Photographic method to measure the vertical distribution of leaf area density in forests

Patrick Meir\textsuperscript{a,}\textsuperscript{*}, John Grace\textsuperscript{a}, Antonio C. Miranda\textsuperscript{b}

\textsuperscript{a} Institute of Ecology and Resource Management, University of Edinburgh, The King’s Buildings, Mayfield Road, Edinburgh EH9 3JU, UK
\textsuperscript{b} Departamento de Ecologia, Universidade Nacional de Brasilia, 70910-900, Brasilia, DF, Brazil

Received 26 July 1999; received in revised form 20 January 2000; accepted 1 February 2000

Abstract

Many current vegetation–atmosphere models require structural information describing the canopy in order to calculate rates of mass and energy exchange. One of the most important pieces of information is the variation with height in leaf area density, $\rho$ (m$^2$ leaf area per m$^3$ canopy volume), but it is notoriously difficult to measure this in forest canopies. Consequently, very few data on $\rho$ exist for tall tropical forests. We describe a relatively rapid photographic method to make this measurement and we demonstrate its use for a rain forest in Cameroon, and two rain forests in Brazil. The method requires an assumption or knowledge of leaf angle distribution, but is relatively rapid and has the benefit of sampling a relatively large volume of canopy. The technique works adequately, especially if the leaf area index of the site is already known; the results agree quantitatively and qualitatively with previous more laborious determinations. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Leaf area density; Tropical forest canopy; Heterogeneity; Foliage; Rain forest; Leaf area index

1. Introduction

Interactions between the land surface and the atmosphere are strongly affected by the vegetation cover. Leaves are the principal sites of mass and energy exchange in a canopy and in consequence the leaf area index, $L$ (m$^2$ leaf per m$^2$ ground area), is an important parameter in productivity models (e.g. McLeod and Running, 1988) and other soil–vegetation–atmosphere transfer models (e.g. Lloyd et al., 1995; Sellers et al., 1997; Waring and Running, 1998).

Many recent models of canopy gas exchange also require the vertical distribution of leaf area density $\rho$ (m$^2$ leaf per m$^3$), with height (Wang and Jarvis, 1990; Reynolds et al., 1992; Williams et al., 1996; Sellers et al., 1997). However, very few such measurements have been made for forests, and even fewer for forests in the humid tropics, where trees may reach 40–60 m and where spatial variation is considerable. A laborious approach to the measurement problem is to sample a forest destructively (e.g. Kato et al., 1978; Hollinger, 1989; McWilliam et al., 1993), although sampling problems are substantial, and there is potential bias in plot selection (cf. McCune and Menges, 1986) as well as the difficulty of assessing leaf height in the original crowns. Where destructive procedures are not possible, indirect methods can be used but are usually limited by the requirement for extensive scaffolding or to canopy heights less than 25 m (MacArthur and Horn, 1969; Wang et al., 1992; Fukushima et al., 1998).

\begin{itemize}
\item Corresponding author. +44-131-650-5744; fax: +44-131-662-0478.
\item E-mail address: pmeir@ed.ac.uk (P. Meir)
\end{itemize}

0168-1923/00/$ – see front matter © 2000 Elsevier Science B.V. All rights reserved.

PII: S0168-1923(00)00122-2
Although there is potential for the remote sensing application of LIDAR to the measurement of $\rho$, this technology may not be available in the near future and will require calibration (Waring and Running, 1998).

Here we describe a method to estimate the vertical distribution in $\rho$ for tall forest canopies where access is limited to a single tower or similar vertical through-canopy structure. The method is similar to one proposed by MacArthur and MacArthur (1961), whereby a target is viewed horizontally through a canopy, and the proportion of the target that is not obscured by leaves is used to estimate the intervening quantity of foliage.

