A GRAZING SIMULATION MODEL: *GRASIM*
B: FIELD TESTING

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ABSTRACT. *A comprehensive grazing simulation model, GRASIM, that links all components of the pasture system was developed. The model predicts growth rate, water drainage, nitrogen leaching, and factors affecting animal intake. In order to ensure validity of the simulation, field testing of GRASIM was conducted using local experimental data. These tests were also performed for better parameter estimation. Field testing and evaluation of GRASIM components, grass growth, nitrogen, and water budget to central Pennsylvania conditions is presented. The model was tested for 1993 and 1994 and two fertilizer treatments—with and without animal manure. Statistical tests indicated a good fit between predicted and observed data for accumulated biomass, nitrate leaching and amount of water drained. Because of the mechanistic nature of the GRASIM, the model did not require any calibration. The model can be used in its present form by researchers, extension personnel, and trained farmers to increase the efficiency of pasture use.*

Keywords. *Production agriculture, Pasture, GRASIM, Dairy farms, Modeling, Grazing, Crop simulation models.*

Recent decreases in profit margins for dairy farms have forced farmers to examine alternative production systems. The use of intensively managed pasture offers the opportunity for significant reductions in total feed costs and other costs during the pasture season. Several whole-farm budgeting studies have indicated that pasture use can increase returns per cow between $85 to $168 (Gripp et al., 1993). In addition to economics, dairy farming systems are under increasing environmental pressure; this increases the variable costs of managing the agricultural chemicals, nutrients, and water that are natural parts of the agroecosystem.

Management of a pasture-based system for economic and environmental sustainability requires consideration of many interactions at the farm level. Several factors must be defined: supplemental feed requirements during the grazing season, use of excess pasture growth for later feeding, and the impact of animal performance during grazing on subsequent animal performance. Because the components of this complex system interrelates, a systems approach is essential to evaluate several technologies and management strategies for dairy farms.

While reductionist science has served production agriculture well for over 150 years, it is becoming inadequate from a broader perspective. Systems thinking and practices are emerging as the preferred alternative to evaluate the problematic relationships between agriculture and the environment in which it is conducted. Toward this end, computer models serve as powerful tools. They simulate complex systems and add to the understanding of the linkages and inter-relations between the system components. Models help to understand, analyze, and optimize systems where traditional experimental tools fail. Over the last decade, access to high computing power has increased, making modeling and model use more possible.

Models are easily adaptable to grazing systems. These systems are naturally cross-disciplinary and interrelate research among several areas of science including whole farm planning and total human and natural resource management. A comprehensive grazing model (GRASIM) that links all components of the pasture system was developed to obtain a better understanding of the pasture system and determine management strategies which yield more efficient utilization of pastures (Mohtar et al., 1997). GRASIM generates information suitable for estimating the financial and environmental consequences of alternative dairy management strategies including partial mechanical harvest in the context of year-round feed needs of the dairy herd. The model can also evaluate storage/harvest needs, year-to-year variability, stocking rate effect on feed supplementation, and amount of harvested feed.

Recently, numerous computer models that simulate transport of nitrate in the environment have been developed; these include LEACHM (Hutson and Wagenet, 1992), NCSWAP (Molina and Richards, 1984), SOILN (Bergstrom et al., 1991), MACRO (Jarvis, 1994), SLIM (Addiscott and Whitmore, 1987, 1991), and RZWQM (USDA-ARS, 1992). Several of these models were evaluated for nitrate leaching under corn (Jabro et al., 1993, 1995; Jemison et al., 1994; Lengnick and Fox, 1994). But to our knowledge, little effort has been directed toward testing and evaluating these models under pasture conditions.

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GRASIM DESCRIPTION

GRASIM data requirements include minimum and maximum daily temperatures, daily rainfall, average daily solar radiation, soil physical properties, grass growth parameters, soil nitrogen transformation coefficients, and initial levels of soil water and soil nitrogen (Mohtar et al., 19967). A complete listing of these parameters is included in the appendix. The model output includes daily biomass production, and water and nitrogen levels in different pools. GRASIM state variables are the grass biomass, grass growth rate, leaf area index, soil moisture content, soil nitrogen content, plant residues, and organic matter content.

