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Soil moisture dynamics in an eastern Amazonian tropical forest

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Abstract:

We used frequency-domain reflectometry to make continuous, high-resolution measurements for 22 months of the soil moisture to a depth of 10 m in an Amazonian rain forest. We then used these data to determine how soil moisture varies on diel, seasonal and multi-year timescales, and to better understand the quantitative and mechanistic relationships between soil moisture and forest evapotranspiration. The mean annual precipitation at the site was over 1900 mm. The field capacity was approximately $0.53 \text{ m}^3 \text{ m}^{-3}$ and was nearly uniform with soil depth. Soil moisture decreased at all levels during the dry season, with the minimum of $0.38 \text{ m}^3 \text{ m}^{-3}$ at 3 m beneath the surface. The moisture in the upper 1 m showed a strong diel cycle with daytime depletion due to evapotranspiration. The moisture beneath 1 m declined during both day and night due to the combined effects of evapotranspiration, drainage and a nighttime upward movement of water. The depth of active water withdrawal changed markedly over the year. The upper 2 m of soil supplied ~56% of the water used for evapotranspiration in the wet season and ~28% of the water used in the dry season. The zone of active water withdrawal extended to a depth of at least 10 m. The day-to-day rates of moisture withdrawal from the upper 10 m of soil during rain-free periods agreed well with simultaneous measurements of whole-forest evapotranspiration made by the eddy covariance technique. The forest at the site was well adapted to the normal cycle of wet and dry seasons, and the dry season had only a small effect on the rates of land–atmosphere water vapour exchange. Copyright © 2006 John Wiley & Sons, Ltd.

KEY WORDS hydrology; soil moisture; root uptake; evapotranspiration; tropical forest; frequency-domain reflectometry; Amazonia; Tapajós National Forest; LBA

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INTRODUCTION

The cycling of water between the land-surface and the atmosphere by evapotranspiration and precipitation plays a critical role in Amazonia's hydrology and climatology. Approximately, half of the total precipitation that falls in the Amazon basin results from upwind evapotranspiration. Much of Amazonia experiences a pronounced dry season. During *El Niño*, the length and severity of the dry season are enhanced, which may increase stress on trees, reduce photosynthesis and transpiration, and increase forest flammability (Nepstad *et al.*, 2004). Similarly, conversion of the Amazonian forests to pasture reduces the moisture in the shallow soil during the dry season (Hodnett *et al.*, 1995), which increases the local sensible heat flux and decreases the local evapotranspiration (da Rocha *et al.*, 1996; Avissar *et al.*, 2002; Durieux *et al.*, 2003; von Randow *et al.*, 2004). Changes in land-surface evaporation, either associated with land-use change or with the effect of drought on vegetation, have the potential to cause changes in downwind precipitation (Nobre *et al.*, 1991).

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The relationship between soil moisture and surface energy exchange in the Amazonian *terra firme* forest is inadequately understood. Soil moisture supplies the water vapour transpired from tropical forest and is therefore a key controller of local hydrology and surface energy exchange (Shuttleworth, 1988). Deep rooting in the *terra firme* forest (>10 m, Nepstad *et al.*, 1994; Jipp *et al.*, 1998) buffers the trees from the immediate effects of drought. da Rocha *et al.* (2004) have even found evapotranspiration in Amazonia to increase during the dry season, wherein the seasonal patterns were largely controlled by solar radiation and not by soil moisture depletion. Tropical rain forests apparently stay green during dry periods, but it has not been explained in detail what the role of soil moisture dynamics is.

An improved understanding of the controls on land–atmosphere energy exchange is important for understanding and predicting Amazonia's future climate and hydrology. In this manuscript, we report 2 years of soil moisture measurements with high spatial and temporal resolution from a 10-m deep pit in an Amazonian rain forest as part of the Large-scale Biosphere–Atmosphere Experiment in Amazonia (LBA) (LBA, 1996; Keller *et al.*, 2004). Micrometeorological measurements of the above-canopy fluxes of energy, water vapour and precipitation were made simultaneously at the same site. Our goal is to examine quantitative and mechanistic relationships between soil moisture and forest evapotranspiration. We focus on the spatial (vertical), diel, seasonal, and multi-year variations in the profile of soil moisture, and compare the integrated column water budget evapotranspiration estimate to that measured independently by the micrometeorological method.

