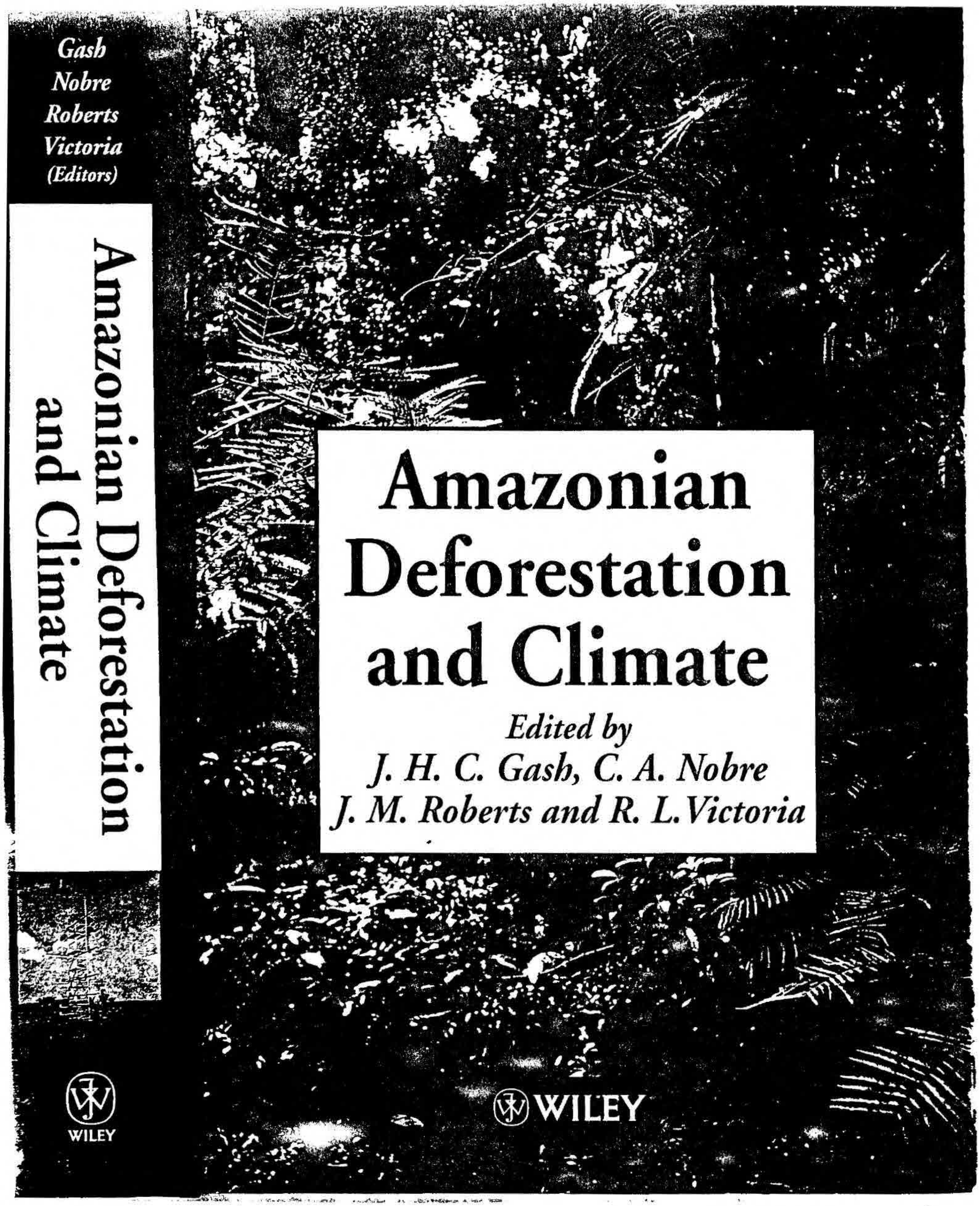

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28 Towards a GCM surface parameterization of Amazonia

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INTRODUCTION

Recent initiatives to improve models of soil, plant and atmospheric processes (Wilson and Henderson-Sellers, 1985; Lean and Rowntree, 1993; Manzi and Planton, 1994) and to calibrate model parameters accurately (Shuttleworth, 1988; Shuttleworth and Dickinson, 1989; Sellers *et al.*, 1989) have significantly improved the realism in models of land-surface processes (Sellers *et al.*, 1986; Warrilow *et al.*, 1986; Noilhan and Planton, 1989). These advances have made it possible to construct and compare plausibly modelled climate scenarios for forested and deforested Amazonia (Dickinson and Henderson-Sellers, 1988; Lean and Warrilow, 1989; Nobre *et al.*, 1991; Polcher and Laval, 1994; Manzi and Planton, 1996; Lean *et al.*, 1996). Generally, these simulations of deforestation have predicted increases in surface temperature and decreases in rainfall and evaporation when Amazonian forest is replaced with pasture.

Advances in climate modelling have identified that simulated regional and global climate can be very sensitive to the values of several key parameters describing the land surface (Mintz, 1984 and Garratt, 1993): particularly albedo (Charney, 1975; Sud and Fennessy, 1982; Lean *et al.*, 1996), aerodynamic roughness length (Sud and Smith, 1985; Dickinson and Henderson-Sellers, 1988; Sud *et al.*, 1988) and soil characteristics (Shukla and Mintz, 1982; Henderson-Sellers and Gornitz, 1984; Wilson *et al.*, 1987; Lean *et al.*, 1996). The importance of reliable surface parameterization for GCM evaporation estimates has been pointed out by several reviews (e.g. Mintz, 1984; Rowntree, 1991), including some with particular emphasis on the interpretation of hypothetical large-scale deforestation in tropical regions (Shuttleworth *et al.*, 1991; Henderson-Sellers, 1992), yet it is these remote areas

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which suffer most from a paucity of suitable information. Furthermore, Pitman (1993) has shown that not all studies agree on the relative importance of key parameters, and although this is partly due to the different models and methods of application, much uncertainty is removed with the use of accurate and representative parameters. It must partly be due to the enforced use of substitute parameters and the absence of validation data from remote places that so much effort has been spent on sensitivity studies.

Given this sensitivity of climate modelling to surface parameters, it is necessary that models should include the most accurate parameters if predictions are to be more plausible than in previous studies. Until now, Amazonian deforestation simulations have used parameters derived at a single location, Reserva Ducke, near Manaus, to describe the entire Amazonian forest, even though Amazonia encompasses regions with different soils, vegetations and climates. Furthermore, no data have been available to calibrate parameters for Amazonian pasture or to validate post-deforestation micro-climate. This is particularly unsatisfactory, for although a GCM may adequately describe the current forested climate, the modification of parameters, without the opportunity for model validation, cannot necessarily be expected to describe the deforested situation. Henderson-Sellers (1992) has demonstrated that compensating interactions between parameters within a particular GCM construction may create a fortuitously satisfactory current climate, yet could be quite unreliable once parameters have been changed: particularly albedo and aerodynamic roughness.

ABRACOS was established to satisfy these modelling requirements, by recording detailed measurements at both pasture and forest sites in three regions of Amazonia. Some of the results from ABRACOS fieldwork have been published, prior to this volume, on the following topics: pasture micrometeorology (Wright *et al.*, 1992), climate (Bastable *et al.*, 1993), biomass (McWilliam *et al.*, 1993); pasture surface conductance (Wright *et al.*, 1995) and albedo (Culf *et al.*, 1995), and parameters from these studies have already been used to improve GCM land surface sub-models (da Rocha *et al.*, 1996; Lean *et al.*, 1996; Manzi and Planton, 1996; Dias and Regnier, 1996). This paper aims to bring together the results obtained from the atmospheric, vegetation and soil disciplines of ABRACOS, enhanced where necessary by the results of other Amazonian research, to present a comprehensive tabulation of parameters for the GCM modelling community.

The parameters are divided into two groups under the following headings:

Vegetation parameters
a) Vegetation height and distribution
b) Rooting depth
c) Leaf area index
d) Albedo
e) Aerodynamic parameters
f) Bulk surface conductance
g) Forest rainfall interception

Soil parameters
a) Water release characteristics
b) Density and structure
c) Thermal properties
d) Spatial distribution of parameters

The vegetation parameters are assumed to be independent of soil type and need only be subdivided into pasture and forest subgroups. However, it is acknowledged that rooting depth is, at times, a function of soil type, especially in the transitional stage of pasture establishment after deforestation. No attempt is made to distribute or vary these parameters geographically.

The soil parameters relevant to four defined soil categories are geographically allocated to a 1°×1° grid map of Amazonia using various pedological sources. Where possible the parameters are presented for various depths to support the increasing number of Soil-Vegetation-Atmosphere Transfer Schemes (SVATS) that have multi-layer soil models. Only limited information is available concerning the modification of soil parameters when forest is replaced by pasture, and although some values and references are given in the text for this process, it is necessary to assume that all other soil parameters are independent of vegetation type.

FIELD SITES

The three ABRACOS field study areas, in which both forest and pasture sites were instrumented, were chosen to be representative of a range of typical Amazonian deforestation scenarios. The Manaus area, in central Amazonia, is predominantly forest whereas Marabá, in eastern Amazonia, is mostly pasture. The vegetation in the region of Ji-Paraná, south west Amazonia, comes between these extremes and is undergoing progressive deforestation (Gash *et al.*, 1996). The forest sites were all representative of *terra firme* forest which predominates in lowland Amazonia (Takeuchi, 1961; Pires, 1978). The pasture sites were considered representative of post-deforestation cattle ranches (Uhl *et al.*, 1988: Eden *et al.*, 1990), having been converted 10-15 years previously and sown with *Brachiaria* spp. and *Panicum* spp. pasture grasses (*B. decumbens, B. humidicola, B. brizantha, P. maximum*). Summaries of site and vegetation details are given by Gash *et al.* (1996) and Roberts *et al.* (1996) respectively. Further details of the vegetation at the various pasture and forest sites are given by Wright *et al.* (1992) and McWilliam *et al.* (1993) for Manaus, by McWilliam *et al.* (1996) for Ji-Paraná, and by Sá *et al.* (1996) and Salomão *et al.* (1991) for Marabá.

