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N rate and transport under variable cropping history and fertilizer rate on loamy sand and clay loam soils: II. Performance of LEACHMN using different calibration scenarios

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Abstract

Testing of existing agronomic models is needed to ensure their validity and applicability to different soils, cropping systems and environments. Data collected from a 3-year field experiment of maize (*zea mays* L.) on a loamy sand and a clay loam soil were used to validate the research version of the LEACHMN model for water flow and N fate and transport. Three calibration scenarios with increasing levels of generalization for transformation rate coefficients were used based on: (i) each year, treatment and soil type (ii) 3-year average values for each treatment and soil type, and (iii) average over years and soil types. Model accuracy was tested using both graphical and statistical methods including 1:1 scale plot, root mean square error and normalized root mean square error, and correlation coefficient values. The model accurately predicted drainage water flow rate and volume under both sites. Calibrated N transformation rate constants for each treatment, year and soil type provided satisfactory predictions of growing season cumulative NO_3–N leaching losses, and accurate predictions of growing season cumulative maize N uptake at both sites. The use of 3-year average rate constant values for each site resulted in fairly satisfactory predictions of NO_3–N leaching losses on the clay loam site, but inaccurate predictions on the loamy sand site. The model provided accurate predictions of cumulative maize N uptake for both sites. Using the rate constant values averaged over years and soil types resulted mostly in inaccurate predictions. Use of year and soil type-specific N rate coefficients results in accurate LEACHMN predictions of N leaching and maize N uptake. When rate coefficients are generalized over years for each soil type, satisfactory model predictions may be expected when N dynamics are not strongly affected by yearly variations in organic N inputs.

Introduction

Several simulation models have been developed to address economic and environmental issues related to the use of nitrogen on soils (Addiscott and Wagenet, 1985). Various approaches include simple capacity models (e.g. Nofziger and Hornsby, 1986), transfer/stochastic models (Jury et al., 1986), and numerical convection-dispersion models (e.g. Ahuja et al., 1991; Wagenet and Hutson, 1989). While numerous N models have been published, none of them has been shown to adequately describe all soil and crop system processes (Clay et al., 1985a; Whitmore and Addiscott, 1987). Most of the currently available N leaching models have received only limited independent evaluation, and more testing is needed to ensure model reliability.

LEACHMN (the N version of LEACHM, Wagenet and Hutson, 1989 that simulates N fate and transport) is a deterministic model, and uses equations of Johnsson et al. (1987) to simulate N transformations. The model solves the classical Richards' equation for water flow to calculate soil water content and water fluxes in one-dimensional layered soil, and uses the convective-dispersion equation for solute transport. It

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balances N in the soil after simulating denitrification, volatilization, leaching and plant N uptake.

Model calibration and validation

Although there is a vast amount of literature concerned with mathematical models, relatively little has been written about calibration and evaluation procedures for characterizing model performance (Loague and Green, 1991). Field data available for calibration are generally scarce. In addition, it is typically unknown whether calibrated models can be used to generalize process simulations to other spatial and temporal domains. Can rate constants determined from a single soil type be generalized over a multitude of soil types? Can rate constants determined in a single or a few years be appropriately used in long-term simulations?

Jemison (1991) suggested that evaluation should include model calibration and validation, especially when transformation processes are modeled by rate constants. He defined calibration as being the process of adjusting model parameters within an expected range to minimize the difference between predicted and observed values. Validation, on the other hand, is essentially an independent test of the model where model predictions are compared with data not used in the calibration testing (Donnigan, 1983). Several proposed model testing methods have been reported by Jemison (1991). One of the most commonly used evaluation methods for N models includes calibrating the model for an individual year by adjusting field-measured input data or rate constants within a range of measured values, and validating the model with additional years of independent data. Another possible model testing procedure is to calibrate the model for each treatment and each year; then average rate constants are determined for specific N transformations. Model validation is done by modeling each of the years again using the average rate constants.

Addiscott et al. (1991) developed the following concept regarding the accuracy of nitrate leaching models: If the model is successful in simulating the changes in the amount of nitrate in the soil, credence can be given to the estimates that it gives of the amounts and concentrations of nitrate leaving the soil. According to this concept, another possible method of model testing is to calibrate the model with measured soil profile nitrate distribution and then validate the model predictions of NO_3–N leached and plant uptake of N based on the calibration data.

Sogbedji et al. (2000b) calibrated the LEACHMN model for each of the same N treatments, years and sites involved in this study by adjusting nitrification, denitrification and volatilization rate constants based on measured values of growing season soil profile nitrate distributions (Table 1).

The objectives of this paper were (i) to evaluate the accuracy of three calibration scenarios of the LEACHMN model on predictions of drainage water flow rate and volume, NO_3–N leaching losses and maize N uptake by comparing the model-simulated data to measured values collected from a 3-year (1992–1994) nitrate leaching experiment, and (ii) to evaluate the appropriateness of using generalized N rate coefficients in model simulations.