MATERIALS AND METHODS

Experimental site

The study focused on the LBA km-83 site in the Tapajós National Forest, which is 70 km south of Santarém in the Brazilian state of Pará (3°01'30"S, 54°58'15"W). Previous analyses of data collected at the site emphasized the temporal patterns of CO₂ exchange (Goulden *et al.*, 2004), the annual rates of CO₂ exchange and how they compare with vegetation growth (Miller *et al.*, 2004), and the temporal patterns of surface radiative, heat, and water vapour flux (da Rocha *et al.*, 2004). The soil water observations reported here were made approximately 20 m from the 2-m deep pit described by da Rocha *et al.* (2004). All of the other observations reported here were made using the same instruments described in our previous papers.

The soil at the site was yellow dystrophic latosol (a clay oxisol). The site was located on flat upland terrain (Hernandez Filho *et al.*, 1993). The climate was hot and humid (Figure 1), with an annual mean precipitation of 1911 mm. The dry season typically lasted from August to December, when approximately 11% of the mean annual precipitation was recorded. The mean temperature ranged from 24.2 °C in July to 25.7 °C in October, and the relative humidity ranged from 85% in November to 93% in May. The vegetation was dense tropical humid forest with a canopy height of ~35–40 m. The area along the tower fetch was selectively logged in September 2001, with 2–3 trees removed per ha. The soil pit was located in an undisturbed patch of forest within the selectively logged area.

Observational methods

The latent heat flux was determined with the eddy covariance method, using a three-axis sonic anemometer (Campbell Scientific, Logan, Utah, USA) installed above the canopy on a 67-m tall tower (Rohn 55G, Rohn, Peoria, Illinois, USA) and infrared gas analyzers (models LI7000 and LI7500; Li-Cor, Lincoln, Nebraska, USA). Further details on the flux and meteorological measurements were included in Goulden *et al.* (2004), Miller *et al.* (2004), and da Rocha *et al.* (2004).

Soil moisture measurements were made from March 2002 to December 2003 in a soil pit ~20 m southeast of the micrometeorological tower. We assume the soil moisture measurements reflect the combined effects of the hydrological processes that occur in tropical forests, including interception, throughfall, infiltration,

Figure 1. Mean monthly (a) temperature (°C), (b) relative humidity (%), and (c) precipitation (mm), near Santarém, PA. Source: 1976–1990 climatological data Instituto Nacional de Meteorologia (2°28'S, 54°57'W), Belterra city, PA. Shaded bar is the dry season

and root extraction. At the same time, we caution the reader that we sampled only a single profile, and that spatial heterogeneity may confound the quantitative relationships between the soil measurements and the entire forest's hydrological budget.

Soil water content was estimated using the transit time (τ) measured in water content reflectometers (CS615-G, Campbell Scientific, Logan, Utah, USA) installed in a 10-m deep vertical pit ($1 \times 1 \text{ m}^2$). Reflectometers were inserted horizontally into shaft walls at 0.15, 0.3, 0.6, 1, 2, 3, 4, 6, 8, and 10 m beneath the surface. Two sensors were installed at each depth and the volumetric water content at each depth was averaged, except at 8 m depth where only one sensor was available. The CS615 is a bistable multivibrator connected to two stainless steel rods (30-cm long, 3.2-mm diameter, and 32-mm spaced). The output signal (period τ) ranges from 0.7 to 1.6 ms, and varies with the medium dielectric constant and therefore the soil moisture. The soil moisture data were recorded at 0.5 Hz throughout the study.

