TECHNICAL NOTE:

IMPROVED NUTRIENT PARAMETERS FOR MODELING DIFFUSE POLLUTION IN THE TROPICS

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ABSTRACT. *Nonpoint-source (NPS) or diffuse pollution is a major environmental problem in developed countries, and modeling is an important tool used to evaluate the effectiveness of pollution control measures. The use of NPS models in the tropics usually involves the application of models developed for temperate regions with little, if any, adaptation to tropical conditions. In this article, we provide a synthesis of the literature values from studies in the tropics, using the GLEAMS model as a reference for the comparable values used in representing temperate conditions. We found that values for the carbon to nitrogen (C:N) ratio, potentially mineralizable nitrogen to total nitrogen ratio (N_0/N_{total}), and base NO_3-N and NH_4-N concentrations representative of tropical soils were all different from the values considered appropriate for temperate soils. Relationships between phosphorus pools in tropical soils and in phosphorus sorption parameters likewise were different from those used in GLEAMS, with the exception that the GLEAMS ratio between labile and organic phosphorus in highly weathered soils was found to be comparable to data specific for tropical soils.*

Keywords. Agroecosystem, Diffuse pollution, GLEAMS, Model, Nitrogen, Nonpoint pollution, Nutrients, Phosphorus, Tropical soils, Tropics.

The major portion of nonpoint-source (NPS) water pollution originates from a broad range of human activities from which the pollutants have no obvious point of entry into receiving waters. Agricultural activities can be a major source of NPS pollution, with the discharge of sediments, pesticides, nutrients, and microorganisms impacting stream water quality (EPA, 2003). NPS pollution is a major environmental problem in developed countries, and is growing as an issue of concern in tropical developing countries as areas used for subsistence or low-intensity agriculture have transitioned to high-technology agriculture with increased use of fertilizers and pesticides. The tropics comprise about 36% of the earth surface, and characteristics differ from temperate areas in many aspects. These differences must be considered when practices developed in temperate areas to control NPS pollution are applied in the tropics.

Modeling is an important tool used to evaluate the effectiveness of NPS pollution control measures, and NPS models are commonly used in developed countries for environmental evaluation and management. However, the use of NPS models is limited in the tropics and usually involves the application of models developed for temperate conditions with only minor, if any, adaptation to tropical conditions. Ecosystem models commonly include regression relationships and default or base parameter values that represent the conditions of the region for which the model was developed. While some values can be specified as inputs, others are part of the model code and cannot be readily changed. It is critical to define the characteristic parameters and default values that represent nutrient dynamics in tropical soils so that they can be integrated into NPS models to better represent rate processes and base conditions in predicting nutrient fate and transport.

The objective of this study was to determine from the literature: values for the carbon to nitrogen (C:N) ratio of soil organic matter, the ratio of potential mineralizable to total nitrogen in the soil (N_0/N_{total}), base soil nitrate (NO_3-N) and ammonium (NH_4-N) concentrations, soil phosphorus sorption, and the relationships between the main pools of phosphorus (P) in tropical soils. The Groundwater Loading Effects of Agricultural Management Systems (GLEAMS) model (Knisel and Davis, 1999), which was developed with data from North America, was used as a reference in comparison with the values and relationships sought here in a synthesis of results of studies in tropical conditions.

CARBON TO NITROGEN RATIO

The C:N ratio for tropical soils was evaluated using published data from 13 studies. Data of organic C and total nitrogen from Brazil (Araujo et al., 2001; D'Andrea et al., 2004; Sampaio et al., 1990; Van Wambeke, 2003), Dominica, Guadeloupe and Santa Lucia (Chotte et al., 1998), Malaysia (Mubarak et al., 2001), Hawaii (Neff et al., 2000), Thailand, Sudan, and Zambia (Van Wambeke, 2003), Australia (O'Connel and Rance, 1999), Venezuela (San Jose et al., 2003), Nigeria (Wong et al., 1987), Martinique (Neff et al., 2000), Colombia (Phiri et al., 2001), Ethiopia (Solomon et al., 2002), and Kenya (Warren and Kihanda, 2001) were included in this analysis.

