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CANOPY STRUCTURE OF THE RIO SURUMONI RAIN FOREST (VENEZUELA) AND ITS INFLUENCE ON MICROCLIMATE

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Abstract. The canopy represents a distinct part of the forest. It functions as the surface for energy and mass exchange between vegetation and the atmospheric environment. This must be taken into account when exploring the impacts of naturally or anthropogenically induced climatic changes. Such anlayses today are based on GCMs (general circulation models). Within these GCMs the vegetation cover is represented only by its bio-geophysical parameters such as the leaf area index (LAI), because the canopy structure directly affects micrometeorological conditions such as energy exchange by turbulent fluxes and radiative transfer, vertical and horizontal temperature gradients within the forest stand, and net rainfall. This paper focuses on the derivation of LAI as a basic parameter of canopy structure. Data from 36 complete light profiles are analyzed and registered every second with a light sensor which was hauled up from the forest floor to the open sky by an electric winch system at a constant speed. The average LAI for the plot, calculated from all 36 profiles, is about 4.24, ranging from 1.4 to 6.0. *Accepted 26 June 2001.*

Key words: *Amazonia, Venezuela, rainforest, light distribution, LAI, climatology, hydrology.*

INTRODUCTION

The canopy represents a distinct part of the forest. It functions as the surface for exchange between vegetation and the abiotic environment. With regard to climatic change, the forest canopy plays the central role in the local and regional water budget. Recent studies have shown that structural differentiation in tropical moist forest canopies is responsible for the varying properties of the water and energy balance (Shuttleworth 1989, Anhuf *et al.* 1999, Szarzynski 2000).

These results must be taken into account when exploring the impacts of naturally or anthropogenically induced climatic changes. Such attempts today are based on GCMs (general circulation models). Considerable progress has been made in simulating the interactions between the atmosphere and the ocean, but the integration of vegetation in these models is still poorly developed. Important progress was achieved by Claussen & Esch (1994) in coupling the atmosphere with the vegetation; for the latter, Claussen & Esch's studies are based on the Biome Model of Prentice *et al.* (1992). Vegetation cover is represented only by bio-geophysical feedbacks such as changes in albedo, roughness length (given as z0 in metres, describing the wind braking efficiency caused by the canopy structure), leaf area index (LAI), etc. Within the Biome Model, the tropical rainforest possesses a LAI of 9.3. This value is used for all rainforests throughout the tropics. A comparison of this figure with those obtained in the field (Table 1) underlines the fundamental need for ongoing investigations of bio-geophysical parameters like LAI or roughness length (Table 2) in order to offer more realistic values in coupled atmosphere-vegetation models.

The structural characteristics of forests are the vertical and horizontal extensions of the canopy surface, as well as the inner structure of the canopy and the vegetation stand (e.g., strata). Different measurements are available to describe the entire stand-structure: maximum tree height (33 m at Surumoni), average canopy height (23 m at Surumoni), zero plane displacement height, i.e., the height at which wind velocity increases (on a logarithmic scale) due to declining surface drag (21 m at Surumoni), basal area per hectare (here 23 m^2/ha), projected crown area (0,78 m^2/m^2), and LAI (see below, 4.24 measured in m^2/m^2) (Table 2).

Different methods are applied in order to obtain these parameters. Surface reflectance (derived from satellite data), transmissivity (light profiles), gap frac-

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TABLE 1. Selected values of LAI from literature.

Location, vegetation type	Method	LAI	Source / year
Marabá, Brazil, tropical lowland rainforest	litter leaf-area sampling	5.38	Roberts *et al.* 1996
Manaus, Brazil, tropical lowland rainforest	litter leaf-area sampling	6.1	Roberts *et al.* 1996
	hemispherical photography	3.9	Honzák *et al.* 1996
	sunfleck photometry	4.6	Honzák *et al.* 1996
	destructive sampling	5.7	Roberts *et al.* 1996
Ji-Paraná, Brazil, tropical moist forest	Light-profile / transmissivity	4.4	Roberts *et al.* 1996
Ji-Paraná, Brazil, tropical moist forest	litter leaf-area sampling	4.63	Roberts *et al.* 1996
Panama, tropical moist forest	destructive sampling	22.4	Honzák *et al.* 1996
North America, forest savanna	optical methods	3.5	Asner *et al.* 1998

tion analysis of hemispherical sky photographs, as well as manual destructive and non-destructive methods are made use of. All these techniques are aimed at registering the radiation and light environment in all three dimensions in the most realistic way possible (Küppers *et al.* 1995, Ermák 1998, Sá *et al.* 1998).

The distribution of radiation and light influences not only the growth of plants but also the behavior of animals, particularly the avifauna (Anhuf & Winkler 1999). Furthermore, the vegetation structure can be derived from the light distribution. This structure directly affects micrometeorological conditions such as energy exchange by turbulent fluxes and radiative transfer, vertical and horizontal temperature gradients within the forest stand, and net rainfall.

This paper focuses on the derivation of LAI as a basic parameter of canopy structure influencing the micrometeorological conditions within the forest stand.

TABLE 2. Structural characteristics of the Surumoni crane-site forest.