GRASIM has four main components, the grass component of the model contains two main carbon compartments, storage and structure. It accounts for the following processes: root growth and maintenance, shoot growth (partitioned into leaf and stem), shoot respiration, senescence, and recycling. The soil matrix is partitioned into two zones. The first zone is where all water and nitrogen additions, surface evaporation, plant uptake, and nitrogen transformations are taking place. The second zone activities includes plant uptake of water and nitrate-N. These activities include: nitrification, mineralization, uptake, volatilization, denitrification, and leaching. Soil water is accounted for using a simplified water balance that considers runoff after a heavy rainfall, evapotranspiration, soil matrix water dynamics, and leaching. The harvest component handles pasture management inputs and controls the grazing events.

OBJECTIVES

The objectives of this study are to perform field evaluation of GRASIM components: grass growth, nitrogen cycling, and water budget to central Pennsylvania conditions. Field testing will compare the model output to actual dry matter accumulation, nitrogen leaching, and water drainage data.

MATERIALS AND METHODS

SOIL CHARACTERISTICS

The soil used in this research study is mapped as a Hagerstown silt loam (fine, mixed, mesic, Typic Hapludalf). Using the Uhland soil sampler, three undisturbed soil samples (76.2 mm long × 76.2 mm in diameter) were collected from each of the four horizons to a depth of 1 m. Soil cores were used to determine soil bulk density, particle size distribution and soil water retention characteristics. Selected measured soil physical and hydraulic characteristics of the site are given in table 1.

FIELD EXPERIMENT AND TREATMENTS

A nitrate leaching experiment was initiated in fall 1992 at The Pennsylvania State University Dairy Research and Education Center at University Park. The experiment was conducted to measure NO_3-N leaching losses from N-fertilized orchardgrass (*Dactylis glomerata* L.) pastures being grazed by dairy cows.

The N-fertilizer treatments consisted of: a control with no animal waste, urine application in the spring, urine application in the summer, urine application in the fall, and feces application in the summer. Each of these five treatments also received 280 kgN ha^{-1} of ammonium nitrate split into five equal applications in 1993. In 1994, each treatment received 220 kgN ha^{-1} of ammonium nitrate (168 kgN ha^{-1} divided into three equal applications which were applied between 11 April and 16 May; 52 kgN ha^{-1} were divided into two equal applications and were applied on 16 June and 15 August).

Table 1. Physical and hydraulic properties* for Hagerstown silt loam soil as used in GRASIM and LEACHM simulations

	Soil Horizon and Depth (m)			
Parameter	Ap (0-0.20)	E (0.20-0.35)	Bt1 (0.35-0.60)	Bt2 (0.60-1.00)
Bulk density (Mg m^{-3})	1.22	1.43	1.50	1.45
Particle size (%)				
Sand	20.4	12.5	7.8	17.4
Silt	58.2	55.4	30.7	43.2
Clay	21.4	32.1	61.5	39.4
Moisture content (m^3 m^{-3}) at pressures (MPa):				
0.005	0.441	0.415	0.454	0.429
0.03	0.336	0.300	0.304	0.290
0.1	0.316	0.277	0.273	0.263
0.5	0.241	0.219	0.247	0.209
1.5	0.221	0.192	0.225	0.185

* Each value is a mean of three observations.

Twenty-five intact soil core lysimeters were installed in Fall 1992 on edges of plots. The lysimeters were designed, constructed, and installed similarly to those described by Moyer et al. (1996). The design was developed to minimize disturbance of the soil within the lysimeter. The lysimeters were checked periodically and water samples were collected following large precipitation events. Water samples were then measured and analyzed for NO_3-N using an automated Cd reduction method (U.S.EPA, 1979).

The feces and urine used for the lysimeters were collected from lactating Holstein dairy cows grazing the pasture. Each lysimeter urine treatment received 3 L and each feces treatment received 2 kg, the average amounts produced by mature cows per excretion (Petersen et al., 1956a,b). Collections were made on the same day as, or one or two days prior to lysimeter applications. In cases where collections were not made on the same day as application, the urine and/or feces were stored at 4°C until the day of application. Applications were made in a manner that simulated animal deposition, i.e., merely dropped or poured near the center of the lysimeter surface. The dates for urine applications are 18 May and 28 April and N rates are 96.6 and 112 (gN m^{-2}) for 1993 and 1994, respectively. Phosphorous and potassium fertilizers were applied to all lysimeters at recommended rates. All treatments were replicated five times.