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Table 1. Area and mean C:N ratio for different soil orders in the tropics.

Soil	Total Area in the Tropics[a]		Mean C:N Ratio[b]
	(10^6 ha)	(%)	
Oxisols	525	35.3	13.0
Ultisols	413	27.7	13.3
Inceptisols	226	15.2	12.3
Alfisols	53	3.6	8.0
Spodosols	19	1.3	44.7
Vertisols	5	0.3	12.3
Entisols	212	14.2	-- [c]
Histosols	27	1.8	-- [c]
Mollisols	7	0.5	-- [c]
Aridisols	2	0.1	-- [c]

[a] From Lal (1995).
[b] Based on data from: Araujo et al. (2001), D'Andrea et al. (2004), Sampaio et al. (1990), Van Wambeke (2003), Chotte et al. (1998), Mubarak et al. (2001), Neff et al. (2000), O'Connel and Rance (1999), San Jose et al. (2003), Wong et al. (1987), Phiri et al. (2001), Solomon et al. (2002), and Warren and Kihanda (2001).
[c] No data for these soil orders.

A summary of the mean C:N ratio by soil order is shown in table 1 along with the total area of each soil order in the tropics. The area-weighted mean C:N value (considering only soil orders with data) is 13.24, which is comparable to values from four other large datasets (Tognon et al., 1998; Post and Pastor, 1985; Sanchez et al., 1982; ISRIC, 2003). For comparison, the default C:N ratio in GLEAMS is set at 10:1. From the data summarized here, a value of 13.0 is suggested for representing the C:N ratio in tropical soils. This value is clearly representative of the three primary soil orders that comprise over 78% of soils in the tropics. However, in areas with Spodosols, Alfisols, or one of the soil orders without data in table 1, the applicability of either value as a default C:N ratio should be questioned.

POTENTIALLY MINERALIZABLE NITROGEN (N_0)

Stanford and Smith (1978) used data of 62 soils from eight soil orders (Alfisols, Aridisols, Entisols, Inceptisols, Mollisols, Spodosols, Ultisols, and Vertisols), all from temperate sites in North America, and observed an average ratio of N_0/N_{total} of 0.165. These data were used in defining the default value of potentially mineralizable N in GLEAMS. The average ratio of N_0/N_{total} for tropical soils was calculated using 27 data values from soils in Venezuela (San Jose et al., 2003), Colombia, Brazil, Costa Rica, Peru (Motavalli et al., 1995), and Australia (Campbell et al., 1981). The data include samples of four Ultisols from Venezuela, two Vertisols and one Andisol from Colombia, one Vertisol and two Andisols from Costa Rica, one Mollisol and four Oxisols from Brazil, and five soils from Australia. All data were from samples collected to a depth of 30 cm.

Table 2 shows summary statistics of the N_0/N_{total} ratio of the temperate and tropical soil datasets. High variation in the data, evidenced by the high values of range and standard deviation (SD), is seen in both data sets. For the tropical data, the confidence interval of the mean was calculated as 0.140 ±0.022 (α = 0.05), and 0.14 was considered the most appropriate value to represent the N_0/N_{total} ratio in tropical soils.

Table 2. Summary statistics of N_0/N_{total} ratio for temperate and tropical soils.

Region	Count	Mean	SD	Min.	Max.
Temperate[a]	62	0.165	0.068	0.046	0.405
Tropical[b]	27	0.140	0.059	0.062	0.303

[a] Source: Stanford and Smith (1978).
[b] Sources: San Jose et al. (2003), Motavalli et al. (1995), and Campbell et al. (1981).

NITRATE AND AMMONIA

The default value for nitrate concentration in GLEAMS is 5 μg NO_3–N/g soil in all horizons, while the ammonium value is set as 2 μg/g soil. Nine studies with values of nitrate and five with values of ammonium at different depths and locations were used to estimate values for the tropics. The nine studies for nitrate were by D'Andrea et al. (2004) in Brazil, Phiri et al. (2001) in a Colombian Inceptisol, Deare et al. (1995) in Trinidad, Mekonnen et al. (1997) in western Kenya, Arora and Juo (1982) in Nigeria, Shepherd et al. (2001) in the highlands of western Kenya, Wild (1972) in northern Nigeria, Hartemink et al. (1996) in the subhumid highlands of Kenya, and Strong et al. (1998) in New South Wales, Australia. Concentrations of NO_3–N and NH_4–N were averaged by soil order and the area-weighted mean determined based on the prevalence of each soil order in the tropics (table 3).

