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RAPID WATER FLOW AND TRANSPORT OF INORGANIC AND ORGANIC NITROGEN IN A HIGHLY AGGREGATED TROPICAL SOIL

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Microaggregated tropical soils have shown high water conductivity even under unsaturated conditions in laboratory experiments. It is not clear, however, what depth the infiltrating soil water reaches during storm events under humid tropical conditions and how this relates to losses of N by leaching. Dynamics and fluxes of water and applied ^{15}N were determined with high temporal resolution to a depth of 5 m in a Xanthic Hapludox of central Amazonia, Brazil. The soil water percolated to a depth of 0.9 m within 2 h of a rainfall event of 48 mm. Water fluxes were significantly slower below 0.9 m (17% of infiltration at 0–0.9 m) due to higher bulk densities. Percolation not only started rapidly after a rainfall event when soil water suction reached a certain threshold (ca. 20–30 hPa) but was also reduced to background levels less than 1 h after the rain had ended. Traces of labeled N reached 5 m within a few days, and ^{15}N maintained high levels to a depth of 1.2 m throughout the rainy season. Organic N was a large proportion (36–44%) of the total N leaching and the proportion increased with depth. However, organic N percolated more slowly than nitrate. The demonstrated extreme short-term dynamics of water fluxes have implications for measurement design of water availability and solute leaching in microaggregated tropical soil that require correct time integrals of solution concentrations and soil water dynamics. Measurement intervals of 30 min or less were necessary in our study. Rapid water flows explain the observed high N losses from the topsoil of microaggregated tropical soil and the large nitrate accumulation in the deep soil to a depth of at least 5 m. (Soil Science 2004;169:330–341)

Key words: Aggregation, Amazon, bypass flow, humid tropics, leaching, nitrogen.

SOILS in the humid tropics are known for their low retention capacity of nutrients and high susceptibility to leaching (Van Wambeke, 1992). Nitrogen is particularly susceptible to leaching losses since mineralization and nitrification both proceed very rapidly under humid tropical conditions and because nitrate is very mobile in most soils.

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In central Amazonian Oxisols, a large accumulation of nitrate in the subsoil (defined here as 0.1–2 m) was found under annual cropping systems (Melgar et al., 1992; Cahn et al., 1993) as well as under tree cropping systems and primary forests (Schroth et al., 1999a) despite their high subsoil root activity (Lehmann et al., 2001b). This result suggests that water and N percolation is not only very rapid at the topsoil but is also more rapid in the subsoil than previously known. Direct evidence for a rapid N leaching into the subsoil has not been provided to date. This is important for understanding the biogeochemistry of terrestrial ecosystems as it relates to forest (Laurance et al., 1999) and crop productivity

(Cravo and Smyth, 1997) as well as to atmospheric N cycles (Verchot et al., 1999).

High water percolation rates in soils with high clay contents, such as the Oxisols in central Amazonia, can be explained by their strong aggregation. The observed microaggregation results in a bi-modal pore size distribution (Teixeira, 2001), which was shown to cause rapid water drainage (Sollins and Radulovich, 1988; Arya et al., 1999). Short-term temporal dynamics of water fluxes have not been determined, however, for microaggregated soil in central Amazonia, and no field data are available that quantify water percolation and N leaching.

Nitrogen leaching may also depend largely on the N form found in the soil solution. Nitrate adsorption to positively charged clay surfaces is known to decrease leaching losses (Qafoku and Sumner, 2001). The high percentage of dissolved organic N in soil solution of Amazonian upland soils (Schroth et al., 2000; Lehmann and Kaiser, 2002) may also affect the dynamics of total N losses from soil as shown in temperate forests (Qualls et al., 2000). Information about rapid water fluxes and leaching of different N forms is lacking at present but will have important implications for the management and design of land-use systems that reduce N losses by leaching and for the understanding of the biogeochemical cycling of N in Amazonian forest ecosystems.

Therefore, the objective of this study was to quantify the short-term temporal dynamics of water and N percolation in a microaggregated upland soil of central Amazonia.

MATERIALS AND METHODS

Study Site

The study was carried out at the Empresa Brasileira de Pesquisa Agropecuaria (Embrapa)-Amazônia Ocidental, 29 km North of Manaus, Brazil (3°8′S, 59°52′W, 40–50 m above sea level), in 1998 and 1999. The rainfall distribution is unimodal, with maximum rainfall between December and May (211–300 mm per month; 75% of annual rainfall) and mean annual precipitation of about 2500 mm, air temperature of 26 °C, and atmospheric humidity about 84% (Tapia-Coral et al., 1999). The vegetation is a tropical lowland rainforest. The soils are Xanthic Hapludox (Soil Survey Staff, 1997), which are derived from Tertiary sediments. They are very deep and clayey, with low pH and medium levels of organic C and N (Table 1).

Experimental Design

The site was first cleared in 1980 for a rubber plantation (*Hevea brasiliensis* (Adr. Juss.) Muell.

TABLE 1
Soil chemical and physical characteristics

Soil layer	pH H_2O	Organic C	Total N	Bulk density†	Particle size distribution			Volumetric soil water content‡			ks‡
					2000-20	20-2	<2μm	pF0.0	pF2.0	pF4.2	
		mg g^{-1}	mg g^{-1}	Mg m^{-3}	g kg^{-1}	g kg^{-1}	g kg^{-1}	m m^{-3}	m m^{-3}	m m^{-3}	mm h^{-1}
0.0–0.1	4.1	29.1	1.7	0.90	214	196	590	0.580	0.410	0.220	600
0.1–0.3	4.1	20.7	0.8	0.95	238	155	607	0.545	0.410	0.260	600
0.3–0.9	4.1	6.2	0.5	0.97	176	125	699	0.535	0.425	0.285	550
0.9–1.5	4.3	2.5	0.3	1.00	129	151	720	0.540	0.460	0.320	18–150
1.5–2.5	4.7	1.9	0.2	1.06	97	223	680	0.540	0.475	0.370	3–125

†Bulk density and water retention measured at lower boundary of each layer (J. D. Marques, unpubl. data).
‡Saturated hydraulic conductivity; in the subsoil, a range is given for the different scenarios calculated (based on experiments by Teixeira, 2001).