Plots were harvested seven times during the growing season, with two- to six-week intervals between harvests. The grass within the lysimeter was clipped by hand to a height of 70 to 100 mm in conjunction with grazing of the paddocks to determine the extent of plant N uptake and forage dry matter.

SIMULATION ACCURACY

Simulation accuracy of GRASIM was evaluated based on its ability to predict cumulative biomass and monthly values of drainage and NO_3-N leaching during each year.

The two statistical procedures used to assess the simulation accuracy were the mean difference:

$$(M_d = \Sigma(P - M)/n)$$

which is a measure of the average deviation of the simulated from the measured monthly values for each year; and the root mean square error:

$$(RMSE = [(\Sigma(P - M)^2/n)]^{0.5}$$

which quantifies the amount of random scatter of the simulated and measured values about a 1:1 line.

In both equations, P is the value predicted by the model, M is the corresponding measured value, n is the number of measurements. A small non-significant M_d indicates the statistical accuracy of the model prediction. The positive and negative signs of the M_d imply that, on average, the simulation is overestimating or underestimating the measured values, respectively. A t-test was used to determine whether M_d was significantly different from zero (Addiscott and Whitmore, 1987). The RMSE can be no lower than zero (no simulation error) and has no upper value. Lower values of RMSE reflect greater simulation accuracy and lower simulation error than higher RMSE values. RMSE has the same units as the values which are being compared. Addiscott and Whitmore (1987), Donigian and Rao (1986), Loague and Green (1991), Smith et al. (1995), Jabro et al. (1995), and others have found that these statistical methods are useful for evaluating model performance.

NUMERICAL SIMULATIONS

GRASIM field evaluations require the following data: frequent biomass measurements during the grazing season; frequent soil water and nitrate measurement for the entire season; pasture or harvest management information (stocking rate, rotation or harvest schedule, number and size of paddocks, fertilizer applications); weather (daily rainfall, daily average temperature, and daily solar radiation) and soil physical and hydraulic characteristics (bulk density, total porosity, particle size distribution, water holding capacity, water contents at potentials: 0, 0.033, and 1500 kPa), initial conditions (biomass at the beginning of the season, initial soil water content, initial nitrogen status in various pools), crop coefficients, and soil nitrogen transformation coefficients. The average temperature, precipitation, and total solar radiation for State College, Pa., during the 1993-1994 growing seasons is shown in figures 1 and 2, respectively. The data in these two graphs were used in the results to follow.

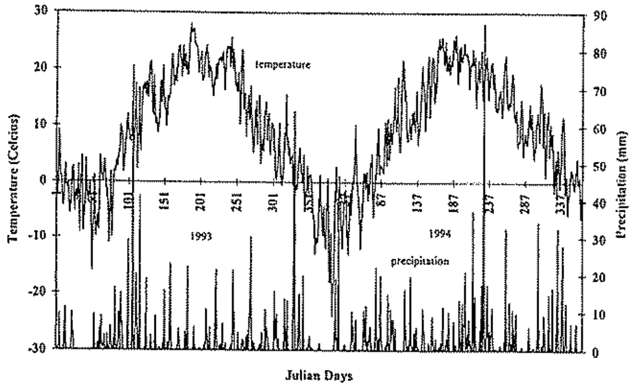

Figure 1–Average temperature and precipitation in State College, Pa., for 1993 and 1994 growing season.

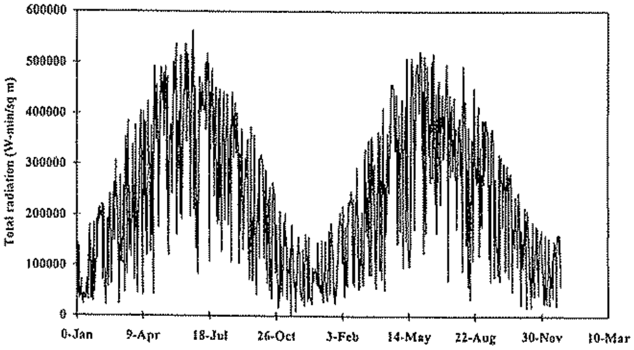

Figure 2–Total solar radiation in State College, Pa., for 1993 and 1994 growing season.

In addition to the weather file, GRASIM reads from an external file that contains the rest of the data required for execution. Four data files were generated representing the four experimental treatments: 1993 and 1994, control, and urine spring treatments. Table 2 presents the list of parameters used in the four simulations. These parameters pertain to the field characteristics, soil type, and plant species for all simulation runs. Parameters were estimated using literature values. Initial conditions at the beginning of the simulation in each pool changed for each simulation run. These include biomass, soil water, and soil nitrogen. The initial conditions for each treatment and year are presented in table 3.

