This N loss probably was responsible for the 13% grain yield reduction relative to spring application in 2006 (Tewolde et al., 2013). The simulated N loss from the fall-applied NH_4NO_3–N treatment (F202F) during this period was nearly 37 kg N ha^{-1} or 18% of the total N applied in the fall as NH_4NO_3–N. The corresponding grain yield loss was 26% relative to the spring application (F202S). With repeated applications, the losses of litter N from the L18F treatment were 11% of the total N in 2007 and nearly 24% in 2008. The corresponding losses from the F202F treatment were 32% of the total applied in 2007 and 42% in 2008. This simulation work showed that applying poultry litter in the fall resulted in loss of a considerable amount of the litter N and should not be a preferred practice in the region.

Much of the N loss from the litter applied in the fall was by leaching during the wet winter and early spring when 67% of the annual rainfall fell. Depending on the year, N leaching losses during this wet period accounted for 39 to 62% of the total loss for the L18F treatment (Table 9). Leaching loss from the F202F treatment ranged between 49 and 67%. This simulation study confirmed other modeling and field results that increasing early-season rainfall results in less plant-available N due to leaching (Kay et al., 2006; Malone et al., 2010). Sogbedji et al. (2001) reported that less N leaching was associated with low early-season precipitation.

Denitrification was the second major path of inorganic N loss from the fall-applied litter during the preplanting period (Table 9). It accounted for approximately 10 to 40% of the total litter N loss from the L18F treatment during this period. The loss in other gaseous forms from the L18F treatment accounted for 16 to 26% of the total loss. Loss of mineral N by runoff was negligible, primarily because the field was nearly level with minimal runoff.

Nitrogen Loss during the Growing Season

The loss of litter N was not restricted to the preplant period because a considerable amount of N was also lost during the growing season. A total of 64 kg ha^{-1} litter N was lost from the L18F treatment during the growing season in 2006. The L18S treatment lost only about 18 kg ha^{-1}, a 72% lower loss relative to the fall-applied L18F treatment. The difference between the L18F and L18S treatments in N loss during the growing season may be due to their difference in the amount of mineralized N present at any time during the period. The mineralization rate of litter N applied just before planting in the spring (L18S treatment) was probably gradual and matched the crop N uptake rate, which probably reduced the degree of exposure of mineral N to risks of loss. The fall-applied litter N, on the other hand, underwent mineralization during the preplant period, and a considerable amount of it carried over to the spring. The fraction of this mineral N that exceeded the uptake capacity of the young corn crop became vulnerable to loss by different pathways. Interestingly, each year the F202S treatment lost considerably more N during the growing season than the L18S treatment, although both treat-

Table 9. Simulated total N loss from poultry litter vs. NH_4NO_3 applied in the fall vs. spring (Table 8) showing the breakdown into component loss pathways. The starting and ending dates of each period in each year were given in Table 7.

