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Amazonian Deforestation and Climate

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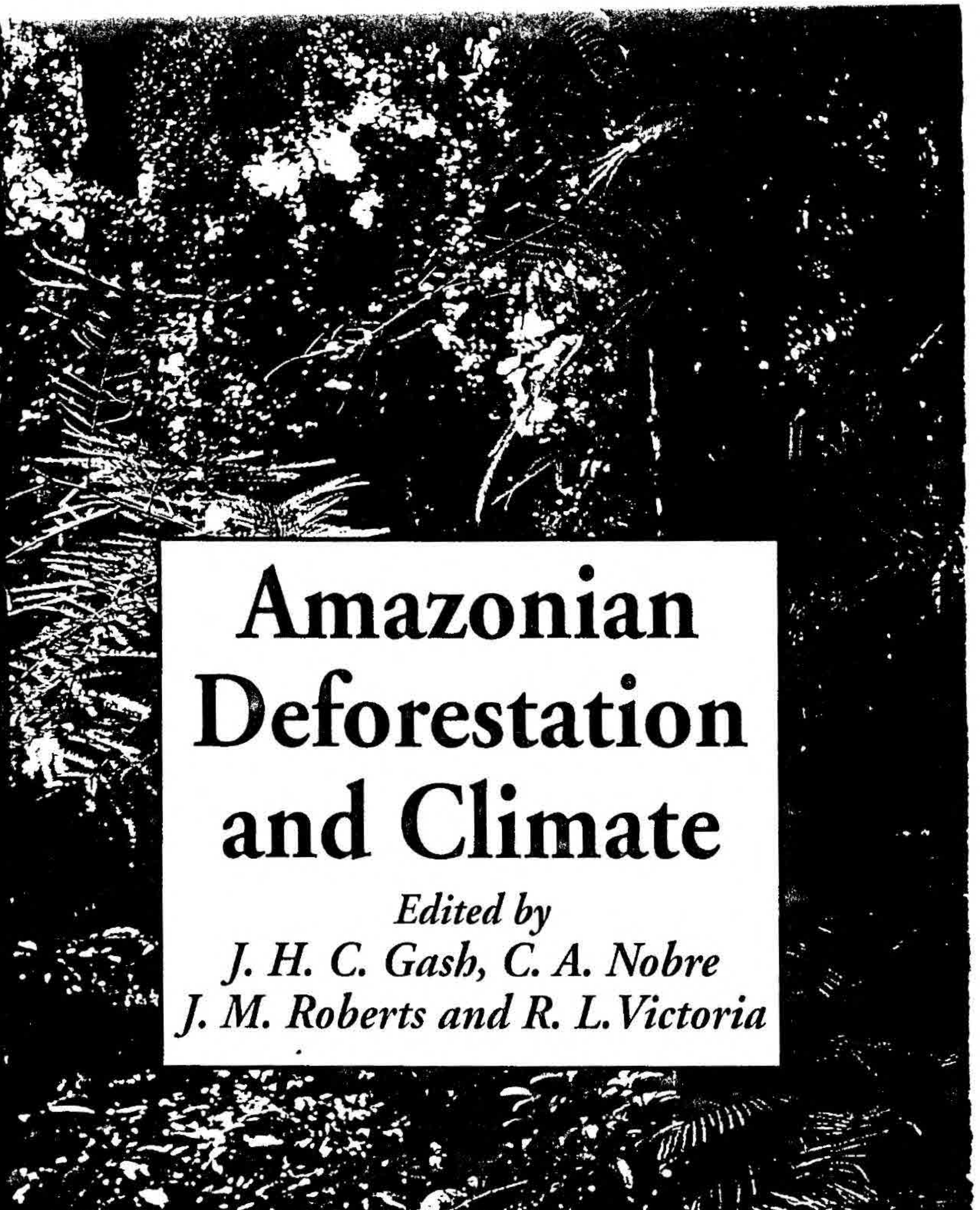

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3 Comparisons of long-term soil water storage behaviour under pasture and forest in three areas of Amazonia

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INTRODUCTION

In simple terms, transpiration can be regarded as being controlled only by atmospheric factors while the vegetation is "well supplied with water" (Penman, 1956). When the supply of soil water becomes limiting, the vegetation suffers "soil water stress" and transpiration decreases, altering the partitioning of incoming solar radiation into sensible and latent heat. Less water (and therefore, latent heat) is returned to the atmosphere and the proportion returning as sensible heat increases. The supply of water to the vegetation depends on the soil properties, and on the type of vegetation and its ability to abstract water from the soil (in particular, its rooting depth). Land-use change, particularly deforestation, on a large enough scale could potentially modify the water and energy balance sufficiently to modify climate. The influence of land surface evapotranspiration on the Earth's climate has been discussed by Shukla and Mintz (1982).

General Circulation Models (GCMs) are being used to predict the effects of large scale forest clearance on climate (e.g. Lean and Warrilow, 1989; Shukla *et al.*, 1990; Nobre *et al.*, 1991). However, their validity and accuracy are dependent on representative parameterisation of the soil and of the vegetative surface before and after deforestation (Henderson-Sellers, 1987). More sophisticated Soil-Vegetation-Atmosphere Transfer (SVAT) models are being developed, for example SiB (Sellers *et al.*, 1986), BATS (Dickinson *et al.*, 1986) and the parameterisation of Noilhan and Planton (1989). The input parameter requirements for these models are increasing, particularly for soil data. Long-term, and, ideally, large scale, soil moisture data are required for the verification of SVAT models, but as Owe and Van de Griend (1990) have noted, the lack of reliable large scale soil moisture data has been a long-standing problem.

As far as is known, the only published medium-term records of soil water content

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for forested or cleared forest sites in Amazonia are those of Nepstad *et al.* (1994), which show nine months of data from sites in Pará, in eastern Amazonia. One of the main aims of the ABRACOS soil water studies was to obtain a minimum of two or three years of weekly soil water content and soil profile storage measurements to enable the calibration of SVAT and soil water uptake models.

The continuous weekly soil water record was particularly important to allow the detailed study missions (micro-meteorology and plant physiology) to be located within the seasonal cycle and within the interannual variability of profile storage change. Periods of very low soil profile storage are of particular interest because of the effects of soil water stress on the energy balance. The longer term context of the soil water data-set from Manaus is discussed in a later paper (Hodnett *et al.*, 1995c).

This paper presents and compares the soil profile storage data for the three paired (forest and pasture) ABRACOS sites. Comparisons are made between sites and between years, and the physical processes influencing the soil water storage behaviour at the different sites are discussed.

MATERIALS AND METHODS

LOCATION

A general outline of the ABRACOS project, and the location of the three main study sites has been presented by Gash *et al.* (1996). Further details can be found in Wright *et al.* (1992), Bastable *et al.* (1993), McWilliam *et al.* (1993) and Hodnett *et al.* (1995).

It should be noted that the forest soil water monitoring site near Manaus was in an area of forest adjacent to the pasture site at Fazenda Dimona, and not in the Reserva Ducke, where the tower was located. This was to ensure that the soil type and rainfall were, as far as possible, identical and to allow simultaneous observations to be made at both sites.

SOILS AND VEGETATION

Site details are summarised in Table 1. N.B.: the "English" soil type names given first are translations from the Brazilian classification.