Arg.), which was abandoned in 1986. The developing secondary forest was cut and burned in 1992 to establish several cropping systems, mainly with fruit trees, during the first half of 1993. Here, we investigated the water and N fluxes in a multi-strata agroforestry system with *Theobroma grandiflorum* (Willd. ex Spreng.) K. Schum. (cupuacu); *Bactris gasipaes* Kunth. (peach palm); *Bertholletia excelsa* Humb. & Bonpl. (Brazil nut); and *Bixa orellana* L. (annatto), and a legume cover of *Pueraria phaseoloides* (Roxb.) Benth. (pueraria). Cupuacu and Brazil nut were grown alternately in the same row with a distance of 7 m. In the adjacent rows, at a distance of 4 m, either annatto (4 m distance within the row) or peachpalm (2 m distance within the row) were grown (Dinkelmeyer et al., 2003). Plots with dimensions of 48 × 62 m were replicated three times (randomized complete block design).

Peach palm was managed for palmito (heart of palm) production and cut every 4 to 5 months. At planting, pueraria was sown between the trees and cut manually under the tree canopy every 3 to 4 months. At the time of this study, pueraria cover was reduced as a result of shading, and little ground cover was present. Fertilizer applications were split equally between the beginning of the rainy season in December and towards the end of the rainy season in May using 95, 42, 85, and 42 g N (as ammonium sulfate) per plant and year for cupuacu, peach palm, annatto and Brazil nut, respectively. Dolomitic lime and Atifos (North Carolina Phosphate, 13% P) were broadcast on the soil surface using 1.9 Mg ha^{-1} and 19 kg P ha^{-1}, respectively, in 1996. By the start of the presented experiment, the trees were six years old and, other than the Brazil nut, in full production.

During the year of the experiment, the regular fertilizer application was delayed by a few weeks because of the late start of the rains. On January 12 and 13, 1999, ^{15}N-enriched ammonium sulfate (10 atom% ^{15}N excess) was added to randomly assigned trees using 1 g ^{15}N excess per individual tree (1–4 trees per plot, see Dinkelmeyer et al. (2003) for detailed description of application sites). The effective amount of applied N (10 g N $tree^{-1}$) by ^{15}N-enriched ammonium sulfate was deducted from the routinely applied N fertilizer. The nutrients were added uniformly on the surface of the mineral soil in a square of 4 m^2 around each stem. The same amount of tracer was added to pueraria between the tree rows in a square of 4 m^2 without additional unlabeled fertilizer. The tracer was applied to 1 m^2 areas at a time using a dilute solution and a sprayer system, which sprayed each quadrant several times to ensure a homogeneous application. The litter layer and pueraria cover were carefully removed before the application and distributed evenly afterwards.

Each replicate tree in the three plots was equipped with time domain reflectometry sensors (TDR, EASY TEST®, Lublin, Poland; mounted on shafts) at depths of 0.1, 0.3, 0.9, and 1.5 m. Suction cups were installed in duplicate at 0.1-, 0.6-, and 2.0-m depths. In 1996, holes for all instruments were prepared using an auger of the same diameter as the shafts and filled with a slurry using the soil material to provide optimum contact. The instruments were inserted at an angle of 25° in a radius of 1 m around the stems, and rubber discs were installed around the tubes on the soil surface to prevent preferential flow along the shafts. In addition, one soil pit was dug to a depth of 3 m in 1997 and equipped horizontally with TDR sensors at depths of 0.1, 0.3, 0.9, 1.5, and 2.5 m, with tensiometers at depths of 0.1, 0.3, 0.9, 1.5, 2.5, 4.0, and 5.0 m, and with suction cups at depths of 0.1, 0.6, 1.2, 2.0, 3.0, and 4.0 m for the pueraria, cupuacu, and peach palm, respectively (one sensor or sampler per depth and position). The cups were made of Al_2O_3 (70%) and SiO_2 (29%), with an average pore size of 1 μm (UMS, Munich, Germany). TDR sensors were read with a hand-held meter (EASY TEST®, Lublin, Poland), and vacuum in the headspace of the tensiometers was measured by inserting a needle through a rubber septum (UMS, Munich, Germany). TDR readings were transformed into volumetric water contents using field calibrations in the same soil (Teixeira, 2001).

Soil solution was collected in dark, acid-washed bottles using an electric vacuum pump. Samples obtained from duplicate cups were combined before analysis. The vacuum was applied at least twice between samplings according to the soil water suction measured by the tensiometers at the same depth. In the replicated experiment, solution samples were obtained weekly, and in the soil pit an additional 2, 4, 7, 10, and 15 days after tracer application. In addition to manual tensiometers, an automated system was installed in the soil pit mentioned above to measure soil water suction under pueraria with a time resolution of 5 min for the first 2 months and 15 min thereafter (after high-resolution measurements had been done for several rainfall events, a lower temporal resolution was chosen in order to reduce the amount of data). The instruments were inserted at depths of 0.1, 0.3, 0.6, 0.9, 1.5, 2.5, and 3.5 m (Silvaq, Marth, Germany; cup specifications

identical to the ones described above). Installation and sampling of soil solution began in 1996 and 1997, and by the time of the present study, the cups were well equilibrated with the soil solution.