VEGETATION PARAMETERS

VEGETATION HEIGHT AND DISTRIBUTION

Pasture

Pasture heights were sampled at irregular time intervals throughout the year, by transects and randomly placed quadrats, and found to have an overall two year mean (and corresponding standard deviation) of 0.28 m (0.05 m), 0.58 m (0.12 m) and 0.76 m (0.24 m) for Fazenda Dimona (Manaus), Fazenda Nossa Senhora (Ji-Paraná) and Fazenda Boa Sorte (Marabá) respectively. Although the crop height surveys for Fazenda Dimona and Fazenda Nossa Senhora are biased towards the dry season months, grazing policy is an additional strong influence over the annual growth and senescence cycle. Crop height was very much less variable than green leaf area index (*q.v.*). At Fazenda Nossa Senhora the grass height at the end of the 1992 dry season had a mean value of 0.53 m (21 August 1992) yet had only reached a height of 0.60 m (9 April 1993) towards the end of the following wet season, while the green leaf area index was more than doubled.

The overall mean Amazonian pasture height is given in Table 1 as 0.53 m. However, in view of the relationship between pasture height and roughness length (see **Aerodynamic parameters**), and the importance of the latter in GCM estimates of surface fluxes (Sud and Smith, 1985; Dickinson and Henderson-Sellers, 1988), it would be clearly advantageous for GCMs to incorporate pasture height variability, assuming that the ability to make seasonal and geographic variations in pasture height becomes available in the models.

All pastures studied had significant areas of bare soil (see Figure 1), which were distributed on two spatial scales and occurred mostly for the following reasons. At a small scale, fertility and seasonal soil moisture constraints had prevented the grass from achieving a fully closed canopy since sowing. At Fazenda Nossa Senhora, even after 20 years, the inability of the grasses to spread, either by self-seeding or the subsurface development of rhizomes, left the original planting rows clearly visible (Figure 1b). At a larger scale, areas of open bare soil were the result of cattle tracks, termite activity and failed seed germination. At Fazenda Dimona overall canopy area was also limited by fallen tree trunks (3-5% of ground area) which had not been cleared or burnt since felling (Figure 1a). The areas of bare soil were 15%, 14% and 16% at Fazenda Dimona (including fallen trunks), Fazenda Nossa Senhora, and Fazenda Boa Sorte respectively, giving an overall mean value of 15%: this value appears in Table 1 as 85% canopy cover.

Forest

Mean canopy-top height of the forest at Reserva Ducke, Manaus, and Reserva Jaru, Ji-Paraná, was measured as 35 m and 30 m respectively. The canopy height at Reserva Vale do Rio Doce, Marabá, is more complex: the height of the closed canopy was typically only 25 m but the overall mean is increased by emergents, mainly Brazil nut trees (*Bertholletia excelsa*), typically 50 m tall (see Sá *et al.*, 1996). This is clearly illustrated in Figure 1c, and may be compared with the relatively uniform canopy-top at Reserva Ducke and Reserva Jaru shown in Figure 2a and 2b respectively. Therefore, although the mean canopy-top height at Reserva Vale do Rio Doce is about 35 m, it is questionable whether conventional near-surface aerodynamic theory or 'big leaf' models of radiation interception, energy partitioning and stomatal behaviour, based upon data from an AWS placed at 52 m, can be expected to model this particular type of forest structure successfully. Mean canopy top height appears in Table 1 as 33 m.

Canopy cover, for estimates of surface fluxes, is given in Table 1 as 100%.

However, for the purposes of rainfall interception modelling, the amount of rainfall reaching the ground without impacting the canopy is estimated as the fraction of sky seen from the ground. This fraction has been measured at the three forest sites and found to be 0.08 at Reserva Ducke (Lloyd *et al.*, 1988), and 0.031 and 0.044 at Reserva Jaru and Reserva Vale do Rio Doce respectively (Ubarana, 1996). The average value of 0.052 appears in Table 1 as the 'free throughfall' fraction, and also as 94.8% canopy cover.

ROOT DEPTH

There is mounting evidence that rooting depths have been underestimated in GCM simulations of forest and pasture root extraction of soil moisture. Furthermore, Wilson *et al.* (1987) showed a sensitivity to a doubling of total soil depth over only 10 days of GCM simulation. It is also important to consider the definition of rooting depth in relation to the intended application. A distinction should be made between (a) the depth of soil in which the vast majority of roots may lie, (b) the effective rooting depth for modelling (which may be deeper) and (c) the depth at which live roots may be discovered by digging (which is very much deeper still). Before ABRACOS, the deepest rooting depths so far used in GCM simulations have been 1.0 m for pasture and 2.0 m for forest (Dickinson and Henderson-Sellers, 1988).

Pasture

For pasture, neutron probe data (Hodnett *et al.*, 1995) show clear root extraction below 1.0 m depth at Fazenda Dimona, and Wright *et al.* (1995 and 1996) have calculated effective rooting depths of 1.5 m and 2.0 m for Fazenda Dimona (Oxisol, 65-80% clay) and Fazenda Nossa Senhora (Podsol, 10-35% clay) respectively. These were defined as the depths in which 95% of soil moisture changes had occurred over a two year period. Digging revealed live roots at 3 m depth at both of these ABRACOS pasture sites.

Forest

There is strong evidence for soil water extraction by deep roots which penetrate below depths of 3.5 m at all ABRACOS forest sites (e.g. Hodnett *et al.*, 1995). Similarly, during a dry season event in eastern Amazonia, Nepstad *et al.* (1994) observed that more than 75% of root water extraction occurred between 2 m and 8 m depth and estimated that 'most of the eastern and southern half of the Amazonian closed-canopy forest ... must rely on water uptake from deep soil'. Uhl (1988) has shown that forest root depths may reach 10 m and Nepstad *et al.* (1994) have observed roots at approximately 18 m. Micrometeorological studies have not shown any significant decline in forest transpiration during periods without rain (Wright *et al.*, 1996). Until soil-moisture-induced stress can be shown for tropical forests, it must be assumed that there is no quantifiable limit to the ability of the trees to obtain water for sustained transpiration, and therefore, the effective rooting depth for modelling must be represented by a sufficiently deep reservoir of available soil water, whose

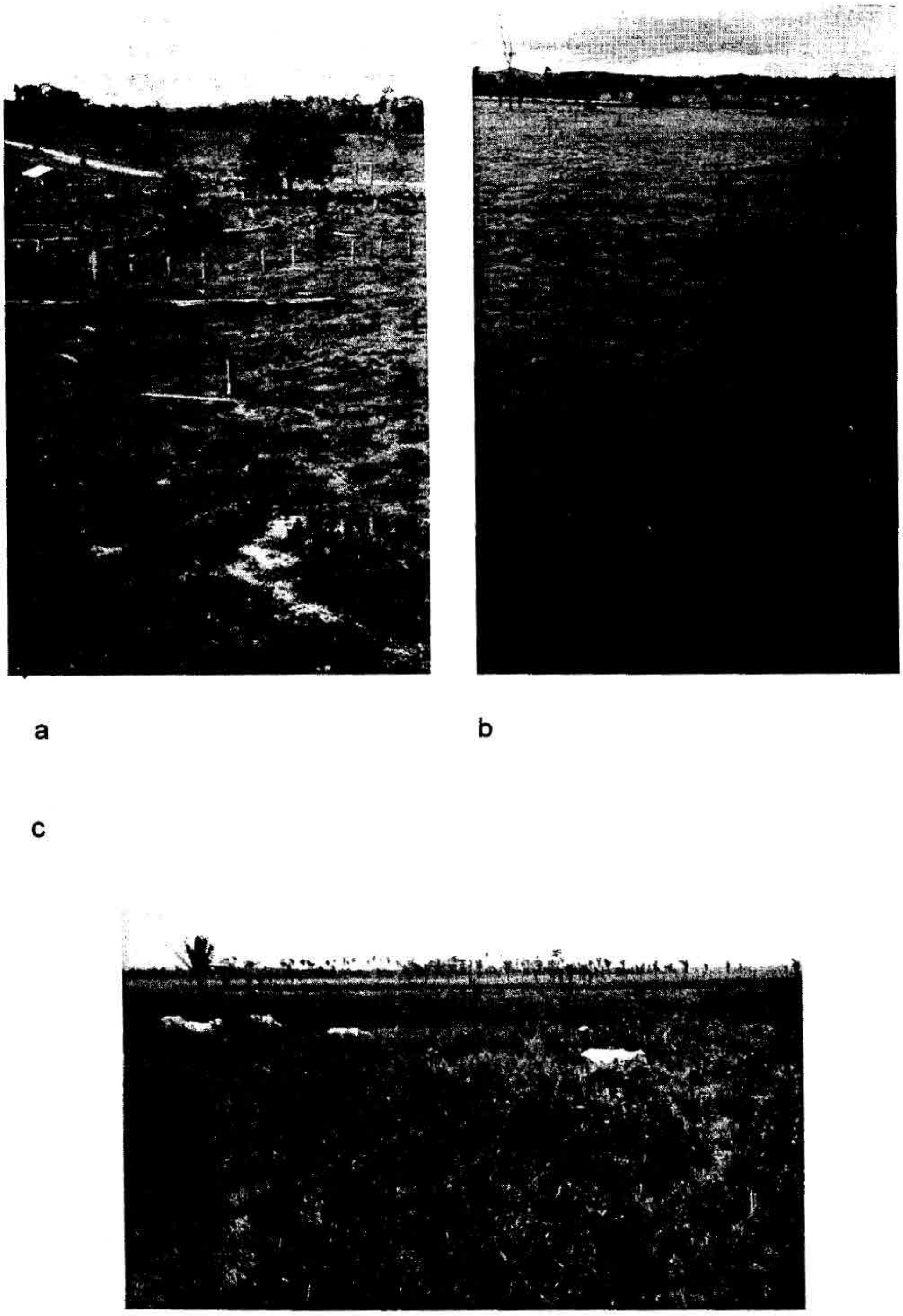

Figure 1 Photographs of the ABRACOS pasture sites at (a) Fazenda Dimona, Manaus (b) Fazenda Nossa Senhora, Ji-Paraná (c) Fazenda Boa Sorte, Marabá

Figure 2 Photographs of the canopy top at (a) Reserva Ducke, Manaus (b) Reserva Jaru, Ji-Paraná (c) Reserva Vale do Rio Doce, Marabá

minimum depth is related to the water retention characteristics of the specified soil.