MANAUS

At the pasture and adjacent forest sites, the soil was a clayey yellow latosol (Latossolo amarelo, álico, textura argilosa - Brazil, Haplic Acrorthox - Soil Taxonomy, or xanthic ferrasol - FAO), very similar to those described by Ranzani (1980) and Correa (1984). The soils have a very high clay content (>75%) and a low dry bulk density of between 0.93 and 1.15 Mg m^{-3}, giving a very high porosity of between

56% and 64%. The lowest bulk density was in the top 0.1 m in the forest; in the pasture the surface density was 1.06 Mg m^{-3}. However, much of the porosity is concentrated in the macropores and large mesopores, which drain rapidly, and the very fine pores containing water that is inaccessible to plants. This means that the available water capacity is low, only about 70 mm m^{-1} in the upper metre of the profile (Correa, 1984). More details of the soil at this site and its hydraulic properties are given by Hodnett *et al.* (1995) and Tomasella and Hodnett (1996).

During most of the period of study reported here, the pasture was in good condition, with little invasion and degradation by woody shrubs (<2% cover). There were two main grass species, *Brachiaria humidicola* and *Brachiaria decumbens*. By July 1993, the shrub cover had increased to about 30%; most of this increase occurred after late 1992.

Table 1 Summary of site details

LOCATION		WEST		CENTRAL		EAST	
SITE NAME		JI-PARANÁ		MANAUS		MARABÁ	
DRY SEASON[1] Months with <150 mm		May - September		June - Sept ember		May - October	
< 50 mm		June - August		----		June - August	
		Pasture	Forest	Pasture	Forest	Pasture	Forest
Soil Type (FAO)		Orthic Acrisol	Orthic Acrisol	Xanthic Ferralsol	Xanthic Ferralsol	Orthic Acrisol	Humic Cambisol
Surface Texture		Loamy Sand	Sand	Clay	Clay	Sandy Clay Loam	Loam
Depth (m)							
0-0.05	Clay (%)	9	4	86	83	20	18
	Sand (%)	85	88	8	16	74	45
	Bulk density (Mgm m^{-3})	1.50	1.38	1.06	0.93	1.40 (0.15 m)	1.24 (0.15 m)
	Porosity (%)	42	47	59	64	46	52
0.5-1.0	Clay (%)	33	24	75	77	40	12
	Sand (%)	58	67	88	80	53	13
	Bulk density (Mgm m^{-3})	1.30	1.38	1.14	-	1.42	1.33
	Porosity (%)	50	47	56	-	45	49
Access Tube Depth (m)		3.6	2-3.6	2.0	1-3.6	3.6	3.6
No of tubes		6	8	15	15	6	6
Start of observations		11/91	11/91	9/90	9/90	8/91	8/91

[1]Mean monthly rainfall data.
Ji-Paraná, Ouro Preto, 1982 - 1992.
Manaus, Reserva Ducke, 1966 - 1992
Marabá, Marabá, 1973 - 1993

MARABÁ

The soil at the pasture site (Fazenda Boa Sorte) was a medium to clayey textured red-yellow podzolic soil (podzólico vermelho-amarelo Tb álico a moderado textura média/argilosa - Brazil, typic haplustult - Soil Taxonomy, or orthic acrisol - FAO). The texture in the upper 0.5 m of the profile was sandy loam to sandy clay loam.

Below 0.5 m the clay content increased to give a sandy clay texture. The bulk density in the top 0.5 m was 1.52 Mg m^{-3} (42%) and between 1.32 Mg m^{-3} (49%) and 1.49 Mg m^{-3} (43%) in the profile to 2.0 m depth. The values in parentheses are porosities based on a particle density of 2.6 Mg m^{-3}. The pasture was mainly grass, but it was becoming degraded with woody shrubs and small palms. The main grass species was *Panicum maximum*.

At the forest site (Reserva Companhia do Vale do Rio Doce), the soil has been classified as a medium textured yellowish cambisol (Cambissolo Tb álico amarelado textura média, probably a typic dystrochrept - Soil Taxonomy, or humic cambisol - FAO). The texture of the profile to about 0.6 m depth was sandy loam, but it was very stony (gravel/stone content, 36% w/w). The stone content decreased abruptly below this depth, where the texture was silt loam. Below about one metre depth, the profile consisted of saprolite (heavily weathered rock, retaining some of the original rock

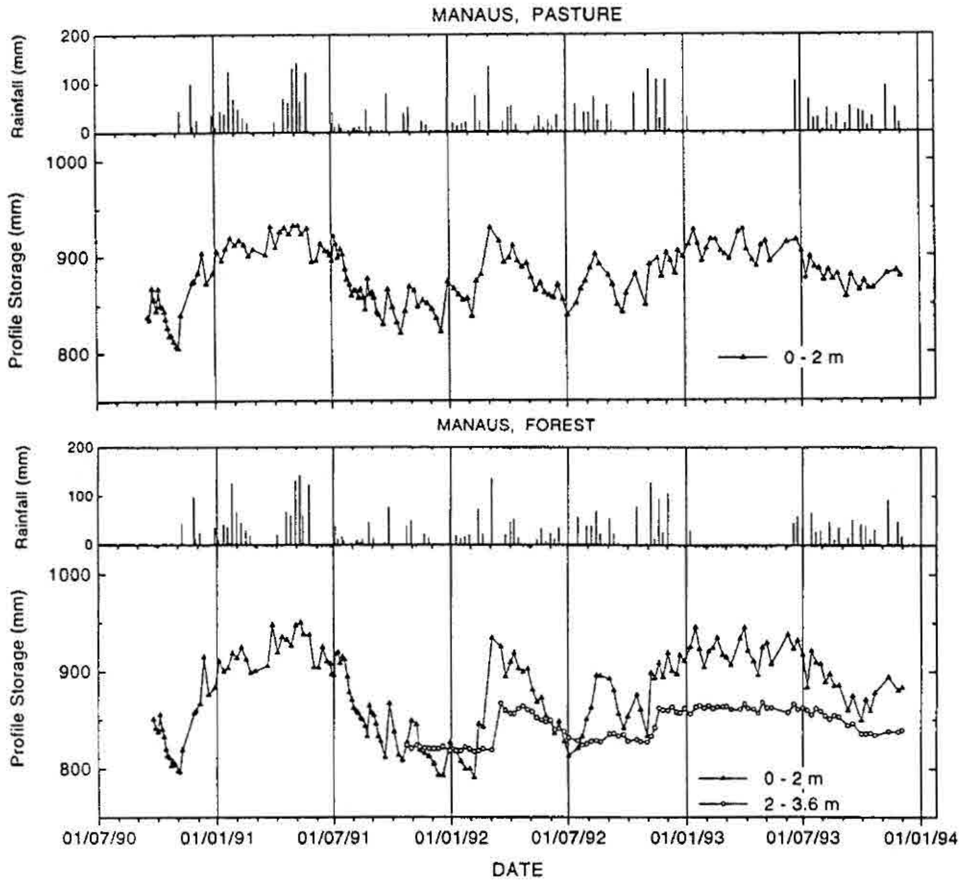

Figure 1 Manaus, Fazenda Dimona, pasture (top): profile storage (0-2 m) and rainfall between reading dates. Note: in all graphs in the following figures, negative values indicate unreliable rainfall data. Manaus Fazenda Dimona, forest (bottom): profile storage in the 0-2 m and 2-3.6 m layers, and rainfall between reading dates.

