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SHORT COMMUNICATION

Fast determination of light availability and leaf area index in tropical forests

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An important property of plant communities is the Leaf Area Index (LAI), which is the vertically integrated surface of leaves per unit of ground area. Leaves are the primary sites of photosynthesis and transpiration, thus the LAI, which conditions the light interception by the canopy, is directly related to carbon and water exchange with the atmosphere at the stand scale (McNaughton & Jarvis 1983). LAI also has an impact on tree growth through the interception of light. Light availability below canopies is the principal limiting factor of tree recruitment and growth in forests (Denslow *et al.* 1990). Several methodologies have been used for measuring LAI in the field. These can be classified in four categories (Marshall & Waring 1986): (1) direct measurements by litterfall collection or destructive sampling, (2) allometric correlations with variables such as tree height or tree diameter, (3) gap-fraction assessment (e.g. with hemispherical photographs), (4) measurement of light transmittance with optical sensors.

In the latter case, light availability is directly measured by the sensor. Light

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attenuation by successive leaf layers is related to LAI and is approximated by the Beer–Lambert law:

$$I = I_o e^{-k\,\mathrm{LAI}} \tag{1}$$

where I is the irradiance at the ground level and I_o is the irradiance above the canopy; the extinction coefficient k is related partly to the optical properties of the leaves and mainly to the structural properties of the canopy (height, stem density, leaf clustering and inclination, etc.); it also depends on the radiation waveband that is considered. Simultaneous measures of I and I_o yield a practical measurement of the LAI, provided that either an estimation of k or an adequate description of the foliage geometry is provided. The LICOR LAI2000 (LICOR, USA) instrument is often used, as it provides a method to reconstruct absorption properties of the canopy and leaf angle distributions from ground-based measurements (Welles & Norman 1991). Extinction properties and geometrical structure of the canopy are calculated from simultaneous measurements of light transmission under five different angles, measured by five annular detectors, normalized to incident light values taken in the open. In an agricultural field it is usually easy to take recordings above the foliage canopy. In forests, this is more difficult: one needs to find clearings that are not too far from measurement sites. In most cases, one must have two devices, that may be widely separated and then possibly uncorrelated. However, it is difficult to use these instruments in tropical forests, as the devices are bulky, heavy and fragile. Moreover they are very expensive, which is a major drawback since most tropical forests are in developing countries. It is thus of interest to devise a fast, easy-to-calibrate and cheap method for measuring light absorption in dense forests.

In this paper we describe a method to measure the light under the canopy with a simple and very handy instrument (further called LAIL, Figure 1 insert). The light sensor combines a hemispherical (fisheye) lens, consisting of standard 180° spy-hole optic (we used several, the type has no great influence on operation, in the experiments shown here we used a cheap off-the-shelf US$4 model), with a commercial photoresistor (ref. VT 935 G, EG & G Vactec, USA) and a digital multimeter available at about US$10 (standard, non-professional type, used on the 10 or 100 kΩ scale). The light collected by the lens is focused on the resistor. The output of the sensor is then a resistance R which gives a 180°-integrated measure of the transmitted light. The photoresistor is sensitive to light in the PAR region, between 400 and 750 nm, its peak response being centred at 600 nm. The detector is completely insensitive in the near infrared region of the solar spectrum (this is important as the visible/NIR ratio is considerably altered under the canopy). We characterized the resistance versus radiation response of the LAIL. For this we set the apparatus in full sunlight, on a day without clouds to have stable conditions. We used neutral filters (NG