Size of area investigated	1.5 ha
maximum canopy height	33 m
average canopy height	26 m
number of trees with dbh > 0.1 m	> 660
projected crown area	0.78 m^2/m^2
basal area per ha	23.4 m^2
stem diameter (average of trees studied)	0.177 m
roughness length	2.22 m
zero plane displacement height	21.2 m
LAI	4.24 m^2/m^2

MATERIAL AND METHODS

In the course of interdisciplinary studies of the Amazonian moist forest at Rio Surumoni, the following operations were carried out to determine canopy and stand structure:

(1) Survey of canopy surface topography and ground relief (Schröder). The canopy surface topography influences basic microclimatic parameters like the roughness length, zero plane displacement height, wind speed, and fraction of radiation able to penetrate the forest stand.

(2) Manual measuring of stem and crown size (Wesenberg/Sattler/Morawetz) and own additional material. The attenuation of the incoming radiation basically depends on structural elements such as crown size or leaf density within the canopy, as well as the kind of leaf arrangement.

(3) Leaf-area scanning (Ellinger and own additional material). This is a method of direct calculation of leaf area index (LAI). In addition, results of leaf harvesting should be compared with results obtained from other methods, e.g., light profiles.

(4) Basal area (Rainer, Wesenberg/Sattler/Morawetz, own additional material). Most tropical forests have a basal area (total cross-sectional area at 1.3 m above ground for all trees ≥ 10 cm dbh) of around 30 m^2/ha (Leigh 1999). These measurements were carried out to compare the Surumoni forest with other lowland tropical forests.

(5) Hemispheric sky photographs (Engwald and Szarzynski). This special kind of photography was used to model the horizontal light distribution on the forest floor.

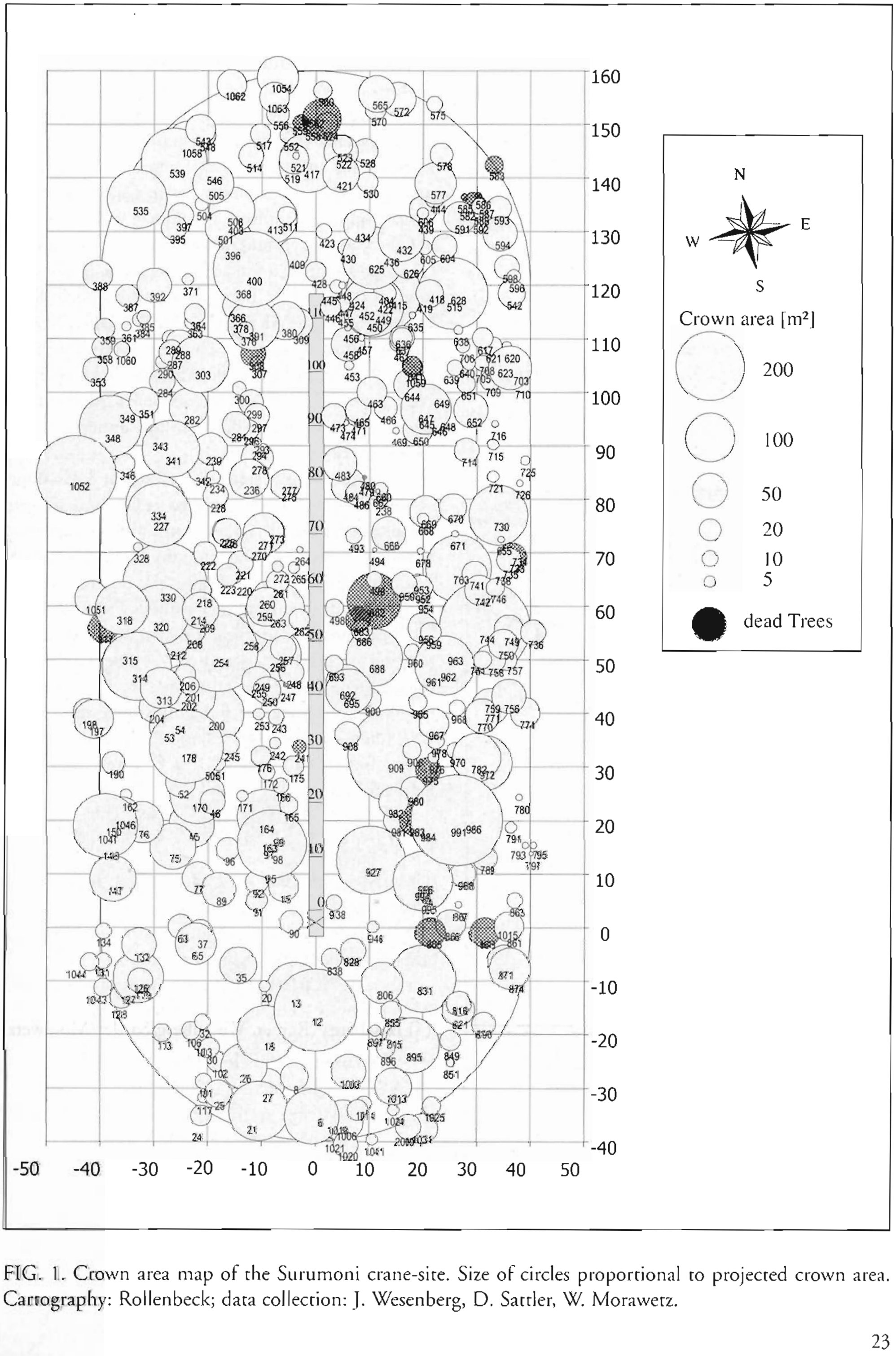

FIG. 1. Crown area map of the Surumoni crane-site. Size of circles proportional to projected crown area. Cartography: Rollenbeck; data collection: J. Wesenberg, D. Sattler, W. Morawetz.