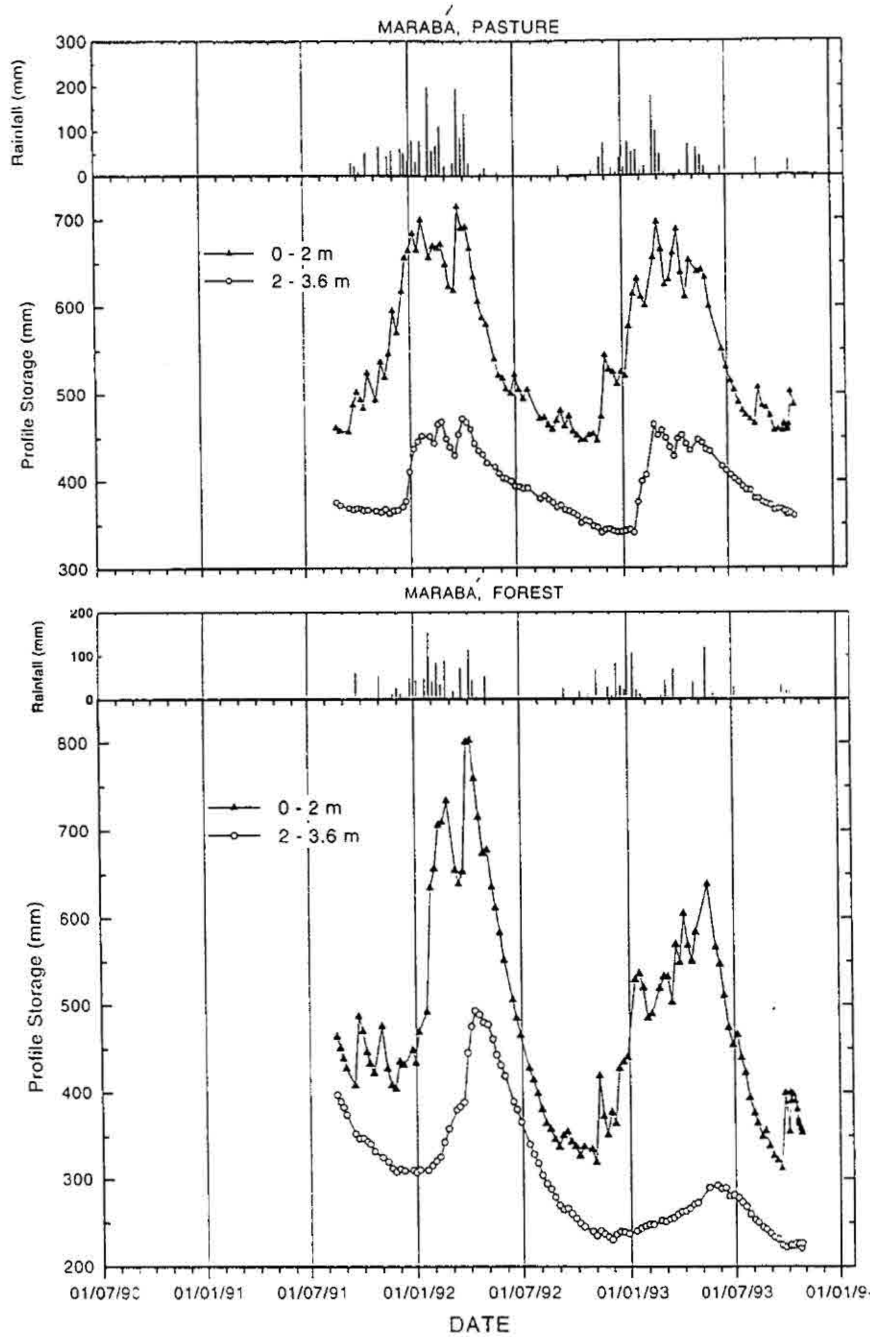

Figure 2 Marabá, pasture (top): profile storage in the 0-2 m and 2-3.6 m layers, and rainfall between reading dates. Marabá forest (bottom): profile storage in the 0-2 m and 2-3.6m layers, and rainfall between reading dates.

structure) which was texturally a silt loam or a silt. The bulk density in the top 0.5 m was 1.19 Mg m^{-3} (54%) and increased gradually to 1.49 Mg m^{-3} (43%) at a depth of 2.3 m.

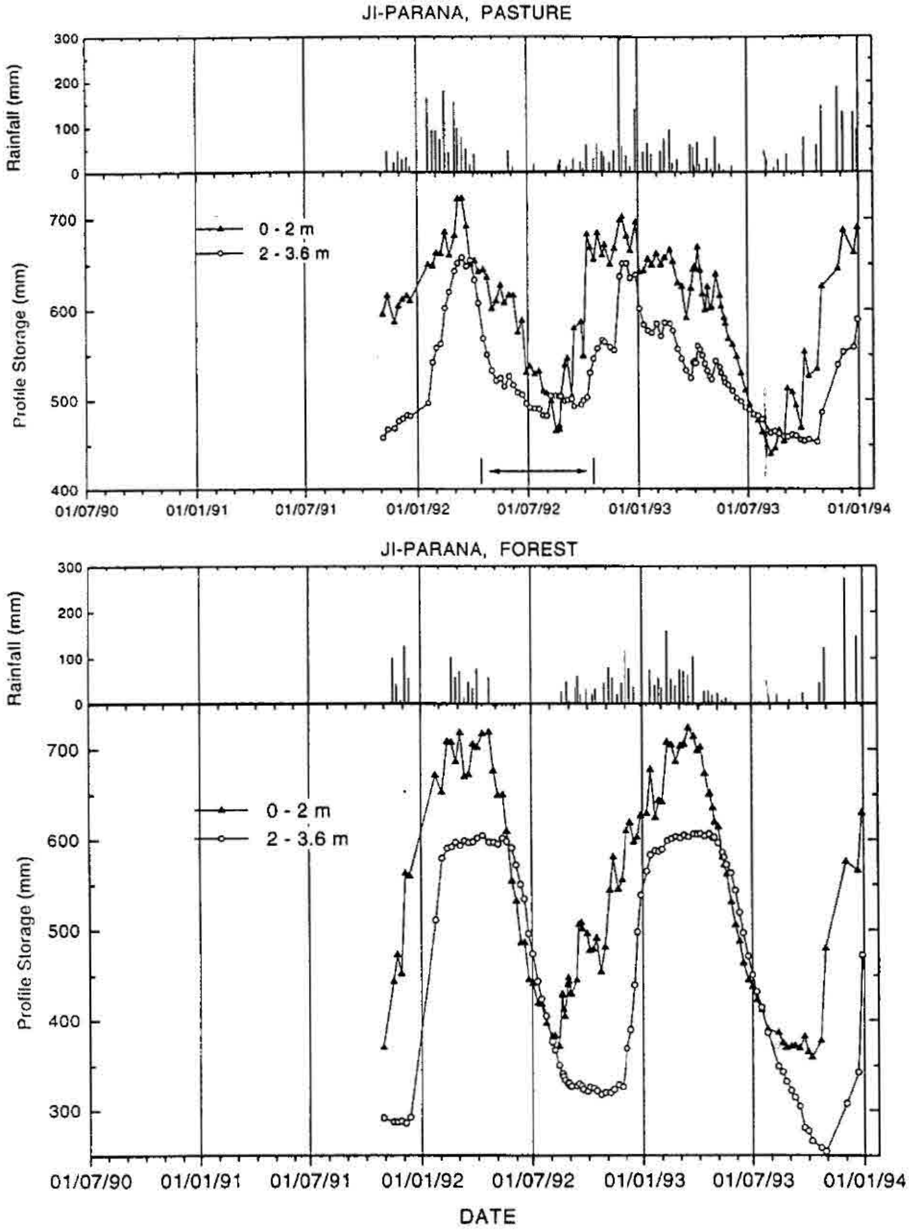

Figure 3 Ji-Parana, pasture (top): profile storage in the 0-2m and 2-3.6m layers and rainfall between reading dates. Ji-Paraná, forest (bottom) Profile storage in the 0-2m and 2-3.6m layers and rainfall between reading dates