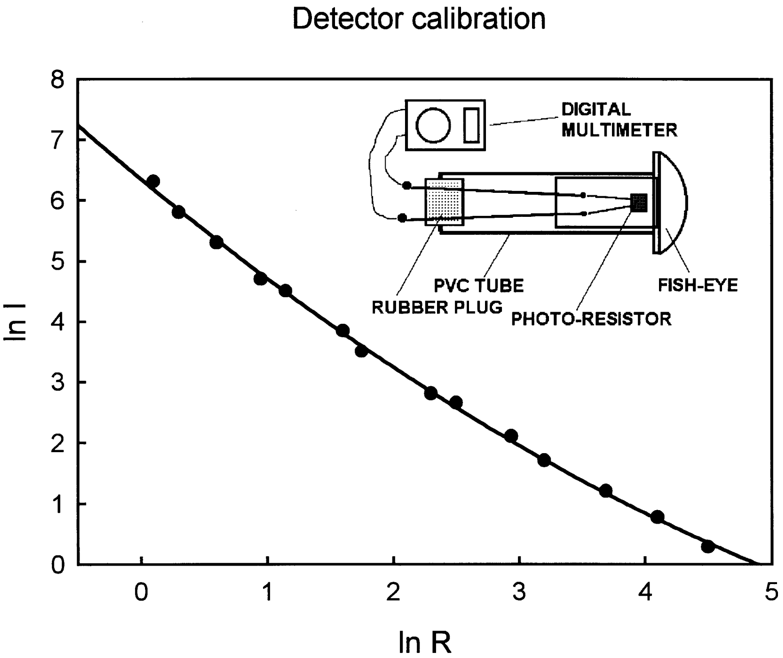

Figure 1. Main: Response of the resistance value R (kΩ) to incident solar radiation I attenuated through neutral filters from 3 to 1100 W m^{-2} –values log$_e$-transformed–. The response curve is approximated by a second order polynomial. Insert: Schematic representation of the LAIL device (total length: 12 cm).

series, Corion, USA) to vary the amount of radiation on the detector. We measured solar radiation in the same conditions with a pyranometer (LI-200SB, LICOR, USA), concurrently with LAIL resistance values (Figure 1 main).

Light measurements in the forest aim to collect the average light transmitted under the canopy. For this, we took readings with the LAIL above head height, in diffuse light (out of sunflecks) and at a reasonable distance from any large leaf or branch (typically 0.5 m). We averaged several readings at each location (obtaining a stable reading typically takes 1 s). To operate in conditions where k is least variable, we choose the hour at which light is most stable and the contribution of leaf angle to light diffusion varies as slowly as possible, i.e. when the sun is close to the zenith (within 1.5 h of solar noon in the tropics). Assuming that light transmitted under the canopy (I) is related to incident light (I_o) through the Beer–Lambert extinction law (Eqn 1) one can calculate the LAI, given k, I and I_o:

$$k \times \mathrm{LAI} = -\ln(I) + \ln(I_o) \tag{2}$$

ln (I) is directly measured by the LAIL, the relationship between ln(I) and ln(R) (Figure 1) being correctly approximated by a second-order polynomial ($R^2 = 0.9996$).

Note that ln(I_o) appears in Eqn 2 as an offset coefficient which depends upon the light incident above the canopy and not upon the apparatus used. The need for a reference I_o measurement in a wide clearing or above the canopy is extremely cumbersome, especially considering the highly variable cloudiness in rain-forest habitats: one must either climb a tree at every spot, and take simultaneous measurements above and below the canopy, or, as is usually done with LAI 2000, to rely on simultaneous automatic data logging done in a clearing distant from the spot, sometimes leading to errors due to differences in local cloudiness.

But the need for a precise I_o reference might not be so critical depending on the precision level which is required. For instance, PAR at noon in French Guiana usually fluctuates between around 500 Wm^{-2} (clear blue sky) and 125 Wm^{-2} (deep cloudiness), and then the amplitude of ln(PAR) variation is around 1.4. Consequently, even if nothing was known about variations in I_o, taking a log-average value of 250 means that $k \times LAI$ error is not expected to be greater than 0.7. These values were estimated from meteorological records at Cayenne (courtesy of Mr J. Groussin), assuming PAR proportion to be about 0.5 of total solar radiation (Ross 1975). On the other hand, some objective (operator-independent although non-quantitative) criteria for characterization of the light conditions can be easily defined *in situ* and used to approximate I_o: presence or absence of sunflecks visible on the ground, and presence or absence of shadows (visibility of the shadow of the operator's arm). We have devised a scale W, with five categories, described thus: B (for Bright), conditions in which the operator clearly sees bright sunflecks on the ground, L (for Lighted), conditions in which no sunflecks are distinguished but shadows are still visible (a common test is to check if the shadow of the operator's arm is visible), BL for intermediate conditions (sunflecks of low intensity with fuzzy contours), C (for Covered) conditions in which no shadow is visible, and LC (between L and C) when shadows are marginally distinguished. The W scale thus reads, with increasing cloudiness: B, BL, L, LC, C. In very dark or rainy conditions, measurements are poorly reliable, so we do not take any. Figure 2 shows means from 200 irradiance records taken in the Nouragues quadrats in French Guiana, grouped by class of W values. In order to determine the relationship between W and $\ln(I_o)$, we plotted $\ln(I)$, averaged among different quadrats, against W classes. Indeed $\ln(I) = \ln(I_o) - k \times LAI$: as we can expect the average $k \times LAI$ value to be constant, variations of average $\ln(I)$ are statistically attributable to fluctuations in $\ln(I_o)$. Between the successive light regimes defined above, variations in $\ln(I)$ show a remarkable linear trend: when offset at 0 for B, deviation is around −0.26 for BL, −0.53 for L, −0.79 LC and −1.06 for C. We can thus directly suggest a $\ln(I_o)$ correction scale for $k \times LAI$ estimation from these W-scale measurements: in practice we add an experimental average offset value corresponding to B (910 W m^{-2} solar radiation, i.e. about 455 W m^{-2} PAR) to the detector response in Eqn 2, so that the 0.26-stepped correction coefficients from 0 (B) to −1.06 (C) are directly applied by the user. We can expect that the use of these eye-based criteria will reduce the approximation