(6) Light and radiation gradients at three height levels (continuous observation by Anhuf's research group). These measurements have been recorded at canopy and sub-canopy levels since the start of climatic studies in December 1995 (Tree No. 1052 in Fig. 1). The recordings are made every 10 minutes and have already been analyzed for the calculation of the energy balance (Szarzynski 2000).

In the vicinity of the sub-canopy station the stand is differentiated into three stories. Within each stratum different light conditions prevail that decisively influence flora and fauna (Engwald 1999). Of special interest is that part of the radiation spectrum that is available for plant photosynthesis. The isolated measurements at 3 different heights (5m, 12m, 21m, and 42m above the canopy) of photosynthetically active radiation (PAR) at the sub-canopy station can only be made at the location of the instrument. The small number of sensors did not permit a detailed vertical and horizontal differentiation, therefore light profile measurements were used to obtain the light conditions for the main plot area. Six profile-tracks were measured at a horizontal distance of 10 m. Every 20 m along each transect a complete vertical profile of light from the ground to the open sky was recorded (Fig. 2). Data from a total of 36 complete profiles are now available. The light sensor (Campbell Skye Quantum Sensor SKP 215) was hauled up by an electric winch system at a constant speed; a Campbell CR-10 data logger recorded the light strength every second. The measurements were carried out between 10:00 h and midday, always under a closed cloud cover.

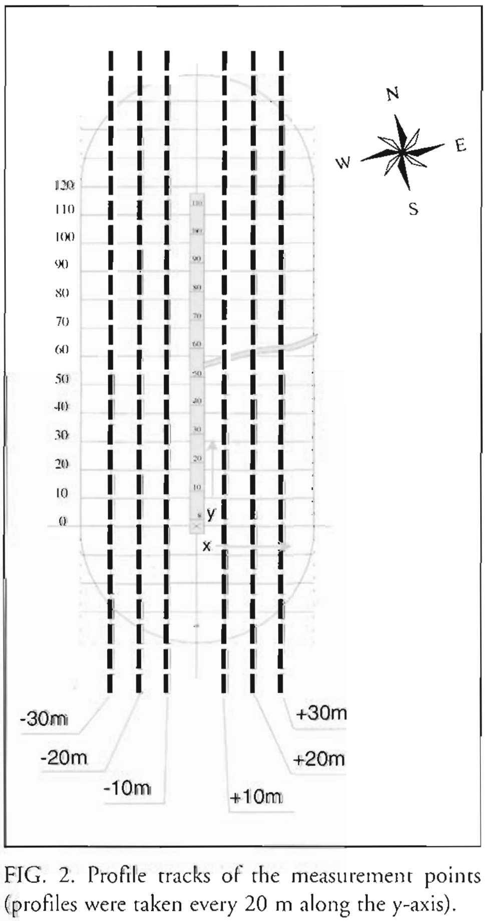

FIG. 2. Profile tracks of the measurement points (profiles were taken every 20 m along the y-axis).

Each profile was standardized to the PAR value of the free atmosphere registered at the same time at the crane station. By doing this, the influence of changing incoming solar radiation was eliminated. The standardized profiles show the relative vertical light-strength (transmittance profiles Figs. 3–5).

Based on these profiles, the spatial light distribution within the forest stand can be calculated from the quotient I_z / I_0 (I_z = radiation at level z [distance below the canopy], I_0 = free atmosphere radiation). This quotient represents a basic element within the Beer-Lambertlaw for calculating LAI from measured light profiles.

RESULTS

The first graph (Fig. 6) is an example of a typical vertical light distribution. Light intensity decreases only slightly between 32 and 24 m, due to two adjacent higher trees (highest crowns of crane-plot tree numbers #178, #1047/1046). Below the canopy, from 24 m down to 10 m, light decreases rapidly. At 10 m only 8% of free atmospheric PAR remains. At ground level the curve drops below 1%.

A contrasting picture is shown in Fig. 6 (right), showing the light conditions at a disturbed location (gap). The initial decrease of radiation between 28 and 14 m is mainly caused by the surrounding higher vegetation. The actual plant canopy of this gap is as low as 14 m. The large difference between 12 and 4 m indicates a rather open leaf coverage, perhaps a liana. Below 4 m height, dense soil-covering vegetation can be found, causing the gradient drop to