Site specific calibrations for the CS615 probes were developed using 10-cm $\times$ 10-cm $\times$ 40-cm soil blocks collected at 6 cm (2 samples) and 76 cm (1 sample) depth (Bruno, 2004). Calibration data were collected continuously comparing the sensor signal with the soil water content determined by gravimetry throughout a drying cycle. Calibration curves were fit using a sigmoidal function that constrained the asymptotic lower (dry soil) and upper (saturation) soil moisture limits

$$\theta(\tau) = a \left[1 + (d - 1) \cdot e^{-k(\tau - \tau_c)} \right]^{1/(1-d)} \quad (1)$$

where θ is the volumetric soil moisture in $\text{m}^3 \text{ m}^{-3}$; τ is the reflectometer output in ms; and τ_c , a , d and k are coefficients ($r^2 > 0.98$; see fitted coefficients in Table I). The use of a site specific calibration resulted in calculated water contents that were as much as 40% greater than those that would have been calculated from a generic cubic polynomial for clayey soil (Campbell Scientific, 1996).

Rainfall was measured at 64 m on the tower and archived at a 0.5 Hz sampling frequency (TE525 Texas Electronics, Dallas, Texas, USA). During the 3-year period between January 2001 and December 2003, gaps in rain data occurred in May 2002, November 2002, and May 2003. The soil moisture data indicated the

Table I. Maxima and minima values for τ , calculated parameters for two sigmoidal equations for the clayey yellow dystrophic latosol beneath tropical rain forest at the km-83 tower site, Tapajós National Forest

Depth (cm)	Minimum and maximum values for τ , in ms, and $\theta(\tau)$, in $\text{m}^3 \text{m}^{-3}$				Calculated parameters				Regression coefficient
	$\tau_{\min}$	$\theta(\tau_{\min})$	τ_{MAX}	$\theta(\tau_{\text{MAX}})$	a	τc	d	k	
6	0.75	0.026	1.236	0.584	0.61897	0.87359	0.63559	5.89914	0.99
76	0.744	0.015	1.285	0.554	0.76855	0.81532	0.2	2.38272	0.98

occurrence of rainfall during the May 2002 and May 2003 periods, such that our measured precipitation is an underestimate during these months. During November 2002, it appears there was no significant rainfall, and therefore our measured rainfall data is likely accurate.

RESULTS

Precipitation

The cumulative wet season precipitation varied only modestly from year-to-year, ranging from 1370 mm in 2001 to 1172 mm in 2002 (Figure 2). The precipitation during the dry season was much more variable, ranging from 397 mm in 2003 to 102 mm in 2001. The monthly precipitation during 2001–2003 wet seasons was generally less than the climatological mean for the region (Figure 2). Only 6 of the 24 wet season months during this period had precipitation that exceeded the monthly climatological means. However, this difference must be interpreted with caution, since the climatological record was collected 50 km from our study site, and spatial variability or methodological bias may account for part of the difference. The precipitation during most of the dry season months in 2001 and 2002 was below the climatological mean, whereas the rainfall throughout the entire 2003 dry season was well above the climatological mean (Figure 2). The 2002 dry season was particularly well defined, with only occasional light showers falling from August to October. The 2002 dry season was broken by a series of storms over 4 days in November that delivered a total of 160 mm.

Soil patterns with depth

We determined the maximum seasonal soil moisture variation by comparing the field capacity at each depth with the absolute minimum moisture content observed for that depth over the study (Table II, Figure 3). The field capacity (θ_{FC}) was determined from measurements of the soil moisture during the wet season that were made at night and a few days after precipitation, when drainage had decreased and the rate of change of soil moisture was less than $0.001 \text{ m}^3 \text{m}^{-3} 30 \text{ min}^{-1}$. Field capacity ranged from $0.515 \text{ m}^3 \text{m}^{-3}$ at 15 cm depth to $0.559 \text{ m}^3 \text{m}^{-3}$ at 6 m depth. The minimum measured soil moisture at each depth (referred to as $\theta_{\min}$ in Table II) ranged from $0.384 \text{ m}^3 \text{m}^{-3}$ at 3 m depth to $0.496 \text{ m}^3 \text{m}^{-3}$ at 10 m depth. The field capacity was generally homogenous throughout the profile, whereas the minimum soil moisture increased at depths below 4 m (Figure 3). The maximum soil water variation ($\Delta\theta_{\text{MAX}}$, Figure 3 and Table II), which we calculated for each depth by subtracting $\theta_{\min}$ from θ_{FC} , varied from $0.08 \text{ m}^3 \text{m}^{-3}$ at 0.15 m depth before increasing with depth to a maximum of $0.149 \text{ m}^3 \text{m}^{-3}$ at 2–3 m and then declining to a minimum of $0.02 \text{ m}^3 \text{m}^{-3}$ at 10 m (Figure 3, Table II). The greatest seasonal variation, as well as the minimum measured soil moisture content ($\theta_{\min}$), occurred at 2–3 m depth rather than at the soil surface, indicating that water uptake was significant at these middle depths. The reduction in $\Delta\theta_{\text{MAX}}$ with depth indicated the uptake of water declined somewhat below 5–6 m depth and markedly below 8 m.

