LAND MODEL: A SIMULATION TOOL FOR ESTIMATING THE NUTRIENT DYNAMICS FROM LAND-APPLIED ANIMAL MANURE

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REFERENCES: Proceedings of the 1999 Georgia Water Resources Conference, held March 30-31, 1999, at the University of Georgia. Kathryn J. Hatcher, editor, Institute of Ecology, The University of Georgia, Athens, Georgia.

Abstract. The primary objective of this study is to develop a simulation model for predicting nutrient fluxes from the land application of animal waste, resulting in the Land Application Nutrient Dynamics (LAND) model. The simulation model is being developed in STELLA® software focusing on the following processes: 1) microbial decomposition of biomass and organic waste constituents; 2) the plant uptake of nutrients, and 3) the volatilization, assimilation, runoff, and leaching of nitrogen compounds. Model structure is based on the PHOENIX model for carbon and nitrogen dynamics in grassland soils with modifications for hydrological processes. Model parameterization and calibration were based on literature values and published data. This model could aid in a better understanding of the physical, chemical, and biological processes that determine the fate and transport of nutrients, mainly carbon and nitrogen, upon application of animal waste to grassland field systems. This model should also aid in developing effective nutrient management strategies for confined animal feeding operations (CAFOs). Preliminary information is presented in this paper.

INTRODUCTION

The concentration of livestock production via large-scale CAFOs has led to water quality issues related to nutrient and waste management. Large concentrations of nutrients over a small area can result from animal operations when more animal manure is produced than can be decomposed and assimilated by the available land.

The state of Georgia is presently a primary producer of poultry and cattle in the U. S. Last year, the state of Georgia was approached by pork producers to construct large-scale facilities in Taylor and Tattnall counties. Based on the lack of sufficient regulatory policy, controversial environmental problems from CAFOs in other states, and local public opposition, the producers were denied permits by the Georgia Department of Natural Resources (GA DNR). Consequently, Georgia lost a potentially valuable economic resource. A simulation tool for assessing and predicting water quality impacts from manure application may assist policy makers, regulators, managers, and farmers in decision-making processes that govern the fate of CAFOs in Georgia. Currently, simulation models for agricultural practices include the Chemical, Runoff, and Erosion in Agricultural Management Systems (CREAMS) and the Groundwater Loading Effects from Agricultural Management Systems (GLEAMS) models (Leonard et al., 1987), the Agricultural Nonpoint Source (AGNPS) model (Young et al., 1989), and the Riparian Ecosystem Management Model (REMM) (Altier et al., 1993). These models have been validated and deemed useful for various best management practice (BMP) implementation; however, these models are not designed specifically for animal waste land application and

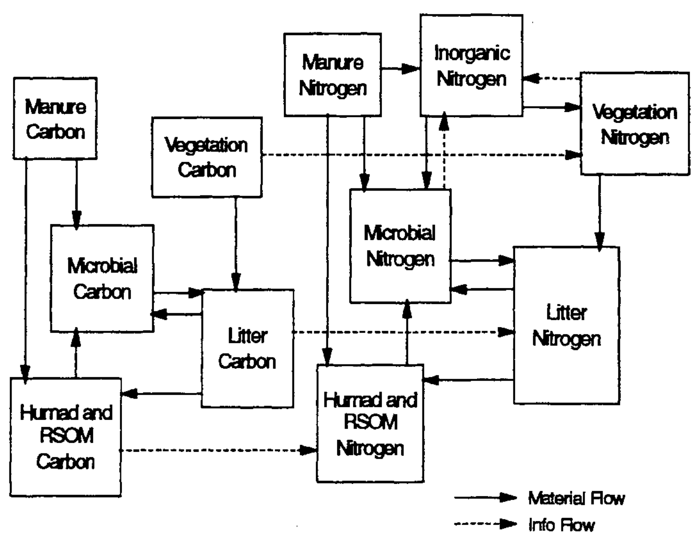

Figure 1. Diagram showing structure of the LAND model.

do not focus on microbial decomposition processes. The LAND model is being developed to incorporate microbial decomposition processes into the prediction of nutrient fluxes from land-applied animal waste.

MODEL STRUCTURE

The Land Application Nutrient Dynamics (LAND) model consists of carbon and nitrogen cycling submodels based on the structure of the PHOENIX simulation model for carbon and nitrogen dynamics in grassland soils (McGill et al., 1981). The PHOENIX model was originally developed to study the interactions between microorganisms and decomposing blue grama grass residues. The structural and metabolic components for biomass utilized in PHOENIX make it a potentially useful model structure for the estimation of nutrient dynamics from land-applied animal waste.