JI-PARANÁ

At the pasture site (Fazenda Nossa Senhora da Aparecida) we have provisionally classified the soil as a medium textured red-yellow podzol (Podzólico vermelho amarelo A moderado textura média - Brazil, typic paleudult - Soil Taxonomy, or orthic acrisol - FAO). The surface soil was a sand/loamy sand (85% sand). The clay content increased gradually with depth from 7% in the top 0.1 m to 35% between 1 m and 1.5 m, where the texture was sandy clay loam. Between 1 m and 2 m, the soil was gravelly (28% w/w), merging into saprolite below 2 m. Bedrock was not encountered within the upper 3.8 m of the profile. Roots were observed throughout the profile examined in a pit to a depth of 1.65 m. Roots were sometimes found concentrated in the channels left by rotted tree roots. The bulk density decreased from 1.50 Mg m^{-3} (42%) at the surface to 1.24 Mg m^{-3} (52%) at 1.35 m.

The pasture was in good condition with little invasion by shrubs. There were a few scattered large palms, but these were not near to the soil water monitoring sites. The grass species was exclusively *Brachiaria brizantha*.

We have provisionally classified the soil at the Ji Paraná forest site (Reserva Biológica do Jaru) as a medium textured red-yellow podzol (Podzólico vermelho-amarelo A moderado textura média - Brazil, typic paleudult - Soil Taxonomy, or orthic acrisol - FAO). The surface soil was a sand (88%) and the clay and silt content increased with depth. At 0.6 m the texture was a sandy loam. Below this depth, the profiles differed because of the large range in the depth to the granite bedrock which varied from 1.6 m in one soil sampling pit to > 3.8 m at two of the measurement sites. In one of the deeper profiles sampled, the clay content reached 34% between 1 m and 1.5 m (sandy clay loam) and then decreased to around 17% at 2.7 m. In most places the soil merged downwards into saprolite, then into fairly hard weathered granite. The bulk density at the surface was 1.38 Mg m^{-3} (47%), which was less than in the pasture. The density at 0.2 m was 1.55 Mg m^{-3} (40%) and decreased gradually with depth to 1.49 Mg m^{-3} (43%) at 0.6 m.

INSTRUMENTATION

Soil water content was measured using a neutron probe. The Fazenda Dimona sites near Manaus were established in September 1990. To represent the "mean" soil water behaviour in the area, the neutron probe access tubes were installed to represent three different landscape elements: plateau, slope and valley floor. Soil water storage behaviour was expected to differ in each element because of the presence of a shallow water table in the valley, and the greater likelihood of surface runoff on the slopes. Access tubes were installed to a depth of 2.0 m in the plateau and slope elements and to 1.0 - 1.8 m in the valley floor. In October 1991, the five forest plateau tubes were replaced by tubes with a maximum reading depth of 3.6 m.

The soil water measurement sites near Marabá and Ji-Paraná were established in August and October 1991 respectively. There were six access tubes at each site, each with a maximum reading depth of 3.6 m, except at the Ji-Paraná forest site. Here, the depth of six of the eight access tubes was limited by the depth to the granite bedrock. Maximum reading depths ranged from 2.0 to 3.6 m. The two deepest tubes did not reach bedrock. At the Marabá and Ji-Paraná sites, only the plateau landscape element was represented. Water content was measured at depths of 0.1 m and 0.2 m, and then at 0.2 m intervals for the remainder of the depth of the tube. At the Marabá sites the measurement depth interval was 0.3 m below 1.2 m depth. Details of the numbers and depths of the neutron probe access tubes at each of the sites are given in Table 1. Observations were made on a weekly basis with twice weekly observations being made during the intensive field missions. At the Manaus sites, simultaneous observations were made in the forest and pasture but at the Marabá and Ji-Paraná sites observations were made at the forest and pasture sites on separate days.

The neutron probe count rates were converted to volumetric water content θ using a soil calibration of the form:

$$\theta = m\,(R/R_w) + n$$

where R is the count rate at a given depth in the soil, R_w is the count rate in a water standard, and m and n are the slope and intercept of the calibration. These were determined by the method of Couchat *et al.* (1975). Bulk density profiles were determined to allow the calibration to be adjusted accordingly. For the Manaus sites, gravimetric calibration was carried out for the readings made at 0.1 m depth. This was not done for the other sites and may have led to an under-estimation of the maximum profile water storage changes of 10 - 20 mm.

The profile storage (S) to depth (D) was determined using:

$$S = \sum_{i=1}^{D} \theta_i \,\Delta_i z_i$$

where θ_i and z_i are the water content and thickness respectively of layer i. For each reading date, the profile storage to the maximum depth in each tube, and the mean storage for each site were calculated.

The soil water balance was used to determine evaporation or deep drainage for selected periods:

$$P = R + E + D + \Delta S$$

where P is the net rainfall, R is the surface runoff, E is the evapotranspiration and ΔS is the change in profile water storage to the depth of interest, all during the same time period.

RESULTS

SEASONAL PROFILE STORAGE CHANGES

Figures 1, 2 and 3 show the mean profile water storage (a) for pasture and (b) for forest for the layers from 0 to 2 m and from 2 m to 3.6 m for the Manaus, Marabá and Ji-Paraná sites respectively. The data are shown from the start of observations until the end of December 1993 (October 1993 for Marabá). All graphs are on the same scale. The data are summarised in Table 2, which shows the maximum recorded seasonal water content variation in the 0-2 m and 2-3.6 m layers, and in the full 3.6 m profile. It should be noted that the maximum change in the full 3.6 m profile is not the sum of the change in two layers. This is because the timing of the minimum water content is not the same in the two layers, mainly because drainage may be reducing the storage in the lower layer while the upper layer is wetting up at the start of the wet season.

Unlike the Manaus sites, the Marabá and Ji-Paraná "paired" sites were far enough apart for there to have been significant differences in rainfall on a weekly basis. Observations were also made on separate (usually successive) days. The Manaus pasture and forest data might therefore appear more similar than those from the other paired sites.

Table 2 Maximum recorded soil water storage changes at each site

Layer	**0–2 m**		**2–3.6 m**		**0–3.6 m**	
Site	Pasture	Forest	Pasture	Forest	Pasture	Forest
Manaus	132	154	-	48	-	200
Marabá	263	483	131	263	376	724
Ji-Paraná	262	365	165	353	450	701

MANAUS

The forest and pasture profile water storage changes in the upper 2 m were very small compared to the Marabá and Ji-Paraná sites. There was also only a relatively small difference between the forest and pasture changes in the 2 m profile. The maximum seasonal variation at the Manaus sites was 154 mm for the forest and 132 mm for the pasture.