We assumed that the absolute maximum moisture values observed for each depth provide a measure of the water content of fully saturated soil, and used these measurements to estimate soil porosity. The soil porosity

Figure 2. Monthly precipitation (vertical bars), in mm, measured at 64 m height at km-83 tower site, Tapajós National Forest, in the period 1 January 2001–12 December 2003. Seasonal total precipitation (P_{AC}) is indicated in each wet season (non shaded period) and dry season (grey shaded period). Horizontal dashes for each month represent the climatological precipitation (see Figure 1)

Table II. Estimates ($\pm$ experimental error) of soil porosity (ϕ , in $\text{m}^3 \text{m}^{-3}$), minimum measured soil moisture ($\theta_{\min}$, in $\text{m}^3 \text{m}^{-3}$), and field capacity soil moisture (θ_{FC} , in $\text{m}^3 \text{m}^{-3}$), maximum soil water variation ($\Delta\theta_{\text{MAX}}$, in $\text{m}^3 \text{m}^{-3}$), for the clayey yellow dystrophic latosol beneath tropical rain forest at km-83 tower site in Tapajós National Forest. Values are given for each measurement depth. Estimates of θ_{FC} were taken from observations during April 2002, and estimates of $\theta_{\min}$ were taken from observations during October 2002

Depth (m)	ϕ ($\text{m}^3 \text{m}^{-3}$)	$\theta_{\min}$ ($\text{m}^3 \text{m}^{-3}$)	θ_{FC} ($\text{m}^3 \text{m}^{-3}$)	$\Delta\theta_{\text{MAX}}$ ($\text{m}^3 \text{m}^{-3}$)
0.15	0.59	0.435 ± 0.009	0.515 ± 0.01	0.08 ± 0.002
0.3	0.59	0.438 ± 0.008	0.529 ± 0.011	0.092 ± 0.002
0.6	0.58	0.414 ± 0.008	0.518 ± 0.01	0.103 ± 0.002
1	0.59	0.411 ± 0.008	0.543 ± 0.011	0.13 ± 0.003
2	0.56	0.41 ± 0.008	0.558 ± 0.011	0.149 ± 0.003
3	0.53	0.384 ± 0.008	0.533 ± 0.011	0.149 ± 0.003
4	0.54	0.424 ± 0.008	0.526 ± 0.010	0.101 ± 0.002
6	0.57	0.458 ± 0.009	0.559 ± 0.011	0.101 ± 0.002
8	0.56	0.469 ± 0.009	0.529 ± 0.011	0.059 ± 0.001
10	0.56	0.496 ± 0.009	0.519 ± 0.01	0.023 ± 0.001

varied with depth from 0.53 to $0.59 \text{ m}^3 \text{m}^{-3}$ (ϕ in Table II), which is 2–15% larger than the estimated field capacities for each depth. The difference between porosity and field capacity was greatest near the soil surface, a pattern that implies a greater incidence of macropores in the shallow horizons.