Soil samples were collected from each tree species in three replicates at the end of the rainy season, April 15–20, 1999. Sampling was done at a 0.5-m distance from the stem using two samples per tree, and samples were combined before analysis. Sampling intervals were at depths of 0–0.1, 0.1–0.3, 0.3–0.5, 0.5–0.8, 0.8–1.2, 1.2–2, 2–3, 3–4, and 4–5 m. A root auger with a 100-mm diameter was used for the first 0.1 m, an Edelman drill with an 80-mm diameter to a depth of 2 m, and a motor auger (Pionjär 120, Atlas Copco, Germany) with a 40-mm diameter to a depth of 5 m. Soil mineral N was extracted from 40 g soil with 150 mL 1*N* KCl for 2 h using a horizontal shaker (100 rpm). The supernatant was transferred after 16 h when the soil had settled. For total N analyses, the soil was air-dried and finely ground.

Chemical Analyses

In the soil solution and extracts, nitrate and ammonium contents were measured photometrically with a rapid flow analyzer (Scan Plus Analyzer, Skalar Analytical B.V., Breda, The Netherlands). Organic N was obtained as total N after in-line digestion and subtraction of inorganic N. Isotopic composition of the soil was determined directly and the isotopic composition of total dissolved N after freeze-drying of the soil solution using an Elemental Analyzer (Carlo Erba NA 1500, Carlo Erba Reagenti, Rodano, Italy; for Dumas combustion) connected to an isotope mass spectrometer (FINNIGAN MAT delta E; Thermo Finnigan, San Jose, CA) via a split interface.

The isotopic composition of ammonium and nitrate in KCl extracts was determined after steam distillation (Buresh et al., 1982) and freeze-drying of the extracts using isotope mass spectrometry as described above. Sixty milliliters of KCl extract were distilled for obtaining each ammonium and ammonium+nitrate. Nitrate values were calculated as the difference between results of ammonium and ammonium+nitrate. The pH was raised by an addition of 1.5 g MgO for the distillation of ammonium. For the distillation of ammonium+nitrate, 2 g devardas alloy was added to the extracts before distillation to reduce nitrate to ammonium. The ammonia was trapped in 20 mL of an acid solution containing 0.01 *M* H_2SO_4. The distillation was done in duplicate, with the first distillation used to clean the apparatus to avoid carry-over and then discarded (Mulvanay, 1986).

Calculation of Drainage in Soil

The rate of water percolation in the soil profile was estimated by calculating the time that was required for the soil water suction to reach a local minimum at a given depth after a rainfall event. This time was called retardation time. The onset of soil water percolation at the upper boundary was set as the time when the soil water suction at a depth of 0.1 m decreased by 10% or more.

Soil water and nutrient leaching was obtained by two different approaches: (i) the gradient method using Darcy's equation and (ii) a water balance. For the gradient method, soil water suction was obtained from the installed tensiometers. The saturated hydraulic conductivity was obtained from disc infiltrometers and laboratory experiments (constant-head) in adjacent soils (Teixeira, 2001). Inasmuch as the saturated hydraulic conductivity was not significantly different between positions in the cropping system (Teixeira, 2001), average values were taken from both field and laboratory measurements (averages of all sites given in Table 1). The estimated values are in the range of published values by Nortcliff and Thornes (1981), with 1567 mm h^{-1} in the topsoil (0.15–0.6 m) and 217 mm h^{-1} in the subsoil (0.9–1.5 m) (laboratory measurements; app. 10 km from our site); by Medina and Leite (1985) with 223 mm h^{-1} at the soil surface (double ring infiltrometer; identical site with Nortcliff and Thornes (1981)); and by Tomasella and Hodnett (1996) with 18–220 mm h^{-1} at the soil surface, 51–133 mm h^{-1} in the topsoil (0.3 m), to 10–24 mm h^{-1} in the subsoil (1.7 m) (ring permeameter; 50 km north of our site).

The unsaturated hydraulic conductivity was computed on the basis of an interpolated water retention curve (capillary bundle approach) following the procedure of Millington and Quirk (1960) modified by Jackson (1972) using a statistical procedure (exponent of water-filled porosity set to 1). The determination of the water retention curve was made in triplicate laboratory experiments using pressure plates (Table 1), and a field water retention curve was determined with simultaneous field measurements using tensiometers and TDR (Renck, 2000). The gradient method was applied using the BAPS program (B. Huwe, 1994, unpubl. program documentation, University of Bayreuth, Germany).

For the water balance, a simple model was used to calculate soil water movement between soil layers:

$$v_i = (S_{i,t1} - S_{i,t0}) + I_i - T_i \quad (1)$$

with v for the vertical flux through layer i, S for soil water storage at the beginning (t_0) and the end (t_1) of each time step, I for the water input by drainage from or rainfall into the respective layer, and T for water uptake and transpiration. The soil layers i were defined by the installation depth of TDR and suction cups as 0–0.2, 0.2–0.6, 0.6–1.2, and 1.2–2.0 m. The time steps correspond to the measurement intervals. Rainfall was obtained from a meteorological station with automatic recording (CR10 data logger, Campbell Scientific Inc.), mounted within 10 m of the soil pit, and modified to account for canopy interception and stemflow. The effective rainfall input was estimated from detailed throughfall and stemflow measurements by Schroth et al. (1999b) as 102, 77, 118, 145, and 98% of the precipitation above the canopy for cupuacu, peach palm, annatto, Brazil nut, and pueraria, respectively. Calculation results suggested that plant transpiration was equivalent to the maximum transpiration possible since soil water contents did not restrict water uptake during the measurement period. Furthermore, soil water uptake was restricted to a depth of 2 m for this model because root abundance and activity (Lehmann et al., 2001b) decreased rapidly in the subsoil to a depth of 1.5 m. The plant uptake distribution of water between the four soil layers was not modified during the experimental period. The water uptake coefficient was determined from measurements of root abundance (Haag, 1997) and root activity distribution (Lehmann et al., 2001b). Total evaporation was calculated as the potential evapotranspiration using the Priestley-Taylor equation (Gunsten and Batchelor, 1983; Shuttleworth, 1988). Relative humidity, radiation, air temperature, and wind speed at 2 m height were obtained in hourly intervals (average values from 10-min intervals). Tracer fluxes were calculated by using weighted average values of total ^{15}N contents over the individual measurement interval. Tracer fluxes were only calculated for the replicated comparison of tree crops using the water balance approach.

Data Analyses

Data analyses were done at positions of the pueraria ground cover, taking advantage of the measurements at high temporal resolution, and on the total losses and N concentrations of the entire cropping system; data from individual trees were not presented here. Statistical comparisons were performed by linear regression (Statistica 5.1; StatSoft, Tulsa, UK). For isotopic composition and

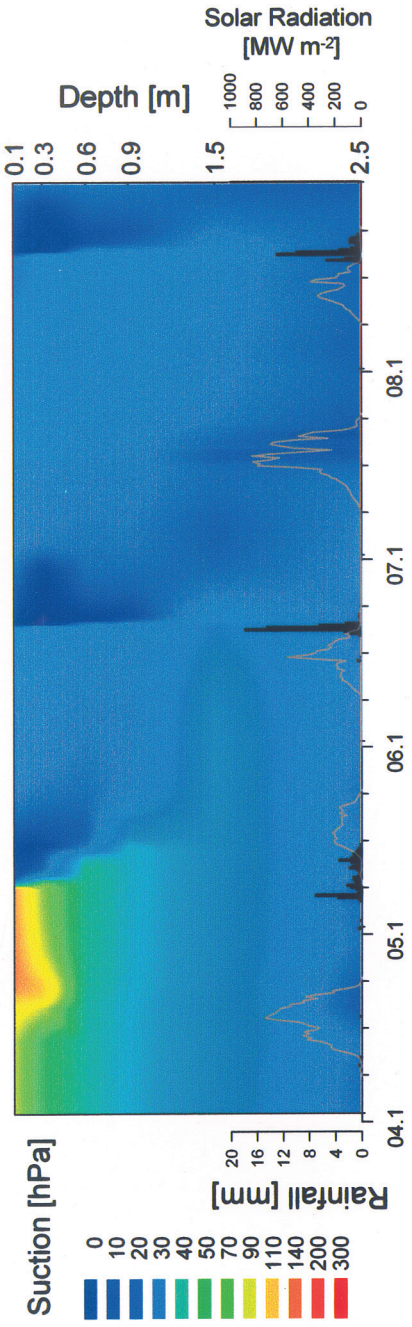

Fig. 1. Rainfall (bars), solar radiation (line), and soil water suction dynamics (colors; 5-min intervals) in a Xanthic Hapludox under a *Pueraria phaseoloides* L. cover crop during three storm events in central Amazonia; linear interpolation was done using Sigma Plot 2000 (SPSS, Chicago, IL).

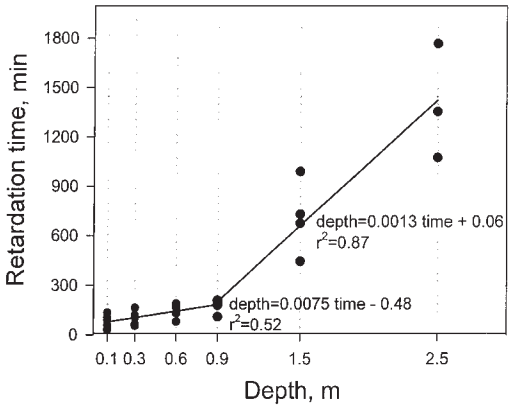

Fig. 2. Retardation time to reach the local minimum of soil water suction at different depths after several storms under a *Pueraria phaseoloides* L. cover crop (n = 30); retardation time is the time required for the soil water suction to reach a local minimum at a given depth after a rainfall event (see methods for explanation).

TABLE 2

Water and nitrogen fluxes in a Xanthic Hapludox under a tree cropping system in central Amazonia during the rainy season (120 and 93 days, respectively); fluxes are calculated per land use system and are adjusted for the area covered by the different tree species (26% of the entire area; N = 3)

Type of flux	Fluxes at different depths					
	0.2 m		0.6 m		2.0 m	
Soil water, mm	847	a†	654	a	453	a
Nitrate, kg ha^{-1}	5.1	a	2.5	ab	1.3	b
Ammonium, kg ha^{-1}	1.8	a	0.2	b	0.2	b
DON, kg ha^{-1}	3.9	a	1.6	a	1.2	a
TDN, kg ha^{-1}	10.8	a	4.2	ab	2.7	b
^{15}N, % of applied	8.2	a	2.6	a	0.02	b

†Values followed by the same letter in one row are not significantly different at $P < 0.05$.

comparisons of depths, the nonparametric test after Kruskal-Wallis was performed (Statistica 5.1; StatSoft, Tulsa, OK). When there were significant effects, multiple comparisons of means were computed with the least significant difference (LSD) test at $P < 0.05$ unless indicated otherwise.