The minimum storage recorded for both forest and pasture was on 5 November 1990, at the end of the dry season. In the pasture, the storage never fell this low again over the next three years, but in the forest the same minimum was recorded on three subsequent occasions, in December 1991 (twice), and February 1992 (once). It is notable that February is (on average) one of the wettest months.

During each wet season, the same narrow range of maxima was seen in the 2 m profile, which wetted up to the same extent (a storage of 900 mm - 920 mm) each year. Large peaks in storage were never seen in the weekly data because drainage from the profile is rapid. The pattern of wet season storage behaviour was very similar in the forest and pasture.

There were considerable differences in the annual cycle of storage change between years as a result of inter-annual rainfall variability. The 1991 dry season extended into 1992, which was very different to the mean pattern, and the 1991-1992 wet season was very weak; storage only remained above 900 mm for about two months, compared to seven months in 1990-91 and nine months in 1992-93. The 1993 dry season was the wettest observed. This three year run of data has been examined in the context of a 27 year rainfall record from Reserva Ducke in a subsequent paper (Hodnett *et al.*, 1996).

Deeper (3.6 m) access tubes were installed in the forest in October 1991 because there was evidence from the water balance for October 1990 that water uptake was taking place from below 2 m depth. After the installation of these tubes, the storage in the 2 - 3.6 m layer decreased only 5 mm, reaching the minimum recorded during the study in January and February 1992. It is clear from these data that most of the storage in this layer had already been utilised by October 1991. Hodnett *et al.* (1995), using a water balance based on these data, have shown that the forest was almost certainly using water from depths greater than 3.6 m during this period. Rainfall and uptake from storage in the upper 2 m of the profile only contributed between 1 and 2 mm day^{-1}, when typical dry season evaporation rates are assumed to be about 3.5 mm day^{-1} (Shuttleworth, 1988).

The maximum observed storage change in the 2 m to 3.6 m layer was 48 mm, equivalent to a mean water content change of only 0.03 moisture volume fraction (MVF). In 1992 and 1993, the maximum depletions in this layer were 40 mm and 31 m respectively. With the data available, it is not possible to define with any certainty how much of the observed change was due to drainage, but the water availability is clearly below 2 m and does not exceed 0.03-0.04 MVF, or 30-40 mm m^{-1}. These are exceptionally low values for any soils. They are about half of the values quoted by Correa (1984) for the upper profile.

MARABÁ – PASTURE

The largest seasonal water storage change in the Marabá pasture 2 m profile (wet season peak - dry season minimum) was 269 mm, which was 114 mm more than for the forest in Manaus. In the two wet seasons shown, the maximum storage recorded was very similar. The minimum storages recorded in all three dry seasons were also similar.

The very low rates of depletion at the end of the dry season in 1992 and 1993 indicate that the abstraction limit was being reached. Between 20 October and 17 November 1992 the depletion in the 0 - 2 m and 2 - 3.6 m layers was 0.5 mm and 4.8 mm respectively. There were 11.7 mm of rain. Applying the water balance and assuming negligible drainage, the evapotranspiration for the period was 17.0 mm, or an average rate of 0.61 mm day^{-1}. Most of this was the result of the evaporation of the rainfall input.

In the 2 - 3.6 m layer, the maximum storage variation was 131 mm. This layer wetted up to the same extent in both wet seasons but the minimum storage was 23 mm lower in the 1992 dry season, which continued longer than in 1991. From May until November 1992, depletion in this layer continued at an almost constant rate of 0.4 mm day^{-1} ceasing only when the upper profile began to wet up. This implies that the depletion below 2 m at this time was the result of water uptake by the roots of the grasses and shrubs and was not due to drainage. Wetting of the profile below 2 m was rapid, but only occurred after the profile above had wetted up by almost 200 mm to within 60 mm of the maximum observed.

MARABÁ – FOREST

The seasonal changes in the 0 - 2 m layer in the forest were far larger than in the pasture. The maximum changes in 1992 and 1993 were 483 mm and 327 mm respectively. A very important observation is that, during the study period, this was the only site where the profile did not rewet to the same condition in both wet seasons. In the 0 - 2 m layer, the 1993 dry season began with 164 mm less water in storage than in 1992. Over the full 3.6 m measured profile, the 1993 dry season began with 349 mm less water in storage.

The rainfall in the 1992/3 season was almost certainly less than in 1991/2 (the rainfall data for the site were not reliable in this period). In addition, the storage at the start of the 1991/2 wet season was 89 mm higher than at the start of the 1992/3 season.

In the 2 - 3.6 m layer, the difference in storage behaviour between years was very pronounced. In the 1992/3 wet season, this layer wetted up only 62 mm, compared to 185 mm in the previous wet season. The minimum storage also varied from year to year; in 1992 it was 77 mm lower than in 1991. The maximum soil water depletion in a single season was 263 mm during 1992, compared to only 72 mm during 1993. The maximum seasonal change in storage over the full 3.6 m profile was 724 mm between 6 April and 2 November 1992.

Rates of soil water uptake from the 3.6 m profile were still substantial even at the end of the 1992 and 1993 dry seasons when the profile storage was very low (606 and 535 mm respectively). Over a 21 day period in August 1992 (rainfall 0.4 mm), the mean evapotranspiration rate determined from the water balance was 2.5 mm day^{-1}, of which 1.17 mm day^{-1} was contributed from the 2 - 3.6 m layer. Over a similar period in September 1993, with 5.4 mm of rain, the mean evapotranspiration rate was 2.16 mm day^{-1}, but in this case, the contribution from the 2 - 3.6 m layer was only 0.66 mm day^{-1}. In contrast, at the end of the 1991 dry season, when the 3.6 m profile storage was 226 mm more than in 1993, the mean evaporation rate from the profile over a 31 day dry period was 3.25 mm day^{-1}, of which 1.43 mm day^{-1}

was from the 2 - 3.6 m layer.

It is notable that in the dry season, depletion in the 2 - 3.6 m layer slowed or stopped almost as soon as the top 2 m began to rewet. Unlike in the pasture, the profile below 2 m began to wet up gradually, well before the profile above had been fully wetted. It is unlikely that there was any significant deep drainage in the 1993 wet season.

JI-PARANÁ – PASTURE

At this site, the maximum storage change in the 0 - 2 m layer in 1993 was 262 mm, which was similar to the change at the Marabá pasture site. This layer wetted up to the same extent in the two wet seasons studied. The minimum storage was not recorded reliably in 1992 because of inconsistencies in the depth location of the neutron probe between April and October 1992.

Over a two week period in late July and early August 1993, at the end of the dry season, the rate of uptake from this layer was about 1.8 mm day^{-1}, indicating that the pasture was still able to continue abstracting water at a significant rate. This is in strong contrast to the end of the dry season uptake rate at the Marabá pasture site.

The 2 - 3.6 m layer wetted up to the same extent in the 1991/2 and 1992/3 wet seasons. In both seasons there was a very steep increase in storage during very wet periods, followed by a rapid decrease. This was caused by the rise of the water table which saturated the profile from below, indicating that there is a low permeability layer below 3.6 m. The total depletion during the 1993 dry season was 165 mm.