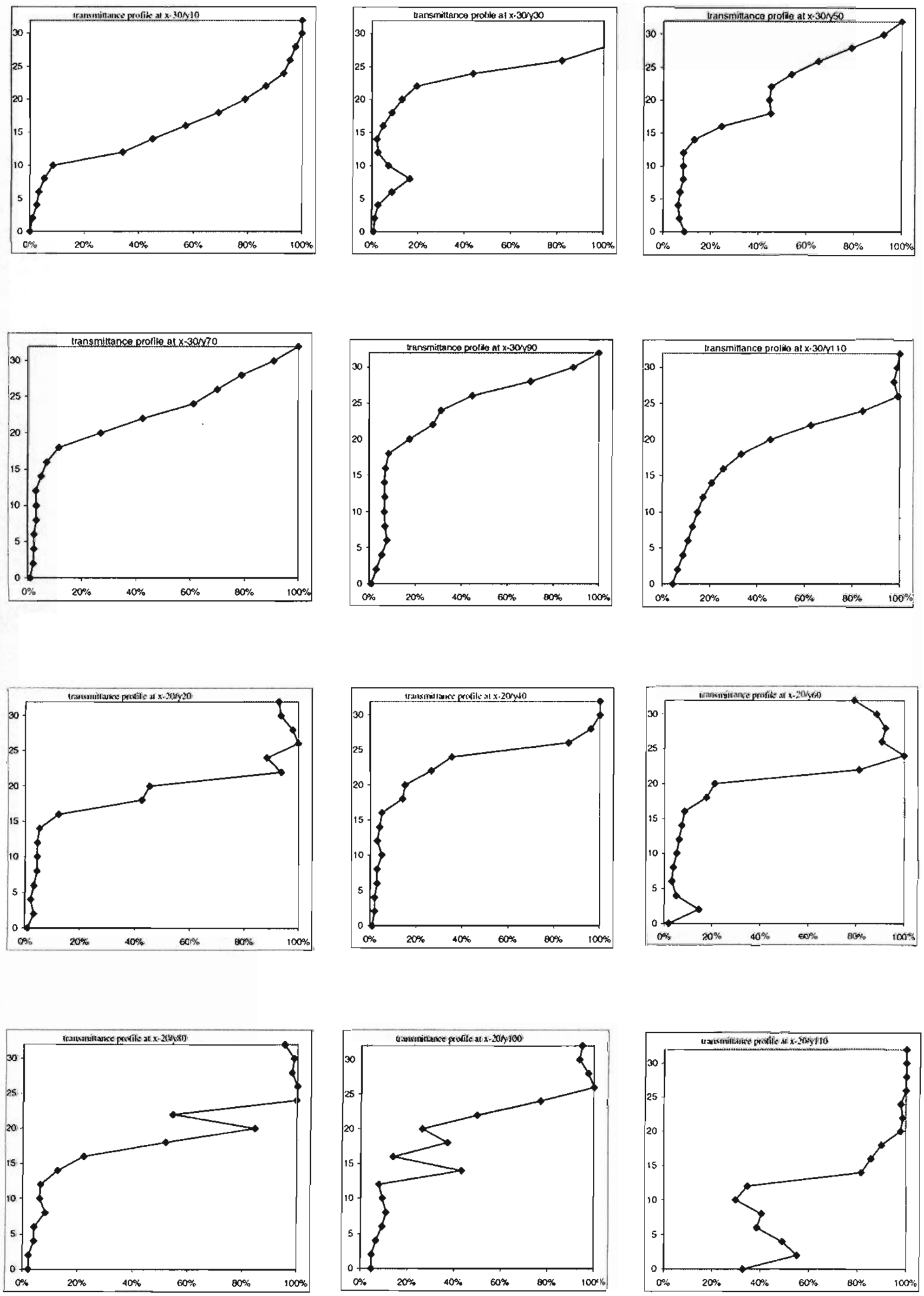

FIG. 3. Measured light transmittance profiles of the west side.