The seasonal changes in the soil moisture profile were striking, with the formation of a dry front near the surface in August 2002 that gradually expanded downward as the dry season progressed (Figure 4). The 2002 dry season was interrupted in October by a few storms that dropped $\sim 60 \text{ mm day}^{-1}$ and moistened

Figure 3. Measured 10-m soil moisture profile (in $\text{m}^3 \text{m}^{-3}$) beneath tropical forest at km-83 tower site, Tapajós National Forest. Shown are θ_{FC} for the wettest period of April 2002 (closed circles), and θ_{min} for the driest period of October 2002 (open circles)

Figure 4. Daily precipitation (vertical bars) (in mm day^{-1}), and 10-m vertical profile of the volumetric soil moisture (in $\text{m}^3 \text{m}^{-3}$), interpolated with daily averages on the depths 0–15, 0–6, 1, 2, 3, 4, 6, 8, and 10 m, for the period from 03 March 2002 to 12 December 2003. Gaps of soil moisture data are shown as blank colour

the profile down to 3 m depth. The 2003 dry season was less severe than the 2002 dry season, and the corresponding drying front was less extreme with respect to both the minimum water contents observed and the depth reached (Figure 2).

The water content was nearly constant with depth during the wet season (March to August 2002), with a modest decrease in moisture content at the surface and an increase in content at 6 m depth (Figure 5). We

Figure 5. Mean monthly vertical volumetric soil moisture profiles (in $\text{m}^3 \text{m}^{-3}$), from 0.15 to 10 m depth, for the period March 2002 to February 2003

suspect the observation at 6 m was anomalous, underscoring the disadvantage of relying on just one set of vertical measurements. The occurrence of comparatively low moisture contents near the surface during the wet season despite almost daily precipitation may have been a result of a reduced field capacity near the surface caused either by the prevalence of macropores or increased soil organic matter. A similar pattern of comparatively low wet season water content between the 0.5 and 1 m depths has been observed in other forest and pasture sites in Amazonia (M.G. Hodnett, personal communication).

The entire soil profile began to dry with the initiation of the 2002 dry season in August. The profile during this period showed a nearly homogenous increase in moisture content with depth, with low moisture near the surface and maximal moisture at 10 m depth. Occasional storms in October affected the profile, with minimal water contents around 3–4 m, a zone that was below the depth rewetted by the storms. The entire soil profile was recharged with the onset of the wet season in 2003 (Figure 4), though the soil moisture levels observed during the 2003 wet season remained somewhat lower than those observed during the 2002 wet season. The year-to-year change in wet season moisture may have been a result of the severe dry season in 2002, though we could not exclude the possibility of a shift in the calibration of the soil moisture sensors.

Evapotranspiration and root uptake

Evapotranspiration was estimated from the soil water balance. The total amount of soil moisture in the upper 10 m (S , in mm) was calculated by integration of the soil water profile at 24 h (local time). The day-to-day

variation (mm day^{-1}) in water storage was calculated as

$$\Delta S_t = S_t - S_{t-1} \quad (2)$$

where S_t is the water stored on day t and S_{t-1} is the water stored on the previous day. The fraction of total root water uptake, that is supplied by an i -th layer (the mean water withdrawal fraction, WWF_i) was calculated as

$$WWF_i = \frac{\sum_{t=1}^T \Delta S_{i,t}}{\sum_{t=1}^T \sum_{i=1}^n \Delta S_{i,t}} \quad (3)$$

where $\Delta S_{i,t}$ (in mm day^{-1}) is the daily soil water storage variation in layer i on day t summed over T days, and the denominator was the total withdrawal throughout the 10 m of soil summed over the same time period. The values for $\Delta S_{i,t}$, WWF_i , and the mean 30-min soil moisture diel cycle were calculated for periods with no measurable rainfall for at least 3 days after a rainstorm event to minimize the effects of infiltration and internal drainage.