Materials and methods

Field experiment

Data used to validate the LEACHMN model were collected from an experiment as reported in Sogbedji et al. (2000a, b). The experiment was designed to measure drainage water flow rate and volume, and concentration and mass of NO_3–N leached from maize on two soil types, a Muskellunge sandy clay loam (fine mixed, frigid, Aeric Ochraqualf) and a Stafford fine sandy loamy (mixed, mesic, typic Psammaquent). The experimental site and plot layout description, crop information, and collection of data related to LEACHMN input parameters (soil physical and chemical properties, and other parameters input values) are described in detail in Sogbedji et al. (2000b). At each site, maize was grown for 3 years (1992–1994) following sod plowdown. Three N fertilizer rates were used in the study. A low rate of 22 kg N ha^{-1} applied at planting, an intermediate rate (PSNT-based, Magdoff, 1991) of 100 kg N ha^{-1} (22 and 72 kg N ha^{-1} as starter and sidedress, respectively), and the Cornell University recommended rate of 134 kg N ha^{-1} (22 and 112 kg N ha^{-1} as starter and sidedress, respectively). Drainage water flow rate and volume, and NO_3–N leaching losses from each experimental plot were measured using a custom-made 22.5° V-notch weir at the end of each central drain line terminating in a manhole. Each weir unit included a box that dissipates excess water energy and distributes the inflow from the drain line so that the water surface is smooth and free from turbulence as it passes over the weir. A submersible pressure transducer in the weir box automatically monitored water height in the weir which was recorded in a data logger (Telog Instruments, Inc. Rochester, NY). Records were collected at ten-minute intervals, and averaged for 2-hour intervals for the duration of the study. At each site, weirs were installed late in March 1992, but removed during the winter periods when soils were generally frozen (January–March) and reinstalled in the early spring of 1993 and 1994.

Hand measurements of water flow rate from each drain line were made to calibrate the recorded weir pressures with actual flow volumes. Drain effluent sampling generally occurred weekly throughout the calendar year but most intensively (up to every 4 h) during the growing season when the drain lines were flowing. The water samples were stored frozen until analyzed for NO_3–N concentration using an Auto Analyzer (Cornell Nutrient Analysis Laboratories, 1987, 1989).

Because of the V-shape design of the weir, the relationship between hand measured flow rates and weir records was assumed to be a non-linear relationship of the form:

$$Y = a + bX^C$$

where Y is the measured flow rate, a, b, and c are constants, and X is the weir-recorded hydraulic pressure (Aisenbrey et al., 1974). The weirs were calibrated using the PROC NLIN routine of the Statistical Analysis System (SAS Inst., 1988) software package which yielded least-square estimates for the coefficients a, b and c. Two-hour flow rates were calculated and summed to determine the drain effluent volumes for each individual plot. Mean drain effluent for the eight plots at each site in each of the 3 years of study was then determined.

Nitrate leaching losses from the drain line under each individual plot were calculated by multiplying the measured NO_3–N concentration under the plot by the weir-determined mean drain line effluent volume (over the interval of the midpoints between the sample collection times and the previous and subsequent samplings) and summing for the period of interest. Mean losses under each N treatment were calculated by averaging values from the plots under the treatment.

The LEACHMN model was calibrated by adjusting nitrification, denitrification and volatilization rate constants to optimize the fit between predicted and measured soil profile NO_3–N distribution (Sogbedji et al., 2000b). Three calibration approaches were used in the model testing effort: (i) calibrated rate constants for each year and soil type, (ii) 3-year average rate constant values for each site, and (iii) rate constant values averaged over years and soil types (Table 1). The use of average rate constant values for all treatments at each site was ignored as we found that N treatments used in this study minimally affected the calibrated transformation rate constants within year at each site (Sogbedji et al., 2000b). The free drainage boundary conditions option of the research version of LEACHMN was used. For each of the calibration scenarios, LEACHMN was executed under each N treatment in each year at both sites, and predicted and measured values of growing season cumulative NO_3–N leaching losses and maize N uptake were compared. Similarly, measured mean and LEACHMN-predicted values of drainage water flow rate and growing season cumulative drainage volume in each year at each site were compared. The examples of Loague and Green (1991) and Addiscott and Whitmore (1987) were followed, using both graphical and statistical methods to test model accuracy. The graphical method consists of plotting measured and predicted data on a 1:1 scale to examine their trends. The statistical method includes the determination of correlation coefficients, the root mean square error (RMSE) and the normalized root mean square error (NRMSE) defined as follows:

$$\text{RMSE} = \left[\sum_{i=1}^{n}(\text{measured} - \text{predicted})^2/n\right]^{0.5}$$

$$\text{NRMSE} = \text{RMSE / measured grand mean}$$

Where n is the number of observations.

According to Addiscott and Whitmore (1987), a positive, highly significant correlation, and non-significant mean difference indicate a statistically satisfactory simulation of the measured values.