1.1. Theory

The probability, $P$, of a beam of light passing through a horizontal plane of opaque leaves orientated at random to the azimuth has been shown to approximate the Poisson distribution (Levy and Madden, 1932; Warren Wilson and Reeve, 1960; Lang and Yuequin, 1986), such that

$$ P = e^{-L} \quad \text{or} \quad L = -\ln P \tag{1} $$

If light passes through a volume of canopy space at a zenith angle of $\theta_i$, containing leaves in the inclination angle class $j$, then the fraction of true foliage area that is projected onto the horizontal can be represented by an extinction coefficient, $K_{ij}$, whose value will vary according to zenith angle and leaf inclination angle (Norman and Campbell, 1991). If the path length, $L$, through which the light travels is known, then $L$ can be decomposed further into leaf area density, $\rho$, and $L$. Hence, over all leaf inclination and zenith angles,

$$ \ln P = LK = \rho lK \tag{2} $$

This theory has been applied to the estimation of $L$ from hemispherical photographs, using the sky as a ‘uniform’ light target, and taking the fraction of transmitted light through the canopy, $\tau$, as an estimate of $P$ (e.g. Ross, 1981). Indeed, a large literature exists on the use of optical measurement methods for estimating $L$ (e.g. Monsi and Saeki, 1953; Warren Wilson and Reeve, 1960; Anderson, 1971; Ross, 1981; Lang et al., 1985; Campbell and Norman, 1989). We apply it here to measure $\rho$ at different heights, $h$, using as a target a white meteorological balloon raised into the canopy at a known distance, $l$, from the tower. The photographs are taken horizontally from the tower, and hence the apparent zenith angle is reorientated such that $\theta_i$ is taken as zero, whilst $K$ must be estimated. To obtain $\rho$ at $h$ ($\rho_{ah}$), $L$ in Eq. (2) is calculated for each layer of the canopy, and is rewritten $L_h$:

$$ \rho_{ah} = \frac{L_h}{l} \tag{3} $$

The estimate of $K$ can be checked against measured leaf angle distributions (LAD) if they are available, and by allowing for the rotation in view angle of 90°, whereby a naturally planophile LAD would be represented as having a low extinction coefficient rather than a high one. If $K$ is unknown then it must be estimated, as has been done here.

2. Methods

2.1. Sites

The main study site, at 3°23’N and 11°30’W and 650 m above sea level, was in the Mbalma Forest Reserve approximately 10 km from the town of Mbalmao and 60 km south of the capital Yaoundé, in the Central Province of Cameroon. A 45 m micrometeorological tower provided access to the canopy of the surrounding semi-deciduous secondary forest, which was dominated by trees of the Sterculiaceae, Ulmaceae and Leguminoseae families (Ngeh, 1989). The mean canopy height was 36 m. Biomass was estimated at $122\,\text{t}\,\text{ha}^{-1}$ using inventory data for two 1 ha plots and an appropriate empirical equation developed for the site by Deans et al. (1996). The mean value for $L$ (4.4±0.4, S.E.) was obtained from 30 ground-based hemispherical photographs taken at 10 m intervals along two 150 m transects located randomly within a 400 m radius of the tower (Meir, 1996). The photographs were analysed following standard procedures (e.g. Campbell and Norman, 1989), using image analysis software (Optimas v.5.2, Washington, USA). $L$ was recovered by inverting the transmitted fraction signal, using the method of Lang (1987). The structure of the forest close to the tower (<40 m) was heterogeneous: the canopy was well developed to the north and west and affected by a canopy gap to the south and east.
Measurements were also made in two undisturbed forests in Brazil, one in the state of Rondonia, SW Brazil, at the Reserva Jarú (10°04′84″S, 61°56′60″W) and the other in the state of Amazonas, in the north of Brazil, in the Reserva do Cuieiras (2°35′22″S, 60°06′55″W). The first was classified as ‘open tropical rain forest’ (IBGE, 1993), and had a canopy height of 35–45 m; the second was classified as ‘dense tropical rain forest’, with a canopy height of 35–40 m. Full site descriptions can be found elsewhere (Jarú: Gash et al., 1996; Cuieiras: Malhi et al., 1998). A published dataset (McWilliam et al., 1993), obtained by destructive sampling of a fourth forest site, ‘Fazenda Embrapa’, which was similar in structure and close to the Cuieiras forest in Brazil, was used to compare with the measurements from the Mbalmayo, Jarú and Cuieiras reserves.