In the LAND model, the major components for each submodel (Figure 1) include a microbial component (bacteria and fungi), a vegetation component (shoots and roots), a litter component, a soil organic matter component [humic and adsorbed soil matter (humad) and resistant soil organic matter (RSOM)], and a manure component. The nitrogen submodel also includes an inorganic nitrogen component. As in PHOENIX, carbon and nitrogen are differentiated into structural and metabolic components within the litter and manure components and for the standing dead compartments of the vegetation component. Structural material in manure is typified by cell walls, lignin, and cellulose. Metabolic manure typically consists of cytoplasmic components and membranes(McGill et al., 1981). The simulation model was developed using STELLA® software Version 5.0 (HPS, 1997).

Hydrology Submodel

A hydrology submodel links the transport of nutrients between four soil horizons (0-2 cm, 2-6 cm, 6-14 cm, and 14-30 cm deep, respectively). The forcing function of the hydrology submodel is daily precipitation data. Infiltration rate is based on the precipitation data but is limited by the soil porosity (cm^3 void space/cm^3 soil) at the top soil horizon. The vertical transport of soil water from one horizon to the next underlying horizon is driven by Darcy's Law as follows (Jury et al., 1991):

$$Q_{out}^{\ X} = \frac{K_0 A \, \Delta H}{L} \qquad (1)$$

where Q_{out} is the soil water flow out of horizon X ($cm^3\ d^{-1}$), K_0 is the constant hydraulic conductivity ($cm\ d^{-1}$), A is the cross-sectional area of flow (assumed 1 m^2 or 1 x $10^4\ cm^2$ in model), ΔH is the change in head (cm), L is the thickness of soil horizon (cm), and X is 1, 2, or 3, respective to soil horizon. Also note that due to an assumed water balance, the following is true:

$$Q_{in}^{\ X+1} = Q_{out}^{\ X} \qquad (2)$$

The hydrology submodel produces changes in volumetric soil water content by soil horizon over time, which can be converted to soil water potential given the water retention curve of a certain soil type (Jury et al., 1991). This soil water potential is used to determine the moisture effects of many biological processes within the LAND simulation model. Runoff (R) is calculated on a daily basis as the difference between precipitation (P) and infiltration (INF). Potential evapotranspiration (PET) is calculated using the Thornthwaite equation [Georgia Department of Natural Resources (GA DNR), 1992].

Carbon Submodel

The carbon submodel is composed of five components described previously. For all components, the conserved units for state variables are in $g\ C\ m^{-2}$, the units for flows are $g\ C\ m^{-2}\ d^{-1}$ and for rate constants are d^{-1}, unless otherwise stated. Details on governing equations for the microbial, vegetation, litter, and the soil organic matter compartments are presented in McGill et al. (1981).

Manure component. The manure component is unique from the model structure developed in the PHOENIX model, but its structure is similar to that of the litter component, being divided into metabolic and structural material. (McGill et al., 1981). The application of manure is the forcing function in this compartment. This is accomplished with the PULSE built-in function in STELLA® (HPS, 1997), which simulates application based on amount and frequency. Manure carbon is immediately partitioned into structural and metabolic compartments by a predefined fractional amount, depending on the content in the applied manure. Microbial decomposition results in the transfer of manure carbon to humads and microbial biomass. The rate of metabolic manure decomposition depends on the amount in solution, similar to that of the litter component. Structural manure decomposition also occurs in a similar manner to that in the litter component, including a density effect on microbial decomposition. Note that manure is only applied to the surface horizon, and it is assumed that manure carbon remains in this horizon.

Nitrogen Submodel

The nitrogen submodel consists of components identical to those in the carbon submodel, plus an inorganic component. The rates of transfer between nitrogen submodel compartments and components are proportional to analogous carbon submodel rates of transfer, with the proportionality factor being the C/N ratios. For all components, the conserved units for state variables are in g N m^{-2}, the units for flows are g N m^{-2} d^{-1}, and for rate constants are d^{-1}, unless otherwise stated. All components except for the shoot compartments of the vegetation component, as well as the manure component, are replicated through all four soil horizons.

Inorganic nitrogen component. The processes of ammonification, nitrification, and denitrification are handled in the inorganic nitrogen component (McGill et al., 1981). A unique feature of the LAND model is that the vertical fluxes of ammonium and nitrate concentrations are driven by the hydrology submodel. The following equation demonstrates the inorganic nitrogen flux from soil horizon X to soil horizon X+1:

$$Q_N^{X \; to \; X+1} = Q_{out}^{X} \bullet N_C^{X} \qquad (3)$$

where Q_N is the flux of NH_4^+ or NO_3^- from horizon X to horizon X + 1, Q_{out} is the soil water flow out of horizon X, which is equal to soil water flow into horizon X+1, N_C is the NH_4^+ or NO_3^- concentration in horizon X, and X is soil horizons 1, 2, or 3. Note that the inorganic nitrogen flux out of horizon 4 is considered to be leached to groundwater. Runoff inorganic nitrogen concentrations are determined in a similar manner, using the runoff flow calculation described in the hydrology submodel section. The volatilization rate of NH_3 was estimated as a function of temperature and pH (Sherlock and Goh, 1985).