Results and discussion

Drainage water

When measured and simulated data (Table 2) were compared, the water flow subroutine of the research version of LEACHMN accurately predicted drainage water flow at both sites. Predicted and measured drainage water flow rates were highly correlated, the RMSEs were low, and the normalized prediction errors ranged from 0.24 to 0.26 (Table 3). The 1:1 scale plot (Figure 1a) shows that measured and simulated water flow rate values followed a similar trend

Table 1. Calibrated N transformation rate constants (Sogbedji et al., 2000b) used for model validation procedures

Treatments	Loamy sand			Clay loam		
	Nitrification	Denitrification	Volatilization	Nitrification	Denitrification	Volatilization
	d^{-1}					
22 kg N ha^{-1}						
1992	0.200	0.200	0.200	0.200	0.260	0.200
1993	0.400	0.004	0.000	0.200	0.100	0.000
1994	0.400	0.003	0.000	0.300	0.080	0.000
3-yr average	0.333	0.069	0.066	0.233	0.150	0.066
100 kg N ha^{-1}						
1992	0.200	0.200	0.200	–[a]	–	–
1993	0.380	0.004	0.000	0.200	0.130	0.000
1994	0.400	0.004	0.000	0.270	0.100	0.000
3-yr average	0.326	0.070	0.066	0.235	0.115	0.000
134 kg N ha^{-1}						
1992	0.200	0.200	0.200	0.200	0.280	0.200
1993	0.380	0.004	0.000	0.200	0.130	0.000
1994	0.390	0.004	0.000	0.270	0.100	0.000
3-yr average	0.323	0.07	0.066	0.223	0.170	0.066
Over years and soil types average	0.281	0.106	0.060	0.281	0.106	0.060

[a]Treatment not applied.

with low bias. Similarly, growing season cumulative drainage volume was well predicted as measured and simulated values were highly correlated with low RMSEs and NRMSE values ranging from 0.07 to 0.17 (Table 3). When plotted on a 1:1 scale for both sites (Figure 1b), the data set distribution showed that the model consistently, although slightly, overestimated drainage volume. This might have resulted from model underestimation of plant transpiration, presumably because crop growth routines included in LEACHMN are based upon empirical equations and there is no feed back between soil conditions and plant growth. However, the general trends followed by simulated and observed data were similar. Results of this study agree with Jabro et al. (1994), Jemison et al. (1994) and Smith et al. (1995) who documented an accurate performance of the water flow subroutine of LEACHMN. This capability of the model to accurately predict water flow rate and volume presumably resulted from the fact that critical input parameters such as hydraulic conductivity and soil water retention were determined from on-site collected undisturbed field soil cores.

Nitrate leaching and N uptake

Using calibrated nitrification, denitrification and volatilization rate constants for each treatment-year combination and soil type to evaluate the performance of LEACHMN in predicting growing season cumulative NO_3–N leached and maize N uptake, resulted in a satisfactory performance of the model. At both sites, the RMSEs between measured and predicted NO_3–N leaching losses were generally low, the normalized prediction errors ranged from 0.12 to 0.30, and the correlation coefficients were generally above 0.90 (Table 3). The 1:1 scale plot of measured vs. LEACHMN-predicted values (Figure 2) showed similar, unbiased, patterns in the data point distribution, indicating a satisfactory match between measured and simulated data. However, on the clay loam soil discrepancies were greater under the highest N rate (Table 3) presumably because the high amount of N

Table 2. Measured mean and LEACHMN-predicted growing season cumulative NO_3–N leached and maize N uptake based on single year calibrated rate constant values, and drainage water volume on the clay loam and loamy sand soils

	Drainage water		NO_3–N leaching losses		Maize N uptake	
	Measured	Simulated	Measured	Simulated	Measured	Simulated
	mm		kg ha^{-1}			
Clay loam						
1992						
Treatments						
22 kg N ha^{-1}			6.4	7.7	158	157
100	34	40	–†	–	–	–
134			5.8	8.7	210	206
1993						
Treatments						
22 kg N ha^{-1}			2.4	3.0	103	103
100	33	35	3.1	2.7	142	141
134			5.0	4.0	186	184
1994						
Treatments						
22 kg N ha^{-1}			3.4	4.6	115	97
100	139	146	3.4	3.2	159	148
134			11.4	9.0	208	204
Loamy sand						
1992						
Treatments						
22 kg N ha^{-1}			11.2	12.8	126	113
100	94	106	12.3	9.4	179	171
134			11.4	10.0	166	163
1993						
Treatments						
22 kg N ha^{-1}			3.1	2.7	126	109
100	56	78	4.6	3.5	176	175
134			8.0	9.1	166	165
1994						
Treatments						
22 kg N ha^{-1}			9.0	7.3	141	115
100	146	162	12.5	10.7	197	182
134			18.0	15.0	186	176

†Treatment not applied.

added in fertilizer and the high initial soil N (due to alfalfa sod plowdown) did not allow for accurate partitioning of N between different pathways based on the adjusted rate constants. Simulations of growing season cumulative maize N uptake at both sites were accurate. Predicted and measured values were highly correlated, the NRMSE values ranged from 0.01 to 0.14 (Table 3), and no significant deviations were observed in their trends (Figure 3). This accuracy however may be in part the result of the fact that the model requires annual