LEAF AREA INDEX

Pasture

Total green leaf area index (leaf and stem), L*, at the pasture sites was estimated by destructive sampling within randomly selected areas of 0.25 m^2 within the study site (Roberts *et al.*, 1996). Each estimate is the mean of between 10 and 12 samples. Values of L* for various months of the year are given in Table 2 of Roberts *et al.* (1996) for the three ABRACOS pasture sites. At Fazenda Dimona a single measurement was made during 1990 in the middle of a particularly dry period. The value, 1.22 ±0.61, is probably close to the lowest likely L* for this site. Fazenda Nossa Senhora has much higher values in both wet and dry seasons. At Fazenda Boa Sorte, L* was not high even though a considerable proportion of the leaf area comprises regenerating shrubs which had developed since the last burning event two years previously.

It is interesting to note that Fazenda Boa Sorte has lower L* values than either of the other ABRACOS pasture sites, yet it has the tallest grass (Figure 1c). This point is also referred to with respect to albedo (*q.v.*). With the exception of surface roughness, many of the pasture state variables discussed below are independent of grass height.

Clearly, representing Amazonian pasture with a single mean value of L* could obscure important seasonal variations and site differences. Also the limited spatial, annual and inter-annual sample presented here, weakens the justification for calculating such a value. However, the range of L* values from the sites with the largest and smallest values provides valuable information for GCM modelling: 0.49-1.64 at Fazenda Boa Sorte and 1.55-3.90 at Fazenda Nossa Senhora. If future GCMs include a spatial distribution of L*, the above ranges will enable simple modelling of a basic annual cycle. Such a cycle could be timed to correlate with the geographically variable dry season and be linked to models of plant growth and senescence, and changes in albedo (*q.v.*). From the two sites, Fazenda Nossa Senhora and Fazenda Boa Sorte, the average maximum and minimum values of L* are 2.7 and 1.0 respectively: the latter also being close to the minimum of L*=1.2 at Fazenda Dimona.

Great care is needed when using L* in models of bulk surface conductance, such as that described by Jarvis (1976). If L* is used as an independent multiplier to modify bulk conductance per unit leaf area (see **Bulk surface conductance**), the large range of pasture leaf areas shown here will generate a proportionally large range of conductances, and consequently have a marked effect on evaporation. Stewart and Verma (1992), and Shuttleworth *et al.* (1989) also found that a large range of L* values did not greatly affect bulk vapour fluxes from tall grass prairie in Kansas, USA. Until more is known about the negative feedback by self-shading of a canopy, effective bulk surface conductance (per unit ground area) should be used for pastures having a leaf area index greater than a specified threshold. Values of this threshold, ranging from 2-3, have been suggested by Rosenberg *et al.* (1983), Schulze *et al.* (1994) and supported by Wright *et al.* (1996) (see also **Bulk surface conductance**).

Forest

McWilliam *et al.* (1993) obtained a leaf area index of 5.7 ± 0.6 by destructive sampling of a 20 m x 20 m mature forest plot near Manaus, and Roberts *et al.* (1996, Table 1) provide two other estimates for this region. The first was derived from literature values of foliage fresh weight biomass and its vertical distribution (Roberts *et al.*, 1993; Klinge, 1973; Klinge *et al.*, 1975). This information was converted into a vertical profile of leaf area indices using assumptions about the specific leaf area and the ratio of leaf fresh weight to dry weight. The total L* was around 15 per cent greater than the measurement of McWilliam *et al.* (1993), but had the same vertical distribution. The second method (Roberts *et al.*, 1996) used the annual cumulative leaf litter area as an estimate of total canopy L*, giving an estimate of 6.1.

It still remains to be shown whether the estimation of L* from annual litter fall is a valid approach in tropical rain forest. Nevertheless, this method was used at Reserva Jaru and Reserva Vale do Rio Doce and gave values of 4.6 and 5.4 respectively. The estimate for Reserva Jaru is nearly identical to that independently estimated by Grace (Pers. Comm.) using a gap fraction approach. The mean L* from the three sites, based on the leaf litter and destructive sampling methods, is therefore 5.2 with a range of ±0.5. However, as discussed by Roberts *et al.* (1996), the very different leaf distributions and canopy complexities may require that a less simplistic approach be adopted: perhaps a more meaningful value of active leaf area should be defined which takes account of leaf distribution, light interception and canopy conductance.

ALBEDO

Culf *et al.* (1995) have presented between two and three years of albedo data from all ABRACOS forest and pasture sites. Overall mean albedos were found to be 0.180 and 0.134 for the pasture and forest respectively, numerically closer to each other than the average albedos used previously to represent these biomes: for example, 0.19 for pasture (Wilson and Henderson-sellers, 1985) and 0.123 for tropical forest (Shuttleworth *et al.*, 1984). Culf *et al.* (1996, Figure 3) illustrate the average seasonal trend in both forest and pasture, and these data are reproduced in Table 1.

For the forest sites, the seasonal variation was shown to be correlated with soil moisture. Care was taken to ensure that solar angle, cloudiness and the shadow or reflectance of the instrument tower were not influencing this result. It was concluded that seasonal changes in leaf reflectance were being detected, probably associated with leaf dehydration and changes in leaf angle.

At the pasture sites, Culf *et al.* (1995) concluded that, notwithstanding the seasonal changes in pasture growth and decay, there was no dependable cycle of monthly albedo on a seasonal basis. However, combining the specific monthly albedo data from Culf *et al.* (1995) with the leaf area index data taken from Roberts *et al.* (1996) revealed a relationship, shown in Figure 3, which appears to be reasonably site-independent and suggests several interesting points.

The albedo appears independent of grass height. Comparing Fazenda Dimona and Fazenda Boa Sorte: these sites are shown to have similar albedos (Figure 3) yet they have the shortest and tallest grass: 0.28 m and 0.78 m respectively (see Figure 1).

Low values of albedo, resulting from low L*, can be attributed to a higher proportion of dead leaves and greater soil exposure: assuming that the soil albedo is significantly lower than that of the green vegetation. However, wet soil albedo is very much lower than that of dry soil (Idso *et al.*, 1975; Allen *et al.*, 1994) and if soil moisture were influential its effect would be to lower the albedo at higher L* during the wet season. This is illustrated in Figure 4 where albedos after rainfall are shown for high and low L* at the two sites with contrasting leaf areas, Fazendas Nossa Senhora and Boa Sorte. When leaf areas are low at both sites during the dry season (Figures 4a and 4b) there is a small influence from preceding rainfall, yet the mean albedo at these times is lower than at high leaf areas (Figures 4c and 4d) and contrary to a notional influence from seasonal soil moisture status. When leaf area is high, the effect of rain and wet soil is undetectable, even though the high L* at Boa Sorte is similar to the low L* at Nossa Senhora. Therefore, it may be concluded that dead leaf material has a low albedo and is mostly responsible for the seasonal variations in pasture albedo. It should be noted in Figure 4, that some of the low albedos during the early morning and late afternoon are associated with overcast conditions.

Albedo at Fazenda Nossa Senhora shows an insensitivity to L*, which, when combined with data from the other sites, suggests no further increases in albedo above values of L* of about 2-3. This value is similar to the values of L* above which it has been suggested that canopy self-shading begins to occur and bulk surface conductance ceases to be linearly related to L* (Rosenberg *et al.*, 1983; Schulze *et al.*, 1994; Wright *et al.*, 1996).

In future studies, it may be possible to introduce a physically based relationship between composite albedo and L* into GCMs. Furthermore, because of the independence of L* from grass height, this study suggests that the relationship between L* and albedo, together with the maximum surface conductances associated with L* (see **Bulk surface conductance**) can be used independently from grass height and the aerodynamic parameters (*q.v.*). This is a particularly relevant result to GCM deforestation experiments and sensitivity studies, as it helps to reduce the uncertainty associated with the interdependence between L* and z_0: an interaction specifically identified by Henderson-Sellers (1992).

In addition to these natural trends, changes in albedo caused by pasture burning have been reported by Fisch *et al.* (1994). In a single burning event at Fazenda Boa Sorte, albedo was reduced from 0.19 to 0.10, and the subsequent recovery to a value of 0.19 took 11 weeks. This burning event is shown to constitute a small but significant perturbation in the seasonal energy balance.