We calculated the mean water withdrawal fraction for each layer using Equation (3) to better understand which soil depths provided the water used during evapotranspiration and how this vertical withdrawal of water changed seasonally. The water withdrawal during the wet season was concentrated in the upper 2 m of soil (Figure 6). In the wet season, withdrawal from the first meter accounted for $40 \pm 2\%$ of the total water withdrawal and withdrawal from the second meter accounted for another 16% of total withdrawal. The pattern of water withdrawal changed markedly with the arrival of the dry season. In the dry season, the contribution from the first meter dropped to 13% of the total, and the contribution of the upper 2 m of soil dropped to $\sim 28\%$ of the total, and the withdrawal was distributed uniformly throughout the upper 6–7 m of soil, with each meter of soil accounting for 10–15%.

The fractional withdrawal at deeper 2-m-thick layer (8–10 m depth) ranged from $\sim 6\%$ in the wet season to $\sim 8\%$ in the dry season. This fractional withdrawal corresponds to an absolute withdrawal of $\sim 0.25 \text{ mm day}^{-1}$ or $\sim 90 \text{ mm}$ over a year. The overall zone of water withdrawal was apparently very deep, extending to a depth of at least 10 m.

Diel variability of soil moisture

The observations from 0.15 m to 0.6 m in the wet season (Figure 7(a), (c) and (e)) and from 0.15 m to 1 m in the dry season (Figure 7(b), (d), (f) and (h)) revealed a marked diel pattern with soil moisture depletion

Figure 6. Fraction of water withdrawal (FWW) for 1-m thick soil layers between the surface and 10 m depth for selected days (Table III) in the 2001/2002 wet season (dark), and in the 2002 dry season (light)

Figure 7. Mean diel cycle of volumetric soil moisture (in $\text{m}^3 \text{m}^{-3}$) for (a) 0–15, (c) 0–3, (e) 0–6, (g) 1, and (i) 2 m depth, in the wet season (left, days: 05/23, 06/04, 07/05 to 07/06, and 07/14 to 07/24/2002), and for (b) 0–15, (d) 0–3, (f) 0–6, (h) 1, and (j) 2 m depth, in the dry season (right, days: 08/05 to 08/09, 08/26 to 08/27, 09/15 to 09/18, 10/08 to 10/09, and 10/16 to 10/17/2002)

during the daytime because of evapotranspiration and a nearly constant, or moderately increasing, water content at night (Figure 7). The rates of moisture depletion at greater depths were comparatively constant from day-to-night. The diel patterns of moisture at depths beneath 2 m depth (plots not shown) were qualitatively similar to those observed at 2 m in both seasons (Figure 7(i), (j)), though the rates of water depletion were reduced at greater depths, with slopes that were generally less than $0.001 \text{ m}^3 \text{m}^{-3}$ per day.

The steady decline in moisture during both day and night at depths of ~ 1 –2 m and below presumably was a result during the wet season of drainage, when the soil moisture content is at or near field capacity (Figure 5). The nighttime decline in deep moisture may also be a partial result of the upward movement of water towards higher surface layers that were comparatively dry and had a greater suction. The possibility of a nocturnal withdrawal of water from deep layers and delivery of water to shallower layers was further supported by the observations at 0.6 m of nocturnal recovery during both the wet and dry season (Figure 7(e) and (f)). The upward movement of water at night presumably resulted from either capillary ascension or from the movement of water through roots by the hydraulic lift mechanism (da Rocha *et al.*, 2004).

The day-to-night changes in soil moisture content ranged from ~ 0.002 and $0.003 \text{ m}^3 \text{m}^{-3}$ per day at 0–15 m and 0–6 m (Figure 7(a), (c), (e)) to less than $0.001 \text{ m}^3 \text{m}^{-3}$ per day below the first meter depth (Figure 7(g), (i)). A change of $0.001 \text{ m}^3 \text{m}^{-3}$ per day in a 1-m thick layer corresponds to a total water withdrawal of 1 mm day^{-1} . The mean daily wet season water withdrawal in the upper 22 cm of soil was therefore 0.6 mm

day⁻¹, while the withdrawal in the upper 0.45 m was 0.9 mm day⁻¹ and the withdrawal in the upper 2 m was 2.3 mm day⁻¹ (Table III). These rates of uptake provided a higher resolution view of the vertical distribution of water uptake, and further illustrated that the withdrawal of water in the wet season is heavily concentrated near the soil surface.