2.2. Measurement procedure

A white meteorological balloon inflated with hydrogen was allowed to rise into the canopy at four points, north, south, east and west of the tower. The balloon was tethered at ground level 25 m from the tower and used for measurements at 2, 8, 16, 24, 32 and 40 m vertically above this point. A Nikon FE2 camera fitted with a Nikkor 300 mm lens and Kodachrome 200 ASA film was positioned on the tower at each measurement height and then levelled using a tripod and spirit level. The exposure for the white target was judged using the light meter of the camera. The balloon diameter was measured before and after taking the photographs (mean diameter was 0.64 m) and used to determine the border of the balloon in dense canopy. Photographs were taken in the early morning to avoid windy conditions, leaf reflections and shadows on the target.

A high resolution digital record (850×1024 pixels per inch) of each photograph was made using a Mikrotek Scanner (Mikrotec, Overath, Germany). Optimas software (Optimas v.5.2, Washington, USA) was then used to analyse the target image, seen as a semi-obscured white disc in the canopy. On a grey-scale image gap fraction estimates were made by setting a threshold value for dividing the pixels into black (leaf) and white (balloon, i.e. ‘gap’). To minimise subjectivity at this point, a number of test slides were used to determine the optimum set up of the software with regard to contrast, brightness and black-white threshold. At the two measurement sites in Brazil this method could not be followed exactly because of logistical constraints, and instead duplicated independent visual estimates were made of the gap fraction visible on the target. The results are presented here for comparison, and only the data from Cameroon are analysed in detail. Further comparison is made with the published data from a destructively sampled site, ‘Fazenda Embrapa’, relatively near to the Cuieiras reserve (McWilliam et al., 1993).

The calculation of $\rho$ was done in two ways using Eqs. (2) and (3). In the first, the leaf angle distribution of the canopy was assumed to be spherical, where $K=0.5$ (Monteith, 1969). In the second, the effect of $K$ on $\rho$ was estimated using three different theoretical ‘canopies’ with specified leaf angle distributions (Table 1). The leaf angle distributions used for these test canopies ($K=0.5–0.8$) cover the range reported for broadleaf canopies (Jarvis and Leverenz, 1983); the $K$ values applied in Eq. (2) represented each canopy volume as viewed horizontally. For the forests at Mbalmayo, Jarú and Cuieiras $\rho$ at each height was subsequently calculated assuming $K=0.5$, summed for each profile to give $L_p$ and the mean of these values, $L_{pa}$, was compared with existing estimates of $L$ obtained using separate methods. These indirect measurements were then compared with direct measurements published for a site similar in structure and close to the Cuieiras forest in Brazil (McWilliam et al., 1993).

### Table 1

<table>
<thead>
<tr>
<th>Height (m)</th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>0.5</td>
<td>0.8</td>
<td>0.5</td>
</tr>
<tr>
<td>8</td>
<td>0.5</td>
<td>0.8</td>
<td>0.5</td>
</tr>
<tr>
<td>16</td>
<td>0.5</td>
<td>0.7</td>
<td>0.6</td>
</tr>
<tr>
<td>24</td>
<td>0.5</td>
<td>0.6</td>
<td>0.7</td>
</tr>
<tr>
<td>32</td>
<td>0.5</td>
<td>0.5</td>
<td>0.8</td>
</tr>
<tr>
<td>40</td>
<td>0.5</td>
<td>0.5</td>
<td>0.8</td>
</tr>
</tbody>
</table>

*Canopy A represents a spherical distribution; B represents a canopy varying from a spherical to planophile distribution (from top to bottom); canopy C represents an erectophile to spherical distribution.*
Fig. 1. Vertical distribution in leaf area density (ρ) within 25 m of a tower in a secondary forest, Mbalmayo Reserve, Cameroon; (a) Individual profiles in ρ (assuming a spherical leaf angle distribution); (b) Mean ρ (ρa) is given ± one standard error.