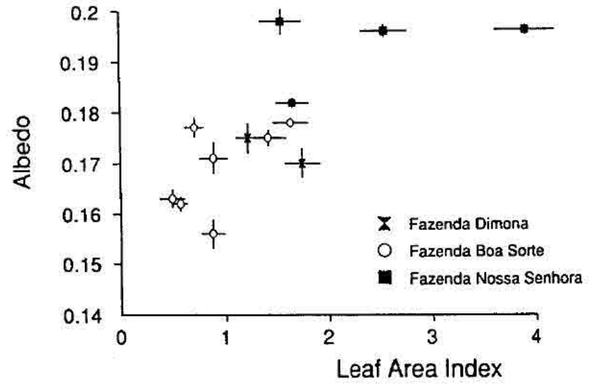

Figure 3 Monthly mean albedos from the three pasture sites plotted against the value of Leaf Area Index measured during that month.

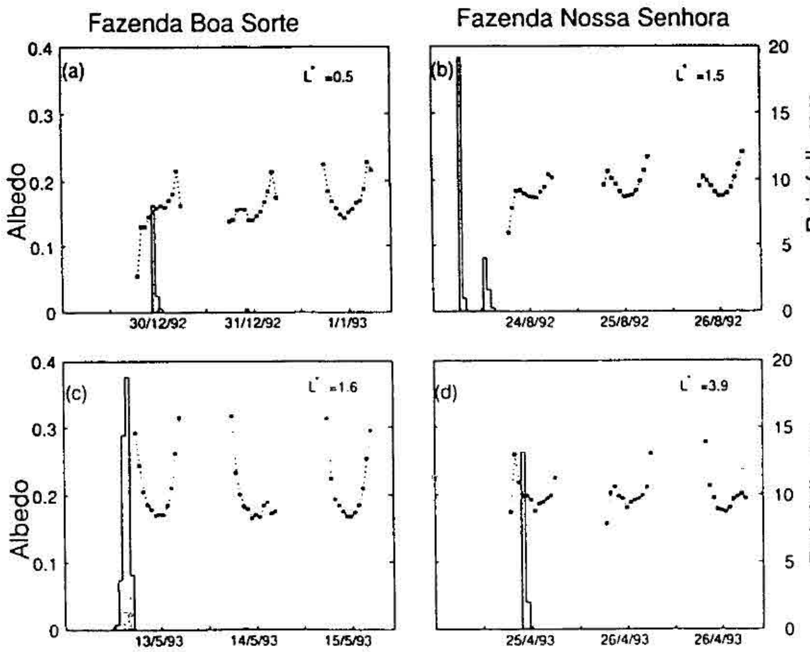

Figure 4 Diurnal changes in albedo (dotted lines) following rainfall (shaded bars) at the Marabá and Ji-Paraná pasture sites representing periods of high and low leaf area index at each site.

AERODYNAMIC PARAMETERS

Pasture

All values of roughness length, z_0, and zero plane displacement, d, have been derived from the momentum flux equation which states that under conditions of neutral buoyancy, wind-speed, u_z, is proportional to the logarithm of height, z, above the zero plane displacement,

$$\frac{ku_z}{u_*} = \ln\left[\frac{z-d}{z_0}\right] \tag{1}$$

where u_* is the friction velocity and k is von Karman's constant, taken as 0.41.

Pasture roughness parameters for Fazenda Dimona and Fazenda Nossa Senhora were calculated from a 9 m high profile of anemometers and thermometers. Full details of the method are given by Wright *et al.* (1992) together with the derivation of d and z_0 for Fazenda Dimona during the 1990 field season: d = 0.17 ±0.03 m and z_0 = 0.026 ±0.003 m. During the 1991 field season the mean values of d and z_0 were not significantly different to those of 1990: d = 0.19 ±0.03 m and z_0 = 0.025 ±0.003 m.

Unlike Fazenda Dimona, where the wind came predominantly from one direction with an uninterrupted fetch of 900 m, at Fazenda Nossa Senhora there was no predominant wind direction and patches of 8 m high palm trees necessitated careful placement of the instruments. Of the hourly mean windspeeds greater than 1.0 m s^{-1}, 62% came from the northern and southerly sectors, totalling 130 degrees of arc: the remaining winds came mostly from an easterly direction (27% within 110 degrees of arc). The tower was placed to minimise the effect of these limitations and only 26% of winds over 1.0 m s^{-1} came from directions having a fetch that was interrupted by palms or the instrument tower. There were no palms closer than 150 m in any direction. The fetch in the northerly and southerly directions was level uniform pasture extending for at least 1000 m.

Using only hours in which the wind came from a fetch of uninterrupted pasture, the overall mean values of d and z_0 for Fazenda Nossa Senhora were found to be 0.38 ±0.09 m and 0.064 ±0.011 m respectively for the 1992 field season: 76% and 13% of the grass height. For the 1993 field season the overall mean value of d and z_0 were found to be 0.40 ±0.07 m and 0.064 ±0.008 m respectively: 67% and 11% of the grass height respectively. An estimate of z_0 from the wind sectors containing the scattered palm trees was 3% higher, but this difference is not significant, even at the 99% level of confidence.

At Fazenda Boa Sorte wind profile data were not available and it was necessary to use turbulent flux data recorded by the 'Hydra' eddy correlation device (Shuttleworth *et al.*, 1988). These data yield a value for u/u_* and hence $\ln[(z-d)/z_0]$ but do not allow evaluation of d or z_0 separately. However, when z is very much larger than d, the derivation of z_0 is insensitive to the value of d and a value of z_0 may be estimated within a reasonable margin of error by applying limits to d with respect to the vegetation height, h_c (Gash, 1986). Using d = 0.6 h_c, z_0 was estimated as 0.085 m and assigned an error of 0.02 m with regard to the various errors associated with the measurement of u/u_* and grass height.

Figure 5 shows the values of pasture roughness length from all sites, with error bars, plotted against the mean vegetation height. Also shown is the weighted mean relationship

$$z_0 = 0.101\ h_c \tag{2}$$

which is identical (to two decimal places) to the commonly accepted relationship of $0.10h_c$. Comparing Figure 5 with the albedos in Figure 3 there is no clear relationship between roughness length and either leaf area index or albedo. In particular, the pastures which represent the extremes of height and roughness, Fazenda Dimona and Fazenda Boa Sorte, have very similar albedos. As already discussed (under **Albedo**) this suggested independence is specifically relevant to GCM deforestation and sensitivity studies.

Forest

At the Reserva Ducke forest site no estimates of zero plane displacement or roughness length were made during the current project due to the previous extensive work by Molion and Moore (1983), Shuttleworth (1988) and Sellers *et al.* (1989). Here we take the values published by Shuttleworth (1989): $d = 30.1$ m ($0.86\ h_c$) and $z_0 = 2.1$ m ($0.06\ h_c$).

For the Reserva Vale do Rio Doce site, flux data were recorded for only a short period and there proved to be insufficient data to derive a well defined relationship between windspeed and friction velocity. Indeed, in view of the complex structure of the Reserva Vale forest canopy (Figure 2c) and the position of the instrument tower close to an emergent tree, it is likely that considerable data would be necessary to investigate the roughness characteristics of this site, and also likely that it might prove impossible to explain the observed momentum fluxes using conventional formulae.

For the best estimate of roughness for the Reserva Jaru forest, the 'Hydra' data were combined with independent data from a 'Solent' eddy flux system (see Grace *et al.*, 1996) operating concurrently on the same tower for carbon dioxide flux measurements. After filtering for wind direction, neutral stability and windspeeds greater than $0.5\ \text{ms}^{-1}$, 461 and 197 hours of momentum flux data were selected from

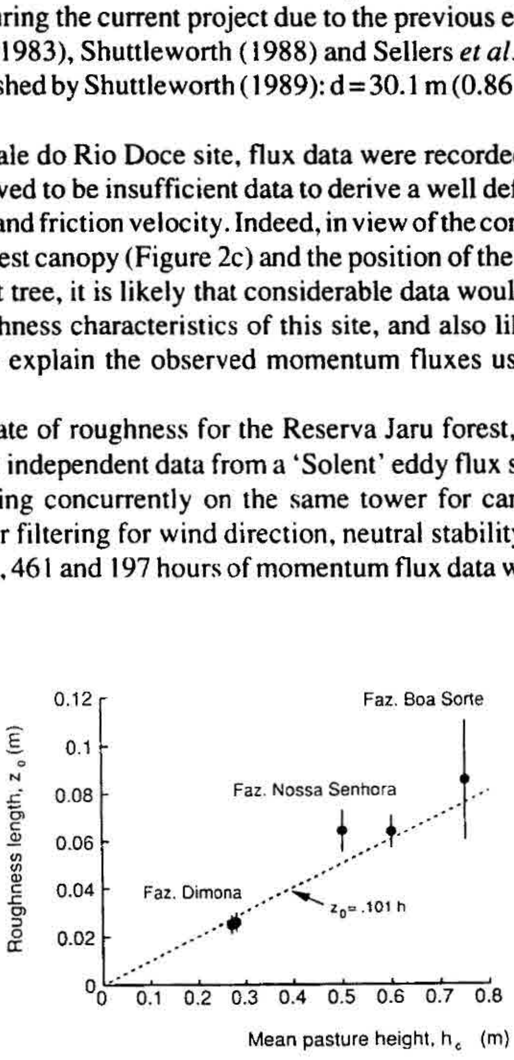

Figure 5 Zero plane displacement from all three pasture sites plotted against vegetation height.

the 1993 Hydra and Solent system data respectively. As d is of comparable size to the instrument height, it is not possible to evaluate d or z_0 separately. However, using the relationships $u/u_* = 0.173$ derived from the combined measurements and $d = 0.86\ h_c$ (25.8 m) from Shuttleworth (1989), and imposing an error of ±0.1 h_c on d, z_0 for the Reserva Jaru forest is estimated as 2.6 ±0.3 m. This value is higher than the 2.1 m observed at Reserva Ducke and raises the mean (two site) Amazonian roughness length to 2.35 m.