The mean and confidence interval for NO_3–N concentration for the entire dataset was 11.33 ±1.07 (α = 0.05), and the area-weighted mean is 10.34 μg NO_3–N/g soil. From these data, the value of 10 μg NO_3–N/g soil is suggested as a more representative default value of NO_3–N concentration for tropical soils. While the dataset is small, the higher value of NO_3–N is supported by the work of Sierra et al. (2003), who found that positive charges in tropical soils retarded nitrate movement, resulting in higher concentrations before losses by leaching.

The data on NH_4–N concentrations were also grouped by sample depth, and summary statistics are shown in table 4. High variation in the dataset is evident in every soil layer, but it is clear that values are significantly higher than the 2 μg NH_4–N/g soil default value used in GLEAMS. The mean values varied from 25.81 μg NH_4–N/g soil in the 1-10 cm layer to 9.62 μg NH_4–N/g soil in the 40-80 cm layer depth. Silva and Vale (2000) also found higher values of NH_4–N than those typical for temperate conditions. They observed values of ammonium concentration ranging from 10 to 23 μg NH_4–N/g soil in the superficial layer of five soils from the southeastern region of Brazil.

One of the main causes for higher ammonium concentration in tropical soils is the inhibition of nitrification in acidic

Table 3. Mean NO_3–N and NH_4–N concentrations for some soil orders in the tropics.

Soil	Total Area in the Tropics		NO_3-N[a],[b] (μg/g soil)	NH_4-N[a] (μg/g soil)
	(10^6 ha)	(%)		
Oxisols	525	35.3	12.5	18.8
Ultisols	413	27.7	8.6	19.1
Inceptisols	226	15.2	7.7	19.2
Alfisols	53	3.6	14.1	--
Area-weighted average:			10.34	18.98

[a] Sources: D'Andrea et al. (2004), Phiri et al. (2001), Deare et al. (1995), Arora and Juo (1982), and Strong et al. (1998).
[b] Sources: Mekonnen et al. (1997), Shepherd et al, (2001), Wild (1972), and Hartemink et al. (1996).

Table 4. Summary statistics of NH₄–N concentration in tropical soils.[a]

Depth (cm)	Count	NH₄-N concentration (µg NH₄-N/g soil)			
		Mean	SD	Min.	Max.
1-10	60	25.81	30.54	0.00	156.00
10-20	12	18.39	9.42	8.93	42.86
20-40	42	14.55	14.63	4.00	99.00
40-80	24	9.62	6.44	3.00	33.93
80-100	6	17.26	2.63	15.18	21.43

[a] Sources: D'Andrea et al. (2004), Phiri et al. (2001), Deare et al. (1995), Arora and Juo (1982), and Strong et al. (1998).

Table 5. Relationships between soil organic P (SORGP), organic carbon (OC), and total nitrogen (TN) for some tropical soils.

Model[a]	Dataset	R^2	Eq.
SORGP = 2.541 OC + 8.8	Ipinmidun (1973)	0.61	5
SORGP = 6.904 OC - 14.3	Condron et al. (1990)	0.52	6
SORGP = 777 TN + 6.0	Condron et al. (1990)	0.35	7
SORGP = 3.026 OC + 23.8	Guerra et al. (1996)	0.28	8
SORGP = 428 TN + 2.6	Guerra et al. (1996)	0.51	9

[a] SORGP is soil organic P (mg P/kg soil), TN is total nitrogen (%), and OC is organic carbon (g C/kg soil).

soils. Sierra et al. (2003) considered the nitrification rate to be a result of factors related to soil moisture, pH, and temperature. According to Silva et al. (1994), nitrification rates decrease sharply at a pH lower than 6 and are very low in soils with pH lower than 5. Besides reducing the nitrification rate, low pH favors the formation of the ammonium cation in its equilibrium reaction with ammonia. Because low pH is a characteristic of tropical soils and was also typical of the soils in the studies used in this analysis, a buildup of NH₄–N may be expected, accounting for the higher values of NH₄–N in tropical soils.