We calculated the total daily soil moisture variation integrated in the 10-m profile, and compared it to the mean above-canopy evapotranspiration measured at the site by eddy covariance. The agreement between the two methods was remarkably good, both with respect to the absolute rates and the variability from day-to-day and period-to-period (Figure 8). The daily water variations varied between ~2.5 and 4.0 mm day⁻¹ in the example we showed. The general agreement between methods increased our confidence in the good accuracy of both the soil water balance method and the eddy covariance measurements and also our estimates of root water uptake.

DISCUSSION

Seasonal and vertical patterns of water withdrawal

The upper 2 m of soil supplied ~56% of the water used for evapotranspiration in the wet season and ~28% of the water used in the dry season. A similar preferential removal of water from shallow horizons during the wet season and from deeper horizons during the dry season was reported for a nearby forest by Romero-Saltos *et al.* (2005). Likewise, the fractional supply of water we observed from the upper 2 m was similar to previous reports for the Amazonian forest. Nepstad *et al.* (1994) estimated that the upper 2 m of soil supplied ~25% of the total water used for evapotranspiration during the 1992 dry season in Paragominas, PA. Hodnett *et al.* (1996a) estimated that the upper 2-m of soil supplied ~52% of the total water used for evapotranspiration near the end of the 1991 dry season and ~38% near the end of the 1992 dry season in Marabá, PA.

The soil surface at our site was usually shaded and covered with litter, a pattern that is typical in evergreen tropical forest. The dense canopy, along with a thick litter layer that was frequently wet and the very high relative humidities observed in the understory, should prevent soil evaporation from contributing significantly to total evapotranspiration. In a nearby forest (15 km apart), in 60% clay and 38% sand soil, Nepstad *et al.* (2002) reported the 12-m root profile with the following content: fine root biomass (2.5–3.5 Mg ha⁻¹ on the 0–0.1 m depth, and between 0.7 and 0.9 Mg ha⁻¹ from 0.1 to 6.1 m depth), and coarse root biomass

Table III. Estimated mean soil moisture daily abstraction (mm day⁻¹) from the successive depths of each 22, 45, 60, and 100 cm, for selected days in the wet season and in the dry season, beneath tropical rain forest at the km-83 tower site, Tapajós National Forest. Selected days in the wet season and in the dry season were 2002: 05/05,06; 06/04,05; 06/12; 06/20; 07/06 to 07/09; 07/14 to 07/25; and 2002: 08/02 to 09/29; 10/06 to 10/10; 10/15 to 10/18; 10/23 to 10/31; 11/12 to 11/30; respectively

Depth (cm)	Soil moisture abstraction (mm day ⁻¹)	
	Wet season	Dry season
22	0.6	0.2
45	0.9	0.4
80	1.5	0.8
100	2.0	1.5

Figure 8. Water vapour flux measured with the eddy covariance method (solid line with filled squares) and daily soil moisture variation (solid line with open circles), in mm day^{-1} , for the following periods: (a) 8–11 June 2002, (b) 10–16 July 2002 and (c) 01–03 August 2002

(30 to 32.9 Mg ha^{-1} from 0 to 12 m depth). We suggest it is reasonable to attribute the patterns of moisture removal from the soil to the uptake of water by roots and subsequent transpiration. The vertical patterns of water withdrawal (Figures 3–7) were therefore determined by the interaction between the vertical distribution of roots and the vertical patterns of soil water potential and soil hydraulic conductance.

The preferential uptake of water from shallow horizons, especially in the wet season, presumably reflects a concentration of root biomass near the surface (Nepstad, 1989). The hydraulic conductance for the movement of water from soil into the main stems of the trees should be lower for water moving from shallow soil than for water moving from deeper soil because of the combined effect of a greater root surface area near the surface, a shorter pathway through the xylem, and a slightly less negative water potential associated with the gravitational effect of depth. Consequently, transpiration preferentially extracted water from near the surface during the wet season when the soil was uniformly wet at all depths. The depth of water extraction then moved to lower soil layers as the dry season progressed and a vertical gradient in soil water potential developed.