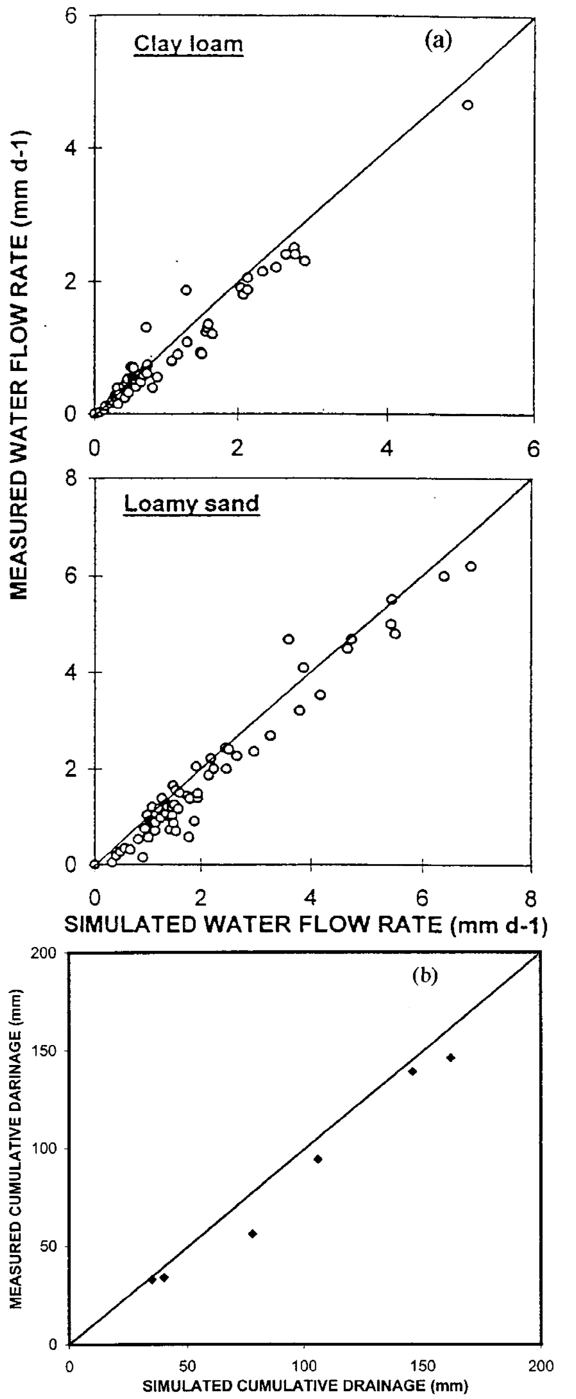

Figure 1. (a) 1:1 scale plot of measured and LEACHMN-predicted drainage water flow rate values in the three years of study on the clay loam and loamy sand. (b) 1:1 scale plot of measured and LEACHMN-predicted drainage water volume values in the three years of study on the clay loam and loamy sand.

Table 3. Statistical evaluation of LEACHMN simulations for growing season cumulative NO_3–N leached and maize N uptake based on single year calibrated rate constant values, and drainage water flow rate and volume on the loamy sand and clay loam soils

	n	RMSE	NRMSE	Correlation coefficient
Loamy sand				
Water			mm d^{-1}	
Flow rate	64	0.43	0.24	0.98
Drainage			mm d^{-1}	
	3	17.1	0.17	0.99
NO_3–N			kg ha^{-1}	
Treatment				
22 kg N ha^{-1}	3	1.4	0.17	0.91
100 kg ha^{-1}	3	2.1	0.21	0.98
134 kg ha^{-1}	3	2.0	0.18	0.93
Cumulative plant N uptake			kg ha^{-1}	
Treatment				
22 kg N ha^{-1}	3	19.4	0.14	0.60
100 kg ha^{-1}	2	9.8	0.05	0.89
134 kg ha^{-1}	3	6.0	0.03	0.98
All treatments	9	13.0	0.08	0.95
Clay loam				
Water			mm d^{-1}	
Flow rate	62	0.24	0.26	0.98
Drainage			mm d^{-1}	
	3	5.4	0.07	0.99
NO_3–N			kg ha^{-1}	
Treatment				
22 kg N ha^{-1}	3	1.1	0.26	0.99
100 kg ha^{-1}	2	0.3	0.10	0.99
134 kg ha^{-1}	3	2.2	0.30	0.65
All treatments	8	1.5	0.30	0.83
Cumulative plant N uptake			kg ha^{-1}	
Treatment				
22 kg N ha^{-1}	3	10.4	0.08	0.95
100 kg ha^{-1}	2	7.8	0.05	0.99
134 kg ha^{-1}	3	2.0	0.01	0.99
All treatments	8	7.5	0.05	0.99