RESULTS

Soil Water

Soil water suction decreased rapidly in the topsoil after rainfall events (Fig. 1). However, at the end of the dry season when the topsoil was dry, soil water percolated within minutes to a depth of 0.3 m, within 5 h to 0.6 m, and within 10 h to 0.9 m. Whenever the soil water suction was already low before the rainfall event, percolation was much faster: the wetting front reached a depth of 1 m within less than 1 h, and maximum water contents were reached 2 h after the rainfall started. Throughout the entire year, much more rapid infiltration was observed to a depth of 0.9 m than below that depth (Fig. 2). To a depth of 0.9 m, soil water percolated at a velocity of 7.5 mm of soil min^{-1} (slope of 0.0075, Fig. 2), whereas percolation was only 1.3 mm of soil min^{-1} at depths of 0.9 to 2.5 m. However, calculated soil water flux over the entire rainy season decreased much less with depth (Table 2) than maximum percolation after rain events (Fig. 2).

At the onset of the rainy season, soil water suction near the soil surface (0.1 m depth) under pueraria dropped from 100 to 300 hPa in January to about 50 hPa and remained at that level until the end of the rainy season in May (Fig. 3). Although weekly averages were constant throughout the rainy season, the soil water suction was highly variable on short time scales of days and hours. During a single day, soil water suction could drop to 0 hPa (satura-

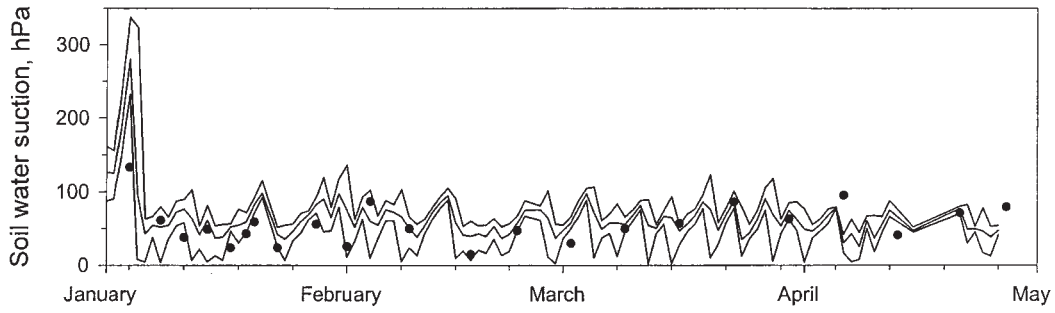

Fig. 3. Soil water suction measured at 0.1 m depth under a *Pueraria phaseoloides* L. cover crop at 5-min intervals (daily means, maxima, and minima with solid lines), obtained from an automatic data logging system, compared with bi-weekly intervals (dots; longer intervals at later stages) obtained from manual tensiometers in a Xanthic Hapludox of central Amazonia.

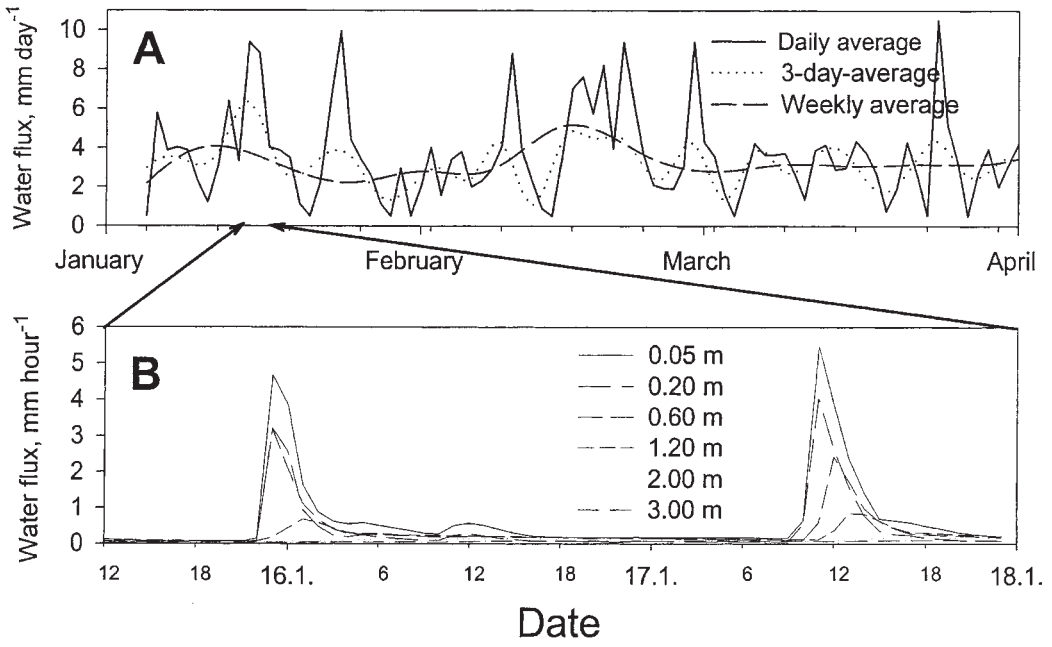

Fig. 4. Water flux under a *Pueraria phaseoloides* L. cover crop using different averages (daily, 3-day, weekly) during the entire rainy season at 0.05 m depth (A), and using hourly averages during 2 days in the entire profile (B) (from 5-min measurement intervals).

tion) or increase to more than 100 hPa. Manually measured tensiometers obtained values within the daily range only in 61% of all measured cases (n = 23), and they rarely coincided with average values obtained by measurements in 5-min intervals.