Treatment†	Preplant					Growing season					Postharvest				
	Leaching	Denitrification	Runoff	Other N gases	Total	Leaching	Denitrification	Runoff	Other N gases	Total	Leaching	Denitrification	Runoff	Other N gases	Total
	kg N ha^{-1}														
	2005–2006														
Control	46.1	7.9	0.3	4.3	58.6	5.7	0.6	0.0	4.0	10.3	1.7	0.4	0.9	4.2	7.2
L18F	50.4	45.6	1.1	18.1	115.2	27.0	15.7	0.0	20.8	63.5	2.0	2.5	2.4	8.6	15.5
F202F	46.6	36.6	0.5	11.7	95.4	16.5	5.6	0.0	4.1	26.2	2.8	2.4	0.9	8.6	14.7
L18S	46.2	7.9	0.3	2.4	56.8	5.7	6.9	0.0	5.3	17.9	2.5	28.9	4.6	9.0	45.0
F202S	46.1	7.9	0.3	5.1	59.4	10.6	15.4	0.1	18.6	44.7	4.6	1.7	1.0	8.8	16.1
Avg.	47.1	19.4	0.5	8.1	75.0	11.9	9.1	0.0	11.0	32.0	2.5	5.5	1.9	7.5	17.3
	2006–2007														
Control	26.2	0.2	0.1	2.2	28.7	2.9	0.1	0.1	3.9	7.0	4.6	0.3	0.1	3.8	8.8
L18F	46.1	7.5	1.2	19.3	74.1	30.7	13.9	0.3	15.0	59.9	14.2	12.6	0.3	11.1	38.2
F202F	63.0	20.8	1.4	9.0	94.2	29.3	1.4	0.1	4.8	35.6	23.8	4.3	0.3	22.1	50.5
L18S	24.1	4.3	0.7	6.7	35.8	2.8	10.6	0.3	16.1	29.8	7.7	19.7	0.4	6.4	34.2
F202S	37.2	1.1	0.1	13.1	51.5	12.4	4.6	0.2	24.8	42.0	18.3	3.1	0.1	17.4	38.9
Avg.	37.3	5.2	0.6	9.8	52.9	15.7	7.2	0.2	13.5	36.7	12.8	6.4	0.2	12.0	31.3
	2007–2008														
Control	19.6	0.2	0.0	3.3	23.1	4.9	0.3	0.0	4.8	10.0	0.6	0.1	0.2	2.8	3.7
L18F	64.4	66.4	0.1	35.9	166.8	35.4	34.2	0.0	21.2	90.8	1.5	8.9	0.4	8.9	19.7
F202F	65.4	26.3	0.1	16.4	108.2	30.7	4.4	0.0	5.4	40.5	0.5	0.7	0.2	4.2	5.6
L18S	28.8	5.0	0.1	8.1	42.0	6.1	11.6	0.0	13.4	31.1	0.7	19.1	0.7	7.3	27.8
F202S	68.3	1.1	0.0	7.6	77.0	28.5	18.1	0.0	14.6	61.2	1.2	1.0	0.2	4.5	6.9
Avg.	44.2	16.7	0.1	14.2	75.2	22.2	17.7	0.0	14.5	54.4	0.7	4.6	0.3	5.7	11.4

† L18, poultry litter applied at 18 Mg ha^{-1}; F202, NH_4NO_3 fertilizer applied at 202 kg N ha^{-1}; final F, fall application; final S, spring application.

ments received their respective N around planting in the spring. The difference between these treatments is that the N source of the F202S treatment was NH_4NO_3, which is 100% mineral N, and that of the L18S is litter and was considered to be 100% organic N. Thus these results support the notion that the level of N loss during the growing season is dependent on the amount of mineral N (NO_3–N, in particular) present in the soil during the period and on the N uptake rate of the crop. These simulation results also support the argument that litter should be applied at planting or soon after planting so that the probability of crop uptake of the mineralized N is increased and the vulnerability to loss is reduced.

Similar to the preplant period, much of the N loss during the growing season each year was by way of leaching and denitrification (Table 9). In the first season in 2006, 40% (21 kg ha^{-1}) of the total litter N loss (53 kg ha^{-1}) from the L18F treatment was simulated as leaching and 28% as denitrification. In contrast, of the small amount of litter N (7.6 kg ha^{-1}) loss from the L18S treatment during the growing season, 83% (6.3 kg ha^{-1}) was due to denitrification and none (0%) due to leaching. This pattern of N loss (where much of the loss from the L18F was by leaching and that from the L18S was by denitrification) held true in the other 2 yr. The difference in the pathways of litter N loss between the L18F and L18S treatments can be attributed to the difference in application timing and the availability of mineral N during the growing season. A considerable amount of the total loss was also due to other gas losses. The loss due to runoff from both treatments was negligible during all three growing seasons.

Nitrogen Loss during the Postharvest Period

The loss of N during the postharvest period was much less than during the other two periods (Table 9). This was particularly true in 2006 and 2008 compared with 2007. This was not surprising because much of the mineral N in the soil was expected to have been taken up by the crop during the growing season, and only a minimal amount is carried over to the postharvest period. Further, the postharvest period was shorter and drier than the other two periods and therefore the breakdown of organic matter and therefore organic N mineralization was slower during this period than the other two periods.

Much of the N loss during the postharvest period in all years, particularly in 2006 and 2008, for both the L18F and L18S treatments occurred via denitrification and other N gas forms (Table 9). Denitrification accounted for approximately 77% of the N losses for the L18S treatment in all 3 yr. There was substantial leaching loss from the L18F treatment in 2007 only, probably because of relatively higher rainfall during this period. Losses due to leaching were minimal in 2006 and 2008.