In terms of the commonly used height, z, and windspeed, u_z, dependent relationship for $g_{a,z}$, the aerodynamic conductance,

$$g_{a,z} = \frac{u_z}{f_z}, \tag{3}$$

where

$$f_z = \left[\frac{1}{k}\ln\left(\frac{(z-d)}{z_0}\right)\right]^2 \tag{4}$$

The value of f_z for use with AWS data at each site is 22.8 (z-d = 14.9 m) and 33.4 (z-d = 27.7 m) for Reserva Ducke and Reserva Jaru respectively. However, the difference between these two f_z values is misleading because of the different measurement heights, and masks the fairly similar roughness of the two sites. For a common reference height of, say, (z-d) = 25 m, $f_z = 36.5$ for Reserva Ducke and $f_z = 0.5$ at Reserva Jaru. When using Equation 3 to estimate aerodynamic conductance, it is important to calculate the correct value of f_z to match the windspeed reference height.

BULK SURFACE CONDUCTANCE

Evaporation measurements from both forest and pasture sites near Manaus and Ji-Paraná have been used to calibrate a Jarvis-type model (Jarvis, 1976) of surface conductance for each of the four sites. These results are described in detail by Wright *et al.* (1995 and 1996). Two calibrations are presented: the first is for use with reference (measurement) height data, and although site specific, gives the most accurate estimate of transpiration at the calibration site. The second calibration, which uses calculated canopy level climate, is much less site specific and may be used for comparison between sites and to derive a general calibration for Amazonia. Although both parameter sets are shown in Table 1, only the latter calibration should be used in GCMs. The reference level sets are provided for use at the sites at which they were derived, and have the advantage of avoiding the necessity to estimate the climate within the canopy.

The definition of the stomatal conductance parameters, a_1 - a_5, and the form of the equations in which they appear are given elsewhere in this volume by Wright *et al.*

(1996). However, it should be noted that there are different conventions for the parameterization of a_1, which in this study and Wright *et al.* (1996) is defined as the maximum bulk stomatal conductance *per unit ground area*, $L^* g_{s,Max}$. This definition is necessitated by the non-linearity between a_1 and L^*, especially when pasture $L^* > 2$. Many studies, including Wright *et al.* (1995), exclude L^* from a_1, equating a_1 to the maximum bulk stomatal conductance *per unit leaf area*, and also use leaf area index without the inclusion of green stem area. This study, and Wright *et al.* 1996, use L^* equal to the total green leaf (and stem) area index as given by Roberts *et al.* (1996, Table 2).

Pasture

The similarity between conductance parameters a_2 - a_5 for the two pasture sites (see Wright *et al.*, 1996) is sufficiently good for the calibration from one of the sites, Fazenda Nossa Senhora, to be placed into Table 1 to represent Amazonia. Maximum stomatal conductance per unit ground area, a_1, has been given a constant value of 43.0 mm s^{-1}: representing pastures having a leaf area index L^* greater than about 2. The calibrations at Fazenda Nossa Senhora suggest that there is little change in a_1 above $L^*=2$. However, for L^* values lower than 2, $g_{s,Max}$ can be made equal to 21.5 mm s^{-1} as a constant of proportionality (i.e. $a_1 = 21.5\ L^*$). This would give a value of $a_1=32.3$ mm s^{-1} for Fazenda Dimona, which is fairly consistent with the 27.1 mm s^{-1} optimised for that site (Wright *et al.*, 1995). New theoretical work on the relationship between bulk surface conductance, L^* and $g_{s,Max}$ is becoming available (Kelliher *et al.*, 1995; Schulze *et al.*, 1994), however much more field data is needed to calibrate this work. The relationship between L^* and $g_{s,Max}$ is clearly an important component in the modelling of seasonal pasture development and evaporation flux.

For a global value of the soil moisture parameter, a_5, a normalised value is derived, $a_{5,G}$, with respect to the available soil moisture of the different soils, thus

$$a_{5,G} = \frac{a_5 - \theta_r}{\theta_{sat} - \theta_r} \tag{5}$$

where θ_r and θ_{sat} are the residual and saturation soil moisture contents respectively. The normalised parameter was found to be consistent between the two Amazonian pasture sites, especially during similar seasonal conditions (Wright *et al.*, 1996). When soil moisture was decreasing during the dry season, $a_{5,G}$ was estimated as 0.68 and 0.66 at Fazendas Dimona and Nossa Senhora respectively. During a period of increasing soil moisture at Fazenda Nossa Senhora, this critical soil moisture parameter was lower: $a_{5,G} = 0.50$. Wright *et al.* (1996) suggest that this hysteresis can be expected when representing the soil as a single layer without regard for the root distribution, and recommend a mean value of $a_{5,G} = 0.58$. Winkworth (1970) suggested a value of $a_{5,G} = 0.50$ for a grassland site in Australia (Lat. 23°S) where the soil was a Red Earth (Soil type 3 in **Spatial distribution of parameters** below).

Forest

For forest conductances, Wright *et al.* (1996) showed that, when using the site calibration from Reserva Ducke to predict evaporation from Reserva Jaru, the evaporation estimate compared moderately well with observations even though some of the parameters were very different. The parameters associated with solar radiation and temperature were similar, but those for humidity deficit and maximum conductance were different in magnitude yet mutually compensating when their influences are combined. This result may be caused either by interdependence between parameters or physiological differences between forests producing similar vapour fluxes from a different combination of climatic interactions. Although some parameter interdependence is unavoidable with the calibration method used by Wright *et al.* (1996), there is evidence from leaf conductance measurements at the Reserva Ducke and Reserva Jaru (Roberts *et al.* 1996), and for temperate forest by Hall and Roberts (1989), that forests having a wide species diversity can also have a wide range of reactions to climate variables. Wright *et al.* (1996) show a similar relationship to Roberts *et al.* (1996) and Hall and Roberts (1989) where species with a high maximum conductance have a rapid response to humidity deficit and *vice versa*. Furthermore, these studies show that the different, but compensating, responses to humidity at each site converge to give similar conductances at or around the predominant humidity deficits measured above the forest. Clearly, as larger vapour fluxes coincide with larger humidity deficits, it is not surprising that the calibrations are almost interchangeable. It is important to note that it is the calibrations (parameters sets) that are interchangeable and not the individual parameters, especially in view of the likely sensitivity of GCM representations of Amazon forest to the humidity deficit parameter (Sellers *et al.*, 1989).

Table 1 contains the forest calibration representative of all available data for Reserva Jaru. This set is chosen to represent tropical forest as it is the most comprehensive calibration based on canopy level climate. The only justifiable adjustment to this calibration would be for forests of a different leaf area index. However, this is not to suggest that the influence of L^* is necessarily linear. The reader is referred to Dolman *et al.* (1991) and Wright *et al.* (1996) for details of other calibrations.

FOREST RAINFALL INTERCEPTION

Measurements of throughfall and stemflow at the Reserva Jaru and Reserva Vale do Rio Doce forest sites have been used to derive the canopy and trunk storage capacities, and the proportions of rainfall diverted to the trunks and reaching the ground without impacting the canopy (the 'free throughfall' parameter). This work is described fully by Ubarana (1996). The experimental design was based on the earlier work of Lloyd *et al.* (1988) at the Reserva Ducke forest site and assumes a Rutter-type model of canopy water dynamics (Rutter *et al.*, 1971). Combining the results of Ubarana (1996) and Lloyd *et al.* (1988), mean interception parameters have been calculated as follows (values in parentheses are for Reservas Ducke, Jaru and Vale do Rio Doce, respectively): canopy capacity, 1.01 mm (0.74 mm, 1.03 mm, 1.25 mm); 'free throughfall' fraction, 0.052 (0.080, 0.031, 0.044); trunk storage capacity, 0.11 mm (0.15 mm, 0.09 mm, 0.10 mm) and the proportion of rainfall that is diverted to the trunks as stemflow, 0.023 (0.036, 0.010, 0.023). The mean values appear in Table 1 as representative of Amazonian *terra firme* forest.

No parameters have been derived for the process of evaporation of intercepted rainfall from the pasture sites.