RESULTS AND DISCUSSION

This section includes selected model output of biomass, water drainage, and nitrate leaching. Because GRASIM is a mechanistic model, particularly the growth module, no calibration was needed. The results presented in this section were non-calibrated and no attempt was made to improve the model fit to experimental data.

BIOMASS PREDICTIONS

The GRASIM biomass predictions for 1993 and 1994 growing seasons (April to October) were compared with field measurements of biomass. Each measured data point is an average of five replicates. The model provided accurate predictions of the measured above ground orchardgrass biomass collected throughout two growing seasons. The statistical results indicated that there were no significant differences between model simulated and measured amounts of biomass for each growing season as reflected by the small mean differences and the low RMSE values. These results are shown in table 4. The M_d and RMSE were 11.6 and –3.4 kg/ha for 1993 and 26.4 and 0.56 kg/ha for 1994, respectively. Based on the statistical tests used in this study, GRASIM performed well and accurately simulated above ground biomass accumulation of orchardgrass for each season.

Figures 3 and 4 show representative comparison between GRASIM output and actual field data for 1993 control and 1994 urine spring treatments, respectively. GRASIM predicted the actual field data accurately.

Table 2. Parameter list used in the four simulation runs

Var.	Description	Units	Value Used
Grass Module			
θ	Conversion from carbon dioxide to carbon	[kg C / kg CO_2]	0.273
ϕ	Fraction available for shoot growth	0.9	
Y	Yield factor	0.75	
m_m	Upper bound of as W_s gets large compared to W_g.	[day^{-1}]	0.4
γ	Recycling coefficient	[day^{-1}]	0.1
β	Senescence rate	[day^{-1}]	0.004
a	Structural specific leaf area	[m^2 leaf area (kg C in $W_g)^{-1}$]	40.0
α	Leaf photosynthetic efficiency	[kg CO_2 J^{-1}]	12e-9
k	Extinction coefficient of the canopy	0.5	
m	Leaf transmission coefficient	0.12	
P_0 & P_1	Constants	[kg CO_2 m^{-2} s^{-1}]	0.5e-5 & 0.05e-5
	Proportion of C available for shoot	0.9	
	Fraction partitioned to leaf	0.5	
T_{opt}	Optimum temperature for growth	[°C]	20
T_{min}	Minimum temperature for growth	[°C]	0
T_{max}	Maximum temperature for growth recycling, and senescence	[°C]	40
	Length of growing season	[days]	208
Nutrient Module			
k_n	Zero order rate coefficient for nitrification	[kg/ha/day]	33.6
k_{omr}	Rate coefficient	0.000072	
k_{resr}	First order rate coefficient	[1/day]	0.03
k_{af}	Rate for nitrate volatilization %/day	0.00072	
k_{det}	Rate for denitrification %/day	0.00072	
K	Leaching coefficient	[unitless]	1.3
Water Module			
γ	A psychometric constant	0.68	
λ	Albedo		0.23(crop),2(soil)
C	Cover factor		0.5(plant),1(soil)
α	Soil evaporation parameter	[in. /$day^{0.5}$]	0.15
$FC1$	Field capacity, soil moisture at 3 bar of suction, top layer	%	0.62
S_{r1}	Residual saturation, top layer	%	0.24
ρ_{b1}	Bulk density, top layer	gm/cc	1.32
ρ_{p1}	Particle density, top layer	gm/cc	2.65
$FC2$	Field capacity, soil moisture at 3 bar of suction, lower layer	%	0.64
S_{r2}	Residual saturation, lower layer	%	0.25
ρ_{b2}	Bulk density, lower layer	gm/cc	1.46
ρ_{p2}	Particle density, lower layer	gm/cc	2.65
	Leaching coefficient:		1.3
	Root depth:	[mm]	1000
	Top layer	[mm]	300
	Lower layer	[mm]	700
A	Area of paddock	[m^2]	1000
	Number of paddocks		1
$SW1$	Soil water in top layer	[cm]	80
$SW2$	Soil water in lower layer	[cm]	180
Grazing Management			
	Intake per cow:	[Kg DM per day]	15
	Mass at which grazing animals are removed from the pasture:	[Kg / hectare]	1000
	Mass at which animals are brought to the pasture:	[Kg / hectare]	2800