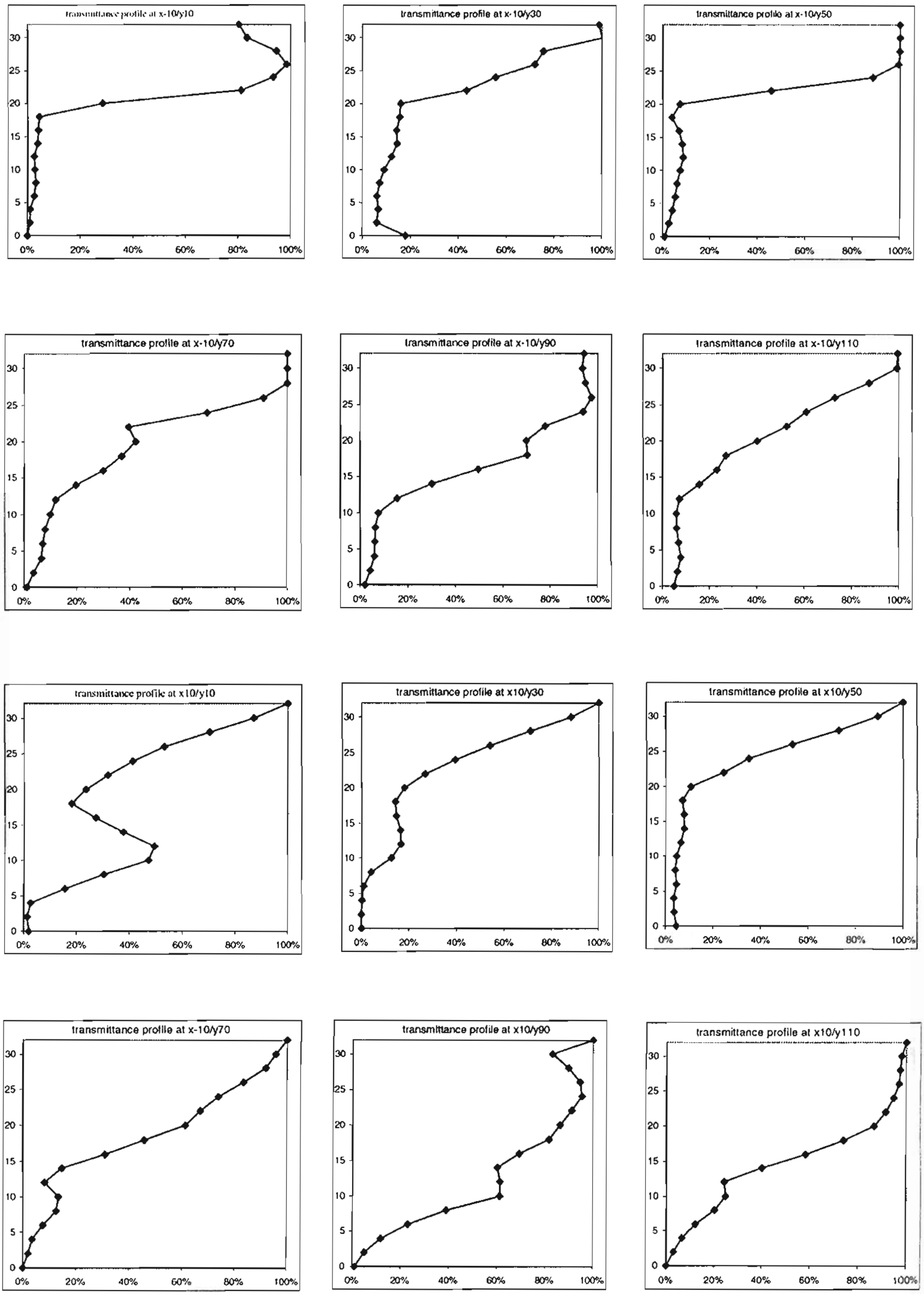

FIG. 4. Measured light transmittance profiles of the central section of the plot.

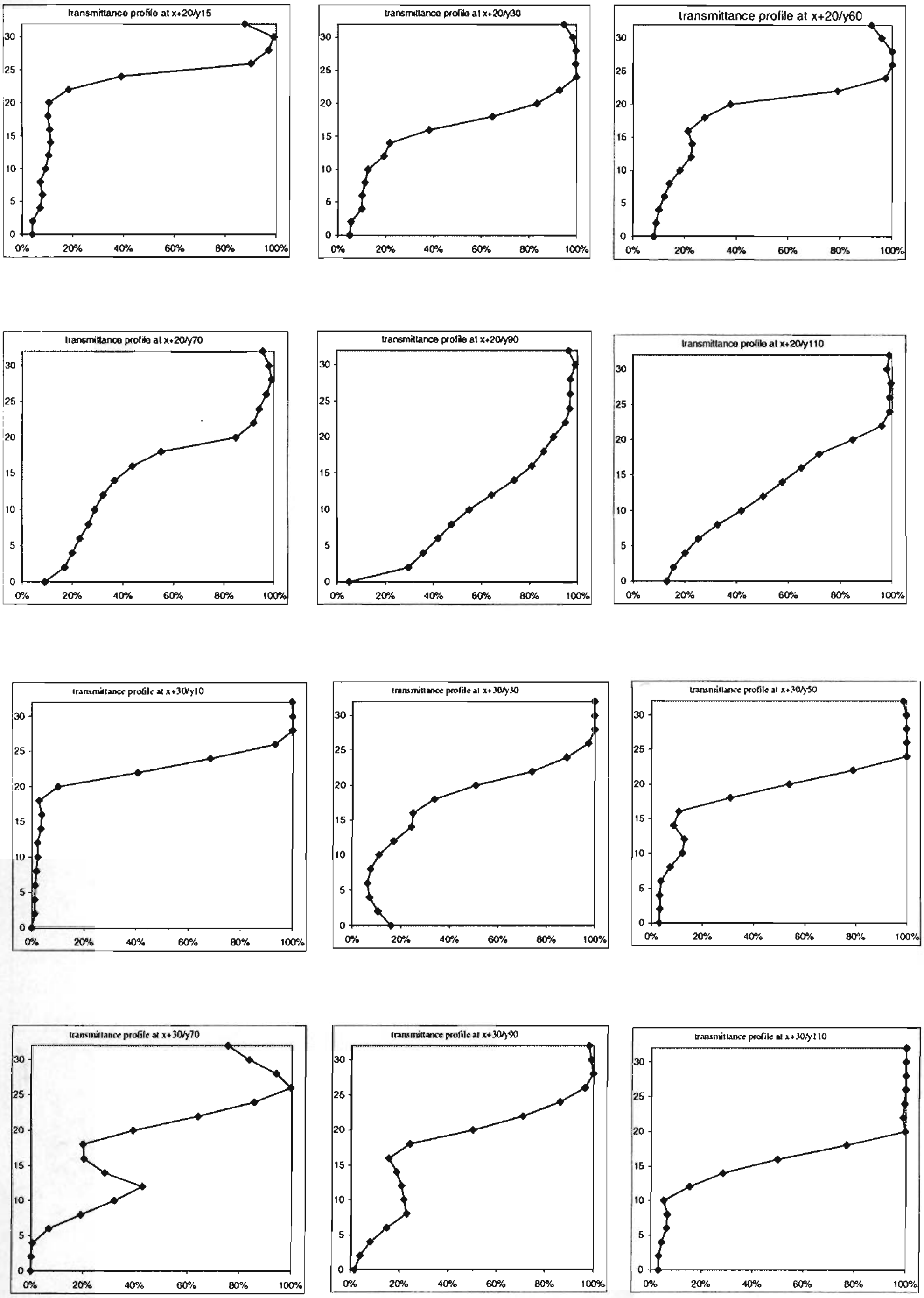

FIG. 5. Measured light transmittance profiles of the east side.