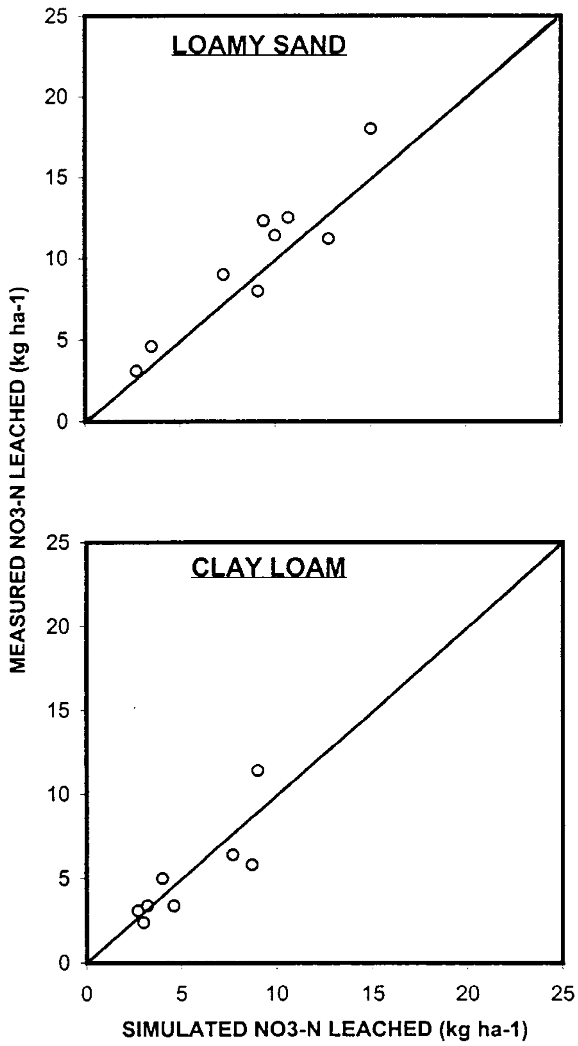

Figure 2. 1:1 scale plot of measured and LEACHMN-predicted based on treatment-year combination calibrated rate constant values of growing season cumulative NO_3–N leached in the three years of study on the clay loam and loamy sand.

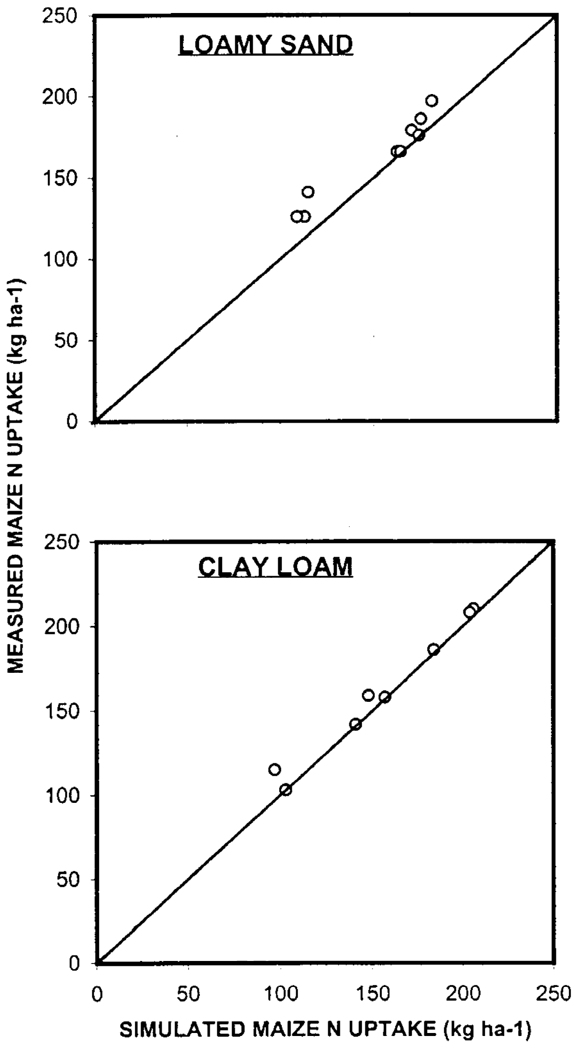

Figure 3. 1:1 scale plot of measured and LEACHMN-predicted based on treatment-year combination calibrated rate constant values of growing season cumulative maize N uptake in the three years of study on the clay loam and loamy sand.

N uptake as input data and therefore, can accurately predict it whenever there is enough N in the soil during the entire growing period and that simulated time course is adequate.

When 3-year average rate constant values for each treatment-site combination were used to test the performance of LEACHMN, predictions were somewhat less satisfactory, depending on the treatment-year combination and the site (Table 4).

On the loamy sand, predictions of growing season cumulative NO_3–N leaching losses were not successful. Noticeable deviations occurred in the trends followed by measured and simulated data when plotted on a 1:1 scale (Figure 4). The predictions were either highly underestimated or overestimated, which resulted in low correlation coefficients (0.13–0.75) and high NRMSE values (0.65 to 0.98) (Table 5). Rate constant values, especially for denitrification, varied significantly among individual years of the study (Sogbedji et al., 2000b) and the use of an average value, therefore greatly reduced the accuracy of model predictions. The model predictions of maize N uptake were similarly less accurate when using the three-year average values rather than the yearly calibrated rate constants (Figures 3 and 5), although normal-

Table 4. Measured mean and LEACHMN-predicted values of growing season cumulative NO_3–N leached and maize N uptake based on rate constants averaged over three years and rate constants averaged over soil types and years