Table 3. Initial values for the state variables used in the two treatments for the two growing seasons

Var.	Description	Control 93	Control 94	Urine Spring 93	Urine Spring 94
Grass Module					
W_s	Storage dry weight [kg C m^{-2}]	0.008	0.015	0.01	0.017
W_g	Structure dry weight [kg C m^{-2}]	0.008	0.015	0.01	0.017
Nutrient Module					
NAF	Ammonia N of the [kg/ha] top foot at end of time step	23.0	21.7	23	30
OMR	Soil organic matter [kg/ha]	50820	69300	50820	12782
	Nitrogen in residues [kg/ha]	42.0	98	42.0	154
	Carbon in residues [kg/ha]	672.0	1568	672.0	2464
NIT1	Nitrate in the [kg/(ha time step)] top layer	8.5	3.6	8.5	82.4
NIT2	Nitrate in the [kg/(ha time step)] lower layer	14.0	5.6	14.0	419.0
	Linear daily N uptake [kg/ha]	1.1	1.52	1.76	4.1

Table 4. Statistical comparison of measured and simulated monthly values

	Statistical Error	
	M_d	RMSE
1993		
Drainage (mm)	–0.029	0.06
NO_3-N (g m^{-2}):		
Control	–0.007	0.02
Urine-spring	–0.003	0.01
Yield (g m^{-2}):		
Control	11.6	46.9
Urine-spring	–3.4	47.8
1994		
Drainage (mm)	–0.325	2.3
NO_3-N (g m^{-2}):		
Control	0.004	0.14
Urine-spring	–0.037	2.1
Yield (g m^{-2}):		
Control	26.4	120.4
Urine-spring	0.56	239.3

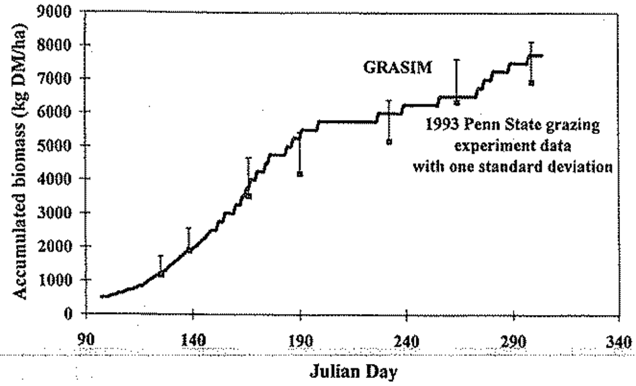

Figure 3–Predicted and measured accumulated biomass for the 1993 control treatment.

WATER FLOW (DRAINAGE) PREDICTIONS

The GRASIM water drainage predictions for 1993 and 1994 growing seasons (April to October) were compared with the average of the 23 lysimeters of measured water flow below the 1 m depth. The model provided accurate predictions of the measured water drainage collected below the 1 m depth throughout two growing seasons under orchardgrass sod. The statistical results indicated that there were no significant differences between model simulated and measured amounts of water leached for each growing season as reflected by the small mean differences and the low RMSE values (table 4). The M_d and RMSE were 0.029 and 0.06 mm for 1993 and 0.325 and 2.3 mm for 1994, respectively. Based on the statistical tests used in this study, GRASIM performed well and accurately simulated water drainage at the 1.0 m depth under orchardgrass pasture conditions for each season.

GRASIM water drainage output was also checked against LEACHM. Figure 5 shows the comparison between

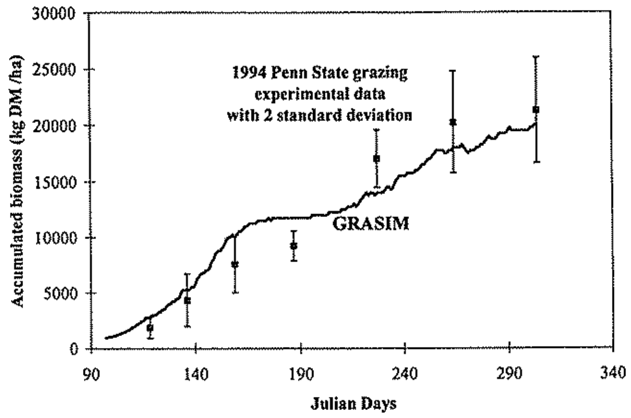

Figure 4–Predicted and measured accumulated biomass for the 1994 urine spring treatment.