The mean and confidence interval of NH₄–N concentration for the entire dataset is 18.9 ±3.67 ($\alpha = 0.05$), while the area-weighted mean based on the distribution of soils in the tropics is 18.98 µg NH₄–N/g soil. For tropical conditions, a value of 19 µg NH₄–N/g soil is recommended as the default value of NH₄–N for all soil layers.

PHOSPHORUS

The equations used in GLEAMS for calculating initial values of phosphorus were based on Sharpley et al. (1984). For the surface horizon of highly weathered soils, soil organic P (SORGP, mg/kg) is calculated as:

$$SORGP = 1130\ TN + 44.4 \qquad (1)$$

where TN is total nitrogen (%). For the other horizons, the relationship is given by:

$$SORGP = 1464\ TN \qquad (2)$$

Sharpley et al. (1989), using data of 32 highly weathered soils (5 Alfisols, 2 Inceptisols, 3 Oxisols, 3 Spodosols, and 19 Ultisols), all with Al saturation greater than 30, derived the following equations:

$$SORGP = 1109\ TN + 42.2 \qquad (3)$$

$$SORGP = 62.1\ OC + 63.4 \qquad (4)$$

where SORGP is organic P (mg/kg), OC is organic carbon (%), and TN is total nitrogen (%).

In our analysis, we used three datasets to calculate soil organic phosphorus (SORGP) based on organic carbon (OC) and total nitrogen (TN). The data represent 15 soils from sites in north-eastern Brazil and Ghana (Condron et al., 1990), 13 soils from Brazil (Guerra et al., 1996), and 16 soils from northern Nigeria (Ipinmidun, 1973). Five new models derived by linear regression from these data are shown in table 5.

Equations 1 and 3 to 9 were then evaluated using the datasets of Condron et al. (1990), Guerra et al. (1996), and Ipinmidun (1973). The equations were used to calculate SORGP and the results compared with measured data through the calculation of the mean square error (MSE):

$$MSE = \frac{\sum_{i=1}^{n}(r_i)^2}{n} \qquad (10)$$

where r_i is the difference between measured and predicted values, and n is the number of observations. The results are shown in table 6.

In every case, the last five models (eqs. 5 through 9) had better goodness-of-fit (MSE) than the models presented by Sharpley et al. (1984, 1989) (eqs. 1, 3, and 4). The equations using OC as an independent variable (eqs. 4, 5, 6, and 8), overall, had lower MSE than the equations based on TN. The model (eq. 6) derived from the dataset of Condron et al. (1990) is recommended for calculating organic phosphorus in tropical soils.

Labile P (CLAB) is estimated in GLEAMS as 10% of SORGP for calcareous soils, 8.7% of SORGP for slightly weathered soils, and 5.6% of SORGP for highly weathered soils. Most studies that report different pools of phosphorus

Table 6. Goodness-of-fit of eight models predicting soil organic P (SORGP) from total nitrogen (TN) and organic carbon (OC) based on comparison with three datasets.

Equation	Model[a]	Mean Square Error of SORGP		
		Condron et al. (1990)	Guerra et al. (1996)	Ipinmidun (1973)
1	SORGP = 1130 TN + 44.4	7,529	24,874	--
3	SORGP = 1109 TN + 42.2	1,183,820	3,234,676	--
4	SORGP = 62.1 OC + 63.4	774,854	972,396	144,172
5	SORGP = 2.541 OC + 8.8	3,612	1,358	*37*[b]
6	SORGP = 6.904 OC - 14.3	*1,681*[b]	1,974	210
7	SORGP = 777 TN + 6.0	*2,270*[b]	2,427	--
8	SORGP = 3.026 OC + 23.8	2,427	*857*[b]	337
9	SORGP = 428 TN + 2.6	3,777	*581*[b]	--