	Rate constants averaged over three years				Rate constants averaged over soil types and years			
	NO_3–N leaching losses		Maize N uptake		NO_3–N leaching losses		Maize N uptake	
	Measured	Simulated	Measured	Simulated	Measured	Simulated	Measured	Simulated
	kg ha^{-1}							
LOAMY SAND								
1992								
Treatments: 22 kg N ha^{-1}	11.2	23.2	126	125	11.2	23.2	126	125
100 kg N ha^{-1}	12.3	18.2	179	178	12.3	18.2	179	178
134 kg N ha^{-1}	11.4	22.0	166	165	11.4	22.0	166	165
1993								
Treatments: 22 kg N ha^{-1}	3.1	1.8	126	87	3.1	1.8	126	75
100 kg N ha^{-1}	4.6	2.4	176	175	4.6	2.4	176	88
134 kg N ha^{-1}	8.0	2.4	166	165	8.0	2.4	166	88
1994								
Treatments: 22 kg N ha^{-1}	9.0	3.4	141	112	9.0	2.0	141	78
100 kg N ha^{-1}	12.5	3.4	197	171	12.5	2.0	197	83
134 kg N ha^{-1}	18.0	8.7	186	180	18.0	7.0	186	94
CLAY LOAM								
1992								
Treatments: 22 kg N ha^{-1}	6.4	8.1	158	157	6.4	8.1	158	157
100 kg N ha^{-1}	–†	–	–	–	–	–	–	–
134 kg N ha^{-1}	5.8	11.0	210	209	5.8	12.0	210	209
1993								
Treatments: 22 kg N ha^{-1}	2.4	2.97	103	102	2.4	3.0	103	102
100 kg N ha^{-1}	3.1	5.5	142	141	3.1	6.3	142	141
134 kg N ha^{-1}	5.0	3.3	186	185	5.0	3.5	186	186
1994								
Treatments: 22 kg N ha^{-1}	3.4	3.6	115	84	3.4	4.0	115	87
100 kg N ha^{-1}	3.4	1.0	159	136	3.4	1.0	159	139
134 kg N ha^{-1}	11.4	7.2	208	167	11.4	8.0	208	182

†Treatment not applied

ized prediction errors only ranged from 0.02 to 0.21 (Table 5).

On the clay loam, predictions of NO_3–N leaching losses using three-year average rate constant values were also inferior to the use of yearly calibrated values. Most data points, however, followed a similar unbiased trend (Figure 4), and normalized prediction errors ranged from 0.25 to 0.53 (Table 5). These values were lower than those for the loamy sand, which resulted from the fact that, as reported in Sogbedji et al. (2000b), the 3 year average and yearly rate constant values were somewhat similar for that site. This presumably also resulted in satisfactory predictions of maize N uptake (Figure 5).

The use of rate constant values averaged over years and soil types to evaluate the LEACHMN predictions of growing season cumulative NO_3–N leaching losses resulted in fairly satisfactory performance of the model for the clay loam, but inaccurate predictions for the loamy sand (Table 4). Normalized prediction errors for the loamy sand ranged from 0.70 to 1.00 (Table 5) and measured and simulated data fol-