SOIL PARAMETERS

WATER RELEASE CHARACTERISTICS

Table 1 Amazonian vegetation parameters
Parameters that are not derived in this paper are accompanied by the relevant reference

	Pasture		Forest
Vegetation height (m)			
Faz. Dimona (Wright *et al.*, 1992)	0.28	Res. Ducke (Shuttleworth *et al.*, 1984)	35
Faz. Nossa Senhora (McWilliam *et al.*, 1996)	0.58	Res. Jaru (Roberts *et al.*, 1996)	30
Faz. Boa Sorte (Sá *et al.*, 1996)	0.76	Res. Vale do Rio Doce (Sá *et al.*, 1996)	20-50(1)
Mean vegetation height	0.53		33
Canopy cover (%)	85		100 (94.8(2))
Rooting depth (m)	1.5-2.0 (Wright *et al.*, 1995,1996)		>4.0(3)
Green leaf area index	1.0-2.7(4) (See also Roberts *et al.*, 1996)		5.2 (McWilliam *et al.*, 1993; Roberts *et al.* 1996)

Notes

1 Complex canopy structure, see **Vegetation height and distribution: *Forest***
2 94.8% of rainfall impacts the canopy for interception modelling
3 No soil/plant stress has yet been identified under forest, see **Root depth: *Forest***
4 Mean annual minimum and maximum
5 h_c = mean canopy height
6 Maximum conductance per unit ground area, $L^*g_{s,Max}$
7 When pasture $L^* < 2$ then $a_l = 21.5L^*$, see **Bulk surface conductance: *Pasture***
8 a_s = Site specific critical soil moisture content
9 $a_{s,G}$ = Normalised critical soil moisture content, $(a_s - \theta_r)/(\theta_{sat} - \theta_r)$

Table 1 Amazonian vegetation parameters (continued)

	Pasture	Forest
Albedo *Month*		
(Culf *et al.*, 1995, 1996)		
January	0.175	0.126
February	0.171	0.123
March	0.181	0.121
April	0.184	0.124
May	0.187	0.132
June	0.186	0.139
July	0.192	0.141
August	0.187	0.144
September	0.171	0.142
October	0.172	0.143
November	0.177	0.141
December	0.180	0.134
Mean albedo	0.180	0.134
Zero plane displacement$^{(5)}$ **(m)**	$0.66h_c$ (See also Wright *et al.*, 1992)	$0.86h_c$ (Shuttleworth, 1989)
Roughness length$^{(5)}$ **(m)**	$0.10h_c$	2.35

Surface conductance

For use with reference height climate

	Site		Site	
	Faz. Dimona	Faz. N. Senhora	Res. Ducke	Res. Jaru
	(Wright *et al.*, 1995 & 1996)		(Dolman *et al.*, 1991)	(Wright *et al.*, 1996)
$a_1^{(6)}$ mm s^{-1}	30.7	33.1	20.8	65.2
a_2 kg g^{-1}	0.0369	0.1127	0.064	0.1064
a_3 °C	-	-	30.2	44.6
a_4 W m^{-2}	470	671	250	743
a_5 $m^3 m^{-3}$	$0.428^{(8)}$	$0.259^{(8)}$	-	-

For use with canopy climate (Wright *et al.*, 1996)

	Pasture	Forest
$a_1^{(6)}$ mm s^{-1}	$43.0^{(7)}$	80.1
a_2 kg g^{-1}	0.0821	0.1248
a_3 °C	-	44.2
a_4 W m^{-2}	17280	3916
$a_{5,G}$ $m^3 m^{-3}$	$0.58^{(9)}$	-

Forest interception

(See also Ubarana, 1996)

	Pasture	Forest
Canopy capacity (mm)	-	1.01
Free throughfall fraction	-	0.052
Trunk storage (mm)	-	0.11
Fraction of rain to trunks	-	0.023

Notes — see previous page

Water release model

The model of soil water release characteristics (van Genuchten, 1980), for which parameters have been derived for the ABRACOS soils, has the principal advantages of being a continuous function with clearly defined limits. For this reason the model has been adopted for use in many GCM descriptions of soil water movement. Soil water content, S_θ, is related to the soil matric potential by

$$S_\theta = [\,1 + (\alpha\Psi)^n]^{(1-n)/n} \tag{6}$$

and hydraulic conductivity by

$$K(S_\theta) = K_{sat} S_\theta^{\,L} \,(1-[1-S_\theta^{\,n/(n-1)}]^{(n-1)/n})^{0.5} \tag{7}$$

where

$$S_\theta = (\theta_r - \theta)/(\theta_{sat} - \theta_r) \tag{8}$$

θ_r = residual soil moisture content

θ_{sat} = saturation soil moisture content

K_{sat} = saturation hydraulic conductivity

Ψ = matric potential

and, n and L are curvature parameters. Tomasella and Hodnett (1996) derived parameter values from routine neutron probe and tensiometer measurements at Fazenda Dimona, and enhanced by intensive field measurement campaigns employing permeameters and the 'instantaneous profile method' of soil water release (Hillel *et al.*, 1972). Full details of the optimisation procedure, application to the Fazenda Dimona data, and the role and relative importance of the various parameters are discussed by Tomasella and Hodnett (1996). Table 2 gives the optimised parameter values derived for four ABRACOS sites: forest and pasture at Manaus and Ji-Paraná. Also shown in Table 2 are the results of similar optimisation studies van Lier (Pers. Comm., van Lier; Moraes, 1991; van Lier and Neto, 1993) in which van Genuchten parameters were derived for a Brazilian 'Structured Red Earth' or 'Terra Roxa Estuturada'.

Parameter interpretation and vegetation influences

Tomasella and Hodnett (1996) recorded data for the Manaus soil under forest close (1500 m) to the Fazenda Dimona pasture site (rather than at Reserva Ducke), and give a good comparison between forest and pasture on the same soil. The soil at Fazenda Dimona is a yellow latosol (Oxisol or Haplic Acrorthox), with a high clay content of typically 65-80%, but has weathered to give high moisture conductivities when close to saturation. This is a particular characteristic of Amazonian latosols (Sanchez, 1976; Hodnett *et al.*, 1995) and is not easily described by single parameter models of soil matric potential and conductivity. This soil has one of the lowest capacities of available soil moisture in Amazônia.

The 'van Genuchten' parameters for latosol shown in Table 2a and 2b vary considerably with depth, yet are remarkably similar under both pasture and forest. Figure 6 shows the shape of the function using parameters for a depth of 0.5 m. This similarity suggests that, even after 15 years, the conversion to pasture has not greatly affected the soil structure at depths below 0.2 m. However, Hodnett *et al.* (1995) observed impeded infiltration and a small amount of runoff at the pasture site, K_{sat} = 50 mm h^{-1}, whereas runoff was never observed in the forest: Medina and Leite (1985) give infiltration rates for undisturbed forest near Manaus as 223 mm h^{-1}. Although very poor infiltration at pastures sites can be caused by the method of forest clearance, particularly when heavy machinery is used (Dias and Nortcliff, 1985; Medina, 1985), this is not likely to be the case at Fazenda Dimona where forest clearance was by 'slash and burn'. At this site the relatively mild reduction in infiltration is consistent with the effects of compaction by cattle (Reategui *et al.*, 1990; Grimaldi *et al.*, 1993).

The podsol at Ji-Paraná (Arenosol or Paleudult) has a particularly high sand content, especially near the surface (85%), and has contrasting water release characteristics to that of the Manaus latosol. The optimised parameters given in Table 2c and 2d were derived in the same way as those for the Manaus soil (Tomasella and Hodnett, 1996) and are published here for the first time. Optimised water release curves for pasture and forest at 0.4 m depth are shown in Figure 6.

Compared to the Manaus clay, there is less similarity between the forest and pasture podsol parameters. However, at most depths there is consistent variation in θ_{sat} and θ_r with depth, indicating the increased weathering and sand content closer to the surface at both sites. Surface compaction in the pasture is evident in the reduced surface conductivity and there is also a suggestion that in the 15 years since conversion there has been a change in the soil characteristics at 0.2 m when compared to the forest. Although the water release parameters at 0.2 m are very

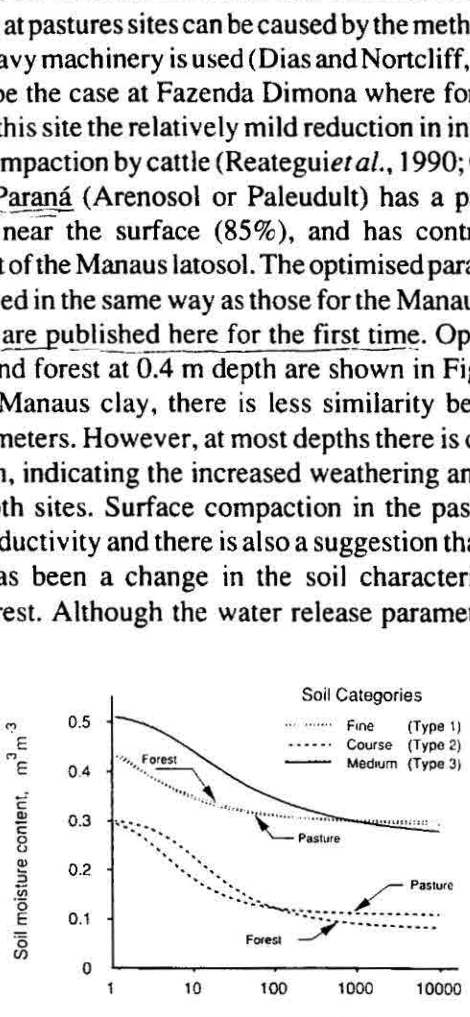

Figure 6 Water release curves derived using the van Genuchten equation and optimised parameters for fine, medium and coarse soils.

different, they describe similar water release characteristics at lower moisture contents: the principal difference is that the pasture has poorer water retention properties closer to saturation. Unlike the Manaus sites, these two soils are less easily compared as they are about 90 km apart, and the seasonally shallow water table at the forest site will account for the change in parameter values at 1.5 m.

The soils of Manaus and Ji-Paraná are close to the textural extremes of fine and coarse soils in Amazonia. It is, therefore, fortunate that a calibration is available for a Structured Red Earth (Alfisol or Kanhapludulf), which represents a third Amazonian soil type and which has contrasting water release characteristics to the ABRACOS soils. The water release parameters for this soil are given in Table 2e and were derived by van Lier (Pers. Comm.) using similar criteria to those used for the ABRACOS soil calibrations (van Lier and Neto, 1993; Moraes, 1991). Figure 6 shows the shape of water release curve for this soil at 0.45 m, and clearly illustrates the contrasting water retention characteristics of the Red Earth when compared to the clay latosol near Manaus and the podsol under pasture at Ji-Paraná. The release characteristic for available soil moisture is fairly similar to that under the Ji-Paraná forest, however, the higher water capacity and, in the other cases, greater range of available soil moisture are clearly shown. Although the data for a Red Earth are from an area south of Amazônia, this soil type and similar well structured soils occur extensively in Amazônia, being derived from the same podsolic pedogenesis. This Red Earth has been extensively studied at the University of São Paulo Agricultural Faculty, Piracicaba. Apart from the work already cited, Table 2e has been enhanced using surface infiltration data from Reichardt *et al.* (1978), and further validated using conductivity data from Saunders *et al.* (1987) and soil texture information from Vieira and Santos (1987).