Manure component. The addition of manure nitrogen to the system is proportional to the rate of application based on the C/N ratio of the manure, and this nitrogen is partitioned into structural and metabolic manure nitrogen in a similar manner as described in the carbon submodel. A predefined percentage of ammonium and nitrate allows for the immediate transfer of these inorganic constituents to the respective inorganic compartments.

Model Inputs and Outputs

The "Control Panel" of the LAND model allows the user to define manure characteristics, including: 1) the manure application amount (kg ha^{-1}); 2) the application frequency (applications/year); 3) the fraction of inorganic constituents in the manure; 4) the percentage of total inorganic constituents in total manure mass; 5) the percentage of structural and metabolic organic constituents in the manure, and 6) the soluble fraction of the inorganic nitrogen compounds ammonium and nitrate in the system (not limited to manure). Also, the user may enter precipitation data on a daily basis in cm, plant growth stage for a certain crop, and porosities (cm^3 void space/cm^3 soil) and hydraulic conductivities (k) (cm d^{-1}) for each of the four soil horizons.

Output from all components is represented graphically, including the following categories: Manure, Bacteria, Fungi, Humads and RSOM (resistant soil organic matter), Inorganic Nitrogen, Vegetation, Litter, and Hydrology.

RESULTS

The LAND model was calibrated without the manure component using published results included with the PHOENIX model description (McGill et al., 1981).

Table 1. Parameter Values for Sample Simulation.

Parameter	Value(s)
k[1],..,k[4] (cm d^{-1})	50, 20, 10, 5
Porosity[1],..,Porosity[4] (cm^3/cm^3)	0.6, 0.5, 0.4, 0.4
AppAmnt[1] (kg ha^{-1})	100
AppFreq[1] (yr^{-1})	20
Soluble Frac NH4	0
Soluble Frac NO3	1.0
Fraction NO3	1.0
Fraction Inorganic	0.45

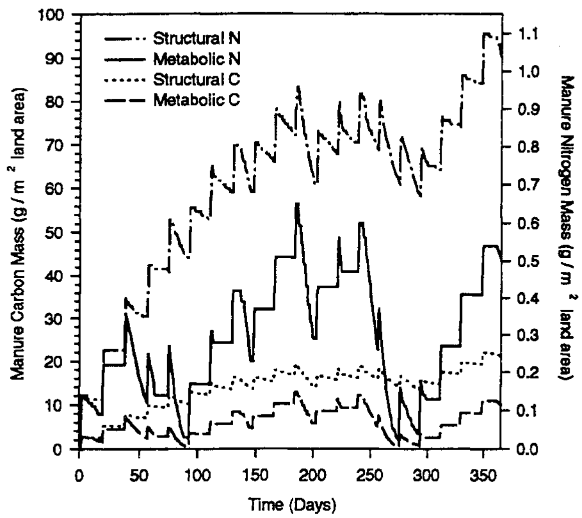

Figure 2. Carbon and nitrogen amounts resulting from simulated manure application.

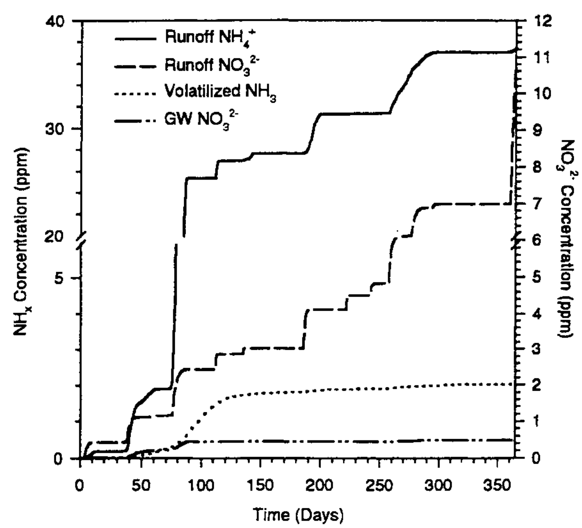

Figure 3. Predicted inorganic nitrogen in runoff, volatilized ammonia, and leached nitrate.

Next, calibration was conducted with the manure component active, using some parameter values from PHOENIX and some published parameters for the manure component. Finally, sensitivity analyses were performed by varying parameters and examining the model's response to these changes. Also, manure application rates and frequencies were manipulated to test the response of the model to these changes, thus comparing the model's behavior with reality. Example inputs are given in Table 1, and example outputs are provided in Figures 2 and 3. Calibration and sensitivity analyses have not yet been statistically analyzed.

DISCUSSION AND FUTURE DIRECTIONS

With the addition of a phosphorus submodel, the LAND model may be developed into a useful research and management tool for animal producers, managers, policy makers, and regulators. In the future, the model must be validated with actual field data.

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