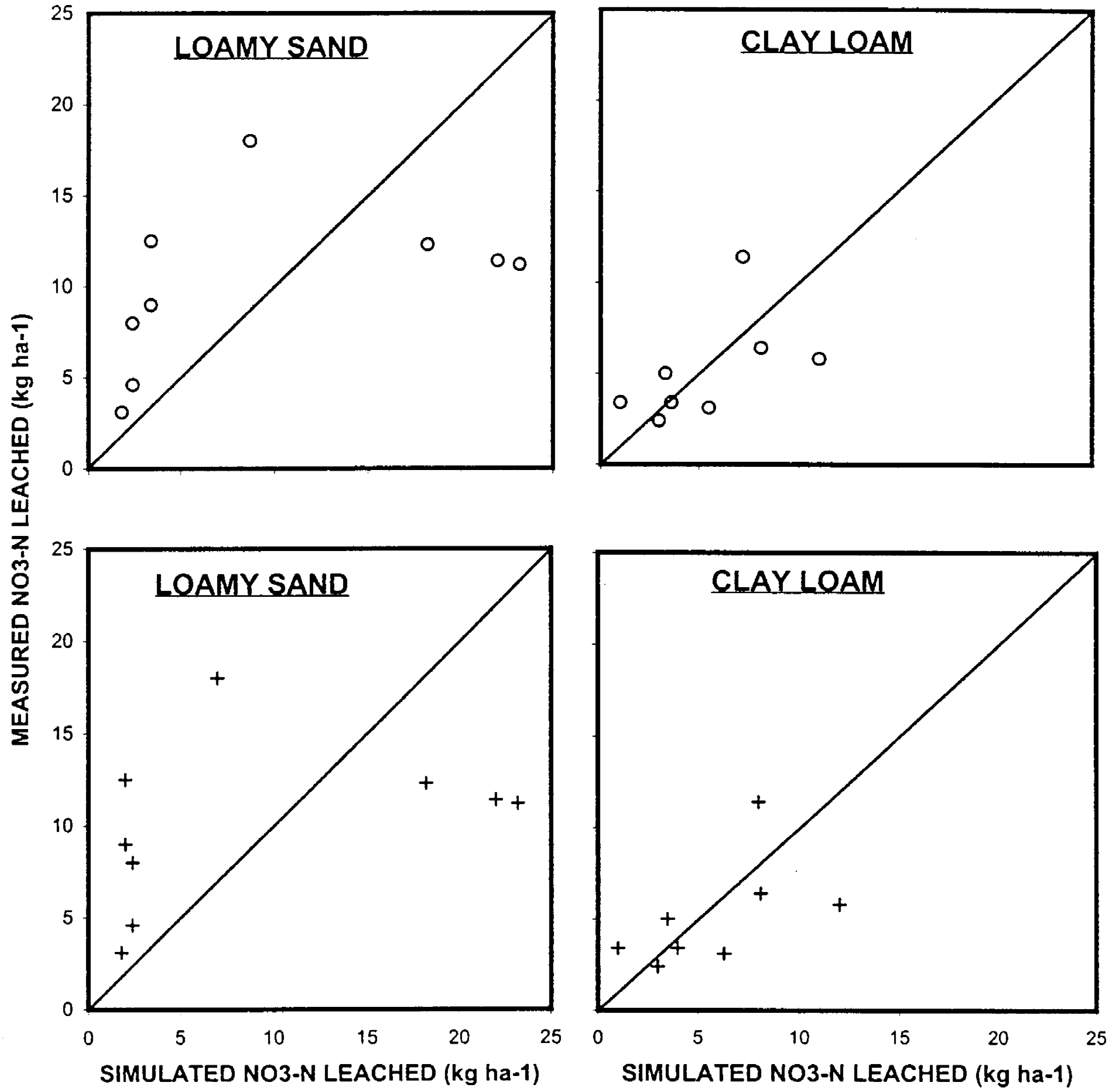

Figure 4. 1:1 scale plot of measured and LEACHMN-predicted based on calibrated rate constant values averaged over three years (o) and averaged over soil types and years (+) of growing season cumulative NO_3–N leached on the clay loam and loamy sand.

lowed systematically different trends (Figure 4). On the clay loam, normalized errors ranged from 0.32 to 0.87 (Table 5) and measured and simulated data point distributions appeared to be similar to those under the testing method using the three-year average rate constant values at that site (Figure 4).

Predictions of maize N uptake were similarly inaccurate for the loamy sand site with normalized prediction errors of around 0.40 and simulated values consistently underpredicting measured values (Figure 5). On the clay loam on the other hand, predictions of maize N uptake were satisfactory, with errors between 0.10 and 0.14 (Table 5), and a good match in the trends followed by measured and simulated values

Conclusions

Without any adjustment of the model-required input data, the water flow subroutine of the research version

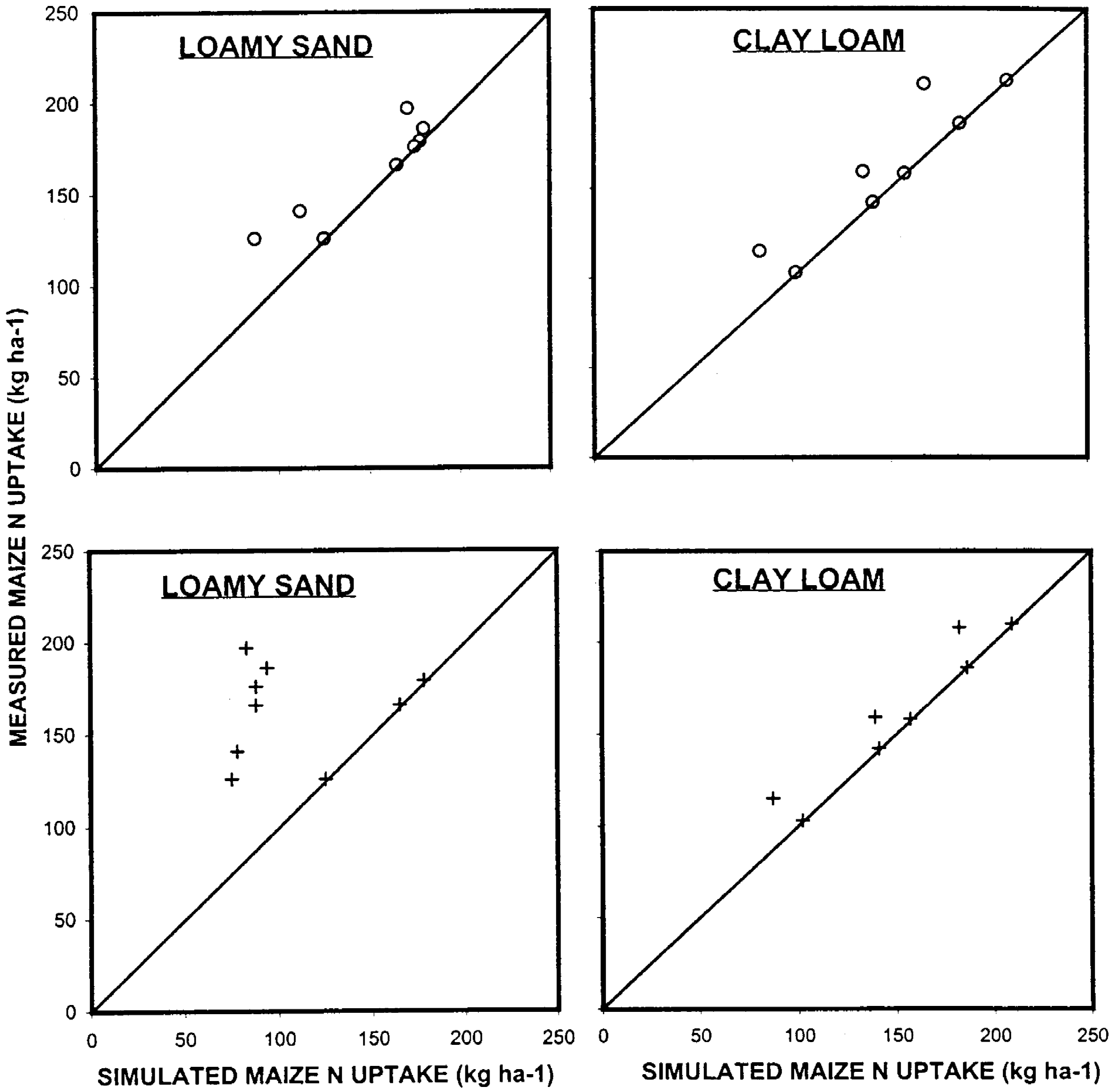

Figure 5. 1:1 scale plot of measured and LEACHMN-predicted based on calibrated rate constant values averaged over three years (o) and averaged over soil types and years (+) of growing season cumulative maize N uptake on the clay loam and loamy sand.