3. Results

For the forest at Mbalmayo in Cameroon, the shape and sum of the vertical profiles in ρ varied somewhat among the cardinal points (Fig. 1a and b, Table 2). The averaged profile showed a relatively high ρ at 25–30 m, and also near the ground, with Lρa=3.5 (±0.7 S.E.; n=4). This is less than, though not significantly different from, the area-averaged mean L of 4.4 (±0.2 S.E.; n=30) obtained from ground-based hemispherical photographs. The differences among the profiles correlated with canopy disturbance near the tower, though most of this disturbance was to branches rather than whole trees. To the south, the canopy was strongly affected by a tree-fall gap and Lρ was low (1.7; canopy-tops 24–32 m), to the east the canopy was slightly affected by the same gap (Lρ=3.2; canopy-tops 32–40 m) and to the west and north the canopy was relatively undisturbed (canopy tops 30 m–40 m). Lρ was higher in these two profiles (4.3 and 4.4, respectively).

The influence of K upon the calculation of ρ in Eqs. (2) and (3) is shown in Fig. 2 where ρa was plotted for the theoretical ‘canopies’ specified in

![Diagram](image1)

![Diagram](image2)

Table 2
Leaf area index, Lρ, calculated by summing measurements of leaf area density at different heights obtained using Eq. (3) and assuming K=0.5:

<table>
<thead>
<tr>
<th>Profile direction</th>
<th>Lρ</th>
<th>Lρ/L</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>4.5</td>
<td>1.02</td>
</tr>
<tr>
<td>W</td>
<td>4.3</td>
<td>0.98</td>
</tr>
<tr>
<td>S</td>
<td>1.7</td>
<td>0.25</td>
</tr>
<tr>
<td>E</td>
<td>3.5</td>
<td>0.73</td>
</tr>
</tbody>
</table>

* Lρ values from four profiles are shown: N, S, E, and W refer to compass directions from the tower. Also shown for each profile is the fraction Lρ/L (units: m² leaf area per m² ground area), where L has been obtained independently.
Fig. 3. Vertical distribution in leaf area density, $\rho_a$, for four rain forests: (1) Mbalmayo; (2) Jarú; (3) Cuieiras and (4) ‘Fazenda Embrapa’. Values for (1)–(3) are scaled to leaf area index, $L_r$, using the formula $(\rho_{ah}/L_{pa})L$, where $\rho_{ah}$ is the mean leaf area density at height, $h$, and $L_{pa}$ is mean leaf area index calculated by summing $\rho_{ah}$ for all heights. The data for site (4), close to site (3), were obtained by destructive sampling (McWilliam et al., 1993).

Table 1, using the gap fraction measurements obtained in the forest at Mbalmayo. $L_{pa}$ varied from 3.5 to 4.5, and the proportional variation in $\rho_{ah}$, that is the shape of the profile, varied by 11–27% ($\rho_{ah}/L_{pa}$ varied by 11–27% of the mean; Fig. 2).

The results for the two additional measurement sites in Brazil showed a pattern similar to that found in Cameroon, with high $\rho$ in the upper-canopy and lower $\rho$ in the middle-lower canopy (Fig. 3). The canopies varied, however, in the understory value for $\rho$ according to forest type: the forest at Jarú, Brazil, had low $\rho$ near the ground, whilst the other two forests had relatively high values. The profile in $\rho$ for the Cuieiras site was also very similar to that obtained by destructive sampling for a similar nearby forest (McWilliam et al., 1993; Fig. 3). The value for $L_{pa}$ was highest for the dense undisturbed forest at Cuieiras, and more similar for the less dense forests at Jarú and Mbalmayo. These values are in approximate agreement with estimates of $L$ obtained using different methods (Table 3).