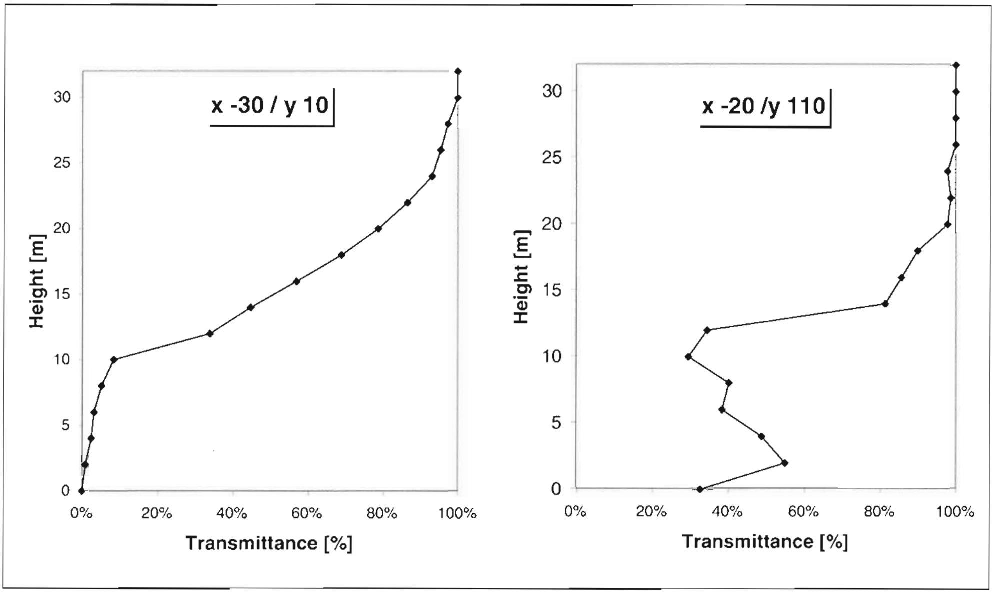

FIG. 6. Representative profiles for two structurally different locations; left, typical location; right, disturbed location.

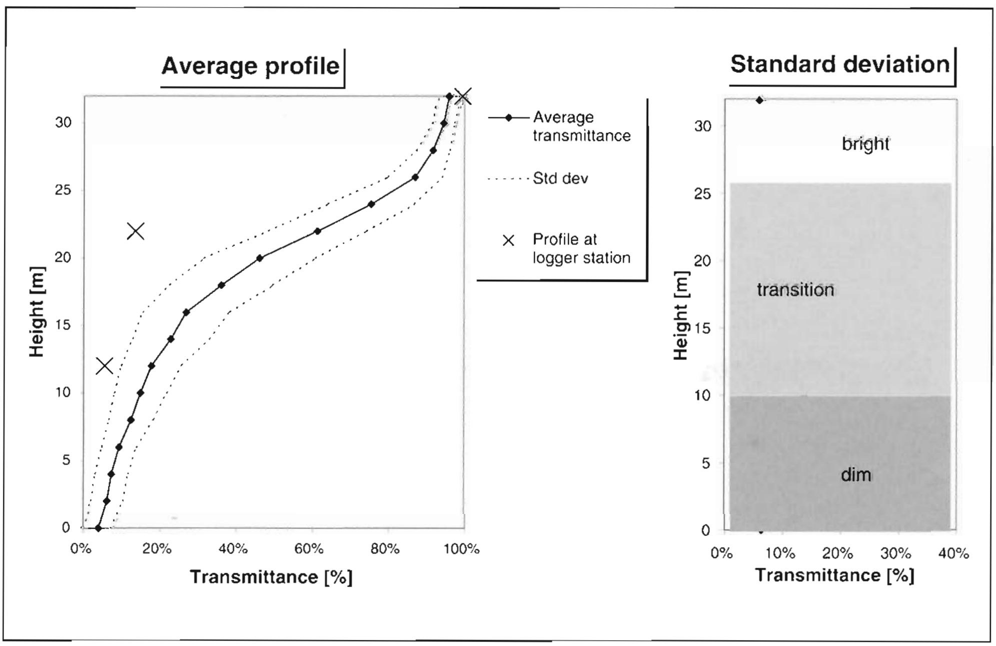

FIG. 7. Average profile of transmittance derived from the 36 measured profiles.

be similar to that of the higher canopy. Possibly this location is still in an early stage of succession.

Fig. 7 displays the average profile of all 36 measuring profiles with the corresponding standard deviations. The average canopy height of 28 m is well expressed in the curve; the zero plane displacement height is found in the middle of the strongest decline of the gradient and, additionally, in the area of highest standard deviation, where structure has the greatest variability. Parker (1995, 1997) separates three light zones in a forest stand: bright, transition, and dim. The transition zone covers the area between 26 and 10 m, a zone where standard deviation is above 15 %.

Yet the average curve shows some significant differences from the ideal curve in Fig. 6 (left). Ideally, light strength drops to 1% at ground level, but the average curve does not drop below 4.5%. The reason for this is that several smaller gaps push the average curve towards greater light intensity. The undisturbed structure of the forest is better represented by the graph in Fig. 6.

The long-term average gradient of the continuous measurements is marked by black crosses in Fig. 7. The steeper gradient of this profile represents a denser high canopy than can be derived from the average curve. It represents the ideal type of high primary forest. Responsible for this is a small-leafed Mimosaceae, *Balizia pedicellaris*, with a dense high crown, to which the sub-canopy station is attached.