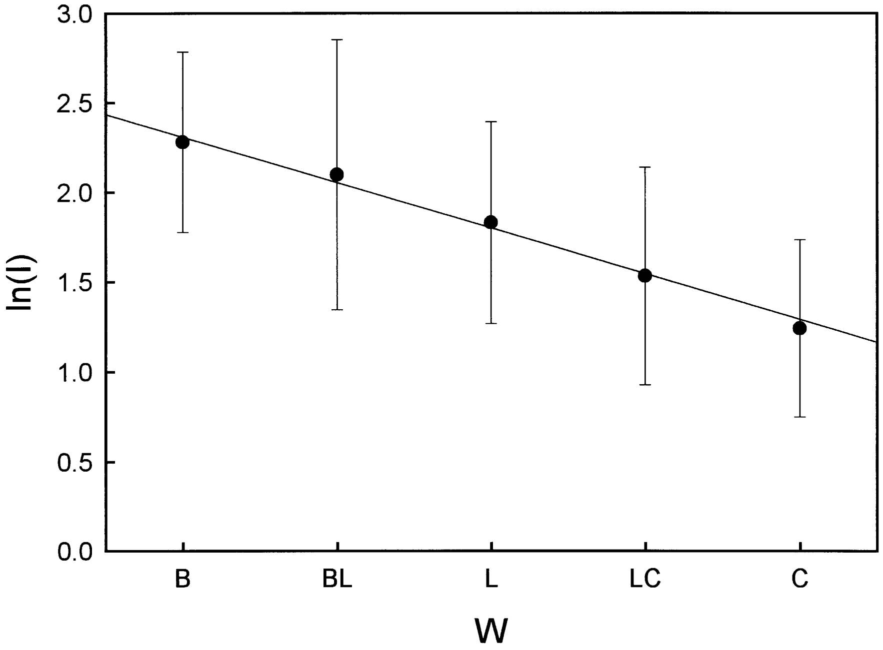

Figure 2. Variations of average ln(I) in the Nouragues quadrats in function of eye-separated classes of incident light (W scale, see text for the meaning of letters on the x-axis).

error in $\ln(I_o)$ (and consequently in k × LAI) to about ± 0.26. This was tested by fixing the sensor on four posts in the open and in the forest: the SD of estimated k × LAI for each post falls from around ± 0.45 from the uncorrected data to ± 0.25 for the corrected data in average (Table 1).

In order to estimate LAI, one must find a way to get a value for k. k might be known (or approximated) from previous studies or can be calibrated with a method that does not need a prior k estimation such as the method developed by LICOR (Welles & Norman 1991). We followed the second option by comparing the output of our sensor to the values given by the LAI2000: this led to an average k value of 0.88 under our measurement conditions. We note that this value is in the higher range of PAR extinction coefficients as measured by Wirth *et al.* (in press) in tropical forests (0.7 to 0.9). Fixing k to this value, we could test the ability of the apparatus to describe LAI fluctuations. In Figure

Table 1. k × LAI (mean ± SD) values calculated from LAIL measurement series made at four sites in the Nouragues station (French Guiana), before and after applying the incident light correction coefficients deduced from the visual W scale. IT: top of the inselberg; DZ: helicopter drop zone (the influence of surrounding trees is still perceptible at the measurement point); and two different sites within the forest.