Density and structure

Bulk densities and particulate content of the three soil categories are given for various depths in Table 2. Values for the ABRACOS sites were derived from laboratory analysis of field samples and those for the Structured Red Earth are taken from Van Lier (Pers. Comm.) and Vieira and Santos (1987). Soil particle density at the ABRACOS sites was 2.6 ± 0.1 Mg m^{-3} and did not vary with depth or between sites. Therefore, this value can be used to infer porosities from the tabulated bulk densities. The clay content profiles are very typical for the soil type and are similar to those published by Ranzani (1980). The reduced bulk density near the surface of the forest soils compared to the rest of the profile, and the weakening of this effect after deforestation, is consistent with the results presented for Amazonian latosols by Martins *et al.* (1991).

Thermal properties

Alvalá *et al.* (1996) derived thermal diffusivity from a 0.40 m profile of soil thermistors, operated in the field during the micrometeorological missions, and recorded temperatures at four levels every 10 minutes. Diffusivity was calculated using a numerical finite difference method, and two analytical methods which consider the change in either the phase or the amplitude of diurnal soil temperature at different depths. These methods gave various estimates for diffusivity at different depths and at different moisture contents, however the methods did not always agree, probably as a result of the vertical heterogeneity of the soils. For this reason a single best estimate of diffusivity is given for each of the two ABRACOS soil types, without regard for depth or moisture content: $0.15\text{-}0.45\times10^{-6}$ m^{-2} s^{-1} for the Manaus (fine) soils and 1.45×10^{-6} m^{-2} s^{-1} for the Ji-Paraná (coarse) soils.

Spatial distribution of soil parameters

Many previous studies have needed to consider the water release characteristics of the soils of the Amazon basin. Most of these have been GCM studies of hypothetical deforestation scenarios, which in the absence of representative water release measurements, have either placed a single best estimate soil type over the whole of Amazonia (e.g. Nobre *et al.*, 1991) or used land-surface classifications (e.g. Dickinson, 1984; Wilson and Henderson-Sellers, 1985) to obtain 1°×1° soil texture information. This textural information is then used to infer water release characteristics (e.g. Dickinson and Henderson-Sellers, 1988; Lean and Warrilow, 1989). Clearly, both of these methods are unsatisfactory although they were the best that could be done at the time. Also, bearing in mind that Tomasella and Hodnett (1996) and Hodnett*et al.* (1995) have demonstrated that it is unwise to 'import' empirical water release functions to represent soils of the Amazon basin, the pedological and textural detail that is currently available in global data bases could be grossly misleading. For example, for the predominant fine soils of Amazonia, 'imported' estimates of available soil moisture would be typically 50% greater than those suggested from Table 2. This difference would radically affect the predicted hydrology of the shallow rooted pastures by delaying the onset of stress in the grass at the beginning of the dry season.

Many Amazonian soils have been extensively studied, but mainly from an agricultural point of view, and only very limited data have been published concerning water retention. From the limited number of studies that have derived parameters for Amazonian soils that are relevant to contemporary GCM modelling (ABRACOS, and Van Lier and Neto, 1993) four categories of soil type have been identified:

1. *Fine soils* (Table 2a and 2b)

   The Manaus clay latosol is probably the most common and most studied Amazonian soil, (Correa, 1984; Tomasella and Hodnett, 1996; Hodnett *et al.*, 1995) and is used here to represent most of the fine soils of the area. Although this category covers large areas of latosol (commonly fine) and podsol (commonly medium-coarse), Ranzani (1980) has shown that these pedological units do not have a unique texture and their clay content can vary widely. With the limited parameters available these soils are considered to be sufficiently well represented by a clay-like soil with high conductivity close to saturation. However, there may be some bias in using a soil with a particularly high clay content as given here.
2. *Coarse soils* (Table 2c and 2d)

   Although the soil around Ji-Paraná is a podsol it has a high sand content for that pedological type and is considered representative of coarse soils in Amazonia, i.e., Arenosols, Lithosols and hydromorphic podsols.

3. *Medium texture soils* (Table 2e)
   This category is based on the work of van Lier (Pers. Comm.) on a Structured Red Earth from the south of Amazonas (see also Moraes, 1991; van Lier and Neto, 1993). Soil types represented by this category are Red Earths, Vertisols and some oxidised and well structured latosols.
4. *Plinthitic soils* (Table 2b - c)
   Plinthitic soils, which cover a large and relatively undisturbed area of Amazonia, could have a considerable impact upon regional hydrology if disturbed by large-scale deforestation. These soils have been found to oxidise rapidly when exposed by machinery or aerated by a lowering of the water table. When disturbed by machinery, this soil has been observed to reduce, in less than 12 months, from a heavy clay podsol to a concreted and coarse structured material with the water holding characteristics of a sandy soil. Although this disturbance represents rather extreme circumstances, it is not unreasonable to suggest that the characteristics of this soil could change from 'fine' to 'coarse' over a period of less than, say, five years. During this transition, the poorly structured soil could not necessarily be represented by the medium textured soil type (3 above) because it is unlikely that the water holding capacity would develop to any great extent.

For GCM experiments investigating the effects of deforestation in Amazônia, these soils should be represented by the 'fine' soil category while they remain undisturbed. Until more is known about the oxidisation of these soils, it is recommended that these areas should be represented by 'coarse' soil parameters when describing the deforested state. In multi-layer soil models it would be relevant to modify only the upper soil layers in a way that is consistent with the estimated depth and rate of oxidation and the type of land use after deforestation.

Figure 7 shows the 1°×1° allocation of soil categories recommended by this study to represent Amazonia. The figure is not intended to be an accurate soils map. The distribution of categories is based on pedological information from various sources (RADAM, 1980; Wilson and Henderson-Sellers, 1985; Vieira and Santos, 1987; Kineman and Ohrenschall, 1992; Webb and Rosenzweig, 1993), and the personal experience of one of the authors. However, particular emphasis has been placed on maintaining the relative proportion of coarse (16%), medium (5%) and fine (79%, including plinthitic) textured soils based on the proportion suggested by the various sources. It should be noted that there is a great disparity between published datasets for classifying Amazonian soil textures. Apart from datasets being superseded by legitimate improvements, this disparity is probably due to, and made more confusing by, the differing pedological classifications to which the Amazonian soils have been required to conform (e.g. FAO, Brazilian, North American).

In summary, although the mapping of soil parameters is greatly simplified in this study, further detail is not relevant until more Amazonian soils have been parameterized for water retention characteristics. More work on mapping actual soil texture, rather than inferred texture, is needed to complement the existing wealth of detailed

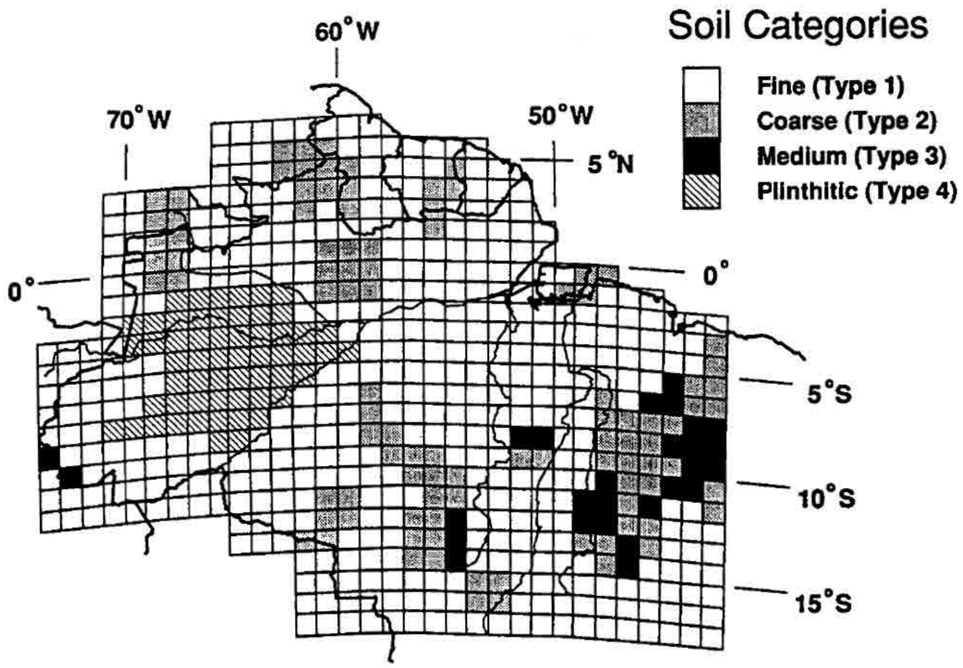

Figure 7 A 1°×1° distribution of the three parameterized soil types over the Amazon region of Brazil, including the area of plinthitic soils where soil characteristics may change after deforestation.

pedological information. However, this study provides sufficient information to investigate the sensitivity of climate and hydrology to simple but well calibrated differences in Amazonian soil type: an important first step to indicate the direction of future work. For example, assuming that forested areas are insensitive to soil type because of their unlimited access to deep water, it is not clear whether pasture on coarse soils will have a significant impact on modelled hydrology or change the severity of dry seasons. For although the available soil moisture is greater in coarse soils, they only cover up to 16% of the total area in this study: 26% if plinthitic soils are included.