Each single profile was integrated to form a picture of the three-dimensional light distribution using the Software Package SURFER 5.02. According to the differentiation by Parker (1997), three horizontal sections are presented (Fig. 8). The 5-m section represents the *dim zone*, the 15-m section the *transition zone*, and the 25-m section the *bright zone*. The *dim zone* encloses only the two larger gaps in the north of the plot, which have a light strength of up to 30%

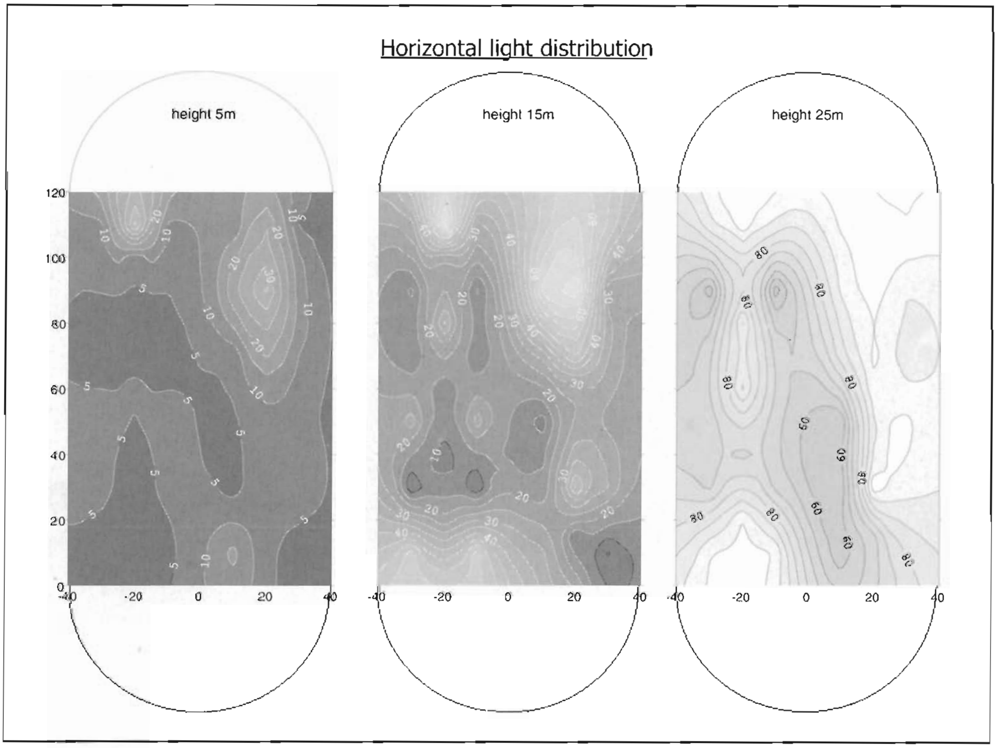

FIG. 8. Horizontal light distribution for 3 height levels as percent of free atmosphere radiation. Levels are associated with the three zones shown in Fig. 7 right.

of the free atmosphere. The eastern gap (right side) was caused by the construction work for the crane, the left gap, however, is natural. The *transition zone* (15 m) shows high horizontal variability (maximum standard deviation). A further gap, already in a mature state of succession, has now become recognizable in the southwestern part of the plot. The ground here is covered by dense vegetation and is accordingly very dark (*dim zone*). The middle story displays the gap character even more clearly. The upper canopy level supports these findings in the *bright zone*. Here, only a few darker patches are visible, which are caused by the few emergent trees. In these images the influence of the crane track was eliminated on purpose.

The spatial light distribution is used to calculate the LAI (leaf area index) by applying the Beer-Lambert law of radiation distribution in porous media. This law assumes that there is an exponential relation between light-strength decline and increasing leaf area. The leaf area (L) for level (z) may then be calculated (Equation 1):

$$\frac{I_z}{I_0} = e^{-kL_z}$$

L_z = LAI at level z
I_z = radiation at z
I_0 = free atmosphere radiation
k = extinction coefficient

A further assumption is the uniform increase of light with height, which is supported by the average curve (Fig. 7). The extinction coefficient (k) is an empirical parameter derived from direct manual measurements of vertical foliage-area distribution. For this study we were able to use data from Hoedl's working group (N. Ellinger), which was collected in collaboration with our own group. Part of the plot was investigated by manually counting leaf number and leaf area for 27 vertical profiles. The LAI for this