Soil water storage and drought avoidance

We observed significant soil moisture variation at a depth of 10 m, and calculated that a 2-m thick layer of soil above this depth contributed $\sim 7\%$ of the total water taken up in the top 10 m of soil. Moreover, we note that we did not make measurements below 10 m depth, and that it is likely that significant soil moisture uptake occurred beneath this depth, especially late in the dry season and during years with particularly severe droughts. Our inference of root water uptake at significant depth conflicts with work in a nearby forest using deuterium-labelled water that did not find evidence of plant water uptake below 2.54 m depth (Romero-Saltos *et al.*, 2005). Nonetheless, we believe there is ample evidence from previous studies, as well as the work we report here, to conclude that tropical forests extract water from great depth during the dry season. For example, Chauvel *et al.* (1992) found abundant roots at 3 m and 6 m depth, Nepstad *et al.* (1991, 1994) found

roots at 18 m depth, and Nepstad (1989) concluded that the mature forest in eastern Amazonia (Paragominas, PA) access water at 6 m depth.

The deep root profile beneath the Amazonian forest plays a major role in allowing the evergreen forest to persist despite a prolonged dry season, and also in controlling the seasonal patterns of water vapour, energy, and CO₂ exchange. The rates of whole-forest photosynthesis and evapotranspiration at the site remained constant, or increased moderately, in the dry season (da Rocha *et al.*, 2004; Goulden *et al.*, 2004), implying that the trees did not experience sufficient drought stress to curtail gas exchange.

In previous work in Amazonia, Hodnett *et al.* (1995) used $\Delta\theta_{\text{MAX}}$ as a measure of the plant available soil moisture. The Hodnett *et al.*'s interpretation assumes that the minimum soil water contents observed corresponds to a complete depletion of plant available moisture, and that the soil intrinsic water release curve poses strong soil suction at deeper levels (Tomasella and Hodnett, 1996). We do not believe that this interpretation of $\Delta\theta_{\text{MAX}}$ applies completely at our site. Our estimate of θ_{min} was not the wilting point, and we did not find evidence that the plants suffered drought stress or that the rate of evapotranspiration at the end of the dry season was limited by soil water. The limiting soil moisture extraction depends on the distribution of root biomass and also the soil properties (Sperry *et al.*, 1998), that we did not observe at the site. In fact, we suspect that the total plant available moisture at our site was significantly larger than the integrated rates of evapotranspiration that occurred in the 2002 or 2003 dry seasons.

We conclude that the forest at our site is well adapted to the normal cycle of wet and dry seasons, and that the effect of the dry season on the land–atmosphere exchange at our site is small. At the same time, we note that this adaptation is based on the exploitation of a deep soil column, and that a series of particularly dry years may begin to deplete this reservoir. We observed a modest year-to-year decline in wet season soil moisture following the particularly severe 2002 dry season, and it is likely that a series of particularly dry years would begin to deplete the soil reservoir and to impact the vegetation. Inter-annual variability in precipitation and soil moisture have been reported for other sites in the Amazonia (Hodnett *et al.*, 1996b; Jipp *et al.*, 1998), where strong soil water depletion below 2 m occurs in long drought spells and can remain for several years before the profile is completely recharged.

Scenarios for the development of the Amazonian vegetation in the next decades point to a possible shift to a new stable equilibrium with 'savannisation' in some regions (Oyama and Nobre, 2003). More extreme scenarios suggest a possible ecological collapse of forest because of a persistently drier climate (Cox *et al.*, 2000). These scenarios are based on mechanistic models of ecosystem function and land–atmosphere exchange that contain many assumptions about the relationships between drought, soil water, plant water uptake, and plant physiology (e.g. Sellers *et al.*, 1996). Scenarios for the development of the Amazonian vegetation can be improved if the forest response to drought is well described. The data set we report can be used to test, validate, and calibrate models of the Amazonian land–atmosphere exchange.

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