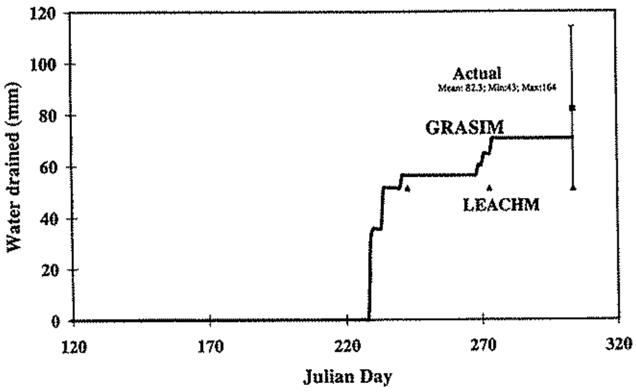

Figure 5–Predicted and measured water drained for the 1994 growing season.

GRASIM, LEACHM, and actual field data for 1994 growing season. GRASIM's predictions were closer to the actual data than those of LEACHM.

NO_3-N LEACHING PREDICTIONS

The model's NO_3-N leaching predictions were compared with the mean of the lysimeter measured monthly values in both the 1993 and 1994 growing seasons. Each measured mean of NO_3-N for each month was calculated from five observations for a control and urine application treatment.

The GRASIM model provided generally accurate predictions of the seasonal measured nitrate leached below 1 m depth for these two treatments in both seasons as reflected by results summarized in table 4. The small, non-significant M_d and low RMSE in table 3 for the control and urine application treatments demonstrated a satisfactory fit of the GRASIM predictions.

GRASIM nitrate leaching output was also checked against LEACHM. Figure 6 shows the comparison between GRASIM, LEACHM, and actual field data for 1994 growing season urine spring treatment. GRASIM's predictions were closer to the actual data than those of LEACHM.

GRASIM was able to provide accurate predictions of annual nitrate leaching beyond the rooting zone of orchardgrass for these two treatments in the 1993 and 1994 growing seasons. Overall, the results from this study showed that the GRASIM model has the potential to predict the fate of fertilizers or manure N from intensively grazed pastures in relation to NO_3-N leaching losses below 1 m depth without the need of calibration.

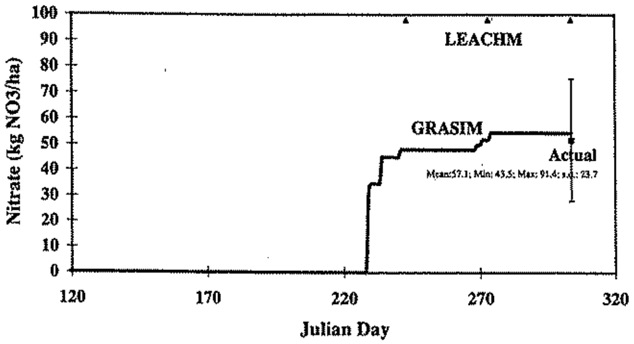

Figure 6–Predicted and measured nitrate leaching for the 1994 urine spring treatment.

SUMMARY AND CONCLUSIONS

A comprehensive grazing model (GRASIM) that links all components of the pasture system was developed to obtain a better understanding of the pasture system and determine management strategies which yield more efficient pastures use. GRASIM can generate information suitable for estimating the financial and environmental consequences of alternative dairy management strategies including partial mechanical harvest in the context of the year round feed needs of the dairy herd. The model can evaluate stocking rate effect on supplementation and amount of harvested feed. GRASIM has been scientifically tested and proven to perform well under field conditions.

The model was tested under field conditions using two fertilizer treatments (time and amount of fertilizer) and two seasons (1993 and 1994). Experiments were located at Penn State research farm in State College. Field testing and evaluation of GRASIM components, grass growth, nitrogen, and water budget to central Pennsylvania conditions were presented. Statistical tests indicated a good fit between predicted and observed accumulated biomass, nitrate leaching and amount of water drained data. Because of the mechanistic nature of the GRASIM, the model did not require any calibration.

GRASIM's water drainage and nitrogen leaching was also tested against another leaching model LEACHM. Tests concluded that GRASIM gave results that were closer to actual field data than LEACHM.