[a] SORGP is soil organic P (mg P/kg soil), TN is total nitrogen (%), and OC is organic carbon (g C/kg soil).
[b] Values in *italics* indicate the model was derived from that dataset.

in tropical soils considered residual P as one pool in which organic and inorganic recalcitrant P were measured together (e.g., Tokura et al., 2002; Silva et al., 2003), making it impossible to calculate total organic P. However, the studies of Guerra et al. (1996), Oberson et al. (2001), and Cardoso et al. (2003) have data that allow the calculation of the relationship between labile P and total organic P. The studies comprise 28 values from different soils and land uses, mostly from Brazil. Using these data, the percentage of CLAB in relation to total organic P was calculated. The confidence interval for the relationship between both P pools was 5.24 ± 1.75, which encompasses the value of 5.6 used in the GLEAMS model for highly weathered soils. Thus, the relationship between both P pools used in GLEAMS for highly weathered soils (CLAB = 5.6% SORGP) was considered appropriate for calculating the default value of labile P in tropical soils.

The phosphorus sorption coefficient or P availability index is a variable that estimates the fraction of fertilizer P that remains in the labile form after a six-month incubation. It is used by GLEAMS to calculate active mineral P (PMINP) using values of labile P. Soil sorption (PSP) is calculated as follows:

$$PSP = 0.46 - 0.0916 * \ln(CLAYPCT) \qquad (11)$$

where CLAYPCT is clay content of the soil layer (%).

Sharpley et al. (1989), using data of 32 highly weathered soils (5 Alfisols, 2 Inceptisols, 3 Oxisols, 3 Spodosols, and 19 Ultisols), all with Al saturation greater than 30, proposed:

$$PSP = 0.7 - 0.19 \log(CLAYPCT) \qquad (12)$$

When clay is equal to or greater than 40%, this equation results in negative values of PSP. Because clay content greater than 40% is common in tropical soils, the model of Sharpley et al. (1989) is not considered appropriate for PSP calculation for tropical soils.

The appropriateness of using equation 11 for tropical soils was assessed using the data from Goncalves et al. (1989), Lopez et al. (2001), and Cardoso et al. (2003). The first two studies were based on 18 soil samples and experimentally determined the value of PSP. In these studies, different amounts of fertilizer P were added to soil samples, which were incubated for 180 days. The following equation was defined:

$$PSP = (P_{lf} - P_{li})/P_f \qquad (13)$$

where P_{lf} is mg/kg labile P after 180 days of incubation, P_{li} is mg/kg labile P in the control (when no P is added to the soil sample), and P_f is mg/kg labile P added as fertilizer. The mean value of PSP for the two datasets was 0.14, with standard deviation of 0.07. The appropriateness of using the mean value of PSP in the place of values calculated using equation 11 was evaluated using data from Cardoso et al. (2003), which contains measured values of CLAB and PMINP. For this evaluation, values of PMINP were calculated as:

$$PMINP = PLAB / (PSP / (1 - PSP)) \qquad (14)$$

The mean square error (MSE) between measured and calculated values of PMINP was 1046 when PMINP was calculated using PSP = 0.14 and 1566 when PSP was calculated by using equation 11. The value of 0.14 is thus considered to be an improvement in representing PSP for highly weathered tropical soils compared to the equation used in GLEAMS based on temperate soils.

CONCLUSIONS

A synthesis of data from studies relating to nutrient dynamics in tropical soils found important differences in parameters and relationships in comparison to values derived from data in temperate soils. Specifically, differences in tropical versus temperate conditions are evident in the C:N ratio, in the ratio of potentially mineralizable nitrogen to total nitrogen (N_0/N_{total}), in soil nitrate and ammonium concentrations, in soil P sorption, and in the relationships between the main pools of P in tropical soils. The ratio between labile and organic phosphorus in highly weathered soils was found to be comparable to that in tropical soils. Improving these parameters and relationships in models concerned with predicting nutrient dynamics and nonpoint-source pollution in the landscape will result in improved representation of the processes in tropical conditions.

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