SUMMARY AND CONCLUSIONS

Conventional methods to track mineralized N from soil-applied manures and quantify the amount lost due to various causes during the year are difficult to implement, inaccurate, and expensive. The RZWQM2 simulation model provided an alternative to estimate these values. The model was calibrated and evaluated for simulating the fate of N derived from 18 Mg ha^{-1} poultry litter vs. the conventional fertilizer NH_4NO_3 applied in the fall vs. the spring on a field under continuous corn production in Mississippi. The model prediction was sensitive and accurate enough to quantify the mineralization and loss of N derived from poultry litter applied in the fall and spring. The model estimated that approximately 30 to 50% of fall-applied litter N (assumed to be 100% in the organic form at application) was transformed to mineral forms by the spring when corn was planted. Such a high mineralization rate in the absence of an actively growing crop is not desirable because of the vulnerability of the mineral N to loss. In fact, the model estimated that 10 to 25% of the total N applied was lost between the time the litter was applied in the fall and the corn was planted in the spring.

When the litter was applied in the spring, the model simulated mineralization to be about the same as for the fall-applied litter. Approximately 25 to 51% of the total litter N applied in the spring mineralized by the end of the growing season. This was comparable with the corresponding mineralization of 30 to 50% of the total fall-applied litter N. However, the loss was much less if the litter was applied in the spring than in the fall. The loss of litter N between application and harvest was an average of 144 kg ha^{-1} across the 3 yr if applied in the fall vs. only 26 kg ha^{-1} if applied in the spring. These results clearly show that poultry litter should not be applied in the fall in the southeastern United States to fertilize spring-planted crops such as corn. We believe the best time to apply litter to fertilize spring-planted crops in regions with mild winters is around planting, from both productivity and environmental quality perspectives. If spring application is not an option for some growers, the quantitative information on N availability and loss by each pathway is provided to help with better management if the litter is applied in the fall. Future long-term simulations using historical weather data may provide more insightful information on the fate and balance of N derived from poultry litter under various management practices. Such simulations could help determine the optimum poultry litter application time and rate under various cultivation scenarios and help frame the guidelines for profitable, sustainable, and environmentally safe application of poultry litter in the southeastern United States and similar environments.

REFERENCES

Ahuja, L.R., K.E. Johnsen, and K.W. Rojas. 2000. Water and chemical transport in soil matrix and macropores. In: L.R. Ahuja et al., editors, Root zone water quality model. Water Resour. Publ., Highlands Ranch, CO. p. 13–50.

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. Trans. ASAE 42:657–664. doi:10.13031/2013.13227

Blicher-Mathiesen, G., H.E. Andersen, J. Windolf, J. Carstensen, B. Hasler, and C.D. Børgesen. 2014. Mapping of nitrogen risk areas. Agric. Ecosyst. Environ. 195:149–160. doi:10.1016/j.agee.2014.06.004

Brooks, R.H., and A.T. Corey. 1966. Hydraulic properties of porous media affecting fluid flow. Proc. Irrig. Drain. Div. Am. Soc. Civ. Eng. 92:61–88.

Kay, B.D., A.A. Mahboubi, E.G. Beauchamp, and R.S. Dharmakeerthi. 2006. Integrating soil and weather data to describe variability in plant available nitrogen. Soil Sci. Soc. Am. J. 70:1210–1221. doi:10.2136/sssaj2005.0039

Kladivko, E.J., T.C. Kaspar, D.B. Jaynes, R.W. Malone, J. Singer, X.K. Morin, and

T. Searchinger. 2014. Cover crops in the Upper Midwestern United States: Potential adoption and reduction of nitrate leaching in the Mississippi River basin. J. Soil Water Conserv. 69:279–291. doi:10.2489/jswc.69.4.279

Kumar, A., R.S. Kanwar, and L.R. Ahuja. 1997. Evaluation of RZWQM simulations for manure applications for a continuous corn field in Iowa. Paper presented at the 1997 Mid-central ASAE meeting, St. Joseph, MO. 11–12 Apr. 1997. Paper no. MC97-119.