CONCLUSIONS

The parameters presented in this paper are a summary of research in many areas of environmental science, resulting in a pair of tables that are designed to be used and interpreted by the GCM modelling community. Vegetation, soil and surface flux related parameters have been derived from data recorded at three contrasting areas within Amazonia, including typical pasture and forest of each area, and encompassing representative Amazonian soils and vegetation structures. Although these six study sites are a very small sample of the vast Amazon basin, this study should result in

Table 2 Soil parameters

Depth **m**	**n** **-**	**α** **kPa^{-1}**	**l(1)** **-**	**θ_{sat}** **m^3 m^{-3}**	**θ_r** **m^3 m^{-3}**	**K_{sat}** **mm h^{-1}**	**Bulk density** **Mg m^{-3}**	**Clay** **%**	**Sand** **%**
a) **PASTURE - FINE SOIL** (Fazenda Dimona)									
0.0	-	-	-	-	-	50	1.06	65	20
0.3	1.50	0.745	5.40	0.448	0.305	546	1.07	75	15
0.5	1.62	0.967	1.98	0.486	0.299	676	0.94	80	10
0.75	1.33	4.62	-1.77	0.573	0.304	1096	1.10	80	10
1.05	1.20	6.64	-4.91	0.565	0.355	422	1.12	80	10
1.35	1.37	0.200	3.65	0.526	0.420	18	-	-	-
b) **FOREST - FINE SOIL** (Fazenda Dimona)									
0.0	-	-	-	-	-	223(2)	0.93	65	20
0.3	1.47	0.704	5.29	0.447	0.304	560	1.04	75	15
0.5	1.44	1.49	1.38	0.489	0.290	1256	1.04	80	10
0.75	1.28	5.45	-2.01	0.574	0.289	1495	1.15	80	10
1.05	1.18	6.35	-6.26	0.565	0.359	626	1.15	80	10
1.35	1.31	0.190	5.32	0.511	0. 382	23	-	-	-
c) **PASTURE - COARSE SOIL** (Fazenda Nossa Senhora)									
0.0	-	-	-	-	-	6(3)	1.50	7	85
0.2	1.92	0.202	0.5	0.259	0.046	20-60(3)	1.50	12	78
0.4	1.77	0.359	0.5	0.309	0.109	-	1.30	16	72
0.6	1.16	0.730	0.5	0.389	0.131	-	1.30	33	58
0.8	1.35	0.293	0.5	0.418	0.257	-	1.30	33	58
1.0	1.56	0.251	0.5	0.465	0.298	-	1.24	36	53
1.2	1.59	0.206	0.5	0.425	0.275	-	1.24	36	53
1.5	1.25	1.103	0.5	0.383	0.191	-	1.24	36	53
d) **FOREST - COARSE SOIL** (Reserva Jaru)									
0.0	-	-	-	-	-	-	1.38	4	85
0.2	1.34	2.209	0.5	0.483	0.025	63	1.55	4	82
0.4	1.60	0.164	0.5	0.305	0.079	66	1.52	6	77
0.6	1.73	0.304	0.5	0.343	0.155	10	1.49	18	63
0.8	1.46	0.209	0.5	0.397	0.212	(10)	1.49	35	58
1.0	1.39	0.212	0.5	0.410	0.231	-	-	35	58
1.2	1.40	0.252	0.5	0.408	0.207	-	-	36	53
1.5	1.57	0.213	0.5	0.418	0.189	-	-	36	53
e) **MEDIUM TEXTURE SOIL** (parameters derived from field data by van Lier (Pers. Comm.)									
0.0	-	-	-	-	-	6(4)	-	38	34(5)
0.15	1.28	1.896	(0.5)	0.493	0.243	-	1.54	49	32
0.3	1.68	0.131	(0.5)	0.527	0.294	2.8	1.43	61	24
0.45	1.36	0.226	(0.5)	0.520	0.262	5.5	1.40	64	21
0.6	1.20	1.167	(0.5)	0.516	0.241	46	1.38	63	22
0.75	1.42	0.629	(0.5)	0.502	0.273	108	1.25	62	22
0.9	1.53	0.390	(0.5)	0.533	0.259	87	1.23	62	22
1.05	1.60	0.478	(0.5)	0.535	0.255	186	1.20	59	24
1.20	1.49	0.516	(0.5)	0.531	0.239	168	1.23	58	24
1.35	1.66	0.263	(0.5)	0.550	0.239	136	1.21	58	24
1.50	1.64	0.365	(0.5)	0.558	0.240	-	1.21	56	25

Notes

1 When insufficient data are available l = 0.5, when not in parentheses l = 0.5 was used in the optimisation of the van Genuchten parameters.
2 Not optimised - measured by Medina and Leite (1985)
3 Not optimised - measured by ABRACOS
4 Reichardt *et al.* (1978)
5 Vieira and Santos (1987)

a marked improvement to the validity of GCM deforestation experiments and will contribute to identifying important areas of future research. Vegetation parameters, such as albedo, canopy structure and aerodynamic roughness, have shown a level of coherence between sites that validates some of the necessary generalities that have to be made in representing the Amazon basin in a GCM. This work has also provided some surface seasonality to complement the modelled GCM annual cycle.

Bulk stomatal conductance and its control on transpiration is an area of empiricism that is still poorly understood, especially for tropical forest. Although the total transpiration from the forest appears to be similar between sites, the complex physiological and structural diversity at each forest site produces different, yet compensating, parameters and creates an element of uncertainty when applying evaporation models to new forest sites. No soil-induced reduction in transpiration has yet been observed from tropical forest: a result which must be considered when setting effective forest rooting depths.

For pasture, the grazing of cattle and the combined influences of soil fertility, dry season severity and species composition, has produced at each pasture site a grass cover whose height is only weakly related to its leaf area index. As the dry season develops and green leaf area declines, the canopy structure remains largely the same. Between sites there is a consistent relationship between height and roughness length, and to a weaker extent between leaf area index and albedo. This means that seasonal variations in leaf area and albedo can be legitimately investigated without necessarily varying crop height. When pasture leaf area index is below about 2, bulk stomatal conductance and albedo are reduced: above this value both of these parameters have a suggested maximum. Although there is insufficient information to derive a functional relationship, future work may lead to a more mechanistic model of plant structure with fewer and more meaningful parameters.

Soil research within ABRACOS has highlighted the paucity of well calibrated parameters to describe the Amazonian surface and sub-surface hydrology. However, a framework for essential future work has been identified. Water release and moisture movement in Amazonian soils cannot be readily represented with parameters 'imported' from soils outside of Amazonia. There may yet be soils which can be treated as more typical of global soils, but until more Amazonian soils are studied with respect to the needs of GCM modelling, it is necessary to exercise some caution.

With the advances in the land surface parameterization of Amazonia, it is now possible to embark upon more focused sensitivity studies: identifying the most relevant areas of future work. The design of future experiments can also be influenced by identifying the relative importance of individual parameters or areas of research. The ABRACOS results show that both soil parameterization and the understanding of vegetation processes require further work. Within the current GCM land-surface schemes there is clearly a mutually dependant relationship between the sub-models of rainfall, evaporation and soil water release. Therefore, for a reliable model of wet season runoff and dry season stress, it is necessary to continue with accurate calibrations to improve realism in GCMs and reduce the empiricism in modelling the biosphere.

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RESUMO

Parâmetros de superfície, para vegetação de pastagem e floresta na Amazônia, são apresentados para a utilização em experimentos de desmatamento realizados por modelos de circulação geral (MCG). Os valores dos parâmetros são baseados, predominsntemente, nas medições registrada peolo projeto ABRACOS, e complementados, quando necessário, pelos resultados de outras pesquisas na Amazônia. Os parâmetros são independentes dos diversos esquemas de transferência Solo-Vegetação-Atmosfera (ETSVA) atualmente em uso, entretanto, quando um particular submodelo é utilizado para calibrar um parâmetro, a estrutura do submodelo é apresentada. A variação sazonal dos parâmetros de vegetação é apresentada quando possível.

Na floresta, sob a influência da umidade de solo, o albedo médio mensal variou de 0,121 a 0,144, ao passo que, na pastagem, sob uma variação no índice de área foliar entre 0,5 e 4,0, o albedo variou de 0,155 a 0,20. A rugosidade aerodinâmica, z_0, nos sítios de pastagem, foi consistentemente 10% da altura da vegetação, variando de $z_0 = 0,025$ m a $z_0 = 0,08$ m, e foi encontrada como sendo independente do índice de área foliar. A média da rugosidade de dois sítios de floresta foi de $z_0 = 2,35$ m. Parâmetros obtidos em três diferentes tipos de solo na Amazônia (Latossol, Podssol e Terra Vermelha) são dados com uma distribuição geográfica simples, consistente com a limitada informação disponível para uma modelagem representativa do sistema solo-água. Os parâmetros de retenção e relativos à dinâmica da água no solo são apresentados para várias profundidades, entretanto, a existência de raízes profundas nas florestas, consequência da ausência de sazonalidade na transpiração, requer cuidado na escolha pelos modelos da

profundidade do sistema radicular.

Para a modelagem da transpiração, a condutância estomática "bulk" continua como o resultado empírico dos métodos de otimização: a falta de independência para com os outros parâmetros dificulta a compreensão da diferença entre os sítios. Também a influência da estrutura das plantas no albedo, transpiração e evaporação do solo não está ainda bem acoplada em muitos ETSVA. Para modelagem hidrológica, o detalhado mapeamento pedológico da Amazônia é insuficiente e pouco completo com relação aos parâmetros do sistema solo-água. Estudos de sensibilidade utilizando os parâmetros publicados pelo estudo do ABRACOS são agora necessários para investigar a importância relativa de cada uma das áreas de pesquisa em trabalhos futuros.