In the 2 - 3.6 m layer, the mean rate of depletion over the last 56 days of the 1993 dry season was 0.60 mm day^{-1}. After the 0 - 2 m layer began to rewet, the depletion rate in the 2 - 3.6 m layer decreased to 0.17 mm day^{-1} and remained almost constant for 70 days until the wetting front arrived. The sudden decrease in depletion rate indicates that root uptake from this layer had been occurring but stopped when water became readily available in the upper profile. The rate of 0.17 mm day^{-1} is probably a reasonable estimate of the underlying drainage rate, implying an average rate of root uptake from below 2 m (over the 56 days) of about 0.4 mm day^{-1}. Over the last two weeks of the 1993 dry season, the evapotranspiration rate estimated from the water content change in the 3.6 m pasture profile was 2.5 mm day^{-1} even though the 0 - 2 m profile storage had decreased by 262 mm from the maximum observed.

JI-PARANÁ – FOREST

In 1993, the change in the 0 - 2 m layer was 365 mm. Peak storage was very similar in 1992 and 1993. The Ji-Paraná forest site differs from all of the other sites in that the water table rises to within 1.2 m of the ground surface at the peak of the wet season. The root zone and the zone of seasonal water table fluctuation overlap and the observed storage changes therefore also reflect the rise and fall of this water table.

Mean rates of water loss from the 2 m profile (evapotranspiration and drainage) determined from the water balance exceeded 8 mm day^{-1} in the early dry season, confirming that the fall of the water table and subsequent unsaturated drainage play an important role in the storage behaviour. The depletion rates decreased gradually, and almost levelled out in August/September 1993. Applying the water balance to the dry period between 13 and 26 August 1993, gave a mean depletion/evapotranspiration rate of 1.28 mm day^{-1}. Between 3 and 17 September, when 7.2 mm of rain fell, the depletion was only 1.8 mm, giving a net uptake rate of 0.64 mm day^{-1}. The very low depletion rate shows that the abstraction limit for the 2 m profile was being reached. Although similar minimum storages were seen at the end of the 1991 and 1992 dry seasons, the levelling out of the storage, as seen in 1993, was not observed because of the timing of the start of the wet season in those years.

The storage response of the 2 - 3.6 m layer was very different to that at the other sites because of the influence of the water table. The flat top to the storage curve marks the period when the entire profile below 2 m depth was saturated. This lasted about three months in both 1992 and 1993. The seasonal change in water content was large, and varied from 287 mm in the 1992 dry season to 353 mm in 1993. In 1992, depletion in the 2 - 3.6 m layer ceased abruptly as soon as the upper profile began to wet up, as observed at other sites. In 1993, there was 63 mm more depletion in this layer than in 1992, most of which occurred after the reserves 0 - 2 m layer had been largely exhausted.

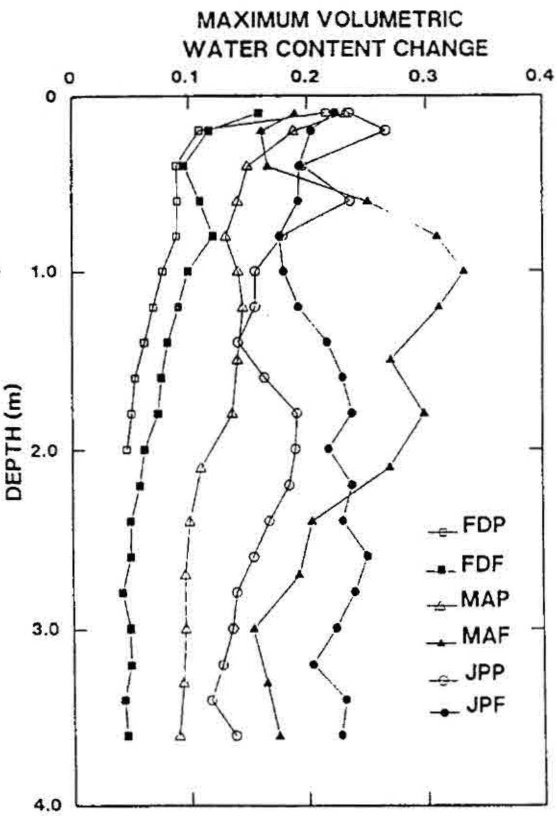

Figure 4 Profiles of maximum observed water content change at each depth for all sites: FDP – Manaus pasture, FDF – Manaus forest, MAP – Maraba pasture, MAF – Maraba forest, JPP – Ji-Paraná pasture, JPF – Ji-Paraná forest

Between 8 and 26 July 1993, the mean depletion rate, determined from the water balance of the entire 3.6 m profile, was 4.5 mm day^{-1} compared to the mean measured evapotranspiration rate of 3.77 mm day^{-1} (Wright, 1994, pers. comm.). The difference is probably caused by drainage from the lower part of the profile. It would appear that, at this stage, the water supply to the forest was not limiting. However, only five weeks later, at the end of the dry season, the depletion rate had decreased to 1.7 mm day^{-1}. Unfortunately, no directly measured evapotranspiration data are available for this period for comparison. Total profile storage on 17 September was 93 mm lower than at the end of July. If evapotranspiration was being sustained at a rate of about 3.6 mm day^{-1}, the remainder must have been supplied from the profile below 3.6 m.

DISTRIBUTION OF WATER CONTENT CHANGES WITH DEPTH

Figure 4 shows the difference between the wettest and driest water contents measured at each depth for all of the sites. Between sites, there was a large range of water content change at all depths.

Apart from in the top 0.2 m, water content changes at all depths were consistently much greater in the forest than in the pasture. At the Fazenda Dimona sites (where the soil type was identical), the differences were less than at the other sites at all depths. The change only exceeded 0.1 in the upper metre of the profile and below 3.0 m the change was only 0.03 - 0.04 MVF. The lowest change at any of the other sites was 0.09 MVF below 3 m beneath the Marabá pasture.

The very large variations between sites and with depth are of note. At 0.4 m, for example, differences ranged from 0.09 MVF in the Fazenda Dimona pasture to 0.19 in the Ji-Paraná pasture. At 1.0 m depth, differences ranged from 0.08 in the Manaus forest to 0.33 in the Marabá forest, and at 2.0 m, from 0.05 in the Manaus forest to 0.28 MVF in the Marabá forest. Below 2.2 m the largest changes were in the Ji-Paraná forest. At all except the Manaus sites, there were significant changes of water content below a depth of 2.0 m, ranging from 0.09 to 0.22 MVF.

DISCUSSION

In the upper part of the observed profiles, the same minimum water content was seen each dry season. Here, the vegetation had the opportunity to extract all of the available water before the profile was rewetted and the lowest water content marks the abstraction limit. The highest measured water contents are likely to have been between "field capacity" (when drainage becomes negligible, about -10 kPa matric potential) and saturation at all of the sites except at Ji-Paraná, where the highest water contents marked saturation below 1.2 m in the forest and below about 2.4 m in the pasture. The differences between the sites seen in the profiles of maximum water content change (Figure 4) therefore mainly reflect the differences in soil properties between the sites.