of LEACHMN accurately predicted drainage water flow rate and volume on both sites. This capability of the model presumably resulted from the fact that critical input parameters such as hydraulic conductivity and soil water retention were collected on-site from undisturbed field soil cores.

When LEACHMN was tested using calibrated N transformation rate constants for each treatment-year-soil type combination, it satisfactorily predicted growing season cumulative NO_3–N leaching losses and growing season cumulative maize N uptake at both sites. The model can better predict NO_3–N leaching losses if the simulation of early growing season maize N uptake is improved.

The use of 3-year average rate constant values for each treatment-site combination to evaluate the model resulted in fairly satisfactory predictions of growing season cumulative NO_3–N leaching losses, and accurate predictions of growing season cumulative maize N uptake on the clay loam. This resulted from the fact

Table 5. Statistical evaluation of LEACHMN for growing season cumulative NO_3–N leached and maize N uptake based on rate constants averaged over three years and rate constants averaged over soil types and years

		Rate constants averaged over three years			Rate constants averaged over soil types and years		
	n	RMSE (kg ha^{-1})	NRMSE	Correlation coefficient	RMSE (kg ha^{-1})	NRMSE	Correlation coefficient
LOAMY SAND							
Cumulative NO_3–N leached							
Treatments: 22 kg N ha^{-1}	3	7.7	0.98	0.75	8.0	1.03	0.76
100 kg N ha^{-1}	3	6.4	0.65	0.53	6.9	0.70	0.48
134 kg N ha^{-1}	3	8.7	0.70	0.13	9.4	0.75	0.04
All treatments	9	7.6	0.76	0.44	8.2	0.81	0.38
Cumulative plant N uptake							
Treatments: 22 kg N ha^{-1}	3	28.0	0.21	0.18	47	0.36	−0.45
100 kg N ha^{-1}	3	15.0	0.08	0.84	81	0.44	−0.38
134 kg N ha^{-1}	3	3.5	0.02	0.99	70	0.40	−0.43
All treatments	9	18.4	0.11	0.90	67	0.41	0.15
CLAY LOAM							
Cumulative NO_3–N leached							
Treatments: 22 kg N ha^{-1}	3	1.0	0.25	0.99	1.2	0.32	0.99
100 kg N ha^{-1}	2	2.4	0.41	−1.0	2.8	0.87	−1.00
134 kg N ha^{-1}	3	3.9	0.53	0.12	4.2	0.56	0.14
All treatments	8	2.4	0.46	0.54	3.0	0.59	0.53
Cumulative plant N uptake							
Treatments: 22 kg N ha^{-1}	3	17.9	0.14	0.90	17.9	0.14	0.91
100 kg N ha^{-1}	2	16.3	0.10	−1.0	16.3	0.10	−1.00
134 kg N ha^{-1}	3	23.7	0.11	0.16	23.7	0.11	0.44
All treatments	8	19.9	0.12	0.91	19.9	0.12	0.95

that the 3-year average rate constant values were in most cases close to yearly rate constant values, which, presumably, was due to cropping history at that site. On the loamy sand site, the use of a 3-year average rate constant values resulted in inaccurate predictions of NO_3–N leaching losses, but satisfactory predictions of maize N uptake. Higher annual variability in rate constants on this site made the use of year-average values less appropriate than for the clay loam site. In particular, denitrification rates on the loamy sand were approximately 50-fold higher in the first year (after grass sod) than in the 2 subsequent years.

When rate constant values averaged over both years and soil types were used, only growing season cumulative maize N uptake on the clay loam site was accurately predicted. Predictions of maize N uptake on the loamy sand and NO_3–N leaching losses on both sites were inaccurate, as a result of large differences in rate constants between the soil types.

These results indicate that the LEACHMN model can accurately predict N fate and transport when rate constants are derived from calibrations for each soil type and year. However, model predictions become less accurate when rate coefficients are based on average values over years and soil types. Generalization of the model over larger temporal and spatial domains should therefore be done with great caution. In this study, most of the yearly variation in rate constants, especially for denitrification, was associated with the transition from a perennial sod crop to maize immediately prior to the first year of the experiment. Such variation presumably resulted from the apparent problem with the rate constant adjustment sub-routine of the model in adequately adjusting rate constants according to substrate supply. Better simulations of N dynamics under cropping systems similar to those involved in this study are subject to improvement of the model's sub-routine controlling rate constant adjustment. Rate constants for the second and third years after conversion were relatively consistent within soil type, implying that average rate constant values can be used for each soil type when N dynamics are not strongly influenced by variations in organic N inputs, such as from green manures.

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