Ma, L., L.R. Ahuja, B.T. Nolan, R.W. Malone, T.J. Trout, and Z. Qi. 2012. Root Zone Water Quality Model (RZWQM2): Model use, calibration, and validation. Trans. ASABE 55:1425–1446. doi:10.13031/2013.42252

Ma, L., H.D. Scott, M.J. Shaffer, and L.R. Ahuja. 1998a. RZWQM simulations of water and nitrate movement in a manured tall fescue field. Soil Sci. 163:259–270. doi:10.1097/00010694-199804000-00001

Ma, L., M.J. Shaffer, J.K. Boyd, R. Waskom, L.R. Ahuja, K.W. Rojas, and C. Xu. 1998b. Manure management in an irrigated silage corn field: Experiment and modeling. Soil Sci. Soc. Am. J. 62:1006–1017. doi:10.2136/sssaj1998.03615995006200040023x

Malone, R.W., D.B. Jaynes, T.C. Kaspar, D.E. James, J. Singer, K.R. Thorp, et al. 2014. Cover crops in the Upper Midwestern United States: Simulated effect on nitrate leaching with artificial drainage. J. Soil Water Conserv. 69:292–305. doi:10.2489/jswc.69.4.292

Malone, R.W., D.B. Jaynes, and L. Ma. 2010. Soil-test N recommendations augmented with PEST-optimized RZWQM simulations. J. Environ. Qual. 39:1711–1723. doi:10.2134/jeq2009.0425

Moriasi, D.N., J.G. Arnold, M.W. Van Liew, R.L. Gingner, R.D. Harmel, and T.L. Veith. 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulation. Trans. ASABE 50:885–900. doi:10.13031/2013.23153

National Agricultural Statistics Service. 2009. 2007 Census of agriculture. AC-07-A-51. Vol. 1. Geographic area series. Part 51. NASS, Washington, DC. http://www.agcensus.usda.gov/Publications/2007/Full_Report/usv1.pdf (accessed Dec. 2011).

Oldham, L. 2011. Nutrient management guidelines for agronomic crops grown in Mississippi. Mississippi State Univ. Ext. Serv., Mississippi State.

Post, D.F., A. Fimbres, A.D. Matthias, E.E. Sano, L. Accioly, A.K. Batchily, and L.G. Ferreira. 2000. Predicting soil albedo from soil color and spectral reflectance data. Soil Sci. Soc. Am. J. 64:1027–1034. doi:10.2136/sssaj2000.6431027x

Preusch, P.L., P.R. Adler, L.J. Sikora, and T.J. Tworkoski. 2002. Nitrogen and phosphorus availability in composted and uncomposted poultry litter. J. Environ. Qual. 31:2051–2057. doi:10.2134/jeq2002.2051

Sanchez, J.F., and R.S. Mylavarapu. 2011. Potential nitrogen mineralization in sandy soils under long-term poultry litter management. Commun. Soil Sci. Plant Anal. 42:424–434. doi:10.1080/00103624.2011.542222

Sistani, K.R., A. Adeli, S.L. McGowen, H. Tewolde, and G.E. Brink. 2008. Laboratory and field evaluation of broiler litter nitrogen mineralization. Bioresour. Technol. 99:2603–2611. doi:10.1016/j.biortech.2007.04.069

Sogbedji, J.M., H.M. van Es, S.D. Klausner, D.R. Bouldin, and W.J. Cox. 2001. Spatial and temporal processes affecting nitrogen availability at the landscape scale. Soil Tillage Res. 58:233–244. doi:10.1016/S0167-1987(00)00171-9

Tewolde, H., K.R. Sistani, and A. Adeli. 2013. Fall- and spring-applied poultry litter effectiveness as corn fertilizer in the mid-southern United States. Agron. J. 105:1743–1748. doi:10.2134/agronj2013.0137

Thomsen, I.K. 2004. Nitrogen use efficiency of ^{15}N-labeled poultry manure. Soil Sci. Soc. Am. J. 68:538–544. doi:10.2136/sssaj2004.5380

USDA–ARS. 1992. Root Zone Water Quality Model (RZWQM): Technical documentation. GPSR Tech. Rep. 2. USDA–ARS, Great Plains Syst. Res. Unit, Fort Collins, CO.

Watts, D.B., H.A. Torbert, S.A. Prior, and G. Huluka. 2010. Long-term tillage and poultry litter impacts soil carbon and nitrogen mineralization and fertility. Soil Sci. Soc. Am. J. 74:1239–1247. doi:10.2136/sssaj2008.0415