	IT	DZ	Forest (1)	Forest (2)
Before correction	0.3 ± 0.48	0.9 ± 0.65	5.5 ± 0.31	6.2 ± 0.36
After correction	0.06 ± 0.26	0.6 ± 0.34	5.1 ± 0.18	5.7 ± 0.21

3a, we show LAI measurements made simultaneously with a LAIL and a LAI 2000 LICOR apparatus, for 20 locations in mature forest (Plot 16) at Paracou Research Station (French Guiana). We can see that LAI estimations were in agreement, except in the fourth series. The reference light measurement for the LAI2000 was made from a post in the middle of a clearing about 3 km from Plot 16. Clouds were conspicuous above the reference post during the fourth series of measurements, while Plot 16 was still in full sun: the low LAI values obtained by the LAI2000 in the fourth series are thus erroneous, and due to the differences of incident illumination between reference and measurements. In other series, we note that LAI2000 and LAIL both give equivalent estimates of LAI variations. We have also tested how LAIL measurements are reproducible and independent of the operator in several locations. Figure 3b illustrates the concordance of W estimates between independent operators: two series of LAI estimations were done on the same forest-savanna transect at Kandara (eastern Cameroon), on different days by two untrained operators, and we see that the two curves are remarkably similar. At ~370 m, the drop in LAI is due to a clearing which was on one side of the transect, while the drop at ~520 m is the transition to savanna. This method thus appears quite reproducible and reliable to assess and quantify vegetation transitions such as forest/savanna ecotones, intensity of perturbations such as clearings, etc. These can be quickly recorded and mapped for monitoring ecological changes or exploitation.

Norman & Campbell (1989) note that taking measurements near noon minimizes penumbral effects. In this case, a simple exponential extinction law should apply to light extinction by the canopy, as shown by Ellsworth & Reich (1993). By choosing these conditions for operation, we show that a simple instrumentation can be used to estimate canopy density in tropical forests. As it does not have angular resolution, the LAIL device estimates k × LAI, i.e. the

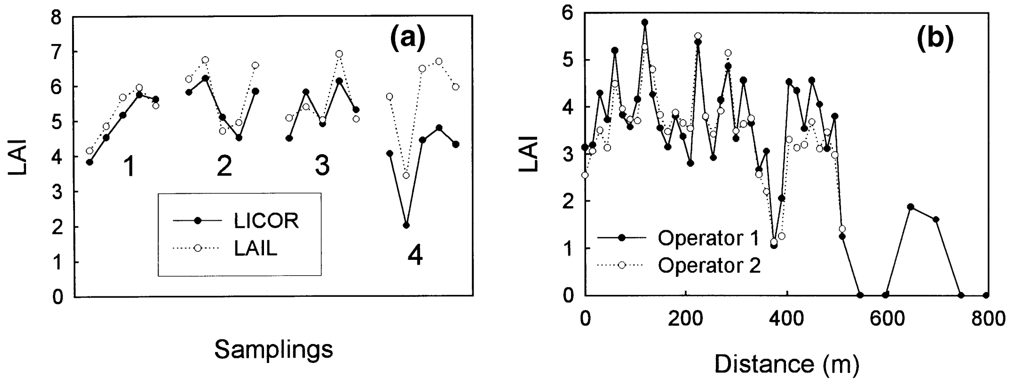

Figure 3. (a): Comparison of LAI estimations obtained simultaneously on 4 transects in plot 16 of Paracou research station, French Guiana, with the LAI2000 (LICOR) apparatus and with the LAIL device. (b): Comparison of LAI values recorded on a transect by two independent operators in the Kandara forest, Cameroon.

light extinction properties of the canopy. To estimate LAI, k must be independently measured or assumed and this is not an easy task. If no previous studies have been performed, several methods are described in the literature and can be chosen to yield k estimates, e.g. foliage collection, geometrical measurements, reconstruction from hemispherical photographs or LAI2000 data. Nevertheless, numerous studies can be performed with an approximate knowledge of k, particularly if only relative measurements are needed, this is the main purpose of our method.

Incident light estimation through visual estimation is particularly useful in forests, as above-canopy I_o values are difficult to measure directly. In the cases that we have studied, it induces an imprecision which can be estimated, when reported on deduced LAI, to be within the range of ± 0.3. Relative values are comparable to results given by a more sophisticated device such as the LAI2000. Reproducibility is of course impaired by the inherent uncertainty due to eye classification of I_o, but the final result is not so far from that of commercial instruments (in part owing to the advantage of *in situ* estimation of incident radiation). Of course, it must be kept in mind that, due to approximation in k, this approach does not give absolute LAI values and it would be hazardous to use it in order to compare forest types from different regions or with different structures without additional information. However, the bulk of data that we acquired in various locations (French Guiana, Cameroon, Madagascar, Bolivia) indicates that correction scales and coefficients should be of comparable values across a wide range of tropical rain forests.

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