Of particular note are the very small seasonal changes of water content at the Manaus sites. It might be considered that this would have been the result of the shorter dry periods between rainfall events compared to the other sites, giving the vegetation less opportunity to take up stored water before the profile was rewetted. Although this determines the total change of storage within the profile, the very small changes of water content are due to the very low available water capacity (AWC) of this type of soil, despite its very high clay content. The low AWC has been shown by Correa (1984) and can be seen from the water release data presented by Ranzani (1980) and the mercury porosimetry curves of Chauvel *et al.* (1991). The low AWC has been discussed in more detail by Hodnett *et al.* (1995) who suggested that it is not advisable to predict the water content of these soils (e.g. at field capacity or wilting point) from their clay content using relationships derived originally from data for temperate soils.

The depth to which the extraction limit was reached depended on the vegetation and also on the rainfall amounts in, and duration of, the dry season. Inter-annual rainfall variability is high, and it is not known for the Marabá and Ji-Paraná sites how representative the seasonal profile storage changes observed during this study were of the normal, or whether abnormally wet or dry conditions were observed. Hodnett *et al.* (1996) examined the longer term context of the Manaus soil water record, addressing in particular the amount of water that might be taken up from below a depth of 2 m in drier years.

Deeper in the profile, the extraction limit was not reached, particularly at the pasture sites. At the forest sites, the fact that significant changes of water content occurred at 3.6 m late in the dry season indicates that root uptake, and not drainage, was mainly responsible. This, and the low rates of depletion in the forest profiles (Manaus, in particular) at this time, implies that uptake almost certainly occurs to greater depth. Several studies in Brazil have shown that the roots of rainforest trees can extend down to considerable depths.

Chauvel *et al.* (1992) found more roots at 6.0 m depth than at 3.0 m beneath forest near Manaus on almost identical soils to those at the ABRACOS Manaus site. Nepstad (1989) reported that mature forest on an oxisol at Paragominas (Pará, eastern Amazonia), can access soil moisture from at least 6 m depth and Nepstad *et al.* (1991 and 1994) found forest roots to 18 m depth in the same area. It is of note that all of this evidence of very deep rooting is from sites with oxisols, which have a very low water availability. Nepstad *et al.* (1994) found that in the severe 5.5 month dry season in 1992, more than 75% of the water for transpiration was supplied by the profile below 2 m depth. The mean evapotranspiration rate for this dry season determined from the water balance was 3.6 mm day^{-1}, which is very similar to the dry season values modelled by Shuttleworth (1988) for Reserva Ducke, near Manaus. These data appear to indicate that the forest at the Paragominas site was not suffering from soil water stress.

It has become clear from studies such as these that the roots of rainforest trees do penetrate and abstract water from deep in the soil profile. However, it is not known how much, or how often, deep abstraction is possible, nor whether the forest is stressed and transpiration rates are restricted when it occurs. This is extremely important because the reliable prediction of climate change depends strongly on this knowledge, particularly if longer dry seasons are likely in future. At present, there is no evidence from plant physiological or micro-meteorological measurements in ABRACOS that the forest transpiration rates decrease in response to lowered soil moisture (Roberts *et al.* 1996; Wright *et al.*, 1996). However, although the detailed plant physiological and micro-meteorological measurements were made under a wide range of soil water storage conditions, the study missions during which they were carried out did not coincide with the driest conditions observed during the weekly soilwater monitoring regime.

Increased leaf fall in the dry season may be an indication of soil water stress. However, although some forest species lose their leaves in the dry season, there is likely to be a compensating increase in transpiration from the lower canopy, which was previously shaded. This may result in only minor reductions in the transpiration rate from the forest as a whole.

An indication of the amount of deep uptake can be obtained from the data presented here. At the Marabá and Ji-Paraná forest sites, the mean uptake rates from the 3.6 m measured profiles at the end of the 1993 dry season, were 2.16 mm day^{-1} and 1.70 mm day^{-1} respectively. This was when the profile storage at both sites was close to the minimum measured during the study, and there was no readily available water in the upper profile following rainfall events. (Note that when the 3.6 m profile is treated as a single layer, a 30 mm rainfall input near the end of the dry season appears to have an insignificant effect on the profile storage. However, this input is in the zone with the highest concentration of roots and is therefore readily available. Stress conditions may be temporarily relieved despite a very large deficit remaining.)

If it is assumed that the forest was not stressed, and a dry season transpiration rate of 3.5 mm day^{-1} is taken (data from Shuttleworth, 1988), 38% and 51% respectively of the water requirements of the forest at the Marabá and Ji-Paraná sites, were being taken up from below 3.6 m depth at the end of the 1993 dry season. At the Marabá forest site, the proportion of water taken up from below 2 m depth at the end of the dry season varied from 48% in 1991 to 62% in 1992. It is not known how extreme these conditions were in the context of the longer rainfall record. These values are much lower than the 75% of uptake from below 2 m (for the entire dry season) found by Nepstad *et al.* (1994). This difference is almost certainly the result of the much lower water availability in the oxisol at the Paragominas site, where the average water content change over the 2 m - 8 m layer was 63 mm m^{-1}, compared to at least 150 mm m^{-1} at the Marabá site.

At the Ji-Paraná site, 6 of the 8 access tubes reached solid bedrock at depths of between 2.0 and 3.2 m. The unweathered rock probably has little ability to store water, and it is clear that the soil water reservoir at this site is probably limited compared to at the other sites. However, deep roots may find their way via cracks and fissures in the bedrock to reach the declining dry season water table.

At the pasture sites, there were significant reductions in transpiration rate as soil water deficits increased, but there were marked variations between the sites.

Hodnett *et al.* (1995) showed that the mean pasture evaporation rate at the Manaus (Fazenda Dimona) fell to 1.2 mm day^{-1} after the 2 m profile storage had decreased 130 mm from the maximum observed. There was little uptake below a depth of 1.5 m. At the Ji-Paraná site, the lowest evaporation rate was 2.50 mm day^{-1}, but this occurred after the 2 m profile storage had decreased 262 mm from the maximum observed. Uptake took place from at least 2.5 m depth. The Marabá site showed a very strong contrast; the evaporation rate fell to 0.61 mm day^{-1} after storage in the 2 m profile decreased 269 mm from the maximum. At this site the grass senesced almost completely and only a few scattered shrubs and stunted palms remained green. The very marked difference between the Marabá and Ji-Paraná pasture sites is partly due to the difference in water availability, but may also reflect the difference in response to water stress between the grass species. Nepstad *et al.* (1991) observed that *Panicum maximum* (the grass species at Marabá) is a nutrient demanding forage species and that in older pasture it suffers competition from less demanding shrub and grass species as nutrient stocks decline after clearance. The Marabá pasture is about 20 years old, and it is likely that nutrient levels are low, which may affect the stress response of the grass. Skerman and Riveros (1990) report that *Panicum maximum* does not tolerate severe drought and is the least drought tolerant of the species at the study sites.

The very large differences in soil water storage behaviour between sites clearly demonstrate the need to quantify and map the distribution of the water retention and hydraulic properties of Amazonian soils. In view of the depth to which abstraction can occur, these properties also need to be determined for the subsoil and soil parent materials, particularly in areas with a long dry season. Very few studies of the hydraulic properties of Amazonian soils have been made, and many more will be required to allow the SVAT sub-models of GCMs to be applied with confidence.