Water fluxes calculated with soil water suction dynamics using a gradient approach ranged from < 1 to >10 mm day^{-1}, if daily means were used (Fig. 4). Using weekly averages, fluxes ranged only between 2 and 5 mm day^{-1}. Longer measurement intervals decreased total fluxes calculated by up to 93%. Since fluctuations in water percolation were less pronounced at greater depths, the error involved using larger measurement intervals decreased with depth. Fluxes in the topsoil (0.05 m depth) increased and decreased rapidly within hours after rainfall events (Fig. 4 B), and 4 h after the maximum flux, values decreased to background levels. Fluxes at 0.1-, 0.2-, and 0.6-m depths responded quickly to the water input, whereas fluxes at 1.2 m responded only 2 to 3 h after the maximum flux in the topsoil, and fluxes at 2.0 and 3.0 m increased significantly later and were less pronounced.

Soil Nitrogen

Applied ^{15}N appeared rapidly in the soil solution to a depth of 0.6 m at the first sampling date (4 days after tracer application; Fig. 5). After 1 week, ^{15}N values increased to a depth of 5 m. At 2–5 m, tracer concentrations decreased again, whereas they had remained constant or increased at depths of 1.2, 0.6, and 0.1 m. The increase of the heavy N isotope at 0.1 m was more pronounced in the organic than in the inorganic N fraction (Fig. 6). The ^{15}N enrichment of organic N decreased with greater depth in relation to nitrate and ammonium. Isotope enrichment was similar in nitrate and ammonium at all depths. Total fluxes of nitrate during the rainy season

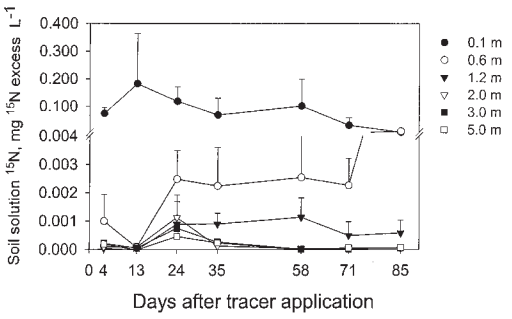

Fig. 5. Concentration of total applied ^{15}N in the soil solution to a depth of 5 m under a *Pueraria phaseoloides* L. cover crop in central Amazonia during the rainy season (means and standard errors; n = 3); note the different scales above and below the break on the y axis.

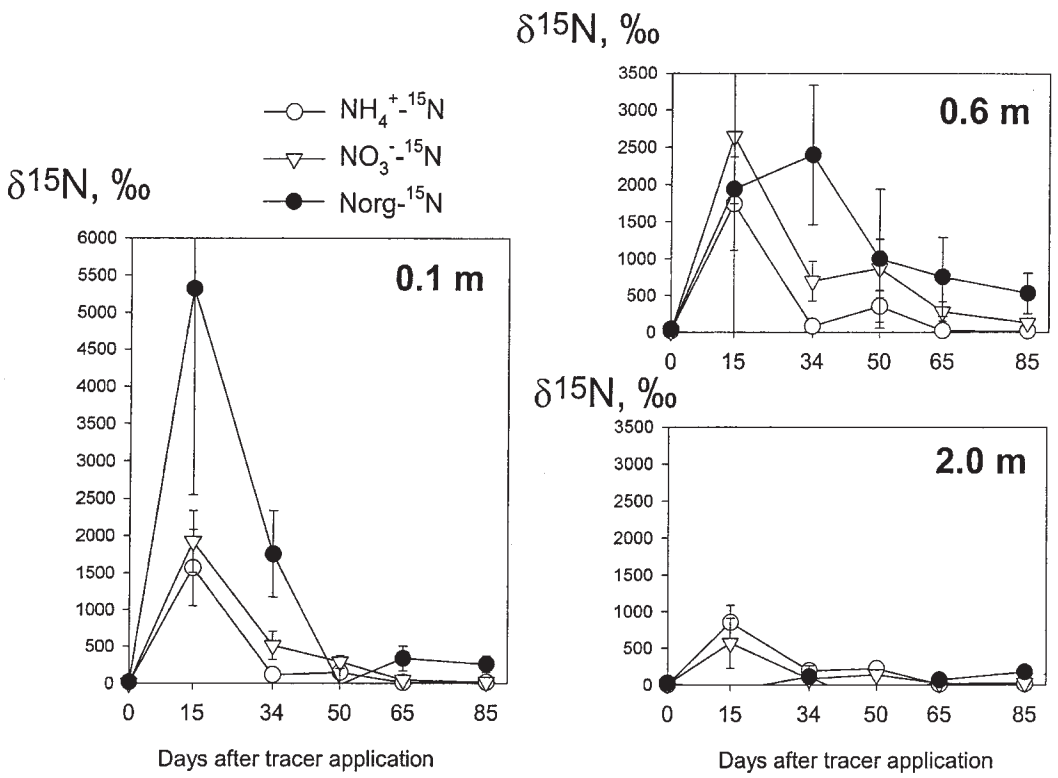

Fig. 6. Enrichment of applied ^{15}N in inorganic and organic N forms of the soil solution at 0.1-, 0.6-, and 2.0-m depths of a tree cropping system in central Amazonia during the rainy season (means and standard errors of all four tree crops; $n = 12$).

were higher than those of ammonium (Table 2). Both nitrate and ammonium leaching decreased more with depth than did leaching of organic N. Whereas most of the total soil N was found in the topsoil, most of the exchangeable nitrate was concentrated in the deep soil below a depth of 2 m (Fig. 7). Depth distribution of exchangeable ammonium largely followed that of total N.