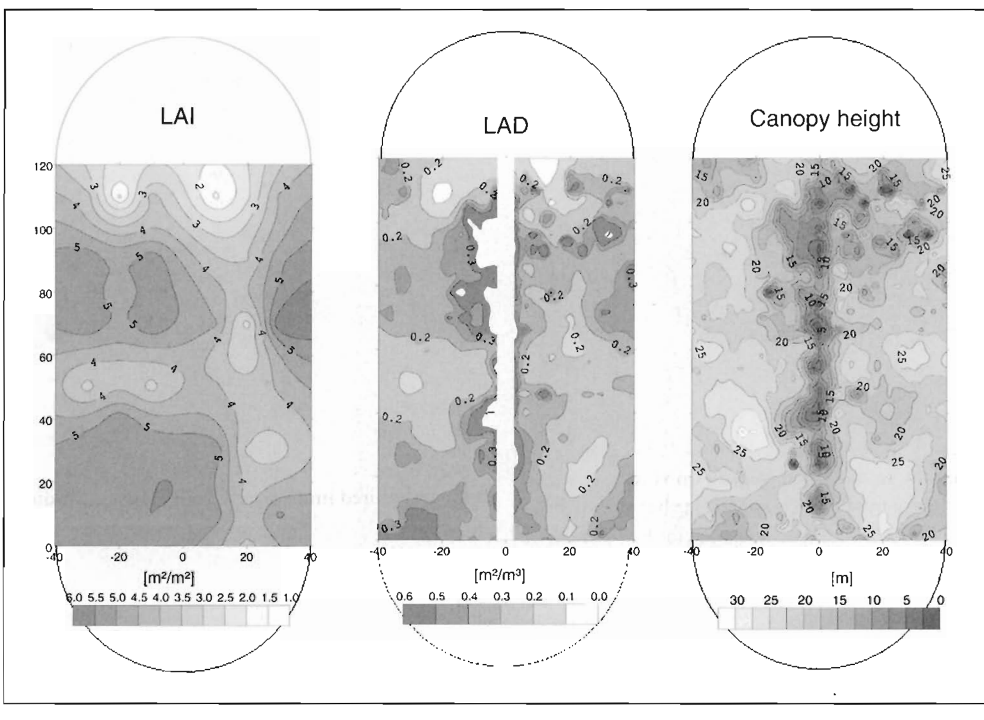

FIG. 9. LAI (left), LAD (center), and canopy height. Because the influences of the crane track (white strip) and the linear gap visible in the canopy height chart (after Schröder 1999) are eliminated in the light measurements by interpolation, the LAD is not calculated in these parts of the plot.

section was determined as 3.7. The inversion of the Beer-Lambert law (Equation 2),

$k = -\ln (I_{ges})/LAI$
$LAI = 3.70$

together with the vertical light profiles of this section, determines the extinction coefficient (k). Proof for the assumption of the uniform increase of light with height is the negative exponential relation to *transmittance* that the cumulated leaf area should have. In our case there are a few deviations from this theory, especially concerning the high canopy. Nevertheless we decided in favor of this approach, knowing that the LAI is slightly underestimated for the upper canopy. Since the actual leaf area plus the entire plant surface were used to calculate the extinction coefficient, we were able to determine the effective LAI according to Chen *et al.* (1998), and not simply the plant area index.

The LAI calculated from all 36 profiles is shown in Fig. 9. The average LAI for the plot is about 4.24, ranging from 1.4 to 6.0. Comparing this number with the manually sampled LAI of 3.7, the higher value may be explained by a number of small gaps in the manually sampled part of the plot.

As expected, spatial distribution of LAI reveals the two younger gaps in the northern section mentioned above (values of 1.4). The mature gap in the southern part already shows the foliage density of the surrounding high canopy (up to 5.5), yet this is not a statement about vegetation height. The highest LAI of 6.0 does not occur at the location of the highest trees but in the eastern limits of the plot. Similar values are recorded at our sub-canopy station (LAI of 5.4), where vegetation height is 27 m.

Calculating leaf area density (LAD = leaf area density m^2/m^3) from absolute canopy height and LAI distribution will result in Fig. 9 (center). Average LAD for the plot area is about 0.25 m^2/m^3. Highest values are usually found where vegetation is relatively low, but where a mature succession stage has already been reached. By contrast, low values are found where there is a high canopy or a young gap.

DISCUSSION

Comparing our results with published data on LAI, they are in agreement with values from other moist tropical lowland forests (Table 2). The average LAI is lower by far than the maximum values of 8 reported in Leigh (1999). Eight m^2 of leaves/m^2 removes more than 99% of the incoming PAR. Only about 1% of the incident light reaches the forest floor, barely enough to allow its ground herbs to survive (Leigh 1999). Honzák *et al.* (1996) point out that light profile measurements generally tend to underestimate LAI compared with other methods. Higher values result from direct sampling methods. The deviations from the ideal exponential light distribution, which is the basis of the Beer-Lambert proposal, are responsible for this underestimate. This problem also occurs with mobile LAI measurement systems like Li-Cor 2000.

The application of the LAI values obtained enables important conclusions to be made. Satellite-based large-scale analyses rely on reflectance data from the vegetation-covered earth surface. LAI values are usually derived by combining different spectral channels (Jordan 1969, Smith *et al.* 1991). To validate these, data ground-checks such as the one presented here are indispensable.

Despite the fact that the average curve (Fig. 7) shows some significant differences from the ideal curve, our results fit well into the model of vertical differentiation of light environments within a tropical moist forest published by Parker (1995 and pers. comm.).

LAI is also of major importance in local water and energy balances. Leaf area is the relevant exchange surface for processes of interception and transpiration, as well as for radiation, converting it to sensible and latent heat.

Our currently published data on the transpiration rate of the Surumoni forest yield an average of 11% of gross rainfall, which is 3151 mm (Szarzynski 2000). Transpiration is measured in a part of the plot with lower than average LAI values of about 3.3. Average LAI of the plot however is 4.2. This could lead to a higher overall plot transpiration rate, such as was measured immediately at the 10 trees studied. Further modification of these values is expected after considering other structural parameters like basal area, crown area, and inventory of species.

The same holds true for the interception data calculated so far. These measurements are made in an area of higher than average LAI (5.3), which could mean a lower interception loss for the whole stand than the proposed 17 % (Anhuf *et al.* 1999).

To summarize, LAI is appropriate for validating the measurements of meteorological parameters on the microscale (10^{-2} to 10^{2} m, Schönwiese 1994), i.e., the scale of the climatic factors affecting fluxes and gradients within the stand and in the boundary layer directly above the canopy. It is also useful in transforming this data to the mesoscale, thus enabling the validation of hydroclimatic factors derived from remote sensing.

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