Extensive soil survey data (Projeto Radambrasil) are available, often to a depth of 3 m, covering texture (% sand, silt and clay), and in some cases bulk density, which allows an estimate of porosity to be obtained. Unfortunately, soils are not mapped on the basis of their hydraulic properties, but on a pedological basis, which includes soil-forming processes, texture, colour, chemical properties and parent material, among others. There are fairly well established means of estimating soil hydraulic properties from other, more commonly measured soil parameters, but all have been designed for temperate soils. There are strong indications that the oxisols studied so far have very different properties, which cannot be reliably predicted using these relationships. The derivation of similar relationships specifically for Amazonian soils is a priority, requiring widespread measurement of hydraulic properties on a range of soil types. These relationships can then be extrapolated to larger areas using the survey data.

In general, the soil classification is based mainly on the upper metre of the profile, with some account being taken of the properties to 2 m, or at most, 3 m. This means that later in the dry season, when stress is most likely, water is being taken up from layers which are hardly regarded as soil (parent material) and which are not, or only barely, included in the soil classification. In the case of Paragominas, more than 75% of the soil water deficit developed in the dry season was in material not regarded as soil. The hydraulic and water retention properties of these materials, usually saprolite (very weathered rock, or less weathered rock) are unknown as they are almost never sampled for soil mapping. It is not known how widespread saprolite is in the subsoils of Amazonia, but it is likely to occur commonly in the "shield" areas. It is unlikely to occur in areas with deep, unconsolidated sediments such as those of the Barreiras formation which lies to the north and south of the Amazon in the central part of the basin. The ABRACOS data provide some indications as to the properties to a depth of 3.6 m at the project sites, but otherwise they are virtually unknown.

SUMMARY AND CONCLUSIONS

There was a large difference in the seasonal variation of soil water storage between sites, determined by soil properties, vegetation cover, length of dry season and water table response. At all sites, there was a consistently larger seasonal variation beneath forest, compared to pasture.

The smallest seasonal storage changes occurred, as expected, at the Manaus sites, which have the shortest dry season. Here, the maximum seasonal change recorded to 2 m depth was 154 mm in the forest and 132 mm in the pasture. For the 3.6 m profile, the maximum change in the forest was 200 mm.

At the Manaus site, where data are available for 4 dry and 3 wet seasons, the driest conditions were observed at the end of the 1990 dry season for forest and pasture. Peak storage was similar in all wet seasons, but the duration of the very wet conditions was 2 months in the delayed and weak 1991/2 wet season, compared to 7 - 9 months in the other years studied.

The largest seasonal change occurred at the Marabá forest site where the change in the 3.6 m measured profile from the 1991/2 wet season to the driest observed, in the 1993 dry season, was 724 mm. The pasture change was 376 mm. The Ji-Paraná forest and pasture sites showed maximum changes of 701 mm and 450 mm respectively, but there was a major contribution from saturated drainage in these figures. The water table rose to within 1.2 m of the soil surface in the forest, and 2.4 m in the pasture. There appeared to be no water table influence at the Manaus plateau or Marabá sites. Water table behaviour must be taken into account in modelling data from sites such as Ji-Paraná.

The forest took up water from beyond 3.6 m at all sites, although in Manaus, this appears to have been necessary only because of the extremely low water availability in the oxisol at that site. On the other soils studied, 200 mm of water could have been readily supplied by less than 2 m depth of profile. At the end of the 1993 dry season, the profile below 3.6 m was estimated to have been supplying 1.34 mm day^{-1} (38%) and 1.80 mm day^{-1} (51%) respectively of the water for transpiration at the Marabá and Ji-Paraná sites. This was based on an assumed unstressed actual transpiration rate of 3.5 mm day^{-1}. Whether or not the transpiration from the forest as a whole is significantly reduced through soil water stress remains an open question.

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RESUMO

Em áreas experimentais (pastagem e floresta) de Marabá (Pará), Manaus (Amazonas) e Jiparaná (Rondônia), a umidade volumétrica do solo foi medida em várias profundidades até 3,6 m. São apresentados três anos de dados para os sítios de Manaus e dois anos para os demais.

Entre os sítios, devido a diferenças nas propriedades do solo, cobertura vegetal, duração da estação seca e comportamento do lençol freático, houve grande diferença

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Since there is significant uptake from the profile below 2 m, it is important to have soil hydraulic properties data from these layers for use in SVAT models. Very little, if any, data is available. There is an urgent need to obtain more data on these properties for all of the main soil types in Amazonia and in particular for their parent materials.

Soil water uptake in the pasture was strongly affected by the increasing soil water deficit. The least affected site was Ji-Paraná, where the end of dry season uptake rate was 2.5 mm day^{-1}, compared to 1.2 mm day^{-1} in Manaus and only 0.61 mm day^{-1} in Marabá. The grass species were different at all of the sites and it is not clear whether the differences were caused by this, or by differences in water availability.

The Marabá forest site was the only site where the profile did not wet up to the same extent each year during the period of study. The 1993 dry season began with 350 mm less water in storage then the 1992 dry season. There was little wetting below a depth of 2.5 m and a very significant deficit (in the measured profile, and probably also below) was carried forward into the next year. It is not known, at this stage of analysis, how frequent an occurrence this is.

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na variação sazonal do armazenamento de água no solo. A variação sazonal foi consistentemente maior na floresta, em comparação à pastagem. A menor variação ocorreu nos sítios de Manaus, os quais tiveram estação seca mais curta. Neste caso, a máxima variação registrada no perfil de 2 m foi de 154 mm para a floresta e de 132 mm para a pastagem. No perfil de 3,6 m, a máxima variação na floresta foi de 200 mm. A máxima variação na floresta de Marabá foi de 724 mm, o qual foi a maior variação registrada entre os sítios, e na pastagem, foi de 349 mm. A floresta e pastagem de Ji-Paraná apresentaram, como máxima variação, 701 mm e 511 mm, respectivamente, mas houve importante contribuição da drenagem saturada nesses valores. O lençol freático elevou-se até 1,2 m da superfície na floresta, e até 2,4 m na pastagem, o que indica a necessidade de se levar em conta o comportamento do lençol freático e o movimento lateral de água no solo nos resultados apresentados para Ji-Paraná. Nos sítios de Manaus e Marabá, parece não ter havido influência do lençol freático.

Houve extração de água abaixo de 3,6 m em todos os sítios de floresta. Apesar da variação sazonal do perfil ter sido pequena em Manaus, a retirada de água a maiores profundidades foi necessária devido à baixa disponibilidade do oxisol nesse sítio. Ao final da estação seca de 1993, estima-se que cerca 38% e 51% da água usada para transpiração, na floresta de Marabá e Ji-Paraná, respectivamente, provém do perfil abaixo de 3,6 m, assumindo-se a taxa de transpiração sem estresse de 3,5 mm d^{-1}.

A extração de água na pastagem foi fortemente afetada pelo déficit hídrico do solo. A pastagem de Ji-Paraná foi a menos afetada, com a taxa de extração de água, ao final da estação seca, de 2,5 mm d^{-1}, enquanto em Manaus foi de 1,2 mm d^{-1} e em Marabá, somente 0,61 mm d^{-1}.

A floresta de Marabá foi o único sítio onde não houve recarga completa do perfil na estação úmida. A estação seca de 1993 iniciou-se com um armazenamento 400 mm menor que a estação seca de 1992. Houve pequena recarga abaixo de 2,5 m e a estação seca subsequente iniciou-se com um déficit substancial (no perfil medido, e provavelmente abaixo). Não é sabido, até o presente, a frequência de ocorrência desse tipo de evento.