Leaching of applied ^{15}N decreased sharply in the deep soil (2 m depth; Table 2), whereas the recovery of the isotope in the soil (Fig. 7) was uniform with depth, and total recovery in the subsoil and deep soil was greater than the calculated flux into the subsoil.

DISCUSSION

Nutrient Forms in Leachate

Very little of the applied ammonium-N was transported down the soil profile as ammonium. Nitrification is usually very rapid in tropical soil (Vitousek and Matson, 1988), and nitrate is usually more mobile in soil than ammonium. Thus, we expect to find a higher leaching of nitrate than of ammonium. That ammonium showed an isotope enrichment even in the subsoil (2 m) may be explained by microbial immobilization and subsequent mineralization or dissimilatory nitrate reduction (Silver et al., 2001) rather than by ammonium leaching. Already very small amounts of applied ^{15}N would result in a significant isotope enrichment of ammonium since the total ammonium contents were very low in the subsoil below 0.5 m (Fig. 7).

The largest part of the applied ^{15}N in the topsoil was leached as organic N, and total fluxes of organic N were similar to those of nitrate in the subsoil. Similarly rapid immobilization of inorganic N inputs by atmospheric deposition into dissolved organic N (43% within 2 days) was observed using ^{15}N in a coastal watershed in Massachussetts (Seely and Lajitha, 1997). Neff et al. (2000) found a significant increase of dissolved organic N losses after fertilization of a N-limited forest on Hawaii. Because most of the organic N in our study was present in hydrophilic dissolved organic matter (Lehmann and Kaiser, 2002), it is expected to be more mobile in soil than total dis-

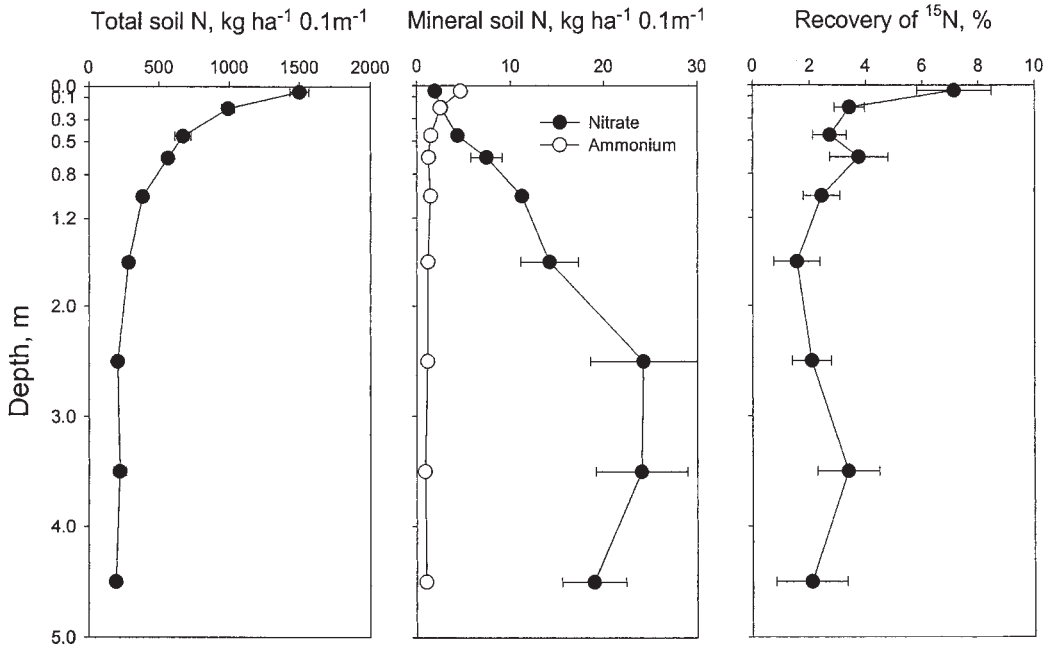

Fig. 7. Total N, inorganic N, and recovery of applied ^{15}N (per unit soil weight) in the soil under a tree cropping system in central Amazonia after the rainy season (means and standard errors of four tree crops; $n = 12$).

solved organic matter (Kaiser et al., 2000). Nevertheless, the isotope data suggest a lower mobility of the dissolved organic N than nitrate, which coincides with results of Qualls et al. (2000) from a deciduous forest in a temperate climate. Mineralization of dissolved organic N seems to be an unlikely explanation for total leaching of dissolved organic N contents decreased to a lesser extent with depth than nitrate (Table 2). Leaching of organic N was an important pathway of N losses from soil and could explain the dominance of organic N export from watersheds such as the ones found in unpolluted forest ecosystems in Chile (Perakis and Hedin, 2002).