### 4. Discussion

In order to use this method, it is necessary to know or assume the leaf angle distribution in the canopy at different heights as this determines the extinction coefficient, $K$, and hence the calculation of $\rho$ in Eq. (2). Fig. 2 shows that $\rho$ and $L_{pa}$ vary by 11–27% in response to the range of $K$ previously reported for broadleaf canopies (Jarvis and Leverenz, 1983). The largest uncertainty is observed near the ground partly because $L_{pa}$ is more sensitive to small changes in $K$ for planophile leaf angle distributions than for spherical or erectophile ones (data not shown).

$K$ is known to vary with height in a canopy (Ross, 1981), but its value is poorly known for forests. More accurate measures of $\rho_{ah}$ will therefore require basic measurements of leaf angle distributions at different canopy heights using direct or indirect techniques. However, since the shape of the vertical profile of $\rho$ does not change qualitatively (Fig. 2) an initial corrected estimate can be made using an independent measure of $L$ to scale $\rho_{ah}$ accordingly ($(\rho_{ah}/L_{pa})L$). The mean profiles in $\rho_{ah}$ for Jarú, Mbalmayo and Cuieiras in Fig. 3 have all been calculated using independent measures of $L$ and assuming $K=0.5$. Despite this assumption, and the additional requirement for Eq. (2) that foliar arrangement in space is random rather than slightly clumped (Nilson, 1971; Chen et al., 1991), the measurements in all three forests yielded profiles in $\rho$ that agreed with those obtained elsewhere (Kato et al., 1978; Chason et al., 1991). Furthermore, the values from the Cuieiras site in Brazil were very close to a previous measurement at a similar nearby forest, obtained using destructive sampling methods (Fig. 3; McWilliam et al., 1993).
the ground, the large $\rho$ in the understorey found by McWilliam et al. was also found for Cuieiras.

Appropriate sampling of spatial heterogeneity is a key problem in the description of forest canopies, and, as expected, measurement uncertainty was greater here in the more open and spatially heterogeneous canopies (Table 3). To overcome this constraint in shorter canopies, appropriate measurements can be made by attaching a sensor to a mobile hydraulic tower (Wang et al., 1992), but this is not practical in tall forests. Strachan and McCaughey (1996) addressed the problem by directing a sensor face-upwards at different heights on each side of a tower. However, the profiles in $\rho$ obtained in this way would have sampled the spatial heterogeneity in their canopy at only a few points very close to the tower.

A different optical point-quadrat method devised by MacArthur and Horn (1969) and later tested by Aber (1979) and Fukushima et al. (1998) allows measurements to be made from the ground, hence making spatially robust sampling a possibility. However, the necessary estimates of leaf height using a telephoto lens include increasingly large errors above 25 m (Aber, 1979), exactly where leaf area and physiological activity are high and individual leaves most difficult to identify in tall dense forests (~50% of leaf area is found above 25 m in Figs. 2 and 3). The method described here samples a total horizontal pathlength of 100 m ($4 \times 25$ m at each height) and with a similar degree of precision through most of the vertical profile of the canopy. Although these measurements remain constrained by certain assumptions and the position of the tower, this is a relatively large spatial sample that extends into several tree canopies and consequently confers more confidence upon the final estimate than has previously been possible.

5. Conclusions

Whilst uncertainties remain with this method, when it is used in conjunction with independent measurements of $L$, a relatively good spatial sample in $\rho$ can be obtained at relatively low cost. If additional basic measurements of the variation in leaf angle distribution with height are combined with this technique it may provide one solution to a challenging measurement problem.

Acknowledgements

The authors wish to thank L. Gormley, B. Kruijt, J. Lloyd, J. McIntyre, Y. Malhi, A. Nobre, and R. Ribeiro for invaluable help in the field or for comments on an earlier draft. This work was supported in part by the NERC programme ‘Terrestrial Initiative for Global Environment Research’, TIGER, (grant no. GST/02/065), and DFID (Brazil-UK, ABRACOS project).

References