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REFERENCES

Addiscott, T. M. and A. P. Whitmore. 1987. Computer simulation of changes in soil mineral nitrogen and crop nitrogen during autumn, winter, and spring. *J. Agric. Sci. Camb.* 109:141-157.

______. 1991. Simulation of solute leaching in soils of differing permeabilities. *Soil Use Manage.* 7:94-102.

Bergstrom, L., H. Johnsson and G. Torstensson. 1991. Simulation of soil nitrogen dynamics using the SOILN model. *Fertilizer Res.* 27:181-188.

Donigian Jr., A. S. and P. S. C. Rao. 1986. Example model testing studies. In *Vadose Zone Modelling of Organic Pollutants*, 103-131, eds. S. C. Hern and S. M. Melancon. Chelsea, Mich.: Lewis Publishers.

Gripp, S., A. Elbehri, R. Yonkers, S. Ford and A. Luloff. 1993. Summary report of 1993 telephone survey with Pennsylvania dairy farm managers. A research report for the Pennsylvania dairy profitability project. Penn State University, University Park, Pa.

Hutson, J. L. and R. J. Wagenet. 1992. LEACHM, Leaching Estimation And CHemistry Model: Ver. 3. Department of Soil, Crop and Atmospheric Sciences, Research Series, No.92-3. Ithaca, N.Y.: Cornell University.

Jabro, J. D., J. M. Jemison Jr., L. L. Lengnick, R. H. Fox and D. D. Fritton. 1993. Field validation and comparison of LEACHM and NCSWAP models for predicting nitrate leaching. *Transactions of the ASAE* 36:1651-1657.

Jabro, J. D., J. D. Toth, Z. Dou, R. H. Fox and D. D. Fritton. 1995. Evaluation of nitrogen version of LEACHM for predicting nitrate leaching. *Soil Sci.* 160:209-217.

Jarvis, N. 1994. MACRO — A model of water movement and solute transport in macroporous soils. Reports and Diss. 9. Uppsala, Sweden: Department of Soil Sciences, Swedish University of Agricultural Sciences.

Jemison Jr., J. M., J. D. Jabro and R. H. Fox. 1994. Evaluation of LEACHM: II. Simulation of nitrate leaching from nitrogen fertilized and manured corn. *Agron. J.* 86:852-859.

Lengnick, L. L. and R. H. Fox. 1994. Simulation by NCSWAP of seasonal nitrogen dynamics in a corn crop: I. Soil nitrate. *Agron. J.* 86:167-175.

Loague, K. and R. E. Green. 1991. Statistical and graphical methods for evaluating solute transport models: Overview and application. *J. Contamin. Hydrol.* 7:51-73.

Mohtar, R. H., D. R. Buckmaster and S. L. Fales. 1996. A grazing simulation model: GRASIM, A: Model development. *Transactions of the ASAE* 40(5):1483-1493.

Molina, J. A. E. and K. Richards. 1984. Simulation models of the nitrogen and carbon cycle in the soil-water-plant system, NCSWAP; Guide for the preparation of input data files and execution of NCSWAP. Soil Series 116. St. Paul, Minn.: Dept. of Soil Science, University of Minnesota.

Moyer, J. W., L. S. Saporito and R. R. Janke. 1996. Design, construction, and installation of the Rodale intact soil core lysimeter. *Agron. J.* 88:253-256.

Petersen, G. R., H. L. Lucas and W. W. Woodhouse Jr. 1956a. The distribution of excreta by freely grazing cattle and its effect on pasture fertility: I. Excretal distribution. *Agron. J.* 56:440-444.

Petersen, G. R., W. W. Woodhouse Jr. and H. L. Lucas. 1956b. The distribution of excreta by freely grazing cattle and its effect on pasture fertility: II. Effect of returned excreta on the residual concentration of some fertilizer elements. *Agron. J.* 56:444-449.

Smith, W. N., W. D. Reynolds, R. de Jong, R. S. Clemente and E. Topp. 1995. Water flow through intact soil columns: Measurement and simulation using LEACHM. *J. Environ. Qual.* 24:874-881.

USDA-ARS. 1992. Root Zone Water Quality Model. (RZWQM) V. 1.0 Technical documentation. GPSR technical report No. 2. Ft. Collins, Colo.: USDA-ARS Great Plains Systems Res. Unit.

U.S. EPA. 1979. Methods for Chemical Analysis of Water and Wastes. Cincinnati, Ohio.: USEPA.