Rapid Soil Water and N Leaching

Soil water infiltration occurred very rapidly in the studied Oxisol of central Amazonia, with percolation reaching a depth of 0.9 m within 2 h under wet soil conditions. Rozanski et al. (1991) studied the recovery of applied tritium at a nearby site after 139 days and did not find the peak of the tracer contents within 2 m depth. This rapid percolation can be explained by the bi-modal pore size distribution of the soils. Central Amazonian Oxisols, like many Oxisols, are characterized by high clay contents of 60 to 70% or more and by a very strong aggregation. The aggregation seems to be stronger in the studied Oxisols than in many other Oxisols in Brazil, and microaggregates are difficult to disrupt even when high energy is applied by sonication (Lehmann et al., 2001a). This pronounced microaggregation creates larger pores characteristic of sandy soils in addition to the fine pores characteristic of clayey soils, even in the very clayey Oxisols of central Amazonia (Teixeira, 2001). Such large pores can lead to bypass flow (Sollins and Radulovich, 1988). Bypass flow can occur even under unsaturated conditions when infiltration exceeds the saturated hydraulic conductivity of the microaggregates (Radulovich et al., 1992). Under these conditions, the surfaces of the microaggregates become saturated, and the soil water percolates through macropores. Because the matrix conductivity of the microaggregates can be extremely low in Oxisols (Sharma and Uehara, 1968), this process occurs very rapidly after soil wetting. Radulovich et al. (1992) calculated that 2700 days would be necessary for soil water to percolate 0.2 m down a profile of a clayey and microaggregated Inceptisol in Costa Rica if bypass flow did not occur. On the other hand, the observed rapid fluxes also disappear soon after the rainfall event (Fig. 4), which indicates that a critical water content in the interpedal pore network is necessary to maintain bypass flow in microaggregated soil. This also explains the observation that the depth of rapid percolation was deeper when

the soil was pre-wetted than when it was dry (Fig. 1). Using a semiquantitative estimate, rapid water flow seemed to require not more than a soil water suction of 20 to 30 hPa (obtained from Fig. 1).

Water percolation at our site decreased significantly between 0.9 and 1.5 m depth. This can be explained by a decrease in macroporosity at a depth of 1.3–1.4 m found in several studies throughout the area (Chauvel et al., 1991; Tomasella and Hodnett, 1996). This decrease in macroporosity and mesoporosity does not seem to be related to decreases in soil C concentrations or increases in clay content since both change higher in the profile (Table 1). The continuously increasing bulk density and decreasing amount of mobile water with depth (difference of soil water content between pF0 and 2; Table 1) indicate that a denser soil and possibly lower aggregation are responsible for the decrease in water percolation below 0.9 m depth.

Most solutes percolate more slowly through soil than water because they adsorb to mineral or organic surfaces. Although nitrate adsorption is usually low in soils, anion exchange capacity is large in the studied acid Oxisols (Cahn et al., 1992), and nitrate retention commonly reduces nitrate losses from acid soils in the tropics (Wong et al., 1990; Qafoku and Sumner, 2001). In addition, organic N is adsorbed to mineral surfaces (Kaiser et al., 2000), explaining the significantly lower movement of applied N than water at our site. Nitrogen uptake by the trees will additionally reduce N fluxes into the subsoil and deep soil.

The observed high percolation rates make it unlikely that even trees with perennial root systems can substantially reduce N leaching from the topsoil (0–0.1 m). The studied tree cropping system had significant nutrient uptake below the topsoil, and, e.g., root activity of the peach palm measured by isotope uptake was higher at 0.6 than 0.1 m depth (Lehmann et al., 2001b). However, this deep root activity could not prevent a significant N leaching even below 1 m depth, as demonstrated by the large nitrate accumulation at 1–5 m depth (Fig. 7). The proposal by Kellman (2002) of soil adsorption and plant absorption as synergistic processes in tropical ecosystems did not provide sufficient opportunity for nutrient retention under the high leaching conditions at the studied site.

Measurement Design for Estimation of Solute Fluxes in Microaggregated Soil

The observed rapid water and solute fluxes cannot be evaluated adequately by measuring soil water dynamics with low temporal resolution. For the topsoil, and even for our soil to a depth of 1 m, weekly or even daily measurements are not sufficient to obtain estimates of water percolation. The present results suggest 30 min as a maximum time step. This value is derived from the observation that water fluxes (Fig. 4B) still show significant changes after 1 h . Fluxes appeared and disappeared within 2 to 3 h (Fig. 4B). Also, soil water availability should be determined in time steps of less than 1 day if the steps are related to the soil water status of plants. Klinge et al. (2001) reported similarly rapid changes of the soil matric potential by obtaining data with 15-min intervals in a sandy Oxisol in Eastern Amazonia.

Nitrogen leaching was greatly underestimated using calculations of water and N fluxes, as demonstrated by the much higher isotope recovery below 2 m depth (Fig. 7) than the actual measured flux at 2 m depth (Table 2). This is a well known challenge in soils with macropore flux because: (i) suction lysimeters do not sample the mobile water in free-draining pores (Van Der Ploeg and Beese, 1977); (ii) calculations of water fluxes do not capture fluxes in large pores (Beven and Germann, 1982); and (iii) calculations do not account for bimodal pore size distributions (Tomasella and Hodnett, 1996, 1998). The much higher top- than subsoil water percolation obtained by direct measurements (Fig. 2) compared with the calculated values without recognizing bypass flow (Table 2) demonstrate this very clearly. The present study indicates that an additional critical challenge for the determination of solute fluxes in microaggregated tropical soil is to obtain correct time integrals of solution concentrations and soil water dynamics under rapid leaching conditions.

CONCLUSIONS

We demonstrated a pronounced temporal fluctuation of soil water contents that resulted in rapid water and N leaching into the deep soil (2–5 m) of a clayey Oxisol. The bimodal pore size distribution with its interpedal pore space led to rapid bypass flow after rainfall events, even under unsaturated conditions. Such rapid flow occurred above a certain threshold of soil water suction and ceased rapidly after rainfall events stopped. Rapid percolation was observed only to a depth of 0.9 m and decreased significantly below that depth as a result of higher bulk densities and lower proportions of mobile soil water. Leaching of organic N was greater in the topsoil than leaching of inorganic N, but it was slower in the subsoil, probably because of adsorption to the soil matrix. The demonstrated rapid N fluxes into the

subsoil require a re-evaluation of the ability of plants to capture N percolating through the profile of microaggregated tropical soil.

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